RECLAMATION

Managing Water in the West

Geomorphic Assessment of Hoh River in Washington State

Hoh River Miles 17 to 40: Oxbow Canyon and Mount Tom Creek

U.S. Department of the Interior
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Geomorphic Assessment of the Hoh River, Washington

River Miles 17 to 40 between Oxbow Canyon and Mount Tom Creek

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1.0 INTRODUCTION

The Hoh River is a gravel-bed stream located on the Olympic Peninsula of northwestern Washington State (figure 1). The river flows westward from the base of Mount Olympus to the Pacific Ocean near the town of Forks, Washington. The watershed has a drainage area of nearly 300 square miles at the mouth, a large portion of which is located within the boundaries of Olympic National Park (Park). The river has an average slope of 1.3 percent, falling about 3950 feet in 56 river miles.

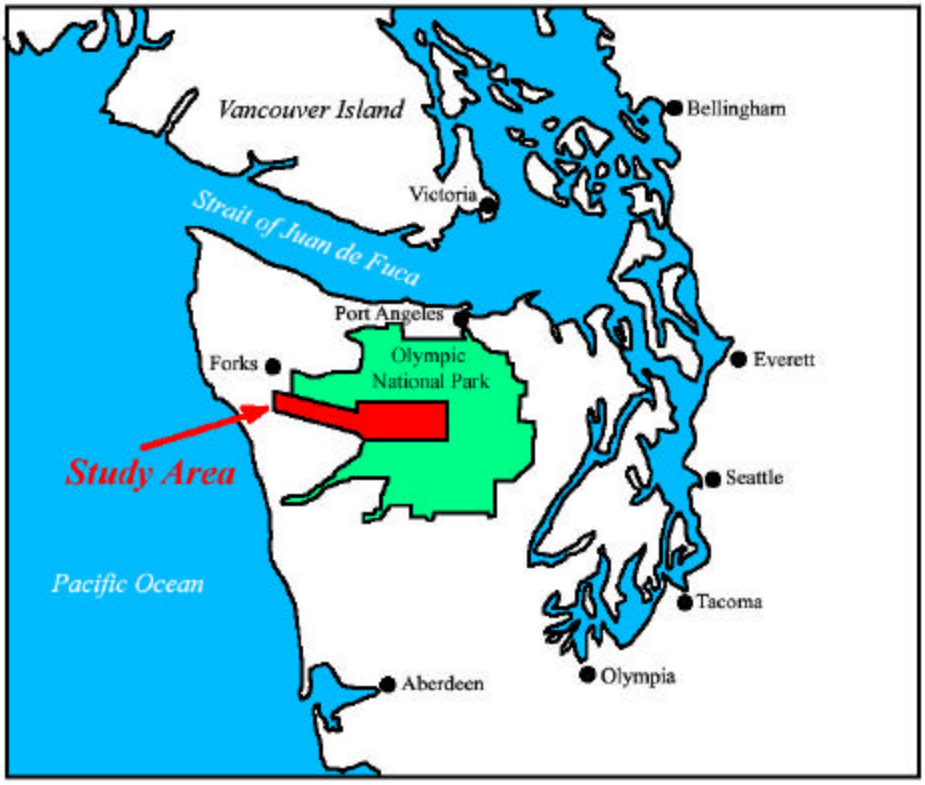


Figure 1. Location of study area.

Management of infrastructure and property along the river has provided a challenge in the past due to the dynamic nature of the river. In October 2003, major flooding washed out 150 feet of the Park Road about 5 miles in from the Park Boundary, private property at several locations, and a section of terrace bank along the County Road near MP 7.7 that had been stable since 1939. Biologists have also questioned the impacts of human activities, particularly bank armoring and logging, on the salmonid and bull trout species (Hatten, 1991; Brenkman and Meyer, 1999). Permitting agencies in Washington State have been increasing requirements to limit or mitigate for these impacts to aquatic habitat. The question has been posed as to whether human activities may have altered and, in some areas, accelerated the natural physical river processes having an adverse affect on fisheries and bank erosion rates along the river corridor.

In 1998, the Hoh Tribe requested a geomorphic study be undertaken by the Bureau of Reclamation (Reclamation) to better understand the existing and historical channel processes on the Hoh River, and how human activities may have impacted those processes. Reclamation does not have any management responsibilities on the Hoh River, but performed this study to provide additional technical information regarding the Hoh River. A multi-disciplined team consisting of backgrounds in hydraulic engineering, geology, and geomorphology from Reclamation and woody debris from Herrera Environmental Consultants (Herrera) performed the study. The results of the analysis were presented on June 5 and 6, 2003 (see Appendix B for list of attendees). Suggestions and comments from these presentations have been incorporated into this document as much as possible.

1.1 Study Reach

The major focus of this study is the Hoh River between the confluence with Mount Tom Creek (RM 40) and the Oxbow Canyon (RM 17) (figure 2). In order to work with name conventions from previous studies, RM 17 to 31 between the Olympic National Park Boundary and the entrance to the Oxbow Canyon will be referred to in this report as the "Middle Hoh", and RM 31 to 40 between the Olympic National Park boundary upstream to the confluence with Mount Tom Creek will be referred to as the "Upper Hoh or Park". Some data collection was performed in the early stages of this study in the "Lower Hoh" reach which extends from the Oxbow Canyon downstream to the mouth. Other studies have investigated the Lower Hoh. Perkins and TerraLogic GIS (2004) conducted a similar geomorphic analysis for RM 5 to 0 of the Hoh River. A geomorphic analysis for the Washington State Department of Transportation was done between the Highway 101 Bridge (RM 14.5) and Nolan Creek (RM 6.5) (Herrera Environmental Consultants and Northwest Hydraulic Consultants, July 2002).

1.2 Study Objectives and Questions

The objective of the geomorphic analysis is to provide information that can be utilized for making future decisions regarding habitat restoration projects and management of infrastructure and property along the Hoh River. Specifically, resource managers expressed a need for information to help with the development of management options for:

1. The Olympic National Park Road
2. The County Road along the north side of the river
3. The Rainforest Campground in Olympic National Park
4. Private property along both sides of the river outside Olympic National Park
5. Landslides adjacent to the river
6. Fish habitat in the side and the main channel and floodplain
7. Timber harvesting on terraces adjacent to the channel migration zone.

To help resource managers address these issues, this study assesses historical and existing river processes, and how human impacts have influenced those processes and the

potential future risk of erosion and channel changes. By understanding the geomorphic characteristics of the river, better decisions can be made regarding river management and how aquatic habitat goals can be integrated into management options.

Based on the objectives provided by resource managers, the following study questions were developed to guide the data collection and analysis for the Hoh River:

- What are the boundaries of the historical channel migration zone (HCMZ)?
- What is the potential for future erosion (expansion) along the HCMZ boundary?
- Has clearing of vegetation within the HCMZ accelerated natural rates of channel migration? Has this had an adverse impact on aquatic habitat?
- Has timber harvest and development outside of Olympic National Park increased sediment delivery to the river? If so, what are the potential impacts on geomorphic processes?
- For areas along the HCMZ where future erosion is predicted to occur, what are potential management strategies?
- Are there future data collection efforts that could be accomplished that would provide more information to build on hypotheses presented in this study? Over what timeframe would this data collection be useful?

1.3 Main Report Organization

Sections 1 and 2 of the main report introduce the project and the study area. Section 2 includes brief summaries of the characteristics of each study reach and the human activities in the valley. Section 3 discusses the methods of data collection. Section 4 is a summary of the hydrologic analysis, the details of which can be found in a separate report (England, 2003) that is included on the CD in the back pocket. Section 5 discusses our conceptual model of channel processes in the Hoh River valley. Section 6 discusses the definition of the historical channel migration zone (HCMZ) and the methodology used to determine the present (2002) and 1939 HCMZ. Section 7 discusses river processes related to large woody debris. Section 8 summarizes the historical channel changes in each reach since 1939. Section 9 discusses the historical expansion of the HCMZ boundary between 1939 and 2002. Section 10 presents the evaluation of sediment supply and transport in the study reaches. Section 11 summarizes the methodology and results of the assessment of the risk of future expansion of the HCMZ. Section 12 presents our methodology for estimating the position of the future CMZ boundary. Section 13 addresses the management considerations in Olympic National Park, specifically the Hoh Ranger Station area and the Park Road. Section 14 discusses management issues related to the Jefferson County road, specifically near the boundary of Olympic National Park, the road near MP 9.7, the road near MP 6.7, the road between RM 21 and 23, and the road in the Willoughby Creek Reach. Section 15 presents some potential management alternatives in relation to areas impacted by river erosion and debris flow crossings. Section 16 presents a summary and conclusions of our study, and provides a good overview in addition to the summary report. Section 17 provides recommendations for future studies that would build upon work described in this report. Section 18 lists the

references that are cited in our report, and Section 19 is a glossary of terms used in our report.

Ten appendices that are included in the main report provide additional details of our studies and document the mapping of channels and other features in each reach. Appendix A shows the acquired historical aerial photographs that document channel changes over decadal time scales for each reach between 1939 and 2002. Appendix B is a list of attendees and locations of three presentations held in Washington State in June 2003 to present the study results to interested parties. Appendix C shows longitudinal profiles of the channel bottom and water surface elevation from a bathymetric survey conducted by Reclamation in April and May 2000. Appendix D documents the survey control network established using global positioning system (GPS) equipment and tied to Washington State Plane Coordinates. Appendix E discusses the methods and results of time-lapse photography used at three locations where bank erosion was occurring during the winter of 2000 to 2001. Appendix F includes the bank descriptions that were done as part of field studies conducted in August 2002. Appendix G gives the detailed methodology used in the delineation of the HCMZ boundary and in the estimation of the potential risk and rates of lateral erosion of the HCMZ boundary. Appendix H describes the methodology and error approximation that was used in rectifying the historical aerial photographs. Appendix I describes the methodology and results of an assessment of the stability and instability in the unvegetated channel and vegetated areas of the floodplain over time. Appendix J is a series of figures that shows the changes in the active channel since 1939 for five of the study reaches. Appendices K and L provide additional documentation on historical forest conditions in the study area and estimates of terrace bank ages.

Previously completed reports on the hydrology of the Hoh River basin by John England (2003) and on mass wasting areas within Olympic National Park by Ed Lyon (2003) can also be found on this CD. The main conclusions of these two reports have been incorporated into the summary report and main report.

The 1891, 1895, and 1918 cadastral survey maps that are used in this study are available electronically upon request, but are not provided in this report. Herrera concurrently studied the role of woody debris in river processes in the study reaches. This analysis is documented in a separate report that is not included with this report. However, the data and results have been integrated into the summary report and main report where applicable.

Figure 2

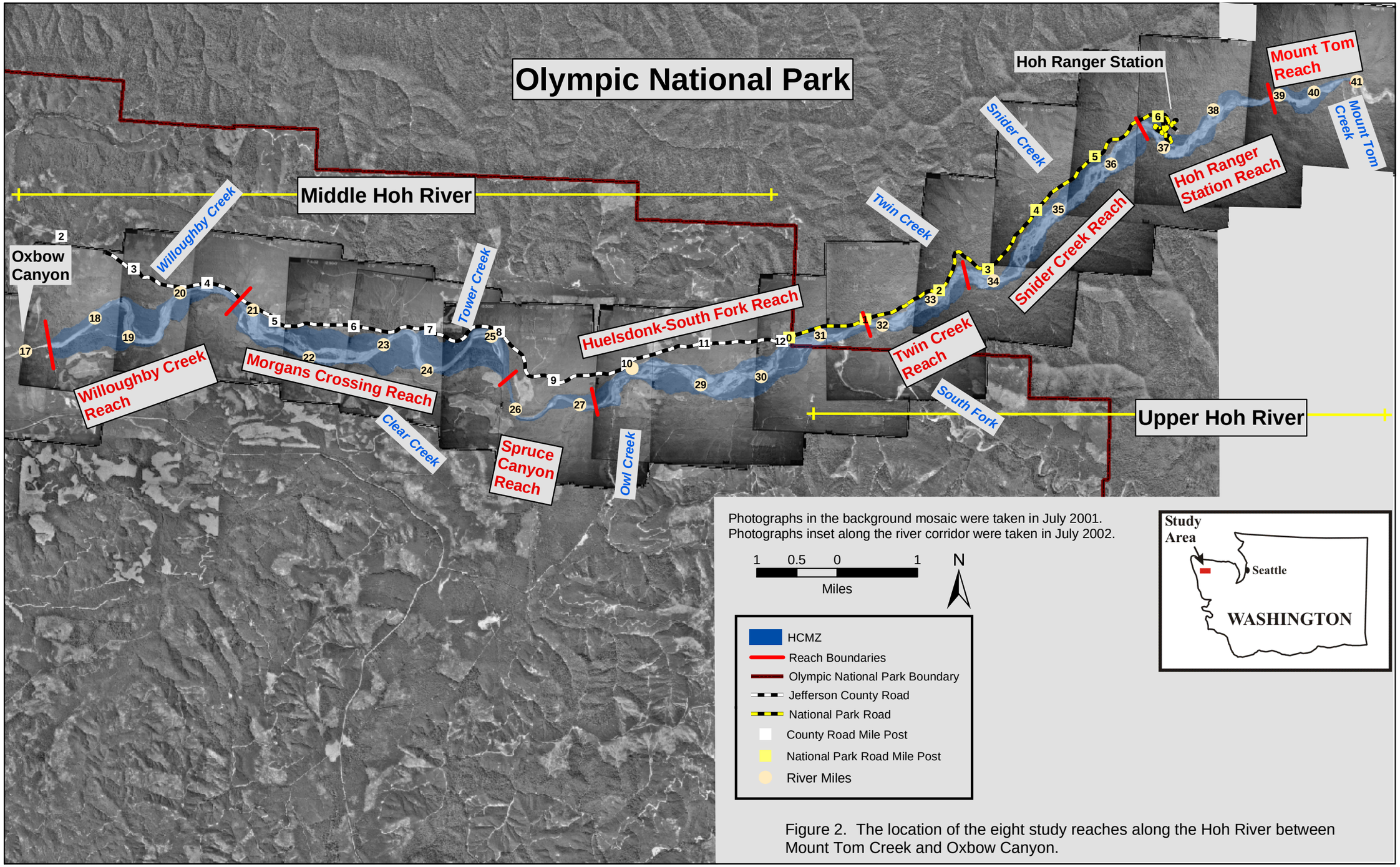


Figure 2. The location of the eight study reaches along the Hoh River between Mount Tom Creek and Oxbow Canyon.

2.0 STUDY AREA

2.1 Physical Setting

Heusser (1974) provides an overview of the physical setting, and Thackery (1996a, 1996b) has completed detailed work on the glacial history of the Hoh River valley. Some excerpts from these references are provided in this section. During the last glaciation, ice advanced down the Hoh River valley at three distinct times. Each advance and subsequent retreat is recorded by extensive moraines and outwash terraces that are preserved between downstream of the Hoh Oxbow and near the mouth of the South Fork (see figure 2). At one time the glaciers may have been as much as 1000 ft thick in the lower Hoh River (Heusser, 1974). The Hoh River has incised into the glacial sediments since the youngest was deposited about 14,000 years ago. The largest glaciers still active today are no greater than 3 miles in length at the head of the Hoh River drainage.

The Hoh River presently heads at the terminus of Hoh Glacier at elevation 4000 feet on the northeast slope of Mount Olympus. For about 8 miles, the river is very steep as it flows through narrow canyons. The most significant tributary inflow in this reach is Glacier Creek, which heads at the terminus of the Blue and White Glaciers. Downstream from this reach, the river passes through a relatively broad "U" shaped valley that ranges in width from approximately 1.2 miles in the upper half to approximately 3.1 miles in the lower half. Several drainages enter the Hoh River along its course in this reach, the two largest being Mount Tom Creek (confluence at RM 40) and the South Fork Hoh River (confluence at RM 31), which have drainage areas of 19.7 (6.6 percent of total) and 53.7 (18.0 percent of total) square miles, respectively. The Hoh River has a large natural sediment load consisting of material ranging in size from predominantly silt (glacially-derived rock flour) to cobbles.

The geology of the Hoh River basin is best described by Tabor and Cady (1978). About 35 percent of the basin is mantled by Quaternary surficial deposits. These deposits are of glacial and non-glacial origin and generally consist of unconsolidated sand, gravel, silt, and clay with an average thickness between 20 to 100 feet, but locally may be up to several hundred feet thick (Tabor and Cady, 1978; Lum, 1986). Underlying the surficial deposits are the rocks of the Western Olympic Lithic Assemblage (Tabor and Cady, 1978). These sedimentary and metamorphic rocks form the bedrock within the basin and are composed predominantly of sandstone, conglomerate, siltstone, argillite, slate and phyllite. The bedrock is exposed along the active channel in Spruce Canyon (RM 25.5 to 27.2) and Oxbow Canyon, and crops out in a few locations between Oxbow Canyon and the mouth of the Hoh River (see figure 2).

The Hoh River Valley has a maritime climate with moderate temperatures and heavy precipitation (Hatten, 1991). At three locations evaluated by England (2003), the annual mean precipitation ranged from 94 to 125 inches. The majority of precipitation falls between November and April, which contributes to the occurrence of winter floods on the Hoh River. The driest period typically occurs in May and June, when snowmelt is a dominant source of runoff for the Hoh River. Within the drainage there is a transition

zone between about elevation 1650 and 2950 feet where precipitation can be in the form of rain and/or snow (Hatten, 1991). When temperatures in this zone are below freezing, runoff into the Hoh River can be heavily augmented during storms.

According to Henderson and others (1989, p.41), most of the Hoh River valley is within the Sitka Spruce Zone, which dominates valleys on the western side of the Olympic Peninsula with at least 100 inches of precipitation. The zone is characterized by Sitka spruce, western hemlock, western red cedar, salmonberry, salal, vine maple, red huckleberry, and Alaska huckleberry (Henderson and others, 1989). The valley at the upstream end of the Upper Hoh reaches and the slopes above the valley in the Middle Hoh reaches are within the Western Hemlock Zone of Henderson and others (1989). Western hemlock or douglas-fir usually dominates in this zone. In older stands, western hemlock and western red cedar may dominate. The highest slopes of both the Upper Hoh and Middle Hoh reaches are within the Silver Fir Zone of Henderson and others (1989). The dominant trees in this zone are silver fir and western hemlock, with lesser amounts of western red cedar, Alaska yellow cedar, mountain hemlock, and Pacific yew. A few relict Douglas-fir may be present in this zone.

2.2 Generation of Study Reaches

Between the confluence with Mount Tom Creek (RM 40) and the entrance to the bedrock-controlled Oxbow Canyon (RM 17), eight geomorphic reaches were defined for this study (see figure 2; table 1). The upstream and downstream boundaries of these reaches are formed by stable controls that have not experienced significant changes in the river-bed elevation or alignment since at least 1891, 1895, or 1918 depending on the earliest documentation of channel position available (see Section 3.3). At Spruce Canyon and Oxbow Canyon the boundaries are formed by bedrock and are expected to remain stable for a long period into the future. However, it is not known why the other boundary areas have remained stable. The longevity of these control areas may be limited relative to the bedrock areas.

The river alignment upstream and downstream of each reach boundary is considered to be independent of each other. Similarly, localized human activities may affect channel position in one reach but would not necessarily impact channel position in another downstream reach. For example, human placed bank protection in one reach could locally influence the channel position in that particular reach. However, the influence on channel position from the bank protection would not extend into the next downstream reach because the reach boundary controls (and limits) the channel position as it enters the next reach. However, human activities that impact sediment supply or wood debris recruitment in an upstream reach could affect downstream reach geomorphology by changing the rate and quantity of sediment and wood transported.

Table 1 lists some of the reach characteristics including reach position within the watershed, channel length, average slope, sinuosity, and average width of the present active channel. Average reach slopes range from to 0.0026 to 0.0059 (14 to 31 ft/mile) and generally decrease in the downstream direction. Lower slopes are maintained all the

way to the mouth of the Hoh River, and continue to decrease slightly to 0.0023 (12 ft/mile) in the downstream most 4 miles of the river. The decrease in slope at Morgan's Crossing Reach may be due to a change in the long-term (>~10,000 years) uplift rate, which is very low at the coast (<~0.05 m/1000 years) and increases into the Olympic Mountains (~0.9 m/1000 years) (Pazzaglia and Brandon, 2001). Pazzagia and Brandon (2001) noticed a change in channel morphology about 25 km upstream from the coast on the Queets and Clearwater River just south of the Hoh River. They attributed this change to the increase in slope caused by the increasing long-term uplift rate in an upstream direction.

The two most downstream reaches (7 and 8) have the lowest slopes of the study area and exhibit characteristics of sinuous channels looking at sinuosity measurements and historical aerial photographs. Montgomery and Buffington (1997) developed a classification system for rivers that considers the presence of wood in the channel. Under this classification system, these channels would be labeled as pool-riffle channels with pools spaced approximately five to seven channel widths apart, except when large amounts of wood are present when they can be spaced closer. Reaches that are more sinuous tend to have a single low flow main channel and can also have side and overflow channels. Water can be conveyed into these side channels from a surface water connection with the main channel, from groundwater flow, and from inflow from tributaries.

The reaches in Olympic National Park tend to have a more complex channel pattern with multiple low-flow channels separated by gravel bars and woody debris. Reaches in Olympic National Park do not fit into typical categories of channel form of sinuous, braided or anastomising. Abundant amounts of woody debris that span low-flow channels can be found in these reaches and create roughness and small backwater pools upstream of the debris. Following the Montgomery and Buffington (1997) classification system, the reaches in the Park would be classified as forced pool-riffle morphology because woody debris can cause local scour, flow divergence, and sediment impoundment (see table 1). The forced pool-riffle morphology can exhibit the same characteristics as pool-riffle morphology, but generally have steeper slopes or lower sediment supply. Smaller low-flow channels within the larger active channel do exhibit characteristics of sinuosity in these upper reaches. However, the active channel, which encompasses the low-flow channels, can be characterized as fairly straight. Based on the size of the drainage areas, it is predicted that the two-year flood in the Middle Hoh reaches is approximately twice that of the Park reaches. Reach 5 is located just downstream of the boundary of Olympic National Park and the confluence with the South Fork of the Hoh River. This reach appears to be a transition reach where the channel adjusts to the additional flow and sediment contributed by the South Fork Hoh River. Reach 6 is a bedrock-controlled reach that has similar geomorphic characteristics as those of the downstream Oxbow Canyon reach. The implication of channel form on the stability of the HCMZ will be discussed later in the report.

Table 1. Reach descriptions for study area (RM 40 to RM 17)

Reach Number and Name		River Mileage		Total Length (river miles) [1]	Average Channel Slope[2]	Estimated 2-Year Flood[6]	2002 Sinuosity Active Channel	% Pools along Length of Low-flow Channel[3]	Average Active Channel Width (ft)[5]
1	Mount Tom	40.0	38.9	1.14	0.0059	11,000	1.0	No data	380
2	Hoh Ranger Station	38.9	36.6	2.29	0.0057	11,900	1.0	No data	490
3	Snider Creek (ONP Road Miles 3.0 to 6.0)	36.6	33.7	2.91	0.0055	13,100	1.1	No data	500
4	Twin Creek (ONP Road Miles 1.0 to 3.0)	33.7	31.6	2.10	0.0045	13,700	1.0	No data	510
5	Huelsdonk-South Fork (County Road Miles 9.5 to 12.0 & ONP Road Miles 0.0 to 1.0)	31. 6	27.2	4.38	0.0036[4]	20,900	1.2[4]	27	470
6	Spruce Canyon (County Road Miles 8.5 to 9.5)	27.2	25.5	1.70	0.0037	21,800	1.0	14	240
7	Morgan's Crossing (County Road Miles 4.5 to 8.5)	25.5	20.8	4.71	0.0028	22,900	1.2	24	350
8	Willoughby Creek Reach (County Road Miles 2.0 to 4.5)	20.8	17.3	3.48	0.0026	23,900	1.3	39	400

[1]Computed from 2002 aerial photography.
[2]For Reaches 3 to 8, slope equals drop in elevation between reach boundaries (2000 channel survey) divided by 2002 active channel length (2000 aerial photographs to match survey not available). Reaches 1 and 2 are fairly stable and the slope is believed to be constant over time. Since 2000 survey data was not available, elevation change was computed from USGS Quad Map contours developed from 1987 aerial photography.
[3]Available from 2000 channel bottom and water surface survey data. Computed as percent of total channel length categorized as pool within each reach.
[4]Does not include small section of Reach 5 just upstream of confluence with South Fork Hoh River.
[5]Average active channel width computing by taking average of several measurements made in GIS on 2002 aerial photographs.
[6]Based on regression equation developed by USGS that relates drainage basin size and discharge (not based on actual gage records). Limitations of these estimates are discussed in Section 4.1 of this report.

2.3 Reach Summaries

The following reaches will be referred to throughout the report by either their name or number. Numbering starts at the upstream most reach, which is labeled Reach 1, and progresses in downstream order to Reach 8 (see figure 2). The term historical channel migration zone (HCMZ) is referred to in the following sections. In general, the HCMZ represents the area occupied by the active channel and active floodplain, that can be documented from historical aerial photographs ranging between 1939 and 2002 and maps of channel position from 1891, 1895, or 1918 depending on the reach (see Section 3.3). This represents a time period from 2002, the most recent aerial photography used, of 84 to 111 years. The HCMZ is the area where the majority of coarse sediment is mobilized and transported during floods. A more detailed explanation of the HCMZ is provided in Section 6. Aerial photographs from 2002 of each reach with the HCMZ boundary are presented in Attachment 2 of the summary report, and for all historical aerial photographs in Appendix A of this report.

