RECONNAISSANCE STUDY OF GEOMORPHIC CONDITIONS

Lake Ozette Watershed

Prepared for

Olympic National Park

March 2006

HERRERA ENVIRONMENTAL CONSULTANTS

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Lake Ozette Watershed

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March 31, 2006

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Executive Summary

This report presents the findings of a reconnaissance study of the geomorphic conditions of the Lake Ozette watershed conducted for the National Park Service. Lake Ozette is located entirely within Olympic National Park in the northwest corner of the Olympic Peninsula, in Clallam County, Washington. The Lake Ozette watershed lies within the greater Ozette watershed, which also includes several tributaries of the Ozette River. Most of the Lake Ozette watershed consists of private land that is used primarily for industrial forestry.

The objective of this study was to assess the current and historical geomorphic conditions of the Lake Ozette watershed in relation to land management activities and the integrity of salmonid habitat. This report documents an evaluation of the impacts of current and historical land use practices on sediment production in the Lake Ozette watershed, the conditions of channels that drain to the lake, and the delivery of sediment to Lake Ozette. It also proposes how changes in these processes may have affected the condition of salmon habitat.

Along with other salmonids in the Ozette watershed, the populations of sockeye salmon (*Oncorhynchus nerka*) in Lake Ozette have declined dramatically over the last century. The National Oceanic and Atmospheric Administration, National Marine Fisheries Service, has determined that Lake Ozette sockeye represent an evolutionarily significant unit, and the population is listed as “threatened,” as defined by the Endangered Species Act. It is likely that Lake Ozette sockeye and other salmonid species historically spawned in tributaries of Lake Ozette, possibly including the Big River, Umbrella Creek, and Crooked Creek, as well as in the Ozette River. Currently, most of the sockeye spawning occurs within Lake Ozette. Channel incision after the removal of logjams and increased sediment production due to forest harvesting activities likely have influenced the decline, and inhibited the recovery, of salmon populations.

A change in the water level in Lake Ozette has been attributed to the removal of logjams from the Ozette River, which initiated widespread channel incision in the lower portion of tributary channels. The change in water level also altered the inundation frequency and elevation zones of nearshore sockeye habitat and may have resulted in the loss of thousands of potential redd sites. These numbers could provide a first-order explanation for the decline in the sockeye population from approximately 14,000 to 18,000 circa 1950 to current estimates of several hundred (Bortleson and Dion 1979; Haggerty et al. 2005). The removal of logjams from the Ozette and Big Rivers was documented in 1952 but may have began as much as a half century earlier. Widespread channel incision in tributaries of the lake is consistent with a lower base water level.

The average rate of sediment production resulting from channel incision after logjam removal is estimated at approximately 12,000 tons per year over the 50 years after the onset of incision. Immediately after the logjam removal, at the onset of the channel response, the annual rates likely were higher than this estimate and have tapered over time.

The onset of extensive clear-cutting in the Ozette watershed during the 1960s initiated an increase in the production of fine sediment that continues to the present. The current rates of

sediment production in the Lake Ozette watershed are estimated to be more than three times the pre-disturbance rates. These estimates of sediment production are associated with significant uncertainty; however, there is a clear indication that fine sediment production has increased as a result of surface erosion from the forest road network.

Channel incision and sediment export from some stream segments observed during the field reconnaissance have been inhibited by relic large woody debris (instream wood within the channel network that was recruited before the harvest of adjacent forests). Because of the harvest of the forests adjacent to the channel network, there is little opportunity for further recruitment of large woody debris to replace the relic large woody debris as its function degrades with time. Therefore, an increase in sediment discharge to Lake Ozette can be expected from these channels when the relic large woody debris is no longer functional.

To improve habitat conditions for Lake Ozette sockeye and other aquatic species, it is necessary to moderate the impacts of increased sediment production that have resulted from past forest harvesting practices and improve the degraded tributary conditions that have resulted from channel alterations including the removal of logjams in the Ozette and Big Rivers. Strategies for improving habitat conditions include the following:

- Placement of grade control structures composed of large woody debris in tributary reaches to promote sediment storage and habitat enhancement (limiting future degradation as relic wood is lost and until riparian forests mature). High-priority reaches for wood placement include the downstream response reaches of Coal, Umbrella, and Crooked Creeks, and Big River between river kilometers 3 and 13.

- Placement of large woody debris in the Ozette River to return the water surface elevations in Lake Ozette to their historical levels. This strategy will raise the base water level of tributaries and increase the extent of nearshore beach habitat available to sockeye salmon.

- Adherence to forestry practices that minimize sediment production and prohibit all forest harvest within channel migration zones.

- Experimental removal of woody vegetation along the shore to evaluate the mobility of gravel and the accumulation of fine sediment.

1. Introduction

This report presents the findings of a reconnaissance study of the geomorphic conditions of the Lake Ozette watershed that was conducted for the National Park Service. This study evaluated the impacts of current and historical land use practices on channel conditions, watershed sediment production, and the delivery of sediment to Lake Ozette. The Lake Ozette watershed is located in Clallam County, Washington. It lies within the greater Ozette watershed, which includes several small tributaries of the Ozette River, which flows 7.5 kilometers from the lake to the Pacific Ocean (Figure 1).

1.1 Study Purpose

Lake Ozette is the third largest natural lake in Washington state. The National Park Service, which owns approximately 15 percent of the Ozette watershed drainage, has a considerable interest in the impact of land use practices on endangered species, habitat, water quality, and infrastructure within the park.

During the early to mid-1900s, populations of sockeye salmon (*Oncorhynchus nerka*) in Lake Ozette declined precipitously. Although the cause of the decline of Lake Ozette sockeye is unknown and may include far-reaching factors such as over fishing and climate variation, hypotheses about local contributing factors include sediment input due to watershed disturbance and wood removal from the Ozette River.

The Lake Ozette sockeye have not fully rebounded from their dramatic decline, and the population is listed by the National Oceanic and Atmospheric Administration, National Marine Fisheries Service (NOAA Fisheries) as threatened, under the Endangered Species Act. Previous research has detected high proportions of fine sediment in substrate material and poor water quality within tributary streams along the eastern shore of Lake Ozette. These conditions are believed to have contributed to the decline of Lake Ozette sockeye (McHenry et al. 1994; Meyer and Brenkman 2001).

1.2 Study Objectives

The objective of this investigation was to assess the role that watershed land management may have played in increasing sediment production, degrading tributary conditions, and potentially influencing the decline (and precluding the recovery) of Lake Ozette sockeye. Lake Ozette sockeye are observed to spawn in gravelly substrate at the lake shoreline. The removal of large woody debris (LWD) from the Ozette River lowered the lake levels, thereby altering the shoreline spawning habitat (Abbe et al. 2001; Herrera 2005). This study was conducted to determine the relative magnitude to which stream clearing, extensive road construction, and widespread timber harvest may have affected salmonid habitat. The companion study, *Hydraulic* *and Geomorphic Evaluation: Analysis of Wood Loading in the Ozette River and Its Effect on Water Levels in Lake Ozette, Clallam County*, *Washington*, was conducted to investigate historical lakeshore changes and the influence of LWD in the Ozette River on the water surface elevation of Lake Ozette (Herrera 2005).

This analysis of the geomorphic conditions of the Lake Ozette watershed describes how current and historical land use practices may have affected sediment production, channel conditions, and sediment transport processes within the Lake Ozette watershed. In addition to evaluating the geomorphic conditions within tributary subbasins, this study evaluated whether lakeshore areas are likely to have been affected by increased sediment production.

The elements of this study included (1) characterization of lake levels, (2) predictions of sediment production potential from tributary subbasins, (2) evaluation of tributary channel conditions and current and historical sediment transport potential, and (4) analysis of potential lakeshore impacts due to tributary sediment delivery. This report includes a discussion of the study findings and their implications for the recovery of Lake Ozette sockeye salmon. It is divided into six sections:

- Introduction
- Background Information and Watershed Characterization
- Methods and Results
- Discussion of Results
- Restoration Strategies, Potential Resource Management Alternatives, and Recommendations for Future Research
- References.

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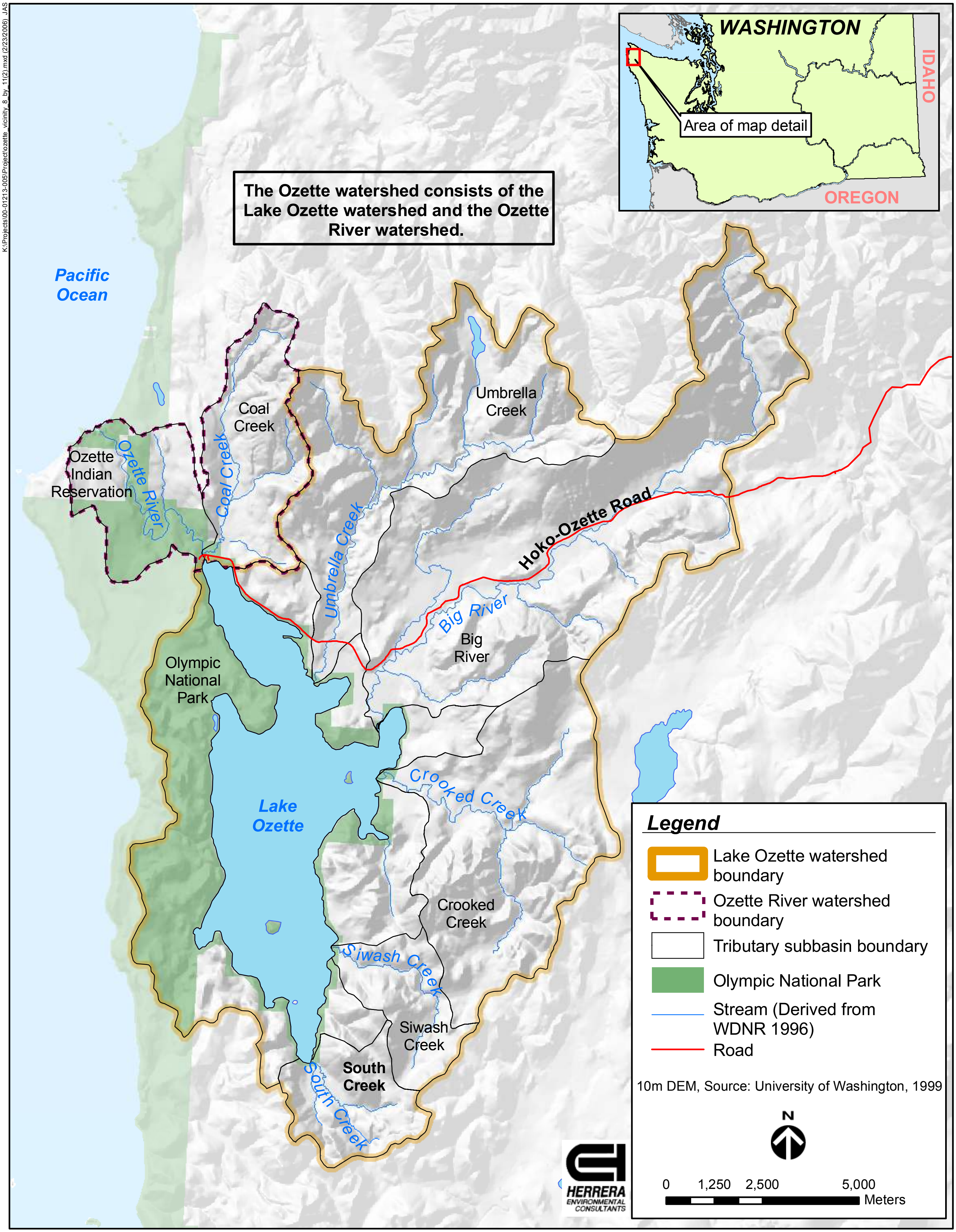

Figure 1. Vicinity map of the Ozette watershed and tributary subbasins, the Lake Ozette watershed, and the Ozette River watershed, in northwest Olympic Peninsula, Washington.

2. Background Information and Watershed Characterization

2.1 Watershed Description

The Ozette watershed is located in the northwest corner of the Olympic Peninsula, in Clallam County, Washington (Figure 1). It includes the land that drains into Lake Ozette, the lake itself, and the land that drains into the Ozette River. The Ozette River is a meandering, low-gradient sand-bedded channel that flows 7.5 kilometers from Lake Ozette to the Pacific Ocean. The entire Ozette watershed covers 233 square kilometers, and the area draining to Lake Ozette covers approximately 179 square kilometers (Table 1). Most of the lake's watershed is located north and east of the lake, which lies only 10 kilometers east of the Pacific Ocean. The major tributaries of the lake include Umbrella Creek, the Big River, Crooked Creek, Siwash Creek, South Creek, and Coal Creek. A number of smaller tributaries drain the lake's western slopes. Coal Creek, which flows to the Ozette River approximately 200 meters downstream of the lake's outlet, is the principal sediment supplier to the Ozette River, since Lake Ozette acts as a large sediment trap for all upstream inputs.

Table 1. Size of the Ozette watershed, Lake Ozette, the Lake Ozette watershed, and tributary subbasins.

Watershed Feature or Subbasin	Area (km^2)
Ozette watershed [a]	233
Lake Ozette	29.7
Lake Ozette watershed (excluding Lake Ozette)	179
Ozette River watershed	24.4
Ozette River subbasin	11.2
Coal Creek subbasin	13.2
Lake Ozette watershed subbasins	179
Umbrella Creek	29.9
Big River	59.1
Crooked Creek	30.9
Siwash Creek	7.9
South Creek	8.7
West-shore tributaries	22.6
Additional east-shore tributaries	19.7

[a] The Ozette watershed area includes the area of Lake Ozette.

The only outflow from the lake is the Ozette River, which begins at the northwest tip of the lake and flows 7.6 kilometers northwest to the Pacific Ocean at Cape Alava. Because of the low relief between the lake and the ocean, the Ozette River has a very low gradient (0.0014), particularly for a Pacific Northwest river. Among Pacific Northwest rivers, the Ozette River is also distinct in terms of its geomorphology; it has a high sinuosity and a relatively stable channel that is lined by old-growth forest on each bank. The Ozette River provides the conduit for anadromous sockeye salmon that travel from the Pacific Ocean to Lake Ozette for spawning.

Lake Ozette lies entirely within Olympic National Park. Lake Ozette is approximately 10 kilometers from north to south and 3 kilometers wide. With a surface area of 29.7 square kilometers, Lake Ozette is the largest lake on the Olympic Peninsula and the third largest natural lake in Washington state. The mean surface elevation of the lake is approximately 33.9 feet above mean sea level (10.3 meters National Geodetic Vertical Datum of 1929 [NGVD 29]), and the lake level fluctuates from 30.8 to 41.5 feet above mean sea level.

2.2 Salmon Habitat Utilization

The populations of sockeye salmon (*Oncorhynchus nerka*) in Lake Ozette have declined dramatically over the last century, along with other salmonids in the Ozette watershed (i.e., chinook and chum) (Haggerty et al. 2005). The National Oceanic and Atmospheric Administration, National Marine Fisheries Service (NOAA Fisheries) has determined that the Lake Ozette sockeye represent an evolutionarily significant unit, and the population is listed as "threatened," as defined by the Endangered Species Act.

Lake Ozette sockeye and other salmonid species historically spawned in tributaries of Lake Ozette. The Makah Fisheries Management hatchery program raises local Lake Ozette native brood stock, currently sustaining spawning populations of sockeye in the Big River, Umbrella Creek, and Crooked Creek, but most of the sockeye spawning occurs within Lake Ozette (Peterschmidt 2005).

Lake Ozette sockeye spawn in unconsolidated mixtures of cobble, gravel, and coarse sand along the perimeter of the lake. The lake depth at spawning sites ranges from 1.0 to 9.2 feet (0.3 to 2.8 meters) with a majority of redds placed in 3.3 to 9.2 feet (1.0 to 2.8 meters) of water (Dlugokenski et al. 1981). Occasional redds may be found at depths up to 20 to 30 feet (6.1 to 9.1 meters) (Peterschmidt 2005). Eggs and alevins at redd sites are extremely sensitive to fluctuations in water level. If the eggs and alevins are too close to the water surface and become exposed to the air, they can be desiccated. On the other hand, if the water is too deep, aeration can be inadequate and the eggs and alevins can receive too little oxygen to survive (Bortleson and Dion 1979; Jacobs et al. 1996). Spawning typically occurs between early November and mid-January, with peak spawning occurring from mid-December to early January. Incubation occurs from November through March. Emergence occurs between February and April. From April to June, emerged juveniles will emigrate to the pelagic zone of the lake and rear for 1 year before they become smolt and migrate to the Pacific Ocean in April or May of the following year (Peterschmidt 2005).

According to surveys conducted by Makah Fisheries Management, Lake Ozette sockeye spawn at two primary beaches: (1) Olsens Beach, located on the lake's eastern shore, north of Siwash Creek, and (2) Allens Beach, located on the lake's western shore, north of Allens Bay (Figure 2)

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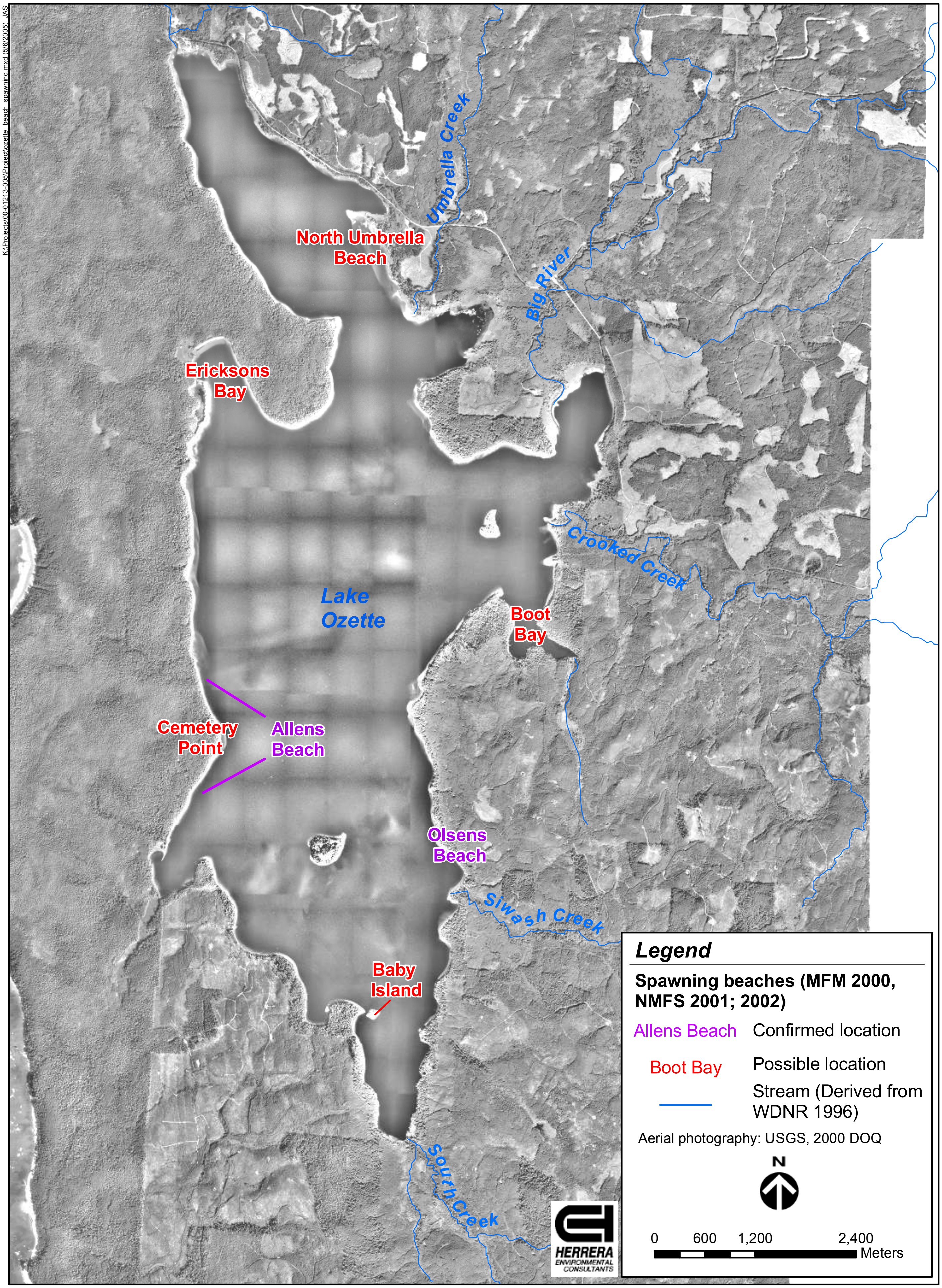

Figure 2. Locations of confirmed and potential spawning beaches in Lake Ozette.

(Haggerty et al. 2005). Spawning has been observed at these two beaches every year since 1976 (Haggerty et al. 2005). Secondary beach spawning also has occurred or does occur around the lake, but these locations have been poorly investigated or documented beyond what is summarized in Table 2. In addition, other apparently suitable spawning habitat exists around the lake but is not utilized for unknown reasons.

Table 2. Details of confirmed and potential sockeye spawning locations in Lake Ozette.

Spawning Locations	Details
Confirmed Primary Spawning	
Allens Bay	Confirmed redds 1976 to 2005, located along the southwest shore of Lake Ozette.
Olsens Beach	Confirmed redds 1976 to 2005, located along the southeast shore of Lake Ozette north of Siwash Creek.
Historical Primary Spawning	
North Umbrella Beach	Confirmed spawning January 1979 (30 spawning sockeye); no observations since then.
Cemetery Point	Confirmed redds during several years, secondary spawning extension of Allens Beach.
North Olsens Beach	Confirmed redds during several years, secondary spawning extension of Olsens Beach.
Baby Island	One time observation of spawning sockeye and at least one redd.
Potential Spawning Locations	
Historic and current gravel beaches around the lake (e.g., Erickson Bay).	
Live Adult Sockeye Observed	
Boot Bay	Several ripe fish captured in gill nets in 1979, no evidence of spawning.

Source: MFM (2000); NMFS (2001); Meyer and Brenkman (2001); NMFS (2002); Haggerty et al. (2005); Peterschmidt (2005).

2.3 Climate

The Lake Ozette watershed lies within the temperate rainforest between the Pacific Ocean and the Olympic Mountains. The nearest weather station to the watershed with a long-term record is located at Quillayute Airport, approximately 11 kilometers to the south. The annual precipitation at the Quillayute Airport station ranged from 153 to 334 centimeters from 1967 to 2004 (Figure 3). The average annual precipitation over this period was 259 centimeters. October through March is the period of heaviest precipitation, and monthly rainfall totals average more than 25 centimeters during these months (Figure 4).

2.4 Geology

The geology of the Lake Ozette watershed influences the morphology of stream channels and the supply and transport of sediment through the channel network. Uplift and accretion of marine sedimentary and volcanic rocks have resulted in highly deformed and faulted bedrock. The

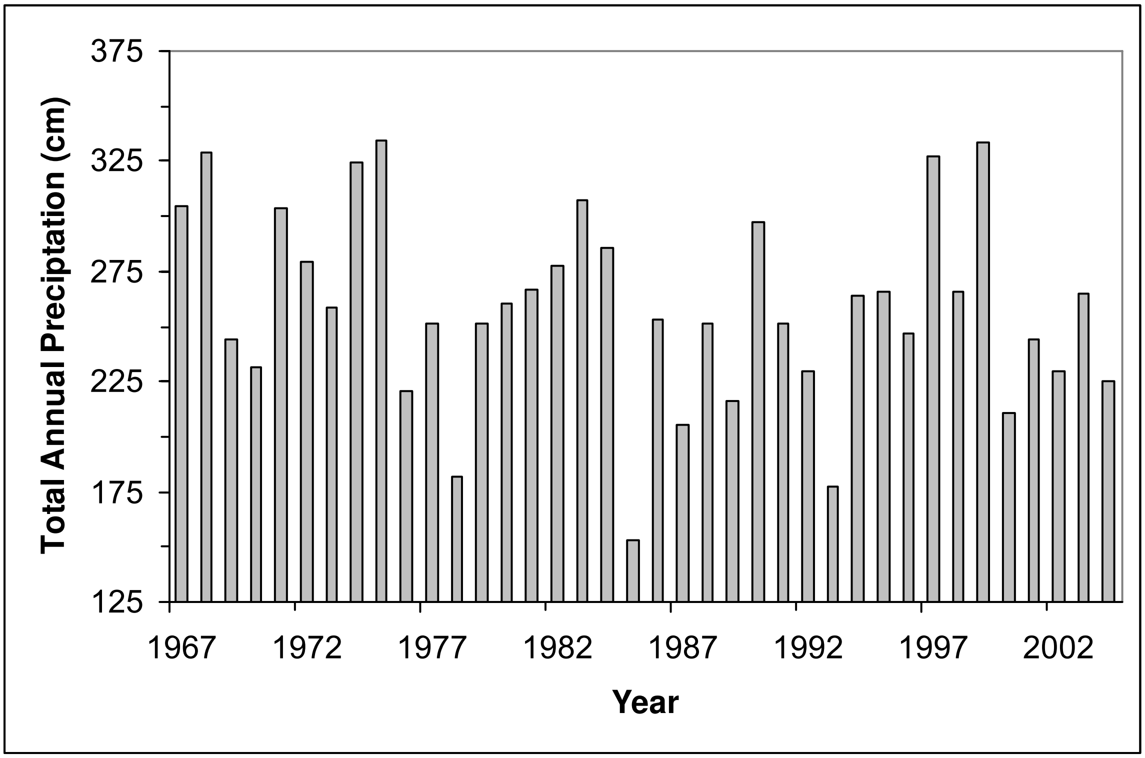

Figure 3. Annual rainfall totals at the Quillayute Airport weather station from 1967 through 2004.

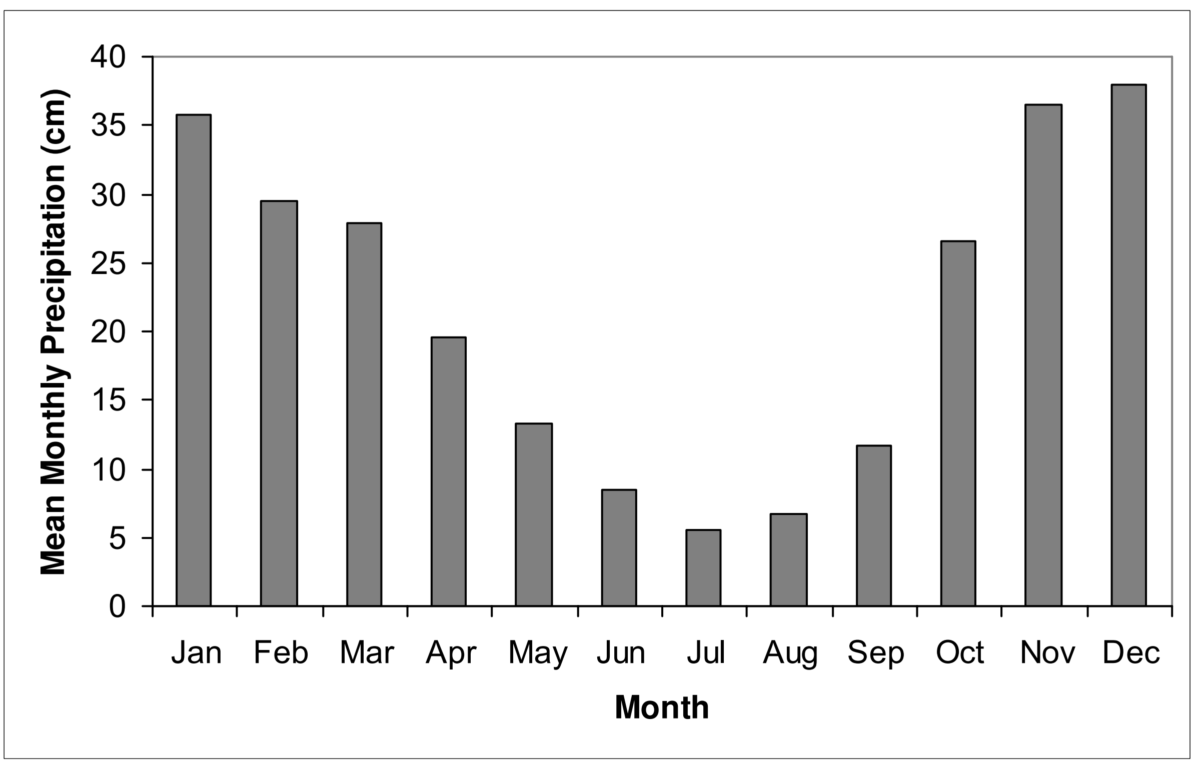

Figure 4. Mean monthly rainfall at the Quillayute Airport weather station from 1967 through 2004.

majority of bedrock units consist of Eocene and Oligocene marine sedimentary rocks that are between 15 and 60 million years old (Figure 5). Additional bedrock geology is made up of volcanic rocks of the Crescent Formation, which consists primarily of basalt with minor exposures of flow breccia and volcaniclastic deposits exposed exclusively in the upper portion of the Big River subbasin at the eastern headwaters of the Ozette watershed (Figure 5).

Thrust fault assemblages in Eocene and Oligocene sedimentary and volcanic rocks in the northern part of the Ozette watershed resulted from the collision of plates during subduction zone uplift. There is little evidence of Holocene deformation (over the 10,000 years) as no faults have been mapped through glacial sediments. However, the basin is still subject to massive earthquakes such as one that occurred approximately 300 years ago (Atwater et al. 1995). Although this study found no evidence that such an event had any significant impact on the lake, large earthquakes could destabilize steeper hillslopes and initiate an influx of sediment to the tributary channel network.

Glacial sediments from the Fraser glaciation, which persisted regionally from 29,000 to 11,000 years bp (before present), mantle the bedrock geology and cover the majority of the basin (Thackray 1996). The glacial units are relatively unconsolidated and are composed of glacial drift, glacial outwash, glacial till, and glaciolacustrine deposits. Alluvial sediments, deposited by rivers and streams since the retreat of the last glacier advance, occupy some floodplains and delta environments in the lower portion of the larger tributaries within the basin.

The relatively low relief of the Ozette watershed is in part a result of the weak character of marine sedimentary and volcanic bedrock units and the relatively unconsolidated condition of glacial units. The thick vegetation covering the watershed has had a significant effect in providing cohesion and limiting erosion. Land use that alters natural drainage patterns, ground exposure, and soil cohesion will tend to increase sediment delivery to Lake Ozette. However, in order for these units to generate significant sediment to the channel network and to Lake Ozette, the conditions of slope, precipitation, and vegetative cover must combine to promote erosion or slope instability.

