

## Overview of Geology, Hydrology, Geomorphology, and Sediment Budget of the Deschutes River Basin, Oregon

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Within the Deschutes River basin of central Oregon, the geology, hydrology, and physiography influence geomorphic and ecologic processes at a variety of temporal and spatial scales. Hydrologic and physiographic characteristics of the basin are related to underlying geologic materials. In the southwestern part of the basin, Quaternary volcanism and tectonism has created basin fills and covered and deranged the surficial hydrologic system, resulting in a relatively low-relief lava-covered landscape with runoff emerging largely from extensive groundwater systems fed by Cascade Range precipitation. The remarkably steady flows of the entire Deschutes River, as depicted in annual and peak flow hydrographs, are due primarily to buffering by the extensive groundwater system of this part of the basin. The eastern part of the basin is primarily underlain by Tertiary volcanic, volcanoclastic, and sedimentary rocks that have weathered into dissected uplands with generally greater slopes and drainage densities than of that of the southwestern part of the basin. Surficial runoff is more seasonal and less voluminous from this more arid part of the basin. The northern part of the basin has been sharply etched by several hundred meters of late Cenozoic incision, resulting in the greatest relief and drainage density of anywhere in the basin. For large floods, such as those of December 1964 and February 1996, more than half of the peak flow at the mouth of the Deschutes River is derived from the northern part of the basin. Modern sediment yield for much of the Deschutes River basin, as determined from reservoir surveys, is exceptionally low and is related to regional slope and drainage properties. Broad-scale sediment budget calculations indicate that more than 50 percent of the sediment produced in the Deschutes River basin produced under modern, pre-impoundment, conditions is from the northern part of the basin. There is ample evidence, however, of much greater sediment yields and large pulses of downstream sediment delivery during Quaternary episodes of volcanism and glaciation.

### INTRODUCTION

The Deschutes River is remarkable. Its uniform, spring-fed hydrologic regime has long impressed geographers and

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hydrologists [e.g., *Russell, 1905; Henshaw et al., 1914*]. Partly in conjunction with the stable flow regime, modern sediment production is exceptionally low over much of the basin. These two factors have combined to create an unusually stable geomorphic system over human time scales. Consequently, as will be seen in following chapters, it is a river system in which impoundments have had few apparent geomorphic effects on the downstream channel and valley bottom of the Deschutes River system.

However, the Deschutes River basin has not been similarly quiescent over geologic time scales. Extensive volcanism, regional and local tectonism, landslides, and cataclysmic floods have all left their mark across the landscape. Moreover, as is the case for most large basins, the resulting geomorphic characteristics, such as topography, hydrology, and sediment yield, vary widely. The modern Deschutes River, with its stable hydrologic and geomorphic regime and rich aquatic ecosystems, is the combined result of (1) these past processes and events and (2) the present regime of sediment and water yield established by the regional geology. To understand the Deschutes River and its response to impoundment, it is necessary to understand this geologic and hydrologic context.

This paper provides an overview of the geologic, hydrologic, and geomorphic setting of the Deschutes River basin, with special emphasis on aspects that have influenced how the river has responded to impoundment by the Pelton-Round Butte dam complex. This overview sets the stage for companion studies of the valley bottom, channel, and fish ecology of the Deschutes River, which comprise the other papers in this volume.

#### GEOLOGY, TOPOGRAPHY, HYDROLOGY, AND SEDIMENT TRANSPORT OF THE DESCHUTES RIVER

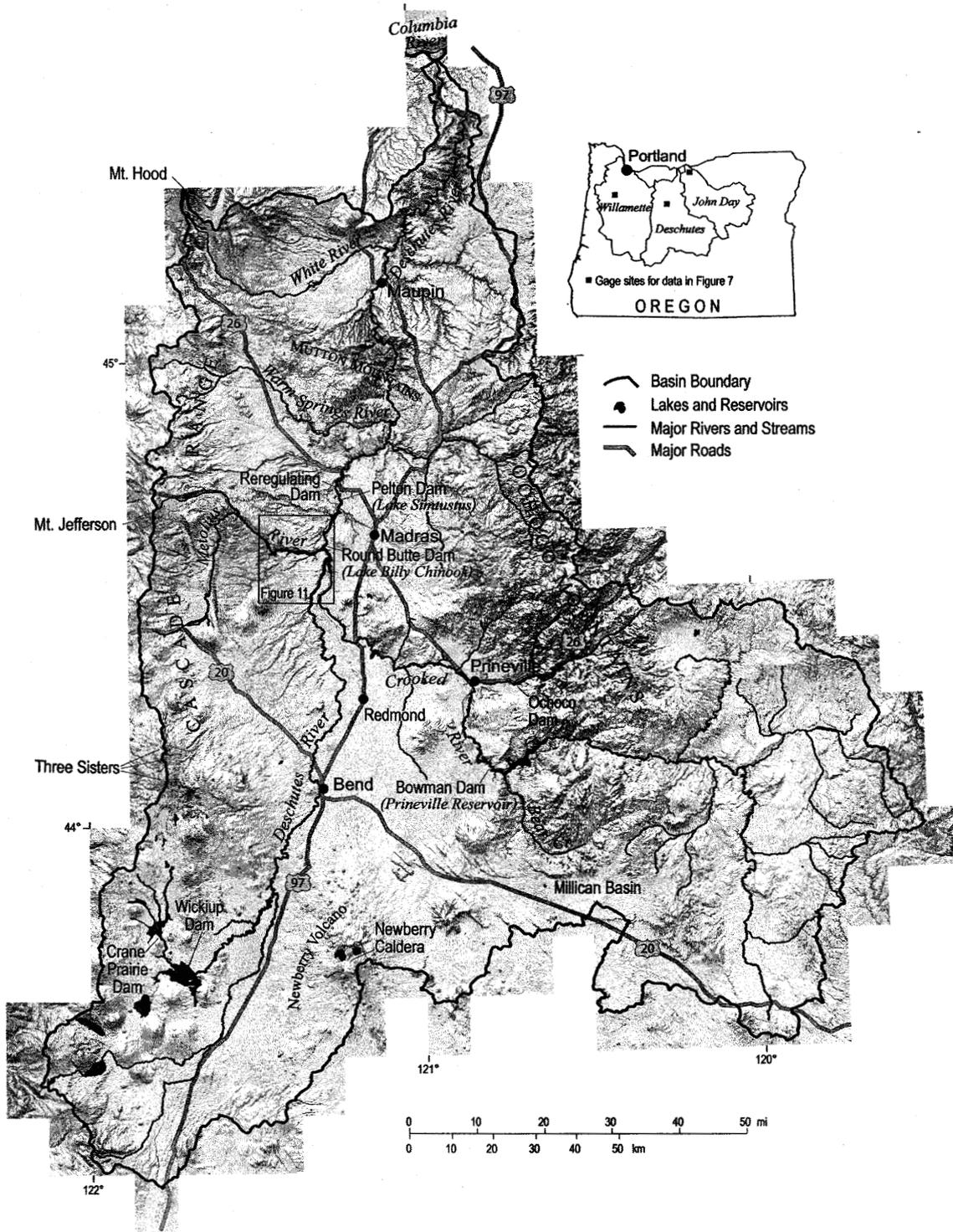
The Deschutes River drains 26,860 km<sup>2</sup> of north-central Oregon<sup>1</sup>, first flowing south from its Cascade Range headwaters, then northward for nearly 300 km along the eastern margin of the Cascade Range before joining the Columbia River 160 km east of Portland (Figure 1). Its principle tributaries, the Crooked and Metolius Rivers, join the Deschutes River at 185 and 180 km, respectively, from the Columbia River confluence. Portland General Electric and the Confederated Tribes of Warm Springs generate 427 megawatts of power from the Pelton-Round Butte dam complex, a set of three hydroelectric dams located 160 to 180 km upstream from the Columbia River confluence.

<sup>1</sup> The drainage area reported by *Hubbard et al.* [1998, p. 118] for the U.S. Geological Survey gage "Deschutes River at Moody, near Biggs, Oregon (station number 14103000)", 2.25 km upstream from the Deschutes River confluence with the Columbia River, is "10,500 mi<sup>2</sup>, approximately". Our estimate of the drainage basin area, from a geographic information system analysis of the basin outline portrayed in Figure 1 (derived from a 30-meter resolution digital elevation model) is 26,860 km<sup>2</sup> (10,370 mi<sup>2</sup>). We will use the 26,860 km<sup>2</sup> value for discussion and analysis.

#### Geologic Setting

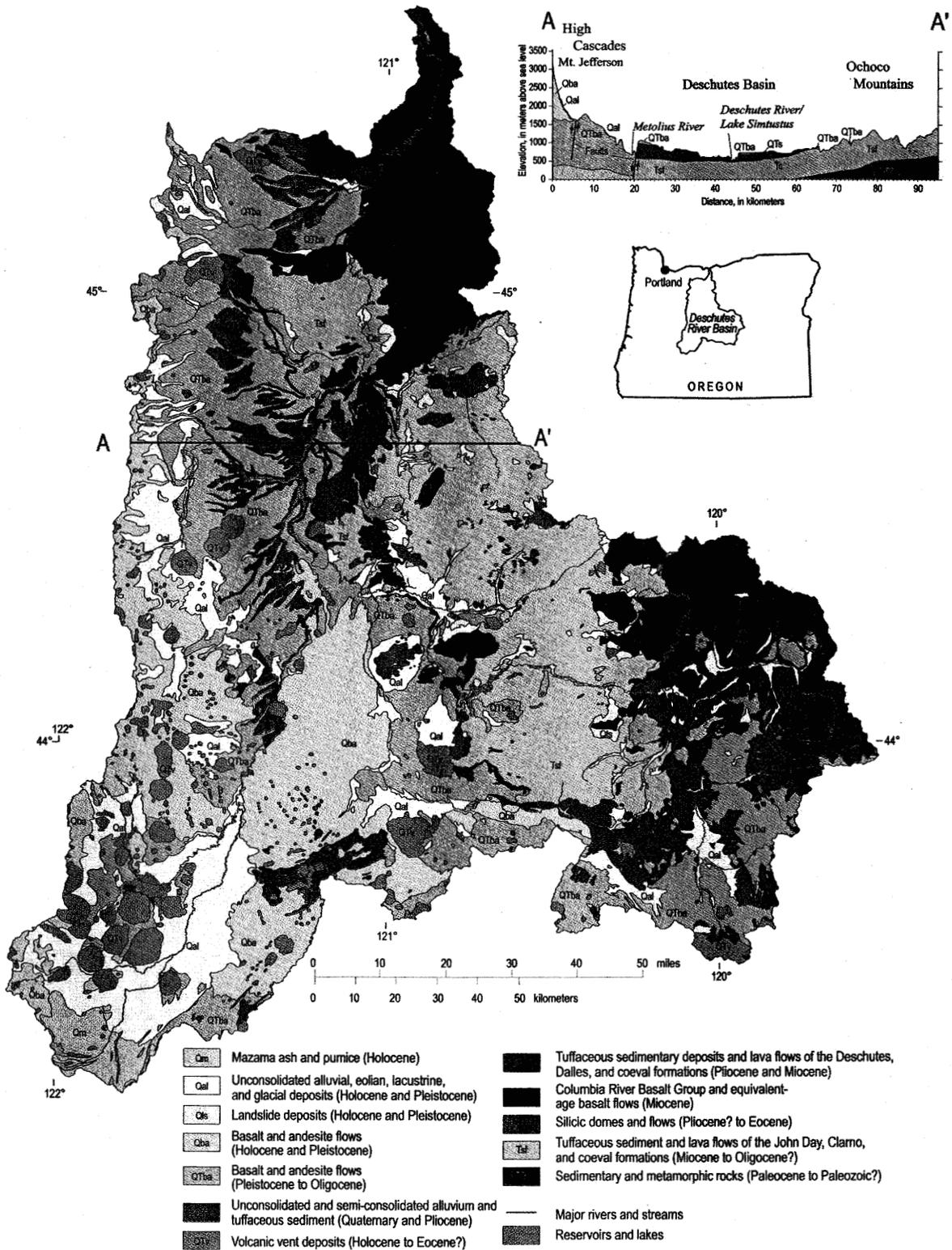
The Deschutes River basin is formed in sedimentary, igneous, and metamorphic rocks, whose ages range from more than 250 million years old to as young as 1300 years old (Plate 1). The vast majority, however, are Cenozoic volcanic rocks (less than 65 million years old), and almost all of these rocks are lavas of various compositions or other eruptive products. In general, bedrock ages become progressively younger from east to west across the basin. Mesozoic (250 to 65 million years old) and Paleozoic (more than 250 million years old) sedimentary and volcanic rocks crop out in a small area at the eastern edge of the Deschutes River basin. Most of the Ochoco Mountains, a low mountain range forming much of the eastern flank of the basin, and the Mutton Mountains, which trend northwest across the north-central part of the basin, are underlain by weathered volcanic, volcanoclastic, and sedimentary rocks of the John Day and Clarno Formations. These rocks date from about 55 to 20 million years old and are remnants of ancient volcanic highlands and their eruptive products [*Robinson et al.*, 1984; *Walker and Robinson*, 1990; *Taylor*, 1990].