2.3.1 Mount Tom Reach (Reach 1)

The Hoh River in the Mount Tom Reach flows in a narrow, steep-walled valley. The historical channel migration zone (HCMZ) takes up nearly the entire valley floor. The steep valley walls are defined by rock, talus, and steep alluvial-fan deposits. The alluvial fan deposits contain gravelly sediment (pebbles, cobbles, and boulders) forming the HCMZ boundary, and the channel position has not changed since at least 1939. The only man-made feature in the reach is the Rain Forest Trail, which traverses steep alluvial-fan deposits and intervening slopes along the right side of the valley outside of the HCMZ. The straight active channel consists of a single low-flow channel, one side channel that has carried water persistently since 1939, and only a few small gravel bars. The position of the active channel at the upstream end of the reach is controlled by a large alluvial fan deposited by Mount Tom Creek. This relatively large tributary, which extends upstream to the glaciated headwaters of the drainage basin, enters the Hoh River from the south so that its alluvial fan deflects the Hoh River to the north side of the valley.

2.3.2. Hoh Ranger Station Reach (Reach 2)

The valley and HCMZ widen in the Hoh Ranger Station Reach; average active channel widths increase from 380 to 490 feet (table 1). The upstream portion of the HCMZ is bounded by alluvial-fan deposits, and the downstream portion is bounded by alluvial terraces. The active channel width is nearly equivalent to the width of the HCMZ, and is composed of multiple low-flow channels. A large amount of wood is present in the active channel in this reach. In the lower portion of the reach, the Olympic National Park Ranger Station and Rainforest Campground have been constructed on the right bank, both within and outside of the HCMZ (figure 3). Various human activities have been conducted in the past to maintain the campground. Several areas of river bank within the HCMZ have been riprapped to prevent further erosion and loss of the campground. Although the exact details of construction work are not known, it has also been noted by Park Service personnel that several small overflow channels that pass

through the riverward areas of the campground have been filled to prevent flooding of the campground. However, this could not be readily detected from field reconnaissance or historical aerial photography dating back to 1939. The largest modification to the HCMZ is evident in the 1977 aerial photographs, when a historical channel entrance was blocked by a campground road (Loop A) thus effectively constricting the HCMZ. This channel was documented on the original land survey of this section conducted in 1918 and can also be seen as an overflow channel in the 1939 aerial photograph. This narrowing has limited potential channels and may have induced or accelerated erosion that is occurring on the opposite bank of the HCMZ (see figure 40 and Appendix A).

Figure 3. Looking upstream at armored bank and engineered fish passage created at outlet of Taft Creek and a portion of the Rainforest Campground. Armoring and fill operations have cut off historical channel paths in the HCMZ. Photograph taken in August 2002.

2.3.3 Snider Creek Reach (Reach 3)

The 2.9 mile long, straight active channel characterizes the Snider Creek Reach. Snider Creek drainage exists on the right side of the valley about halfway down in the reach. Based on historical analysis of aerial photography, the low-flow channels are dynamic, and the relative amount of flow in each channel changes often. Because of a persistent point on the left HCMZ boundary at the upstream end of the reach, the channels have been directed toward the left side of the HCMZ in the upstream portion of the reach leaving persistent gravel bars on the right side. It is not presently known why this particular area at the upstream end of the reach has been stable, but it could possibly contain bedrock or buried log jams that help resist erosion. The HCMZ boundaries have been nearly stable since at least 1939. The Olympic National Park Road traverses terrace surfaces along the right HCMZ boundary. The Olympic National Park Road does not appear to affect the HCMZ boundary or the positions of channels within the HCMZ, but in a few places it acts as a small levee that may limit a portion of large flood flows accessing portions of the floodplain.

2.3.4 Twin Creek Reach (Reach 4)

Glacial deposits form a ridge about 3.5 km (2.3 mi) long along the right side of the HCMZ at the upstream end of the Twin Creek reach. This ridge consolidates tributary flow into Twin Creek and directs it into the Hoh River at the upstream end of the ridge. The ridge also limits the migration of the HCMZ to the north (right). As a result, the HCMZ boundaries have been stable, and a relatively small amount of lateral erosion has

occurred. The Park Road roughly follows the right HCMZ boundary. At the upstream end of the reach the Park Road may restrict the outward translation of meanders, but where this occurs the HCMZ boundary is so close to the valley side that meander movement would be restricted naturally. Even though future erosion of the HCMZ boundary is expected to be minimal, small amounts of erosion could jeopardize the road in places where it is close to the boundary. Sections of road along glacial deposits are particularly vulnerable to erosion. The Park Road has already been setback to the valley edge in two places near MP 1.5 and 1.7 where river erosion was making travel on the road unsafe (Figures 4 and 5). In October 2003, a 150-foot section of road was washed out by the river and was rebuilt.

Figure 4. Looking downstream at section of Park Road near MP 1.7 in October 2000. Photograph courtesy of Olympic National Park.

Figure 5. Looking at same section of Park Road shown in Figure 4 in May 2001 following setback of road.

2.3.5. Huelsdonk-South Fork Reach (Reach 5)

In the Huelsdonk-South Fork Reach the valley and HCMZ both widen noticeably. The valley and HCMZ both widen noticeably. The valley between bounding rock ridges was filled with glacial and alluvial sediments that were subsequently incised by the Hoh River. Thus, the boundaries of the HCMZ commonly are composed of easily erodible glacial and alluvial deposits. Tributaries in the reaches downstream of the Park often flow across fairly flat terrace surfaces between the valley walls and the Hoh River. The coarse sediment being transported down the tributary channels often gets deposited along the terrace surfaces, and does not all make it to the Hoh River as in the upstream steeper drainages. The largest tributary to the Hoh River, the South Fork, enters on the left near RM 31 at the upstream end of the reach. Contributions of discharge and sediment from the South Fork influence the characteristics of the Hoh River active channel and the HCMZ downstream of this point. Overflow channels are common in this reach and may only receive water through groundwater connections during low flow but convey a portion of flood flows at higher discharges (figure 6). These channels often have woody debris throughout them that help create small backwater pools.

Figure 6. Looking downstream into overflow channel just downstream of confluence with South Fork along left side of HCMZ. Photograph taken in August 2002.

The boundary of Olympic National Park traverses the valley at the upstream end of this reach. Outside of Olympic National Park, Lewis Ranch and Huelsdonk Ranch were homesteaded by the early 1900s, which resulted in clearing of old growth trees on a portion of the terrace surfaces (figure 7). On the left side at the upstream end of the reach (just downstream of confluence with the South Fork), some development occurred which is evident in the 1950s aerial photography.

Figure 7. Huelsdonk Ranch is a historical homestead that is located along the left side of the HCMZ in Reach 5. Photograph taken in August 2002.

Timber harvest has also occurred on almost all of the valley hillslopes in this reach, which has increased mass wasting relative to 1939 conditions (Parks, 1999). The Park Road (MP 0 to MP 1) and the County Road (MP 12 to the start of the Park Road) approximately parallel the right HCMZ boundary at the upstream end of the reach (see figure 2). Downstream only two short sections of the County Road (near MP 10) are near the HCMZ boundary. The Park Road between MP 0 and MP 0.5 is armored within the HCMZ resulting in a constriction of the natural HCMZ boundary (figure 8). The road in this area has been in various locations since 1939 and has had continued problems with bank erosion (see figure 43). By 1960, a portion of the road had been setback onto the valley wall, but a small landslide from the adjacent steep slope removed the road. The upstream portion of the road in this area was rebuilt within the HCMZ, the only available flat area not prone to landslide impacts. The downstream portion of the road in this area forms the boundary of the HCMZ. Further downstream in the reach near County Road

MP 9.7, significant seepage is occurring along a portion of the right HCMZ boundary and slumping has continuously occurred (figure 9).

Figure 8. Looking upstream at right bank of river where the County and Park Roads and a portion of Lewis Ranch have been armored within the HCMZ to protect them from further erosion. Photograph taken in March 2002.

A bridge across the Hoh River is visible on the 1950 and 1960 aerial photographs. Local accounts suggest that the log-stringer bridge was constructed in 1943 and that piers for the bridge were placed within the Hoh River channel. Jefferson County is believed to have removed the bridge in 1965.

Figure 9. Looking at right bank of HCMZ near County Road MP 9.7 where continual slumping of the bank has been a management concern. Photograph taken in May 2001.

2.3.6. Spruce Canyon Reach (Reach 6)

In most of the Spruce Canyon Reach, the HCMZ is confined by bedrock and HCMZ boundaries have not changed since at least 1939 (figure 10). The HCMZ is composed of a single active channel and a few small gravel bars. The high elevation surfaces at the top of the canyon walls (adjacent to the HCMZ) have been logged. The County Road is located well back from the HCMZ boundary throughout most of the reach.

Figure 10. Looking downstream in Spruce Canyon at exposed bedrock. Photograph taken in August 2002.

2.3.7. Morgan's Crossing Reach (Reach 7)

The upstream boundary of the Morgan's Crossing Reach is formed by the mouth of Spruce Canyon. Flow entering into this reach is directed north to the right side of the valley as a result of the orientation of Spruce Canyon. This configuration affects the position of the downstream active channel in this reach. In 1939 this reach had a wide, straight active channel. Since 1950, the upstream half of the reach has formed a significantly narrower active channel and a fairly sinuous pattern. The downstream half of the reach has remained fairly straight against a high glacial bank on the left side of the HCMZ in recent years. The most significant side channel in this reach is located along the left side of the HCMZ and is known as Clear Creek side channel. This side channel has a large log jam at its entrance that limits the amount of surface flow and sediment that can enter from the Hoh River, but the side channel also receives flow from tributaries.

The County Road parallels the right HCMZ boundary in several places in this reach. The downstream half of the meander bend (in the upstream portion of the reach) is pinned along the County Road near MP 6.7 by rock armor that has been placed to protect the road (figure 11). Erosion is currently occurring at the upstream end of the bank at County Road MP 6.7 and at MP 7.7 slightly upstream. A log jam was placed along the outside of the meander bend slightly upstream of MP 6.7 and has remained stable. The purpose was to mitigate for the bank armoring by introducing additional wood to the aquatic habitat area, and to help to deflect flow away from the bank and limit additional erosion. Three additional engineered log jams were placed between this log jam and the upstream end of the armored section at MP 6.7, but unfortunately were partially eroded in a large flood in October 2003. Downstream of MP 6.7 on the opposite left side, a high glacial bank has glacial-lacustrine deposits that repeatedly slump into the Hoh River (figure 12).

Logging has occurred on the hillslopes and terraces on both sides of the valley that bind the HCMZ. Clearing for development is nearly continuous along the right HCMZ boundary in the downstream half of the reach. Some of the area was cleared as early as 1939.

Figure 11. Looking downstream at County Road MP6.7 where armoring has been placed to prevent further erosion. A log jam constructed by the County is visible on the right side of the photograph. Photograph taken in August 2002.

Figure 12. Looking upstream and across at high glacial bank located in the downstream half of Reach 7 along the left side of the river. Photograph taken in August 2002.

2.3.8. Willoughby Creek Reach (Reach 8)

The valley remains wide in Reach 8. Two terraces at the upstream end of the reach have remained stable since at least 1939, and likely since at least 1891 based on the old survey maps. The right side terrace is located between RM 20 and RM 21 where the HCMZ boundary coincides with the valley wall; the other terrace is on the left side near RM 19.5 just upstream of a long section bounded by unstable glacial-lacustrine deposits. In addition, the downstream end of the HCMZ is fixed (static) where the Hoh River enters Oxbow Canyon, a narrow bedrock canyon section.

Elk Creek side channel is located on the left side of the present Hoh River main channel (figure 13). Elk Creek side channel has a surface water connection with the main channel and also receives additional flow from Elk Creek tributary to the left of the river. Willoughby Creek drainage is also located in Reach 8 along the right side of the river. A homestead was established on the right terrace surface at the downstream end of the reach in the early 1900s. A large portion of the homestead property was eroded by the river by 1960.

Figure 13. Elk Creek Side Channel in Reach 8 has a significant surface water connection with the main channel. Photograph taken in August 2002.

The County Road is near the right HCMZ boundary only at the upstream end of the reach (about MP 3.5 to MP 4.5 and RM 20 to RM 21). The HCMZ boundary coincides very closely to the valley wall along this section, but riprap has been placed along the road for protection. Large areas outside of the HCMZ on both sides of the valley in this reach have been logged.

2.4 Historical Human Activities in the Study Area

It is necessary to characterize historical human activities in order to assess what potential impacts those activities may have had on river processes. In the draft Middle Hoh Watershed Analysis, information is provided regarding the history of white settlers in the Hoh Valley (Wray, 1999). Information from that report along with documentation from the original land survey maps in the valley is summarized below.

Native Americans have been utilizing the Hoh River valley for many centuries, but white settlers have just recently begun settling in the valley in little more than the last century. The Hoh Valley was opened to homesteading by non-Indians in 1862, but documentation of land management history begins in the 1880s (Wray, 1999). In 1891, the Forest Reserve Act established the Olympic Forest Reserve which included the Hoh River Valley, but the enforcement of this was suspended until March 1, 1898, so prospectors could make claims on their homestead or trade the land for other public land in a different area.

In 1891, Cornelius Huelsdonk and his brother John claimed homesteads two miles below the confluence with the South Fork (Wray, 1999). However, between the confluence with Winfield Creek on the west (downstream end of our Reach 8), and the juncture of the South Fork Hoh on the east, settlers had already homesteaded or squatted (Wray, 1999). Wray notes that many homesteaders left early on because it was too difficult to live in this undeveloped area. In a United States Geological Survey (USGS) report prepared from field work in 1899 and 1900, the only road mentioned on the Hoh River at that time is one near the mouth, although trails were documented as going up the Hoh River from the mouth into near Huelsdonk Ranch. The 1918 map documents a trail and a

phone line up into the Hoh Valley along the right HCMZ past the upstream end of the study area. The first roads did not get built in the watershed until the 1930s.

Because of the controversy over allowing timber harvest versus preserving land in the Upper Hoh Watershed, several battles proceeded over management of the land within the Hoh River valley in the late 1800s and early 1900s, and land was continually added and removed from the reserve. Throughout this time period homesteading continued but commercial timber harvest was limited prior to the opening of Highway 101. Wray (1999) documents two hurricanes in 1921 and 1937 that damaged a large portion of the forest timber in the Hoh River valley. Some of this timber was harvested in the lower Hoh, but it was too difficult to access and harvest in the Middle and Upper Hoh areas. During World War I, the Fletcher Brothers harvested selected spruce in the Lower Hoh River that they floated down river for shipment (Wray, 1999). Commercial logging is not evident in the 1939 aerial photographs in the Middle Hoh, but clearing was done along the river banks at homesteads. Commercial logging is visible in the aerial photographs on the Middle Hoh by 1950, and increased dramatically by 1960.

After many years of struggle to save the timber and elk, in 1938 the 634,000-acre Olympic National Park was established. This change resulted in the addition to the Park of the Hoh watershed from Jackson Guard Station (near current Rainforest Campground ranger station) downstream to the Lewis Ranch. No significant homesteading or logging has been documented upstream of the South Fork other than to clear small areas for the Park Road and Rainforest Campground facilities.

In her report, Wray (1999) documents how loss of land has been a continual problem even for the early settlers on the Hoh River. Most settlers built close to the river to be able to access water easily, although some found springs and were able to settle farther back away from the river. Wray notes the following: "One writer stated that the loss of cleared land to the river was a "heartbreaking calamity" (Fletcher 1983:83). Another states that "about the time a settler got a patch cleared for his cabin, garden patch and pasture the river would turn on him to relentlessly eat out the bank and destroy the work of months overnight" (Felt 1985:2). "During the spring of 1896 it rained so much that all the land the homesteaders had cleared that first summer moved on down river to become part of the many sandbars and logjams along the Hoh" (Felt 1985:7). There are a few accounts of the use of fire to manage the dense vegetation of the Hoh. The most significant homesteads and their earliest documentation are as follows:

<u>Reach 8</u>: Homesteads on right side of river surveyed in 1900 (160 acres downstream of Willoughby Creek); much of property eroded between 1939 and 1960 (T27N, R12W, Section 26NE); Wray documents that Snell, Moritz, and Willoughby owned property here that was bought by Schmidt and later sold to a timber corporation

<u>Reach 7</u>: Approximately 140 acre homestead surveyed in 1899 (in vicinity of Hard Rain Café on right side of river; T27N, R11W, Section 29NE, 29NW)

Approximately 155 acre and 128 acre homesteads surveyed in 1904 and 1907, respectively (in vicinity of Minnie Peterson Campground on right side of river; T27N, R11W, Section 30NE)

Reach 5: Huelsdonk Ranch homestead (160 acres on left side of river) surveyed in 1904 and documented as being homesteaded in 1891 (T27N, R11W, Section 36NW)

Approximately 156 acre homestead surveyed in 1904 on right side (downstream of Lewis Ranch near Canyon Creek; T27N, R10W, Section 25)

Lewis Ranch homestead (101 acres on right side of river just downstream of Park boundary) surveyed in 1915; house and root house shown as present on survey map (T27N, R10W, Section 30)

Approximately 61 acre homestead just north of Lewis Ranch surveyed in 1915 (T27N, R10W, Section 30); house, root house and barn shown on survey map

Crippen homestead on left side of river just downstream of confluence with South Fork surveyed in 1915 (91 acres) (T27N, R10W, Sections 29 and 32); house and barn noted on survey map

Homestead areas on left side of river surveyed in 1915 (66 acres in Section 31 and 36 upstream of Huelsdonk Ranch) and in 1928 (52 acres in Sections 31 and 30 across from Lewis Ranch) (T27N, R10W)

Two bridges were first observed in the 1950 aerial photography. The first bridge was located across from Huelsdonk and was built in 1943 and removed in 1965. The second bridge was located just upstream of Willoughby Creek Campground. It is not known when this bridge was built or removed, but it was not present in the 1939 or 1960 aerial photography. Several dirt roads within the HCMZ are also present by 1950 indicating that some clearing of vegetation within the HCMZ had started by at least this time period. Most roads within the HCMZ were likely used for recreational purposes to access the river. The Rainforest Campground and Olympic National Park campground facilities are not visible in the 1939 aerial photography, but have begun to be developed by the 1950 aerial photography. A road that leads to near where the campground is now located is visible in the 1939 aerial photography.

3.0 DATA COLLECTION IN STUDY REACH

3.1 Helicopter Reconnaissance

A helicopter reconnaissance flight on October 5, 2000 was taken to film the Hoh River from the mouth to the terminus of the Hoh Glacier. The video provides a tool for evaluating the relative characteristics of the Hoh River channel, particularly in the upper watershed where the river is not easily accessible. The video was also used to help evaluate the extent of the active channel and floodplain along with oblique views that helped characterize the HCMZ boundary. Some excerpts from the video for the Hoh River and the South Fork of the Hoh River are provided in Attachment 1 of the summary report.

3.2 Survey Data

The objective of collecting channel survey data was to document the position of the low-flow channel, characterize the amount of pool habitat, and determine the slope of the river in the study area. This data will also serve as a baseline set of channel profile data for the Hoh River. Future data sets could be collected and used to determine the relative change in channel bed over time.

Survey data of the channel bottom, water surface, and exposed, unvegetated gravel bars were collected during April 27 to May 3, 2000, using global positioning system (GPS) survey equipment combined with a depth sounder (transducer) on a cataraft. The average river flow during the survey was 2,415 ft^3/s, and nearly 9000 data points were collected from the Olympic National Park boundary (RM 31) to the mouth of the Hoh River. Profiles of the channel bottom and average water surface elevation during the survey are contained in Appendix C. A reconnaissance trip by kayak was done upstream of RM 31 and it was determined that it was not feasible to survey this area by cataraft. Several portages would be required due to large amounts of woody debris in the channel, and the large amount of vegetation within the active channel made using GPS equipment difficult. Some total station survey measurements were made to determine topography of river banks, the Park Road, and the river water surface elevation in this reach.

The data was collected in Washington North State Plane Coordinates, North American horizontal datum 1983, and North American vertical datum 1988, feet. The survey data were tied to a permanent control network established by a Reclamation survey crew from Ephrata, WA (Appendix D). This control network was based upon three permanent monuments set by the Washington State Department of Transportation. Each of these monuments was set using GPS equipment and has a published horizontal accuracy of +/-2 cm and vertical accuracy of +/-5 cm (ellipsoid height).

3.3 Aerial Photography and Historical Maps

A series of aerial photographs and maps was acquired to document historical change along the river in the study area (Appendix A). Image dates for the historical photos include 1939, 1950-51, 1960, 1971, 1977, 1981, 1994, 1998, 2001, and 2002. All of the aerial photographs were matched to the horizontal scale of an ortho-rectified 2001 photo mosaic created by the Washington Department of Natural Resources (WDNR). This process allows all the photographs to be viewed at the same scale and projection so that river channel characteristics and any changes can be compared directly to each other. All photography and maps were geo-referenced and projected in the same datum as the survey data, Washington North State Plane Coordinates, North American Datum 1983.

The original cadastral survey maps for the Hoh River watershed were acquired from the Mapping Office of the Bureau of Land Management for the states of Washington and Oregon (www.or.blm.gov/lo). These maps show the channel position in 1891 for Reach 8, in 1895 for Reach 7 and the downstream end of Reach 5, and in 1918 for Reaches 1 to 4 and the remaining upstream portion of Reach 5. These maps and associated information also document when homesteads were acquired and likely cleared for development of houses. These maps were created at a scale of 1:31,680, and geo-referenced to the 2001 aerial photographs so they could be viewed at the same scale.

Another historical map created from field work in 1899 and 1900 was available from USGS that documents the channel position at a fairly large scale (exact map scale not known but shows contour interval of 250 feet) and percentages of harvestable timber in each township that covers the Hoh River watershed (Dodwell and Rixon, 1902).

3.4 Time-Lapse Photography

Three cameras were installed on the right side of the Hoh River to take time-lapsed photography during the 2000 to 2001 winter flood season at sites where bank erosion has threatened the County and Park Roads (Appendix E). The goal of the time-lapsed photography was to better understand the process linkages of flooding, bank erosion, and the transport and deposition of large woody debris. The three sites chosen provided a comparison of an eroding bank located in Olympic National Park without any human placed protection (see figure 41 for location), a bank protected by riprap near Taft Creek in Olympic National Park, and a bank protected by a combination of riprap and a constructed log jam at County Road MP 6.7 (see figure 47 for location). The river discharge data was recorded at a USGS gaging station located at the Highway 101 Bridge downstream of Reach 8. When a flood occurred at the USGS gaging station, floods were also occurring at the three upstream sites where photography was being recorded, although at a slightly earlier time than recorded at the gage. Sample photos from each of the camera sites are located in Appendix E of this report. Unfortunately, the winter of 2000 to 2001 was relatively dry compared to other years and only a few small floods occurred. However, a park ranger did continue to take photographs at the upstream most site at Taft Creek during the winter of 2001 to 2002 which helped confirm the size flood

(relative to the USGS gaging station data) that it takes to inundate gravel bars in the active channel and transport woody debris.

3.5 Bank Descriptions

Banks along the HCMZ boundary were described at 17 localities where the bank was actively eroding and was easily accessible. At each description locality, the following characteristics were noted: sediment size, bank height, slope, vegetation on bank and associated surface, root size and depth, evidence for active landslides and active erosion, bank protection, and human activities along the bank and associated surface (Appendix F). Each bank investigated in the field was generally categorized as being glacial or alluvial. The characteristics of the actively eroding banks investigated and their measured rates of past erosion were used to try and estimate the characteristics and possible rates of future erosion on other HCMZ banks that could not be accessed in the field due to permission or budget and time constraints.

3.6 Historical Timber Assessment

One question posed by resource managers is whether historical logging of old growth timber has influenced the rates of HCMZ expansion and quality of aquatic habitat by reducing the recruitment of large woody debris that can help slow the rate of bank erosion and provide complexity to aquatic habitat in the river. The aerial photography presented in this study dating back to 1939 indicate that commercial logging did not start in the Middle Hoh until the 1950s, although homesteading as mentioned in the previous section did result in local clearing of old growth timber. To better document the sizes of old growth timber present in the Hoh River prior to homesteading and commercial logging, a literature review was done to try and gather information about historical timber conditions and logging in the Hoh River basin.

A USGS report was found that documents the timber conditions in the Olympic Forest Reserve, created in 1897, which covered the majority of what is known as the Olympic Peninsula (Dodwell and Rixon, 1902). Although the reserve was slightly reduced in 1900 in parts of Clallam County, it still comprised 3,030 square miles. Field work for the report in the western part of the reserve, which included the Hoh River, was carried out in 1899 and 1900.

Documentation of timbered, burned, cut, and non-timbered areas was accomplished along with the depth of humus and forest litter, the total stand of timber, and characteristics of principal species recognized by the lumber industry at the time (Appendix K). Unfortunately, the report does not distinguish between timber located along the river corridor versus other areas within the township. However, some information about the size of old growth timber can be extracted from this documentation. Average tree diameters of the old growth forest trees ranged from 1.3 to 4.6 feet in diameter and heights ranged from 66 to 200 feet tall. It is also interesting to note that a large portion of the cedar trees were described as being diseased.

The USGS report mentions that if any of the reserve land were to be cleared of timber, the cost of clearing it for agricultural purposes would not be justified, even if the timber were sold. However, the report also documents that "very little timber on the west slope of the Olympic Forest Reserve can not be easily reached, and when the time comes when that quality of timber is marketable there are very few reserves, if any, that can be logged so easily and thoroughly as the western slope of the Olympic Forest Reserve". Interestingly, the report estimates that the amount of timber present in the reserve could supply the entire United States demand at the time for two years.