2.5 Land Ownership and Land Use History

Current land ownership within the Ozette watershed is distributed among private timber companies, the National Park Service, the Washington Department of Natural Resources (WDNR), and the Makah Indian Tribe (Figure 6). Private timber companies own 63 percent of the greater Ozette watershed (Table 3). Of the lands draining directly to Lake Ozette, 75 percent are currently privately held and most are located east of Lake Ozette. State-owned land (WDNR) constitutes 10 percent of the Ozette watershed and is dispersed throughout the privately owned portion of the basin, mostly east of the lake. Over 90 percent of the Coal Creek, Umbrella Creek, and Big River subbasins and over 80 percent of the Crooked Creek and South Creek subbasins are privately held. Land ownership in the Siwash Creek subbasin is split between WDNR (49 percent) and private ownership (51 percent). Federally owned lands administered by the National Park Service and Olympic National Park constitute 15 and 13 percent of the lands within the Ozette watershed and Lake Ozette watershed, respectively, as well as all of Lake Ozette. Land within Olympic National Park includes a buffer around the perimeter of the lake, the majority of hillslope tributaries along the lake's west shore, and the Ozette River corridor northwest of the lake. A number cabins are located within the narrow lakeshore holdings of Olympic National Park surrounding the lake. Some cabins are accessible by forest roads and others can be reached only by boat from the lake. The Ozette Indian Reservation, which is included within the Makah tribal land ownership, constitutes 1 percent of the greater Ozette watershed and is located west of the Ozette River (draining to the lower Ozette River and not Lake Ozette).

Table 3. Distribution of land ownership within the Ozette watershed.

Watershed Feature or Subbasin	Area (km^2)	Ownership (percent)			
		WDNR	Private	NPS	Tribal
Ozette watershed [a]	233	10	63	26	1
Lake Ozette	29.7	0	0	100	0
Lake Ozette watershed (excluding Lake Ozette)	179	12	75	13	0
Ozette River watershed	24.4	3	62	27	8
Ozette River subbasin	11.2	1	23	59	17
Coal Creek subbasin	13.2	5	95	0	0
Lake Ozette watershed subbasins	179				
Umbrella Creek	29.9	6	94	<1 [b]	0
Big River	59.1	10	90	<1 [b]	0
Crooked Creek	30.9	5	95	<1 [b]	0
Siwash Creek	7.9	49	51	<1 [b]	0
South Creek	8.7	14	86	<1 [b]	0
West-shore tributaries	22.6	2	14	84	0
Additional east-shore tributaries	19.7	11	71	18	0

[a] The Ozette watershed area includes the area of Lake Ozette.
[b] The NPS boundary includes a buffer around the lake that includes tributary outlets.

Timber harvest in the greater Ozette watershed was evaluated using historical aerial photographs. Timber harvest before 1964 was delineated using a photograph set from 1964, and harvest between 1965 and 2003 was delineated using photograph sets from 1994, 2000, 2002/2003, and 2003. Historical forest clearing was evaluated between 1970 and 2000 for part of the Ozette watershed by the Makah Indian Tribe using historical aerial photographs and satellite imagery (Shellberg 2004). This data set included neither the Siwash and South Creek subbasins nor the areas cut before 1970 that may not have been recognized by the satellite imagery. Due to these limitations, the data set was used to qualitatively describe spatial and temporal patterns of timber harvest in the basin.

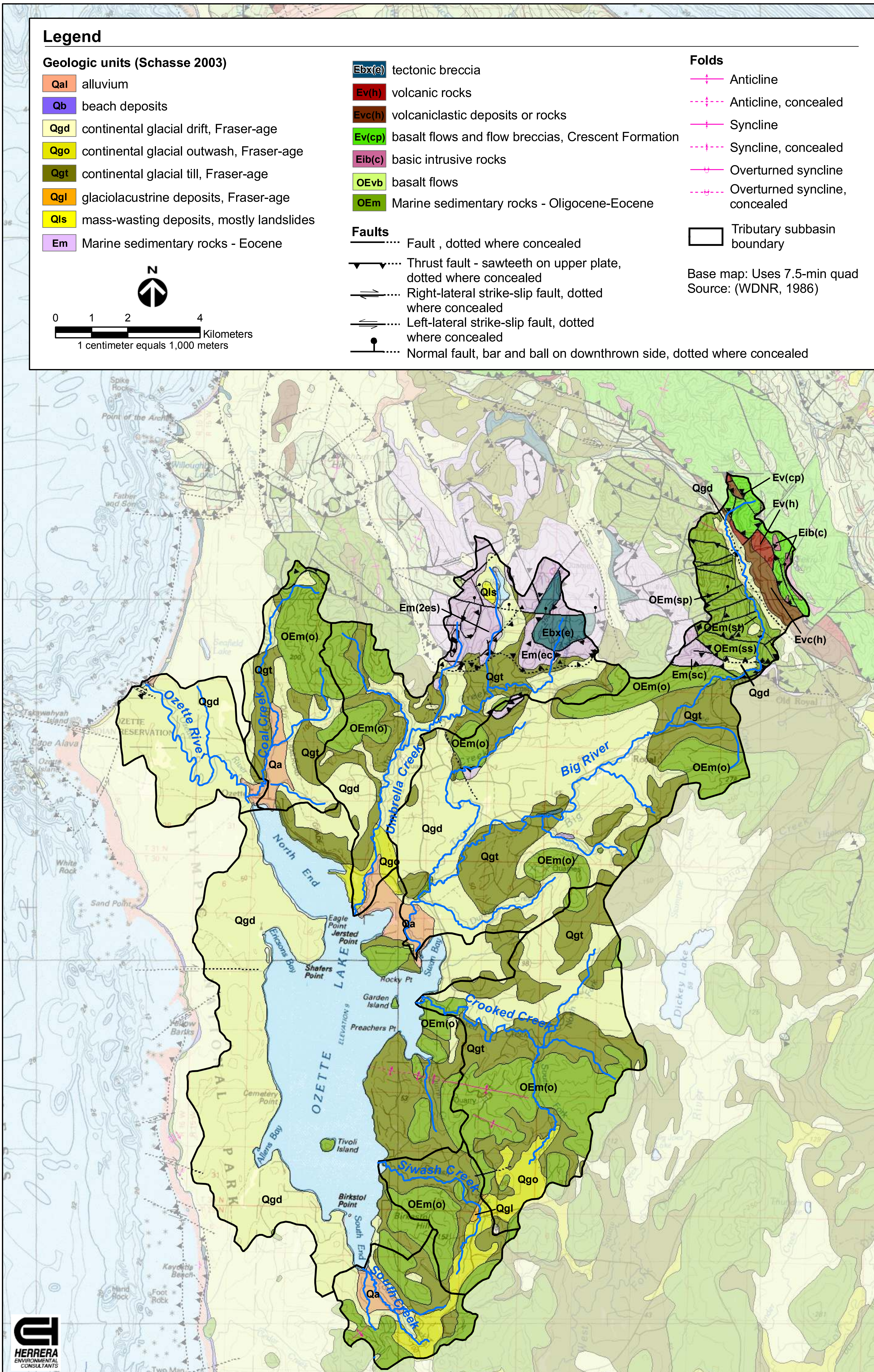

Figure 5. Geology of the Ozette watershed.

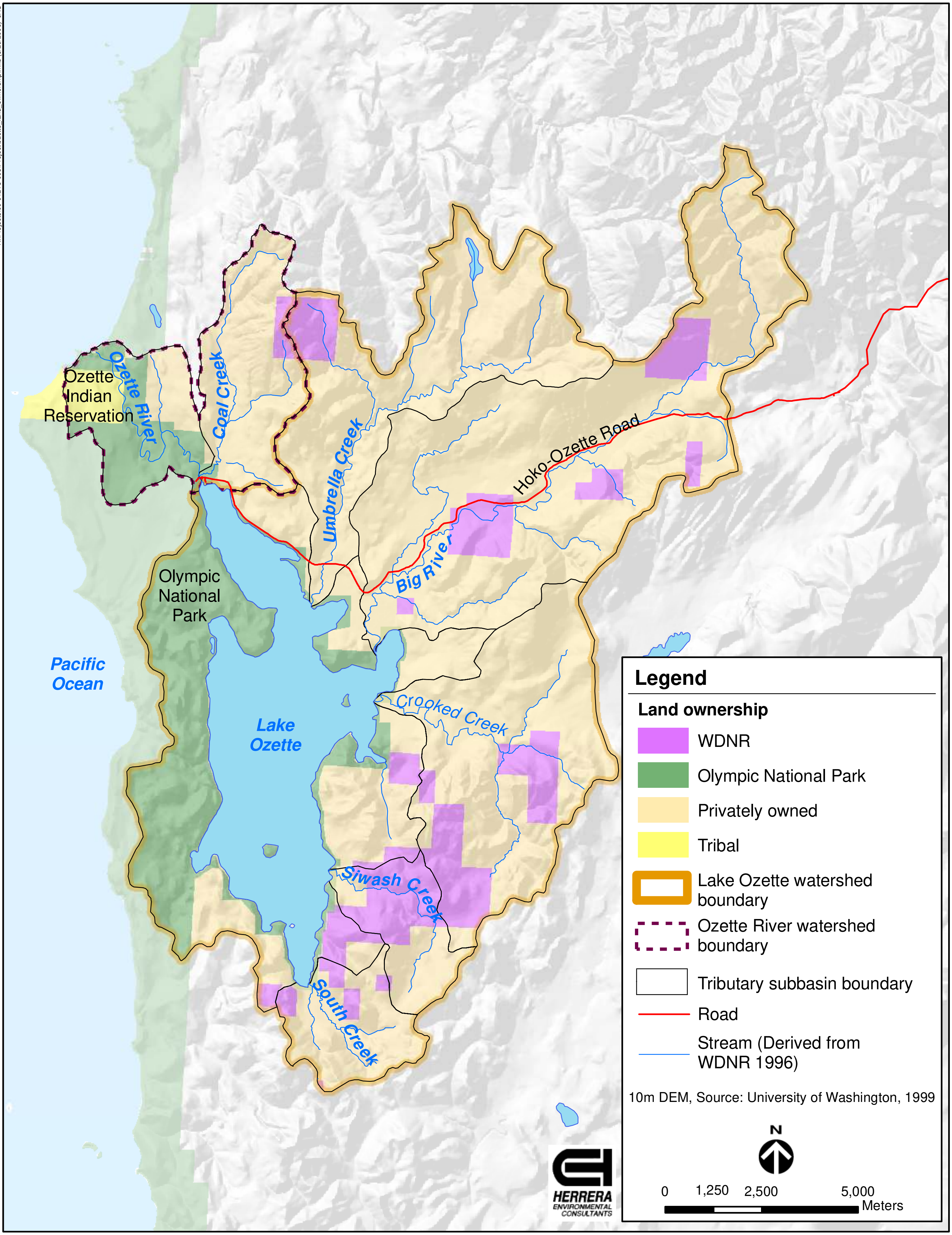

Figure 6. Land ownership within the Ozette watershed.

By 1964, approximately 20 percent of the greater Ozette watershed had been harvested, including 41 percent of the Big River subbasin, 26 percent of the Coal Creek subbasin, 21 percent of the Crooked Creek subbasin, and less than 15 percent of the Umbrella Creek and South Creek subbasins (Table 4). By the 1990s, almost the entire subbasins of Crooked Creek, Umbrella Creek, and South Creek had been harvested. By 2003, the cumulative area affected by timber harvest was approximately 85 percent, with most of the subbasins east of the lake having over 90 percent of their area harvested. Similar results are presented in studies of Bortleson and Dion (1979) and Blum (1988), who also found that approximately 85 percent of the greater Ozette watershed had been harvested by the late 1990s. Figure 7 illustrates the extent of the forest harvests that had occurred in the greater Ozette watershed prior to 1964 and until 2003.

Table 4. Summary of forest harvest in the Ozette watershed.

Watershed Feature or Subbasin	Percent of Subbasin Harvested at Least Once	
	1964	2003
Ozette watershed [a]	19	85
Lake Ozette	NA	NA
Lake Ozette watershed (excluding Lake Ozette)	23	84
Ozette River watershed	16	73
Ozette River subbasin	2	42
Coal Creek subbasin	26	100
Lake Ozette watershed subbasins	23	84
Umbrella Creek	15	98
Big River	41	98
Crooked Creek	21	93
Siwash Creek	0	86
South Creek	7	88
West-shore tributaries	0	15
Additional east-shore tributaries	19	65

[a] The Ozette watershed area includes the area of Lake Ozette.

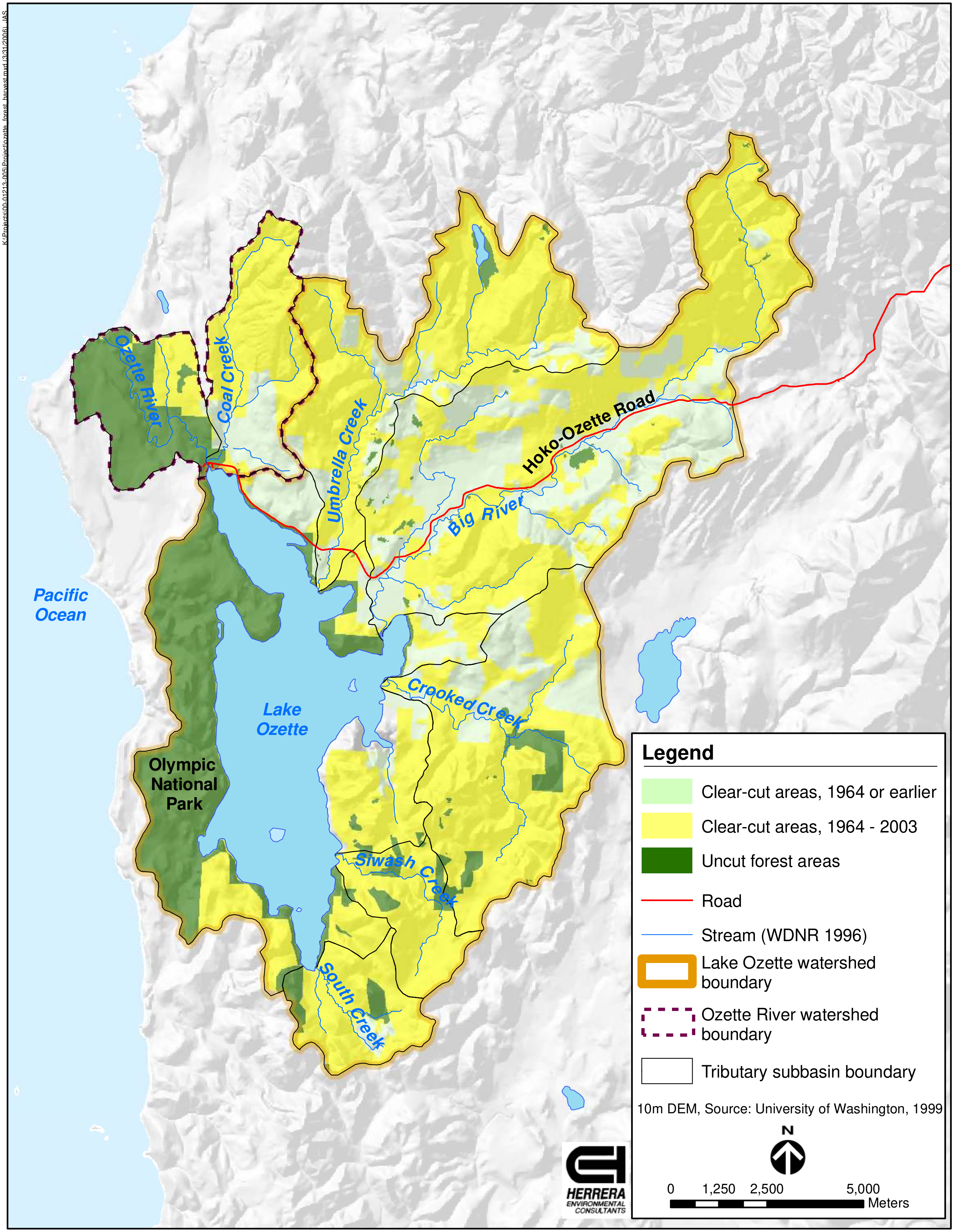

Figure 7. Timing and extent of forest clearing in the Lake Ozette watershed.

3. Methods and Results

This section describes the methods used to assess the significance of forest harvesting practices and channel modifications in the greater Ozette watershed in terms of their relative effects on sediment production, stream habitat, water quality, and lakeshore conditions. This section also presents the results of the assessment, which focused on when the most significant impacts occurred or are likely to occur and the identification of land use practices, if any, that have been responsible for the most significant impacts.

Forest harvest is the dominant land use activity in the Ozette watershed. Physical changes associated with harvesting practices include the removal of trees; the construction, use, and maintenance of forest roads; and related alterations to the drainage network. These changes can significantly increase sediment production within the watershed.

The components of this investigation included an evaluation of lake levels, an analysis of the relative amounts of sediment production in various subbasins and the importance of forest harvesting practices in terms of their effects on sediment production, a geomorphic characterization of tributary channels and their potential for sediment transport, and an assessment of lakeshore conditions and longshore transport of sediment in Lake Ozette. Included in this lakeshore assessment was an analysis evaluating the loss of potential nearshore sockeye habitat resulting from a change in lake levels caused by the removal of logjams in the Ozette River.

The framework of a sediment budget was used to organize the components of the study and describe the conditions of sediment production, transport, storage, and delivery within the Lake Ozette watershed (Figure 8). The mass balance of sediment in the Lake Ozette watershed can be described by the following equation:

$$O = I + \Delta S$$

Where: O = sediment output from tributary subbasins to Lake Ozette

I = input to tributary channel network

ΔS = change in tributary sediment storage.

The sediment inputs that were evaluated included soil creep, landslides, road surface and hillslope surface erosion, and channel incision. The conditions of tributary sediment storage were evaluated by means of reconnaissance surveys of the tributaries, and sediment transport calculations were used to describe the conditions of tributary sediment storage. These study components, along with the lakeshore characterization at tributary outfalls and the evaluation of longshore transport, also improved the understanding of sediment output from tributary subbasins to Lake Ozette. The range of lake levels and the duration of certain levels affect shoreline inundation and the base level of tributaries draining to Lake Ozette. Changes in the range or duration of lake levels could alter the tributary base level, which in turn could promote incision in the channel network that would influence sediment transport and storage.

3.1 Lake Level Analysis

The water levels in Lake Ozette were recorded by Olympic National Park at the Ozette ranger station from 1981 to 1994 and from 1998 to 2003. Since 2003, Makah Fisheries Management has been recording water levels at this same location as well as at Tivoli Island at the south end of the lake (Figure 9). The available lake level data obtained from Olympic National Park and the Makah Fisheries Management were evaluated to determine the magnitude and seasonality of variations in lake level.

The water surface elevation of Lake Ozette ranges between 30.8 and 41.5 feet (9.4 and 12.6 meters) above mean sea level (NGVD 29). The average annual water surface elevation is 33.9 feet (10.3 meters) above mean sea level (NGVD 29). The average range between maximum and minimum water surface elevation during the water years from 1982 to 1994 and 1998 through 2003 is 7.4 feet (2.3 meters), with a maximum range of 10.2 feet (3.1 meters) and a minimum range of 2.7 feet (0.8 meters). The standard deviation of the annual variability is 1.9 feet (0.6 meters). Figure 10 shows the water surface elevations for Lake Ozette for water years 1982 to 1994 and 1998 to 2004.

The water surface elevation of Lake Ozette fluctuates seasonally, rising as precipitation increases in October and typically peaking during periods of intense precipitation during the months of November through March (Figure 11). The water surface elevation begins to drop in March or April as precipitation declines and generally falls to its lowest elevation of about 31.1 feet (9.5 meters) (NGVD 29) in September or October.

The report *Hydraulic and Geomorphic Evaluation: Analysis of Wood Loading in the Ozette River and Its Effect on Water Levels in Lake Ozette, Clallam County*, *Washington* (Herrera 2005) provides a description of the hydraulic variability of lake levels and the impacts on lake levels that resulted from the removal of woody debris from the Ozette River in the early 1950s (Kramer 1953). In this evaluation, Herrera (2005) developed a continuous one-dimensional hydraulic model of the Ozette River using the unsteady module of HEC-RAS. The objective of the modeling was to analyze the effects of alternative scenarios of wood loading in the Ozette River on the water levels in Lake Ozette. Model inputs included channel survey data gathered in October 2003 and July 2004 and stage discharge data from Lake Ozette and the Ozette River from December 2003 through January 2005. The characteristics of woody debris in the upper 1,000 meters of the Ozette River were documented during a survey on July 16 and 17, 2004. The characteristics of observed woody debris jams included their dimensions, the number of key pieces, and the percentage of the bankfull channel that was obstructed. Major woody debris jams were represented in the model as obstructions, and smaller jams were represented as an increase in channel roughness. The model was calibrated against observed water surface profiles surveyed in October 2003, July 2003, October 2004, November 2004, and December 2004.

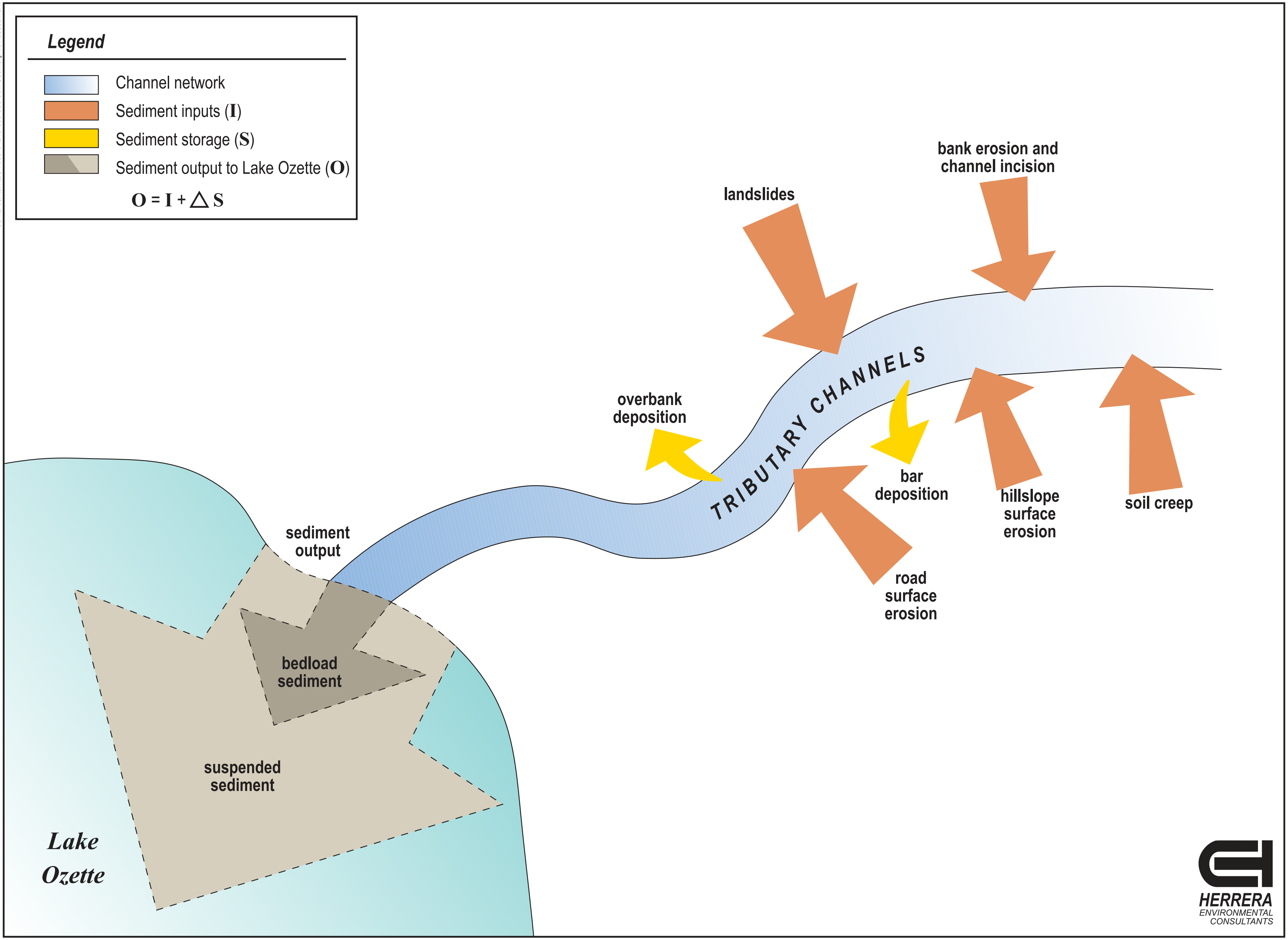

Figure 8. Conceptual model of the Lake Ozette watershed sediment budget.

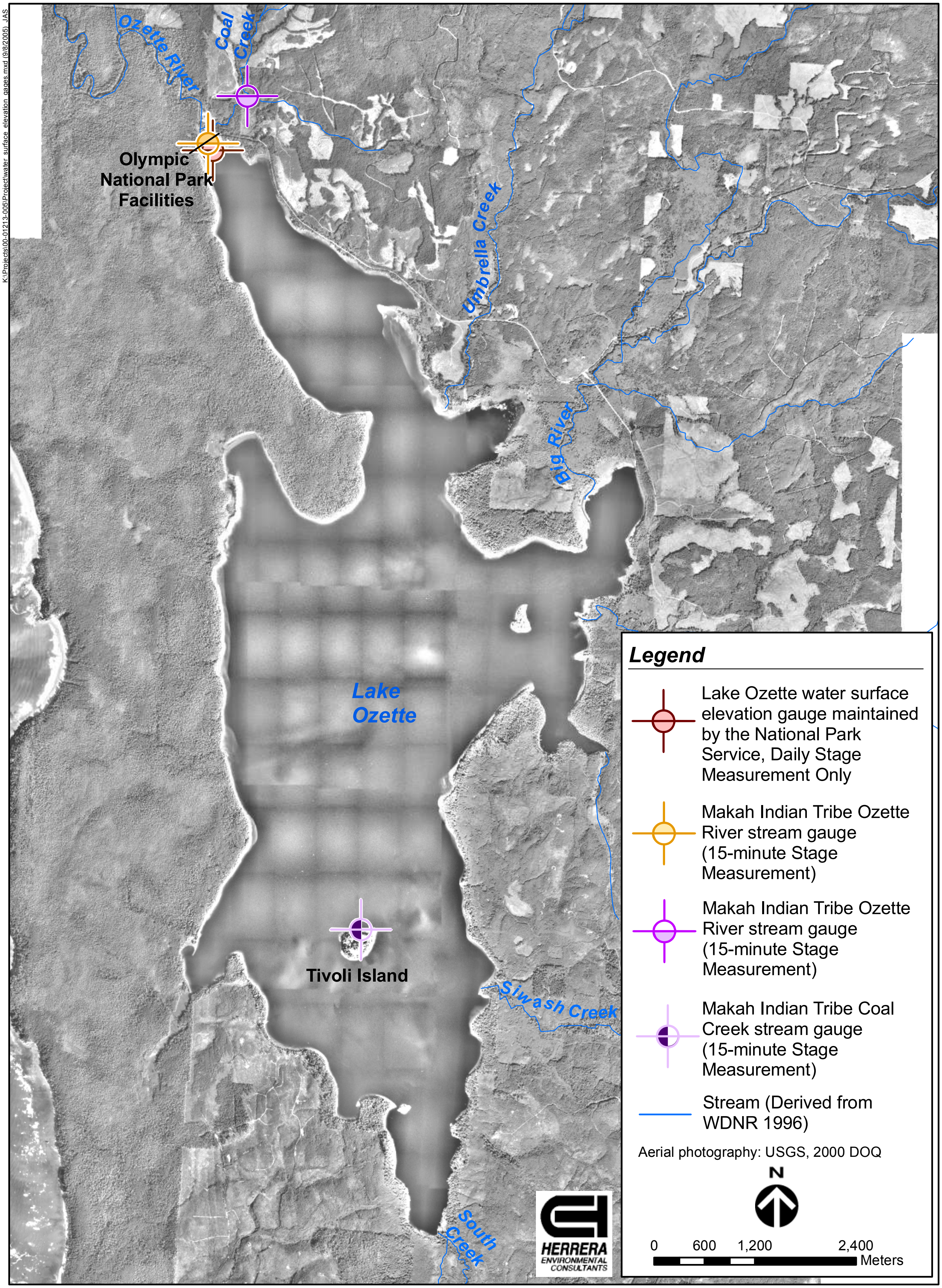

Figure 9. Locations of Lake Ozette water surface elevation gauges.

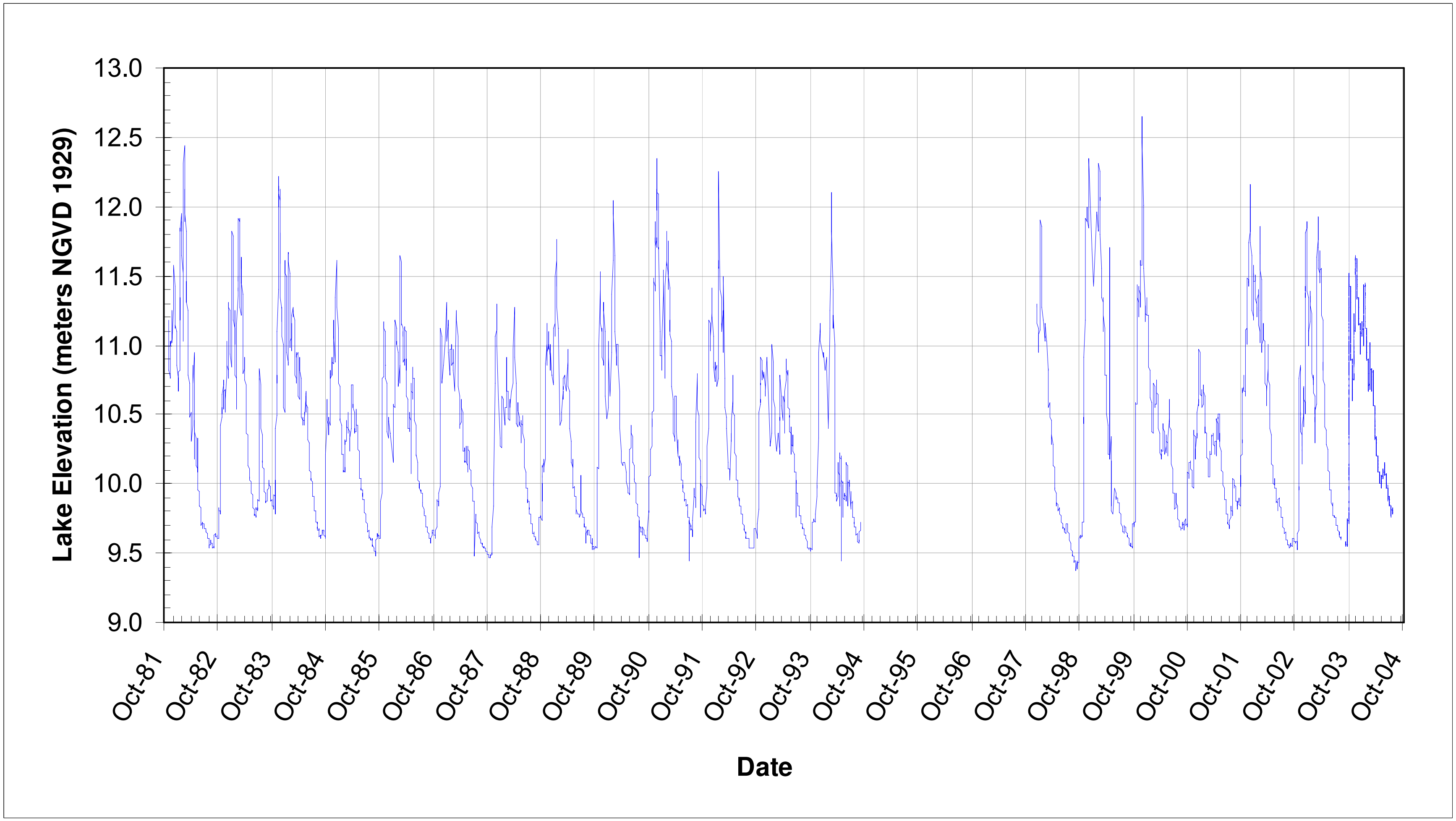

Figure 10. Lake Ozette water surface elevations for water years 1982 to 1994 and 1998 to 2004. The gauge location is located at the national park facility at the north end of the lake. Lake levels for water years 1982 to 1994 and 1998 to 2003 are mean daily values; water year 2004 data were collected at 15-minute intervals.