Much of the northern and eastern parts of the Deschutes River basin is underlain by the Columbia River Basalt Group (CRBG), a series of accordantly layered basalt flows erupted primarily between 17 and 14.5 million years ago and covering 165,000 km<sup>2</sup> of southern Washington, northern Oregon, and western Idaho [*Tolan et al.*, 1989]. The CRBG in the eastern part of the Deschutes River basin issued from vents in the John Day River basin, whereas CRBG in the northern Deschutes River basin originated as flows that came westward down the ancestral Columbia Plain from numerous vents in eastern Washington, eastern Oregon, and western Idaho, filling the Columbia Plain with up to 600 m of lava, locally separated by thin sedimentary interbeds [*Newcomb*, 1969; *Smith*, 1986, 1991]. The contemporaneous "Prineville chemical-type" basalt flows (mapped as part of the CRBG in Figure 2, although geographically and chemically distinct from the CRBG [*Goles*, 1986; *Reidel et al.*, 1989; *Hooper et al.*, 1993]) erupted near the location of Bowman Dam in the central part of the basin and flowed northward along an ancestral Crooked River to where they are interbedded with the CRBG that filled the Columbia Plain from the north. The distribution of the CRBG and contemporaneous basalt flows indicates that by 17 million years ago, the present overall geometry of the northern Deschutes River basin had been established with northward drainage through lowlands bounded by the Ochoco Mountains on the east and the ancestral Cascade Range on the west [*Smith*, 1986].

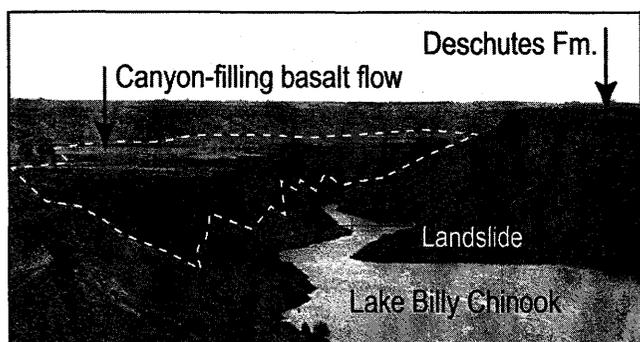


**Figure 1.** Location map showing major physiographic and cultural features of the Deschutes River basin. Hillshade topographic base derived from U.S. Geological Survey 30-m resolution digital elevation data.

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**Plate 1.** Geologic map of the Deschutes River basin, map units and descriptions generalized from *Walker and MacLeod* [1991]. Cross-section after *Smith* [1986].



**Figure 2.** View south up the Crooked River arm of Lake Billy Chinook, impounded behind Round Butte Dam. A basalt flow, age  $1.19 \pm 0.08$  Ma [Smith, 1986], has partly filled the canyon previously incised into lava flows, pyroclastic deposits, and fluvial sand and gravel of the Deschutes Formation. The top of the intercanon basalt flow is 140 m above lake; top of Deschutes Formation is 210 m above lake. Photograph by J.E. O'Connor, 1998.

Deformation during and after emplacement of the Columbia River Basalt Group resulted in isolated basins that accumulated sediment, ignimbrite, and airfall tuffs shed eastward from the emerging Cascade Range and from volcanic highlands in the eastern part of the Deschutes River basin [Smith, 1986; Smith *et al.*, 1989]. These deposits formed primarily between 15 and 4 million years ago and include the Simtustus, Deschutes, and Dalles Formations in the central and northern parts of the Deschutes River basin, and the Rattlesnake Ash Flow Tuff in the southeastern Deschutes River basin [Smith, 1986, 1991; Smith *et al.*, 1989]. Basalt flows and gravel deposits within the Deschutes Formation near Madras show that the course of the Deschutes River 7.4 to 4.0 million years ago was similar to the present course [Smith, 1986, 1987a].

Near the top or capping the Deschutes and Dalles Formations are widespread basalt flows, including the basalt of Juniper Flat near Maupin [ $2.77 \pm 0.36$  Ma; R.M. Conrey, unpublished data, cited in Sherrod and Scott, 1995] and the Agency Plains basalt flow north of Madras [ $5.31 \pm 0.05$  Ma; Smith and Hayman, 1987]. These Pliocene basalt flows cover vast surfaces on the uplands, indicating that the landscape at the time was incised little if at all, and that the Deschutes River and its tributaries were flowing at an elevation near the present canyon rims near Madras and Maupin. Specific evidence is found at Round Butte, near Round Butte Dam, where a  $3.97 \pm 0.05$ -million-year-old basalt flow invaded Deschutes River gravel about 275 m above the present river level [Smith, 1986, 1987b].

The Deschutes and Dalles Formations grade westward into Miocene volcanic rocks of the Cascade Range [Smith *et*

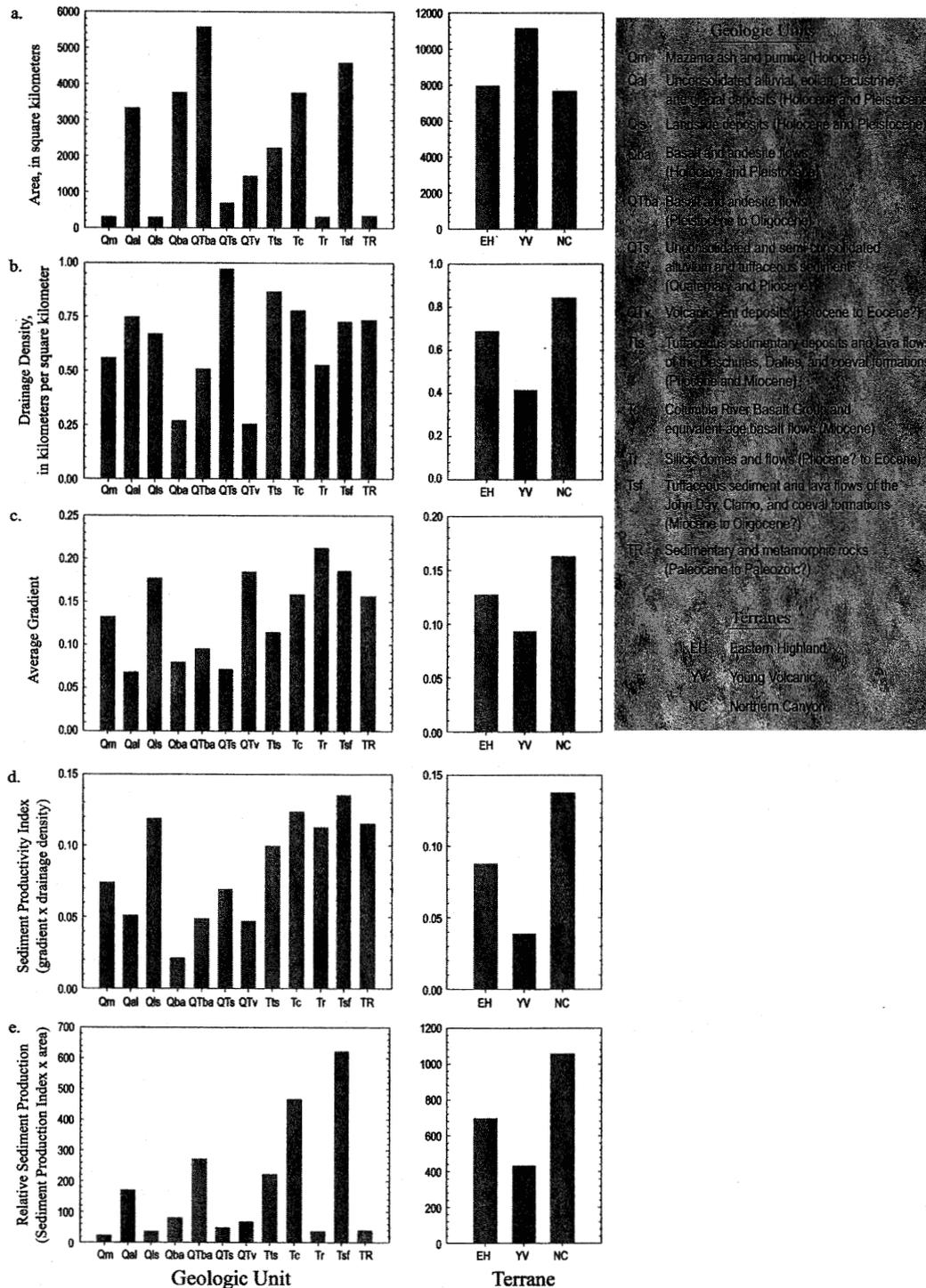
*al.*, 1989]. These rocks are in turn overlain by the active volcanic arc of the present Cascade Range that forms the western boundary of the Deschutes River basin. Volcanism along the crest of the range, as well as at numerous vents that pepper the eastern flank of the range, has resulted in a largely constructional topography of young volcanoes and lava flows that are mostly less than 2 million years old [Plate 1; Taylor, 1990; Walker and MacLeod, 1991].

Extensive lava flows from Newberry Volcano south of Bend flowed into and partly filled the Crooked and Deschutes River canyons between 1.2 and  $<0.4$  million years ago [Figure 2; Russell, 1905; Stearns, 1931; Smith, 1986, 1991; Bishop and Smith, 1990; Sherrod *et al.*, in press]. Their distribution and thickness show that by 1.2 million years ago, the Deschutes River system had incised to near its present elevation near Round Butte Dam. Similarly, a  $0.9 \pm 0.1$  million year old basalt flow from Stacker Butte [Shannon and Wilson Inc., 1973, cited in Bela, 1982], flowed down the north valley wall of the Columbia River to near present river level near the mouth of the Deschutes, indicating that local base level at the Columbia-Deschutes confluence has not changed substantially in the last million years. The 275 m of incision between about 4 and 1 million years ago indicates a period of regional incision and canyon formation affecting at least the north half of the Deschutes River basin, during which downcutting averaged nearly 0.1 mm/yr. Repeated episodes of incision through the subsequent canyon-filling lava flows (Figure 2) were at even more rapid rates.