In 1900, only 16 square miles within the reserve had been logged and 177 square miles (5 percent) had been burned. The burned areas were mainly on the northern border and northeastern part of the reserve. The logged areas were located on the northern border, and at the southern part of the reserve, but no documented logging occurred on the western side of the reserve where the Hoh River is located. The report mentions that more logging had not yet occurred because many of the rivers were too swift and subject to too many freshets. This caused the logs to be hung up on gravel bars or washed into the brush out of the river bed rather than easily floated down the river. However, some rivers in the reserve are identified to be potential logging streams. The Hoh River is identified as a potential logging stream from the mouth upstream to the upstream end of Reach 8. This means that the river could be used to drive logs down it rather than needing to build a logging road or railroad to haul the harvested logs out. There is no further documentation of whether the Hoh River was actually used as a logging stream prior to the development of trucks that could haul the logs out of the valley.

4.0 HYDROLOGIC ANALYSIS

The frequency and magnitude of floods on the Hoh River are one of the major drivers for the rate and extent of channel changes that occur. In addition, bank stabilization and restoration projects should be designed to withstand a certain magnitude flood, for example the 100-year event. A hydrologic analysis was undertaken to develop the peak flood frequency and mean daily flow-duration for the Hoh River at Highway 101 (river mile 14.8) near Forks, Washington (England, 2003). This gaging site is approximately 2.5 river miles downstream from the downstream end of Reach 8, most of which is confined by a bedrock canyon (Oxbow Canyon). The primary basis for the flood frequency and flow duration estimates is USGS peak discharge and mean daily flow records from two gage sites on the Hoh River. During the analysis it was observed that floods in recent decades are larger in magnitude than floods in the earlier part of the 20th century. Budget constraints did not allow for additional detailed hydrologic analysis, but some simple techniques were used to look at whether the increase in flooding could be related to an increase in precipitation in the area.

4.1 Peak Discharge Frequency Estimates

The log-Pearson Type III distribution was fit to annual peak discharge estimates using the Expected Moments Algorithm (England, 2003). Table 2 provides peak flood frequency estimates based on two stream gages on the Hoh River that provide data from 1927 to 2001 (England, 2003). Historical information obtained directly from USGS (1937, 1955) was used to supplement peak discharge estimates and extend record lengths back to 1891 for peak flow frequency estimation. The model estimates listed in table 2 can be used to represent an approximate discharge for the corresponding exceedance probability, but the associated 5 percent to 95 percent confidence limits should also be considered for sensitivity purposes. The most recent floods recorded on the Hoh River at the Highway 101 gage occurred on January 7, 2002, which had an estimated peak of 45,900 ft^3/s, and on October 17, 2003 with an estimated peak of near 60,000 ft^3/s (provisional data and incomplete records for October 2003 flood). These discharges are estimated to have return periods between the 10- and 100-year. The highest peak flow recorded at the U.S. Highway 101 gage prior to the October 2003 flood is 54,500 ft^3/s on November 24, 1990, and the lowest mean-daily flow recorded was 252 ft^3/s on October 23, 1987 (flow record for Highway 101 gage available between 1960 and 1998).

The magnitude of discharge for a given flood increases with distance downstream on the river, particularly where the South Fork comes in because it is the largest tributary to the Hoh River. Because channel changes and erosion rates are largely dependent on discharge, it is of interest to try and estimate what the magnitude of the change is with distance downstream for later comparison discussions between reaches. A USGS regression equation was utilized to determine what the change in discharge would be relative to the Highway 101 gage values for the two-year flood based on a change in drainage basin area in the downstream direction (England, 2003). The drainage basin areas for the Hoh River above the Highway 101 gage were computed using an ESRI proprietary grid format and USGS DEM data. Based on the limits of this equation (looks

at increase in drainage area from point where discharge is measured), it is only applicable from the Highway 101 gage upstream to the point of the confluence with the South Fork. However, because there are no other equations readily available to predict change in flood magnitudes it was used to look at order of magnitude changes in the Park versus the Middle Hoh reaches. The computations indicate that the two-year flood in the Middle Hoh reaches would be roughly twice that of the Park reaches, mostly due to the increase in drainage area from the South Fork River that is contributed at the upstream end of the Middle Hoh reaches (see table 1 for computed values).

Between 1985 and 1989, stream gages were operated by USGS on the South Fork of the Hoh River (at a bridge about two miles upstream from the confluence) and upstream on the Hoh River near the confluence with Mount Tom. During this time period about a dozen floods occurred. Two nearly equivalent annual peak floods recorded on the Hoh River were 48,600 cfs and 49,300 cfs. When directly compared to the South Fork magnitudes for the same day (not accounting for travel time), the magnitude of the floods at the South Fork gage were 25 and 11% of the Hoh River peaks, respectively. The South Fork contributed 36% of a slightly smaller flood on the Hoh River of 41,700 cfs. The mean daily flows were also compared for the two gages and indicated that the South Fork may contribute anywhere between 9 to 49% of the Hoh River mean daily flow.

The variability in contribution of flow to the Middle Hoh in part stems from the variation in flow contributed from the upper portions of the South Fork and Hoh River drainage basins. A comparison was made between the Mount Tom location and the USGS Highway 101 to look at the relative productivity of the drainage basin. Assistance for this analysis was provided by National Park Service personnel. A cursory look at the data indicated that the Hoh River might get up to 2.7 times as much flow per square mile above Mt Tom then between Mt Tom and 101 gage during summer low flows when snow is melting in the upper basin and is the main source of water for the river. However, during winter months when storms occur, the drainage area above Mount Tom contributed about the same flow or down to only half as much per square mile as the reach between Mount Tom and the Highway 101 gage.

Much more gage data than the four years available is needed to better understand the contribution of flow from the Upper Hoh and South Fork basins. However, based on this cursory analysis it appears that flood magnitudes in the Middle Hoh reaches may typically be about two to three times that of values in the Park reaches of the Hoh River.

4.2 Mean-daily Flow Duration

Flow-duration curves can be used to infer median river flow in a typical or hypothetical year (figure 14). A series of flow-duration curves (annual, seasonal, and monthly) were developed using the mean-daily flows for the period of record (England, 2003). The annual median daily flow (50 percent) is 1,810 ft^3/s. The mean daily flow for the period of record is 2,524 ft^3/s. The majority of floods occur between November to March.

Table 2. Peak discharge frequency estimates for the Hoh River at U.S. Highway 101 Bridge (taken from England, 2003)

Annual Exceedance Probability (%)	Return Period (years)	Peak Discharge (ft^3/s)		
		5% Confidence Limit	LP-III Model Estimate	95% Confidence Limit
75	1.33	18,100	19,900	21,700
66.7	1.5	20,200	22,000	23,900
50	2	24,200	26,200	28,400
20	5	33,700	36,400	39,300
10	10	39,500	42,800	46,700
4	25	46,300	50,600	57,200
2	50	50,600	56,200	65,600
1	100	54,400	61,700	74,300
0.5	200	57,700	67,000	83,500

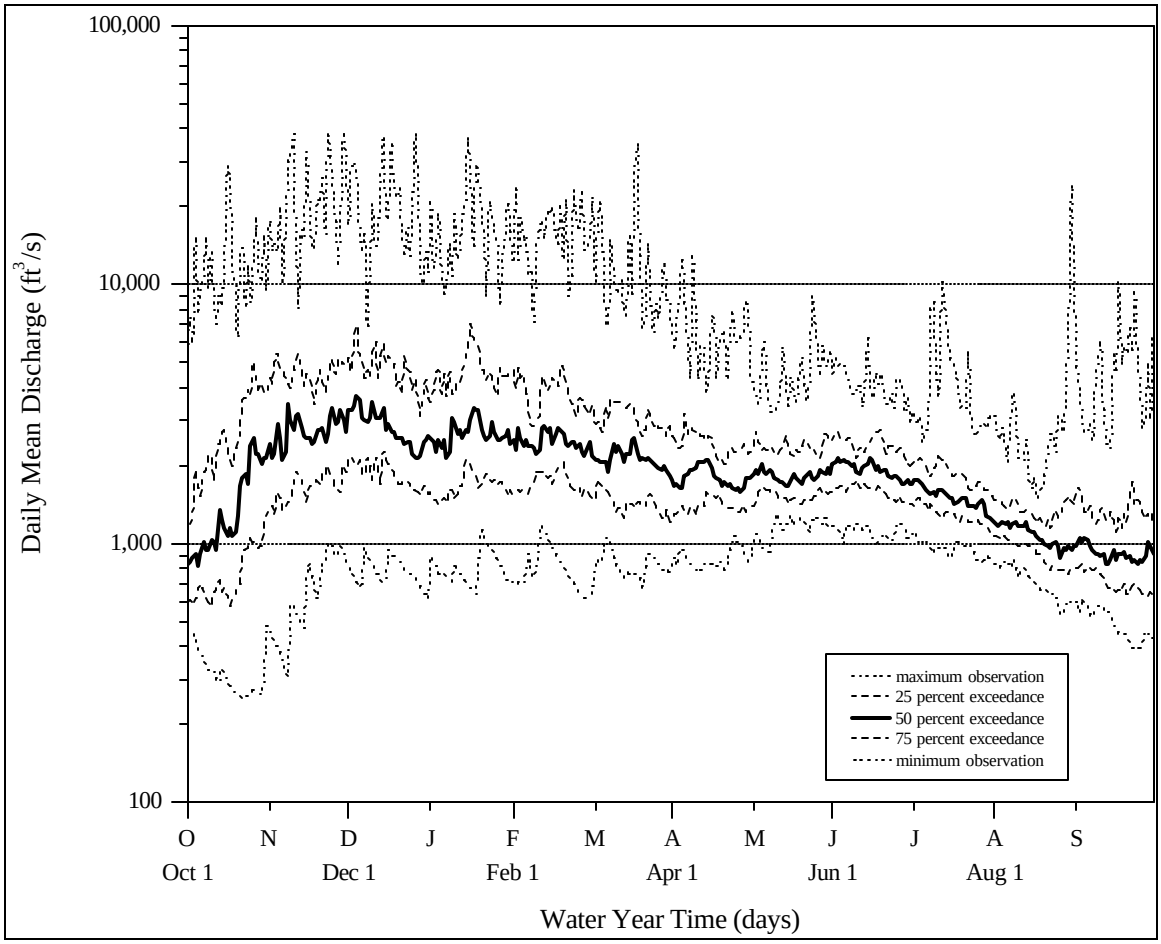


Figure 14. Period of record annual flow duration curve for Hoh River (taken from England, 2003).

4.3 Precipitation

A flood on the Hoh River can occur as a result of rainfall or a combination of rainfall and snowmelt. Edmonds et al (1998) measured the annual precipitation at the Hoh Ranger Station and found a wide range of rainfall from 105 inches in water year 1993 up to 187 in water year 1991. These authors also mention that fog can significantly contribute to precipitation, but no measurements have been made on the Hoh River to date. There is a transient zone in the watershed where the precipitation can fall as rain and/or snow depending on the temperature. Therefore, depending on the temperatures in the basin during a storm event, additional runoff from the transient zone and rain-on-snow in the upper elevations of the basin may also contribute significantly to river discharge. Some simple trend analyses were done with the available precipitation data to determine if there was any noticeable increase in recent decades that would correlate with the observed increase in magnitude of flooding (England, 2003). This initial assessment did not find any statistically significant trends, but more detailed hydrologic trend analysis could be done to further confirm the validity of this initial finding.

4.4 Channel Forming Flows

All high flows can transport sediment, but the question is often asked as to what flow results in the majority of sediment transport and channel changes over a long period of time. One school of thought is that something between the annual peak flood and the 2.5-year flood is the floods that do the majority of channel reworking over long periods of time (Leopold, 1994, Soar and Thorne, 2001). This size of flood is often referred to as the bankfull flood because it fills the channel with water up to the tops of the banks on either side of the active channel. As flows increase above the bankfull discharge, a large portion of the water may spill off into side and overflow channels or onto terraces. Another school of thought is that although these smaller floods do rework the channel, the majority of changes are caused by less frequent larger floods. One way to measure the amount of channel change and verify which floods are doing the most work is to look at the difference in channel position and bank erosion using aerial photography. However, for this study the aerial photography was spaced roughly a decade apart and several floods occurred between each photo set, making it difficult to specifically determine how much channel change and bank erosion occurred from each flood.

As a different approach, time-lapse photography was used at three sites during the winter of 2000 to 2001 to try and identify the size of flood that fills the active channel. These observations helped identify the discharge (as recorded at the downstream USGS gage) that was capable of transporting sediment and woody debris (see Appendix E). During the largest flow recorded (15,900 ft^3/s on January 5, 2001), small secondary channels began conveying water and gravel bars at the three sites began to be inundated. Bank erosion was observed at the unarmored site, but the majority of woody debris located on the gravel bars at each site was not inundated. Following this high flow, the gravel bars in the river looked very similar to conditions prior to the high flow. Subsequent photography was taken at the Taft Creek site in Olympic National Park the following winter. This photography covered a time period when a flood occurred with a peak

discharge between the 10- and 25-year floods. During this flood, the gravel bars within the active channel and the active floodplain area were completely inundated in this reach. This indicates that it takes a discharge greater than 16,000 ft^3/s at the USGS gage to completely inundate the active channel, probably something on the order of the 1.5- to 2-year flood, and that a 10-year flood completely inundates the active channel and floodplain (HCMZ area).

The annual flood peaks for the period of record are shown in figure 15. Table 3 lists the number of floods that occurred between the available sets of aerial photographs. Between 2 and 6 floods occurred that exceeded the 2-year flood in the time interval between aerial photographs sets. It is interesting to note from table 3 that the annual flood peaks and the frequency of annual flood peaks exceeding the 2-year flood have increased since 1927. It would be expected that on average the 2-year flood has a 50 percent chance of occurring in any given year. Between 1927 and 1971 (44 years), the 2-year flood was exceeded between 18 and 50 percent of the years evaluated, but since 1971 it has been exceeded in greater than 70 percent of the years evaluated. However, the rates at which the HCMZ has expanded (erosion of terrace boundaries) do not consistently follow the trend of increasing flood frequency after 1971 (see section 9). For example, the greatest amount of HCMZ expansion in one area occurred in Reach 8 between 1939 and 1960.

The causes of the increased flood frequency and magnitude are unknown, but potential reasons for an increase in the frequency of floods could be changes in weather patterns. It has been suggested that an increase in cleared areas and roads due to timber harvest in the Middle Hoh has increased the amount of total runoff and the magnitude of peaks flowing into the Hoh River during storms. Edmonds et al (1998) suggest that watersheds with as few as 6 percent of their surfaces covered in roads can have higher peak storm discharges. In a study of West Twin Creek in the Hoh River basin, Edmonds et al (1998) found that monthly throughfall (precipitation reaching forest floor) during wet months (precipitation greater than 10 inches) ranged from between 35 to 89 percent of monthly precipitation totals. This indicates that the amount of forest canopy cover could significantly influence the amount of precipitation that reaches the Hoh River. Timber harvest activities in the study area were visible in the 1939 aerial photographs, but were concentrated along the valley floor rather than on the steep hillslopes of the valley. However, since 1950 large areas of timber harvest on the hillslopes can be seen in the aerial photographs.

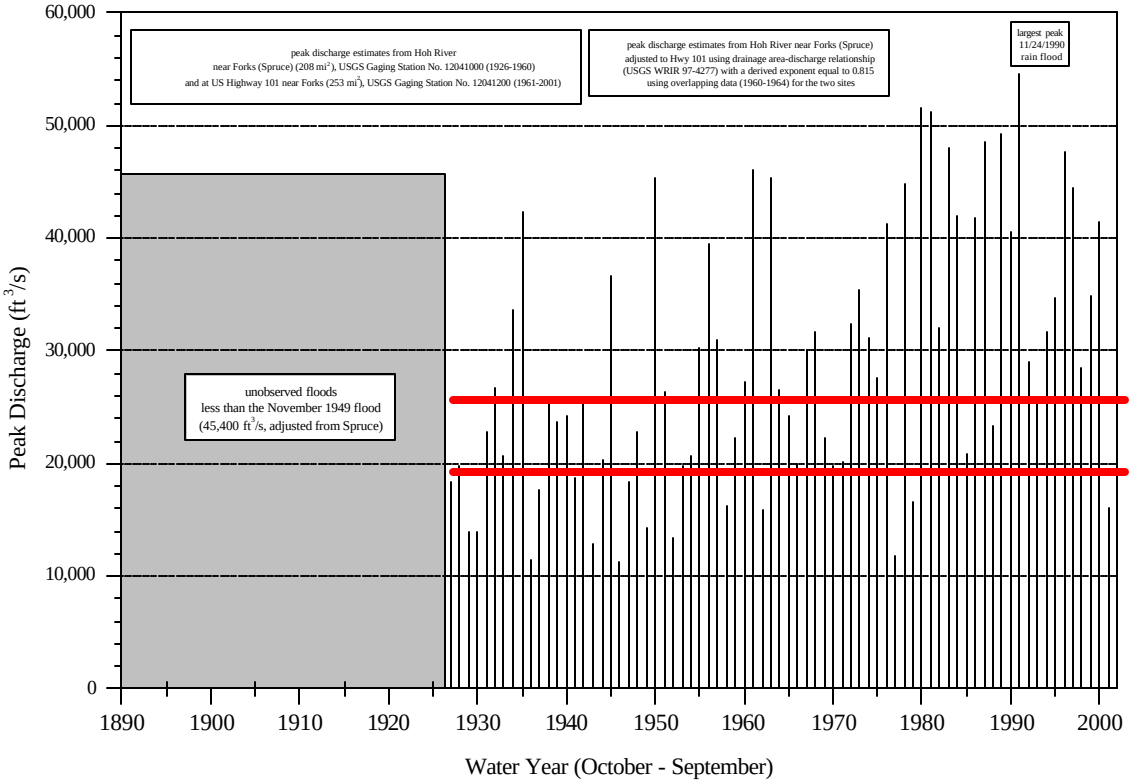


Figure 15. Historical annual peak discharges on the Hoh River (taken from England, 2003). The annual flood discharge and the 2-year flood are shown in red lines for reference.

Table 3. Frequency of floods related to spacing of aerial photography analyzed in study (based on USGS Gage Data)

Time Period	Number of Years Between Photos	Occurrence of Floods				
		> 2-yr	> 10-yr	> 25-yr	% years greater than 2-year flood occurred	Maximum Annual Peak Discharge (ft^3/s)
1927 to 39	12	3			25%	42,300
1939 to 50	11	2	1		18%	45,400
1950 to 60	10	5			50%	39,400
1960 to 71	11	5	2		45%	46,000
1971 to 77	6	5			83%	41,200
1977 to 81	4	3	3	2	75%	51,600
1981 to 87	6	5	1		83%	48,600
1987 to 94	7	5	2	1	71%	54,500
1994 to 2001	7	6	2		86%	47,600

5.0 CONCEPTUAL MODEL OF CHANNEL PROCESSES

A conceptual model of the Hoh River for the study area is described in this section to provide the reader with a generalized description of channel processes that were used as the basis for study analyses discussed in this report.

In a natural river system, the active channel, floodplain, terraces, and adjacent slopes are formed primarily as streamflow alternately erodes, transports, and deposits sediment and woody debris. Because the relative amounts of water, sediment, and woody debris are continually changing, the channels and floodplain are continually adjusting to the variable supplies of these three components. Response to the changes may be different and may occur at different times and in different places along the river depending upon local conditions and the frequency of flooding. Water, sediment, and woody debris may move longitudinally down the valley, but alteration in these components may also result in vertical downcutting or aggradation, or in lateral erosion or deposition. In this way, natural river channels are dynamic and are subject to change over time, especially as bankfull and higher flows pass through the channel and rework sediment and woody debris.

Sediment is supplied to the study reach from several sources. As the glaciers in the headwaters of the Hoh River melt, silt (rock flour) and coarser sediments are transported downstream. Sediment deposits already present in the riverbed and low elevation alluvial bars within the HCMZ are also constantly being reworked and transported downstream during floods. As the channel migrates, it also sometimes erodes the terraces that bound the HCMZ and this contributes additional sediment to the river. Tributaries throughout the watershed also deliver sediments to the Hoh River during storm events. Finally, mass wasting events (landslides, debris flows, etc) can supply additional sediment to the Hoh River.

Smaller sized sediments ranging from clay to fine sand are transported in suspension in the Hoh River (figure 16). These sediment sizes are referred to in this report as fine-sized sediments. They do not affect channel form by inducing channel changes, but can affect the water quality (turbidity) and aquatic habitat in the river. The smallest sediments, including silt and clay sizes, are often referred to as washload because they typically remain in suspension even at low flows. Slightly larger sediments including medium to fine sand will usually remain in suspension during high flows, but as floods recede they may deposit in areas of low velocity, such as overflow and side channels. If substantial, the fine-sized sediments can fill the interstitial spaces between the gravels and cobbles in the channel bed material.

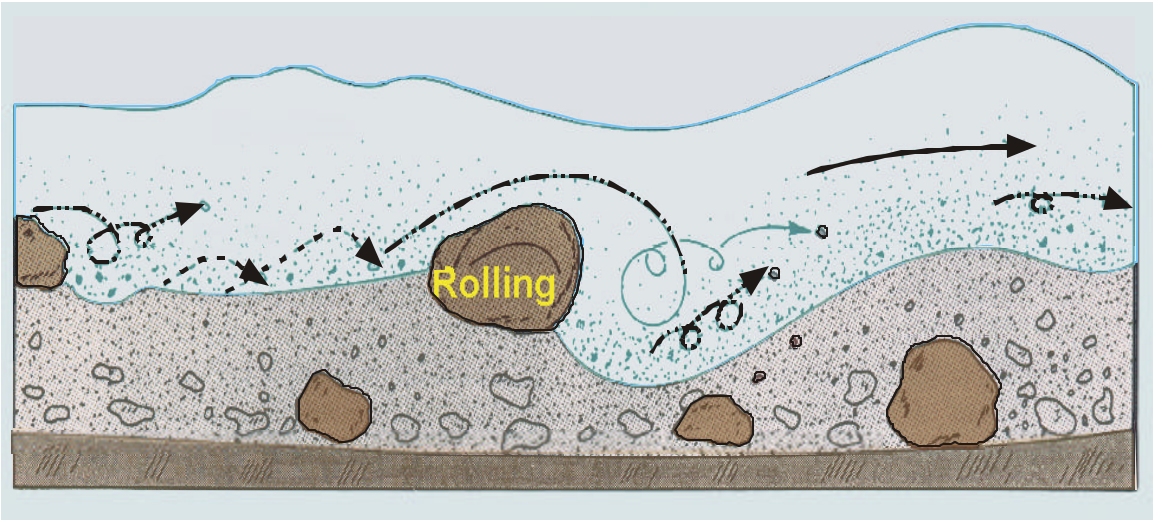


Figure 16. Conceptual figure of bedload & suspended load sediment transport

Larger-sized sediment ranging from coarse sand to cobbles is transported as bedload and is referred to in this report as coarse-sized sediment. If the capacity of the river is not sufficient to transport coarse-sized sediment or if the supply increases thus exceeding the capacity, sediment will deposit on the bed. In contrast to fine-sized sediment which can be transported all the way to the river's mouth, coarse-sized sediment is usually transported short distances along the active channel bed. A small amount of coarse-sized sediment transported into a reach can cause the existing channel path to fill with sediment and result in the channel flowing in a new direction if it is an area of low transport capacity, such as a meander bend ready for a cutoff. In this case, the net deposition and erosion within a reach is not usually significant and there is not an impact in supply to the next downstream reach.

If the hydrologic and geologic controls in the basin do not change, large increases in coarse-sized sediment over a long enough period of time can actually cause the channel form to change from a meandering to straight channel in order to increase the slope and transport capacity to maintain a balance with the increased supply. If the balance can still not be obtained by running straight or if the river channel alignment is already straight, additional sediment deposits will result in a braided river with multiple channels. If the upstream sediment supply rate is less than the sediment transport capacity, then the channel bed and banks can erode and the resulting alignment will tend to follow a more meandering pattern. If coarse particles remain on the riverbed while finer particles erode, then eventually a coarse layer of particles will armor the riverbed and limit channel bed incision. However, a subsequent flood can later erode the armor layer if there is enough sediment transport capacity to move the larger sized particles.

When straight, the channel may have the potential to undercut and erode banks on either side of the river, and will often deposit sediment during high flows in the form of mid-channel or longitudinal bars that run parallel with the river channel. When meandering, the river will typically erode the outside bank of the meander bend while maintaining enough channel width to convey high flows by depositing sediment along the inside of

the bend (point bar). This continual process of erosion along the outside bank of a meander bend and deposition along the inside bank allows the river channel to migrate laterally across the valley and build and rework the floodplain.

The deposit of woody debris on gravel bars and subsequent formation of log jams also play an integral role in the occurrence of channel changes by creating multiple channel paths and either causing or mediating meander cutoffs or avulsions (Collins and Montgomery, 2002). Large trees along the banks and deposited woody debris within the channel can increase the roughness, which in turn increases river depth upstream of the wood, decreases velocities, and sediment transport rates. Large trees and woody debris can slow or limit lateral bank erosion and channel migration along alluvial banks within the HCMZ and along terrace banks on the boundary. When large amounts of woody debris increase the river depth within a reach, it can reduce the hydraulic slope and the sediment transport capacity (increasing sediment storage) of the reach.