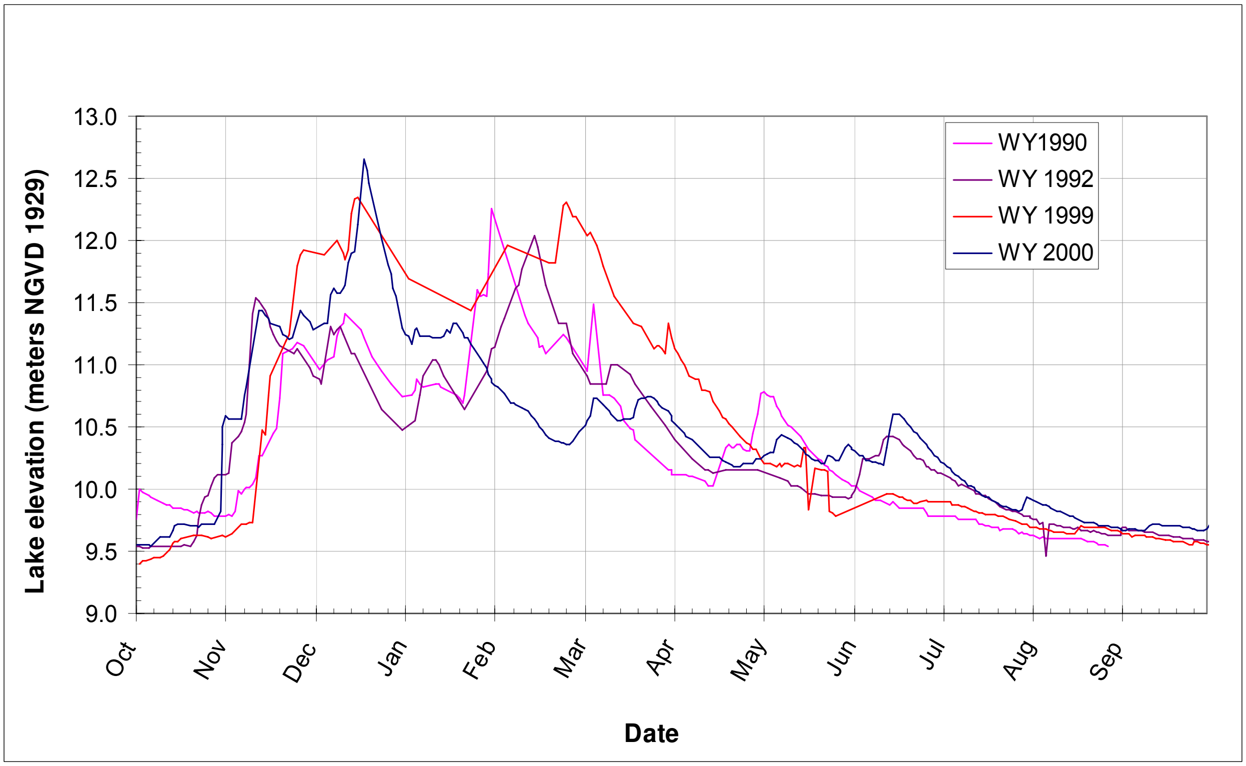

Figure 11. Lake Ozette water surface elevations for water years 1990, 1992, 1999, and 2000, illustrating the annual variability in lake levels.

Once the model was calibrated to existing conditions, several alternative wood loading scenarios were defined and evaluated to assess the effects of wood loading on lake levels. Two classes of scenarios were defined. The first class included the existing conditions and an additional scenario to evaluate how lake levels would respond if the existing three large jams stayed in place and accumulated more wood; the bankfull blockage was increased by 20 percent at the location of each major logjam to represent this anticipated accumulation. This scenario was selected to represent a realistic condition that could be expected to occur in the absence of channel clearing or additional wood placement. The second class included 12 scenarios developed for the purpose of understanding the relationship between jam characteristics and the magnitude and duration of lake levels in Lake Ozette. Logjam characteristics were evaluated by adjusting the distance between logjams and the percentage of the bankfull channel that was obstructed.

Results of this evaluation indicate that lake levels are directly affected by the conditions of wood loading in the upper kilometer of the Ozette River at the lake's outlet (Herrera 2005). For the time period evaluated in the model (December 2003 through January 2005), Figure 12 presents results of hydrodynamic (unsteady) flow simulations of Lake Ozette water levels for existing conditions and two scenarios of potential wood loading. Figure 13 shows an inundation frequency plot or the duration as a percentage of time that elevations are exceeded in Lake Ozette. The existing conditions represent the lake elevation at the national park ranger station near the inlet to the Ozette River. The two modeled scenarios represent the historical lake levels for the same lake outflows under high and low wood loading in the Ozette River.

Lake elevation predictions for predisturbance conditions under high wood loading are up to 1.8 meters greater than those for low wood loading and up to 1.1 meters greater than the existing conditions (Figure 12). The difference in lake elevations among the scenarios is greatest during the late fall, winter, and early spring, critical periods for salmonids. Modeling results indicate that the water surface elevation of the lake before the clearing of the Ozette River would have exceeded 11.5 meters approximately 30 percent of the time over the 2-year period for which the model was run, as opposed to approximately 8 percent of the same period under existing conditions and only 1 percent of the time when the channel was relatively clear of wood debris (Figure 13).

As modeled, the wood clearing that occurred in the Ozette River during 1952 had a measurable effect on lake water levels; however the history of river management and wood clearing before 1952 is not well documented. It is possible that wood clearing in the Ozette River may have been initiated before 1910 in order to provide access to the lake for homesteaders along the river (Haggerty 2005).

It should also be recognized that wood recruitment to the Ozette River has occurred over the last 50 years and has resulted in increased instream obstructions. The logjams that presently exist in the upper 1,000 meters of the Ozette River have likely resulted in increases in water surface elevation from the minimum that would have occurred immediately after river clearing.

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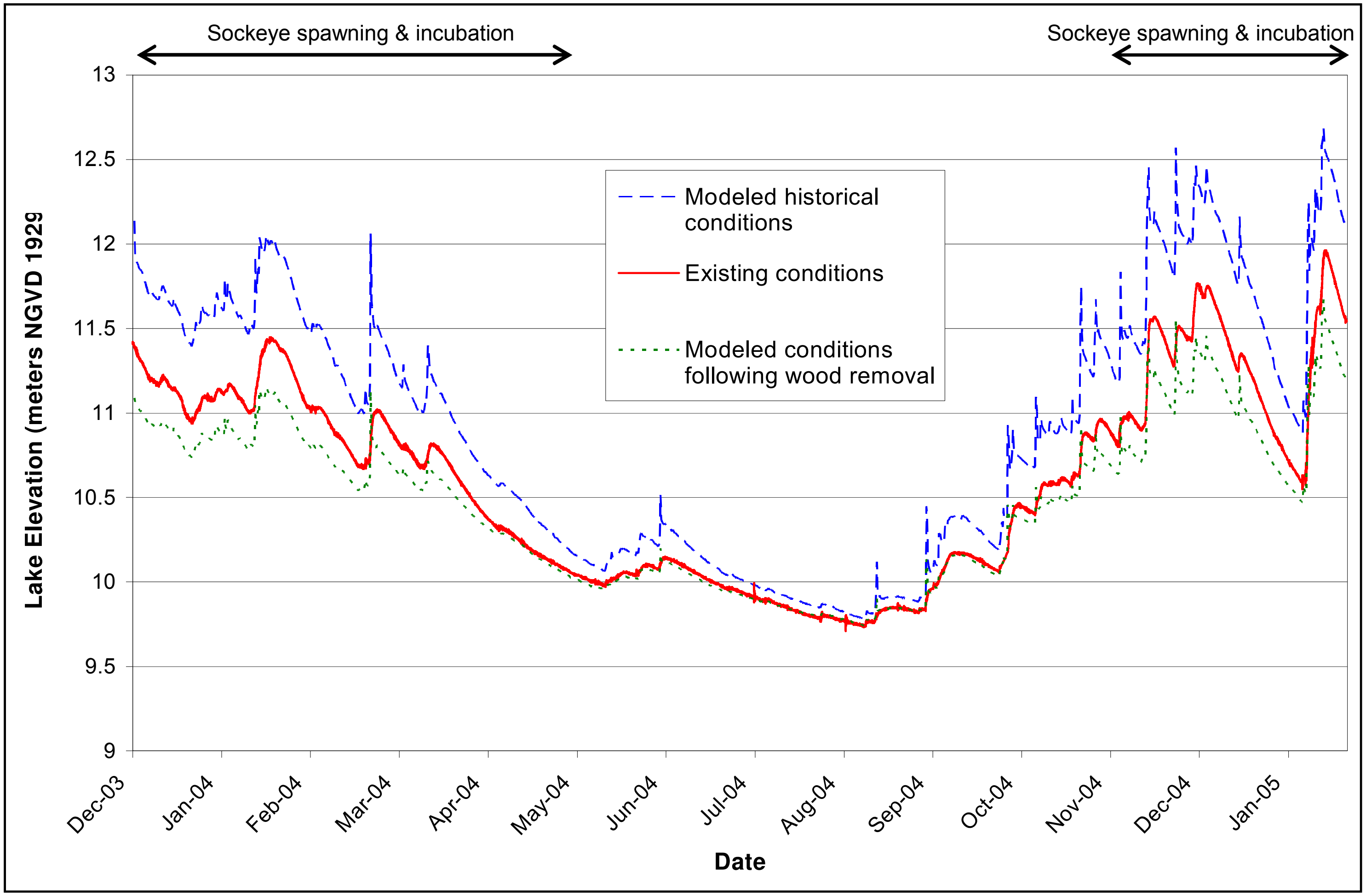

Figure 12. Lake Ozette water surface elevations for the existing and modeled conditions over the hydraulic model analysis period. The lake elevation for existing conditions represents lake elevation data from the gauge at the national park facilities near the mouth of the Ozette River. The lake elevations for historical conditions are results from the hydraulic model scenario assumed to best represent wood loading conditions in the Ozette River prior to LWD removal (woody debris accumulations every 60 meters that obstruct 60 percent of the bankfull channel). Modeled conditions following wood removal include no obstructions from woody debris in the modeled reach.

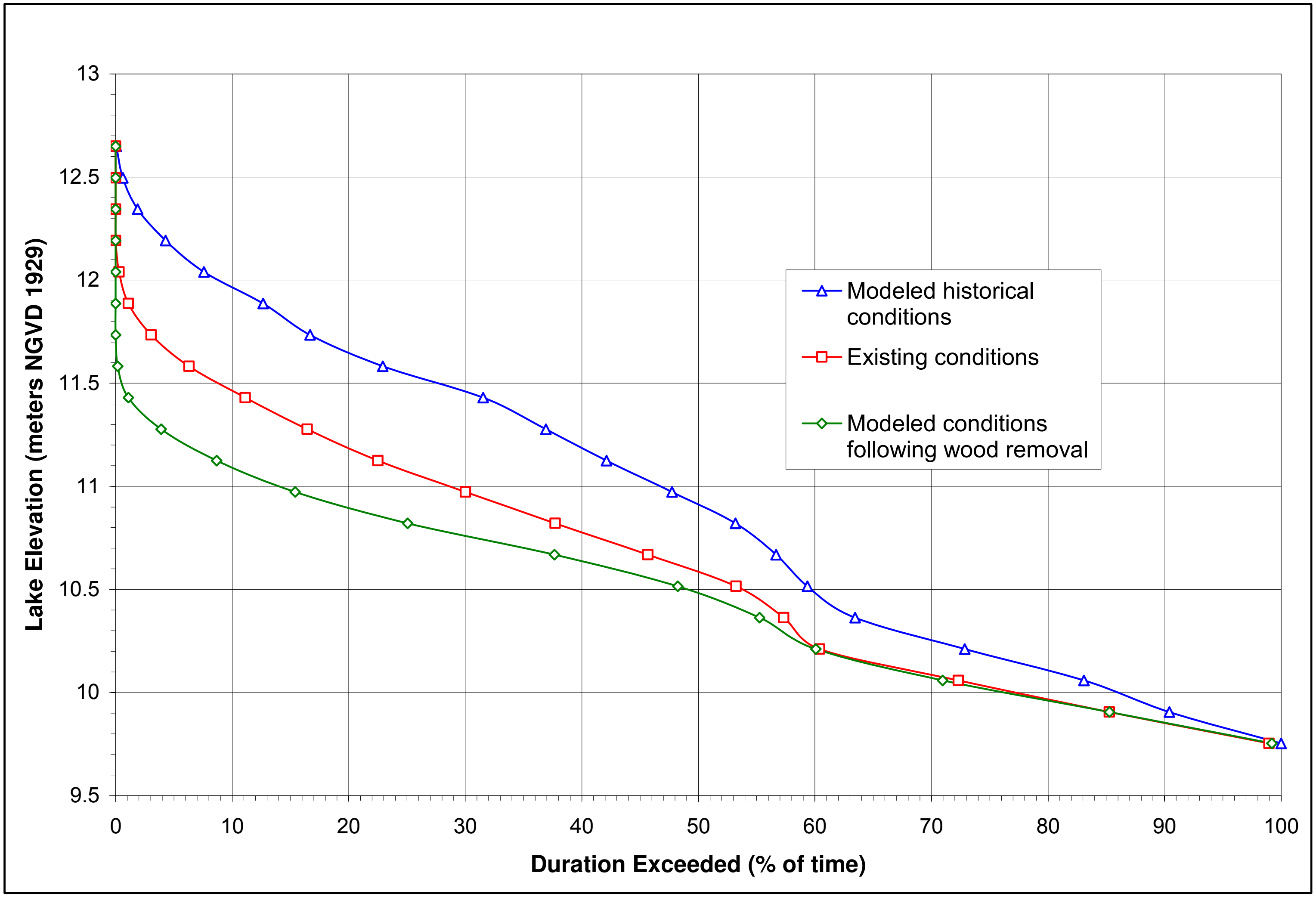

Figure 13. **Stage duration analysis for Lake Ozette lake elevations for the existing and modeled conditions based on continuous hydraulic modeling. Modeled scenarios include historical conditions and conditions following wood removal in the Ozette River. The duration analysis was completed over the model period from December 2003 through January 2005.**

3.2 Assessment of Mass Wasting and Surface Erosion

The production and delivery of sediment to the channel network within the Ozette watershed subbasins were evaluated using a variety of analytical techniques to determine how changes in land use and road construction associated principally with forest harvesting practices may have influenced upland sediment production within the watershed. This assessment of mass wasting and surface erosion analyzed soil creep, landslides, road surface erosion, and erosion from hillslopes as sediment production sources. For each of these sediment sources, considerations included the potential for land use changes to affect sediment productions rates and how these changes have occurred through time. The rates of sediment production estimated here are based on limited field data and rely heavily on investigations completed in similar watersheds. The rates calculated below help identify the relative sediment production in the various subbasins and illustrate the magnitude of the impacts on watershed sediment production that may result from widespread changes in land use.

3.2.1 Soil Creep

Soil creep is the slow, downslope, gravity-driven movement of unconsolidated colluvium and soil and is influenced by the character of soil and rock material, hillslope hydrology, and slope angle (WDNR 1997). The rates of soil creep sediment production provide an indication of the magnitude of sediment production that could have been expected in the Lake Ozette watershed before the disturbances associated with forest harvesting practices. For the purposes of this analysis, the annual soil creep erosion rate (Q_{sc}) in cubic meters/year was calculated by the following equation:

$$Q_{SC} = 2 \times L \times C \times D$$

Where: L = length of stream channel (meters)

C = soil creep rate (meters/year)

D = average soil depth (meters).

To convert volume sediment production rates to mass production rates, a conversion factor of 1.7 tons/cubic meter was applied (Madej 1982).

Stream lengths were estimated in a geographic information system (GIS) platform using the 1996 WDNR channel network, and the soil depth adjacent to the channel network was measured in a number of locations during field reconnaissance in July 2004. Relatively little research has been conducted on the rates of soil creep in forested watersheds with conditions similar to those surrounding Lake Ozette. Hillslope gradients in the Ozette watershed are typically less than 30 percent (more than 95 percent of hillslopes have gradients less than 35 percent); however, annual precipitation in the Ozette watershed ranges from 1,500 to 3,300 millimeters. Due to the high precipitation and consistent with investigations in regions with comparable gradient and precipitation, soil creep rates of 1.5 and 2.0 millimeters/year were selected to evaluate soil creep sediment production for the Ozette watershed (Table 5). Soil depths adjacent to tributary channels in the Ozette watershed were typically observed between 1.0 and 1.5 meters in depth. This range of depths was used to calculate estimates of potential soil creep sediment production.

Table 5. Creep rates and basin characteristics for six studies in comparable regions.

Reference	Precipitation (mm/year)	Gradient (percent)	Creep Rate (mm/year)
Madej 1982	1,300-1,700	10-70	1.5
Everett 1963	990	25-65	0-2.2
Young 1960	1,400	35-55	1.0-2.0
Kirkby 1967	1,710	15-35	1.0-3.0
Lewis 1976	3,050, 4,500	35, 32	1.8, 2.3
Eyles and Ho 1970	2,540	18	3.2
WDNR 1997		<30, >30	1, 2 [a]
Ozette watershed	1,500-3,300	5-35	1.5, 2[b]

[a] The *Watershed Analysis Manual* (WDNR 1997) recommends using a creep rate of 1 millimeter (mm)/year where average gradients are less than 30 percent and 2 mm/year where the average hillslope exceeds 30 percent.
[b] Soil creep rates of 1.5 and 2.0 mm/year were selected for the Ozette watershed based on values derived for comparable regions.

The assessment of background erosion rates indicates sediment yield from soil creep is a relatively minor component of the total sediment budget for the Lake Ozette watershed. The total annual sediment yield from soil creep ranged from approximately 3,200 to 6,400 tons/year for the Ozette watershed (Table 6). The Big River, Crooked Creek, and Umbrella Creek subbasins are estimated to produce the largest amount of sediment through soil creep, whereas the Coal Creek and Ozette River subbasins are expected to produce the least. The annual sediment yield per square kilometer from soil creep within the Ozette watershed drainage area was estimated at 16 to 32 tons/square kilometer/year. The stream length and sediment yield from soil creep for each subbasin are summarized in Table 6.

Table 6. Estimates of potential sediment yield from soil creep in tributary subbasins.

Subbasin	Stream Length (km)	Sediment Yield [a] (tons/year)	Sediment Yield [b] (tons/year)
Ozette River	17.5	89	179
Coal Creek	37.4	191	381
Umbrella Creek	95.8	489	977
Big River	195	995	1,989
Crooked Creek	117	596	1,193
Siwash Creek	31.4	160	320
South Creek	43.2	221	441
West-shore tributaries	39.5	202	403
Additional east-shore tributaries	51.2	261	522
Totals		**3,204**	**6,406**

[a] Based on a creep rate of 1.5 mm/year and soil depth of 1.0 m.
[b] Based on a creep rate of 2.0 mm/year and soil depth of 1.5 m.

Although the effect of forest harvest on creep rate is poorly documented, forest harvest is believed to increase rather than decrease creep rates. Swanston (1981) reported that data from one site in southwestern Oregon showed an increase in creep rate beginning the second year after logging. Although the influence of timber harvest may be subtle, a small increase in creep rate may result in a large increase in the quantity of soil delivered to stream channels. Calculated production rates from soil creep may therefore underestimate the influence of forest harvest on overall sediment production as the same creep rate was used for all time periods and all forest conditions.

3.2.2 Landslides

Sediment production from landslides was estimated from an inventory of historical landslides mapped from historical aerial photographs taken in 1964, 1994, and 2000. Supporting material for the calculation of landslide sediment production is presented in Appendix A. Landslides were delineated within the portion of the basin with aerial photograph coverage (Table 7 and Figure 14). Landslides delineated in the landslide inventory were assigned to one of six geomorphic terrains. The six geomorphic terrains were defined based on three slope and two geologic categories. Slope categories ranged from 0 to 30 percent, 30 to 65 percent, and greater than 65 percent. Geologic categories were classified as either glacial in origin, nonglacial marine sediments, or volcanic rocks.

Table 7. Aerial photographs used in the historical landslide inventory.

Year of Aerial Photograph	Source	Percentage of Ozette Watershed Covered
1964	Olympic National Park	84
1994	U.S. Geological Survey	100
2000	Washington Department of Natural Resources	70

Only landslides large enough to be seen in the aerial photographs were mapped. Landslides were classified as either rotational, translational, or debris flows based on the appearance of the landslide depletion and accumulation zones. Rotational landslides are characterized by ellipsoid failure surfaces with pronounced head scarps, whereas in translational landslides, the displaced mass appears planar and relatively shallow. Debris flows typically occur in hillslope hollows or channels, and their tracks are significantly longer than they are wide. Natural levees and fan-shaped depositional areas are other common features of debris flows (Cruden and Varnes 1996). The rate of landslide sediment delivery (Q_{LS}) in cubic meters/acre/year was calculated independently for each geomorphic terrain within the sample area from:

$$Q_{LS} = \frac{A_{LS} \times D \times R_D}{A_S \times \Delta t}$$

Where: A_{LS} = area of landslide features delineated in each geomorphic terrain (square meters)

D = average landslide depth (meters)

R_D = delivery ratio

A_S = area of each geomorphic terrain within the total sample area (square meters)

Δt = duration of sediment production (years).

As in the soil creep calculations, sediment production rates by volume were converted to mass production rates using a conversion factor of 1.7 tons/cubic meters (Madej 1982).

The average landslide depth (D) was based on typical depths reported in the literature for similar study areas. Prior studies have found that the failure depth of shallow landslides is controlled by the depth of the weathered soil profile, which is approximately 1 meter on forested slopes of the Pacific Northwest (Dietrich et al. 1982; Madej 1982). Large, deep-seated landslides that fail within bedrock can exceed 2 meters in depth. Since few deep-seated landslides were observed in the Ozette watershed, a depth of 1 meter was used to calculate landslide volumes for all landslides.

The delivery ratio (R_D) describes the percentage of sediment mobilized by landslides that is contributed to the channel network and is typically determined from field measurements of landslide scar volumes and sediment volumes remaining on slopes (Reid and Dunne 1996). Depending on the mechanism of hillslope failure, varying proportions of sediment mobilized by landslides are either redeposited on slopes or delivered to the stream channel. Alternatively, debris flows convey most of their sediment load to the channel network because of higher water content and confinement within low-order hollows (Dietrich et al. 1982). Based on regional studies in basins with similar geologic and climatic conditions (Madej 1982), as well as the dominant types of mass wasting observed in the Ozette watershed, a delivery ratio of 75 percent was assigned for all mass wasting features identified in aerial photographs.

Based on observations of the extent of vegetative cover on recent landslides in basins with similar characteristics, the duration of sediment production (Δt) was assumed to be 20 years for the observed mass wasting features. Additionally, Smith et al. (1983) found that surface erosion processes are active for 20 years on landslide scars in coastal British Columbia.

A total of 19 landslides were delineated during the inventory; four in 1964, three in 1994, and 12 in 2000 (Figure 14). Based on assumptions of landslide depth, the volume of individual landslides ranged from 109 to 6400 cubic meters. Of the 19 landslides delineated, 17 occurred on hillslopes with gradients ranging from 30 to 65 percent. The same 17 landslides occurred in marine sediments. The other two observed landslides occurred within glacial sediments and on hillslopes with gradients between 0 and 30 percent. In other watersheds of the Olympic Peninsula, landslides are similarly found in steeper terrain; however, only 1 percent of the land area within the Ozette watershed has a gradient exceeding 30 percent. The majority of landslides identified in 2000 and 1994 were associated in some way with recent forest harvest activity. Evidence of recent forest harvest activity observed within the aerial photographs included limited regrowth, recently improved or established road alignments, and slash or draglines visible on hillslopes. Of the 12 slides identified in 2000, eight were in areas of recent harvest and six of

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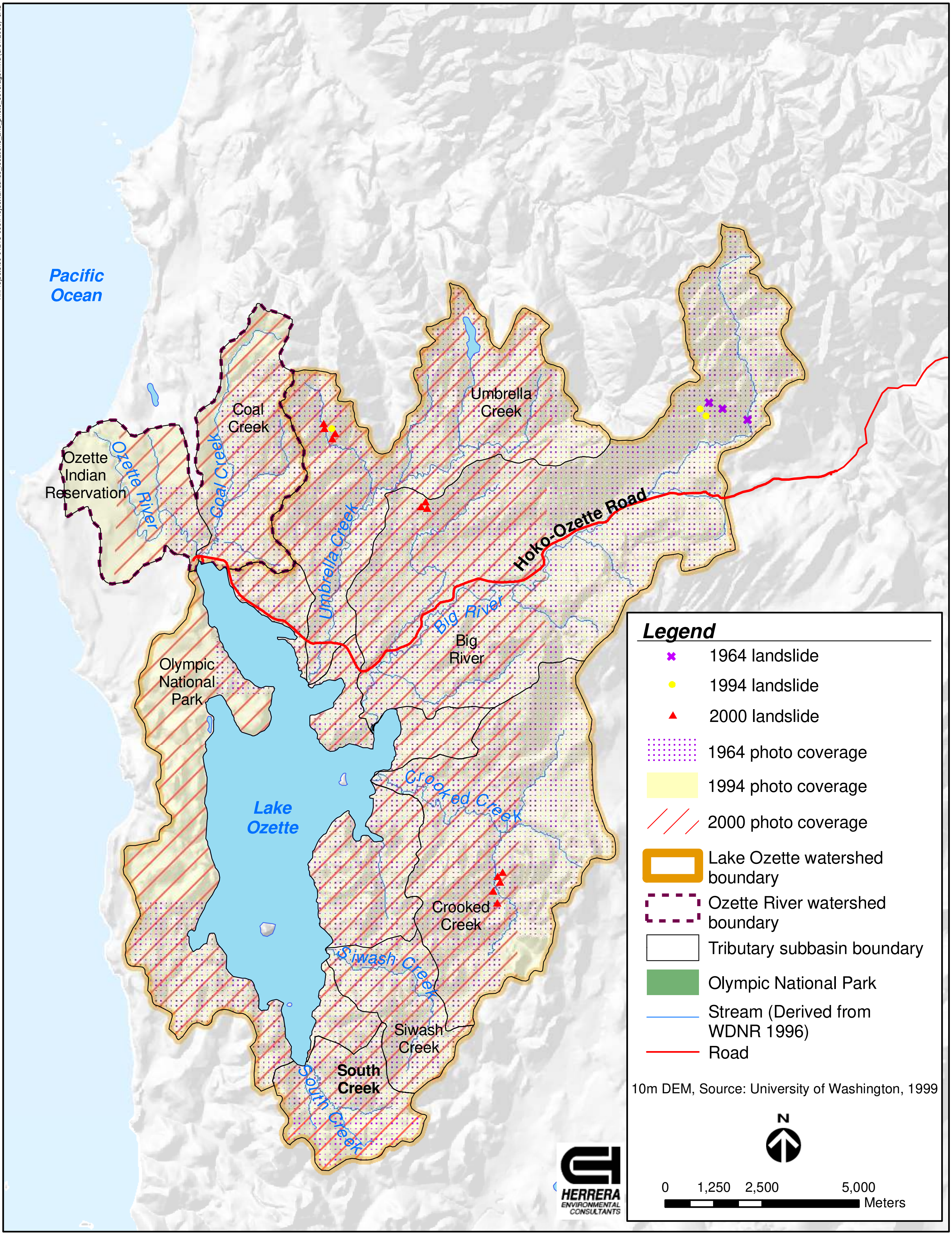

Figure 14. Landslide locations and extent of aerial photographs used in the historical landslide inventory.

those were associated with forest roads. Of the three slides identified in 1994, two were associated with areas of recent harvest. These results are consistent with similar studies of forested watersheds, where an increase in landsliding is commonly observed with forest harvest activities (Swanson and Dyrness 1975; Furniss et al. 1991). Additional analysis of photographs taken in other years could further investigate this relationship in the Ozette watershed.

Estimates of the annual rates of sediment delivery for each subbasin (tons/year) were calculated as the product of the annual delivery rate (tons/square kilometer/year) of the two geomorphic terrains where landslides were observed and the respective areas of each terrain present in each subbasin (square kilometers) for each of the years for which aerials photographs were analyzed. The average annual sediment delivery to channels within the Ozette watershed as a result of landslides was approximately 1,320 tons/year in 1964, 2,700 tons/year in 1994, and 2,000 tons/year in 2000 (Table 8). The Big River subbasin, with its steep headwater region, is likely to produce the greatest amount of landslide-derived sediment. The region was not harvested by 1964, but is where the two landslides associated with recently harvested areas were observed in 1994. The photographs from 2000 do not include this region. Even without this coverage, the sediment yield calculated for the year 2000 was approximately 50% greater than that estimated for 1964, although the estimated average yield per landslide decreased from approximately 300 tons/year in 1964 to 110 tons/year in 2000. The sediment yield calculated for 1994 is approximately two times the rate calculated for 1964, even though only three slides were observed. This results from an average landslide yield of almost 900 tons/year in 1994.

Table 8. Estimates of landslide-produced sediment delivered to the Ozette watershed channel network.

	Average Annual Sediment Yield from Landslides by Date of Aerial Photograph					
	1964		1994		2000	
Subbasin	(tons/yr)	(tons/km^2/yr)	(tons/yr)	(tons/km^2/yr)	(tons/yr)	(tons/km^2/yr)
Ozette River	34	3	0	0	5	0
Coal Creek	80	6	181	14	133	10
Umbrella Creek	163	5	345	12	255	9
Big River	615	10	1,522	26	1,110	19
Crooked Creek	163	5	308	10	230	7
Siwash Creek	59	7	137	17	100	13
South Creek	74	8	189	22	138	16
West-shore tributaries	68	3	0	0	10	0
Additional east-shore tributaries	63	3	12	1	17	1
Total	**1,320**	**7** [a]	**2,700**	**13** [a]	**2,000**	**10** [a]

[a] Calculated for Ozette watershed drainage area.

The temporal variability in landslide sediment production calculations may be the result of the relatively limited number of landslides that were observed during each time period, such that a small increase or decrease in the number or magnitude of observed landslides results in a significant variation in the total production volume. Furthermore, depending on factors such as precipitation and patterns in forest harvest, sediment production from landslides may vary considerably from year to year and from the rates presented in Table 8 (Grant and Wolff 1991).

The production rate estimates presented are sensitive to assumptions of landslide depth. Production estimates and actual sediment production may be considerably higher if the failure depth of shallow landslides is typically greater than 1 meter. Because of the translational nature of the landslides observed in this inventory, estimates for landslide sediment production would increase proportionally to an increase in the average failure depth. An increase in average landslide depth to 1.5 meters, for example, would result in a 50 percent increase in estimated sediment production. Further field verification of landslide conditions would better constrain this variable.