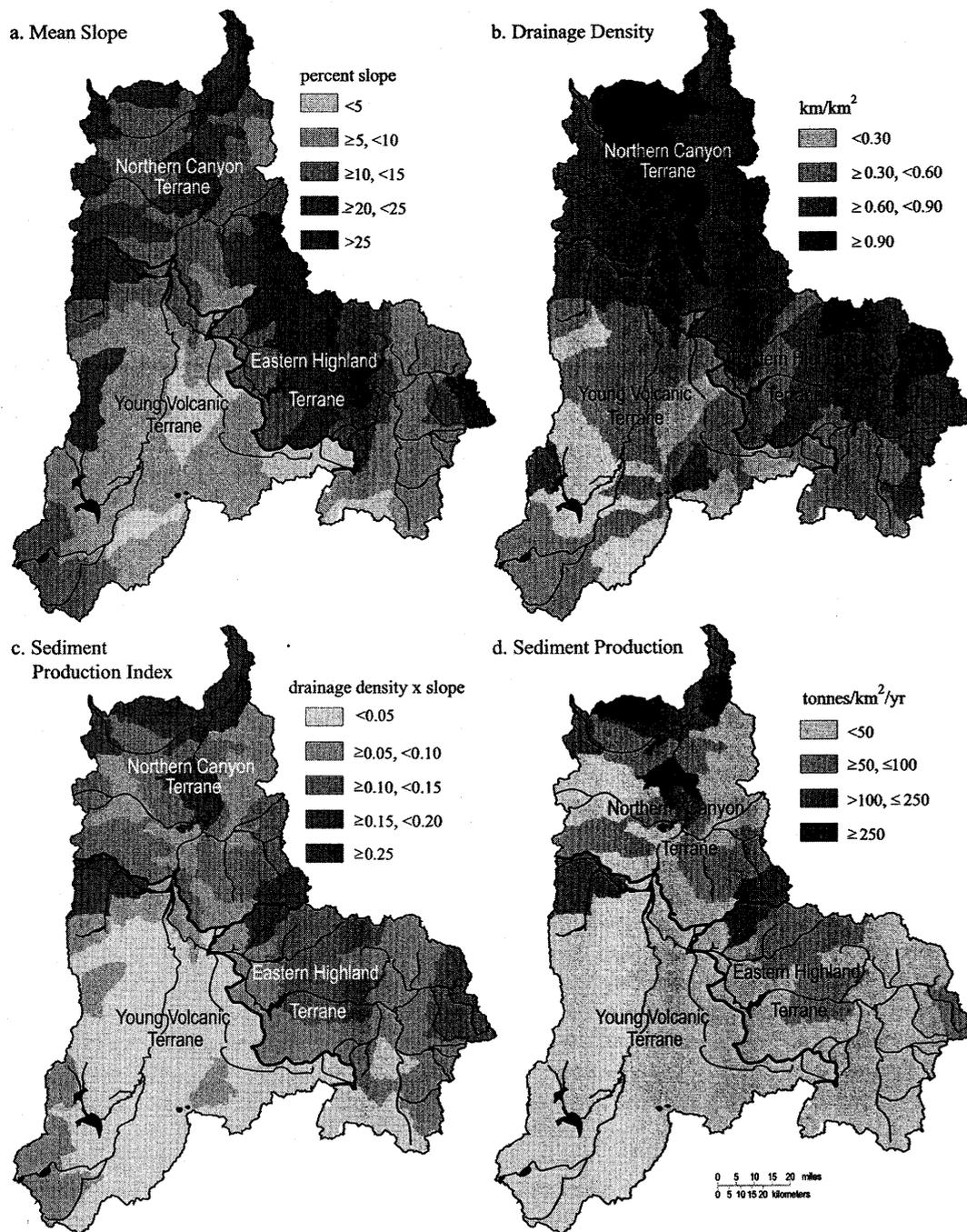
#### *Topography and Drainage Network*

The overall topography and drainage network development within the Deschutes River basin is the result of this geologic history. To frame discussion of the overall geologic, topographic and hydrologic characteristics of the basin, we have subdivided the watershed into three terranes on the basis of general geologic and topographic characteristics (Figures 3 and 4).

*Eastern Highlands Terrane.* The Ochoco Mountains and high lava plains form the southeastern part of the Deschutes River basin. This region, largely drained by the Crooked River, is underlain by a variety of rocks, but the main Ochoco Mountains are formed primarily of the John Day and Clarno Formations (unit Tsf on Plate 1). These formations are mainly composed of weathered lava flows and poorly consolidated claystone, siltstone, and volcanic ash-flow tuff deposited between 55 and 20 million years ago. The John Day and Clarno Formations are susceptible to landsliding, and almost all of the landslides in the Deschutes



**Figure 3.** Geomorphic and physiographic attributes of each of the twelve major geologic units (Plate 1) and three terranes (Figure 4) within the Deschutes River basin. (a) Area of surface exposure. (b) Drainage density, from U.S. Geological Survey 1:100,000 digital hydrography. (c) Average hillslope gradient, calculated from U.S. Geological Survey 30-meter digital elevation data. (d) Sediment Production Index (SPI), calculated as the product of mean gradient and drainage density. (e) Relative potential for sediment production, calculated as the product of SPI and area.



**Figure 4.** Distribution of geomorphic attributes and estimated sediment production for 100 approximately equal-sized subbasins of the Deschutes River basin. (a) Mean subbasin hillslope gradient, calculated from U.S. Geological Survey 30-meter digital elevation data (depicted in Figure 1). In many subbasins there are areas of significantly higher and lower slopes. (b) Subbasin drainage density, from mapped watercourses shown by U.S. Geological Survey 1:100,000 digital hydrography (shown on Figure 6). (c) Sediment Production Index (SPI), calculated as the product of mean gradient and drainage density as depicted (in a generalized fashion) in 4a and 4b (where slope is expressed as a fraction). (d) Calculated sediment yields, developed from empirical relation between SPI and surveyed accumulations in Deschutes River basin reservoirs (shown in Figure 14).

River basin are within these units (Plate 1). This landscape is one of the oldest in the Deschutes River basin, and more than 10 million years of weathering has produced a well-integrated hydrologic network in the erodible rocks of the region. The Ochoco Mountains have a high density of stream channels (Figure 4b) that connect steep hillslopes and source channels to trunk channels flowing within alluvial valleys.

*Young Volcanic Terrane.* The southern and southwestern part of the basin, drained by the Deschutes and Metolius Rivers upstream of the Pelton-Round Butte dam complex, is bounded by the high and rugged Cascade Range on the west, the western margin of Newberry Volcano lava flows on the east, and indistinct low divides between the Klamath Basin and the Basin and Range Province to the south. The Young Volcanic terrane is underlain by young volcanic rocks (units QTba, Qba and QTV on Plate 1) and basin-filling deposits (unit Qal) that have accumulated behind drainage-blocking lava flows and fault scarps. Pleistocene glacial deposits and outwash locally mantle uplands along the east flank of the Cascade Range. Pumice from Mount Mazama (Crater Lake) forms a widespread surface layer in the southern part of the province (mapped as unit Qm on Plate 1 where it obscures the underlying bedrock). The largely constructional volcanic landscape coupled with Quaternary faulting and channel-damming lava flows has resulted in a sparse and locally disconnected surface channel network traversing low-relief alluvial and lacustrine basins (Figures 4a and 4b).

*Northern Canyon Terrane.* The northern part of the Deschutes River basin is composed of dissected tablelands formed along the eastern rampart of the Cascade Range and the western Columbia River Plain. The central axis of the basin consists of sharply etched canyons rimmed by young basalt flows and incised into basin-filling sediment and older volcanic and volcanoclastic rocks. From Lake Billy Chinook downstream, the Deschutes River is deeply incised within a canyon variously carved into the relatively soft John Day and Clarno Formations, cliff-forming CRBG basalts, and younger strata of the Simtustus, Deschutes, and Dalles Formations with their capping basalt flows. Large tributaries from the west drain the Cascade Range, whereas tributaries from the east drain tablelands of CRBG and landslide-dominated uplands of the John Day and Clarno Formations. This terrane has the highest average slope and drainage density of the entire basin (Figures 3 and 4).

*Geology, Topography, and Drainage Pattern.* Topographic and stream-network properties in the basin result from the strong correspondence of geomorphic properties, such as slope and drainage density, with geology. This correspon-

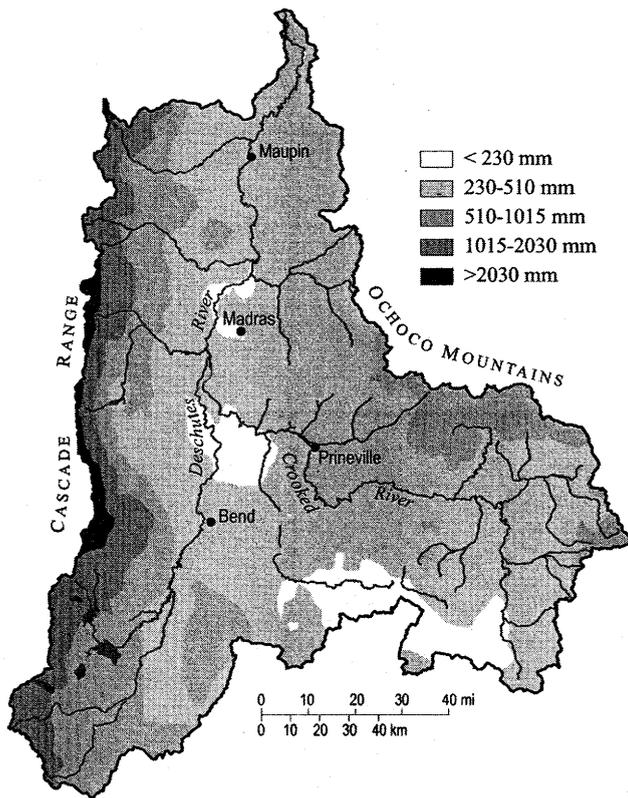
dence gives each of the terranes its distinct topographic and hydrologic characteristics (Figures 3 and 4). The older rock units that underlie most of the uplands of the Eastern Highlands and Northern Canyons have the greatest average slope. Of the widely distributed units, the John Day and Clarno Formations (grouped on Plate 1 as unit Tsf) and the CRBG (unit Tc on Plate 1) have the greatest average hillslope gradients. Late Tertiary and Quaternary vent complexes (unit QTV) also have relatively high average gradients. The older high-relief uplands underlain by the John Day and Clarno Formations and the CRBG also have relatively high drainage densities (Figure 3). The greatest drainage densities in the Deschutes River basin have developed on the poorly consolidated and unconsolidated Tertiary and Quaternary sedimentary rocks. These units (Tts and QTs on Plate 1), which were deposited during times of basin filling, regional aggradation, and higher base levels, are now densely drained by closely spaced channels, especially in the Northern Canyons province. In contrast, the young volcanic rocks (units Qba, QTba, and QTV of Plate 1), which characterize the Young Volcanic terrane, have drainage densities typically less than half that of most other units in the basin (Figure 3).

#### Hydrology

The unique hydrologic characteristics of the Deschutes River basin are largely controlled by the geology, topography, and stream network [see also *Gannett et al.*, this volume]. Average annual runoff for the 26,860 km<sup>2</sup> basin is 5.2·10<sup>9</sup> m<sup>3</sup>, which is equivalent to about 0.19 m over the entire drainage area. By far the largest portion of this water is derived from the high Cascade Range along the western part of the drainage basin, where high elevation and oceanward position promote greater precipitation and substantial winter snowpack (Figure 5). Farther east within the Cascade Range rain shadow, annual precipitation and runoff diminish rapidly, resulting in semi-arid rainfall and runoff conditions for much of the basin (Figures 5 and 6).

Near its confluence with the Columbia River, the Deschutes River has a mean monthly flow ranging from 124 m<sup>3</sup>/s in August to 213 m<sup>3</sup>/s in February (Figure 6, Deschutes River at Moody, 1965-1996). Prior to regulation, the highest monthly averages were in early spring and resulted primarily from snowmelt in the Cascade Range. Lowest flows are typically during the late summer months of July, August, and September. The relatively small range between low and high flows is unusual and was noted by *Russell* [1905], who wrote that:

“The Deschutes is of especial interest to geographers, as it exhibits certain peculiarities not commonly met with.