In most wide valleys with a flat floor, one can expect that the river has been in many positions across the valley floor at some point in the past. Terraces within the valley are remnants of old floodplains and consist of old channel deposits of gravel and sand. A change in the relative proportion of water and sediment resulted in incision into these channel deposits, which left them exposed above the new active channel and floodplain (figure 17). The old channel bed and floodplain, now a terrace, may still receive some water during large floods and the old channel deposits are often covered by fine sand and silt. If incision continues, the terrace may eventually be high enough above the level of the channel so that flood flows no longer reach its surface. In this way, the terrace surfaces slowly stabilize, vegetation establishes, and soils begin to form. Progressively higher terraces are often progressively older. Terraces outside of the active channel on the Hoh River are probably at least 100 years old and higher terraces are more likely a few hundred years old (Fonda, 1974; Swanson and Lienkaemper, 1982).

A schematic cross section was developed to help illustrate a typical section of the Hoh River in the study area (figure 17). The terraces are discontinuous throughout the valley, so that the number of terraces shown in this figure does not exist at all localities. Numbers in meters and feet are approximate heights of surfaces above the low-flow channel. Numbers in years are estimates of the minimum age for when a particular surface became a terrace, and was no longer part of the active floodplain. The heights and ages shown are based on the work of Swanson and Lienkaemper (1982) for a section of the South Fork Hoh River, where tree ages were used to estimate terrace age. Although these ages may not be directly applicable to the mainstem Hoh River, the order of magnitude of the terrace ages and relative differences in ages should be comparable, because both drainages have been subject to the same hydrologic processes during similar time periods.

Fonda (1974) estimated minimum ages for the terraces along the Hoh River on the basis of vegetation succession and soil development. Because his estimated ages correlated with tree-ring ages of trees growing on end moraines on Mount Rainier, he concluded that the terraces on the Hoh River were formed by ice advances during the last 600 years.

Although Fonda (1974) used a different approach, he noted terraces at heights similar to those found along the South Fork by Swanson and Lienkaemper (1982). Fonda's (1974) ages for the 2-to-3-m-high terraces are similar to those for terraces of similar heights along the South Fork (Swanson and Lienkaemper, 1982). In addition, Fonda (1974) estimated a minimum age of 500 to 600 years for the 5-m-high terrace along the mainstem Hoh River, and this terrace is likely correlative to the 5-m-high terrace along the South Fork, which Swanson and Lienkaemper (1982) estimated to be markedly older than the oldest (266 years) living trees on the surface. See Appendix L for more data from Swanson and Lienkaemper (1982) study and Fonda (1974) study.

The active channel shown in figure 17 includes the low-flow channels and intervening and adjacent gravel bars inundated by the bankfull discharge. The gravel bars in the active channel are often unvegetated, but may be sparsely covered with small trees, grasses, and shrubs. The higher elevation gravel bars are often covered with deposits of sand from recent high flows. In many areas of the Hoh River, the active channel includes multiple channels that can convey water, but often there is one dominant channel that carries the majority of flow. This main channel may be straight or meandering in planform. The channel alignment and width depend on the rate of river flow and sediment supplied from upstream and local geology and slope. In an alluvial river reach the channel bed and banks are composed of sand, gravel, and cobble-sized sediments and not constrained by bedrock. In these alluvial reaches, the channel width, depth, and longitudinal alignment will tend to adjust over time so that the upstream supply of water and sediment can be conveyed through the reach without an excessive degree of long-term erosion or deposition, a state of dynamic equilibrium. The hydraulic capacity of the river to transport sediment increases primarily with the longitudinal slope of the river, flow velocity, and depth. The longitudinal slope of the river is limited by the valley slope (straight channel), but can be less if the river meanders back and forth across the river valley.

The terraces present in the valley were formed by variations in climate that occurred over time scales of a few hundred to a few thousand years. This variability affects rivers by altering the hydrology and sediment load in response to a changed relationship among vegetation, soil, and primarily precipitation. Ice extended down the Hoh River valley to near the South Fork or the Pacific Ocean at least five times between about 55,000 years ago and about 14,000 year ago (Thackray, 1996a, 1996b). As the ice retreated, water and sediment loads in the Hoh River were likely much larger than today. As the glaciers ceased to melt and the climate changed to a relatively dryer condition, the Hoh River channel incised the floodplain because there was a greater proportion of river flow to the sediment load supplied from the upstream watershed. The incised glacial banks form the valley walls for much of the Middle Hoh reaches.

Terraces also can form when incision is triggered by tectonic uplift. The tectonically active Olympic Peninsula currently has a short-term uplift rate of 1.2 to 3.2 mm/yr, which has been determined from geodetic and tide gauge data (Reilinger and Adams, 1982; Holdahl and others, 1989; Savage and others, 1991; Mitchell and others, 1994). The fastest uplift rates are on the western side of the peninsula along the Cascadia forearc, and

most likely include a component of elastic deformation, assuming the Cascadia subduction thrust is currently locked. Furthermore, geologic evidence suggests that the long-term uplift rates along the west coast of the peninsula are very slow and that the uplift rate increases to its maximum in the center of the Olympic Mountains (Pazzaglia and Brandon, 2001). A comprehensive study on the relationship between tectonic uplift and fluvial erosion along the Clearwater River, located approximately 10 miles south of the Hoh River, was conducted by Pazzaglia and Brandon (2001). These workers concluded that formation of fluvial terraces along the western margin of the Olympic Mountains appears to be driven by the glacial climate cycle and its influence on local climate, sediment supply, and eustasy.

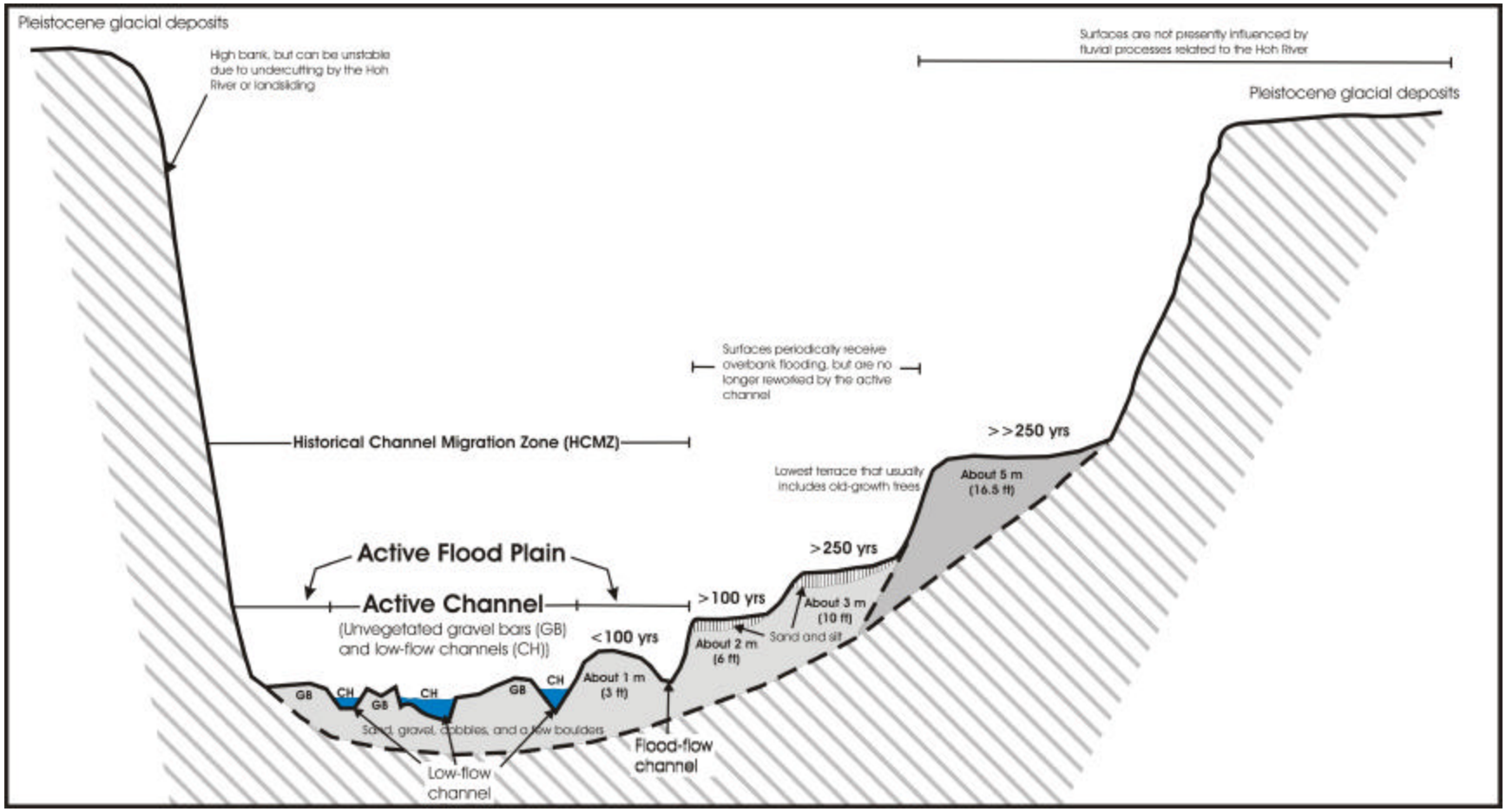


Figure 17. Generalized schematic cross section across the Hoh River valley showing the relationships among active channel, extent of floods, and terraces.

6.0 IDENTIFICATION OF HISTORICAL CHANNEL MIGRATION ZONE

The discussion in this section explains how the historical channel migration zone (HCMZ) was defined for the Hoh River study area. Maps showing the HCMZ boundary for each reach are provided in Attachment 2 of the summary report. Identification of the risk for future expansion of the HCMZ is discussed in Section 11.

6.1 Definition

The HCMZ boundary is defined for this study by the extent of the existing active channel and active floodplain exhibited in historical aerial photography and maps extending back to 1891. The active channel represents the low flow river channel and gravel bars that are frequently reworked during floods and over which bedload is transported. The active channel is free of mature woody vegetation. The active floodplain was built by lateral migration of the active channel. It includes side channels, secondary or flood-flow channels, and low-elevation vegetated surfaces that are frequently inundated by floods exceeding the 1.5- year flood (22,000 ft^3/s). The upper limit of floods that completely inundate the active floodplain varies by reach, but may be something on the order of the 10-year flood (42,800 ft^3/s). Photographs taken by National Park Service personnel at Taft Creek near the Rainforest Campground during the January 7, 2002 flood (45,900 ft^3/s) show the active channel and floodplain within the HCMZ being completed inundated. The area outside of the HCMZ boundary can still be inundated, but it takes larger floods to overtop the terrace banks that form the HCMZ boundary, such as the 25-year flood (50,600 ft^3/s) and greater.

The area within the HCMZ is dynamic and continually changing form during floods. It represents the area where the majority of coarse sediment (sand, gravel, and cobbles) and woody debris has been transported. This represents a period between 84 to 111 years of documentation when using the 2002 aerial photography as the most recent channel position documentation. It has been documented that terraces along the HCMZ boundary in the Hoh River valley range in age between a few hundred to several hundreds of years (Fonda, 1974; Swanson and Lienkaemper, 1982). This would indicate that the HCMZ likely encompasses a longer time interval than 84 to 111 years of active channel and floodplain, but the exact time interval is unknown.

The HCMZ can be bounded by terraces composed of glacial material (till, outwash, or lacustrine sediments) or alluvium, alluvial fans, bedrock, or engineered bank protection (riprap, engineered log jam, bridge abutment, levees, road embankment). In some locations, future channel changes are expected to expand the HCMZ boundary where the boundary consists of erodible material. The differences between the 1939 and more recent HCMZ boundaries represent areas of terrace bank erosion along the boundary since 1939.

6.2 Methodology for Determination of Historical Channel Migration Zone

For the Hoh River, the HCMZ was determined by examining channel position and geologic evidence observed during field trips, aerial photography, and maps. This method is described below:

- Analysis of historical aerial photographs and maps to document historical main channel paths and active floodplain areas. Historical channel paths show areas where the active channels have been in the recent past, which helps define the HCMZ. Older channel paths are often still visible in the existing active floodplain as side and overflow channels. In other cases, development or logging activities have disturbed or filled in the older channel paths and floodplain making them undetectable from aerial photography. For the Hoh River, historical aerial photographs ranging from 1939 to 2002 were used, along with historical maps documenting channel position in 1891, 1895, 1918, and 1987.

- Stereo analysis of 1998 aerial photographs to verify the boundary of the HCMZ. These aerial photographs were used to identify terrace boundaries and low surfaces that show topographic evidence of old channels, such as narrow zones of lower or sparse vegetation on an otherwise densely vegetated surface. These low surfaces would be included in the HCMZ even if the historical photo and map analysis revealed no active channels at these locations. On the other hand, high terrace surfaces that appear to be smooth and uncut by channels would be excluded from the HCMZ. Stereo analysis was also used to identify intermediate surfaces between the HCMZ and the valley wall where the surfaces could be seen through the vegetation.

- Field inspections to verify delineated terrace banks and confirm the location of the HCMZ boundary. Terrace banks were identified in the field to verify mapping done from aerial photography and maps. Where the location of the HCMZ boundary was questionable, low surfaces were investigated to determine if they contained evidence of frequent flooding and active channels. Frequent flooding would mean the surface was part of the active floodplain in the HCMZ as opposed to being a higher terrace that forms the HCMZ boundary. Characteristics looked for were overflow paths that were fairly unvegetated, debris backed up against woody vegetation, and fine sediment deposition. As defined for this study, the active floodplain contains lower magnitude floods such as the 1.5- to 10-year annual flood peaks (22,000 to 42,800 ft^3/s). Therefore, it would take a larger magnitude flood, such as the 25- or 100-year flood, to overtop terrace surfaces outside the active floodplain and outside the HCMZ. During January 2002, a 43,300 ft^3/s flood occurred, which is near the 10-year return interval. This flood would be expected to have inundated a significant portion, if not all, of the HCMZ, and evidence of fine sediment deposition and debris on questionable low surfaces was investigated.

6.3 Methodology for Defining the 1939 Historical Channel Migration Zone

It was desired to identify the HCMZ as far back in time as possible to quantify the amount and rate of terrace bank erosion that has occurred. The 1939 aerial photography was the oldest possible date to determine a HCMZ boundary. Unlike the determination of the 2002 historical channel migration zone, which integrates extensive field work and could incorporate field observations, the 1939 HCMZ was estimated solely on the basis of aerial photography and historical maps. An interpretation was made of the 1939 HCMZ based on the distinction between vegetation in the active floodplain (1939 HCMZ) and on terraces that bound the 1939 HCMZ. In general, the vegetation within the 1939 HCMZ is dense, appears of the same age or height, and is often discontinuous because of recently active side channels that have removed vegetation or have kept it from growing. The vegetation on the terraces that bound the HCMZ is less dense and appears irregular, because individual trees are large enough to be visible and the trees are of differing species and heights. The original land survey maps from 1891, 1895, and 1918 document channel position prior to 1939. These maps have been found to be very accurate in many different watersheds studied and were used as a check on the 1939 HCMZ to ensure the older channels did not exceed the 1939 HCMZ boundaries in any areas. In many cases the 1950 aerial photography was also used to check the 1939 HCMZ boundaries because the 1950 aerial photographs were flown at a lower elevation and had a higher level of clarity regarding vegetation and channel paths.

Overall in Olympic National Park, little change between the 1939 and 2002 HCMZ boundaries was observed. In contrast, large amounts of lateral erosion were observed in several areas of the Middle Hoh reaches along the HCMZ boundary between 1939 and 2002. Because field verification could not be accomplished for the 1939 HCMZ, some verification is needed to determine if the differences in the HCMZ boundaries between 1939 and 2002 are real or are an artifact of the methods used to identify the boundaries. Another source of error could be the rectification process that allows the photographs to be viewed at the same scale in a GIS system. An analysis of the error involved in the rectification of the aerial photographs is included in Appendix H. Root mean square (RMS) errors were documented for approximately 20 percent of the transformations. RMS values ranged from 1.5 feet to 200 feet. However, the RMS values for the 1891 to 1918 maps were only 5 feet because these maps provided the original survey lines for sections and townships which make them very applicable to pulling them into GIS at the same scale as other aerial photographs used (Appendix H). The lateral extent of error observed in the Middle Hoh between 1939 and 2002 was often in the range of a few hundred to a thousand feet, where as in Olympic National Park it was typically on the order of tens of feet. Although some error did occur when rectifying the photographs, the amounts of change in the HCMZ since 1939 are still more than the possible error.

To provide additional verification, physical characteristics of the Middle Hoh and Park reaches were investigated to determine if there were plausible explanations for the difference in erosion amounts. These factors will be discussed in more detail later in the report, but are provided here in brief summary. In the Park, alluvial fans limit channel migration because large cobbles and boulders are transported down the drainages to the

edge of the HCMZ boundary and the active channel is unable to erode these large sizes of sediment. Overall, the active channel in the Park is wider, more dynamic, has multiple channels and more large woody debris deposited, and runs straighter relative to the valley than reaches of the Middle Hoh. While channels in the Park can still erode the terrace banks, the lateral extent of erosion tends to be small. Susceptibility to accelerated erosion from human impacts is also limited within Olympic National Park because development and logging in the active floodplain and on terraces that bound the HCMZ have been minimal. However, in the Middle Hoh the valley is wider, there is usually a single, meandering channel that has a tendency to migrate both outward and downstream, the HCMZ boundary has more erodible glacial banks and fewer alluvial fans with large material, and development and logging are common. Additionally, the Middle Hoh has larger flow magnitudes due to the South Fork and woody debris is not as common in the active channel flow path. All of these factors provide plausible explanations to the occurrence of large lateral erosion areas in the Middle Hoh when compared to the Park reaches. Therefore, it is assumed that the discrepancies between the boundaries in 1939 and 2002 are not an artifact of identifying the boundaries or of errors associated with the rectifying of the 1939 aerial photography to the same scale as the 2002 photography.

7.0 ROLE OF WOODY DEBRIS

Woody debris plays a large role in the Hoh River by helping to shape channel processes and by creating important aquatic habitat. In Reaches 1 to 4, there is a greater abundance of large woody debris in the HCMZ (Figures 18 and 19) than in Reaches 5 through 8. The large woody debris in the upstream reaches increases the channel roughness and water depth and generally reduces the river velocity and sediment transport capacity. In some cases, log jams span across the river channel and actually form hydraulic controls that create pools upstream of the log jams and hydraulic drops as flow passes through and over the log jams. The large woody debris also helps to create more complex channels as flow is divided and diverted around log jams and large pieces of woody debris.

Herrera found that currently there is a greater amount of large woody debris within the HCMZ (relative to the active channel area) in the upstream Park reaches than in the Middle Hoh reaches (written communication, 2004). The large woody debris in the Park increases channel roughness and water depth, and generally reduces the river velocity and sediment transport capacity. The large woody debris also helps to create a more complex channel pattern, because flow is divided and diverted around log jams and large pieces of wood.

The large woody debris is believed to have a greater influence on Reaches 1 through 4 because there is a greater source of large trees within Olympic National Park and because river flows and water depth are less in the four reaches upstream from the South Fork confluence. At all 10 sites evaluated by Herrera in the Park reaches, large woody debris eroded by the river was found to form snags and log jams within 50 m of where the large trees had been eroded (written communication, 2004). Downstream from the South Fork confluence, the river flow tends to be greater, so single pieces of woody debris require a larger diameter to remain stable in the active channel compared to upstream reaches. Within the Park and Middle Hoh reaches, there are also areas more and less prone to woody deposition based on local morphology. Herrera found that the Middle Hoh reaches has less roughness and complexity than Reaches 1 through 4 in the Park (written communication, 2004).

The abundant source of large woody debris along the river reaches within the Olympic National Park is available because the Park area has never been logged. A USGS report documented the average diameters of trees in the townships including the Hoh River valley in 1900 prior to logging activities (Dodwell and Rixon, 1902). These diameters ranged between 1.3 and 5.4 feet depending on the species, and the trees were on average 126 to 242 years old. This indicates old growth forests would include at least some large diameter trees that could remain relatively stable along the river reaches within Olympic National Park.

Figures 18 and 19. Examples of large woody debris in Olympic National Park reaches. Photographs taken in August 2002.

If the majority of individual pieces of large woody debris tend to remain stable in the Park near where they were eroded, they would not often be transported to the lower reaches downstream of the South Fork confluence. Therefore, recruitment of large woody debris in the Middle Hoh would largely be from eroding terrace surfaces along the boundaries of the HCMZ. Trees growing within the HCMZ are not likely large enough to remain stable in the river channel over a decadal time scale. In the lower reaches most of the terraces and glacial banks that bind the HCMZ have been logged at least once within the past century. It has also been noted that historically large woody debris was cleared or burned within the river channel, although it is not known to what extent this was done. Both of these factors limit the amount of large wood that may be currently recruited to these reaches downstream from the South Fork confluence.

In the Middle Hoh, where the flow and sediment loads increase, historically large woody debris would have increased the local roughness within the HCMZ and may have impacted the rate of channel migration across the floodplain when present in large enough quantities. Presently, woody debris can be observed in the Middle Hoh along the outside of meander bends, on gravel bars, and at the entrance to side channels. In most instances the wood can be easily transported because it is small in size relative to wood in the channel in the Park reaches, and flows are larger in the Middle Hoh. In a few cases log jams do help limit channel migration. For instance, a log jam is present on the edge of the low-flow channel near County Road MP 6.7 in Reach 5 (figure 20). This log jam creates a small scour pool in the vicinity of the jam that provides aquatic habitat and cover. At the entrance to Clear Creek across from MP 6.7 on the County Road, a log jam is currently limiting the surface water connection into this side channel (figure 21). If the log jam were not present, a substantial amount of river flow would enter directly into this side channel based on the current meander position of the channel. The log jam is significant in size and continues to collect additional wood during floods. However, this jam could eventually be blown out by the river or the river could cut a channel around the jam and flow through the Clear Creek side channel.

Slightly downstream from the Clear Creek side channel entrance, woody debris can also be observed along the edge of an alluvial bank and the left side of the low-flow channel

within the HCMZ (figure 22). This wood provides some roughness within the active channel, which helps dissipate energy and can slow the rate at which the channel may erode the gravel bar and migrate further to the left. However, small woody debris may not have much influence on physical river processes if it is easily transported by the river during floods.

Figure 20. Looking upstream at log jam adjacent to the low-flow channel near County Road MP 9.7 and opposite Huelsdonk Ranch. Photograph taken in August 2002.

Figure 21. Looking downstream at log jam blocking entrance to Clear Creek side channel located slightly upstream of County Road MP6.7 in Reach 7. The log jam currently prevents the low flow river from entering this side channel and limits the amount of water and sediment that can enter the side channel during floods.

Figure 22. View looking upstream at a gravel bar lined with woody debris in Reach 7 just downstream of the entrance to Clear Creek side channel. Woody debris accumulation along alluvial banks within the HCMZ creates roughness and limits the rate at which the channel can erode the gravel bar and migrate in that direction. Photograph taken in August 2002.

8.0 ASSESSMENT OF HISTORICAL CHANNEL CHANGES

To better understand at what rate and where channel changes may occur in the future, it is necessary to evaluate the rates and locations of historical channel change. It is also necessary to understand what natural processes and human activities may limit or accelerate rates of channel change and how that may impact aquatic habitat and expansion of the HCMZ. This section discusses channel changes from an evaluation of historical hydrology, aerial photography, and maps. The earliest aerial photography used was taken in 1939, and some inference can be gathered from these 1939 photographs about channel position in the few years prior to 1939 where recently abandoned channels are visible. Additionally, maps composed in 1891, 1895, and 1918 show channel position and provide some implication for channel morphology prior to significant human influence in the river channel.

Characterizing the historical channel form provides a tool to help understand the rates and patterns in the river, show how it has changed in the past, and how it may change in the future. Channel form can be evaluated by looking at sinuosity, active channel width, meander migration, and deposition patterns of sediment and woody debris.

8.1 Channel Sinuosity

Sinuosity measurements were used to look for indications of differences in channel form between reaches, and to see if a particular reach had changed channel form since 1939. Sinuosity is a measure of the curvature of the channel relative to the valley through which it flows. Sinuosity values for rivers typically range from 1 to 2, where 1 represents a straight channel and the closer the number is to 2 the more sinuous the channel. Typically the centerline length of the channel is divided by the centerline length of the valley floor to compute sinuosity. For the Hoh River, there are several geologic controls that define and limit potential channel positions within the valley walls. Therefore, sinuosity was measured by comparing the centerline length of the channel relative to the centerline length of the natural geologic surfaces that bound the HCMZ. This method was chosen because in many areas of the Hoh River studied the active floodplain (area where the channel can migrate within) is limited by terraces, bedrock, or glacial banks rather than the edge of the valley wall. For instance, Spruce Canyon (Reach 6) is confined by bedrock, which has remained stable in position since at least 1895. Because the river channel in Spruce Canyon cannot migrate laterally outward, the centerline length of the area confined by bedrock is the same as the length of the active channel, and the sinuosity is 1. If the centerline distance between the valley edge had been used, the sinuosity measurements would have been higher for this essentially straight reach and would be difficult to interpret.

Sinuosity was computed for both the low flow and active channels. The sinuosity of the wider, active channel can be used to compare the channel form in the various reaches relative to each other. It can also indicate changes in channel form within a reach that may be due to a change in the balance between sediment supply and transport capacity.

Sinuosity of the low-flow channel may be more important from a fisheries perspective to evaluate the morphology of critical low flow periods during each year.