Overall estimates for sediment production from landslides in the Ozette watershed are relatively low when compared to those for other temperate coastal watersheds. These comparatively low values likely result from the relatively gentle topography of the watershed. Also, this method for estimating sediment production from mass wasting accounts only for large failures that are visible in aerial photographs. Smaller features, such as landslides which occur directly adjacent to stream banks may not be detected. Due to the low estimates for landslide-derived sediment production presented here, such small slope failures may cumulatively contribute a large source of sediment to the channel network.

3.2.3 Road Surface Erosion

Sediment production from road surfaces is typically fine grained and can be one of the principal sediment sources in a watershed following the onset of forest harvest (Reid et al. 1981; Madej 1982). In the Ozette watershed, significant forest harvest has occurred over at least the last 50 years, and the fine sediment produced from forest roads used for the transport of harvested trees may have resulted in a significant increase in basinwide fine-sediment production. Sediment production from forest roads in the Ozette watershed was assessed using the WDNR watershed assessment protocol (WDNR 1997). This protocol utilizes a “reference road” condition with known sediment production rates that can be modified with correction factors according to the local characteristics of forest roads.

The basic erosion rate for the reference road is based on the conditions of road age and parent geologic material. Correction factors include the following:

- Surface material correction factor
- Traffic use and precipitation correction factor
- Groundcover correction factor.

Once sediment production rates are estimated through correction of the reference road sediment production rates, the connectivity between the road and stream network is evaluated to determine the percentage of the produced sediment that will reach the tributary channels. In order to evaluate how road surface sediment production may have changed with progressively greater proportions of the basin under harvest rotation through time, the magnitude of road surface sediment production was also evaluated for the conditions approximately the 1964 forest road network.

Application of the WDNR watershed assessment protocol (WDNR 1997) allows the generation of estimates of "potential" delivery rates of sediment to the stream network; however, the actual sediment volumes delivered to surface waters were not measured. Additionally, because a thorough reconnaissance of the forest road network was not possible for this analysis, a range of values was evaluated for the variables that influence the basic erosion rate and the correction factors. Based upon qualitative observations during the field survey and assumptions made during similar investigations, values for each of the variables were selected in order to calculate the potential magnitude of road surface sediment production. The sensitivity of this estimate to the values selected is discussed as is the potential error within the estimate. The calculations of sediment production from road surfaces are provided in Appendix B.

The sediment production estimates determined here *do not* represent actual sediment delivery to streams resulting from road surface erosion. They do, however, provide an indication of the order of magnitude of sediment produced from road surface erosion that can be compared to other sediment sources in the watershed in order to determine their relative importance and potential impact on stream and aquatic habitat conditions. Further, the estimates allow subbasins to be ranked in comparison with each other with respect to their ability to deliver fine sediment to streams without knowing the absolute amount of actual sediment delivery.

There are also additional sources of sediment that are related to forest roads that were not considered in this analysis including construction of stream crossings, ditch cleaning, road reconstruction and resurfacing. These are periodic activities that were not explicitly evaluated in this assessment but may be significant sources of sediment delivered to tributary streams to Lake Ozette.

Reference Road Basic Erosion Rates and Correction Factors

The characteristics of the reference road include the following:

- Insloped with ditch
- Native surface road tread and ditch
- General use traffic (pickup trucks and sedans)
- Cut slope 1:1 and fill slope gradient 1.5:1
- Initial groundcover density of zero on cut and fill slopes
- Sustained grade of 5 to7 percent
- Average cross-drain spacing of 500 feet.

Basic erosion rates for roads built in different geologic materials and road of various ages are presented in Table 9. Considering that most of the Ozette River watershed consists of volcanic and marine sedimentary rocks and consolidated glacial sediments, a basic erosion rate of 30 tons/acre of road prism/year was evaluated.

Table 9. Basic erosion rates of road prism per year by road age and parent material, based on reference road conditions.

General Category	Parent Material	Erosion Rates (tons/acre) of Road Prism per Year Road Age	
		New (0 to 2 years)	Old (>2 years)
High	Mica schist Volcanic ash Highly weathered sedimentary	110	60
High/moderate	Quartzite Course-grained granite	110	30
Moderate	Fine-grained granite Moderately weathered rock Sedimentary rocks	60	30 [a]
Low	Competent granite Basalt Metamorphic rocks Relatively unweathered rocks	20	10

Source: WDNR (1997).
[a] Erosion rate used in this analysis.

The basic erosion rates were multiplied by the proportion of the total long-term average road erosion rates for each component of the standard road prism (Figure 15). To calculate the initial road surface erosion rates for each prism component, the distribution of these components were assumed to be consistent with the reference road conditions (Table 14). The initial road surface erosion rate for each of the road prism components was then modified by the groundcover density factor and the tread component of the prism was further modified by the factors that account for road surface material, traffic use, and precipitation.

Table 10. Proportions of total long-term average road erosion rates attributed to the components of the standard road prism.

Component of Standard Road Prism	Proportion of Total Long-Term Average Road Erosion Rates (percent)
Tread	40
Cut slope/ditch	40
Fill slope	20

Source: WDNR (1997).

The WDNR Forest Practice Application Reviews System (FPARS) 1996 road network was used for this analysis of forest road sediment production (WDNR 1996). Figure 16 illustrates the 1996 forest road network in the Ozette watershed; Table 11 presents a summary of road lengths and road densities for each tributary subbasin. Road density is highest in the Umbrella Creek and Siwash Creek basins at 3.8 and 3.7 kilometers/square kilometer, respectively.

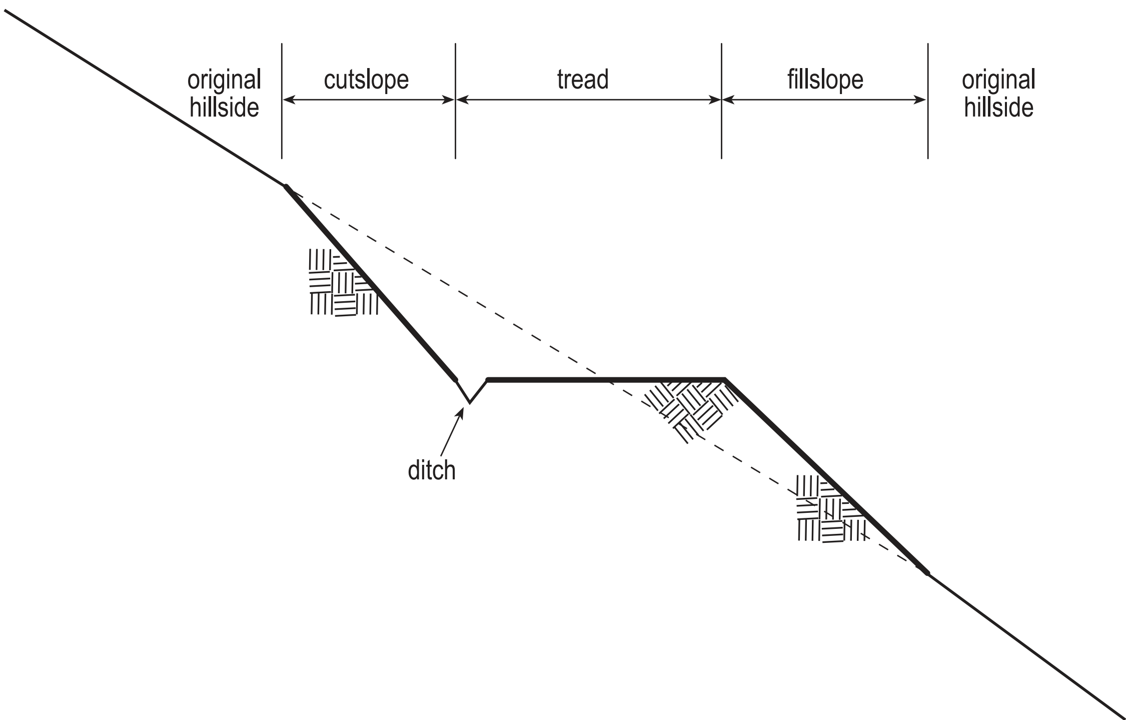

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Figure 15. Definitions of typical elements of a road prism.

Table 11. Road length and road density in Ozette watershed tributary subbasins in 1996.

Subbasin	Area (km^2)	Total Road Length (km)	Road Density (km/km^2)
Ozette River	11.2	11.2	1.0
Coal Creek	13.2	38.8	2.9
Umbrella Creek	29.9	112.2	3.8
Big River	59.1	169.1	2.9
Crooked Creek	30.9	100.1	3.2
Siwash Creek	7.9	26.9	3.7
South Creek	8.7	27.8	3.2
West-shore tributaries	22.6	14.9	0.66
Additional east-shore tributaries	19.7	52.8	2.7

Surface Material Correction Factor

A reference road is assumed to have native surfacing material, so sediment production depends on local geology. It is also assumed that any additional surfacing material will reduce the erosion from the road. Correction factors for different road surface materials range from 0.03 to 1.0 (Table 12). The surfacing material of roads in the Ozette River watershed consists of both gravel and native material. The Ozette watershed consists primarily of volcanic and sedimentary rock units, and it was assumed that native road-surfacing materials are derived from these sources (WDNR 2004). Based on field observations, road surface sediment production was evaluated using a range of correction factors from 0.5 to 1.0.

Table 12. Correction factors for road-surfacing materials.

Surfacing Material	Factor
Paved	0.03
Dust-oil	0.15
Gravel >6 inches deep	0.20
Gravel 2 to 6 inches deep	0.50
Native soil/rock	1.00

Source: WDNR (1997).

Traffic Use and Precipitation Correction Factor

The number of vehicles using a road in a given timeframe, or traffic, is one of the principal factors influencing sediment production from road surfaces (Reid and Dunne 1984; Sullivan and Duncan 1980). Traffic grinds the road surface material into smaller particles that can be transported more easily by rainfall runoff. Traffic increases the quantity of sediment that is potentially available, and precipitation controls how much of this sediment is transported from the road. Road networks are typically divided into separate road categories based on the amount of traffic they carry. From high- to low-traffic conditions, the road categories are mainline, K:\Projects\00-01213-005\Project\ozette_road_network.mxd (3/31/2006) JAS

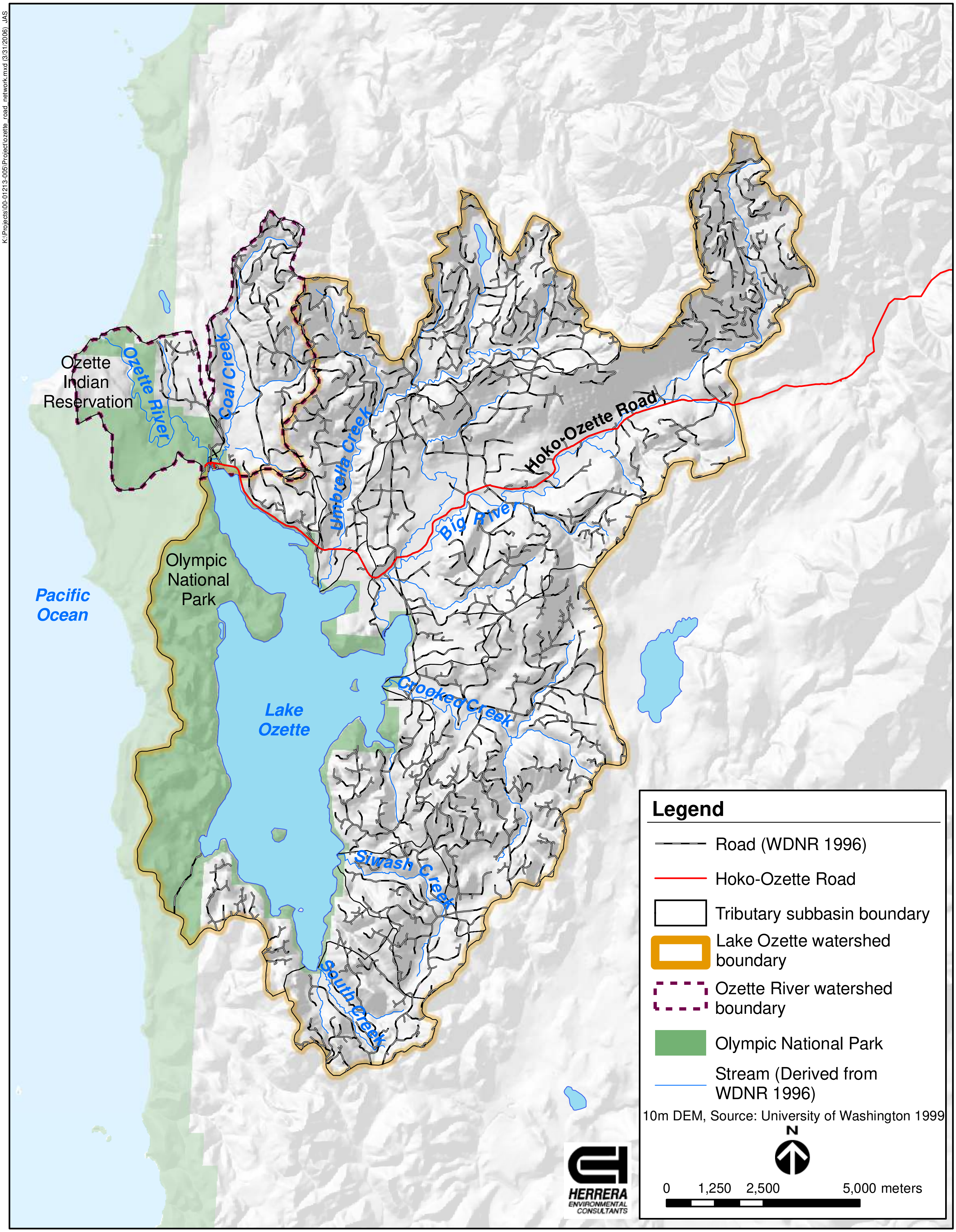

Figure 16. Extent of 1996 road network in Lake Ozette watershed.

secondary, non-active, and abandoned. Limited data were available to describe the distribution of these road categories in the Ozette watershed (Merrill and Ring 2001). The data available for the Ozette watershed were compared with road distribution data from two other Olympic Peninsula basins (Table 13). Based on these data, the percentages of each road type to be applied in this analysis were determined to be 25 percent for mainline roads, 10 percent for secondary roads, 30 percent for non-active roads, and 35 percent for abandoned roads. Road widths ranging from 17 to 20 feet were used to calculate the acres of road in each category for sediment production calculations.

Table 13. Percentage of roads in traffic-use categories from three references from the Olympic Peninsula, Washington.

	Merrill and Ring Ozette Watershed Holdings [a]	Christmas Basin [b]	Stequaleho Basin [b]	Ozette Watershed
Drainage area (km^2)	18.0	15	26	203
Total road length (km)	52.8	37.7	47.4	553 [c]
Percent mainline roads	28%	17%	26%	25%
Percent secondary roads	16%	0%	12%	10%
Percent non-active roads	55%	23%	11%	30%
Percent abandoned roads	0%	60%	45%	35%

[a] Merrill and Ring (2001); ~8 percent of entire Ozette watershed.
[b] Reid (1981).
[c] Road network based on FMAP road layer (WDNR 1996).

Correction factors for traffic use by annual precipitation categories range from almost zero (0.02) for no traffic to 120 for heavy traffic (Table 14). Annual precipitation in the Ozette River watershed is approximately 2,590 millimeters/year (WRCC 2004); therefore, a correction factor of 50 was used for mainline roads, 4 for active secondary roads, 1 for non-active roads, and 0.05 for abandoned roads.

Table 14. Correction factors for traffic use by annual precipitation categories.

Road Category	Annual Precipitation (mm)		
	<1,200	1,200 to 3,000	>3,000
Mainline	20	50	120
Secondary	2	4	10
Non-active	1	1	1
Abandoned	0.02	0.05	0.1

Source: Modified from WDNR (1997).

Groundcover Correction Factor

Groundcover correction factors for cut and fill slopes apply to all surfaces other than bare soil (vegetation, rock, slash, and erosion control materials). The reference road has unvegetated cut and fill slopes; therefore, cover protecting these slopes will reduce the basic erosion rate. Correction factors for different groundcover densities are shown in Table 15. Groundcover correction factors estimated for the Ozette River watershed are shown in Table 16.

Table 15. Correction factors for groundcover densities on road cut and fill slopes.

Groundcover Density	Factor
>80%	0.18
50%	0.37
30%	0.53
20%	0.63
10%	0.77
0%	1.00

Source: WDNR (1997).

Table 16. Groundcover correction factors estimated for roads in the Ozette watershed.

Road Category	Groundcover Correction Factor		
	Tread	Cut Slope/Ditch	Fill Slope
Mainline	1.00	0.37	0.37
Secondary	0.63	0.37	0.37
Non-active	0.53	0.37	0.37
Abandoned	0.18	0.18	0.18

Source: WDNR (1997).

Sediment Delivery from Roads to Streams

Sediment from road surfaces is delivered to the stream network through flowing water in roadside ditches, gullies, culverts, or overland flow. Only a portion of sediment derived from the road system reaches the stream network. The portion of sediment delivered to the stream system is highly dependent on the drainage design of the roads, mainly the connectivity of the road/ditch to the stream channel. To estimate the percentage of sediment delivered to the channel network, delivery rates are broken into three categories according to the proximity of the road to the stream channel (WDNR 1997):

- 100 percent of sediment produced, if the road drains directly to a stream channel via a ditch or gully
- 10 percent of sediment produced, if the road drains onto a hillslope within 60 meters of a stream
- 0 percent of sediment produced, if the road drains onto a hillslope more than 60 meters from a stream.

Road segments that drain onto hillslopes within 60 meters of a stream were identified in GIS, and summarized in Table 17. Lacking significant field measurements indicating the proportion of these road segments that drain directly to a stream channel via a ditch or gully or alternatively onto adjacent hillslopes, half of the road segment lengths were assigned to each of these two categories. It was therefore assumed that half of the total road length within 60 meters of the channel network drains directly to a stream channel and has a delivery rate of 100 percent and that the other half drains onto hillslopes and has a delivery rate of 10 percent (Burroughs and King 1989). The portion of road network draining onto hillslopes greater than 60 meters from streams is assumed to have a delivery rate of 0 percent.

Table 17. Length and percentage of total road length in each Ozette watershed subbasin within 60 meters of stream channel network.

Subbasin Name	Subbasin Area (km^2)	Length of 1996 Road Network (km) [a]	Length of 1996 Road Network within 60 Meters of a Stream (km)	Percentage of Total Road Length within 60 Meters of a Stream (Delivery Rate of Either 100 or 10 Percent)
Ozette River	11.2	11.2	4.3	38
Coal Creek	13.2	38.8	12.0	31
Umbrella Creek	29.9	112	34.7	31
Big River	59.1	169	50.7	30
Crooked Creek	30.9	100	33.0	33
Siwash Creek	7.9	26.9	10.8	40
South Creek	8.7	27.8	14.7	53
West-shore tributaries	22.6	14.9	4.2	28
Additional east-shore tributaries	19.7	52.8	21.9	41

[a] Road network based on FMAP road layer (WDNR 1996).

Temporal Analysis of Road Surface Sediment Production

To illustrate how ongoing forest harvest within the Ozette watershed may have affected sediment production from forest road surfaces, road sediment production was evaluated for an approximated forest road network from 1964. The length of road existing in 1964 was estimated based on the observed extent of forest harvest at that time using a relationship between road density and slope class established for the 1996 road network.

Road densities were calculated for each slope class based on the length of road (in 1996) occurring within the areas occupying each slope class (Table 18). These densities were then applied to the areas defined by that slope class within the harvested areas in 1964. With these road length estimates, sediment production from the 1964 road network was estimated assuming a direct relationship between road length and sediment production.

Table 18. Densities of the 1996 Ozette watershed road network by slope class.

Slope Class (%)	Road Density (km/km^2)
0-9	2.4
9-18	3.0
18-27	2.7
27-36	2.4
36-47	2.1
47-58	2.2
58-70	1.6
70-84	1.8
84-100	0.75

Summary of Road Surface Erosion Sediment Production

Surface erosion from the 1996 road network in Ozette River basin was calculated for each Ozette watershed tributary subbasin. Results of the sediment delivery to Ozette River tributary subbasins from road surface erosion are presented in Table 19. Within the Lake Ozette watershed, the highest sediment delivery rate occurs in the Big River subbasin, with an estimated production total of approximately 3,600 tons/year and the lowest is from the Siwash Creek Subbasin, at approximately 760 tons/year. Mainline roads are estimated to make up 25 percent of the forest road network and contribute 90 percent of road generated sediment. Calculations for the estimates of road surface erosion presented in Table 19 are included in Appendix B.

Table 19. Summary of estimated 1996 road surface sediment production from mainline, active secondary, non-active, and abandoned roads in each Ozette watershed subbasin.

Watershed or Tributary Subbasin	Estimated Sediment Delivery by Road Class (tons/year)				Total (tons/year)
	Mainline	Active Secondary	Non-Active	Abandoned	
Ozette River	270	13	12	4	300
Coal Creek	750	36	33	10	830
Umbrella Creek	2,230	110	100	29	2,470
Big River	3,260	160	140	42	3,600
Crooked Creek	2,100	100	90	27	2,300
Siwash Creek	690	30	30	9	760
South Creek	930	40	40	12	1,020
West-shore tributaries	260	10	11	3	280
Additional east-shore tributaries	1,380	70	60	18	1,530
Ozette River watershed	1,020	50	45	13	1,130
Lake Ozette watershed	10,850	520	471	141	11,980
Ozette watershed	11,870	570	516	154	13,110

Based on 1996 slope-class road densities, 113 kilometers of road were estimated to have been present within the approximately 44 square kilometers of harvested areas observed in 1964, only

20 percent of road network length in 1996. Assuming similar rates of sediment production and that sediment production is proportional to road length, the Ozette watershed may have experienced a five-fold increase in road surface sediment production between 1964 and 1996 (Table 20).

Table 20. Road surface sediment production in the Ozette watershed for 1996 and 1964.

Year	Total Road Length (km)	Sediment Delivery (tons/year)
1996	573	13,110
1964	113 [a]	2,585 [b]

[a] Based on 1996 road densities in harvested areas by slope class.
[b] Assuming 1964 road surface sediment production is proportional to road length.

Due, however, to recent improvements in forest road construction and maintenance management practices, sediment production may have been considerably greater in 1964 than the estimate based on road lengths would indicate (Table 20). Therefore, it is likely that road surface sediment production has been a considerable sediment source to tributary channels since the onset of forest harvesting practices. While the production rate per unit area of road has likely decreased with the improvements in management practices, the area contributing sediment from road surface erosion increased as increasing percentages of the Ozette watershed were harvested.

Assumptions about the characteristics of the Ozette watershed road network strongly influence estimates of road surface sediment production and delivery. Table 21 presents a number of the variables that were utilized in calculating these estimates that are presented in Table 19 and detailed in Appendix B. Tables 13 and 16 present additional variables that influence these estimates.

Table 21. Variables used in calculating the estimated road surface sediment production for the 1996 Ozette watershed road network.

	Value Used in Road Surface Sediment Production Estimate by Road Class			
Variable	Mainline	Active Secondary	Non-Active	Abandoned
Basic erosion rate (tons/year)	30	30	30	30
Road widths (feet)	20	20	17	17
Correction factor for road-surface materials	0.5	1.0	1.0	1.0
Correction factor for traffic use by annual precipitation categories	50	4.0	1.0	0.05

Application of alternative values for these variables would result in distinct sediment production estimates.

- If the basic erosion rate were assumed to be 60 tons/year as opposed to 30 tons/year the reported sediment delivery would double.
- Changes in the assumptions of road widths influence the values for road area of each road class and would proportional influence production estimates; likely alternative values would result in an approximately 25 percent decrease in production estimates.
- Application of alternative correction factors for road surface could decrease overall production and delivery; a factor of 0.2 (for gravel road surfacing greater than 6 inches in depth) would result in a 60 percent decrease in mainline sediment production estimates and an 80 percent decrease for other road classes.
- Annual precipitation in the Ozette watershed tends toward the high end of the correction factors class applied. If it was determined that the higher precipitation class was more appropriate, estimates for mainline sediment production would increase by a factor of 2.4.

The variability that may result from application of alternative variables indicates that there is a considerable level of uncertainty regarding the presented road surface sediment production and delivery estimates. The variables selected in the analysis however represent relatively moderate values for sediment production and application of alternative values could both increase and decrease production estimates. It is likely, therefore, that the production estimates presented represent an accurate order of magnitude estimate for road surface sediment production.

Regardless of the absolute value of road surface sediment production, the widespread road network has clearly resulted in is an increase over predisturbance conditions. The majority of sediment produced from road surface sediment production is fine grained and therefore the increase in sediment production from road surface erosion may potentially contribute to degraded salmonid spawning habitat.

A thorough survey of road conditions within the Ozette watershed, completed in cooperation with principal landholders including private timber companies, the National Park Service, Washington Department of Natural Resources (WDNR), and the Makah Indian Tribe, would provide necessary inputs to refine road surface sediment production estimates and would also likely identify improvements in road maintenance and construction practices that could be implemented to decrease road surface sediment production.

3.2.4 Hillslope Surface Erosion

Hillslope, or sheetwash, erosion occurs as a result of overland flow and is strongly influenced by conditions of soil type, hillslope gradient and length, rainfall amount and intensity, vegetative cover, and land use practices. In old-growth forests of the Olympic Peninsula overland flow rarely occurs due to the multi-stage forest canopy and thick duff layers of organic matter covering the ground. These old-growth forests presently occupy portions of the Ozette watershed and at one time probably covered the majority of the basin. Changes in land use, such as forest harvest, remove vegetation and disturb hillslope soils and increase the probability of hillslope erosion.

Consistent with investigations in nearby watersheds such as the Sekiu, hillslope surface erosion is not believed to be a significant source of sediment production in the Ozette watershed (Sekiu Watershed Analysis 2001). Dense vegetative cover typically protects the soil surface and limits surface erosion processes. In certain circumstances, logging practices can create ruts that intercept water and generate sediment through gully erosion. However, such cases have been observed rarely, and the sediment that has been produced through these processes has been deposited before it could be delivered to the stream channel network (Haggerty 2005). For these reasons, sediment production rates from hillslope surface erosion are not included in estimates of upland sediment production.

3.2.5 Summary of Upland Sediment Production Results

Estimates of sediment production from upland sediment sources indicate that there has likely been a significant increase in sediment production between the current and predisturbance conditions resulting from widespread changes in land use. Estimates for historical, or pre-forest-harvest, sediment production rates include sediment production from soil creep and landslides (Table 22). Soil creep presented in Table 22 is the average of the two creep scenarios evaluated and the presented landslide production rates are those calculated in 1964 when landslides were not observed in harvested areas. Based on these estimates, annual predisturbance sediment production in the Lake Ozette watershed is estimated at 5,560 tons/year or 30 tons/square kilometer/year.

Table 22. Summary of estimated historical sediment production rates in the Ozette watershed.

Watershed or Tributary Subbasin	Estimated Sediment Production Rates (tons/year)			Subbasin Total Production Rate (tons/year)	Subbasin Unit Production Rate (tons/km^2/year)
	Soil Creep	Landslides	Road Surface Erosion		
Ozette River	130	30	–	160	10
Coal Creek	290	80	–	370	30
Umbrella Creek	730	160	–	890	30
Big River	1,490	610	–	2,100	40
Crooked Creek	890	160	–	1,050	30
Siwash Creek	240	60	–	300	40
South Creek	330	70	–	400	50
West-shore tributaries	300	70	–	370	20
Additional east-shore tributaries	390	60	–	450	20
Ozette River watershed	420	110	–	530	20
Lake Ozette watershed	4,370	1,190	–	5,560	30
Ozette watershed	4,790	1,300	–	6,090	30

Estimates for current tributary subbasin sediment production rates for sediment sources evaluated in this study are summarized in Table 23. These production rates include: the average of two rates evaluated for soil creep, the average landslide production rate calculated from 1994 and 2000, and road surface erosion rates based on the 1996 road network. Big River, Umbrella Creek, and Crooked Creek subbasins have the highest average annual rate of sediment production. However, the unit production rates (total production rate divided by subbasin area) for the Siwash Creek and South Creek subbasins are highest. Road surface erosion and soil creep are estimated to be the most significant sources of sediment currently delivered to the channel network in the Ozette watershed.

Table 23. Summary of estimated current sediment production rates for tributary subbasins in the Ozette watershed.

Watershed or Tributary Subbasin	Sediment Production Rates (tons/year)			Subbasin Total Production Rate (tons/year)	Subbasin Unit Production Rate (tons/km^2/year)
	Soil Creep	Landslides	Road Surface Erosion		
Ozette River	130	0	300	430	40
Coal Creek	290	160	830	1,280	100
Umbrella Creek	730	300	2,470	3,500	120
Big River	1,490	1,320	3,600	6,410	110
Crooked Creek	890	270	2,320	3,480	110
Siwash Creek	240	120	760	1,120	140
South Creek	330	1,600	1,020	1,510	170
West-shore tributaries	300	10	280	590	30
Additional east-shore tributaries	390	10	1,530	1,930	100
Ozette River watershed	420	160	1,130	1,710	70
Lake Ozette watershed	4,370	2,190	11,980	18,540	100
Ozette watershed	4,790	2,350	13,110	20,250	100

Based on these figures, therefore, the estimated rate of sediment currently delivered to tributaries draining to Lake Ozette on an annual basis is three times the rate estimated for the watershed in predisturbance conditions. The difference between these values results from surface erosion from the forest road network that was constructed throughout the majority of watershed as forested areas were harvested and an increase in landslide sediment protection which appears related to forest harvest activity. Further, because the sediment produced through road surface erosion is largely fine grained the increased sediment production from widespread changes in land use is also expected to be dominated by fine-grained sediments.

Sediment production in Lake Ozette tributary subbasins in 1964 was estimated to be approximately 40 percent of the estimated current production rate (Table 24). The increase in sediment production from 1964 to the current period is attributable to an increase in the extent of forest harvesting practices.

Table 24. Summary of estimated 1964 sediment production rates in the Ozette watershed.

Watershed or Tributary Subbasin	Sediment Production Rates (tons/year) Soil Creep	Landslides	Road Surface Erosion [a]	Subbasin Total Production Rate (tons/year)	Subbasin Unit Production Rate ($tons/km^2/year$)
Ozette River	130	30	–	160	10 [b]
Coal Creek	290	80	–	370	30 [b]
Umbrella Creek	730	160	–	890	30 [b]
Big River	1,490	610	–	2,100	40 [b]
Crooked Creek	890	160	–	1,050	30 [b]
Siwash Creek	240	60	–	300	40 [b]
South Creek	330	70	–	400	50 [b]
West-shore tributaries	300	70	–	370	20 [b]
Additional east-shore tributaries	390	60	–	450	20 [b]
Ozette River watershed	420	110	230	760	30
Lake Ozette watershed	4,370	1,190	2,350	7,900	40
Ozette watershed	4,790	1,130	2,590	8,700	40

[a] Road surface erosion was not calculated explicitly for each subbasin in 1964. Ozette River and Lake Ozette watershed production rates are based on those calculated for the Ozette watershed and are proportional to the percent of each watershed harvested at least once in 1964.