**Figure 5.** Mean annual precipitation in the Deschutes River basin for the period 1961-1990. From data provided by the Spatial Climate Analysis Service, Oregon State University. ([http://www.ocs.orst.edu/prism/prism\\_new.html](http://www.ocs.orst.edu/prism/prism_new.html); August, 2001).

Although flowing from high mountains on which precipitation varies conspicuously with seasonal changes and where snow melts rapidly as the heat of summer increases, its volume, throughout a large section of its course, is practically constant throughout the year.” and by *Henshaw et al.* [1914, p. 12] who more specifically observed:

“The flow of the river is more remarkably uniform than that of any other river in the United States comparable with it in size, and its economic value is almost incalculable. At the mouth of the stream the maximum discharge is only six times the minimum. Ocular evidence of this uniformity of flow is presented by the low grass-grown banks between which the river flows for much of its course.”

The steadiness of flow is illustrated by comparing the annual hydrographs and flood peak records of the Deschutes River basin with those of the adjacent and similar-sized basins to the west (Willamette Basin) and east (John Day Basin) (Figures 7 and 8). For the John Day River, the mean monthly discharge for April is more than thirty times that for September. Likewise for the Willamette River, the mean

monthly discharge for January is about ten times that for August. In contrast, the Deschutes River varies only by a factor of 1.5 between the months of greatest and least flow. Just as the annual response to flow is tempered in the Deschutes River basin, so is the response to individual climatic events. The maximum meteorologic peak discharge for the Deschutes River just downstream from the Pelton-Round Butte dam complex was 540 m<sup>3</sup>/s on February 8, 1996<sup>2</sup>—less than five times the mean flow of 125 m<sup>3</sup>/s. In contrast, the largest flood discharges on both the Willamette and John Day Rivers have been more than twenty times the rivers’ mean flows (Figure 8).

The uncommonly steady flow of the Deschutes River is due primarily to the poorly integrated surficial drainage system along the eastern flank of the Cascade Range in the southern and western parts of the Deschutes River basin. Much of the seasonal precipitation and snow melt infiltrates into extensive groundwater systems within the highly permeable young volcanic fields and basin fill deposits, emerging months to years later in large springs at the headwaters of the Metolius River, along the lower Crooked River, and between River Mile (RM) 100 and 120 on the Deschutes River<sup>3</sup> [*Russell*, 1905; *Henshaw et al.*, 1914; *Stearns*, 1931; *Manga*, 1996, 1997; *Gannett et al.*, 2001, *Gannett et al.*, this volume]. Consequently, there is little monthly or seasonal variation in flow for many headwater drainages in the southern and western parts of the Deschutes River basin (Figure 6). As a result, the annual hydrograph of the Deschutes River shows minimal seasonal variation near the Pelton-Round Butte dam complex, where springs contribute the majority of the total flow volume [*Gannett et al.*, this volume]. In contrast, seasonal flow variations are much greater in the headwater basins of the older, steeper, and more dissected terrain in the eastern Deschutes River basin (Figure 6), but because the total volume of flow from these more arid drainages is small, they do not substantially affect the annual distribution of flow in the lower Deschutes River. Some additional flow regulation is provided by the abundant lakes and glaciers in Cascade Range headwaters, and also

<sup>2</sup> The February 8, 1996, flow was not substantially attenuated by the Pelton-Round Butte dam complex [*Fassnacht*, 1998]. A larger flow (640 m<sup>3</sup>/s) on July 16, 1983, resulted from a short accidental release from the Pelton-Round Butte dam complex.

<sup>3</sup> Units given are metric except for locations, which are given as river miles (RM), or miles upstream from the river mouth as marked on USGS topographic maps. These values are close to, but not necessarily the same as, actual distances along the present channel. Fractional river miles given herein are based on interpolations between these published river miles.

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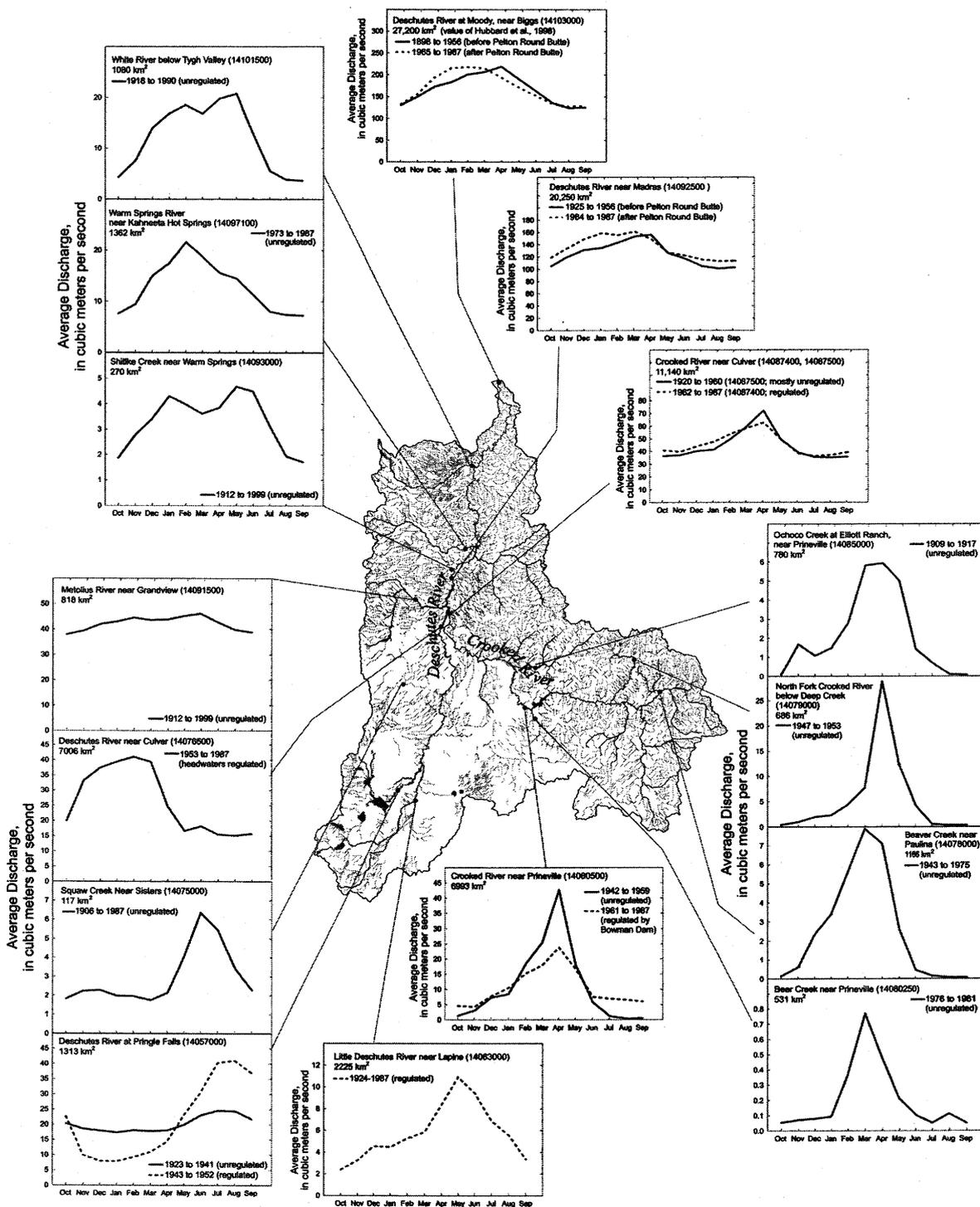
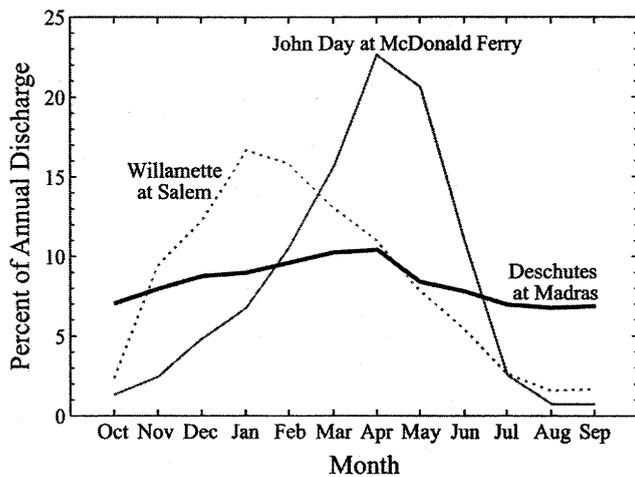


Figure 6. Hydrography and representative annual hydrographs for U.S. Geological Survey stream gaging stations in the Deschutes River basin. Data from *Moffatt et al.* [1990] and the U.S. Geological Survey National Water Information System (<http://water.usgs.gov/nwis>).



**Figure 7.** Mean monthly discharges for the John Day River at McDonald Ferry (station No. 14048000, period of record 1905-1987, drainage area 19,630 km<sup>2</sup>), Deschutes River near Madras (14092500, 1925-1956, 20,250 km<sup>2</sup>), and Willamette River at Salem (14191000, 1910-1941, 18,855 km<sup>2</sup>). Discharges are expressed in terms of percent of annual flow to emphasize differences in seasonal distribution of runoff. Periods of record selected to minimize effects of upstream dams. Data from *Moffatt et al.* [1990]. Basin locations shown in Figure 1.

by two storage reservoirs in the Crooked River system and three reservoirs in the Deschutes River headwaters.

Steady discharge and muted response to individual meteorologic events are pronounced for flow entering Lake Billy Chinook at the Pelton-Round Butte dam complex, where the largest flows are less than five times the mean annual flow. However, flow response to individual runoff events becomes progressively greater downstream in the Northern Canyons terrane. For example, large inflows to the Deschutes River from Cascade Range tributaries (primarily Shitike Creek, Warm Springs River, and White River) during the February 1996 flood (the largest flood in nearly 100 years of record) increased the peak discharge from 540 m<sup>3</sup>/s (Deschutes River near Madras) to 1990 m<sup>3</sup>/s (Deschutes River at Moody), an increase of a factor of 3.7 despite only a 26 percent increase in drainage area. Similar increases occurred during the December 1964 flood, although more runoff was captured by storage reservoirs during this event [*Beebee and O'Connor*, this volume; *Hosman et al.*, this volume]. The large peak flows generated in the Northern Canyons terrane result from the steeper and more dissected tributary drainages and the absence of an extensive regional groundwater system such as found in the southern Deschutes River basin. This heightened storm response of the Northern Canyons tributaries is reflected in the early winter peaks and the greater month-to-month