Figure 23 shows a comparison of the low-flow channel sinuosity to the active channel sinuosity for each reach in 2002. In every reach the low-flow channel is slightly more sinuous than the active channel, which would be expected. The reaches in Olympic National Park (Reaches 1 to 4) presently have the lowest sinuosity measurements in addition to Spruce Canyon (Reach 6), which is bedrock controlled on either side of the channel. Huelsdonk-South Fork Reach (Reach 5) has a noticeably higher sinuosity than the upstream Park reaches. The Morgan's Crossing area (Reach 7) and the Willoughby Creek area (Reach 8) have the highest low flow and active channel sinuosity measurements for existing conditions ranging between 1.3 and 1.4 for low flow and 1.2 and 1.3 for the active channel. The reaches with the highest sinuosities are also the reaches that have the flattest slopes and have had the most lateral HCMZ expansion.

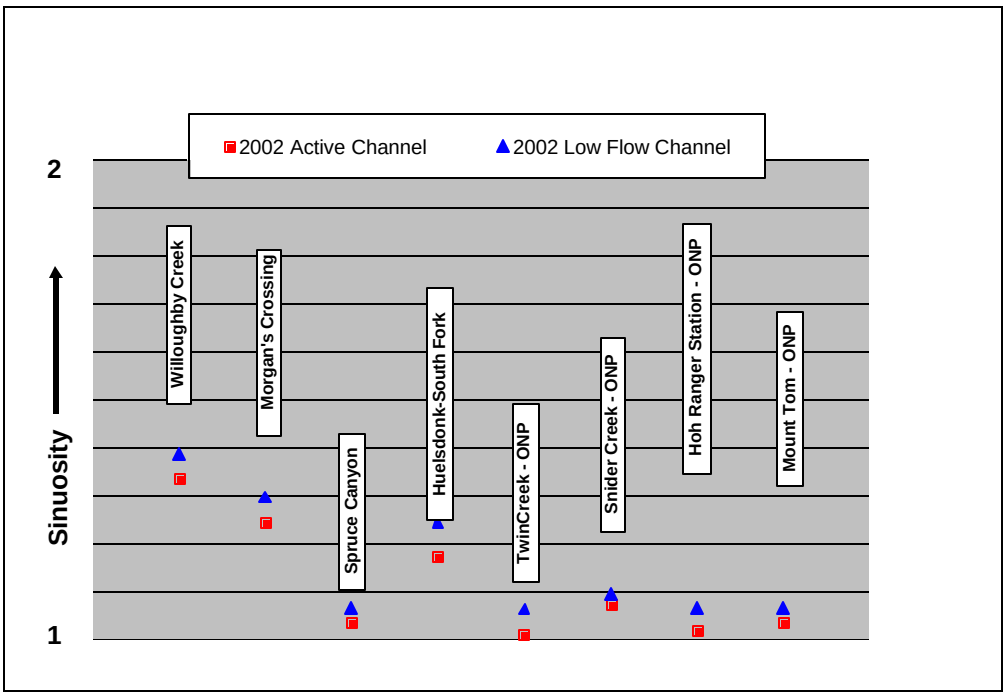


Figure 23. Comparison of 2002 low flow and active channel sinuosity for study reaches.

Next the historical active channel sinuosity was compared in each reach (table 4). It was found that some variability occurred in meandering reaches dependent on whether the channel was in a meander migration cycle or was in a cutoff. However, the typical sinuosity values for each reach have been relatively stable over time such that no channels were observed to change since 1939 from a braided to meandering channel planform or vice versa. This was confirmed by visual observations of the active channel made from the aerial photography. The Huelsdonk-South Fork (Reach 5), Morgan's Crossing (Reach 7) and the Willoughby Creek (Reach 8) areas have consistently had the largest sinuosity measurements since 1939. As will be discussed later in this report, there

has also been more expansion of the HCMZ in these reaches than in the upstream Olympic National Park reaches or in the bedrock controlled Spruce Canyon Reach.

Table 4. Active channel sinuosity from 1939 to 2002

Reach	1939	1950	1960	1971	1977	1981	1994	2001	2002
Reach 1	1.1						1.1	1.0	1.0
Reach 2	1.0						1.0	1.0	1.0
Reach 3	1.1	1.1			1.1	1.1	1.1	1.1	1.1
Reach 4	1.0	1.0	1.1		1.1	1.0	1.1	1.0	1.0
Reach 5	1.2	1.2	1.2		1.2	1.3	1.2	1.2	1.2
Reach 6	1.0	1.0	1.0		1.0	1.0	1.1	1.0	1.0
Reach 7	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Reach 8	1.2	1.1	1.1	1.1	1.2	1.2	1.3	1.3	1.3

The position of the Hoh River was also mapped on the original land survey maps for the Olympic Forest Reserve in the study reaches. These maps show channel position in 1891 (Reach 8), 1895 (Reach 7 and part of Reach 5), or 1918 (Reaches 1 to remaining section of Reach 5). These channels represent a point in time before much human activities occurred within the active channel and floodplain of the river. The 1891 and 1895 mapping shows significant gravel bars where braiding occurred and a single meandering channel where sinuous, and, therefore, are interpreted to show the low-flow channel. The 1918 map shows one wide channel with no detail of low flow channels or gravel bars and is assumed to represent the active channel.

The 1918 active channel sinuosity of the reaches in Olympic National Park was similar to measurements between 1939 and 2002 indicating the active channels in these reaches have always been fairly straight with multiple threads and complex deposition patterns. Reach 5 has always had at least one meandering low-flow channel, and often has multiple low-flow channels during transition periods when the channel is shifting to a new location. Reach 7 was shown as a single sinuous channel in 1895 in the upstream half and more multi-threaded with mid-channel bars in the downstream half. However, the 1939 aerial photograph shows Reach 7 as a straight, wide active channel in the upstream half, probably representing a transitional period when the upstream meander cut itself off. Reach 8 is shown as a single channel meandering in 1891 and 1939, but in 1950 runs straight indicating this is the time period when the meander cut itself off. This indicates that the Reaches 5, 7, and 8 have always been meandering but at times the meander is cut off and a new meander cycle begins.

Measurements of the active channel sinuosity in the lower 4 miles of the Hoh River (RM 4 to 0) (Perkins and TerraLogic GIS, 2004) found that sinuosity varied between 1.0 and 1.8 between 1929 and 1998. They also saw several meander cutoffs and fast migration rates in the lower 4 miles (See Section 8.4 below on migration rates). Based on these measurements, the Hoh River appears to have a wider range of and larger values of sinuosity as the river becomes larger and the valley widens in the downstream direction.

8.2 Active Channel Width

The next step in evaluating channel form was to compare the width of the active channel between 1939 and 2002 to see if it had substantially changed over time and how it related between reaches. As shown in table 1, currently the Olympic National Park reaches have wider active channel widths than the downstream meandering Reaches 5, 7 and 8. The historical maps from 1891 to 1918 could not be used to make active channel width measurements because it is difficult to distinguish the active channel from the low-flow channel in the 1918 mapping. The active channel is defined as the area where coarse bedload is transported during floods. A change in active channel width might indicate a change in the balance between sediment supply and transport capacity or a significant change in hydrology. Figure 24 shows the active channel width for all photo years between 1939 and 2002.

For the entire study area, the active channel width has ranged between 150 and 800 feet. Even with the addition of the South Fork Hoh River flow and sediment, the active channel width does not significantly change in the downstream reaches relative to the upstream reaches that are about the same length (Reach 3). While the width does vary from year to year, there are no significant trends in increasing or decreasing width within each reach or between reaches. Reach 7 appears to have had the greatest fluctuation in active channel width since 1939. Looking at the aerial photography this can be explained by whether the channel in this reach is meandering (narrower active channel width), or running straight (wider active channel width) due to a meander cutoff, or is braided with multiple channels creating a very wide active channel. Two of the widest active channel widths measured in Reach 7 was in 1950 when the meander position was transitioning to a new location and two channels were being occupied, and when the channel was fairly braided in 1994. Relative to the upstream portion of the reach, the downstream portion of Reach 7 has overall had a straighter planform with much smaller meander amplitudes.

8.3 Active Channel Slope

Assuming the elevation change has remained constant between reach boundaries, the historical channel slopes can be computed by dividing the drop in elevation by the channel length (table 5). The validity of this assumption is not known, but it is plausible considering the reach boundaries are constricted sections with relatively high sediment transport capacity that are not likely to have significantly changed in bed elevation since 1939. Over time, the computed slopes for each reach have not significantly varied for a given reach between 1939 and 2002 (less than 6 percent change). Reaches 7 and 8 have the flattest slopes relative to the upstream reaches and the active channel is 0.6 and 0.24 miles longer, respectively, today than in 1939. As a result of the increase in channel length, the slopes have flattened in Reaches 7 and 8 even further from 0.0032 and 0.0028 percent in 1939 to 0.0028 and 0.0026 in 2002, respectively. Reach 4 was flattest in 1977, and Reach 5 was flattest in 1981.

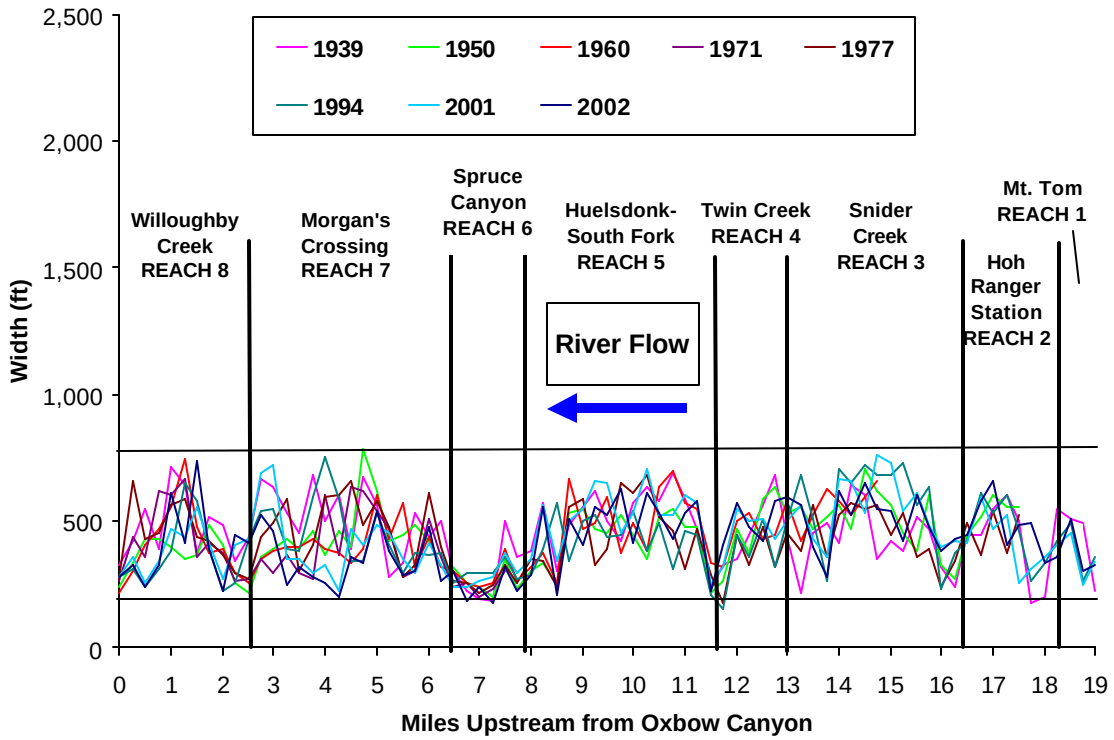


Figure 24. Comparison of average active channel width in study reaches between 1939 and 2002 at the same locations over time.

Table 5. Historical active channel slope for study reaches

Reach	Active Channel Slope								
	1939	1950	1960	1971	1977	1981	1994	2001	2002
1	0.0057						0.0057	0.0059	0.0059
2	0.0059						0.0059	0.0058	0.0057
3	0.0056	0.0055			0.0053	0.0055	0.0055	0.0054	0.0055
4	0.0045	0.0044	0.0042		0.0040	0.0044	0.0043	0.0045	0.0045
5	0.0036	0.0036	0.0036		0.0035	0.0034	0.0035	0.0036	0.0036
6	0.0037	0.0037	0.0038		0.0037	0.0037	0.0036	0.0037	0.0037
7	0.0032	0.0030	0.0029	0.0029	0.0030	0.0030	0.0029	0.0028	0.0028
8	0.0028	0.0032	0.0031	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026

8.4 Meander Migration in Reaches 5, 7, and 8

Reaches 5, 7, and 8 are the reaches with sinuous channels in the study area and the meander migration discussion will be focused on these reaches. In Reaches 7 and 8, the migration rate of the upstream-most meander bend was measured from repeat aerial photography and early maps (table 6). Although there are inherently some errors in the rectification of the historical photographs and maps, the amount of river channel migration during the time period between aerial photographs is much greater than the rectification error. The time period of historical aerial photographs and maps included a

meander cutoff and the development of a new sinuous channel. In all three reaches, the upstream portion of the meander bends was migrating into alluvial banks within the HCMZ.

Presently, the meander channels in both Reaches 7 and 8 are almost perpendicular to the valley and are likely to cut off because the slope is flattening and the channel flow and sediment transport capacity are reducing (see Figures 2.1 and 2.2 in Attachment 2 of summary report and Appendix A). In 1895, the historical channel position within Reach 7 included a meandering channel in the upstream half of the reach, but, by 1939, the meander bend had been cut off and the river channel was following a straight alignment. In Reach 8, the 1939 meandering channel is in a different location than the 1891 channel, which suggests that a channel cutoff occurred sometime during the 1891 to 1939 time period. The 1939 meandering channel of Reach 8 was again cut off by 1950. This suggests a meander cycle in these reaches is on the order of 50 to 75 years. While it is not known exactly when the next cutoff will occur, it is estimated that the meander bend amplitude and river slope have reached the limits of what is possible to maintain flow conveyance and sediment transport capacity.

Table 6. Maximum recorded floods, meander bend amplitude, and measured migration rates in the upstream most meander bend of Reaches 7 and 8.

Time Interval	Number of Years Between Photos	Number of Floods > 2-yr	Maximum Flood (ft^3/s)	Meander Bend Migration Rate (ft/yr)		Meander Bend Amplitude[1] (ft)	
				Reach 7	Reach 8	Reach 7	Reach 8
1891/95 to 1927	-	No gage data	No gage data			2600	2400
1927 to 39		3	42,300	-	-	Straight	2400
1939 to 50	11	2	45,400	-	-	Straight	Straight
1950 to 60	10	5	39,400	22	-	1400	1400
1960 to 71	11	5	46,000	15	26	1800	1800
1971 to 77	6	5	41,200	28	20	2200	1700
1977 to 81	4	3	51,600	48	76	2500	2000
1981 to 87	6	5	48,600	28	15	2500	2400
1987 to 94	7	5	54,500	13	39	2600	2500
1994 to 2001	7	6	47,600	16	14	2800	2600

[1] Meander amplitude was measured from the outside of meander bends. The meander bend amplitude measurement refers to the second date in each row (i.e. for 1927 to 1939 measurement is for 1939 photography). In the first row only, the meander amplitude represents a measurement made from the 1891 map for Reach 8 and the 1895 map for Reach 7 because no photography or maps were available from 1927.

The meander bend amplitude history provides additional verification that the amplitude increases over time as the meander migrates outward in these reaches, but eventually cuts off when it reaches its limits of flow conveyance and sediment transport capacity (see

table 6). Currently the meander amplitude in Reaches 7 and 8 has been increasing to a distance near what it was before the last cutoff occurred.

What is more difficult to predict is the path the channel will take when a flood flow cuts off the meander bend and where the new channel will migrate to. However, historical channel paths in the form of existing side channel and overflow channels provide a hint as to where the channel may head next. These areas already convey flow and offer a path of least resistance for the river when the existing meander bend is no longer able to contain enough flow or transport enough sediment. Often these side channels have log jams at their entrance which limits the present amount of sediment and wood that enter the channel. The probability that the log jams will be blown out and the main channel will move to the side channel path depends on the stability of the log jam, the flood magnitude, and the direction the river migrates.

The rate of channel change is closely related to the occurrence and magnitude of floods. The average annual rates of meander migration were also compared to the history of annual peak discharges. Each time period between aerial photographs had at least two floods greater than the 2-year flood. Earlier discussion noted that the occurrence of the 2-year flood was less than every 2 years in the early history of the aerial photography, but has increased to occur almost annually in the last few decades (see table 3). In addition, larger magnitude floods have been occurring in the last few decades (see figure 15). The highest average rate of migration for Reaches 7 and 8 correlates with the time period 1977 to 1981 when the highest magnitude of flooding occurred (2 floods greater than the 25-year flood – see table 3). Therefore, bank erosion and migration appear to be accelerated by flood magnitude. On the other hand, migration rates may be limited when the meander becomes so elongated that the channel begins losing capacity to convey flow and transport sediment.

For example, Reach 7 had cutoff in 1939 and was running straight, but by 1950 had formed a new meander that has been steadily migrating outward and downstream since that time. Reach 8 had a meander that was cutoff sometime between 1939 and 1950, and then began a cycle of new meander migration again in a steady outward and downstream direction that has continued to the present time (Appendix A). Both channels now have greater meander bend amplitudes, longer channels, and flatter slopes than they have had since the start of the latest meander migration cycle. Since 1994, both meander bends have been migrating in an upstream direction indicating that they are further losing capacity to convey flow and transport sediment. This is a typical natural process for meandering channels where they translate outward and downstream over time, and eventually cutoff and form a new meander cycle. Therefore, both meander bends would be expected to cutoff during a future flood.

Reach 5 is a transition reach between the complex channel form in the Park reaches to the more sinuous Reaches 7 and 8 in the Middle Hoh. Reach 5 generally has a meandering channel, but also has had sections since 1939 that would be classified as more split flow with two to three channel paths present separated by gravel bars. Meander migration has had an interesting history in the upstream portion of Reach 5. The ability of the meander

bends to migrate outward has been limited along the right boundary of the HCMZ by efforts to maintain the County and Park Roads and on the left side by the confluence with the South Fork. Just downstream from the confluence with the South Fork, the channel has frequently migrated to the left side of the HCMZ into former channel paths. In 1918 and 1939 the channel flowed along the left boundary of the HCMZ. From 1939 to 1981, the meanders in this reach generally migrated outward and slightly downstream within a range of 10 to 25 feet per year. Between 1994 and 2001, the meander bends generally migrated more downstream than outward, occupying different areas of the HCMZ. A portion of the terrace on the right side has been eroded as a result of the meander migration. In general, the meander amplitudes measured in Reach 5 have fluctuated within a range of 100 to 1,300 feet, but do not follow a trend of increasing amplitude with an increase in sinuosity as measured in Reaches 7 and 8 (see table 6 for Reach 7 and 8 measurements).

The meander pattern at the upstream portion of Reach 5, where the South Fork enters the Hoh River, controls the meander migration through the rest of the reach (see figure 2.4 in Attachment 2 of summary report and Appendix A). Between 1950 and 1977, the river migrated to the left towards the confluence with the South Fork of the Hoh River. However river flow and sediment from the South Fork limit the extent of lateral migration of the Hoh River on the left side. When the Hoh River could no longer migrate any farther to the left because of the confluence with the South Fork, it began migrating downstream. This set up the meander path for the rest of the reach.

In 1939, just downstream from where the South Fork enters the Hoh River, the river was flowing alongside the Park Road, at the right edge of the HCMZ (see figure A.7 in Appendix A). From there, the river channel turned left and flowed across the HCMZ to the left boundary. Between 1939 and 1960, the upstream meander migrated outward and slightly downstream at about 20 feet per year until it hit the valley wall on the right side. Subsequently, the next downstream meander bend also migrated to the right and away from the left HCMZ boundary. As the upstream meander moved to the right, it washed out the Park Road, and the National Park Service was forced to place the road at the edge of the valley wall. This induced a landslide that is visible in the 1960 aerial photography. By the next available photography in 1977, a portion of the Park the road was moved back to its original location in 1939. This resulted in the outside of the bend being cut off so that the channel ran parallel to the road in 1977. Because the meander bend could no longer migrate to the right toward the valley wall, it migrated 900 feet downstream by 1981. In addition, since the channel was pushed back to the left, it reoccupied the 1939 channel adjacent to the left HCMZ boundary. The river would have likely reoccupied the 1939 channel at some point, but the reconstruction of the Park Road might have accelerated the time period in which the 1939 channel was reoccupied. Note that the 1939 channel path reoccupied in 1981 is part of the natural HCMZ and was occupied by the river before the management issues with the Park Road began.

Between 1987 and 1994, the meander bend at the Park Boundary cut itself off and abandoned the channel path along the left edge of the HCMZ, concentrating more flow along the right boundary of the HCMZ. Subsequently, about 22.4 acres of Lewis Ranch

on the right side were eroded between 1987 and 1994 as a new meander bend, at river mile 30 (see purple star in figure 2.4 of Attachment 2 in summary report), migrated outward and expanded the HCMZ along the right side. Between 1994 and 2001, another section of the road was washed out (4.6 acres of erosion likely during the 1996 flooding) as the meander bend continued to migrate downstream and toward the right at the same time. Portions of the Park and County Roads were again repaired and put back to their original locations. The river channel in 2001 and 2002 flowed almost parallel to the road and began migrating slightly downstream. Presently, the river is migrating through an area that was formerly active channel in 1939. At higher flows, water spills into a side channel that flows along the left boundary. This side channel was visible in the 1939 aerial photography and is within the natural HCMZ boundary.

Short segments of the existing Park and County Roads are a few feet higher in elevation than the surrounding terrace and tend to act as levees when flows might otherwise overtop and inundate portions of the right terrace. These road segments prevent the channel from migrating outward and force the meander bend to either migrate downstream (1977 to 1981) or cutoff as it did between 1987 and 1994. Although the bank protection along the Park and County Roads prevents the expansion of the right HCMZ boundary, it has not caused measurable expansion of the left HCMZ boundary between 1939 and 2002. The left HCMZ boundary is composed of alluvial fan material and is generally more resistant to erosion than material along the right HCMZ boundary. Since 1939, the right HCMZ boundary has expanded due to river bank erosion of right the terrace. However, any expansion of the left 1939 HCMZ boundary could not be detected from aerial photography through 2002.

A report by Herrera Environmental and Northwest Hydraulic Consultants (2002) document that in the reach between the U.S. Highway 101 Bridge (RM 14.8) and the mouth of Nolan Creek (RM 6.2) meander migration rates have varied between 30 to 50 feet per year since 1939. These meander migration rates fall within the range of 13 to 76 feet per year found in this study for the 2 reaches upstream from the Highway 101 Bridge (between RM 17 and RM 25). Perkins and TerraLogic GIS (2004) performed a geomorphic analysis of the lower 4 miles of the Hoh River at the mouth (RM 4 to 0) and found faster rates of lateral meander migration and a greater frequency of meander cutoffs. Average channel migration rates for the lower four river miles over the period 1952 to 1998 varied between 25 to 88 feet per year. Repeated channel cutoffs within the lower four miles occurred between 25 and 38 years. Of the five significant meander cutoffs that were documented in this lower four river miles, there was no evidence that any were caused by large woody debris. In one reach, large woody debris was believed to help cause numerous small cutoffs and lateral erosion.

Other literature suggests that the rate of meander migration is also a function of where the meander bend is in the meander migration cycle. For instance the migration rates might be slower at the beginning of the cycle, peak in the middle, and decline again toward the end of the cycle when it is nearing a cutoff. In both reaches the peak migration rate occurred in about the middle of the meander migration measurements, but this was also when the second largest flood occurred. When the largest recorded flood since 1939

occurred in 1990 the migration rates were slower than previous measurements. This may provide some support that the rates do slow as the meander gets closer to a point where it is ready to cut off. However, for this study the rates of meander migration are averaged and related to several floods between aerial photographs, making it difficult to formulate conclusions about meander migration rates for shorter periods of time.

8.5 Assessment of Vegetation and Active Channel Stability

Areas of unvegetated channel and vegetated floodplain within the HCMZ were compared among the years of record for six reaches (all except the Spruce Canyon and Mount Tom Reaches). The purpose of this analysis was for each reach to see which areas of the active floodplain are most frequently reworked, and to determine if there have been any stable vegetation patches that have been resistant to erosion by the river since at least 1939. Assessing which areas of the HCMZ are most often reworked will help provide information needed to determine how often the channel might run against the HCMZ boundary making it susceptible to erosion. Additionally, this analysis provides some information as to whether the active channel consists of a single meandering channel that gradually migrates across the HMCZ, or whether it consists of several smaller channels interspersed with sediment and wood deposits. The methods used in this analysis and detailed discussion of the results are provided in Appendix I. An example of the results is visually shown for the Morgan's Crossing Reach (figure 25).