[b] Sediment production from road surface erosion is not include included in this subbasin unit production rate.

Rates of sediment production after the onset of forest harvesting practices but before the implementation of current road management practices, however, are difficult to accurately calculate. This period would clearly be characterized by a regime of increased sediment production relative to predisturbance conditions but the degree of increase is unknown. The production of sediment on road surfaces likely reached a maximum at some point between 1964 and the present time, when the forest road network was expanding throughout the Ozette watershed but significant improvements in road management practices had not been implemented. The current regime, even after continued expansion of the forest road network, may therefore represent a slight decrease in total sediment production. In any case, even considering the level of uncertainty inherent in such an analysis, the current rates of sediment production are estimated to be many times the predisturbance rates.

3.3 Tributary Channel Assessment

Field reconnaissance to determine the current geomorphic character of tributary stream segments and sediment transport calculations were used to evaluate the capacity of selected streams to transport sediment to Lake Ozette. The analysis provides a preliminary assessment of whether Lake Ozette tributaries are functioning as capacitors to regulate sediment flux to the lake or whether they are efficiently transporting sediment to the lake.

3.3.1 Geomorphic Characterization

The morphology of stream channels is primarily a function of the gradient, discharge, the quantity and grain-size distribution of the sediment supply, wood debris and riparian vegetation.

Channels can be separated into transport reaches (those that have transport capacities that exceed sediment supply) and response reaches (those in which supply exceeds transport capacity). Land use practices can alter the conditions of sediment supply, sediment transport capacity and riparian vegetation and response reaches can react to these disturbances through changes in channel form and sediment storage (Table 25).

Table 25. Summary of channel response to land use practices.

Disturbance	Change	Potential Channel Response
Upland forest clearing	Increase in sediment supply to stream	Aggradation/sedimentation Channel widening
	Increase in discharge to stream	Channel incision and widening
Riparian forest clearing and agricultural conversion	Destabilization of banks Increase of local sediment supply Reduction in functional wood debris recruitment	Channel widening Accelerated channel migration Channel sedimentation Decreases in channel complexity Increases in turbidity
Roads	Increase in fine sediment production	Infilling of coarse bed sediment with fines Increase in turbidity
	Increase in drainage density	Channel incision and widening
Channel clearing	Increase in stream gradient	Downcutting, incision, and headcuts Channel simplification Bank destabilization Initial channel narrowing followed by channel widening
Lowered base level	Increase in stream gradient	Similar to above; typically in lower portions of channel network
Increase in base level	Decrease in stream gradient	Sedimentation, bank erosion and channel widening in lower portions of channel network

In a given system, channel response reaches generally have alluvial channels and floodplains that retain sediment. The larger the size and number of channel response reaches, the greater the moderating effect on sediment flux. Wood debris is an important component of functional response reaches as it not only can act as a significant grade control element limiting incision, it can be very effective at trapping bed material and storing large volumes of sediment (Abbe 2000; Abbe and Montgomery 2003). Response reaches, however, can be converted to transport reaches when wood debris and riparian vegetation are removed or discharge increases. A reduction in the number and effectiveness of response reaches would result in greater sediment discharge to Lake Ozette.

The reconnaissance survey of tributary channels was focused on observing the condition of stream segments predicted to be response reaches. These were evaluated to determine whether they are currently functioning as sediment capacitors or have simply converted to sediment transport reaches (sediment output equals or exceeds sediment input). In order to predict the distribution of response reaches within the tributary channel networks the process-based classification of Montgomery and Buffington (1997) was used to divide the channel network into geomorphic channel units.

The Montgomery and Buffington (1997) classification of channel-reach morphology was developed for mountain channels. The classification synthesizes stream morphologies into five alluvial channel types along opposing continua of increasing sediment supply and decreasing sediment transport capacity. The classification ranges from cascade and step-pool channels, which are supply limited (the stream's energy to move sediment exceeds the delivery of sediment to the channel), to plane-bed, pool-riffle, and dune-ripple (or sand-bedded) channels, which are transport limited (sediment supply exceeds river's ability to transport it). The classification also recognizes colluvial channels, which are transport-limited reaches (also termed "supply reaches") located high in the channel network above cascade channels. Hence, there is a peak in transport capacity between the tips of the channel network and the low-gradient response reaches. The range in channel slope (derived for the Ozette watershed from a 10-meter digital elevation model) reported by Montgomery and Buffington (1997) to predict the reach morphology throughout the Lake Ozette tributary channel networks was used for this analysis (Table 26).

Table 26. Slope range used to predict channel reach morphology.

Reach Type	Slope
Pool-riffle	<0.02
Plane bed	0.02-0.04
Step pool	0.04-0.08
Cascade/colluvial	>0.08

Source: Montgomery and Buffington (1997).

Response reaches act like capacitors within the channel network, and naturally moderate the flux of sediment through the system. Based on the channel typing classification of Montgomery and Buffington (1997), response reaches are predicted to be widely distributed within the channel network of the Ozette watershed (Figure 17). The reconnaissance survey focused primarily on predicted response reach segments of each of the major tributaries to determine how they have been affected by land use practices, including forest harvest and logjam removal (Figure 17).

Morphologic evidence of channel responses to changes in sediment supply, sediment transport capacity and riparian vegetation were documented during reconnaissance surveys of tributary channels. The primary objectives of these surveys were to observe conditions relating to:

- Channel evolution
- Channel incision
- Channel sedimentation
- Floodplain connectivity
- LWD loading
- Riparian forest condition.

Channel evolution was evaluated following the methodology developed by Simon (1995). This methodology is based on the observation that undisturbed alluvial channels that are destabilized by different natural and human-induced processes pass through a sequence of channels forms through time. The various stages of channel evolution were identified according to the extent of degradation, as well as the degree to which the channel may have restabilized following aggradation and widening. When incision was observed during tributary reconnaissance, the extent and magnitude were documented for estimates of sediment production from changes in channel form. Table 27 presents the field guidelines used to aid in identifying the various stages of channel evolution. Figure 18 illustrates models of channel evolution based on Simon (1995).

Table 27. Guidelines for determining the stages of channel evolution.

Stage		Conditions
I	Premodified (stable)	Sediment transport; mild aggradation
		Basal erosion on outside bends; deposition on inside bends
		Vegetated banks to flow line
II	Constructed (disturbed)	Trapezoidal cross-section; linear bank surfaces
		Flow line lower relative to top of bank; removal of vegetation
III	Degrading/ incising	Basal erosion on banks; pop-out failures; heightening and steepening of banks; alternate bars eroded
		Flow line lower relative to top of bank
		Riparian vegetation high relative to flow line and may lean toward channel
IV	Degrading and widening	Basal erosion on banks
		Slab, rotational, pop-out failure; scalloped bank; bank retreat
		Vertical-face and upper-bank surfaces; failure blocks on upper bank; some reduction in bank angles
		Flow line very low relative to top of bank
		Tilted and fallen riparian vegetation
V	Aggrading/ depositional and widening	Development of meandering thalweg; initial deposition of alternate bars; reworking of failed material
		Slab, rotational, pop-out failure; low-angle slides of previously failed material
		Scalloped bank; bank retreat; vertical face, upper bank and slough line; flattening of bank angles
		Flow line very low relative to top of bank
		Tilted and fallen riparian vegetation; reestablishing vegetation on slough line
VI	Restabilizing (aggrading)	Further development of meandering thalweg; deposition of alternate bars; reworking of failed material
		Some basal erosion on outside bends; deposition of floodplain and bank surfaces
		Low angle slides; some pop-out failures near flow line
		Stable alternate bars; convex-short vertical face on top of bank; flattening of bank angles; development of new floodplain
		Reestablishing vegetation extends up slough line and upper bank; some vegetation establishing on bars

Source: Simon (1995).

Conditions of floodplain connectivity and sedimentation are integral to evaluation of channel evolution. These conditions, along with those relating to LWD loading and riparian forest condition were documented according to the protocols below. A series of photographs illustrating stages of channel evolution and additional tributary channel conditions follows (Figures 19 through 22).

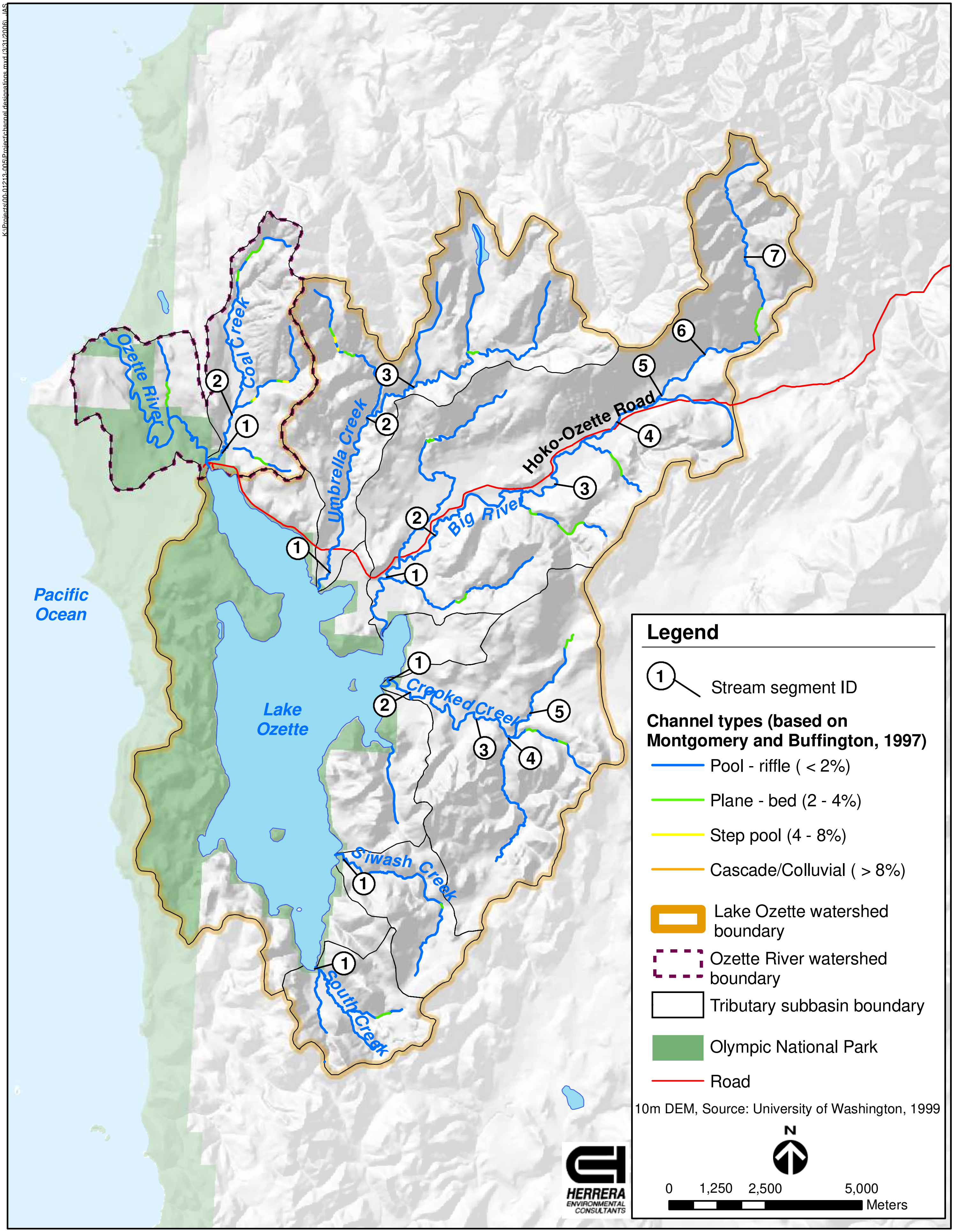

Figure 17. Predicted spatial distribution of channel types based on channel slope derived from the 10-meter DEM.

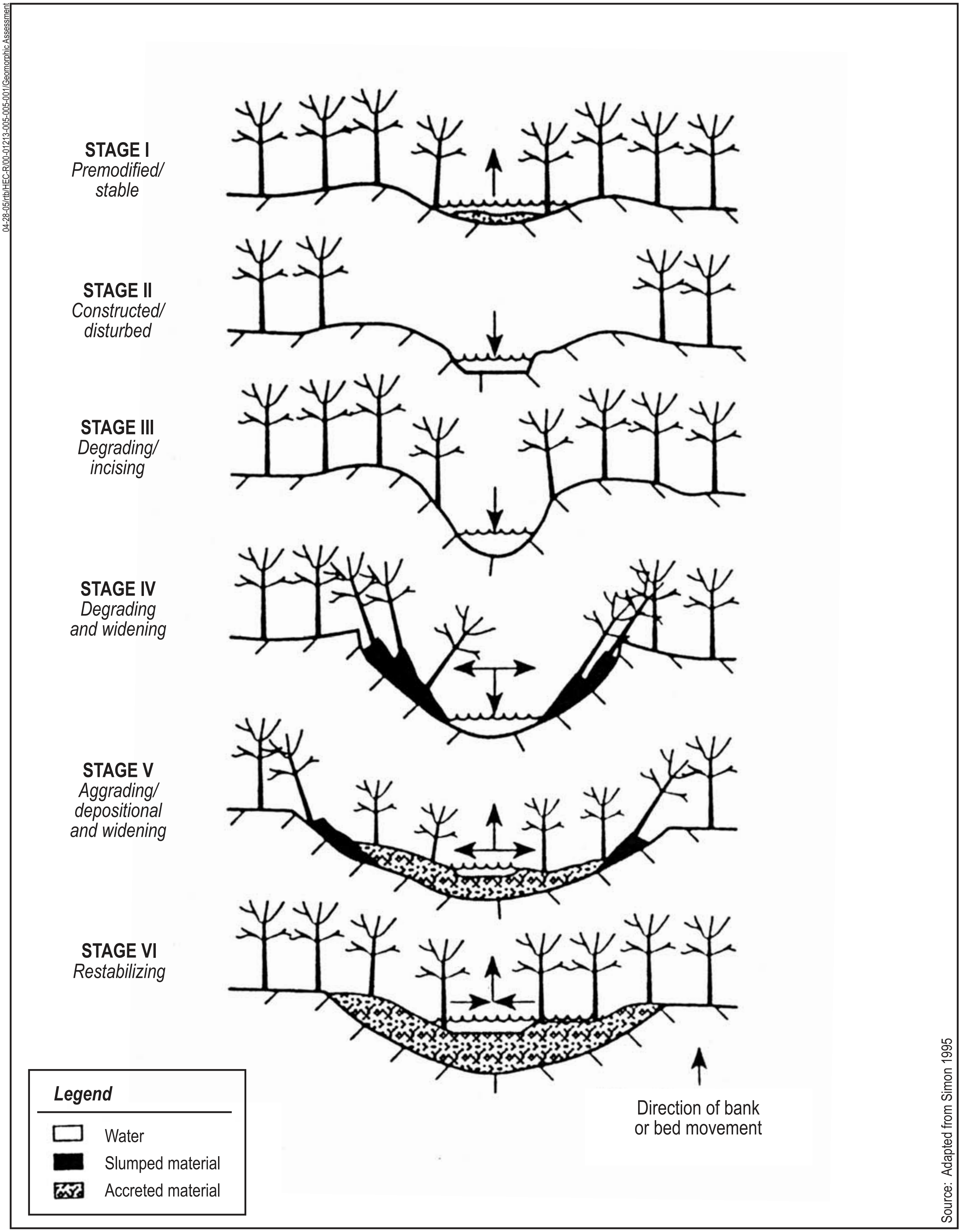

Figure 18. Models for determining channel evolution.

Figure 19. Example of a degrading reach (Stage III) along Crooked Creek (July 16, 2004). Surfaces adjacent to the channel show little evidence of recent or frequent inundation and indicate down cutting. Infrequent recruitment of alders from the riparian corridor show limited widening. The riparian vegetation consists of immature alders and offers poor recruitment potential. Flow direction is toward the camera.

Figure 20. Example of a Stage IV–V channel in the North Fork of Crooked Creek (July 16, 2004). Deposition is evident by the bar formation at the downstream end of the logjam. Widening is indicated by recruitment of riparian vegetation and eroding banks. LWD provides hydraulic complexity and roughness. The direction of flow is away from the camera.

Figure 21. Example of a Stage V channel in Coal Creek (July 14, 2004). The channel shows evidence of aggradation following incision. The person in the foreground is standing on a bar surface in the active channel. The person in the middle ground is standing on an inset floodplain surface, and the person in the background is standing atop an abandoned floodplain surface. Conditions of good recruitment potential and moderate loading of fine and coarse grained (graded) sediment are also evident. The direction of flow is from left to right.

Figure 22. Example of a Stage V–VI channel in Coal Creek (July 14, 2004). The tree "knees" in the upper right part of the photograph indicate relative bank stability over the age of the riparian vegetation, suggesting a channel that has been stable over the last approximately 40 years. This reach also shows conditions of moderate, graded sediment loading with bar deposits evident behind woody debris roughness elements, good LWD recruitment potential, and fair LWD loading. The flow direction is from the top to the bottom of the photograph.

Floodplain connectivity was assessed through observations of flow indicators outside of the main stem channel, such as in side channels or on floodplains (Table 28). Examples of such indicators include vegetation bent by flow, racked debris in floodplain vegetation, and fine sediment deposited on floodplain surfaces or within side channels.

Table 28. Protocol for describing floodplain connectivity.

Classification of Floodplain Connectivity	Description
Poor	Little or no evidence of vegetation bent by overbank flows, racked debris in floodplain vegetation, or fine sediment deposited on floodplain surfaces or in side channels.
Fair	Moderate or limited evidence of vegetation bent by overbank flows, racked debris in floodplain vegetation, or fine sediment deposited on floodplain surfaces or in side channels.
Good	Obvious and widespread evidence of vegetation bent by overbank flows, racked debris in floodplain vegetation, or coarse and fine sediment deposited on floodplain surfaces or in side channels.

The amount and character of instream sediment can assist in determining a channel's evolutionary stage and also indicate the conditions of sediment that is both delivered to the channel and routed downstream (Table 29). Frequent bar deposits or local braiding of the channel indicates high levels of sediment loading and deposition. Conversely, predominantly limited depositional features indicate that sediment supplied to the reach is typically transported downstream. The grain-size characteristics of instream sediment can also illustrate both local and systemic conditions of sediment transport. For example, coarse substrate and bar deposits in a reach that receives both fine and coarse-grained sediment input indicates that the fine sediment is transported downstream. The relative amount (high, moderate, low) and dominant grain-sizes (coarse, fine, graded) of instream sediment was described during stream segment surveys.

Table 29. Protocol for describing the character of instream sediment loading and composition.

Classification of Instream Sediment	Description
Loading	
High	Frequent mid-channel bars; local braiding of the channel; ample fine sediment is released when the substrate is disturbed; frequent elongated deposits of fine sediment on the streambed.
Moderate	Occasional mid-channel bars; moderate fine sediment is released when the substrate is disturbed; occasional elongated deposits of fine sediment on the streambed.
Low	Deposits are primarily in point bars in pool-riffle sequences and lateral bars in plane-bed channels; fine sediment is limited to sheltered locations behind flow obstructions or large clasts.
Composition	
Coarse	Channel substrate sediment and bar deposits are dominated by gravel to cobble sized particles
Fine	Channel substrate sediment and bar deposits are dominated by sand and smaller particles
Graded	Channel substrate sediment and bar deposits are well-graded and include fine and coarse sediment.

The extent and condition of LWD in the channel network was observed to determine its role in promoting instream and floodplain sediment storage, creating areas of hydraulic complexity, and providing grade control. Table 30 details the qualitative classification criteria used to describe the role of instream LWD.

Table 30. Protocol for characterizing the frequency of functional instream large woody debris.

Classification of Functional LWD Loading	Description
Poor	Little to no hydraulic complexity and roughness provided by LWD.
Fair	Moderate hydraulic complexity and roughness provided by LWD.
Good	Extensive hydraulic complexity and roughness provided by LWD.

The input of large wood to the channel network is largely dependant on the availability of mature trees in the adjacent riparian community. The classification criteria for describing the potential for LWD recruitment from the riparian community adjacent to the tributary channel and within the channel migration zone is described in Table 31.

Table 31. Protocol for describing the potential for recruitment of large woody debris.

Classification of LWD Recruitment Potential	Description
Poor	Little or no mature conifer forest adjacent to the channel and within the historical channel migration zone.
Fair	Occasional or limited mature conifer forest adjacent to the channel and within the historical channel migration zone.
Good	Widespread mature riparian conifer forest adjacent to the channel and within the historical channel migration zone.

3.3.2 Summary of Geomorphic Characterization Results

Widespread degradation was widely observed in the channel network of the Ozette watershed during the July 2004 tributary reconnaissance survey. All tributaries showed some degree of channel incision, decreased channel-floodplain connectivity, high sediment loading, limited LWD loading and diminished future LWD recruitment potential (Table 32). The channel evolutionary stage of stream segments observed during the tributary reconnaissance survey is presented in Figure 23. Disturbed and incised channels, some of which are now aggrading and a few of which appear to be restabilizing, were broadly distributed throughout the reconnaissance survey area.

Channel incision in the Ozette watershed channel network likely resulted from the removal of logjams and woody debris from both tributary channels and the Ozette River. Incision in the Big River, for example, is likely due in large part to the removal of 17 logjams between river

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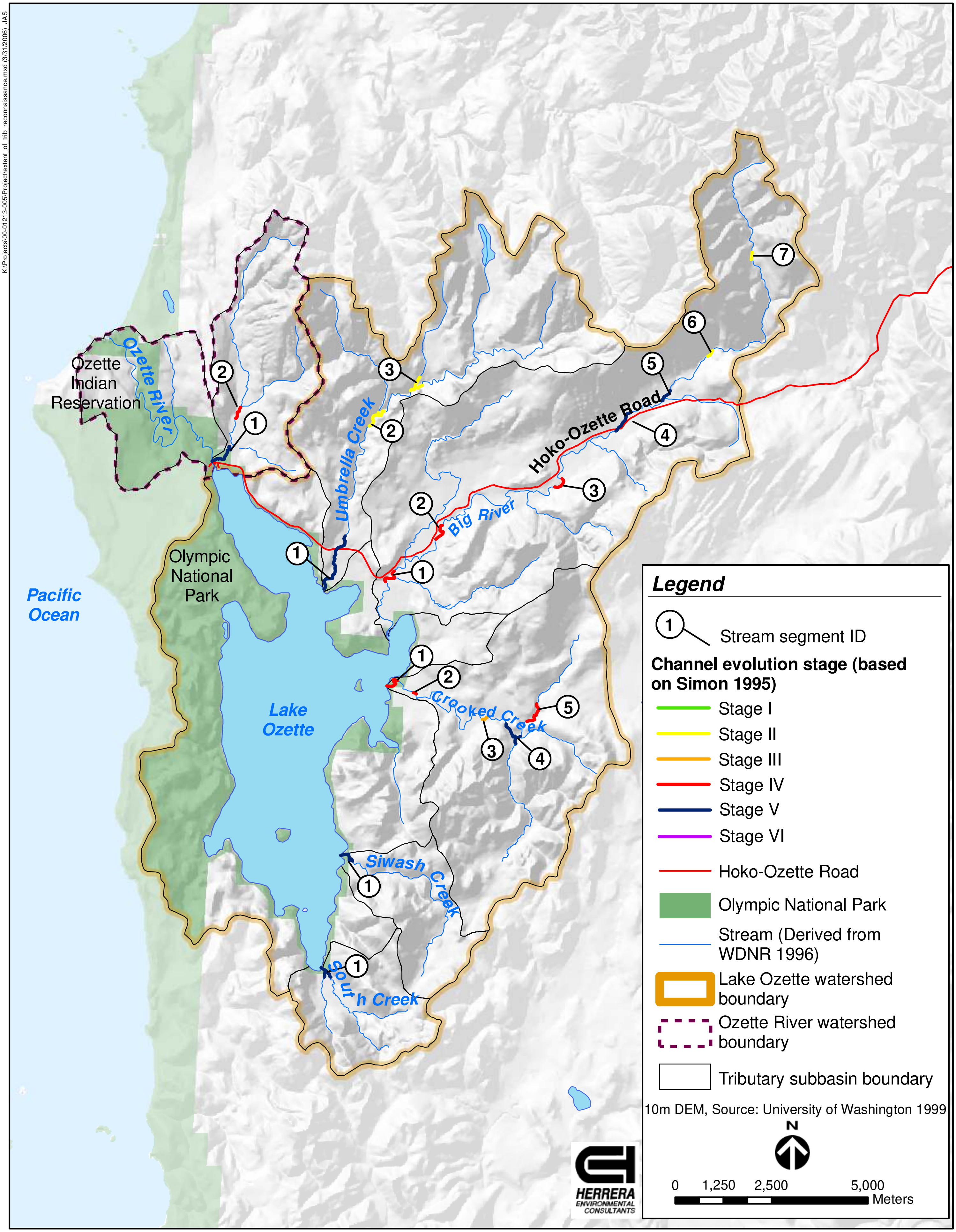

Figure 23. The extent of the tributary channel reconnaissance survey and observed stages of channel evolution.

kilometer (RK) 1.5 and RK 9 in 1952 (Kramer 1953). The removal of these logjams likely destabilized the channel by removing significant grade control features. The majority of sediment produced from this adjustment would have occurred rapidly following logjam removal. The clearing of forests adjacent to the Big River has also contributed to ongoing channel instability and sediment production (Figure 24). Sediment contributed to the channel from incision was likely largely coarse grained bedload material and sediment recruited through bank erosion was observed to consist of both coarse and fine-grained alluvial sediment.

Table 32. Summary of the geomorphic channel conditions of the tributary stream segments observed during the reconnaissance survey.

Stream Segment ID	Channel Evolution Stage	Channel Sedimentation [a]	Floodplain Connectivity	LWD Loading	Riparian LWD Recruitment Potential
Coal Creek - 1	V - Aggrading and widening	High - Graded	Poor	Fair	Fair
Coal Creek - 2	IV - Degrading and widening	Moderate - Graded	Fair	Fair	Fair
Umbrella Creek - 1	IV - Degrading and widening	High - Graded	Fair	Fair	Poor
Umbrella Creek - 2	II - Disturbed	High - Graded	Fair	Fair	Poor
Umbrella Creek - 3	II - Disturbed	Moderate - Coarse	NA [b]	Fair	Poor
Big River - 1	IV - Degrading and widening	Moderate - Fine	Poor	Poor	Poor
Big River - 2	IV - Degrading and widening	Moderate - Graded	Poor	Poor	Poor
Big River - 3	IV - Degrading and widening	Moderate - Graded	Fair	Poor	Poor
Big River - 4	V - Aggrading and widening	High - Coarse	Poor	Poor	Poor
Big River - 5	V - Aggrading and widening	High - Coarse	Poor	Fair	Poor
Big River - 6	II - Disturbed	Moderate - Coarse	Fair	Fair	Poor
Big River - 7	II - Disturbed	Moderate - Coarse	Fair	Poor	Poor
Crooked Creek - 1	IV - Degrading and widening	High - Fine	Fair	Fair	Fair
Crooked Creek - 2	IV - Degrading and widening	High - Graded	Fair	Fair	Poor
Crooked Creek - 3	III - Degrading	High - Graded	Fair	Fair	Poor
Crooked Creek - 4	V - Aggrading and widening	High - Graded	Fair	Fair	Fair
Crooked Creek - 5	IV - Degrading and widening	High - Graded	Fair - Good	Good	Fair
Siwash Creek - 1	V - Aggrading and widening	High - Graded	Fair	Fair	Fair
South Creek - 1	V - Aggrading and widening	High - Graded	Fair	Fair	Fair

[a] The character of channel sedimentation is described by loading and character.
[b] Channel is confined and so floodplain connectivity does not apply.

Although it is unknown whether significant channel clearing occurred in other tributaries of Lake Ozette, much of the observed incision in these tributaries can be attributed to the removal of logjams in the Ozette River. Water surface elevations in Lake Ozette act as the base level control for the tributary creeks and this base level directly influences channel profiles. The removal of logjams in the Ozette River caused changes in Lake Ozette water levels and resulted in a subsequent lowering of the base level for Lake Ozette tributaries and Coal Creek. Evidence of incision that resulted from this change in base level was observed in the lower reaches of all of the tributaries surveyed.

A good illustration of evidence indicating channel adjustment following a change in base level is provided in Figure 21. Base level lowering typically causes channel incision low in the channel network. As incision progresses upstream the main channel becomes a conveyor for increasing amounts of upstream sediment. Aggradation in the main channel typically results, and an alluvial surface will form in the newly cut channel (Schumm 1973). As tributary channels adjust to the new base level, sediment loads decrease and a new active channel is downcut into the new alluvial surface. In the Ozette watershed, sediment produced from the early forest harvesting activities may have augmented sediment produced from channel adjustments. Figure 21 shows a historical floodplain surface which was likely active prior to incision, as well as the inset floodplain (or alluvial) surface which has formed as the channel network has re-equilibrated to a lower base level. The sediment produced following changes in base level from channel adjustments low in the channel network was likely rapidly delivered to Lake Ozette, or in the case of Coal Creek, to the Ozette River.

The sediment produced from channel incision following logjam removal was calculated approximately using measurements of bankfull widths and depths and estimates of the length of incised channels (Table 33). The magnitude of sediment produced from the tributaries assessed in this investigation is presented in Table 34. The channel lengths used to estimate sediment produced from channel incision are based on observations limited to the extent of the stream segment surveys. Estimates of sediment production from channel incision could therefore be improved following a more thorough channel reconnaissance.

As mentioned above, sediment production from channel incision may have occurred rapidly following a decrease in base level. In that case, annual sediment production rates shortly following base level lowering would likely have been higher than the estimated values presented in Table 34. Similarly, the current rates of sediment production from this source may be lower than those presented as the channel has had time to equilibrate to the base level adjustment. The annual rates presented, therefore, best represent long-term annual averages associated with the channel adjustment. Further, the production rates presented in Table 34 are based on the assumption that tributary incision initiated following the documented logjam removal in 1952. If however, the removal of logjams in the Ozette River, and related decreases in lake levels occurred at an earlier time, the estimated long-term average annual rates may be half of those presented, although the estimate of the total volume of sediment produced would not be affected.

Because channel incision due to a lowering of base level would have potentially affected smaller tributaries upstream of the tributaries assessed in this investigation as well as those draining directly to the lake, the total magnitude of sediment production from channel adjustment following changes in base level may exceed the estimates provided here. In tributaries where adjacent forested areas were not harvested at the time of base level changes, however, the grade control provided by functional woody debris may have limited the extent and magnitude of incision. Additional reconnaissance of small tributaries of the lake could provide an indication of how significantly they were affected by changes in base level.

Localized sediment production due to changes in channel form was also observed higher in the tributary drainage network. These changes in channel form include channel expansion and were typically observed to be associated with road crossings. At these locations, enlarged channel cross-sections and actively eroding stream banks were observed where road crossings had

Figure 24. Lateral instability along agricultural reaches of Big River. This photograph, taken between Big River Stream Segments 4 and 5, shows a Stage IV reach where buried LWD is being exhumed from fine-grained floodplain deposits by lateral channel migration (July 16, 2004). The reach has high sediment loading and poor LWD recruitment potential. Flow in Big River is from right to left. Bank height is on the order of 3 meters.

artificially constricted the active channel or floodplain. The sediment produced from such channel enlargement and ongoing bank erosion was not quantified in this study. Due to the extensive forest road network, however, the cumulative sediment production from these sources may be significant. A more extensive survey of forest road and stream intersections could provide an indication of the magnitude of sediment produced through this mechanism.