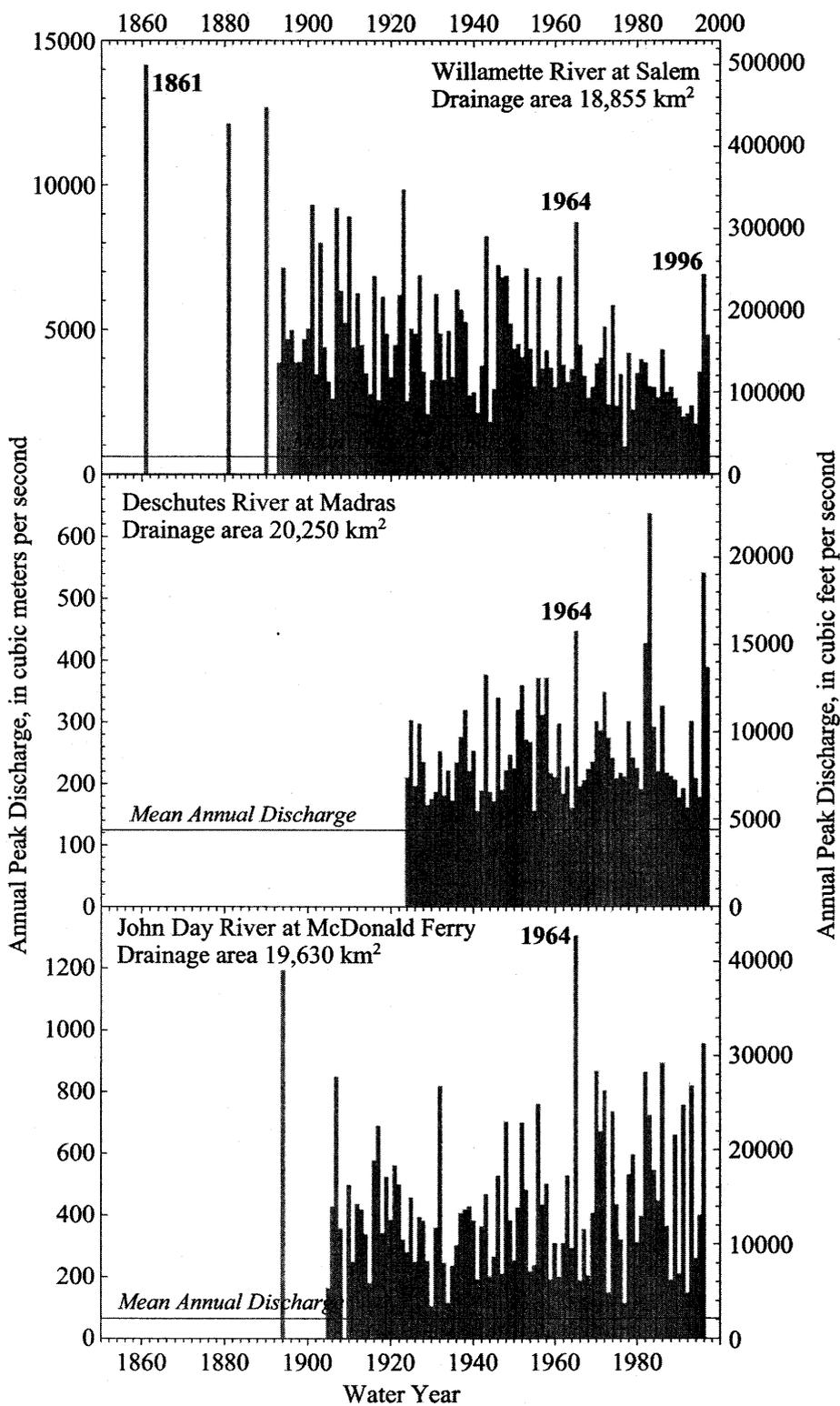
variation of the annual hydrographs for Shitike Creek, Warm Springs River, and White River compared to Cascade Range stations in the Deschutes River headwaters (Figure 6).

#### *Regional Sediment Production and Transport*

Together, the geology, geomorphology, and hydrology of the Deschutes River basin substantially influence the type and quantity of sediment delivered to the Deschutes River as well as the frequency of sediment movement. There are few data on actual sediment delivery in the Deschutes River basin, so the following discussion is largely qualitative and founded on consideration of the overall geologic history as well as current geomorphic and hydrologic characteristics. In a later section, we apply sparse sediment-transport measurements and the record of modern sediment delivery to Lake Billy Chinook, Prineville Reservoir, and Ochoco Reservoir to provide quantitative support for the inferences derived here from more general observations.

Within the Young Volcanic terrane of the southern and southwestern parts of the basin, the primarily basaltic and andesitic volcanic rocks are generally unweathered and do not produce large volumes of sediment. These lava flows typically break down to gravel (by physical weathering processes such as freeze-thaw) and clay (through chemical weathering). Modern processes produce very little sand. Reworked tephra, ash, and Mazama pumice also contribute in some degree to bedload. The low drainage density (Figure 4b) coupled with the small and steady surface flows in this part of the basin (Figure 6) result in only infrequent sediment transport in the river systems draining this terrane. In the southern part of the basin, much of the transported sediment is probably trapped in lakes and alluvial basins formed behind young lava flows and by basin-range faulting.

Nevertheless, large volumes of sediment have been produced episodically in the Young Volcanic terrane during periods of extensive glaciation and during large volcanic eruptions. Large glaciers and ice sheets covered much of the high Cascade Range during Pleistocene ice ages [*Crandell*, 1965; *Scott*, 1977]. These glaciers eroded and transported a substantial volume of gravel, sand, and silt derived from erodible Cascade Range stratovolcanoes and formed large moraines and outwash plains near their termini. These deposits compose much of the alluvium along the eastern flank of the Cascade Range (Plate 1, unit Qal). Sand and gravel outwash terraces can be traced from moraines down many of the tributaries to the Deschutes and Metolius Rivers [e.g. *Scott*, 1977; *Sherrod et al.*, in press], indicating that at times of peak sediment production there was abundant sand and gravel delivered continuously to the Metolius and Deschutes Rivers.



**Figure 8.** Annual peak discharges for the Willamette (station No. 14191000), Deschutes (14092500), and John Day (14048000) Rivers. Basin locations shown in Figure 1.

Most of the remaining glacial deposits, however, are perched on ridgetops, lava flows, and hillslopes away from active channels, so that little of this sediment now makes its way into modern channels.

Large volcanic eruptions have also episodically fed immense quantities of sediment to the Deschutes and Metolius Rivers. During the last 500,000 years, major eruptions from volcanic centers west of Bend [Hill and Taylor, 1989], Mount Jefferson [Beget, 1981; Conrey, 1991] and Mount Mazama [Crater Lake; Sarna-Wojcicki and Davis, 1991] have spread vast quantities of fallout ash and pumice over large parts of the Deschutes River basin, but the thickest accumulations have been along the eastern flank of the Cascade Range in the upper Deschutes and Metolius drainages. Several individual pumice and ash falls from the Tumalo volcanic center west of Bend are locally thicker than 10 m [Hill and Taylor, 1989]. The 7500-year-old Mazama pumice is sufficiently thick to obscure the underlying geology over more than 250 km<sup>2</sup> of the southern margin of the Deschutes River basin (unit Qm on Plate 1). Sand- and gravel-sized pumice is readily mobilized from hillslopes and transported downstream; consequently, during the decades following these major eruptions, there were likely periods of greatly enhanced sediment transport of silt-sized tephra and sand- and gravel-sized pumice grains, resulting in substantial channel aggradation. Pyroclastic flows (hot gas-rich flows of volcanic rock fragments) and lahars (volcanic debris flows) from Cascade Range eruptions have likely also episodically introduced large quantities of sand and gravel directly into the upper Deschutes and Metolius Rivers [e.g. Smith, 1986; Hill and Taylor, 1989]. Although there is sparse stratigraphic record of such events in Quaternary deposits above Lake Billy Chinook, deposits from a >75 ka<sup>4</sup> lahar from Mount Jefferson are preserved along the lower Deschutes River [O'Connor et al., this volume].

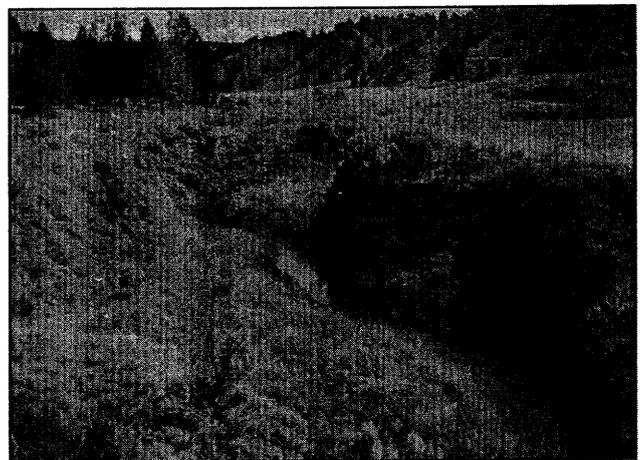
Within the Eastern Highlands terrane, including the Ochoco Mountains and high lava plains of the southeastern part of the Deschutes River basin, the deeply weathered lava flows and poorly consolidated claystone, siltstone, and ashflow tuffs of the John Day and Clarno Formations are highly erodible, producing silt and clay from extensively dissected uplands. The fine-grained material produced in the uplands locally accumulates as valley fill along larger tributaries. Over geologic time scales, however, the dense stream network within this province efficiently conveys abundant fine-grained sediment from the eroding highlands into the Crooked and Deschutes Rivers.

The distinctly different hydrologic character of the Eastern Highland terrane of the Deschutes River basin likely amplifies

sediment transport efficiency. The Crooked River has a more arid hydrologic regime with less total runoff but significantly greater month-to-month variation than does the upper Deschutes River (Figure 6). Prior to construction of Prineville Reservoir, the mean March flow of the Crooked River near Prineville was 100 times the mean August flow, whereas the variation for the Deschutes River near Culver is less than a factor of three [Figure 6; Moffatt et al., 1990]. Because the ability to entrain and transport sediment increases exponentially with discharge, the flashier flows of the Crooked River probably expedited sediment delivery to the Deschutes River under pre-dam conditions.

As in the Young Volcanic terrane, there has probably been significant variation in the sediment delivery from the Ochoco Mountains over geologic and historic time scales. During the last 0.5 million years, the drainage area of the Crooked River has also been repeatedly blanketed by eastward drifting plumes of ash and pumice from Cascade Range eruptions. These deposits were probably eroded rapidly from steep hillslopes and moved into the channel system. There were no glaciers in the Ochoco Mountains during Pleistocene glacial periods, but the colder climates may have enhanced rates of weathering and hillslope sediment production. Pleistocene sand and gravel terraces 15 meters above the modern floodplain near Prineville reflect regional stream aggradation and increased sediment delivery that probably resulted from glacial climates.

Historic incision of fine-grained valley alluvium in the Crooked River basin has formed extensive gully networks [Russell, 1905; Buckley, 1992; Welcher, 1993] that continue to erode headward up the stream channel network (Figure 9). Incision has been widely attributed to overgrazing [e.g.



**Figure 9.** Bear Creek eroding fine-grained valley alluvium in the Crooked River drainage. Cut bank is about 3 m high. Photograph by J.E. O'Connor, 1998.

<sup>4</sup> "ka" = kilo-annum, or thousands of years before present.

Russell, 1905; Buckley, 1992]; however, in a study of Camp Creek in the upper Crooked River basin, Welcher [1993] identified several periods of prehistoric incision followed by aggradation that may have corresponded to subtle climate shifts. Regardless of their cause, periods of channel incision and gully formation would lead to substantially elevated rates of sediment transport downstream into the major watercourses.

Within the Northern Canyon terrane, a variety of sediment size and abundance is produced from the diverse rock types and environments. The John Day, Clarno, Simtustus, Deschutes, and Dalles Formations produce primarily silt and clay from fluvial erosion and mass movements of soft ash beds. CRBG and younger basalts, as well as lava flows within the John Day, Clarno, and Deschutes Formations, physically weather into boulders and cobbles that enter the Deschutes River by tributary floods, debris flows, and canyon rockfalls. Chemical weathering of basalt typically generates clay minerals that are incorporated into overlying soils and can wash into the river system during periods of soil erosion.

With the Deschutes River flowing as much as 600 m below the adjacent uplands, many tributaries are short and steep. Larger tributaries such as the Warm Springs and White Rivers are incised into narrow valleys that lead directly from the Cascade Range. Consequently, the hydrologic response to both regional runoff events (such as December 1964 and February 1996 rain-on-snow events) and short-duration local events such as summer thunderstorms can be swift and intense. As described above, more than 70 percent of the February 8, 1996 peak discharge, was contributed by tributaries downstream of the Pelton-Round Butte dam complex. This integrated hydrologic network coupled with abundant sediment sources allows for efficient transport of relatively large quantities of sediment (compared to the areas of young lavas upstream) to the Deschutes River valley bottom during local and regional runoff events.