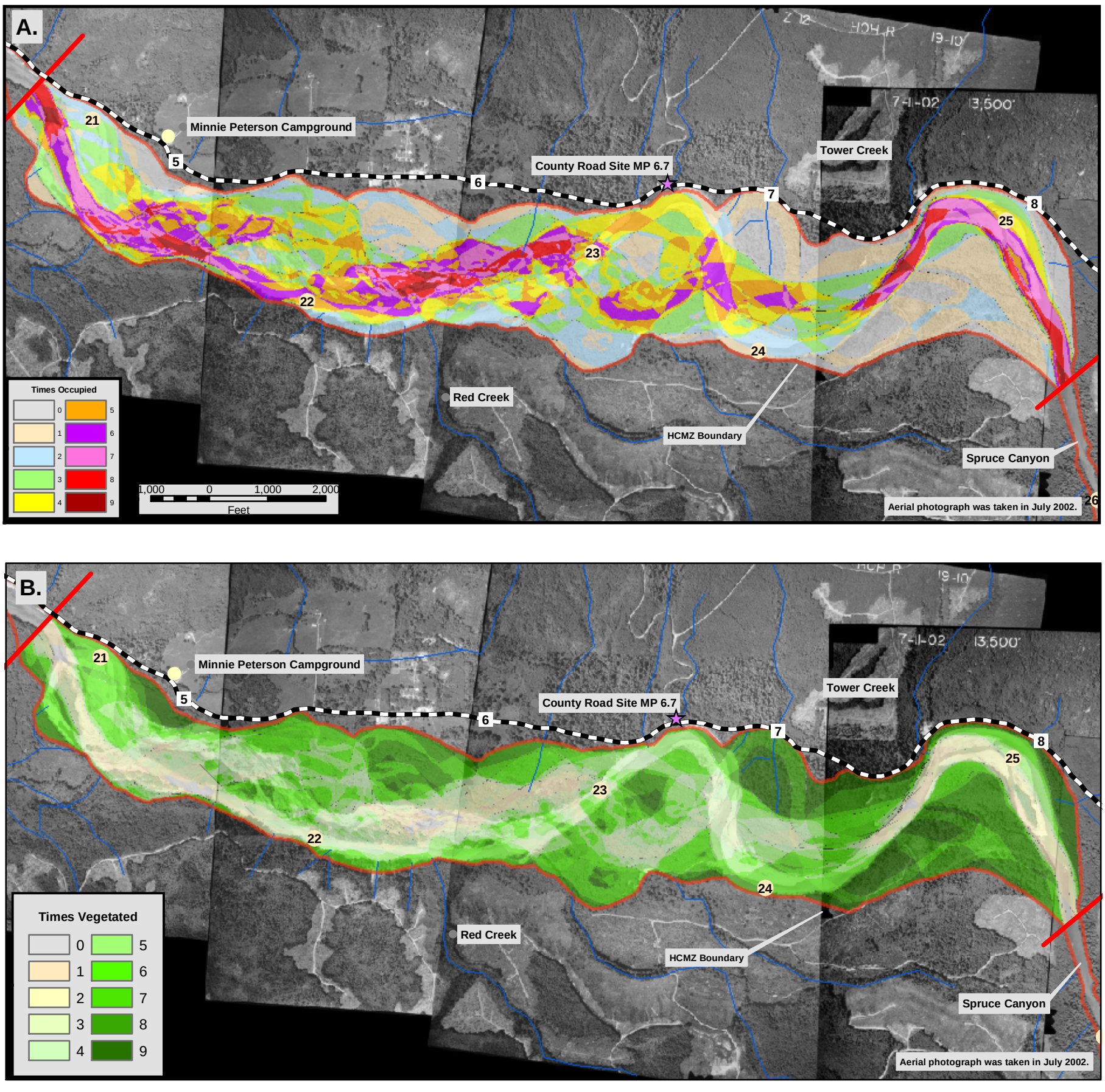
In the reaches with primarily straighter active channel paths (Twin Creek, Snider Creek, and Hoh Ranger Station Reaches), the areas that have been persistently unvegetated channel are longer, wider, and more continuous than in the reaches where the unvegetated channel has a more meandering path. The straighter unvegetated channel has remained in the same locations, repeatedly reworking these areas of the HCMZ. Channel paths outside of this zone have occurred, but usually have been unvegetated channel only once or twice. In these reaches, vegetated floodplain is preserved almost solely along the edges of the HCMZ, outside of the unvegetated channel. Very few remnants of vegetated floodplain occur near the middle of the HCMZ.

The Huelsdonk-South Fork Reach appears to be a transitional reach and shows patterns between the reaches with a more meandering unvegetated channel and those with a straighter unvegetated channel as discussed above. In general, in the meandering Willoughby Creek Reach and the upstream portion of the Morgan's Crossing Reach, the curving, relatively narrow unvegetated channel has been throughout most of the HCMZ at one point in time. In most places the unvegetated channel has occupied an area only a few times. Areas that have been persistently unvegetated channel are small and discontinuous. Both of these reaches have small remnants of vegetated floodplain preserved near the middle of the HCMZ around the curving paths of the unvegetated channel. Some larger areas of vegetated floodplain have been persistent along the boundaries of the HCMZ also.

The Morgan's Crossing Reach also shows characteristics of both a meandering and straight channel path. At the upstream end of this reach, the location of the unvegetated

channel is determined by the mouth of Spruce Canyon, and the unvegetated channel has been persistently along the north (right) side of the HCMZ near RM 25 (figure 25A). Areas of vegetated floodplain have occurred repeatedly on the south (left) side at this location (figure 25B). Between RM 23 and RM 24.5, the unvegetated channel has had a meandering path, which is reflected in the numerous locations of the curving, narrow channel across most of width of the HCMZ. A few places near the middle of the HCMZ have been unvegetated channel repeatedly, some up to six of the nine years of record, but no areas have been unvegetated channel in all nine years. A few small areas of vegetated floodplain are preserved near the middle of the HCMZ (e.g., near RM 23) in this section.

In contrast, in the Morgan's Crossing Reach downstream of RM 23, the unvegetated channel has been straighter and wider. The unvegetated channel has been repeatedly in the same location, some times during all nine years of record, as indicated by the brighter and redder colors on figure 25A. In this band of persistent unvegetated channel, the HCMZ has been repeatedly reworked along a single path, with only a few paths outside of this that have been the unvegetated channel more than once. In this portion of the reach, areas that have been repeatedly part of the vegetated floodplain are located along the HCMZ Boundary, especially along the north (right) boundary.



River miles are measured from the mouth of the Hoh River and are based on a river survey conducted in 2000.

Explanation

- HCMZ Boundary
- Tributaries
- Reach Boundaries
- River Miles
- County Road Mile Post
- Jefferson County Road

Figure 25. Changes within the HCMZ in the Morgans Crossing Reach between 1895 and 2002.

A. The number of times that the unvegetated channel has occupied positions within the HCMZ. The brighter an area, the more times the unvegetated channel has been in that location.

B. The number of times that an area has been vegetated flood plain within the HCMZ. The darker green an area, the more times that the area has been vegetated flood plain.

9.0 HISTORICAL EXPANSION OF HCMZ

A change in the width of the HCMZ indicates areas where the HCMZ has expanded since 1939 due to river erosion along the boundary (figure 26; does not distinguish between erosion on right or left side of HCMZ). Reaches 5, 7, and 8 have experienced the largest amounts of measurable expansion and the bedrock controlled Spruce Canyon (Reach 6) and the Mount Tom Reach (Reach 1) has had no measurable expansion. Overall, the reaches in Olympic National Park have had much less expansion of the HCMZ than the Middle Hoh reaches. This report section evaluates the amounts of erosion that have occurred since 1939 along the HCMZ, and discusses several reasons for why different rates and extent of erosion have occurred in the Park and Middle Hoh reaches. Factors considered that could influence erosion include the types of bank material that compose the HCMZ, channel morphology, occurrence and magnitude of floods, and human impacts, particularly clearing of old growth forest on terrace surfaces.

Because there has been limited human activity in the Park reaches, it was originally thought this entire area could serve as a control section to better understand if the larger rates of erosion outside the Park were due mainly to human impacts. During the investigation, differences in channel slope, planform, discharge, and HCMZ bank material between the two reaches were observed that could also affect the occurrence of and rate of erosion along the HCMZ. However, a few sections of the Park reaches did have comparable channel and HCMZ characteristics as the Middle Hoh and could still be used as a control reach. In these areas, an attempt was made to normalize features that noticeably change between the two reaches, such as slope and river discharge, to more effectively compare erosion amounts and determine if they were indeed accelerated in the Middle Hoh.

9.1 Measured Erosion

The total area of HCMZ boundary that has eroded since 1939 for Reaches 1 to 4 inside Olympic National Park was 47 acres, and almost 6 times as much, or 276 acres, for the erodible Reaches 5, 7, and 8 outside Olympic National Park (figure 27). There are only 8 total miles of HCMZ bank (includes right and left side) for the reaches inside Olympic National Park compared to 12 total miles of HCMZ bank outside Olympic National Park. However, this works out to be approximately 6 acres per mile of erosion in the Olympic National Park reaches and 23 acres per mile outside Olympic National Park, almost four times as much.

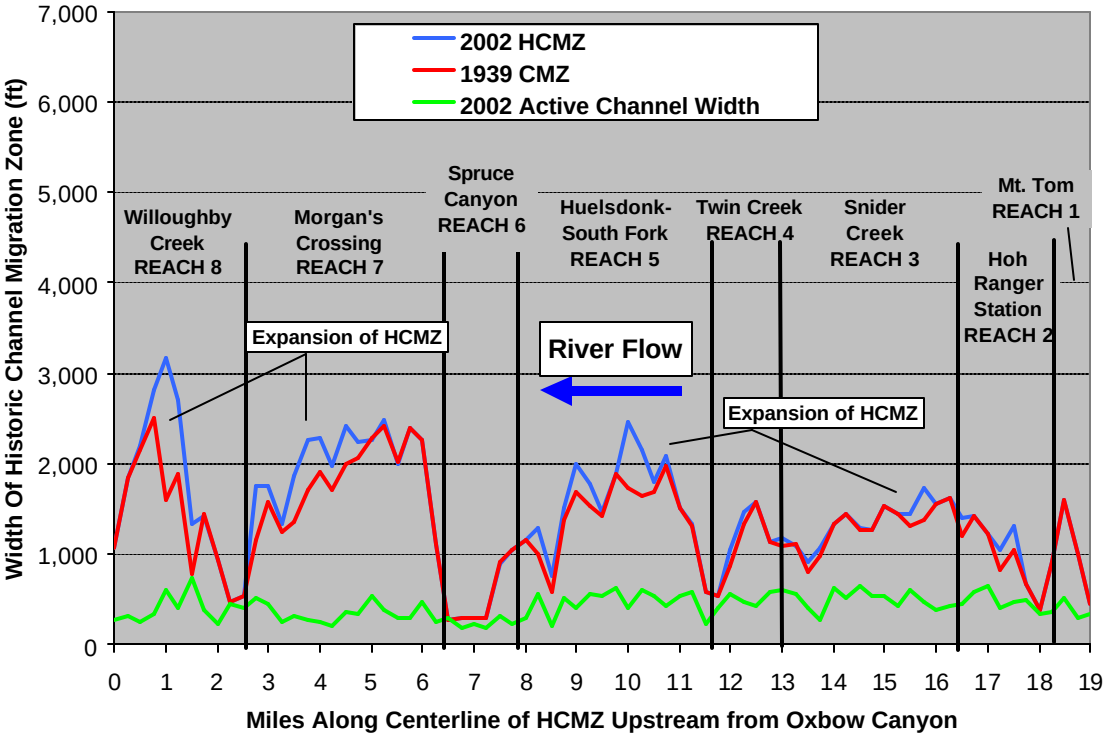


Figure 26. Comparison of 2002 active channel and HCMZ width in 1939 and 2002.

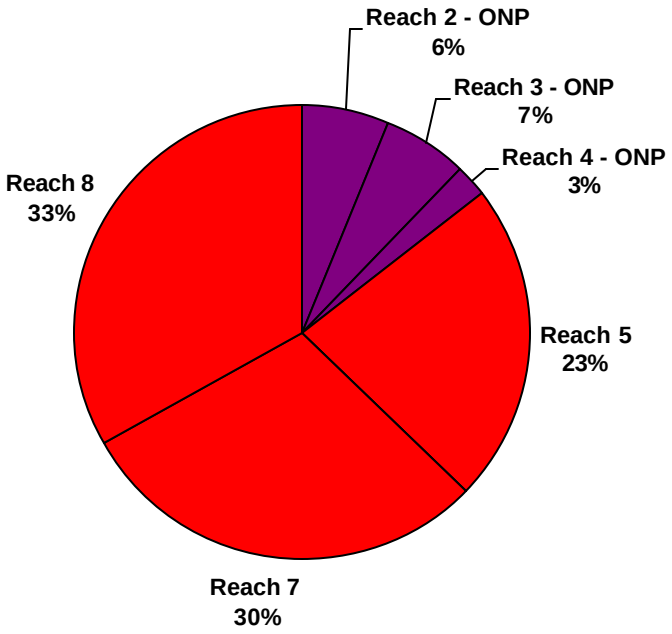


Figure 27. Total acres of bank erosion between 1939 and 2002 HCMZ boundaries in each study reach. Purple areas are located within ONP and red areas are located outside ONP.

Realistically, the bank erosion does not occur everywhere along the HCMZ boundary, but only in areas where the river runs against the bank and the bank is composed of erodible material. The maximum measured rate of erosion was computed for a single area within a reach for a given time period between aerial photography (about a decade). The maximum rate measured in Reaches 7 and 8 were 4 to 9 times greater than the maximum rates in the Park reaches. The maximum rate measured in Reach 5 was about twice as fast as the maximum rates in the Park. However, many of the erosion rates in the Middle Hoh were at similar levels as the Park rates. Two areas in the Park exceeded an erosion rate of 20,000 ft^2 per year. There were eight areas in the Middle Hoh where erosion rates exceeded 40,000 ft^2 per year.

Looking more specifically at the left HCMZ boundary, 26 percent of the 8.1 miles inside Olympic National Park have eroded since 1939 and 31 percent of the 12.2 miles outside Olympic National Park. Of the 144 acres of erosion that have occurred along the left boundary, 26 percent of the area was eroded in Olympic National Park and 74 percent of the area eroded outside Olympic National Park.

Along the right HCMZ boundary, 10 percent of the 8.0 miles have eroded since 1939 inside Olympic National Park, but 35 percent have eroded along the 12.5 miles outside Olympic National Park. Of the 179 acres of erosion that have eroded since 1939 along the right HCMZ boundary, 95 percent of that has occurred outside Olympic National Park.

This data indicates that about one-third of the right and left HCMZ bank length has eroded outside Olympic National Park. Inside Olympic National Park about one-fourth of the left HCMZ bank length has eroded, and only 10 % of the right. But when looking at total lateral expansion (total area eroded), significantly more erosion area has occurred outside of Olympic National Park compared to reaches within Olympic National Park, particularly along the right HCMZ boundary.

9.2 Bank Material Composition along HCMZ

The type of material that composes the HCMZ banks provides some explanation as to why the erosion has occurred along certain parts of the HCMZ and not along others where the channel has run against it. HCMZ banks were broken into general categories of alluvial, glacial, alluvial fans, bedrock, or armored. Of the 11.3 miles of HCMZ bank that have eroded since 1939, 94 percent was composed of alluvial or glacial material. Additionally, of the total area eroded since 1939, 86% (278 acres) occurred in alluvial banks. The alluvial fans formed at the mouth of tributaries can be erodible, but in most areas on the Hoh River were not observed to erode since 1939. Detailed descriptions of the alluvial fans have not been accomplished in the Hoh basin. Based on general observations made during site visits, a possible reason for the resistance to erosion of the alluvial fan may be the large volume of material in the deposit, which in certain cases may also contain coarser material than the Hoh River can transport. However, recent sediment deposits transported from tributary channels to the Hoh River often extend past the boundaries of an alluvial fan. When these recent sediment deposits contain finer sizes

of sediment, although they can temporarily impact channel position during low flow conditions, they typically are eroded during the next flood.

The glacial deposits are much more variable in their composition than the alluvial deposits, and they erode by a combination of processes (figures 28 and 29). Some initial observations from field work are presented here to provide a general description of the erosion processes, but a more detailed study of the banks would be an appropriate future study to better understand the existing erosion processes and the potential for future HCMZ expansion. The erosion rate of the glacial banks is variable among the banks and for a single bank over time. Of the five 35-to-50-m-high exposures that Thackery (1996) described along the middle Hoh River, at least half of each exposure except one is composed of gravelly outwash (primarily) and till in its upper part. The outwash includes a range of sediment sizes including boulders. The lower about 5 to 20 m of these exposures is mostly lacustrine deposits of silt and clay, which alternate with beds of sand and gravel several feet thick. The finer deposits are easily eroded, but these deposits are often armored with the coarser material from the gravelly units.

The glacial banks appear to be relatively stable (non-eroded) in the aerial photography until the river is seen running against them. While erosion occurs within the outwash, the erosion process and rate are similar to those of the alluvial banks. Once the lacustrine silt and clay are exposed, the banks begin to fail because of slope instability, which is aided by the lateral movement of water along the fine-grained beds to the exposed bank and by runoff from the surface of above the exposure. At this point, the glacial banks fail mostly by slumping along the exposure and by gullies that erode from the top of the exposure. If the Hoh River channel is along the toe of the glacial bank, then the fine sediment will be removed. The coarse sediment may be removed, depending upon its size and the flow in the river, or it may remain as armoring for the bank. If the Hoh River channel is not along the toe, then the sediment accumulates at the toe of the slope, and may become fairly stable once it reaches the angle of repose, becomes armored by the gravel, and, in some cases, vegetated. However, if water continues to issue from the bank or flow over the top of the bank, the glacial deposits may remain unstable, regardless of the position of the Hoh River channel.

Figure 28. Glacial bank along left HCMZ boundary in Reach 7. Photograph taken in August 2002.

Figure 29. Glacial bank along HCMZ boundary in Reach 5. Photograph taken in August 2002.

To analyze the potential for erosion of the HCMZ boundary in the Middle Hoh versus the Park reaches, the bank material along the HCMZ was lumped into erodible (alluvium and glacial) and fairly resistant to erosion (alluvial fans & bedrock) categories (table 7). Because areas that are protected (armored) are generally alluvial or glacial banks that have experienced erosion, protected banks were also categorized as erodible for purposes of this discussion.

Looking at the data in table 7, a greater percentage of the HCMZ banks outside Olympic National Park are composed of erodible material based on the amount of alluvial and glacial banks. There are relatively similar amounts of alluvial banks both inside and outside Olympic National Park. However, there are more glacial banks in the Middle Hoh and less steep alluvial fans that deliver large sediment to the Hoh River which can limit HCMZ expansion. The susceptibility to erosion based on bank material composition may partially explain why a greater length and area of HCMZ bank has eroded outside Olympic National Park.

Table 7. Bank Material Categorization for the HCMZ in study area (RM 40 to 17)

CATEGORY	Right HCMZ (%)			Left HCMZ (%)	
	Inside ONP	Outside ONP		Inside ONP	Outside ONP
Glacial	8	22		0	23
Alluvium	54	53		58	58
Armored (Alluvium)	3	9		0	0
Erodible Total	65 %	84 %		58 %	80 %
Alluvial Fan	35	8		42	12
Bedrock	0	7		0	8
Resistant to Erosion Total	35 %	16 %		42 %	20 %

9.3 Channel Morphology

Channel planform also plays a role in the occurrence and extent of bank erosion. The majority of the Park reaches have a straight, steep, and wide active channel in which the total flow is divided into multiple flow paths. In addition, the size of flood occurring in the Park reaches is estimated to be ½ to ? times less than the downstream reaches, which have a significant increase in drainage area at the confluence with the South Fork Hoh River. These factors result in less flow being conveyed against any particular section of HCMZ boundary and for a shorter amount of time in the Park reaches than in the Middle Hoh reaches. In Reaches 5, 7, and 8 the active channel usually contains one meandering channel that conveys the majority of flow and transports the majority of sediment and wood during floods. This produces high velocities and erosion along the outside of the meander bends in the Middle Hoh reaches. Further, the channel tends to remain against the same left or right HCMZ boundary and for longer periods of time than in the more

dynamic Park reaches. There are a few sections of the Park reaches that do have a single meandering channel that is very similar in planform to the Middle Hoh reaches.

9.4 HCMZ Expansion Related to Annual Peak Floods

The total area of HCMZ bank erosion within a given reach was computed for each time sequence between aerial photographs. This resulted in an average HCMZ erosion rate for each reach in acres per year (figure 30). The erosion rates outside Olympic National Park have typically been faster than the rates inside Olympic National Park. Erosion rates in Reach 2 at the Rainforest Campground area have increased, during the last decade, to a level similar to the erosion rates outside Olympic National Park. The peak annual flood values are also plotted in figure 30 (blue triangles). These data show there have been several floods between each interval of aerial photographs when lateral erosion was measured. Although the frequency and magnitude of floods have been larger in recent decades, some of the largest rates of erosion occurred in the earlier time periods evaluated.

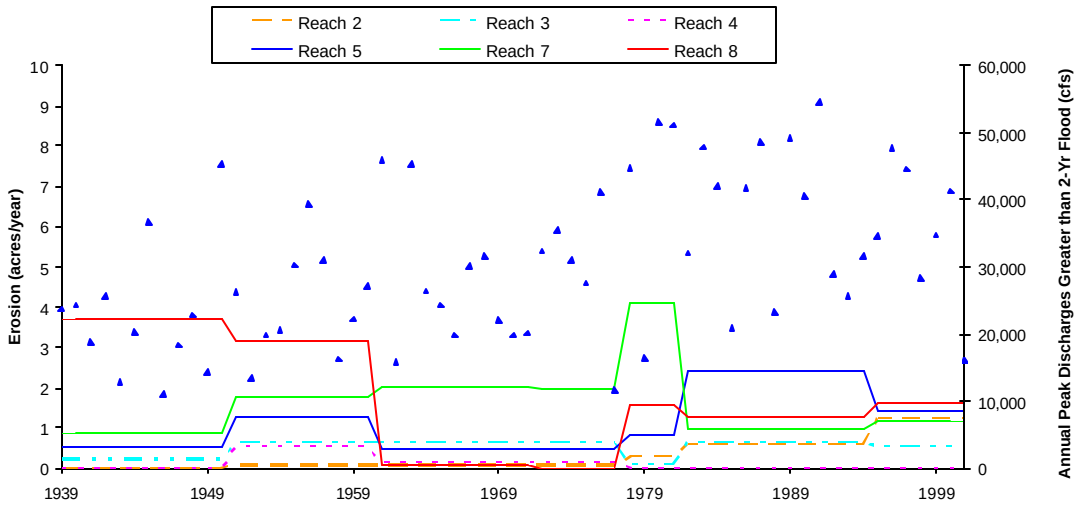


Figure 30. Comparison of historical erosion rates for total area eroded in each reach between 1939 and 2002. Annual peak discharges are also shown (by the blue triangles) for the period between 1939 and 2001 at a gage located downstream of Reach 8.

9.5 Human Activities in Areas of HCMZ Erosion

HCMZ expansion is a natural process, but the historical rates and extent of erosion in Reaches 5, 7, and 8 since 1939 have been much larger than in the less disturbed Olympic National Park reaches. All of the erosion areas outside of Olympic National Park occurred where the forest was cleared on terrace surfaces adjacent to the boundary of the HCMZ prior to the erosion. In some cases the areas were cleared for homesteading or commercial timber harvest, and other areas were cleared for road construction. One area that has eroded within Olympic National Park is across and downstream from the Rainforest Campground where the HCMZ has been constricted by a dike that cuts off a

historic channel path to protect the campground from erosion. This constriction increases local water stage and velocities and may have been part of the reason for the erosion occurring on the opposite bank.

Bank erosion occurs when the hydraulic forces, acting to cause bank erosion, exceed the capability of the bank to resist the erosion. The majority of erosion typically occurs along the outside of a meander bend of the main channel, but can also occur along overflow and side channels. The factors acting to resist bank erosion can include (Randle, 2004):

- tree roots, if trees are present;
- large woody debris, especially if trees along the bank fall in;
- cohesive bank soils; and
- rocks that are too coarse to be transported by the stream flow.

If trees are cleared from areas along the outside bank of a meander bend, then two of the resistance factors are eliminated and the rates of bank erosion and channel migration can accelerate. Herrera found that in the Park trees of at least 21" in stem diameter can remain stable when they fall into the river and help slow the rate of bank erosion. The reaches within Olympic National Park have less discharge than the reaches downstream of the confluence with the South Fork. This may indicate that it takes a larger diameter tree to protect the banks downstream of Olympic National Park.

A historical survey of the old growth forest documented that typical tree diameters ranged from 1.3 to 5.4 feet in the Middle Hoh area (Dodwell and Rixon, 1902). The height of a few actively eroding alluvial banks, outside the Park, were measured and ranged in height between 6.5 to 15 feet (see Appendix F). Based on visual observations, most alluvial banks that compose the HCMZ boundary are within this height range. This information suggests that the root structure of large, old growth trees may have likely interfaced with the water surface for lower elevation alluvial banks in the Middle Hoh prior to logging. There is one significant area containing large diameter trees within the HCMZ of Reach 8 that has been present and resistant to erosion since at least 1939 (see figure I.2 in Appendix I).

One of the objectives of this study was to identify whether human activities have actually accelerated the rates of bank erosion and channel migration in the Middle Hoh reaches. The ideal way to determine this would be to examine historical rates of erosion in the Middle Hoh reaches both prior to, and after, the clearing of old growth forest on the HCMZ terrace banks. Unfortunately, everywhere erosion was observed to occur along the Middle Hoh HCMZ, it was along a bank that had already been logged at least once prior to the river running against it during the period 1939 to 2002.

To determine if logging may have had an impact on erosion rates in the Middle Hoh reaches, erosion areas in the Park reaches were selected to serve as a control for the Middle Hoh erosion areas were the riparian forests had been cleared. While much of the Park reaches exhibit a wide braided channel, there are a few areas that do have a single

meandering channel with alluvial terrace banks along the outside of the meander bend, just like in the Middle Hoh reaches. Two primary differences between the Middle Hoh and Park reaches in these areas of similar channel form are changes in discharge, slope, and human disturbance. Generally speaking, discharge increases in the downstream direction while longitudinal channel slope decreases. Discharge and slope are two of the primary variables for predicting sediment transport.