Table 33. Bankfull width and depth measurements during the tributary reconnaissance survey.

Stream Segment ID	Typical Channel Dimensions	
	Bankfull Width (m)	Bankfull Depth (m)
Coal Creek - 1	15	2
Coal Creek - 2	10	1.5
Umbrella Creek - 1	19	1.5
Umbrella Creek - 2	17	1.8
Umbrella Creek - 3	13	1.5
Big River - 1	17	2
Big River - 2	16	3
Big River - 3	20	2
Big River - 4	22	2
Big River - 5	25	1.5
Big River - 6	19	1.5
Big River - 7	15	1.5
Crooked Creek - 1	18	2
Crooked Creek - 2	20	2
Crooked Creek - 3	20	2
Crooked Creek - 4	15	1.5
Crooked Creek - 5	13	1.5
Siwash Creek - 1	15	2
South Creek - 1	8	1.5

Table 34. Summary of estimated sediment production resulting from channel incision.

Tributary	Typical Depth of Incision Observed (m) [a]	Estimated Length of Incised Channel (m)	Estimated Sediment Production From Channel Incision (m^3)	Average Annual Rate of Sediment Production [b] (m^3/year)	Average Annual Rate of Sediment Production [c] (tons/year)
Coal Creek	1	2,000	25,000	500	850
Umbrella Creek	1	1,250	22,500	450	770
Big River	1 to 2	7,500	225,000	4,500	7,650
Crooked Creek	1	4,000	76,000	1,520	2,590
Siwash Creek	1	500	7,500	150	260
South Creek	1	500	4,000	80	140
Total	–	19,250	360,000	7,200	12,260

[a] An incision depth of 1.5 meters was used to estimate sediment production from channel incision in Big River.
[b] Sediment production rates were calculated assuming channel incision was initiated at the time of lake level lowering associated with the removal of logjams in the Ozette River and dividing the total sediment produced by a period of 50 years.
[c] A conversion factor of 1.7 tons/m^3 was applied to convert volume sediment production rates to mass production rates.

In terms of tributary sediment production from changes in channel form, production from the Big River resulting from channel incision following the removal of logjams is considered the most significant source (Table 34). Bank instability associated with lateral channel migration resulting from changes in land use and the removal of riparian vegetation has also been a cause of sediment production along portions of the Big River. Sediment production from bank erosion caused by ongoing channel migration was not quantified in this assessment but was observed to be most severe near at Stream Segments 4 and 5 (Figure 24). Considerable sediment deposition was also observed in Stream Segments 4 and 5 during the field reconnaissance in July 2004 (Figure 25). At that time, portions of the Big River were observed to flow exclusively through the subsurface sediments in these survey reaches (Figure 25). The surface sediments were observed to be largely coarse grained indicating that the fine-grained sediment fraction delivered to the main stem from upland sources is largely being transported downstream toward the lower reaches of the Big River and Lake Ozette.

The fine-grained character of instream sediment deposits in the lower portions of the Big River provide further evidence of the high levels of fine sediment production and delivery. Historical accounts document “an almost continuous bed of gravel from the bridge at the seven mile point downstream to about one mile from its mouth” (Kramer 1953). This is not the case today, and the sand and fine-grained gravel that dominates much of this length of the Big River is an indication of the significant sediment delivered from upstream sources. At Big River Stream Segment 1, bar deposits made up almost exclusively of fine sediment indicate that the coarse-grained sediment load in the Big River has largely been stored in the channel upstream of this location. This indicates that the sediment delivered to Lake Ozette from Big River is almost entirely fine grained.

Downstream of Stream Segment 1, in the lower approximately 1.5 kilometers of the Big River, overbank flow events have deposited sand and other fine sediment on the floodplain, indicating that a portion of the fine sediment load that enters the Big River may not be routed directly to the lake (Shellberg 2005). This region of the Big River was not cleared during 1952 due to limited accessibility and the long-term maintenance of functional woody debris appears to have somewhat moderated the delivery of sediment to the lake. The overall length of the Big River where floodplain connectivity has been maintained, however, is markedly shorter than that which would have existed prior to widespread channel incision.

The other tributary channels that were observed during the field reconnaissance also show evidence of decreased channel-floodplain connectivity as well as other indications of channel degradation including channel incision, high sediment loading, limited LWD loading and fair to poor future LWD recruitment potential (Table 32). Following the Big River, Crooked Creek, Coal Creek, and Umbrella Creek appear to have been most prolific in terms of sediment production from channel incision (Table 34). Of these, Coal Creek shows the most significant evidence of floodplain disconnection, although the presence of inset floodplain surfaces within portions of the incised and widened channel indicates that the channel may be restabilizing (Figure 21).

Figure 25. High levels of sediment loading in Big River Stream Segment 5 (July 16, 2004). Flow is subsurface at this location. The flow direction is toward the camera.

Near its confluence with the Ozette River, a number of distributary channels initiate from Coal Creek. Prior to channel incision these channels would have transported flows south from Coal Creek toward Lake Ozette during flood events. Though the current alignment of Coal Creek flows into the Ozette River it is possible that this confluence area was more dynamic prior to anthropomorphic influences and historical alignments of Coal Creek were directed into Lake Ozette. The observed high flow channels may have served as distributary channels across the Coal Creek deltaic floodplain prior to incision. The invert elevation of these channels is approximately one meter above the observed inset floodplain surface elevations.

Although channel incision was observed within the lower portions of Crooked, Umbrella, Siwash, and South Creeks, conditions of LWD loading appear to influence the magnitude of channel incision and floodplain connectivity. Whereas incision was observed to be widespread in the Big River and Coal Creek, the more localized conditions of incision observed in Crooked, Umbrella, Siwash, and South Creeks may be a function of grade controlling relic LWD (see below). Lower Crooked Creek is a good illustration of the influence of LWD on floodplain connectivity and sediment storage. Though the channel is incised, a large channel spanning raft jam has formed approximately 350 meters upstream of the mouth and there is evidence of distributary channel connectivity toward the lake (Figure 26). Deposition and aggradation are now occurring behind the jam and in time this will likely result in a channel avulsion at this location that will bypass the lowest 350 meters of Crooked Creek.

Though LWD loading was observed to provide grade control and opportunities for sediment storage, conditions of LWD loading in tributary channels was typically poor to fair and much of the instream wood appeared to have been delivered to the channel network prior to the time of forest clearing (“relic LWD”). Also, poor LWD recruitment potential was observed in the majority of the surveyed stream segments (Figure 27).

High levels of instream sediment loading were observed in each of the tributary channels (Figure 27). Not all stream segments were overwhelmed with fine sediment but a large percentage exhibited significant sediment storage in bars and lee areas behind instream roughness elements (Figure 28). In all reaches observed, the occurrence of LWD in the active channel provided increased opportunities for sediment storage. The overall amount of fine sediment observed in instream deposits was highest in stream segments closest to the lake; however, fine sediment was observed locally in the upper reaches of all the tributaries.

3.3.3 Sediment Transport Capacity

Channel responses to increased sediment supply depend largely on the ratio of transport capacity to sediment supply. Increases in sediment supply that overwhelm transport capacity result in channel widening, aggradation and pool filling. The relationship between sediment supply and transport capacity was evaluated to determine whether tributary sediment transport capacity is adequate to transport the amount of sediment estimated to be supplied in the current regime of sediment production. Additionally, alternative channel geometries, aimed at replicating potential historical channel forms prior to tributary channel responses (that are observed to include downcutting or incision), were also evaluated.

Hydrologic data for water year 2004 and channel geometry at gauge locations were provided by the Makah Fisheries Management for Coal Creek, Umbrella Creek, the Big River, and Crooked Creek. These data were supplemented with bulk instream samples acquired during July 2004 for input into sediment transport calculations, in context of observed geomorphic conditions, to estimate the current sediment transport potential from each tributary. Bulk-sediment samples were obtained from response reaches low in the channel network. Samples were collected from the upstream end of mid-channel bars. If an armored layer was present it was removed so that the sample would reflect the character of sediment mobilized during bedload transport events. Grain-size distributions are presented in Appendix C. Figure 29 shows the location of stream gauges and bulk sediment sample locations used in this analysis.

Flood Frequency Analysis

Due to the limited duration of hydrologic data for gauged tributaries in the Lake Ozette watershed, it was necessary to estimate flood discharge frequencies representing sediment mobilizing flow events. The U.S. Geological Survey (USGS) developed regional regression equations to estimate peak discharges for naturally flowing, unregulated streams in Washington State were used to estimate these peak flow events (Sumioka et al. 1998). USGS regional regression equations for the west side of the Olympic Peninsula were used to estimate peak flows for recurrence intervals from 2 to 200 years for the Ozette subbasins (Region 1 of Sumioka et al. 1998):

$$Q_2 = 0.350A^{0.923}P^{1.24}$$
$$Q_{10} = 0.502A^{0.921}P^{1.26}$$
$$Q_{25} = 0.590A^{0.921}P^{1.26}$$
$$Q_{50} = 0.666A^{0.921}P^{1.26}$$
$$Q_{100} = 0.745A^{0.922}P^{1.26}$$

Where: Q_T = peak discharge (cubic feet/second)

A = drainage area (square miles)

P = annual precipitation (inches).

Precipitation estimates were drawn from Quilluyute Climate Summary (August 1, 1966, to September 30, 2004) (WRCC 2004) and were estimated to be approximately 102 inches/year.

The recurrence interval flow calculated for Ozette tributaries using the USGS regional regression equations are presented in Table 35 (Sumioka et al. 1998). Because sediment transport was evaluated for each of these tributaries based on physical data acquired at the stream gauges presented in Figure 29, recurrence intervals were calculated based on the contributing drainage areas to the stream gauge locations.

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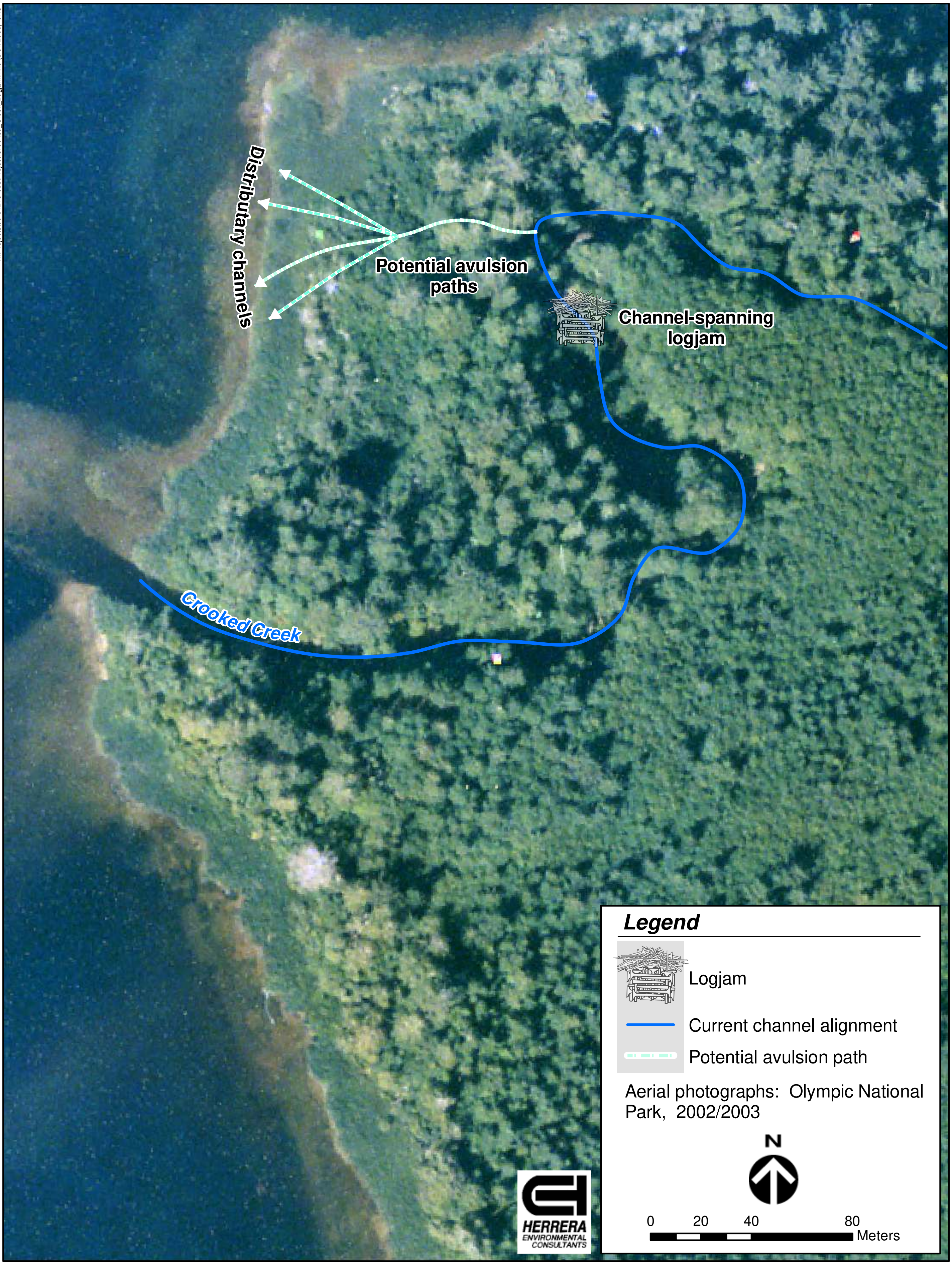

Figure 26. Potential avulsion path near the mouth of Crooked Creek resulting from the formation of a raft jam.

Figure 27. High levels of sediment loading in Umbrella Creek Stream Segment 1 (July 15, 2004). The flow direction is away from the camera. The large lateral bar at the left bank consists of fine and coarse sediment. The photograph also illustrates the limited riparian buffer which results in poor LWD recruitment potential.

Figure 28. An incised reach of Umbrella Creek in Stream Segment 1 (July 15, 2004). Channel is currently widening as evidenced by the undercut and leaning vegetation. High sediment loads consist of fine and coarse particles. The flow direction is toward the camera.

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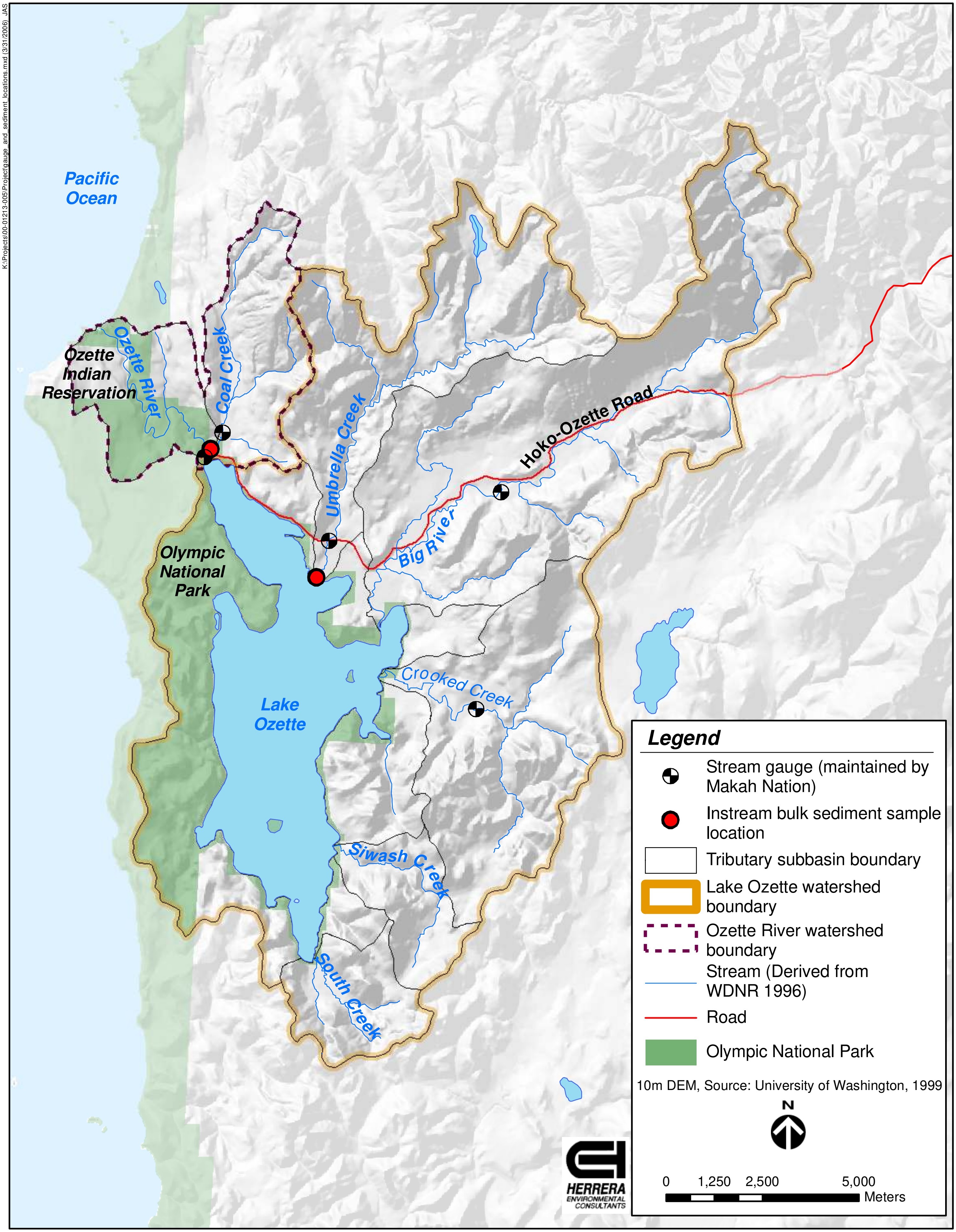

Figure 29. Locations of bulk sediment samples and stream gauges used in the evaluation of tributary sediment transport.

Table 35. Flood frequency discharge values based on U.S. Geological Survey regional regression equations.

Recurrence Interval	Coal Creek [a]	Umbrella Creek [b]	Big River [c]	Crooked Creek [d]
2-year	391	775	1,203	791
10-year	614	1,214	1,882	1,240
25-year	722	1,427	2,212	1,457
50-year	815	1,611	2,497	1,645
100-year	912	1,805	2,801	1,844

Source: Sumioka et al. (1998).
[a] Recurrence intervals were calculated for a contributing drainage area of 10.4 km^2.
[b] Recurrence intervals were calculated for a contributing drainage area of 21.8 km^2.
[c] Recurrence intervals were calculated for a contributing drainage area of 35.1 km^2.
[d] Recurrence intervals were calculated for a contributing drainage area of 22.3 km^2.

Estimating recurrence interval flows using an alternative method such as presented by Amerman and Orsborn (1987) may produce more accurate discharge estimates but was beyond the scope of this investigation.

Sediment Transport Evaluation

Sediment transport capacity was evaluated for Coal Creek, Umbrella Creek, the Big River, and Crooked Creek. Input parameters for the calculation of sediment transport capacity include site-specific channel characteristics (side slopes, bottom width, channel slope, Manning's *n*) and the recurrence interval flow rates described above. Longitudinal profiles and cross-sectional profiles for each tributary were surveyed in October 2004 by the Makah Fisheries Management. Channel side slopes, bottom widths and longitudinal slope were obtained from these surveys and used to generate trapezoidal approximations of the surveyed channel in order to estimate uniform depth and basal shear stress for input in the Meyer-Peter and Müller (MPM) equation. To estimate the conditions of historical sediment transport capacity, the depth of surveyed cross-sections was reduced by raising the channel invert. The effect of this adjustment is to reduce bank heights that have increased throughout much of the channel network, including the gauge locations, due to channel incision. The cross-sections, trapezoidal representations, and longitudinal surveys used in sediment transport calculations are presented in Appendix D. Channel roughness, described by a Manning's *n* value, was derived from the stage discharge relationships established by Makah Fisheries Management at each of the gauge locations.

Using discharge, channel geometry (bottom width, side slope, bed slope), and Manning's *n*, uniform depth can be calculated by optimizing the following equation:

$$V = Q / A = K_n n {R_h}^{3/2} S^{1/2}$$

Where: V = velocity (feet/second)

Q = discharge (cubic feet/second)

A = channel area (square feet)

n = Manning's n

R_h = hydraulic radius (feet)= channel area/wetted perimeter

S = channel slope

K_n = 1.49 for U.S. units; 1.00 for SI units.

The channel geometry and uniform depth can then be used to calculate the shear stress required to mobilize a certain grain size.

$$\tau_* = \frac{\tau_0}{g(\rho_s - \rho)D_{50}}$$

Where: τ_* = Shields parameter

τ_0 = boundary shear stress (pounds/square foot) $\tau_0 = g\rho R_h S$

g = acceleration of gravity (feet/seconds, squared)

ρ_s = sediment density = 5.14 slugs/square foot

ρ = fluid density = 1.94 slugs/square foot

D_{50} = median diameter of bed material (feet).

Sediment transport capacity can be calculated using several approaches. In this study, the Shields equation was used to assess the conditions under which bedload transport is initiated and the MPM equation was used to assess the relative proportion of sediment being transported through or being deposited in the channel network. Bedload transport was calculated for each tributary using the median grain size and critical shear stress, using the following relationship (Richards 1982; Meyer-Peter and Müller 1948):

$$q_b = \frac{1}{(\rho_s - \rho)}\left(\frac{8}{\sqrt{\rho}}\right)\left[\left\{\left(\frac{n_g}{n}\right)^{3/2}\tau_0\right\} - \tau_c\right]^{3/2}$$

Where: q_b = unit bedload transport per unit channel width (square meters/second)

n_g = Manning's coefficient due to grain roughness,

defined by Strickler (1923) $= \frac{D_{50}^{1/6}}{21}$

τ_c = Critical shear stress necessary to move D_{50} $= \tau_*(\rho_s - \rho)gD_{50}$

τ_* = Shields dimensionless critical shear stress used to solve for τ_c.

Shields dimensionless critical shear stress has been shown to range between 0.03 and 0.086 (Buffington and Montgomery 1997). For this analysis, a Shields dimensionless critical shear stress, τ_*, of 0.047 was used to calculate τ_c (Meyer-Peter and Müller 1948; Richards 1982; Buffington and Montgomery 1997).

Sediment inputs to the MPM equation are based on the upland sediment production rates. Because bedload generally constitutes approximately 5 to 20 percent of the total sediment transported through the channel network, a value of 10 percent of the estimated average annual sediment production rate was employed for evaluation of sediment transport competence in the study reaches (Dietrich and Dunne 1978; Hicks and Gomez 2003). To evaluate the existing conditions, bedload sediment input was assumed to be 10 percent of the total annual rates of sediment produced from landslide production rate, soils creep, and road and hillslope surface erosion. For historical conditions, bedload sediment input was 10 percent of the annual rate of sediment produced from soil creep and landslide sediment production.

The grain-size distributions of bedload sediment samples gathered in July 2004 were used in the analysis of transport capacity using the MPM equation. Sediment transport calculations for Coal and Umbrella Creeks were completed using the grain-size distributions of bedload samples taken from each creek. Bulk samples from the Big River and Crooked Creek were gathered at their outfalls to Lake Ozette and the grain-size distributions are significantly finer than those observed near the gauging stations where sediment transport was evaluated. Sediment transport calculations for the Big River and Crooked Creek, therefore, were completed using an average grain-size distribution of the samples from Coal and Umbrella Creeks.

Quantitative analysis of bedload sediment transport capacity was completed on Coal Creek, Umbrella Creek, the Big River, and Crooked Creek. Details of the sediment transport calculations in the analysis of sediment transport are presented, along with the channel geometry data, in Appendix D, . At one reach for each of these tributaries, the proportion of bedload transported or deposited in the reach during a range of recurrence interval flows was evaluated for conditions of both current and historical sediment transport capacity (Table 36). Table 36 also includes a ratio of the transported to deposited bedload material for each scenario. When this value is near one it indicates that there is a state of quasi-equilibrium and that the amount of material deposited in a reach is nearly equivalent to the amount that is transported through. When this ratio is much greater than one it indicates transport conditions control the reach and similarly when it is much less than one it signifies that deposition will be the dominant process.

The results indicate that only moderate changes in bedload transport are expected following the channel incision observed in the Ozette channel network. Sediment transport calculations for Coal Creek indicate a doubling of bedload transport capacity under the current conditions, whereas calculations for Umbrella Creek indicate elevated transport rates during the 10- to 25-year recurrence interval flows. Sediment transport results for the Big River indicate that the evaluated reach is largely transport dominated in both its current and historical condition at almost all recurrence interval flows. Results for Crooked Creek are largely unchanged and show a moderate transition from depositional to transport character above the 10-year recurrence interval flows.

Though field evidence indicates that reaches of the Big River are aggrading near the gauge location where sediment transport was evaluated, the grain-size of bedload material in these aggrading reaches is much coarser than the distribution of material that was input into sediment transport calculations. Therefore, the indication that fine bedload material is passed through these reaches is generally consistent with field observations.

Table 36. Estimated percentage of bedload transported through each tributary reach evaluated over a range of recurrence interval flows.

	Recurrence Interval Flow									
	2-year		10-year		25-year		50-year		100-year	
	Historical	Existing	Historical	Existing	Historical	Existing	Historical	Existing	Historical	Existing
Coal Creek										
% bedload transported	24%	43%	24%	49%	24%	49%	24%	49%	24%	50%
% bedload deposited	76%	57%	76%	51%	76%	51%	76%	51%	76%	50%
Ratio	**0.31**	**0.76**	**0.31**	**0.95**	**0.31**	**0.95**	**0.31**	**0.95**	**0.31**	**1.02**
Umbrella Creek										
% bedload transported	38%	41%	41%	53%	41%	58%	58%	58%	58%	63%
% bedload deposited	63%	59%	59%	47%	59%	42%	42%	42%	42%	37%
Ratio	**0.61**	**0.69**	**0.68**	**1.14**	**0.68**	**1.38**	**1.39**	**1.38**	**1.39**	**1.69**
Big River										
% bedload transported	43%	56%	71%	67%	71%	67%	71%	67%	71%	69%
% bedload deposited	57%	44%	29%	33%	29%	33%	29%	33%	29%	31%
Ratio	**0.75**	**1.27**	**2.50**	**2.03**	**2.50**	**2.03**	**2.50**	**2.03**	**2.50**	**2.25**
Crooked Creek										
% bedload transported	41%	44%	44%	44%	60%	60%	60%	60%	60%	60%
% bedload deposited	59%	56%	56%	56%	40%	40%	40%	40%	40%	40%
Ratio	**0.69**	**0.80**	**0.79**	**0.80**	**1.47**	**1.47**	**1.47**	**1.47**	**1.47**	**1.47**

Sediment transport results for Coal Creek demonstrate a shift from largely depositional conditions in the historical analysis to near quasi-equilibrium conditions at present. The analysis of historical sediment transport indicates that overbank flows would diminish the sediment transport capacity at flows exceeding a 2-year recurrence interval event. Distributary channels from Coal Creek near the confluence with the Ozette River support this conclusion. Field evidence indicates that Coal Creek has experienced widespread incision and now appears to be aggrading and restabilizing. Results of the analysis of current sediment transport are validated by these observations and imply that rates of transport and deposition are similar within the evaluated reach.

Results for Crooked Creek and Umbrella Creek suggest that the reaches evaluated tend to be transport dominated and that sediment transport conditions have not changed significantly between the evaluated current and historical conditions. The results are slightly inconsistent with field observations in both creeks that indicate channel enlargement and incision. There are a number of reasons that may explain these results. One, the cross-sections used in sediment transport calculations were established for the measurement of discharge, and optimal reaches for this purpose are straight and confined, such that at high discharges there is limited overbank flow so as not to affect a stage-discharge relationship. This confined condition is not typical of all locations in Umbrella and Crooked Creeks where a certain degree of floodplain connectivity has been maintained locally in areas with instream LWD. Use of a more representative cross-section location may have reduced transport in both of these reaches, and it would be expected that the transport capacity would be greater under current conditions when incision has increased the flow depth necessary to initiate overbank flows.

The pre-incision channel geometries used in this analysis are only estimates of the channel form that would have existed prior to channel modifications and responses. Because channel widening is often associated with incision, it is possible that the cross-sectional area of the pre-incision cross-sections evaluated, due particularly to the channel width, is larger than true historical conditions. If channel widths were reduced in this scenario it would result in increased sediment transport during low magnitude events due to increased flow depths, but decreased capacity during high magnitude events once channel banks were over topped and flood flows activated side channels and were spread across the floodplain.

Sediment transport was not evaluated quantitatively in South and Siwash Creeks. Observations indicate that channel incision in these tributaries would reduce the occurrence of overbank flow events, increase flow depths and decrease opportunities for sediment storage on floodplains. The expected net result of these conditions would be an increase in sediment transport capacity from pre-incision conditions.

Improved estimates of the sediment transported to Lake Ozette could be achieved by constructing bedload and suspended load rating curves for each of the tributary channels and applying these curves to the hydrologic records building at each stream gauge site.

3.4 Lakeshore Characterization at Tributary Outfalls and Evaluation of Longshore Transport

3.4.1 Lakeshore Characterization at Tributary Outfalls

Historical shoreline changes and current sediment characteristics at tributary deltas were analyzed to determine the degree to which increases in sediment output associated with historical watershed disturbance may have affected the nearshore environment of Lake Ozette. Documentation of shoreline changes and delta growth provides an indication of the magnitude of sediment that has been delivered to the lake and may therefore be available, either through longshore transport or suspension, for delivery to areas of lakeshore habitat. If limited changes are observed through time at a tributary delta, it may be that the impact from tributary-delivered sediment is negligible. If, however, evidence indicates significant sediment delivery, then it is possible that this sediment source is affected the lakeshore habitat.

Aerial photographs taken at each tributary mouth were analyzed to estimate the aerial extent of delta growth. Photographs from 1953 (limited extent), 1964, 1994, 2000, 2002 and 2003 were available for this analysis (Table 37). Georeferenced photographs from 1964 and 2002/2003 were used to determine the magnitude of shoreline changes associated with the period of the most severe disturbance in the watershed. The 1953 photographs were used to qualitatively verify features that were unclear in the 1964 photographs.

Table 37. Aerial photographs used in tributary delta analysis.

Year of Aerial Photograph	Source
1953	Rayonier Timber Operating Company
1964	Olympic National Park
1994	U.S. Geological Survey
2000	Washington Department of Natural Resources
2002/2003	Olympic National Park
2003	Produced for the Makah Indian Tribe by Optimal Geomatics, Vancouver, B.C.

The photographs from 2002/2003 and 2003 were used for most of the analysis. The mouth of each tributary (Umbrella Creek, the Big River, Crooked Creek, Siwash Creek, and South Creek) was evaluated in detail by delineating the edge of vegetation and, in some cases, the edge of the delta in the aerial photographs from 1964, 2002/2003, and 2003. The lake level in the 1964 photographs appeared to be higher than the level in the 2002/2003 and 2003 photographs; therefore, photographs from 1953 (where available) were used to clarify the edge of vegetation in the 1964 photographs. The 1953 photographs have much higher resolution, but they were not georeferenced at the time this analysis was completed; therefore, they were used qualitatively to verify the edge of vegetation in the 1964 photographs.