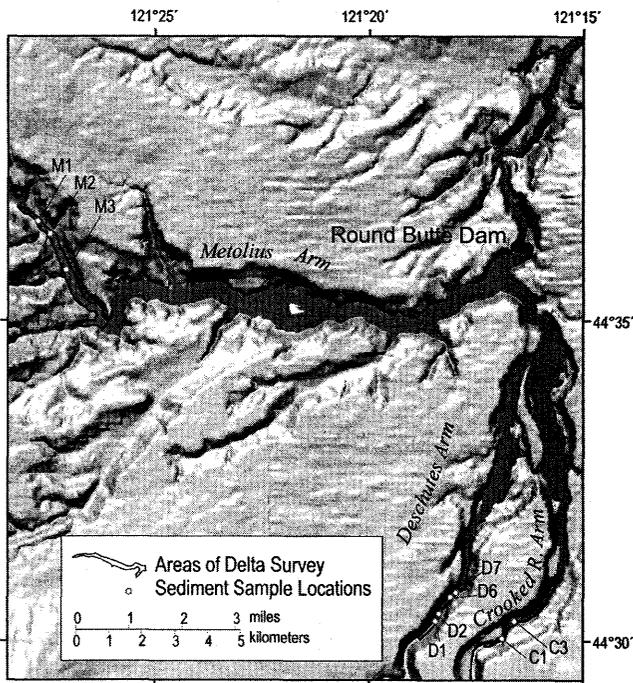
As with both the Young Volcanic and Eastern Highland terranes, Quaternary rates of sediment input to the Deschutes River system in the Northern Canyons have probably varied substantially. This section of the Deschutes River basin has also been episodically blanketed with ash and pumice falls, although not as thickly as have the southerly parts of the basin. Large glacial-age ice caps and glaciers formed around Mount Hood and the adjacent Cascade Range, resulting in outwash gravels that contributed significantly to the sediment load of the Deschutes River. Lahars and pyroclastic flows from Cascade Range eruptions have episodically delivered large quantities of gravel and sand to the Deschutes River. A recent example is

a circa AD 1790 sandy lahar from Mount Hood (Jon Major, USGS, oral communication, 1998) that reached the Deschutes River via the White River. Large Quaternary landslides, primarily within the John Day and Clarno Formations have directly injected large volumes of sediment into the Deschutes River valley bottom [O'Connor *et al.*, this volume]. The northern part of this area has also been episodically mantled with windblown silt and fine sand derived from the Columbia Plain, and up to 10 m of silt and fine sand was deposited during backflooding 100 km up the lower Deschutes River valley during the late Pleistocene Missoula Floods [O'Connor *et al.*, this volume].

#### *Deschutes River Basin Sediment Budget*

These largely qualitative inferences on modern sediment supply are bolstered by limited data on sediment production and transport in the Deschutes River basin. Bathymetric surveys and bottom sampling of Lake Billy Chinook (the reservoir impounded by Round Butte Dam, Figure 1) undertaken as part of this study, as well as surveys of Prineville and Ochoco Reservoirs by the Bureau of Reclamation (Figure 1), furnish volume and size estimates for regional sediment production during the last 34-90 years. Suspended load measurements conducted by the U.S. Geological Survey for short periods at five gages provide sparse additional records of annual sediment production.

*Reservoir Sedimentation Surveys.* Surveys and sampling of sediment accumulated in Lake Billy Chinook provide estimates of the volume and type of sediment trapped by the Pelton-Round Butte Project operations and precluded from moving from the upper Deschutes, Crooked, and Metolius River basins to the lower Deschutes River. Each of the three arms of Lake Billy Chinook were surveyed by Portland General Electric crews during the summer and fall of 1998, allowing determination of the individual sediment contributions from the Deschutes, Crooked, and Metolius Rivers for the 34 years since closure of Round Butte Dam (Figure 10). Electronic total stations and satellite telemetry were used to gather positions of depths acquired by a vessel-mounted electronic depth finder. For each of the three arms of Lake Billy Chinook, 30 to 44 cross sections were measured from the point where the river entered the lake to approximately 3 km downstream (Figure 11). Resulting cross-sections were compared to cross-sections derived from 1.5-m (5-ft) contour maps surveyed by Portland General Electric prior to inundation. This analysis shows that deltas up to 15 m thick have formed where the Crooked and Deschutes Rivers enter Lake Billy Chinook. No detectable delta could be resolved by the repeat cross sections for the Metolius arm, although



**Figure 10.** Location of delta surveys and sediment samples in Lake Billy Chinook. Survey and sample location data from Portland General Electric (Scott Lewis and Gary Reynolds, Portland General Electric, 1998 written communication). Hillshade topographic base from U.S. Geological Survey 30-m digital elevation data.

reconnaissance diving by Scott Lewis (Portland General Electric, oral communication, 1998) revealed local accumulation of silt, sand, and gravel up to 2 m thick, which is about the maximum uncertainty associated with comparing pre- and post-reservoir bathymetry.

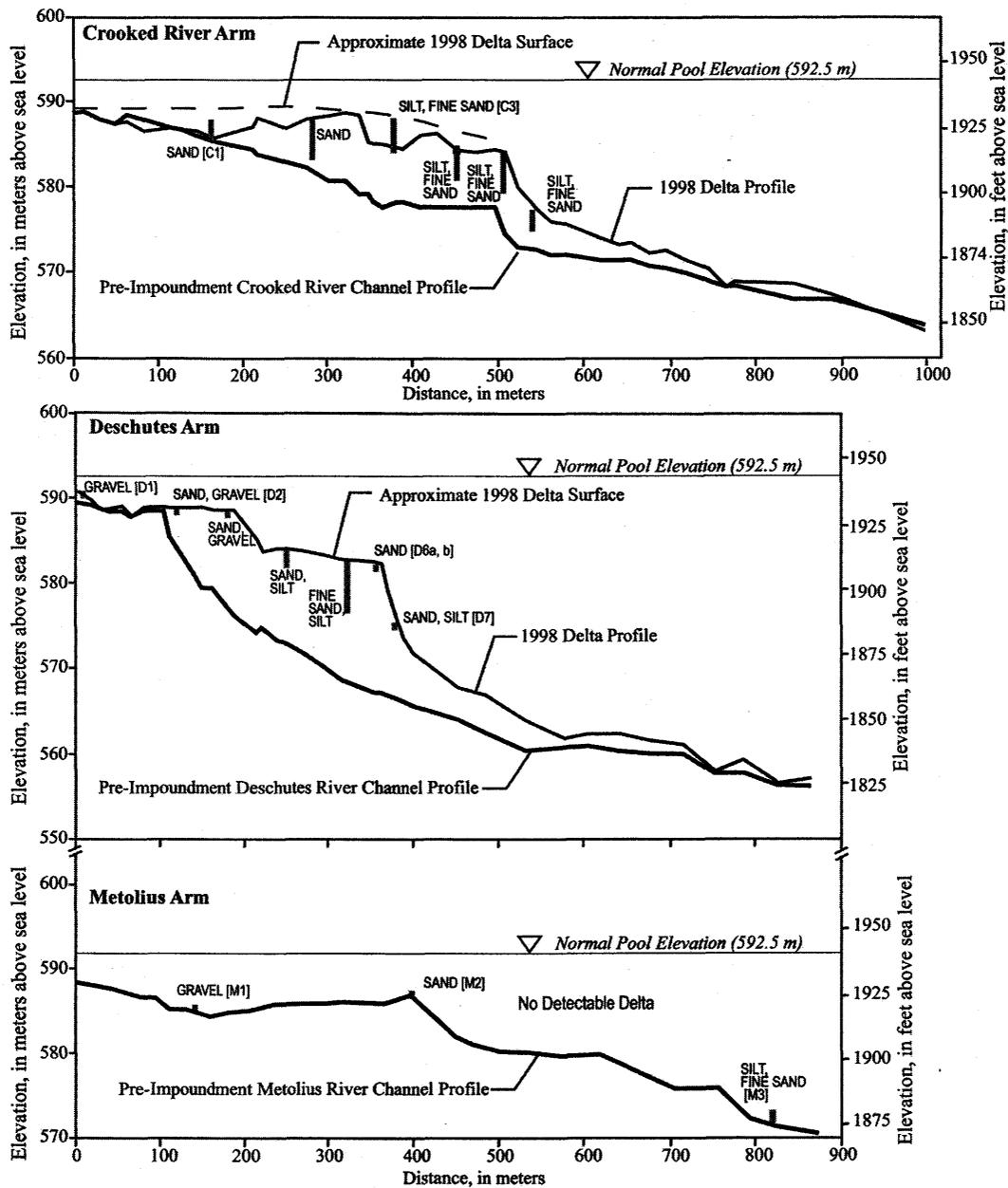
The volumes of each of the Deschutes and Crooked River deltas were calculated by multiplying the average change in area for each pair of adjacent cross sections by the distance between each pair. Using this approach, the estimated volume of the delta where the Crooked River enters Lake Billy Chinook is about 627,000 m<sup>3</sup>, and that for the Deschutes River is about 622,400 m<sup>3</sup> (Table 1). Composition of the deltas is not completely known, but reconnaissance augering and analysis of ten samples from the delta surfaces show that all three deltas are primarily composed of sand and gravel at their apices and become finer-grained farther and deeper into the reservoir (Figures 11 and 12). The Deschutes River delta is coarsest, having a pebbly delta apex that grades downstream to mostly sand. The Crooked River delta is distinctly finer than both the Deschutes and Metolius River deltas, with

the upstream part of the delta formed primarily of sand, grading downstream to mostly silt and clay. These analyses support qualitative observations during reconnaissance diving and collection of the samples (Scott Lewis, written communication, 1998) that the Crooked River delta is primarily composed of silt, fine sand, and organic detritus; and the Deschutes River delta is composed of coarse sand with minor gravel at the delta apex grading to fine sand at the downstream crest of the delta.