Of the 14 erosion areas with meander bends along terrace banks, 4 were within the Park reaches and 10 were within the Middle Hoh reaches. The average erosion width, over the period 1939 to 2002, was determined for each erosion area (column 4 in table 8). The average erosion width was then normalized (column 8 in table 8) by dividing the average erosion width by the maximum average erosion width.

The 2-year flood peak at the downstream end of each reach, and the average hydraulic slope for each reach (see table 2) were determined to compute the total stream power (column 7 in table 8) and also normalized (column 9 in table 8) by the maximum stream power. The relative erosion width was then computed by dividing the normalized erosion width by the normalized total stream power (column 10 in table 8). The relative erosion width accounts for differences in the 2-year flood peak and slope for erosion of terrace banks along meander bends in both the Park and Middle Hoh reaches.

The relative erosion widths are compared between the Park and Middle Hoh reaches in figure 31. The relative erosion rate incorporates both the 2-year flood peak and longitudinal channel slope and, therefore, can be used to compare channel migration rates in the Park and Middle Hoh reaches. The Middle Hoh shows a wider range of dimensionless erosion widths, and several areas of the Middle Hoh reaches exceed the erosion widths of the Park reaches.

The average of the relative erosion widths for the Park reaches and the Middle Hoh reaches were compared to estimate the potential increase in erosion that can be attributed to logging impacts. The average of the relative erosion widths in the Park reaches is 0.33. However, the average of the relative erosion widths in the Middle Hoh reaches is 0.60, which is nearly twice the average rate for the Park reaches. This indicates that on average about half of the erosion in the Middle Hoh since 1939 would have occurred naturally, but the other half may be due to human impacts, particularly logging.

The primary assumptions for this analysis are summarized below:

- The alluvial terrace bank materials in the Park reaches are essentially the same as the terrace bank materials in the Middle Hoh reaches.
- The four selected erosion areas in the Park reaches are representative of natural erosion rates.
- The ten selected erosion areas in the Middle Hoh reaches are representative of unnatural erosion rates.
- The differences in the relative erosion widths that cannot be explained by the differences in total stream power can be attributed to unnatural causes.

The computations of relative erosion width indicate that erosion in the Middle Hoh reaches is greater than in the Park reaches that can not be explained solely by a change in channel planform, 2-year flood peak, or slope. This provides a clear indication that logging of the terrace surfaces adjacent to the HCMZ in the Middle Hoh has, on average, led to twice as much terrace bank erosion since 1939 in cases where the river has run against the alluvial terrace banks.

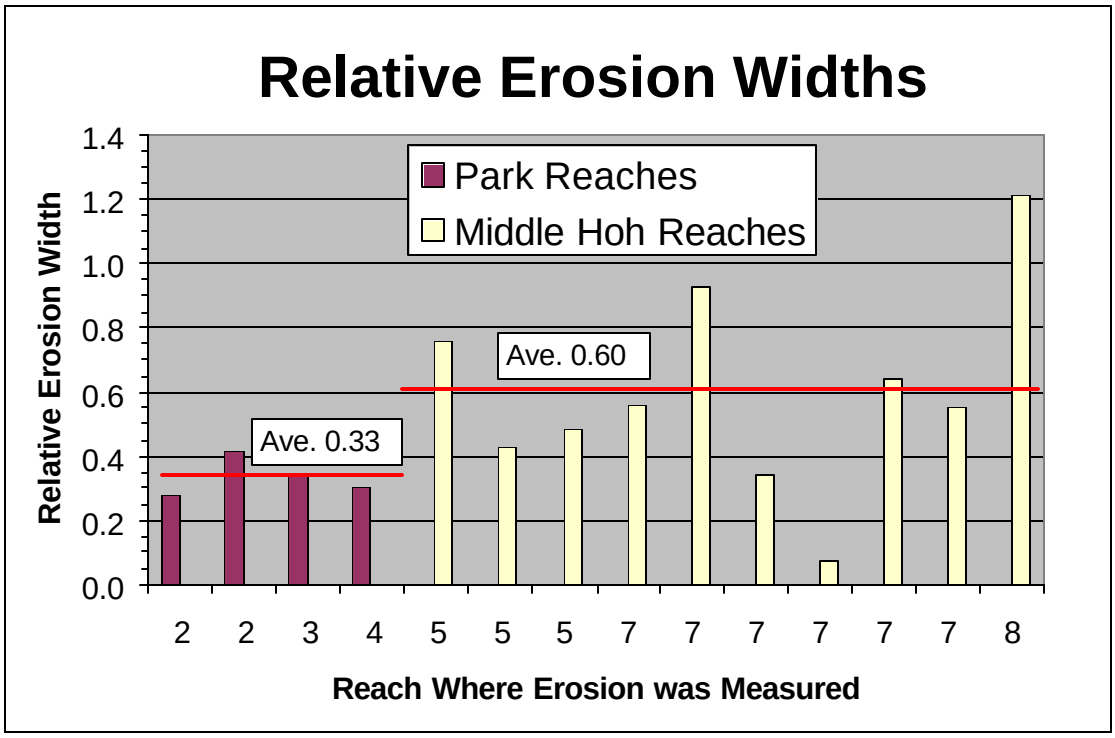


Figure 31. Dimensionless comparison of Park and Middle Hoh HCMZ erosion areas in alluvial banks on outside of meander bends. Each bar grouping represents an erosion area that was measured along the HCMZ between 1939 and 2002.

Table 8. Computation of historical erosion area attributable to changes in total stream power between reaches.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Reach Where Erosion Area was Measured	Total Erosion Area (acres)	1939 HCMZ Erosion Length (feet)	Average Erosion Width "W" (feet)	Estimated 2-Year Discharge "Q" (cfs)	Average Hydraulic Slope, "S"	Total Stream Power "?QS" (lbs/s)	Normalized Erosion Width W/W_{max}	Normalized Total Stream Power $?QS/?QS_{max}$	Relative Erosion Width (W/Wmax)/ $(?QS/?QS_{max})$
2	6.1	2,046	130	11,900	0.0057	4,233	0.25	0.90	0.28
2	12.1	2,748	192	11,900	0.0057	4,233	0.37	0.90	0.41
3	12.2	3,147	169	13,100	0.0055	4,496	0.33	0.96	0.34
4	4.4	1,510	127	13,700	0.0045	3,847	0.25	0.82	0.30
5	32.5	3,638	389	20,900	0.0036	4,695	0.76	1.00	0.76
5	9.9	1,968	219	20,900	0.0036	4,695	0.43	1.00	0.43
5	5.6	977	250	20,900	0.0036	4,695	0.49	1.00	0.49
7	9.7	1,729	244	22,900	0.0028	4,001	0.47	0.85	0.56
7	21.8	2,328	408	22,900	0.0028	4,001	0.79	0.85	0.93
7	6.7	1,941	150	22,900	0.0028	4,001	0.29	0.85	0.34
7	1.4	1,920	32	22,900	0.0028	4,001	0.06	0.85	0.07
7	22.9	3,527	283	22,900	0.0028	4,001	0.55	0.85	0.64
7	18.4	3,311	242	22,900	0.0028	4,001	0.47	0.85	0.55
8	87.6	7,414	515	23,900	0.0026	3,878	1.00	0.83	1.21

10.0 SEDIMENT

Changes in the balance between sediment supply and sediment transport can also impact channel changes. When the balance is stable, it would be expected that the channel form characterization (meandering versus braided) within a reach would also be fairly consistent over time, even though the channel may migrate across the floodplain. For instance, a meandering channel would not become braided if the sediment transport capacity were in balance with the upstream sediment supply. On the other hand, if the sediment supply significantly increases and exceeds the transport capacity, then aggradation can cause a meandering channel planform to become straighter and even braided. Channel aggradation can increase flood stage and can disrupt aquatic habitat. There is limited data on the sediment supply or transport capacity of the Hoh River, but some inferences can be made from visual observations and available data. It is helpful to examine the natural sources of sediment in the watershed (see conceptual model in Section 5), the capacity of the river to transport that sediment, what human activities may have increased the sediment supply rates, and how those increases may impact channel processes. For this discussion, sediment sizes are defined as listed in table 9.

Table 9. Sediment size class and particle diameter range.

Sediment Size Class	Particle Diameter Range (mm)
Clay	< .004
Silt	.004 to .062
Sand	.062 to 2
Gravel	2 to 64
Cobble	64 to 256
Boulder	256 to 4096

10.1 Sediment Load Estimates

When evaluating the sediment impacts from mass wasting and bank erosion, it is necessary to have some quantification of the sediment supply from all sources and the hydraulic capacity of the river to transport sediment. The data for such an evaluation are limited, but some rough estimates for the Hoh River are provided.

10.1.1 Suspended Sediment Estimate

As part of a water quality study, Nelson (1986) measured turbidity and suspended sediment concentrations at various river locations between March 1978 and February 1980 when some substantial flooding occurred. These measurement locations included the USGS gage near the Highway 101 Bridge, downstream of the Park boundary at the entrance to Spruce Canyon, and at the Hoh River mouth. The study found that suspended sediment and turbidity in the mainstem river did increase between the Park boundary and the mouth of the mainstem Hoh River (RM 0). The study also documented that annual suspended sediment transport (clay, silt, and sand-sized sediment) was approximately 630,000 tons per year, but it should be noted that the measurements during the two year

study period ranged between 82,000 and 1,510,000 tons per year. The difference from year to year occurs because of the variation in glacial melt, snowmelt, rainfall, and river flow that can occur within the watershed in any given year (see Section 4). The study estimated that 60 percent of the suspended sediment load, transported by the Hoh River to its mouth, originated from 70 percent of the total drainage area, which is within Olympic National Park. The additional suspended sediment downstream of the Park boundary could be contributed from tributary channels, streambank erosion, or overland runoff into the mainstem Hoh River.

10.1.2 Bedload Estimate

Bedload transport has not been measured on the Hoh River, likely due to the difficulty in accurately measuring coarse-sized sediment transport on large gravel-bed rivers. Large equipment, such as a truck mounted crane, would be needed to measure bedload on this size of river. The only bridge crossing on the Hoh River is Highway 101 near the USGS gaging station, but this bridge is high above the river and one lane of the two-lane bridge may have to be closed to traffic to take bedload measurements.

Coarse-sized sediment is contributed to the mainstem Hoh River from erosion of terrace banks and from tributary channels. While it is not known what fraction of the total natural sediment load of the Hoh River is bedload, sediment data from the nearby Elwha River can provide an estimate. The Elwha River has two large dams, the upstream most one being Glines Canyon Dam which traps the majority of coarse sediment load from the upper watershed in its reservoir (Lake Mills). Using the quantity of coarse sediment deposited in Lake Mills since its initial filling in 1927, an estimate of bedload of 170,000 tons per year is computed for a drainage area of 269 square miles (assuming a unit weight of 100 lb/ft^3) (U.S. Geological Survey, 2000). At the USGS Highway 101 gage on the Hoh River, the drainage area is 253 square miles so the bedload estimate from the Elwha River may be of the same order of magnitude of what exists on the Hoh River.

10.2 Evaluation of Increases to Sediment Supply from Surface Runoff, Mass Wasting, and HCMZ Bank Erosion

A question has been posed as to whether sediment supply to the mainstem Hoh River has significantly increased in recent decades and if so, why and what are the potential impacts on channel processes. Three sources of sediment that were compared are surface or hillslope runoff, mass wasting (landslides) along the valley walls, and bank erosion along the HCMZ boundary. Fine-sized sediment is easily suspended by the river, but if levels were increased enough it could impact water quality in tributaries or in areas of slow velocity where the sediment could deposit during the recession of high flows. Coarse-sized sediment moves as bedload and if upstream supply significantly exceeds the sediment transport capacity of the river, it can cause changes in channel position or channel form.

10.2.1 Sediment Contribution from Surface Runoff in Middle Hoh

The Middle Hoh Watershed Analysis investigated the contribution of sediment from surface runoff or hillslope erosion (Powell, 1999). Surface erosion of soils from hillslopes would produce fine-sized sediment that could be easily suspended by the Hoh River. The background sediment yield from erosion of tributary channel beds was estimated at 531 tons per year for the Upper Hoh and 1,811 tons per year for the Middle Hoh (Powell, 1999). Erosion of hillslopes was also investigated that includes skid trails and landings from timber harvest, borrow pits, range area, and cropland. However, Powell found little evidence of disturbed soils in these areas; although it was noted that re-vegetation in some areas may mask an area that did contribute some sediment for a short period of time. Sediment erosion associated with roads was also calculated and found to be the most significant component of surface erosion. The total sediment erosion from roads was estimated at 2,159 tons per year, which was 119 percent of the background sediment yield from hillslope erosion (Powell, 1999). The total sediment contribution from surface runoff of 4,500 tons per year is mostly fine-sized sediment that is easily suspended by the river and would be difficult to detect relative to natural suspended sediment loads. Nelson (1986) measured sediment suspended sediment concentrations and determined the average annual load to be 630,000 tons per year, much larger than the estimated increase to suspended sediment supplied. However, the increased suspended sediment levels from roads could impact water quality during runoff events, especially if the increase was concentrated in certain basins.

10.2.2 Evaluation of Mass Wasting and Debris Flows

There has been no documented timber harvest along the hillslopes within Olympic National Park. Therefore, mapping of mass wasting within Olympic National Park was done to indicate how much mass wasting naturally occurs without timber harvest and whether these areas have increased in number since 1939. A cursory (reconnaissance-level) landslide study of the Upper Hoh watershed in the Olympic National Park was conducted by Lyon (2003) as part of Reclamation's study efforts. Landslide features were interpreted on the basis of their geomorphic expression on 1939 and 2001 aerial photographs and were mapped using ArcGIS. Due to the large-scale of the project and time-constraints, the interpreted landslides were evaluated in a qualitative way on the basis of landslide density (number of landslides) present in 1939 and 2001. Based on visual estimations, the study concluded that there was about a 5 percent increase in the number of landslides in Olympic National Park between 1939 and 2001. The types of mass wasting observed in the upper watershed are similar to those in the middle watershed including landslides and debris flows. This indicates that mass wasting is a natural process in the Hoh River watershed. The drainages in the upper watershed are much steeper than in the middle watershed and most of the sediment from mass wasting reaches the mainstem river in a relatively short amount of time. However, this represents a natural sediment source that helps maintain the natural balance between supply and transport capacity.

A comprehensive assessment of landslides along the Middle Hoh watershed was conducted by Parks (1999). His study systematically mapped landslides and their attributes using aerial photographs, topographic maps, field mapping, and previously inventoried deep-seated landslides documented by Gerstel (1999). Some of the attributes recorded for the study include the type of landslide, its area, if it delivered sediment to surface waters, type of land use, hillslope gradient, slope form, elevation data, and other observations. A couple of the study's conclusions are (1) that about 90 percent of inventoried landslides in the Middle Hoh River watershed are either shallow rapid failures or debris flows, and (2) about 80 percent of observed landslides are associated with human disturbance (timber harvest, roads, etc.). Using the tabulated data collected by Parks (1999), it can be shown that there has been about a 195 percent increase in the observed number of landslides in the Middle Hoh River watershed between 1939 and 1998.

Based on these two studies one can only theorize that the marked increase in the number of landslides in the Middle Hoh watershed has increased the amount of sediment in that section of the river since 1939. In contrast, it would be expected that the slight increase in the number of landslides in the Upper Hoh watershed in Olympic National Park has not significantly changed the amount of sediment that reaches the river. However a comprehensive assessment of the landslides in the Upper Hoh watershed, similar to the criteria used by Parks (1999) on the Middle Hoh watershed, is needed to better compare and contrast mass wasting between the Middle Hoh and Upper Hoh watersheds. Additionally, further research needs to be conducted to quantify the amount of sediment contributed to the Hoh River by mass wasting processes throughout the Middle and Upper Hoh watersheds so that the volume of sediment production can be analyzed for each of the reaches. Such studies may be feasible along the Middle Hoh, but would present difficult access issues in Olympic National Park.

The impact from additional sediment delivery from mass wasting to the mainstem Hoh River can vary depending on the size of sediment and the rate at which it is delivered. Sediment delivered to the Hoh River from mass wasting contains both fine- and coarse-sized sediment along with large boulders. The sediment sieve analyses presented by Logan (1991) indicated that 30 to 40 percent of the head scarp material of debris slides in the Huelsdonk Ridge basins was composed of 0.84 mm or finer material, which is coarse sand and finer and easily transported by the Hoh River. It was estimated that boulder-sized sediment was deposited along the tributary channels and may not reach the mainstem Hoh River, but sands, gravels and cobbles likely do. It was not possible to estimate what portion of the 109,000 tons estimated to reach the main tributary and river channels was coarse-sized sediment versus fine-sized sediment, or what volume or over what timeframe the sediment was actually delivered to the mainstem Hoh River.

In the mass wasting module for the Middle Hoh Watershed Analysis, Parks (1991) did not calculate the volume of sediment mobilized by mass wasting. However, by distributing a previous study's estimate of coarse sediment mobilized from Huelsdonk Ridge (Logan, 1991), Parks noted that sediment production from mass wasting in the Middle Hoh watershed may be on the order of 24 times the sediment produced from

surface and road erosion. This would work out to be about 95,000 tons per year. Parks (1999) also noted that the other sub-basins in the Middle Hoh watershed have fewer landslides than the Huelsdonk Ridge sub-basin, so this estimate may be on the high end of actual production. As Logan (1991) noted, only one-third of Huelsdonk Ridge sediment is estimated to have reached the main tributary and river channels. It can also be assumed that not all of the mass wasting sediment in the remaining sub-basins of the Middle Hoh would be delivered to the mainstem Hoh River and what would be delivered is a combination of fine- and coarse-sized sediment. More studies need to be done to quantify what portion of mass wasting sediment is actually reaching the mainstem Hoh River and on what frequency to better define the impact it may have on channel processes and habitat. Although beyond the scope of this study, additional studies related to the impact from mass wasting on tributary channels would also provide valuable information for fishery habitat assessments.

Some previous work has been done to estimate if mass wasting impacts the levels of fine-sized sediment in the active channel or in side channels in the Middle Hoh reaches. Cederholm (1991) measured the fraction of fine-sized sediment (<0.85mm) in the active channel of the Hoh River and found that it was less than 12 percent of the total sediment in the channel in areas affected by mass wasting and that there was no significant difference in the percentage of fine sediment along the mainstem channel between sections affected by mass wasting and those in the Upper Hoh reaches, which have only minimal mass wasting. Kennard (1999) also measured the fraction of fine-sized sediment in the active channel in both unmanaged and managed sections of the South Fork Hoh River and found no significant difference. However, Hatten (1991) found that side channels of the Hoh River that are used as spawning grounds in areas affected from mass wasting on Huelsdonk Ridge did have elevated levels of fine-sized sediment relative to unaffected spawning grounds. He noted that these elevated levels could degrade the quality of habitat. It is not known if these measurements represent a temporary condition or if they have continued to persist from repeat landslide occurrences. Kennard noted that many tributaries in the Middle Hoh reaches had excessively high levels of fine sediment. This indicates the fine-sized sediment that reaches the mainstem Hoh River is easily transported downstream and is likely undetectable relative to the natural sediment load. However, when fine-sized sediment is transported into areas of slow velocity, such as side and overflow channels, it may deposit during the recession of high flows. If mass wasting has elevated levels of fine-sized sediment, this could result in additional deposition in side channels.

In order for coarse-sized sediment from mass wasting to reach the mainstem Hoh River, the sediment must be delivered to a tributary drainage and then be transported downstream into the mainstem Hoh River. Coarse-sized sediment can be mobilized in tributaries by debris flows or through bedload transport during high flows. Debris flows have the ability to move larger sized sediment than bedload transport, but are less frequent. Debris flows can also mobilize large wood, which can be deposited in debris dams that block the channel. As part of this study, the mouth of tributaries were investigated to document any evidence of recent sediment deposits from debris flows reaching the mainstem Hoh River and the range of particle sizes in these deposits (see

Figures 42 and 51). Many of the larger drainages did show evidence of debris flows that contain coarse-sized sediments, but the amount and size range of coarse sediment varied (notes on sediment sizes at observed sediment deposits contained in ArcGIS files for this project).

High sediment loads from floods and debris flows will deposit alluvial fans or debris fans at downstream locations where the slope significantly reduces. These fans are formed when the sediment being transported down the channel exceeds the transport capacity at downstream sections where the slope is flatter, and the channel is forced to shift to another location across the fan. Where the river valley is relatively narrow (within Olympic National Park), alluvial fans tend to deposit within the floodplain or adjacent to the main Hoh River channel. Where the river valley tends to be wider, alluvial fans may deposit on a terrace and, therefore, the sediment may not be readily available to the Hoh River.

Within the Park, tributaries tend to traverse down the steep valley wall directly into the mainstem Hoh River. Based on visual observations, the sediment reaching the mainstem Hoh River in these steep drainages contain larger sizes of sediment that are not as easily mobilized as the sediment delivered to the Hoh River by drainages downstream from the Park. Outside the Park, tributaries typically cross a portion of the valley floor before entering the mainstem Hoh River. This reduction in slope results in only smaller sizes of coarse material reaching the mainstem Hoh River. Where there was coarse sediment, it appeared to be easily transported by the Hoh River during high flows. Historical maps and aerial photography show that while the sediment from debris flows may temporarily cause a channel to shift positions, during the next subsequent flood the channel returns to its original location at the mouth of the tributary. This suggests that recent sediment pulses deposited at the mouth of tributaries may temporarily cause the channel to locally shift when gravel and larger sediment are transported down the tributary, but eventually the river will erode the material and reoccupy the area until the next sediment pulse is transported.

The frequency of debris flows down the various tributaries is unknown, but local observations suggest it can happen as often as every couple of years if enough big rainstorm events occur. Recent studies and observations suggest the frequency of debris flows has been increasing, partly due to timber harvest activities on the hillslopes. The contribution of coarse sediment from the Middle Hoh tributaries at any given time is likely small relative to the total coarse sediment load of the mainstem river. However, the debris flows can damage road culverts and bridges and can become a hazard for private property owners. In particular, where debris flows have been initiated due to clear cut areas, the rate at which sediment is transported down the tributaries can be increased. This can cause a reduction in habitat along the tributary and management issues for property located along the path of the tributaries. For instance, along Iron Maiden Creek, Sand Creek, and Washout Creek near the Park Boundary, debris flows have been a management issue for residents located along the debris fans. Additionally, debris flows in other areas of the Hoh River basin regularly occur in areas such as Owl Creek, Virginia Falls Creek, Split Creek, and Maple Creek, and those on Willoughby

Ridge on the north side of the river. A detailed assessment of debris flows was generally beyond the scope of this study, but the locations of debris flows that were observed to be a potential management issue along the Park and County Roads on the right side of the HCMZ boundary are discussed in Sections 13 and 14. Many of the tributaries have also experienced incision and a subsequent decline in pool habitat and a loss of woody debris as a result of increased sediment flows and dam break flood passage and deposition (Kennard, 1999; Hatten, 1991).

10.2.3 Contribution from Terrace Bank Erosion

Bank erosion naturally occurs as a meandering channel migrates across the floodplain into the HCMZ boundary or because a straight channel simply runs parallel to the boundary. As the bank is eroded, both fine- and coarse-sized sediment is being contributed to the Hoh River sediment load. The contribution of coarse sediment is of most interest because, if large enough in volume, it can temporarily deposit on the channel bed and cause changes in the channel position or impact channel form and cause a meandering river channel to straighten.

The exact contribution and impact of coarse sediment from alluvial and glacial terrace erosion in the Middle Hoh is not known, but some general observations can be made. A total of 243 acres of alluvial bank have been eroded since 1939 in Reaches 1 though 8. Descriptions of the exposed portion of alluvial banks along the HCMZ boundary indicate that an estimate of the total contribution of coarse-sized sediment may be on the order of 20 to 30 percent of the natural bedload per year, but it is difficult to compute this with a high level of confidence.

When channel migration causes erosion of a terrace bank, more sediment is eroded than deposited. The width of sediment erosion along the outside of the meander bend is about the same as the width of deposition that is concurrently occurring along the inside of the meander bend (point bar). Therefore, the active channel width remains relatively constant. Even though the erosion width along outside bank may equal the deposition width along the inside bend, the volumes are not the same because the eroding terrace bank is higher than the deposition on the point bar. Even though the volume of terrace bank erosion may exceed the volume of point bar deposition, the terrace banks typically contain a higher percentage of fine-grained sediment than the point bars, which generally contain higher percentages of coarse sediment. The fine-grained sediment can be easily suspended and transported downstream and may not contribute to the bed material load of the river.

The two highest glacial banks along the left HCMZ in Reaches 7 and 8 have been eroded by the river only in the last decade when the river flowed along these banks. As long as the river flows along these eroding banks, the toe of the glacial banks is subject to erosion during floods which contributes additional fine- and coarse-sized sediment. In Reach 7, the river is presently flowing parallel and adjacent to the glacial bank along the left HCMZ boundary. The HCMZ is wide enough that if the river is directed from the upstream meander into the right side of the HCMZ instead of the left side, it may for a

period of time no longer flow against the glacial bank. In Reach 8, the river is also flowing against a glacial bank, but the meander bend at this location is thought to be near the end of its cycle and likely to cutoff into a new channel path. However, in either reach even if the channel temporarily finds a new path the channel would eventually flow along the glacial bank again in the future and cause additional terrace bank erosion. As shown in figure 23, the terrace bank erosion does not happen consistently over time at all locations that experience large amounts of erosion.