Sediment samples were collected at each tributary delta, and in some cases from mid-channel bar deposits upstream, to characterize the grain-size distribution of sediment being supplied by tributaries and entering Lake Ozette. Locations of bulk sediment samples and grain-size distributions are presented in the results section of this report; grain-size distributions are also presented in Appendix C.

An analysis of aerial photographs of tributary deltas in 1964 and 2002/2003 indicates evidence of variable delta growth at each tributary mouth (Table 38). Lake water surface elevations were higher in the 1964 photographs than in the more recent photographs; however, the absolute water surface elevation could not be determined for the time of either set of photographs. As a result, measurements of delta growth are best used to qualitatively indicate depositional trends over the 40-year analysis period. Aerial photographs from 1964 and 2002/2003 and the delineations of tributary deltas are presented in Appendix E.

Table 38. Estimated areal delta growth of Lake Ozette tributaries and grain-size descriptions for bulk sediment samples.

Tributary	Delta Growth from 1964 to 2002/2003 (m^2)	Sediment Sample ID	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)
Umbrella Creek	23,000				
		Umbrella Creek	0.44	12.14	37.09
		Umbrella Creek Mouth	0.13	0.43	8.88
		Umbrella Creek Delta 1	0.04 [a]	0.19	0.36
		Umbrella Creek Delta 2	0.24	1.62	11.5
		Umbrella Creek Delta 3	0.22	0.84	11.64
		Umbrella Creek Delta 4	0.07	0.33	1.37
Big River	–				
		Big River	0.02 [a]	0.11	0.34
Crooked Creek	12,000				
		Crooked Creek	0.22	0.68	2.54
		Crooked Creek Delta	0.2	0.35	0.67
Siwash Creek	–				
		Siwash Creek	0.17	1.58	12.16
		Siwash Creek Delta	0.09	0.36	1.95
South Creek	8,000				
		South Creek	0.2	2.83	10.38
		South Creek Delta	0.04 [a]	0.34	2.16
Coal Creek	NA				
		Coal Creek	0.42	10.12	34.8
		Ozette River	0.47	7.76	27.65

[a] Estimated through linear interpolation of grain-size distribution data; presented in Appendix C.

The Umbrella Creek delta appears to have grown most significantly over the analysis period followed by the Crooked Creek delta. There is moderate evidence of delta growth at the South Creek delta, and little evidence of delta growth at the mouth of the Big River and Siwash Creek. Analysis of bulk sediment samples gathered near tributary mouths indicates that delta sediments are typically finer than sediments sampled within the active channel upstream. The majority of sediment samples from tributary mouths and deltas indicate over 80 percent of deltaic sediment is finer than 0.85 millimeters in diameter. The exception to this trend is Umbrella Creek where multiple sediment samples indicate a range in delta grain-size distribution.

Between 1964 and 2002/2003, the Umbrella Creek delta may have grown in area by up to 23,000 square meters (Figure 30). The majority of delta growth has occurred to the north of the tributary mouth. Two of the four delta sediment samples from Umbrella Creek (Figure 30) are significantly coarser than other delta sediments evaluated in this study. Umbrella Creek Delta sample numbers 2 and 3 contain approximately 40 percent more material greater than 0.85 millimeters in diameter than Umbrella Creek Delta sample numbers 1 and 4. All samples form the mouth and delta are significantly finer grained than the sample gathered approximately 125 meters upstream from a mid-channel bar.

There is little evidence for delta growth at the mouth of the Big River (Figure 31). Between 1964 and 2002/2003, there may have been minor amounts of deposition directly south of the mouth as well as around the shoreline to the south west; however, the differences in water surface elevation between the 1964 and 2002/2003 photographs make this growth difficult to evaluate even qualitatively. A sediment sample from the mouth of the Big River indicates that over 99 percent of the sample is finer than 0.85 millimeters in diameter (Figure 31).

The delta at Crooked Creek has grown up to 12,000 square meters between 1964 and 2002/2003 (Figure 32). The majority of this growth, approximately 85 percent, has occurred north of the mouth. The grain-size distribution of sediment samples taken from both the channel and the delta are fine grained, with 64 and 99 percent finer than 0.85 millimeters, respectively (Figure 32).

There is little evidence for delta growth at the mouth of Siwash Creek between 1964 and 2002/2003 (Figure 33). The grain-size distribution from the Siwash Creek delta sample is slightly coarser than delta samples from the Big Creek and Crooked Creek, with 77 percent finer than 0.85 millimeters (Figure 33).

At the mouth of South Creek, delta growth up to 8,000 square meters may have occurred between 1964 and 2003 (Figure 34). Because of the unknown difference in water surface elevation between the 1964 and 2003 photographs, and the apparent low gradient of deltaic sediments in the 1964 photographs, there is little confidence in the estimated extent of South Creek delta growth, although evidence for vegetative encroachment is clear. Sediment samples from the channel and delta of South Creek indicate that 36 and 77 percent finer than 0.85 millimeters, respectively (Figure 34).

Bulk sediment samples from the Ozette River and Coal Creek were gathered near their confluence (Figure 35). Though Coal Creek enters the Ozette River downstream of the Ozette River sample location, the grain-size distribution of each sample is nearly identical. A topographic low point in a longitudinal survey of the entrance to the Ozette River from Lake Ozette indicates that coarse sediment is not being delivered to the Ozette River from the lake (Herrera 2005). The similarity in grain-size distribution between the two samples in Figure 35 indicates that the coarse sediment in the Ozette River is being delivered from Coal Creek.

The sediment that is delivered to the Ozette River from Coal Creek has formed a riffle with midchannel bars. This feature controls the lake outlet stage at low to moderate flows (Haggerty 2005). Cross-section elevation data for the riffle collected from the footbridge over the Ozette River between 1979 and 2003 indicate approximately 1 foot of aggradation (Haggerty 2005). This value correlates with an average 1 foot upward shift in the Lake Ozette stage and Ozette River discharge rating curve over the same period (Haggerty 2005).

This analysis of current and historical lakeshore conditions complements a companion study, *Hydraulic and Geomorphic Evaluation: Analysis of Wood Loading in the Ozette River and Its Effect on Water Levels in Lake Ozette, Clallam County, Washington* (Herrera 2005), which also investigated historical changes in the Lake Ozette shoreline with an emphasis on determining

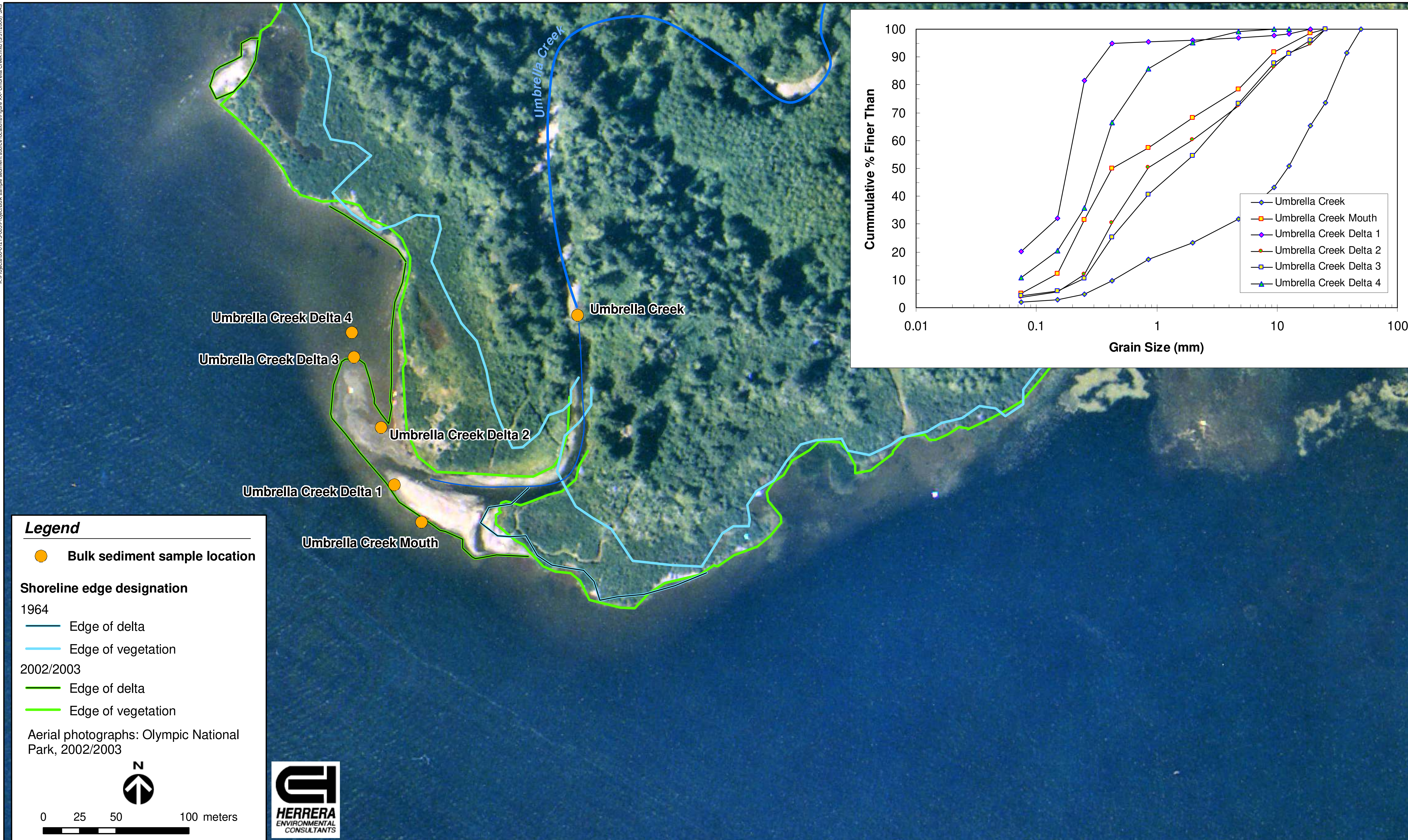

Figure 30. Shoreline changes, bulk sediment sample site locations, and grain-size distributions from the mouth and delta of Umbrella Creek.

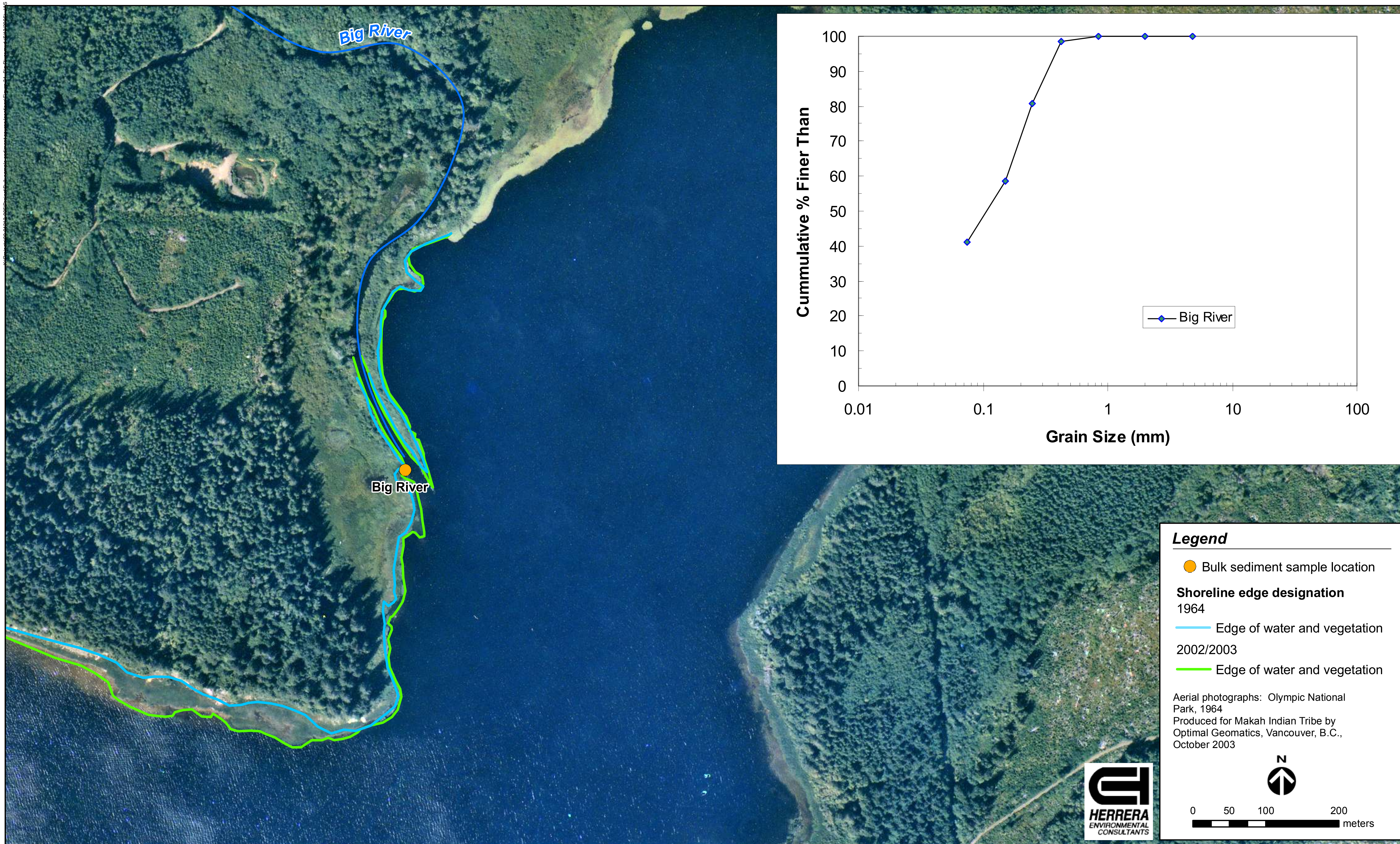

Figure 31. Shoreline changes, bulk sediment sample site location, and grain-size distribution from the mouth of Big River.

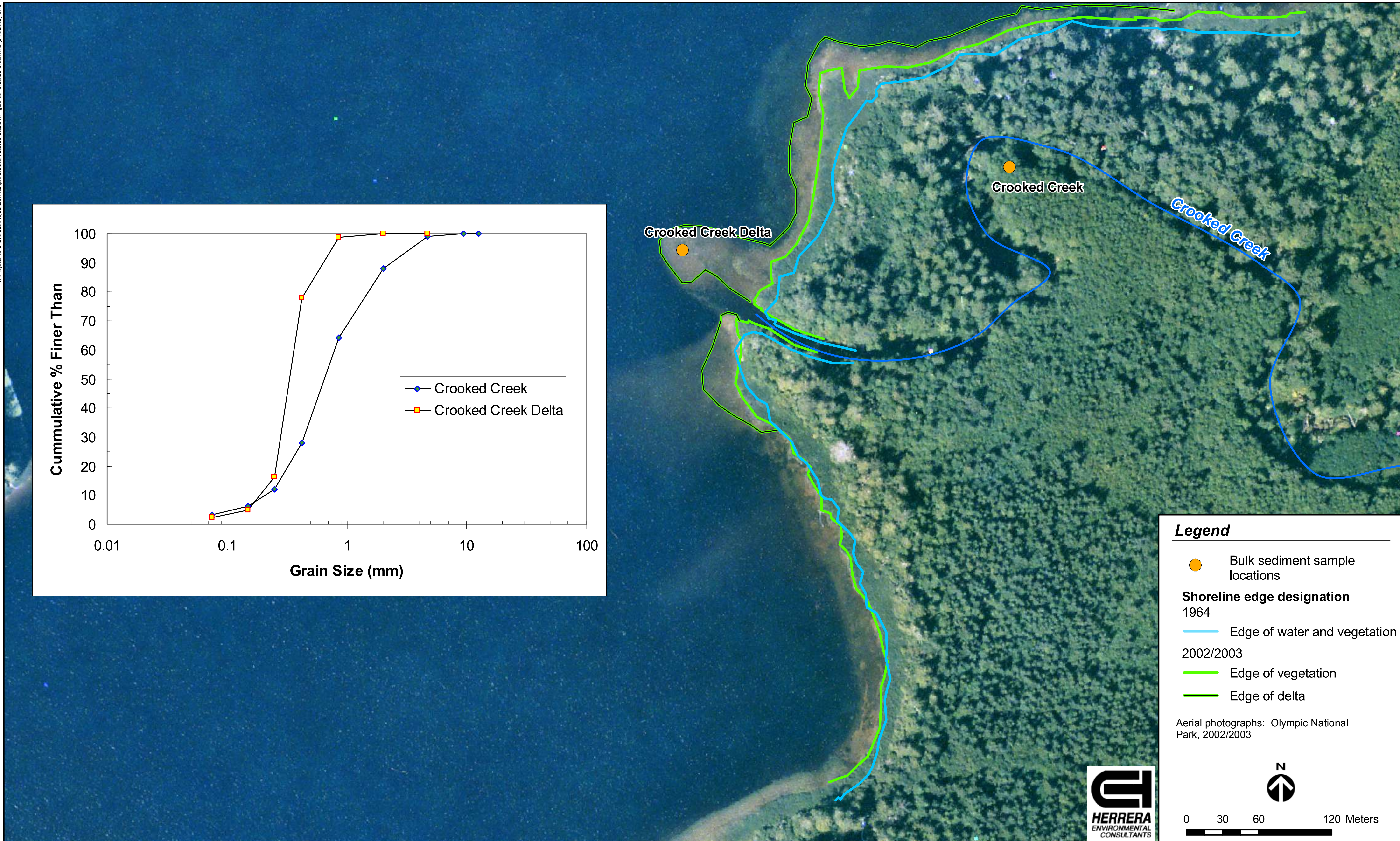

Figure 32. Shoreline changes, bulk sediment sample site locations, and grain-size distributions from the mouth of Crooked Creek.

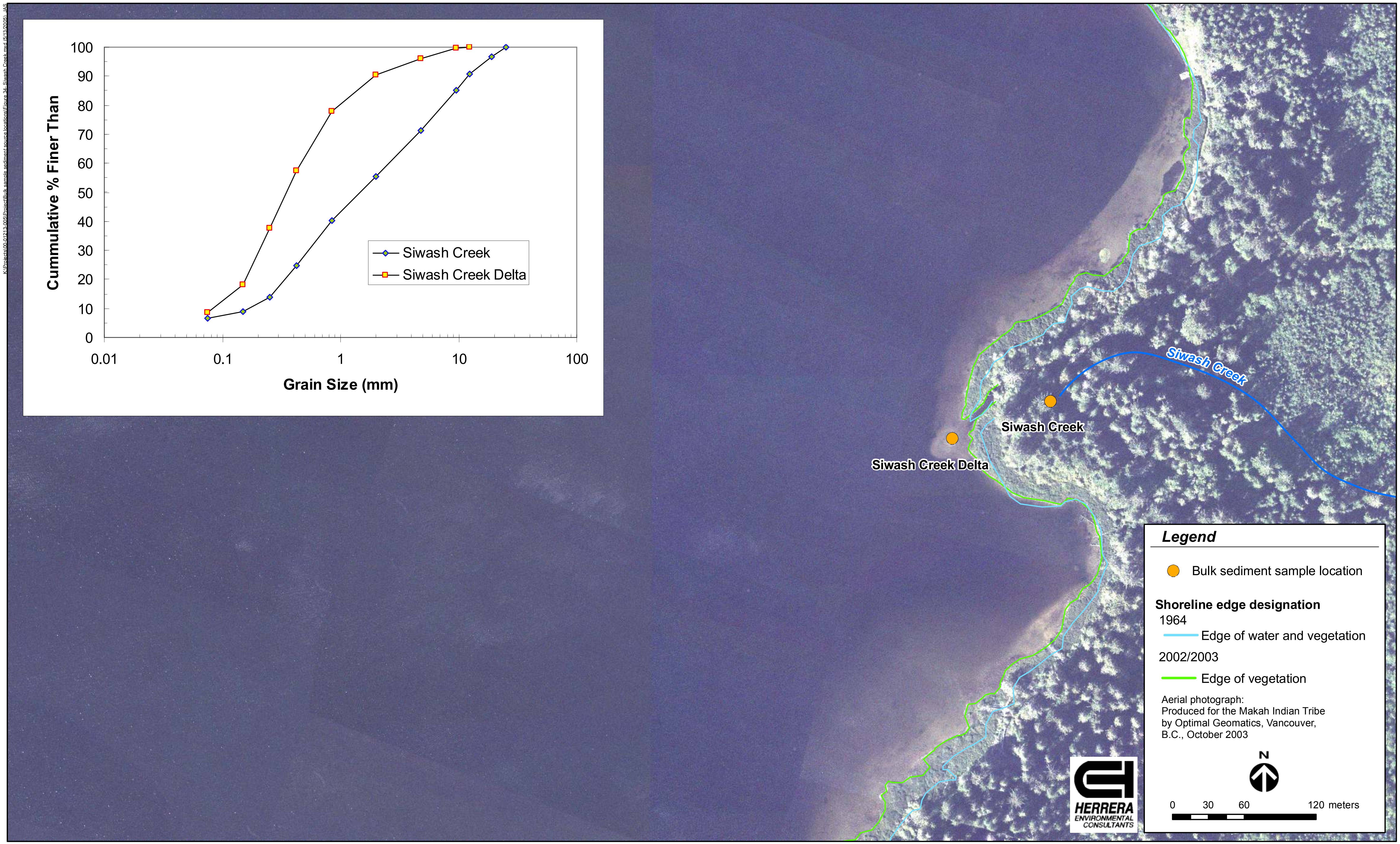

Figure 33. Shoreline changes, bulk sediment sample site locations, and grain-size distributions from the mouth of Siwash Creek.

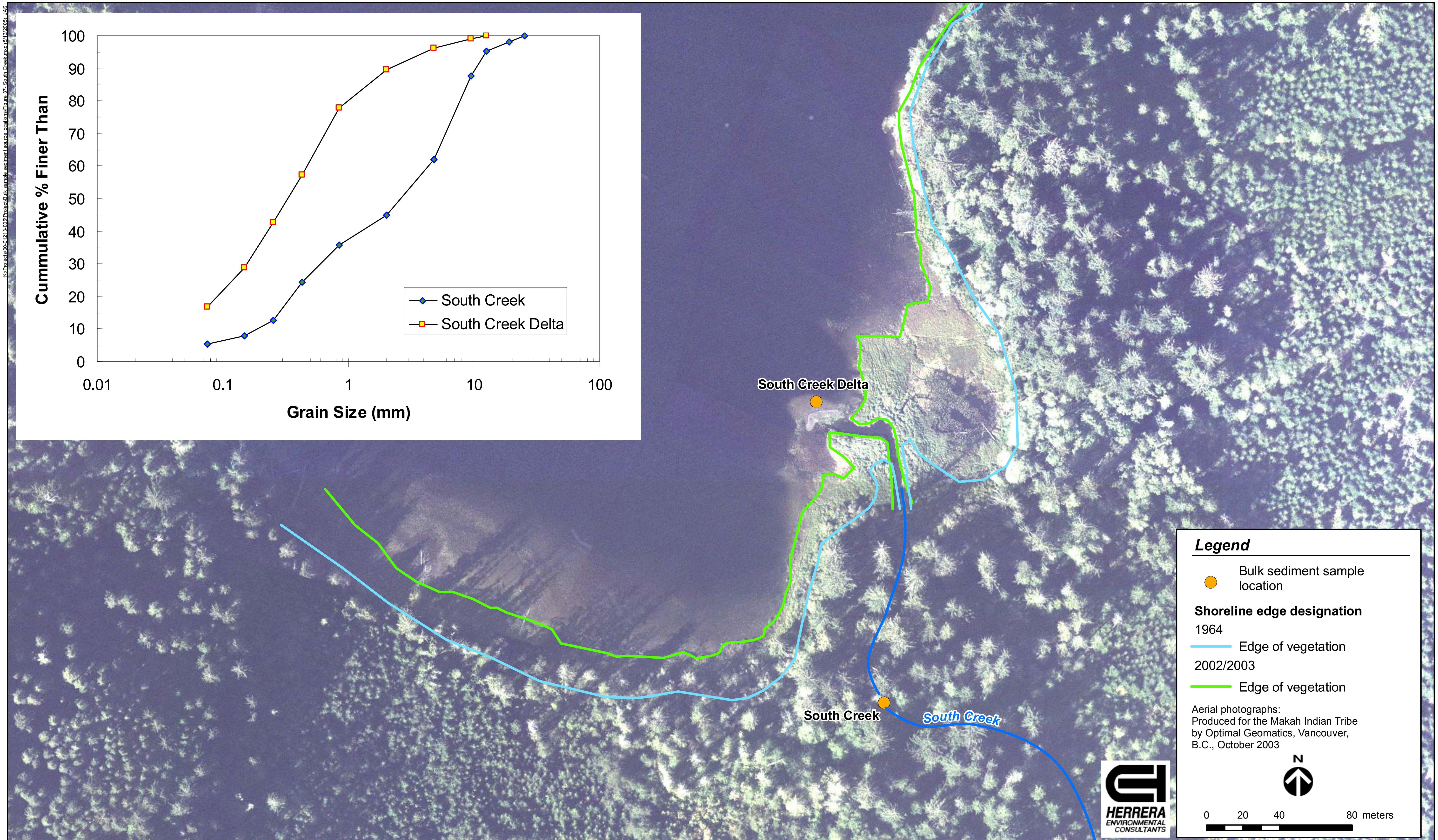

Figure 34. Shoreline changes, bulk sediment sample site locations, and grain-size distributions from the mouth of South Creek.

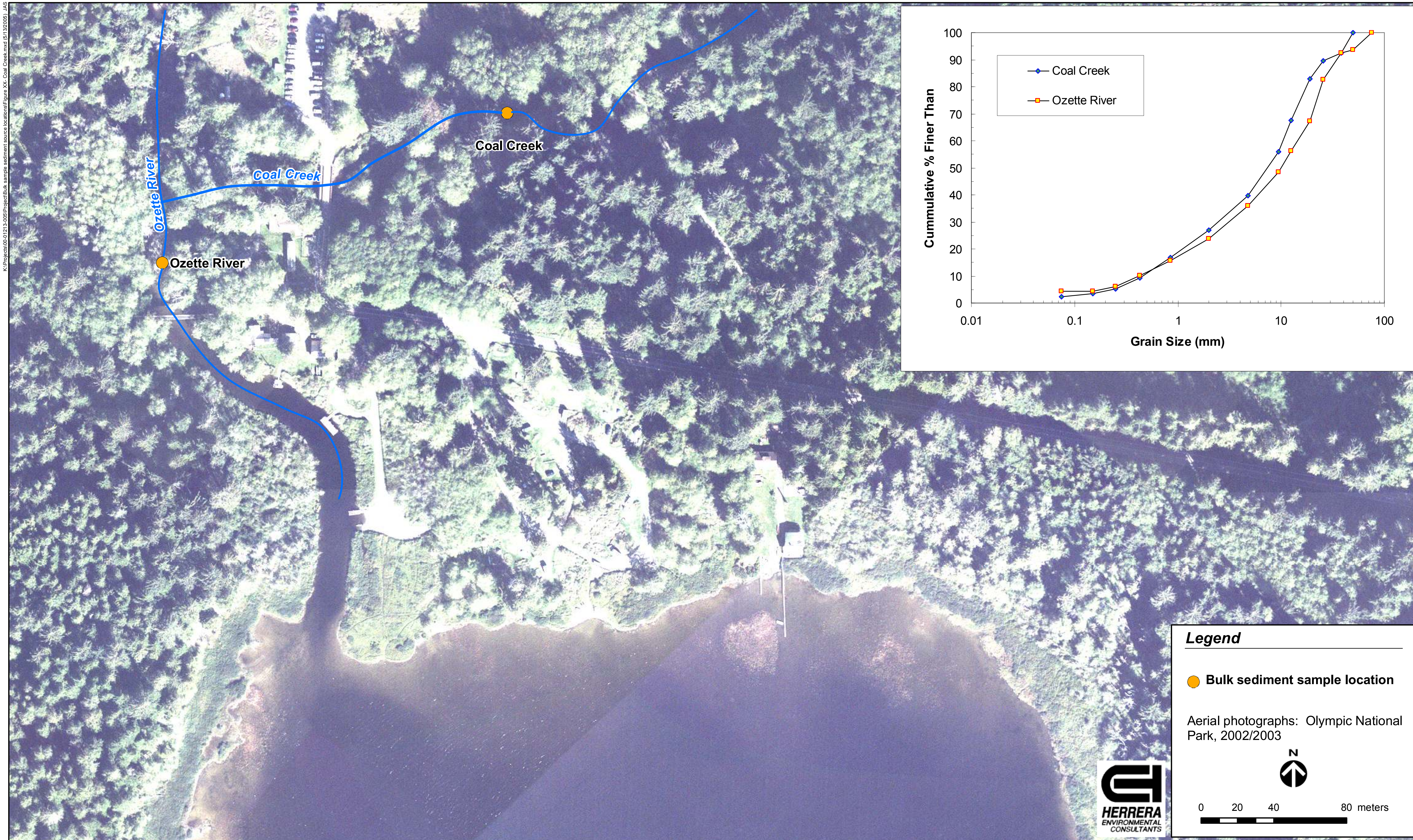

Figure 35. Bulk sediment sample site location and grain-size distribution from Coal Creek and Ozette River.

the magnitude of change of shoreline position and the extent to which vegetation has encroached on the lake. In addition to tributary delta sites, the investigation evaluated nondelta sites including Allens and Olsens Beaches. Although the results of this investigation do not indicate a notable change in shoreline position at Allens and Olsens Beaches, significant vegetation encroachment was documented at these and other lakeshore sites (Appendix E). These findings are consistent with the results of a similar study performed by Ritchie (2005), who compared shoreline and shoreline vegetation positions between 1953 and 1994, 2000, or 2003 aerial photographs.

Ritchie (2005) found that of the 46.5 km of shoreline surveyed for vegetation trends (of a total lake perimeter length of 567 km), more than 40 percent showed evidence of increased cover. Included in these areas are known sockeye spawning locations. The impact to sockeye spawning from significant shoreline changes is not understood.

3.4.2 Evaluation of Longshore Transport Potential

Longshore sediment transport potential in Lake Ozette was evaluated to better understand the fate of sediment once it is delivered by tributaries of the lake. Longshore transport of beach sediment occurs either by suspension, where fine sediment is carried above the bottom in turbulent eddies, or by bedload transport, where coarse particles remain close to the bed and move by a rolling or saltatory motion. Along the Lake Ozette shoreline, wind-driven wave action and lake currents combine to transport beach sediment. The principal factors influencing the waves that promote longshore sediment transport relate to wind conditions, including the speed, duration, direction, and fetch length. Other factors that influence longshore transport include the size and distribution of beach sediments, the angle that waves approach the shoreline, and the slope of the lake bottom where waves approach the shore.

Quantitative estimates of longshore sediment transport necessitate intensive field surveys or computational techniques that were beyond the scope of this investigation. As wave height is a significant influence on the longshore transport rate, calculations of wave height can serve as an indicator for relative longshore transport conditions in Lake Ozette. A wave height calculator developed by USGS was used to determine wave heights at select locations in Lake Ozette (USGS 2005). Based on equations 3-39 and 3-40 in the *Shore Protection Manual* (USACE 1984), wave height based on inputs of wind velocity and fetch and water depth were generated. Whereas the magnitude of wave height is sensitive to changes in wind velocity and fetch, changes in water depth have limited influence on wave height results. A water depth of 10 meters was assumed for all calculations.