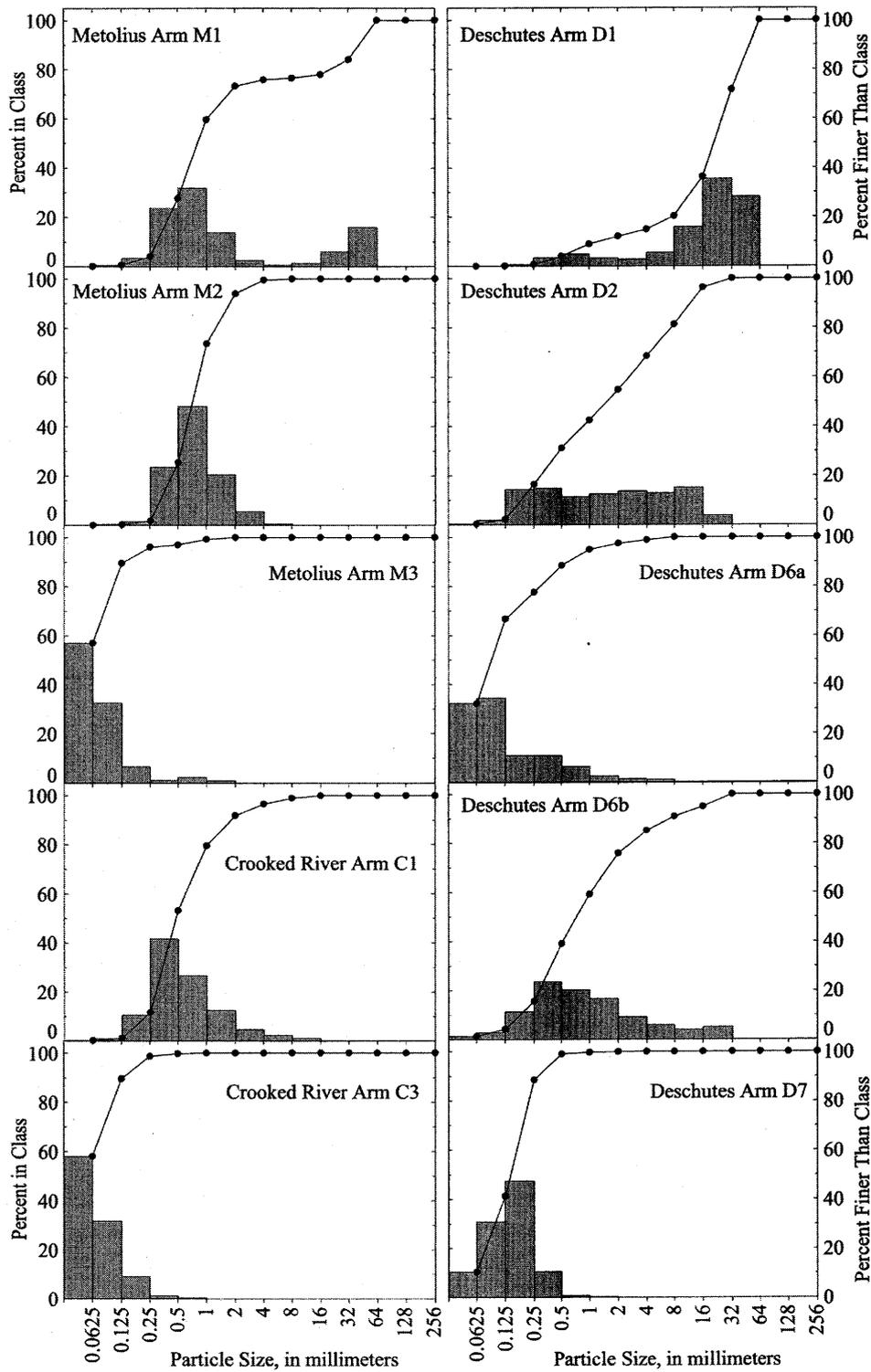
Reservoir sediment volumes have also been measured by the Bureau of Reclamation for Prineville and Ochoco Reservoirs in the Crooked River drainage (Table 1; Ronald Ferrari, U.S. Bureau of Reclamation, written communication, 1999). In Prineville Reservoir, behind Bowman Dam on the Crooked River, a May 1998 survey indicated that about 5,657,400 m<sup>3</sup> had accumulated since the December 1960 closure of the dam. Ochoco Reservoir accumulated about 3,802,000 m<sup>3</sup> of sediment between January 1920 closure and a June 1990 survey. There are no available sediment-size data for these reservoirs.

These volume estimates were converted to masses by assuming *in situ* sediment densities of 1.3 to 1.5 tonnes/m<sup>3</sup> for sediment in Lake Billy Chinook and about 1.1 tonnes/m<sup>3</sup> for the presumably finer sediment in Ochoco and Prineville Reservoirs, for which large parts of their source areas are underlain by the John Day and Clarno Formations (Table 1). These sediment density values were based on empirical observations of reservoir sediment density presented in Vanoni [1975, pp. 38-44], which show that the density of reservoir deposits composed primarily of sand and gravel typically ranges between 1.3 and 1.5 tonnes/m<sup>3</sup>. The 1.1 tonnes/m<sup>3</sup> density assumed for Ochoco and Prineville Reservoirs corresponds to an assumed sediment composition of silt and fine sand.

**Sediment Yield.** These measurements of reservoir sediment accumulation provide for independent decadal-scale estimates of modern sediment yield for parts of the basin (Table 1). The yield contributing to the Deschutes and Crooked River arms to Lake Billy Chinook for the 34-year period between 1964 and 1998 is remarkably low—on the order of 4 to 6 tonnes/km<sup>2</sup>-yr. The yield from the Metolius arm is even lower. These low sediment yield values are all the more notable because the 34-year period that they encompass includes the two largest flow events in the last 140 years. Sediment yield in the upper Crooked River basin is substantially higher, ranging from 26 tonnes/km<sup>2</sup>-yr in Prineville Reservoir (also including the sediment delivered by both the 1964 and 1996 floods) to 80 tonnes/km<sup>2</sup>-yr for Ochoco Reservoir (only including the 1964 flood, but representing a much longer duration than the other reservoirs).



**Figure 11.** Upper 1 km of longitudinal profiles of the three arms of Lake Billy Chinook, showing pre-impoundment river profile, present delta profiles over the former channel thalwegs, and dominant substrate composition along each delta. Areas of surveys shown on Figure 10. There was no detectable difference between the present reservoir bottom and the former channel profile in the Metolius arm, although there has been up to 1.5 m of deposition locally (Scott Lewis, Portland General Electric, written communication, 1998). The approximate delta surface depicted for the Crooked arm represents the overall uppermost elevation of delta deposits along the survey transects. In contrast, the surface of the Deschutes arm delta was more uniform across its breadth. Drawn from data from Portland General Electric (Gary Reynolds, 1998 written communication). Substrate descriptions from subsurface augering conducted by Scott Lewis (Portland General Electric, written communication, 1999; depth indicated by extent of vertical bars). Locations of analyzed samples (with sample designations) shown in Figure 10.



**Figure 12.** Grain size analyses showing percent in each size class (histogram) and cumulative weight percent (curve) for ten samples from Lake Billy Chinook. Sample locations shown in Figures 10 and 11. Samples collected by Scott Lewis, Portland General Electric. Analyses conducted by U.S. Geological Survey, Vancouver, Washington.

**Table 1.** Summary of sediment yield estimates determined from Deschutes River basin reservoir surveys.

Reservoir	Contributing Basin Area (km <sup>2</sup> )	Closure and Survey Records	Surveyed Sediment Volume (m <sup>3</sup> )	Assumed Sediment Density (tonnes/m <sup>3</sup> ) <sup>1</sup>	Sediment Mass (tonnes)	Sediment Yield (tonnes/yr/km <sup>2</sup> )	Unit Area Sediment Production Index (km <sup>-3</sup> )
Deschutes Arm, Lake Billy Chinook	6000	Round Butte Dam closed Jan. 2, 1964; surveyed May 1998	622400	1.44	898700	4.4	0.032
Crooked River Arm, Lake Billy Chinook	3920	Round Butte Dam closed Jan. 2, 1964; surveyed May 1998	627000	1.25	803200	6.1	0.046
Prineville Reservoir	6346	Bowman Dam closed Dec., 1960; surveyed May, 1998 <sup>2</sup>	5657400	1.12	6342000	26.0	0.078
Ochoco Reservoir	752	Ochoco Dam closed Jan., 1920; survey date June 1990 <sup>2</sup>	3802000	1.12	4262100	80.4	0.136

<sup>1</sup>Estimated from measured and inferred delta composition and empirical observations of reservoir sediment density portrayed in *Vanoni* [1975, pp. 38-44].

<sup>2</sup>Sediment volumes, survey dates, and dam closure information provided by Ronald Ferrari, U.S. Bureau of Reclamation (written communication, 1999)

We have found no other measurements of regional sediment yield for equivalent contributing areas that are as low as the sediment yield of the areas contributing to the Crooked and Deschutes River arms of Lake Billy Chinook (Figure 13). These rates are generally two to seven times less than sediment yields reported by *Judson and Ritter* [1964] for the Columbia and Snake River basins, about seven to fifteen times less than reported for the Klamath River basin (as calculated from data attributed to Janda and Nolan in *Milliman and Syvitiski* [1992]), and more than two orders of magnitude smaller than those predicted by area-based regression equations developed by *Milliman and Syvitiski* [1992] for mountain drainage basins in temperate regions. These low overall rates of sediment yield from the areas contributing to Lake Billy Chinook reflect the predominance of young volcanic rocks (which produce little sediment), limited surficial hydrologic network in many of the sediment source areas, and the absence of modern processes that supply and deliver abundant sediment. The sediment yields of the areas contributing to Ochoco and Prineville Reservoir are more typical of other landscapes, but still lower than for most basins of similar size for which there are sediment yield measurements (Figure 13).

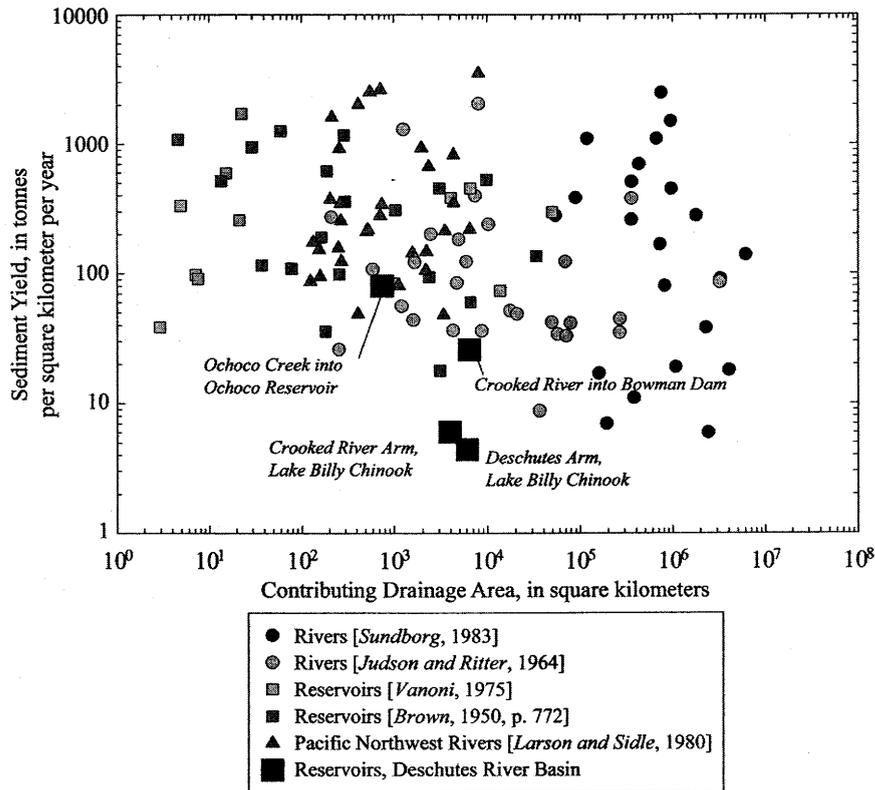
*Sediment Budget.* Sediment yield values from isolated parts of the basin document regional sediment contributions to the Deschutes River system, but do not fully portray basin-wide patterns of sediment yield. A basin-wide sediment budget is critical to fully evaluate the effects of impoundment on overall sediment flux. In this section we extrapolate the reservoir sediment yield data to the rest of the basin on the basis of basin physiography in order predict the spatial distribution of sediment input into the Deschutes

River system and the effects of impoundment on overall sediment supply.

Our approach follows from the premise that in steady-state landscapes dominated by diffusive processes of surficial sediment mobilization (e.g. biogenic activity, rain-splash, soil creep, freeze-thaw action), sediment flux per unit stream length is proportional to the gradient of the flanking hillslope [Culling, 1960, 1963; Hirano, 1968], although this relation is not necessarily linear in steeper terrains [Andrews and Buckman, 1987; Roering et al., 1999]. Consequently, the sediment yield per unit area will be proportional to the product of average slope gradient and drainage density, which we term the *sediment production index* (SPI). To apply this reasoning on a spatially explicit basis, we divided the Deschutes River basin into 100 approximately equal-sized and hydrographically defined subbasins for which area, drainage density, and average hillslope gradient were calculated from digital topographic and hydrographic data (Figure 4a, b). For each subbasin we then calculated the sediment production index as the product of subbasin drainage density and mean hillslope gradient (Figure 4c). Combining the areas now contributing sediment into the Crooked River and Deschutes arms of Lake Billy Chinook, and Prineville and Ochoco Reservoirs, and comparing the calculated sediment production index to actual sediment yields as recorded in the reservoirs yields the regression relation:

$$Q_s = 3.74 (SPI)^{2.23} (r^2 = 0.98; P = 0.015),$$

where  $Q_s$  is sediment yield, in tonnes per square kilometer per year, and SPI is in units of km<sup>-1</sup> (Figure 14).

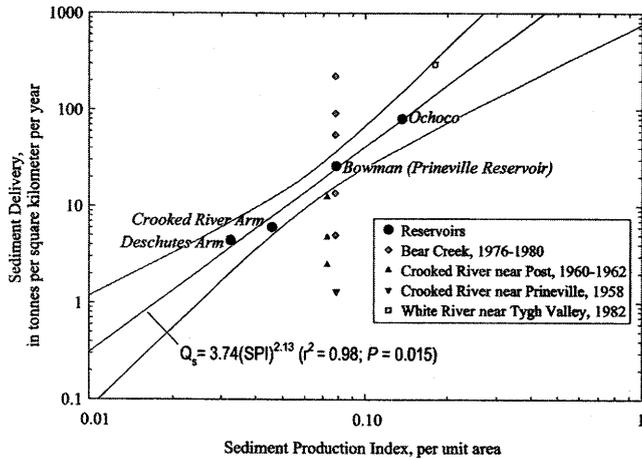


**Figure 13.** Compilation of sediment yield data from various sources, comparing sediment yield from parts of the Deschutes River basin to yields from other basins. Ochoco Creek and Crooked River sediment yields derived from surveyed sediment volumes behind Ochoco and Bowman Dams (Table 1; Ronald Ferrari, U.S. Bureau of Reclamation, 1999 written communication). Lake Billy Chinook (LBC) volumes measured by Portland General Electric survey crews in 1998 (Figures 10 and 11).

This result is only strictly applicable to transported bed-load and suspended sand and silt ( $>0.002$  mm) that drops out rapidly in these large reservoirs. Clay-sized particles probably stay in suspension long enough to bypass the reservoirs. This result is also broadly consistent with the central tendencies (on a logarithmic plot) of the annual volumes of suspended load recorded at four U.S. Geological Survey gaging stations for short periods (Figure 14), although these gages also depict the substantial year-to-year variation in sediment transport. The results of a single year of suspended load measurements for White River, a large tributary draining the eastern Cascade Range and entering the Deschutes River downstream of the Pelton-Round Butte dam complex, are consistent with extrapolation of this relation to even higher values of SPI.

By applying this relation to the SPI calculated for each of the 100 subwatersheds (Figure 4d) and summing the resulting estimates of sediment yield downstream, we may estimate the overall downstream sediment flux and the incremental effects of impoundment in the Deschutes River basin

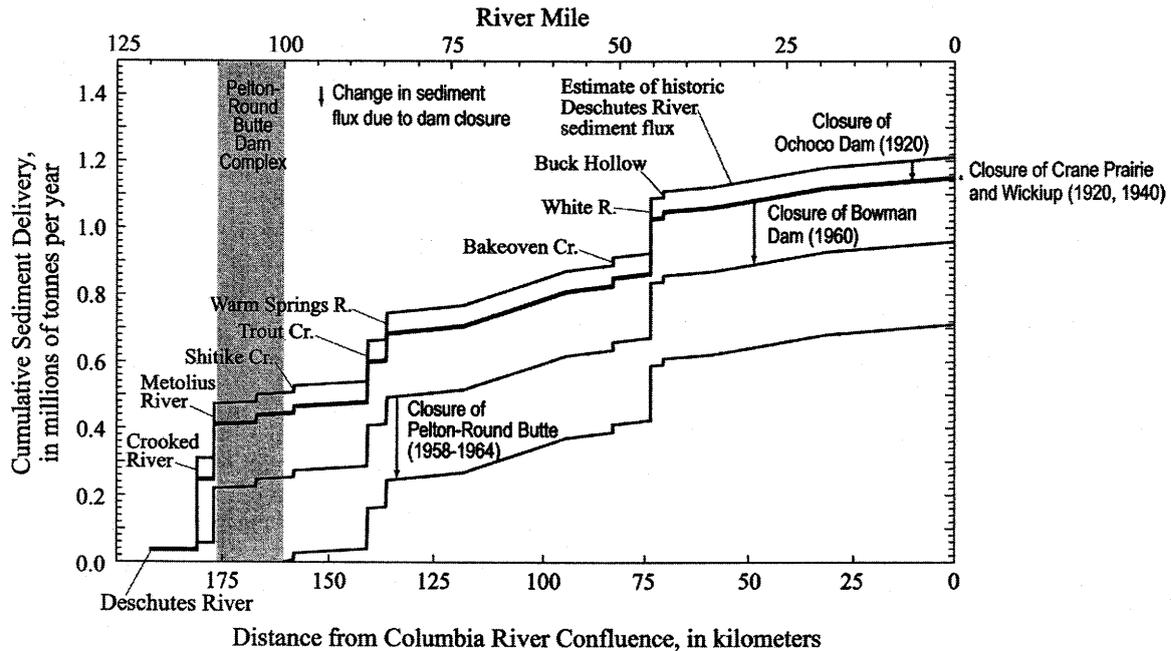
(Figure 15). Under pre-impoundment conditions, modern sediment flux downstream of the confluence of the Deschutes, Crooked, and Metolius Rivers, 180 km upstream of the Columbia River confluence, is estimated to have been about 480,000 tonnes/yr. More than half of this volume was from the Crooked River basin. Downstream at the Columbia River confluence, the total annual sediment flux under pre-impoundment conditions is estimated to have been slightly more than 1,200,000 tonnes/yr, indicating that 60 percent of Deschutes River pre-impoundment sediment flux into the Columbia River is derived from below the Pelton-Round Butte dam complex. On the basis of this analysis, Trout Creek, Warm Springs River, and White River are likely to be major sources of sediment along the lower Deschutes River (Figure 15). In addition, the steep and dissected terrain formed where the Deschutes River has incised through the Mutton Mountains, between 120 and 90 km from the Columbia River confluence, (Figures 1 and 4) is also predicted to be an area of substantial sediment production and delivery. Consistent with this prediction is a concentration



**Figure 14.** Regression and 95 percent confidence limits between unit Sediment Production Index values (SPI) and measured sediment yields (Table 1) for areas contributing to reservoirs in the Deschutes River basin. Shown for comparison are annual suspended load volumes measured at U.S. Geological Survey streamflow stations within the Deschutes River basin. Suspended load data from U.S. Geological Survey annual reports and water-supply papers.

of tributary fan deposits along this section of Deschutes River [Curran and O'Connor, this volume), likely formed by floods and debris flows triggered by summer convective storms precipitating on the numerous short and steep tributaries.

These sediment yield and delivery estimates portrayed in figures 4c, 4d, 13, 14, and 15 represent modern pre- and post-impoundment conditions for the past 50 to 80 years, including the effects of two large regional floods. Nevertheless, the short time window of sedimentation recorded in Lake Billy Chinook and other basin reservoirs does not adequately reflect basin-wide sediment delivery over longer time scales that incorporate periods of volcanism, cataclysmic flooding, and glacial climates. Such events and processes that operate over longer time scales are important in controlling valley geomorphology and the transport of sediment into the Deschutes River system. Thus, a key to assessing the effects of Deschutes River basin dams on river, channel, and valley bottom conditions is the role of the modern sediment transport regime relative to sediment yield and delivery events that occur over geologic



**Figure 15.** Calculated sediment budget for the lower 200 km of the Deschutes River showing spatial distribution of sediment input and the incremental effects of sediment trapping by upstream reservoirs. Sediment volumes determined on the basis of calculated SPI values (Figure 4) and the empirical relation between SPI and sediment yield shown in Figure 14. Uppermost curve shows calculated cumulative sediment delivery for preimpoundment Deschutes River upstream to Crooked River confluence, and lowest curve shows calculated cumulative sediment delivery after the stepwise reduction resulting from each of the major impoundments in the Deschutes River basin.

time scales. Several papers in this volume explore this matter in greater detail, but the remarkably low sediment transport rates of the modern (both pre- and post-impoundment) Deschutes River basin help tip the scales toward greater importance of rare high-magnitude events.

#### SUMMARY OF IMPORTANT BASIN-SCALE PROCESSES AND CONDITIONS

The cumulative result of the geologic history of the Deschutes River basin is that the basin has distinct geologic, hydrologic, and geomorphic attributes when compared to other western U.S. rivers. Of these attributes, the remarkably steady flows and low sediment flux are important factors for understanding the geomorphology of the Deschutes River below the Pelton-Round Butte dam complex. These modern processes and conditions, as well as the history of geologic events such as canyon cutting, volcanism, and glaciation, form the framework for the studies of valley geomorphology, channel processes, and fish ecology reported in accompanying papers. The most important aspects of this framework are:

1. The present stream network and valley morphology have resulted from tens of millions of years of tectonic, volcanic, and erosional processes. The overall northward course of the Deschutes River was established by about 12 million years ago. The present canyon of the lower Deschutes River was carved between 4 and 1 million years ago, but there have been subsequent episodes of partial refilling and incision initiated by lava flows, volcaniclastic debris, and glacial outwash.

2. The vast extent of young and permeable volcanic rocks and the poorly developed surface channel network in the southern Deschutes River basin have resulted in a hydrologic system buffered by substantial groundwater flow. Consequently, flow entering the lower Deschutes River is unusually steady—the annual variation of flow is small and the response to regional climatic events is muted compared to other rivers of its size. More than 70 percent of the peak discharges of both the December 1964 and February 1996 flood flows in the lower Deschutes River entered downstream of the Pelton-Round Butte dam complex despite encompassing only 26 percent of the total drainage area.

3. The rock types in the southern and western parts of the Deschutes River basin, especially the Quaternary volcanic rocks, do not produce substantial sediment, and the sediment that has been produced is primarily gravel, silt, and clay deposited as glacial moraines and outwash now preserved on ridgetops and in disconnected alluvial basins. The older and more weathered volcanic rocks of the John Day and Clarno

Formations that underlie the Ochoco Mountains are susceptible to landsliding and likely produce more sediment than any of the other broadly defined rock types in the basin. In the northern part of the basin, Tertiary lava flows of the CRBG are relatively resistant to erosion and produce mainly cobble- and gravel-sized material. Aside from the lahar-filled valley of the upper White River draining Mount Hood, there are few sources of sand readily accessible by the modern channel network anywhere in the Deschutes River Basin.

4. The steady stream flows coupled with low sediment supply have resulted in extremely low rates of sediment delivery to the Deschutes River. Sediment yield from the southern part of the Deschutes River basin, determined from reservoir surveys, is the smallest yet reported for basins of such size. The eastern part of the Deschutes River basin, underlain by the weathered and uplifted volcanic and volcaniclastic rocks of the John Day and Clarno Formations has greater sediment yield and is a major source of silt and clay, but most of the areas underlain by these formations are now upstream of reservoirs and do not contribute sediment to the lower Deschutes River. Extrapolation of sediment yield measurements from reservoir surveys on the basis of an empirical relation between sediment yield and physiography leads us to infer that more than 60 percent of the total Deschutes River sediment load was derived from downstream of the Pelton-Round Butte dam complex prior to impoundment in the basin. This also corresponds to the greater relative runoff volumes derived from the lower part of the basin. The Pelton-Round Butte dam complex now traps about 50 percent of the total, basin-wide, pre-impoundment sediment load entering the lower Deschutes River. But because of the large volume of sediment introduced from downstream, this equates to less than 25 percent of the total load at the Columbia River confluence (Figure 15).

5. Most sediment delivered to the Deschutes River over time periods of thousands to millions of years has probably been delivered in pulses by episodic events such as major pumice and ash falls, volcanic debris flows, landslides, or during periods of radically altered basin conditions such as extensive glaciation or short-lived rapid incision. The total volume of sediment, especially sand and gravel, delivered during these episodic events is probably orders of magnitude greater than the volume of sediment that enters the system during more quiescent times, such as those recorded by the 20<sup>th</sup> century reservoir surveys.

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and hydrology of the Deschutes River basin. Portland General Electric conducted the reservoir surveys and sampling. Previous versions of this report were reviewed by Gary Smith and David Sherrod.

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