Hourly average wind velocity and direction was obtained for water years 2002 through 2004 from the National Weather Service station at the Quillayute Airport in Washington. A wind rose of these data was created using Lakes Environmental WRPLOT View program. The wind rose indicates the percentage of time the wind blew in a given direction over a range of wind velocities.

Locations where longshore transport was evaluated were based on proximity to tributary deltas and geomorphic features of the Lake Ozette shoreline that provide further indications of longshore transport magnitude and direction. At each location where longshore sediment transport potential was evaluated, the wave height was calculated for the longest possible fetch length at the location for each of the wind velocity ranges (using the median velocity from each velocity range). The wave height for each velocity range was then multiplied by the percentage of time the wind blew in that direction within the velocity range. The sum of these products of wave height and wind duration for each velocity range represents the value of relative longshore sediment transport potential. Identical calculations were completed at each location for the direction opposite the maximum fetch length to generate a vector pair of longshore sediment transport potential. Calculations of relative longshore sediment transport potential are presented in Appendix F.

Calculated values for relative longshore transport potential at select locations in Lake Ozette suggest that the highest transport potential is in the northern part of the lake, at Location 3, near the mouth of Umbrella Creek (Table 39, Figure 36). The conditions of longshore transport potential result from the strongest and most frequent winds blowing to the north and the longest fetch lengths occurring at either end of the lake (Table 40).

Table 39. Relative longshore transport values at select evaluation locations in Lake Ozette.

Evaluation Location	Longest Fetch Direction	Longest Fetch Length (m)	Relative Longshore Transport Value (x 10^2)	Opposite Fetch Direction	Opposite Fetch Length (m)	Relative Longshore Transport Value (x 10^2)
1	NW	6,700	3.7	SE	300	0.3
2	NW	7,600	3.9	SE	2,700	1.0
3	N	9,400	8.3	S	1,100	0.3
4	N	5,500	6.5	S	1,200	0.3
5	NE	4,100	2.2	SW	2,100	1.2
6	SW	4,600	1.7	NE	1,400	1.3
7	S	6,900	0.8	N	1,700	3.7
8	S	9,100	0.9	N	300	1.6

Table 40. Summary of hourly average wind speed and direction from the National Weather Service station at the Quillayute Airport in Washington.

Wind Direction	Percentage of Time Wind Blew within a Range of Speeds (m/s)						Total
	0.5 to 4.0	4.0 to 8.0	8.0 to 12.0	12.0 to 16.0	16.0 to 20.0	>20.0	
N	1.4%	6.5%	5.0%	2.3%	1.0%	0.2%	16.4%
NE	0.8%	3.9%	2.3%	0.5%	0.2%	0.0%	7.7%
E	0.7%	4.6%	3.6%	0.8%	0.2%	0.0%	10.0%
SE	0.7%	2.6%	1.4%	0.2%	0.0%	0.0%	4.9%
S	1.0%	1.8%	0.4%	0.0%	0.0%	0.0%	3.3%
SW	2.0%	3.4%	1.2%	0.4%	0.1%	0.0%	7.0%
W	3.5%	7.0%	0.4%	0.0%	0.0%	0.0%	10.9%
NW	1.3%	4.0%	2.8%	1.2%	0.3%	0.0%	9.6%
Total	11.4%	33.8%	17.0%	5.4%	1.8%	0.3%	–

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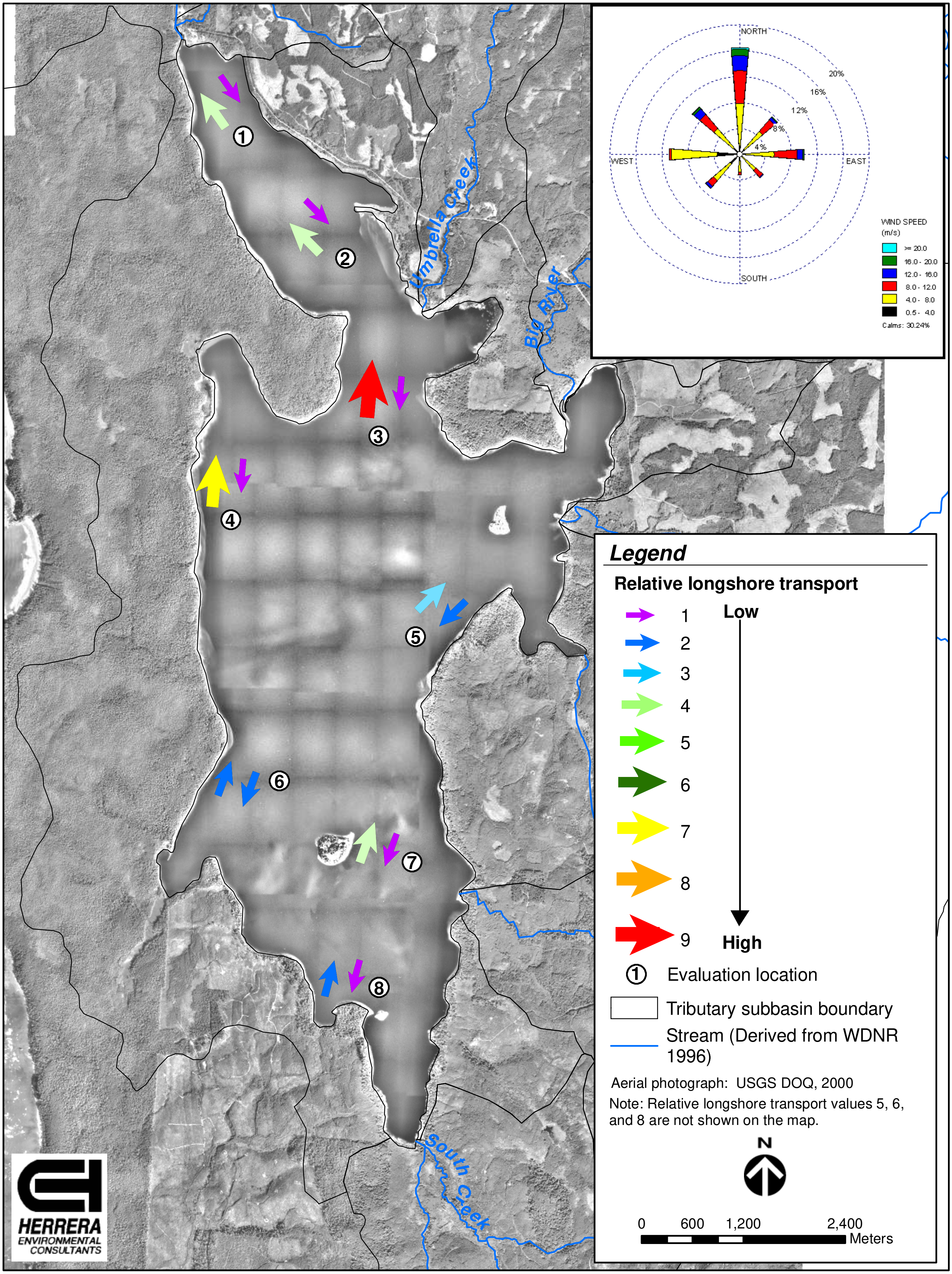

Figure 36. **Magnitude and direction of dominant relative longshore transport in Lake Ozette. Inset figure shows wind speed and duration for data acquired from the National Weather Service station Quillayute Airport, WA (#94240).**

Patterns of delta growth at Umbrella and Crooked Creeks, as well as along the west shore of the lake near Location 4, support north-trending dominant longshore transport at these locations (Figure 36).

Ritchie (2005) noted that between 1953 and 2003 significant erosion occurred on the shoreline north of the evolving Umbrella Creek delta. This erosion site is currently partially exposed to the waves that are generated at evaluation location 3 in Figure 36, where transport potential to Lake Ozette is highest. It is likely that before the evolution of the Umbrella Creek delta, the site was more fully exposed to strong and frequent winds blowing to the north and longshore transport rates were higher.

Shoreline features in the south part of the lake indicate distinct cells of longshore transport. A spit along the west shore of Allens Bay near Location 6 strongly suggests southward longshore transport, whereas deposits along the east side of Tivoli Island indicate northward transport.

Longshore transport rates for coarse sediment may be significant in only a handful of locations, the beach north of Umbrella Creek being the most prominent. Wind-generated wave action, however, results in currents that both keep fine sediments in suspension and affect the distribution of fine sediment in the lake.

Grain-size distribution data for sediment samples from Allens and Olsens Beaches (see Figure 2) may provide evidence that fine sediment delivered to the lake from the major tributaries evaluated in this study contributes to increases in fine sediment concentrations throughout the lake. The sediment samples were gathered from core spawning areas at Allens and Olsens Beaches in 1999 and from Olsens Beach in 2000, typically at elevations below 32.5 feet (Haggerty et al. 2005). In 2000 at Olsens Beach, paired samples were collected along a transect perpendicular to the beach, with samples typically 2.5 meters apart. The grain-size analysis data presented in Table 41 for 1999 and Table 42 for 2000 are variable, but a number of the samples contain high proportions of fine sediment, with an average of 24 to 27 percent of the sediment samples by weight being finer than 0.85 millimeters. Further investigation is necessary to determine whether these fine sediments are being delivered to the lake from local tributaries or whether they have been transported in suspension from larger tributaries.

3.4.3 Evaluation of Potential Losses in Salmonid Spawning Area Resulting from Changes in Lake Elevations

Historical removal of logjams within the Ozette River lowered water surface elevations in Lake Ozette which in turn reduced the potential beach area available for sockeye spawning. Lower lake levels did not eliminate all beach spawning, they altered the inundation frequency and shifted elevation zones of habitat down the beach (Herrera 2005). Clearly the most dramatic historical impact has been the long-term loss of ephemeral unvegetated high water beach that once existed around the lake. These high water beaches are no longer available viable for spawning because of the reduced times of inundation and the encroachment of woody vegetation onto previously unvegetated gravel. The vegetation has added cohesion to previously uncohesive sediment and has reduced wave energy allowing for deposition of fine sediment onto beach gravel.

Table 41. Grain-size distribution data for sediment samples from core spawning areas at Allens and Olsens Beaches in 1999.

Sample ID	Cumulative Percentage Finer Than Particle Diameter (%)					
	26.5 mm	9.9 mm	3.35 mm	2 mm	0.85 mm	0.106 mm
Allens-1	62.2	29.5	14.4	9.7	6.5	0.2
Allens-2	56.9	39.7	30.3	27.6	25.5	1.3
Allens-3	84.2	68.1	53.5	47.7	39.9	3.3
Allens-4	64.6	50.4	39.3	35.3	27.2	4.5
Allens-5	91.3	45.2	27.4	18.4	7.9	0.4
Allens-6	76.6	67.1	58.5	52.7	44.3	5.4
Allens-7	73.0	55.3	45.4	41.9	39.0	2.4
Allens-8	82.7	54.7	40.1	33.5	26.5	2.5
Allens-9	72.5	50.9	36.8	30.8	24.1	1.9
Allens-10	74.3	54.8	38.1	32.5	24.7	2.0
Allens-11	58.6	39.7	19.9	7.8	4.6	0.9
Maximum	91.3	68.1	58.5	52.7	44.3	5.4
Minimum	56.9	29.5	14.4	7.8	4.6	0.2
Average	72.5	50.5	36.7	30.7	24.6	2.3
Olsens-1	68.7	43.2	29.5	22.6	13.8	1.4
Olsens-2	31.7	37.6	24.0	18.5	13.0	0.4
Olsens-3	25.6	54.0	47.0	44.3	41.5	3.1
Olsens-4	37.5	30.6	18.5	14.3	10.8	0.8
Olsens-5	36.8	44.8	36.3	32.4	29.2	2.2
Olsens-6	20.2	57.8	49.2	44.3	39.5	3.5
Olsens-7	21.5	59.8	55.7	50.0	42.9	3.1
Olsens-8	21.9	53.2	36.9	30.0	22.3	10.6
Olsens-9	44.9	34.7	27.7	24.6	20.3	0.8
Olsens-10	0.0	82.3	82.2	66.2	54.1	9.7
Olsens-11	32.8	41.1	25.7	19.3	13.0	1.2
Olsens-12	45.5	29.1	18.8	13.8	9.1	0.4
Olsens-13	19.9	42.2	27.5	23.0	18.5	0.6
Maximum	68.7	82.3	82.2	66.2	54.1	10.6
Minimum	0.0	29.1	18.5	13.8	9.1	0.4
Average	31.3	46.9	36.9	31.0	25.2	2.9

Table 42. Grain-size distribution data for paired beach-transect sediment samples from core spawning areas at Olsens Beach in 2000.

Sample ID [a]	Cumulative Percentage Finer Than Particle Diameter (%)					
	26.5 mm	9.9 mm	3.35 mm	2 mm	0.85 mm	0.106 mm
1-U	85.0	49.7	35.6	29.5	22.8	2.8
1-D	70.8	43.0	33.2	29.2	24.4	2.1
2-U	78.5	52.1	43.5	40.3	36.6	5.0
2-D	77.3	55.2	47.0	43.0	38.5	2.8
3-U	71.9	55.0	47.3	43.2	38.6	3.4
3-D	72.7	49.9	42.0	37.8	32.5	3.3
4-U	84.4	53.0	37.9	30.6	22.9	1.6
4-D	72.9	36.2	23.9	18.6	13.7	1.3
5-U	77.2	39.7	24.6	18.4	11.5	1.0
5-D	81.3	56.0	48.0	44.7	41.0	2.6
6-U	74.6	49.2	31.6	23.9	14.5	0.6
6-D	69.8	36.3	23.0	17.8	12.4	0.8
7-U	89.5	58.9	44.8	38.1	29.2	3.4
7-D	77.0	57.1	45.3	40.0	33.7	2.1
8-U	78.5	59.2	45.3	39.7	33.0	5.8
8-D	88.7	59.6	46.5	41.8	35.8	4.2
9-U	94.1	77.9	63.6	56.3	46.2	8.3
9-D	93.4	72.8	60.1	53.7	45.3	9.0
10-U	94.0	87.7	80.2	77.4	72.7	11.4
10-D	70.5	62.4	52.2	48.2	42.2	5.8
11-U	92.3	55.8	39.9	34.6	27.4	4.8
11-D	89.6	47.4	29.2	24.0	18.0	2.7
12-U	66.8	26.5	13.7	9.9	7.0	1.0
12-D	79.6	41.9	27.9	23.7	20.1	3.9
13-U	79.0	31.9	17.5	13.2	9.7	1.3
13-D	69.5	38.8	23.1	17.0	12.1	1.1
14-U	76.5	49.0	30.4	23.1	15.7	0.9
14-D	73.4	60.0	30.4	24.7	19.1	1.1
15-U	74.0	46.2	30.8	26.0	20.9	1.3
15-D	67.3	35.6	21.8	16.8	11.9	0.9
Maximum	94.1	87.7	80.2	77.4	72.7	11.4
Minimum	66.8	26.5	13.7	9.9	7.0	0.6
Average	79.0	51.5	38.0	32.8	27.0	3.2

[a] U indicates the sample was collected at the distal end of the transect from the lake and D indicates the sample was collected at the proximal end of the transect from the lake.

Recent sockeye spawning has been primarily limited to just two sites, Allens and Olsens beaches (Haggerty et al. 2005). Historical observations, however, indicate that spawning at other select portions of the lake shore may have once been greater (Dlugokenski et al. 1981, Meyer and Brenkman 2001). Sockeye spawning utilization at Allens and Olsens beaches varies considerably and is likely influenced by conditions such as lake hydrology, beach slope, substrate, vegetation, and groundwater upwelling.

The reduction in beach area that resulted from lowering lake levels and the associated impact to potential sockeye spawning was calculated from known physical characteristics of Lake Ozette and spawning characteristics of Lake Ozette sockeye. The reduction in total ephemeral beach area was calculated by:

$$A_B = P_L \times \left[\frac{\Delta h}{\sin(\alpha_B)} \right]$$

Where:
A_B = Total beach area lost (m^2)
P_L = Perimeter of lake affected (m)
Δh = Change in water surface elevation (m)
α_B = Average angle of beach affected (degrees).

The total perimeter of Lake Ozette is approximately 57 km. The proportion of this perimeter that was once used for spawning is not known; however, suitable spawning areas would have existed along some fraction of this total perimeter. Based on observations of the characteristics of current and historical spawning areas, a range 10 percent to 40 percent of the total lake perimeter was evaluated. For this analysis, therefore, a range of lengths from 5,700 m to 22,800 m was used as an estimate of the affected beach length that may once have been suitable spawning habitat. The change in water surface elevation was estimated at 1 meter. This value is equivalent to the estimated decrease in mean lake level during the sockeye spawning and incubation period that has resulted from the removal of logjams within the Ozette River (Herrera 2005). The average angle of the beach affected was approximated at 6.3° (11 percent). This value is based on a summary of shoreline characteristics derived from 1-foot lidar (light detection and ranging) data (Herrera 2005). Based on these assumptions the total area of beach lost that may once have been suitable spawning habitat was calculated to range form 52,000 to 210,000 m^2 (13 to 52 acres).

The reduction in potential sockeye spawning, i.e. the number of potential redd sites lost due to lake level lowering was then calculated. The number of redd sites lost was based on the calculated beach area lost, redd size data, spawning coefficients, and assumptions regarding the occurrence of overprinting or superimposition of redds (Haggerty et al. 2005). The number of potential redd sites lost due to lake level lowering was therefore calculated as:

$$R_L = \frac{A_B}{R_A} \times \Phi_S$$

Where: R_L = Potential number of redd sites lost

R_A = Average redd area (m^2)

Φ_S = Spawning coefficient (% of potential spawning area actually used by salmon).

These calculations include data and assumptions that are based on observations of Lake Ozette sockeye. The value for average redd area (R_A) of 1.3 m^2 was derived from data provided in Haggerty et al. (2005). For these calculations, it was assumed that there was no overprinting, i.e., spawning did not occur in the same location more than one time, thus providing a conservative calculated value for the potential number of redds lost. Observations of beach spawning conditions in Lake Ozette indicate, however, that overprinting is common and is an indication of limited suitable or preferred spawning areas (Haggerty et al. 2005). A range of spawning coefficients from 0.17 to 0.33 were used in these calculations (Haggerty et al. 2005). Spawning coefficients are a measure of utilization and are determined as the percentage of spawning units utilized out of the total number of potential units.

The potential number of utilized sockeye spawning sites lost due to lake level lowering resulting from the historical removal of logjams within the Ozette River were calculated to range from 6,800 to 53,000 (Table 43). There results could provide a first-order explanation for the decline in the sockeye population from approximately 14,000 to 18,000 circa 1950 to current estimates of several hundred (Bortleson and Dion 1979; Haggerty et al. 2005). These numbers clearly indicate that lake level changes could have been a significant limiting factor in sockeye spawning habitat.

Table 43. Potential redd sites lost as a result of a change in lake levels following the removal of logjams within the Ozette River.

Proportion of Lake Perimeter Evaluated (%)	Beach Area Lost (m^2)	Potential Number of Redd Sites Lost	
		Low Spawning Coefficient (0.17)	High Spawning Coefficient (0.33)
10	52,000	6,800	13,000
40	210,000	27,000	53,000

4. Discussion of Results

Populations of Lake Ozette sockeye have declined dramatically in the past century. Although the cause of this decline is not known, sediment inputs due to forest roads associated with harvesting activities, and changes in lake levels and tributary channel conditions following the removal of logjams in the Ozette River, may have at least contributed to limiting sockeye salmon recovery.

The results of this study indicate that surface erosion of the forest road network has resulted in an increase in watershed sediment production and the majority of this sediment produced is predominantly fine grained. The current sediment production rates in the Lake Ozette watershed are estimated to be three times historical rates (Table 44). The increased sediment production is attributed entirely to road surface erosion processes. The sediment produced from this source is almost entirely fine-grained meaning that the delivery of fine-grained sediment to the Lake Ozette tributary channel network has at least tripled since the onset of forest harvest. Due to the scope of this investigation the field inventory to support sediment production estimates was not exhaustive. There is some uncertainty, therefore, with respect to the precision of sediment production estimates from each upland source evaluated. All assumptions that were made, however, were based on reported conditions for similar watersheds within scientific journals and reports, and there is a high level of certainty around the conclusion that fine sediment production has increased many times over historical levels.

Table 44. Summary of sediment production rates in the Ozette watershed estimated for historical and current conditions.

	Historical Sediment Production Rates		Current Sediment Production Rates	
Watershed or Tributary Subbasin	Upland Sediment Production Rate (tons/year)	Subbasin Unit Production Rate (tons/km^2/year)	Upland Sediment Production Rate (tons/year)	Subbasin Unit Production Rate (tons/km^2/year)
Ozette River	160	10	430	40
Coal Creek	370	30	1,280	100
Umbrella Creek	890	30	3,500	120
Big River	2,100	40	6,410	110
Crooked Creek	1,050	30	3,450	110
Siwash Creek	300	40	1,120	140
South Creek	400	50	1,510	170
West-shore tributaries	370	20	590	30
Additional east-shore tributaries	450	20	1,930	100
Ozette River watershed	530	20	1,710	70
Lake Ozette watershed	5,560	30	18,540	100
Ozette watershed	6,090	30	20,250	100

While it is clear that forest harvesting activities have increased the rate of sediment production in the Ozette watershed, the timing of peak upland watershed sediment production remains uncertain. Although the forest road network has expanded considerably over the last half-century, it is believed that the unit rate of sediment production from forest roads and harvesting activities was much greater during earlier periods of forest harvest than at the present time. It is probable, therefore, that road surface sediment production experienced a maximum rate at some point between the onset of commercial forestry practices and the present time, when the forest road network was expanding rapidly throughout the Ozette watershed, and yet prior to significant improvements in road management and sediment reduction practices. The current rate of upland sediment production, even as it is estimated to be three times the historical rate, may therefore be reduced from maximum rates that have occurred since the onset of forest harvest.

In addition to increased sediment production from changes in land use, channel incision resulting from logjam removal generated considerable sediment within the tributary channel network, likely delivering significant amounts of sediment to the lake. Logjam removal was documented in both the Big and Ozette Rivers in 1952, although logjam removal may have occurred as much as a half-century earlier. The removal of logjams in Big River contributed directly to channel incision between RK 1.5 and RK 9. In the Ozette River, the removal of logjams has been shown to have caused a lowering of lake levels and channel incision observed in many parts of the lower tributary channel network is attributed to an adjustment in base level associated with this lowering. The change in lake levels may also have resulted in the loss of thousands of potential sockeye spawning sites.

Estimated sediment production rates from channel incision and enlargement range between 8 and 54 percent of the total subbasin sediment production resulting from both channel incision and upland sources (Table 45). Sediment production rates as presented are average annual rates, as production typically varies significantly from year to year. In addition, sediment production from channel incision resulting from logjam removal may have peaked shortly following the disturbance, and current production rates directly resulting from incision may be less than the average presented.

Table 45. Summary of sediment production rates including channel enlargement in the Ozette watershed under historical and current conditions.

	Historical Sediment Production Rates			Current Sediment Production Rates		
Watershed or Tributary Subbasin	Upland Sediment Production Rate (tons/year)	Sediment Production from Channel Enlargement (tons/year)	Total (ton/year)	Upland Sediment Production Rate (tons/year)	Sediment Production from Channel Enlargement (tons/year)	Total (ton/year)
Ozette River	160	–	160	430	–	430
Coal Creek	370	–	370	1,280	850	2,130
Umbrella Creek	890	–	890	3,500	770	4,270
Big River	2,100	–	2,100	6,410	7,650	14,060
Crooked Creek	1,050	–	1,050	3,400	2,590	6,070
Siwash Creek	30	–	30	1,120	260	1,380
South Creek	400	–	400	1,510	140	1,650
West-shore tributaries	370	–	370	590	–	590
Additional east-shore tributaries	450	–	450	1,930	–	1,930
Ozette River watershed	530	–	530	1,710	850	2,560
Lake Ozette watershed	5,560	–	5,560	18,540	11,410	29,950
Ozette watershed	6,090	–	6,090	20,250	12,260	32,510

The incision that followed logjam removal not only immediately contributed to sediment production but also resulted in significant impacts on channel morphology. These impacts, including decreased floodplain and side-channel connectivity, reduced the potential for sediment storage outside of the main channel and likely increased particle transport rates through the channel network. Sediment transport results in this analysis show moderate increases in bedload transport capacity. However, since the majority of sediment that is produced from the upland part of the watershed is fine grained, the transport of coarse-grained sediment may not be the most illustrative factor for evaluating how morphological changes have affected aquatic habitat. An increased in fine-grained sediment transport, however, is likely the result of the observed decreases in floodplain and side-channel connectivity, and this may in turn have resulted in an increase in delivery of fine-grained sediment to the lake.

Increases in wood loading would increase channel complexity, and provide local grade control and opportunities for sediment storage thereby improving the chances for improved floodplain and side-channel connectivity. In the stream segments surveyed, however, few opportunities for functional woody debris recruitment were observed. In stream segments where evidence of channel incision was limited, sediment storage and grade control were observed to be sustained by relic LWD. Given that the channel segments maintained by relic LWD lack a significant source of functional wood, they are at potential risk of future degradation. There are potentially significant implications arising from these instream wood loading conditions. If the functional lifetime of relic LWD is similar throughout the basin, a major peak in sediment discharge to Lake Ozette is likely to occur when this wood is no longer functional.

Documented water quality conditions in Lake Ozette support results indicating increased upland fine sediment production and observations indicating delivery of these sediments to the lake. Since 1990, there have been at least two accounts, reportedly in 1994 and 1999, of widespread turbidity throughout much of Lake Ozette (Ritchie 2004; Meyer and Brenkman 2001). The extent of turbidity documented in 1994 extended from the mouth of Crooked Creek past the mouths of the Big River and Umbrella Creek, with a decrease in turbidity toward the lake outlet (Meyer and Brenkman 2001). Turbidity measurements taken in Umbrella Creek, the Big River, and Crooked Creek at the time of the fine sediment plume indicated that discharges from the Big River contained the highest concentration of suspended sediment (Meyer and Brenkman 2001). Documented delta growth at Umbrella, Crooked, and South Creeks is another indication of high rates of sediment delivery to the lake.

The fate of sediments within Lake Ozette once they are delivered by tributary channels is not entirely clear. A qualitative evaluation of relative longshore transport rates at different locations along the lakeshore indicates areas of high and low potential for longshore transport. Observations of morphologic lakeshore features are consistent with these results, however, the rate and extent of fine sediment distribution is not well understood. The widespread turbidity observed in 1994 and 1999 indicates that fine sediments delivered from the tributaries evaluated in this report may be suspended and distributed beyond areas immediately adjacent to tributary deltas. How far fine sediments are distributed and the impact that they have on lakeshore sockeye spawning habitats are currently unknown but may be far reaching. If the proportion of fine sediments documented at Allens and Olsens Beaches are a limiting factor for successful sockeye spawning and emergence, then the fine sediment being produced from forest road activities in upland areas of the watershed, and delivered to the lake, would be contributing to the degradation of habitat for sockeye.

5. Restoration Strategies, Potential Resource Management Alternatives, and Recommendations for Future Research

To improve habitat conditions for Lake Ozette sockeye, it is necessary to repair the degraded tributary conditions that have resulted from the removal of logjams in the Ozette and Big Rivers. In addition, the impacts of increased sediment production that has resulted from forest harvesting practices must be moderated. This can be accomplished by means of three strategies:

- Placement of grade control structures composed of large woody debris in tributary reaches to promote sediment storage and habitat enhancement (limiting future degradation as relic wood is lost and until riparian forests mature). High-priority reaches for wood placement include the Big River between RK 3 and RK 13 and downstream response reaches of Coal, Umbrella, and Crooked Creeks.

- Placement of large woody debris in the Ozette River to return water surface elevations in Lake Ozette to their historical levels. This strategy will raise the base level of tributaries and increase the extent of nearshore beach habitat available to sockeye salmon.

- Adherence to forest practices that minimize sediment production and prohibit all forest harvest within channel migration zones.

Improving functional wood loading conditions in tributary reaches would promote sediment storage both in the active channel and on floodplain surfaces. Where tributaries are currently degraded, this would rapidly repair the function of these response, or "capacitor," reaches. In tributaries that are not currently degraded but are being maintained by relic large woody debris, placement of addition large woody debris could sustain functional channel processes while mature riparian forests develop. Once conifer forests throughout the tributary channel migration zones have reached maturity, the natural cycle of large wood recruitment and conifer forest regeneration will be self-sustaining. The placement locations of woody debris within tributary channels should consider the change in lake water surface elevations that will accompany wood placement in the Ozette River so that these placements achieve the maximum benefit possible.

Placement of large woody debris in degraded channels will repair only the pathways of sediment delivery to the lake and the habitat available to salmonids. In order to establish long-term self sustaining functional stream corridors, sediment production must also be reduced. This will require adhering to forest practices that minimize the delivery of fine sediment to Lake Ozette tributary channels and enforcement of existing forest regulations mandated by the Washington Department of Natural Resource, Washington Department of Ecology, and Washington Department of Fish and Wildlife.

Practices that can decrease upland sediment production include implementing best management practices (BMPs) for forest road maintenance and road culvert crossings, rerouting forest roads adjacent to streams, and decommissioning forest roads to reduce the overall density of roads in the watershed.

The restoration of riparian corridors will also result in a reduction in sediment production and recovery of the forested areas that serve as a source of functional woody debris to channel. The restoration of riparian corridors could include reforestation of riparian buffers where land adjacent to channels as been permanently cleared, such as portions of the Big River between RK 10 and RK 16. Further, in riparian areas that are dominated by deciduous trees, under planting of conifers would accelerate the successional process that leads to mature forests which provide functional woody debris for tributary channels.

This report provides a broad characterization of the geomorphic processes within the Ozette watershed and how changes in land use have influenced sediment production, channel characteristics, and salmonid habitat. There is considerable additional research that could improve on estimates made within this report and further elucidate the state of geomorphic processes that influence aquatic habitat. The following list provides recommendations for future research objectives:

- Expand data collection to support a more accurate and complete sediment budget to reduce uncertainty in sediment production estimates.
- Establish and maintain expanded network of channel cross-section locations on tributary channels to monitor and quantify rates of lateral migration and patterns of aggradation and degradation.
- Repeat tributary channel bedload sample study by McHenry et al. (1994) to document temporal trend in bedload sediment conditions.
- Conduct bedload and suspended load transport evaluations from tributaries of Lake Ozette.
- Collect core samples of lake bed sediments to determine the rates of fine sediment delivery under predisturbance and contemporary land use conditions.
- Model lake dynamics, longshore transport, and fine sediment transport through suspension.
- Conduct a flood hazard assessment of lake shoreline conditions under the no-action alternative and the restoration alternatives for the Ozette River.
- Expand data set describing grain-size distribution of sediments at known and potential sockeye spawning locations.

- In a pilot study, remove woody vegetation from portions of the lower shoreline to evaluate if beach gravel is used for spawning.
- Monitor turbidity and suspended sediment concentrations at known and potential sockeye spawning locations.

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