10.2.4 Summary of Impacts from Increased Sediment Loads

The levels of fine-sized sediment of concern to aquatic habitat (< 0.85 mm) have increased within the Middle Hoh watershed as a result of clear cut timber harvesting on the hillslopes, the associated road building, and from accelerated bank erosion along the boundary of the HCMZ. At least one study on the Hoh River has documented high levels of fine-sediment in side channels downstream from landslides associated with logging relative to levels in unaffected reaches within Olympic National Park immediately following the mass wasting occurrence. Once delivered to the mainstem Hoh River, the fine-sized sediment would increase river concentrations and turbidity, but fine particles in the main river channel would be easily transported downstream to the Pacific Ocean and would be difficult to distinguish from the natural suspended sediment load. However, in areas of slow velocity, such as the forested floodplain and side channels, some of the fine-sized sediment may deposit. Additional increases in fine sediment concentrations from landslides and bank erosion would increase turbidity and could increase fine sediment deposition in slow velocity areas in addition to what would naturally occur.

Following the 1989 to 1990 mass wasting on Huelsdonk Ridge, Hatten (1991) found that the fine-sediment (<0.85 mm) composition of tributary and side channel streams increased in areas downstream from the landslides relative to areas upstream. The fine-sediment compositions of tributary streams affected by landslides increased by 41 percent, while the fine-sediment composition of tributaries unaffected by landslides increased by only 10 percent. The fine-sediment composition of side channels affected by landslides increased by 21 percent while the fine-sediment composition of side channels within Olympic National Park only increased by 13 percent. Hatten (1991) notes that fine-sediment deposition in redd areas normally utilized by salmon can cause a decline in habitat usage. This study indicates that the tributaries are most affected by increases in fine sediment from landslides.

If the coarse sediment contributed from the accelerated mass wasting and bank erosion was great enough, it could result in an imbalance between the sediment transport capacity of the river channel and the upstream sediment supply. The episodic deposition of sediment at tributary mouths can sometimes cause a lateral shift in the position of the low-flow river channel. However, the sediment deposits along the Hoh River are typically eroded during the next flood. Changes in channel planform from meandering to straight or even braided channels would be evident if the sediment supply began to significantly exceed the transport capacity of the downstream river channel. The historical channel planform patterns of the 20th Century were evaluated, but no significant

long-term changes in river planform were observed in any of the reaches evaluated. Based on field inspection, there appear to be large quantities of sediment stored along the channel in all reaches, except Reach 6 in Spruce Canyon. River Reaches 1, 2, 3, and 4 had straight and braided channel planforms with large woody debris. Reaches 5, 7, and 8 had meandering planforms and woody debris of smaller sizes than the upstream reaches that are within Olympic National Park. These findings indicate that the sediment transport capacity of the Hoh River is likely in balance with the natural, upstream sediment supply and that there is no significant, long-term erosion or deposition of sediment along the Hoh River. This statement can be confirmed by the evaluation of total stream power and unit stream power along the Hoh River channel.

10.3 Sediment Transport Capacity

Sediment transport capacity, for a given flood frequency, was evaluated to determine if it varies with river mile. Longitudinal variations in the sediment transport capacity, for a given flood frequency, could lead to long-term aggradation or degradation (incision) and changes in channel planform (e.g., meandering or braiding). Changes in channel planform and sinuosity are of interest because it has implications for the rate and extent of channel migration, HCMZ expansion, and of the disturbance to aquatic habitat. Sediment transport capacity was assessed using field observations and available data of the bed-material sediment sizes and computations of total stream power and unit stream power.

From visual observations of, it was noted that the majority of the active channel bed and floodplain is composed of sediment sizes ranging from sand to cobble. Measurements of sediment sizes on gravel bars along the lower Hoh River show that cobble sizes are present, however, the percent of cobbles declined in the downstream direction along the lower 4 river miles from 46 percent to 22 percent (Perkins and TerraLogic GIS, 2004). This shows that while there may be a decline in sediment transport capacity near the mouth, the cobble-sized sediments do get transported downstream through most of the river system. The rate at which these coarse sediments are transported during floods is not known. Based on these observations, the sediment transport capacity would be expected to remain relatively high through the system. Total stream power and unit stream power was computed to test if the sediment transport capacity varies in the longitudinal direction through the study reach and system.

10.3.1 Total Stream Power

The computation of total stream power along the Hoh River was used to estimate changes in sediment transport capacity along the river. Total stream power is an indicator of sediment transport capacity along a river and is computed as the product of the river hydraulic slope, river discharge, and the unit weight of water. In general, the hydraulic slope of a river channel tends to decrease with distance downstream, while the river discharge tends to increase as flow is added from tributaries. The unit weight of water does not significantly change with time or distance along the river, so this constant value can be ignored for comparison purposes.

The relationship between drainage area and discharge (presented in the hydrologic analysis, England, 2003) was used to compute the corresponding 2-year flood peak at the downstream end of Reaches 1 through 8 and at the river mouth. However, the 2-year flood peak was not computed for the intervening reaches between the USGS stream gage in Oxbow Canyon and the river mouth. The average slope for each river reach was computed using either the USGS Quadrangle contour data, for the reaches upstream from the South Fork confluence, or from the 2002 channel survey data for the reaches downstream of the South Fork confluence.

The total stream power results are shown in figure 32 and indicate that the total stream power is nearly the same at the river mouth as the average value for reaches 1 through 8. The total stream power tends to increase somewhat through Reaches 1 to 3, decrease through Reach 4, and then increase through Reaches 5 and 6. The total stream power is nearly constant through Reaches 7, 8, and at the USGS stream gage, and then is somewhat higher at the river mouth. The increases and decreases in total stream power indicate reaches where sediment transport capacity may be locally higher or lower relative to other reaches. Areas with lower total stream power may be subject to deposition, and areas with higher stream power may be areas subject to erosion. Except for Reach 6 (Spruce Canyon), the difference in total stream power between a given reach and the average is only about ± 15 percent. In addition, no field evidence was found that would indicate any of these reaches were experiencing trends of long-term erosion or deposition. However, the channel and floodplain are still dynamic through the processes of channel migration and sudden occurrence of meander cutoffs. Additionally, a landslide or expansion of the HCMZ that occurs during a flood can contribute large amounts of sediment to a reach relative to the total load. This may cause short-term changes in the bed elevation and even changes in channel planform. However, the total stream power computations do confirm the visual observations and indicate that sediment transport capacity is maintained through the system, and no long-term trends of deposition or incision would be expected.

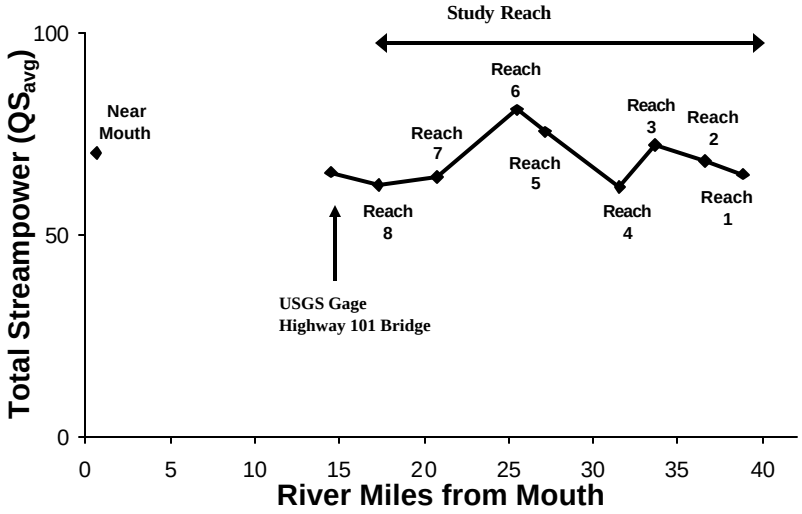


Figure 32. Average total stream power by reach for a portion of the Hoh River.

10.3.2 Unit Stream Power

Total stream power accounts for changes in river discharge and slope, but not the flow velocity which is also a function of channel roughness, width, and depth. Yang (1986, 1996) theoretically derived a quantitative equation for the prediction of dynamic adjustment of a river channel based on his unit stream power equations (1973, 1979). Utilizing this approach, unit stream power, which is a product of mean channel velocity and slope, was also computed for each reach to further evaluate the ability of the Hoh River to transport sediment. This approach can also provide an indication of the ability of the river to transport woody debris, which is incorporated in the roughness estimations. A hydraulic model that would predict mean velocity for the bankfull discharge has not been developed for the Hoh River. However, the Manning's equation and the continuity equation can be used to compute velocity for the 2-year flood peak (Chow, 1959), assuming a wide, rectangular channel.

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

$$Q = VA = VWD$$

$$Q = \frac{1.486}{n} WD^{5/3} S^{1/2}$$

where V = Mean channel velocity (ft/s)
n = Manning's roughness coefficient (Barnes, 1967)
R = Hydraulic radius (ft), which is equal to the mean depth for wide channels
S = Channel slope
A = Cross sectional area of flow (ft^2)
Q = Discharge (ft^3/s)
W = Channel width (ft)
D = Mean channel depth (ft)

These three equations were used to compute the mean channel velocity and then the unit stream power to evaluate if there are changes with river mile and changes over time. The computations of mean channel velocity were based on the following data:

- 2-year flood peak discharge
- the reach-averaged active-channel width, measured from aerial photography
- channel roughness, estimated from field inspection; and
- channel slope, derived from survey data and quadrangle maps (table 10 and figure 33).

The three equations provide rough estimates of unit stream power that are adequate to evaluate the relative differences between reaches and the differences between 1939 and 2002 conditions.

Herrera (2004) found that the abundance of large woody debris in the active channel is greater in the Park reaches than in the Middle Hoh reaches. Therefore, the roughness within the active channel should be less in Reaches 5 through 8 because the woody debris tends to be smaller and less abundant than in Reaches 1 through 4. Reasonable estimates of roughness values were chosen based on past experience for rivers with similar characteristics, and the values assigned in the Park were made higher than those in the Middle Hoh reaches that are downstream. The computations presented in this report assume the channel roughness has remained consistent since 1939.

Logging of terrace surfaces adjacent to the river has reduced the ability of the Middle Hoh reaches to recruit large, old growth woody debris as it erodes the HCMZ. If the change in wood present between 1939 and 2002 were great enough, it would be justified to increase the roughness value used in the unit stream power computations for 1939. If there were more large woody debris and roughness in the channel in 1939, the river channel may have compensated for the decrease in roughness by increasing its sinuosity, which would mean the channel used to be straighter, and perhaps more complex, than today. However, the 1895 cadastral survey map indicates that the channel was meandering in a similar fashion as it is today, prior to any substantial logging. Even if there is less large woody debris in the present channel, the decrease was not enough to cause a change in channel planform. However, a reduction in large woody debris in the channel over time would reduce the amount of fish habitat created by the wood, particularly along the low-flow channel.

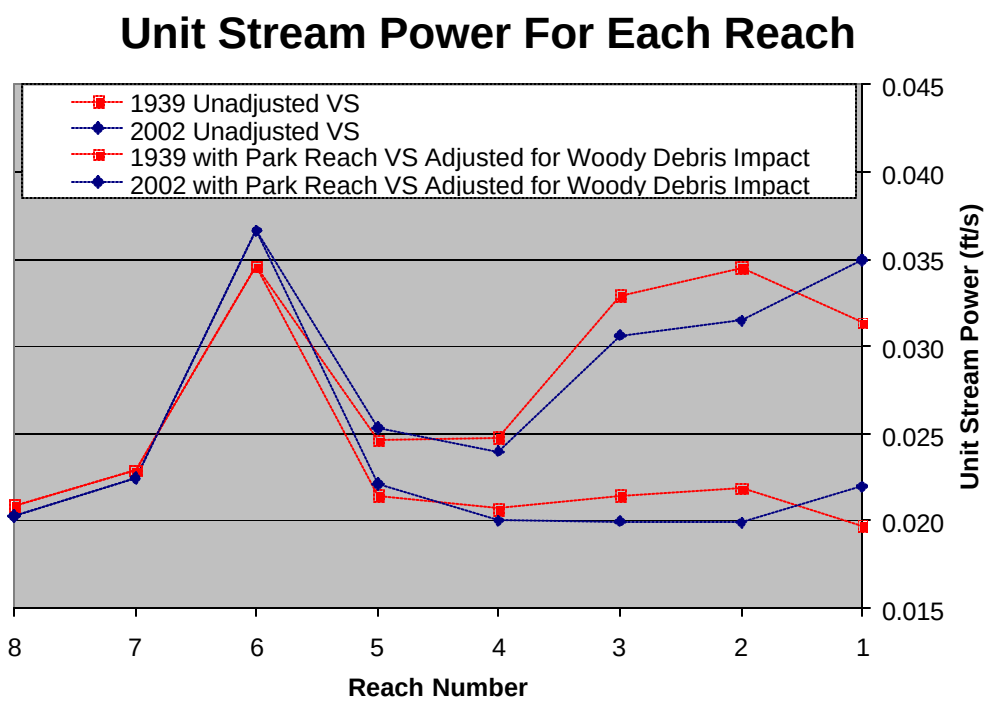


Figure 33. Comparison of unit stream power for study reaches between 1939 and 2002.

Slope decreases and river flow increases in the downstream direction in the study area. These factors tend to decrease the average flow velocity and subsequently the unit stream power in the downstream direction as shown by the unadjusted unit stream power (VS) in figure 33. These computations indicate the sediment transport capacity of the Hoh River decreases in the downstream direction, but this does not correlate well with visual observations and the total stream power results discussed previously. The decreasing trend in unit stream power is caused by the steep average channel slopes in the Park reaches. The steep average channel slopes are the result of steep riffles that may not become drowned out during the bankfull discharge as they do in the Middle Hoh reaches (figure 34). Additionally, there is a greater source of old growth woody debris and less flow to float away the wood, so there is more wood in the river (snags and log jams) that remains stable for long periods of time (figures 35 and 36). During floods, much of this wood in the Park reaches acts as a hydraulic control forming additional pools that do not get drowned out.

The sediment transport capacity through the upstream Park reaches is limited by the flatter slope segments through the pools, formed by riffles, and large woody debris jams. Therefore, the effective slope that controls the sediment transport capacity through these reaches is less than the average channel slope. For the downstream reaches with a meandering planform, the hydraulic drop through the riffles is not as great and the riffles are drowned out during the bankfull discharge so that the water surface profile tends to be smooth, and the effective slope is the same as the average channel slope (see figure 34).

To test the sensitivity of adjusting the average channel slope to account for this, an effective slope was computed based on a slope factor. All other parameters in the unit stream computation were kept the same. The slope factor was determined by adjusting it until the unit stream power was generally of the same order of magnitude as the Middle Hoh reaches. The slope factor ranged between 70 to 87% of the average slope for each reach, which is a reasonable adjustment that could be caused by the woody debris. The slope was also adjusted by a factor of 90% in Reach 5 even though it is in the Middle Hoh reaches because it is a transitional reach and is still steeper than the downstream Reaches 7 and 8.

The adjusted unit stream power computations suggest that the stream power is relatively uniform with distance downstream, except that it is locally high in Reach 6 through Spruce Canyon. Additionally, estimates of unit stream power in 2002 are also very similar to conditions in 1939 even in Reach 7 where the active channel was much wider in 1939 than in 2002.

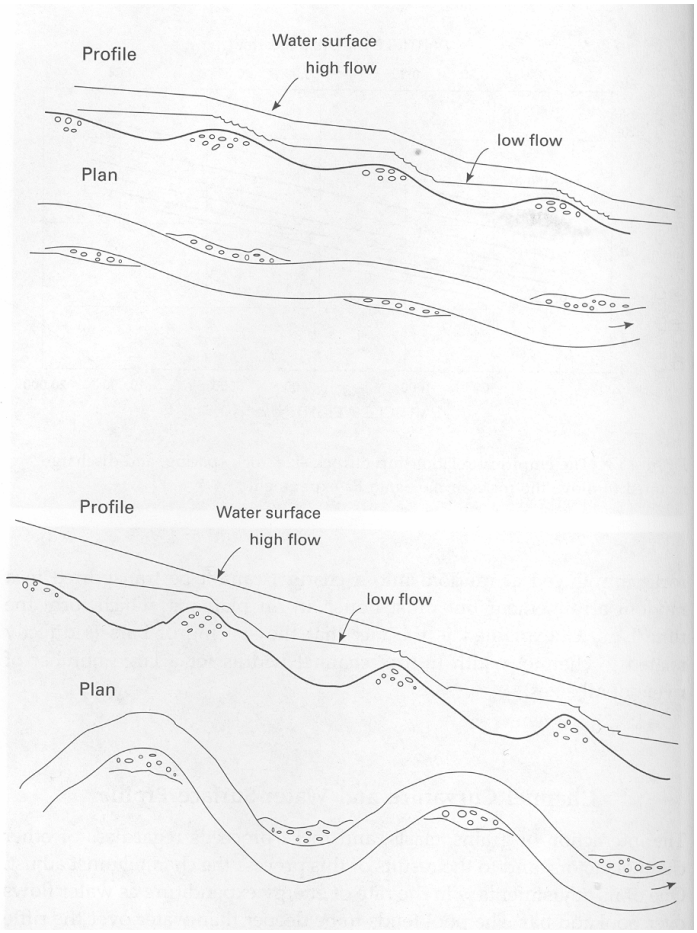


Figure 34. Schematic of bed and water-surface profiles of a meandering (lower half) and a straight reach (upper half) of channel at low and high flows (figure reproduced from p.78, Leopold, 1994).

Figures 35 and 36. Photograph of two locations in the Park reaches showing an area where woody debris is large enough and in great enough abundance relative to the active channel that it likely impacts the hydraulic slope of the river during floods.

Table 10. Computations for unit stream power for study reaches in 2002 and 1939 with adjusted slope factor.

2002 CHANNEL CONDITIONS											
Reach	2-year Flood Peak (ft^3/s)	Active Channel Width (feet)	Average Channel Slope	Slope Factor	Effective Channel Slope	Channel Roughness	Flow Depth (feet)	Flow Area (ft^2)	Flow Velocity (ft/s)	Unit Stream Power, VS (ft/s)	Channel Sinuosity
1	11,040	380	0.00587	70%	0.00411	0.055	5.4	2,064	5.3	0.0220	1.04
2	11,950	490	0.00571	70%	0.00402	0.055	4.9	2,412	5.0	0.0199	1.02
3	13,090	500	0.00547	72%	0.00394	0.055	5.2	2,582	5.1	0.0200	1.07
4	13,720	510	0.00450	87%	0.00391	0.055	5.3	2,683	5.1	0.0200	1.01
5	21,760	470	0.00362	90%	0.00326	0.045	6.8	3,209	6.8	0.0221	1.17
6	21,830	240	0.00370	100%	0.00370	0.040	9.2	2,204	9.9	0.0366	1.04
7	22,950	350	0.00281	100%	0.00281	0.040	8.2	2,868	8.0	0.0225	1.24
8	25,510	400	0.00262	100%	0.00262	0.040	8.2	3,293	7.7	0.0203	1.34
1939 CHANNEL CONDITIONS											
Reach	2-year Flood Peak (ft^3/s)	Active Channel Width (feet)	Average Channel Slope	Slope Factor	Effective Channel Slope	Channel Roughness	Flow Depth (feet)	Flow Area (ft^2)	Flow Velocity (ft/s)	Unit Stream Power, VS (ft/s)	Channel Sinuosity
1	11,040	440	0.00566	70%	0.00396	0.055	5.0	2,213	5.0	0.0198	1.07
2	11,950	420	0.00585	70%	0.00411	0.055	5.4	2,251	5.3	0.0218	1.00
3	13,090	440	0.00556	72%	0.00401	0.055	5.6	2,442	5.4	0.0215	1.05
4	13,720	470	0.00450	87%	0.00391	0.055	5.5	2,597	5.3	0.0207	1.01
5	21,760	510	0.00363	90%	0.00327	0.045	6.5	3,312	6.6	0.0215	1.17
6	21,830	290	0.00375	100%	0.00375	0.040	8.2	2,367	9.2	0.0346	1.02
7	22,950	520	0.00322	100%	0.00322	0.040	6.2	3,225	7.1	0.0229	1.08
8	25,510	470	0.00282	100%	0.00282	0.040	7.3	3,436	7.4	0.0209	1.24

11.0 RISK OF FUTURE EXPANSION OF HISTORICAL CHANNEL MIGRATION ZONE

Expansion of the HCMZ is a natural process that results from a continually changing, dynamic river channel. However, the risk of erosion can be increased by human activities that diminish the erosion resistance of floodplains and terraces or by direct manipulation of the active river channel.

In addition to delineating the HCMZ, the potential risk of lateral expansion along the HCMZ boundary in the near future was estimated. This section identifies the risk of erosion based on the potential of a given bank to erode and on how soon the river is expected to erode it. This risk analysis is meant to help identify which areas along the HCMZ may need monitoring or management action in the near future based on where the river is expected to change its present course. It also shows which areas may be at low risk for river erosion, even over a long period of time, because the river may never be likely to flow against these banks. Historical rates and locations of channel change and bank erosion were used to predict where future bank erosion and channel changes may occur in the next several years to decades, depending upon the magnitude, duration, and frequency of future flood events. The next section of the report uses this risk assessment to delineate a maximum extent of possible future HCMZ expansion over a time scale of a few centuries.

For sections of the HCMZ boundary at risk of erosion, the extent and rate of lateral erosion are affected by the characteristics of the bank along the boundary of the HCMZ, the amount of time the active channel runs against the boundary, geologic features in the valley that may limit expansion or active channel paths, river discharge (number of floods), river slope, sediment and large woody debris deposition, bank vegetation, and land use within and along the boundaries of the HCMZ. The toe of the valley walls represents the maximum possible geologic limit of future lateral expansion since the walls are generally composed of bedrock that is not easily eroded. However, in many areas the river is a substantial distance from the toe of the valley wall and it is unlikely that the expansion would continue that far given the existing discharge, slope, and sediment load of the river, and other geologic controls (e.g. at the reach boundaries) that have remained stable for almost a century.

11.1 Potential for HCMZ Expansion in Study Reaches

The Park reaches have more than one low-flow channel with several areas containing mid-channel sediment bars, woody debris and vegetated islands. They also have lower magnitude peak discharges because they are upstream of the South Fork confluence, and greater percentages of large woody debris within the HCMZ and along its boundary. This woody debris creates roughness and stable hard points both in the HCMZ and along the boundary, and helps to dissipate energy and lower velocities during floods (Herrera, 2004). Locally around the woody debris, scour holes and erosion can also occur depending on the orientation and size of the woody debris. The log jams create riffles and rapids that lower the hydraulic slope within the reach. So even though the overall

bankfull slope of these reaches is steeper than outside the Park, the energy is decreased because there is less flow and there is a large amount of wood within the HCMZ that creates roughness. Additionally, the area of HCMZ most often reworked by the channel is in the center of the HCMZ rather than along the boundaries (Appendix I). These factors help limit the potential for expanding the HCMZ in the Park reaches.

Reach 1 has steep alluvial fans with coarse-grained sediment that reach the mainstem Hoh River and confine it on either side. Virtually no measurable expansion of the HCMZ has occurred in Reach 1 between 1939 and 2002. Reach 2 is different from the other reaches in Olympic National Park because historically there has been manipulation of the channel and floodplain in the vicinity of the Rainforest Campground to maintain safe access to visitors. This will be discussed more in Section 12, but the general impact is that potential channel paths are limited due to existing riprap that has been placed along alluvial banks within the HCMZ to cut off historical channel paths. This channel path was shown as active in the 1918 map and appears to be an overflow channel in the 1939 aerial photography. While most areas of Reach 2 have a fairly stable HCMZ boundary, across from the campground erosion rates have been higher than in other areas of the Park. In most areas of Reaches 2, 3, and 4 within the Park the rates of expansion are expected to remain low relative to reaches outside of Olympic National Park because of their historical behavior, the difference in the amounts of old growth forest along the boundary of the HCMZ, the amount of woody debris within the HCMZ, and the lower flow magnitudes upstream of the confluence with the South Fork. However, even small amounts of erosion can pose management problems when roads or other infrastructure are located adjacent to the HCMZ boundary. In areas where clearing of old growth forest has occurred between the road and river, additional erosion may occur that may not have been likely in a natural setting.

In the more sinuous Reaches 5, 7, and 8 in the Middle Hoh, the active channel follows a meander migration cycle where the meanders typically move both outward and downstream. At times the meanders migrate into the HCMZ boundary and these reaches are the areas where the most expansion of the HCMZ has occurred in the study area (see figure 26). Reach 5 appears to be a bit of a transition reach between the upstream Park reaches and the downstream meandering Reaches 7 and 8. The active channel in Reach 5 is more meandering than upstream reaches, but the meanders have less width and the bankfull slope is steeper than in the downstream Reaches 7 and 8. Portions of the HCMZ in Reach 5 are bound by large alluvial fan deposits which are difficult to erode, but many other sections are composed of erodible alluvium and glacial deposits that have eroded in the past and have the potential to continue eroding if the channel runs against them in the future.

In Reaches 7 and 8 historical rates of channel migration can be used to help predict the rate of future migration, but limitations on additional expansion of the HCMZ must also be considered. As the meander amplitude and channel length have increased in these two reaches, the slope as also decreased. At some point the potential for expansion of the HCMZ and new channel paths will be limited. This is because the channel length cannot extend past a point where the slope is so low that the sediment transport capacity is

reduced to a point where sediment deposits in the channel path and the river cuts off the meander bend. If this is correct, the future expansion of the HCMZ may be at much slower rates than historical amounts. Therefore, the future channel paths may be similar to historical paths given the geologic constraints at the reach boundaries and natural and human-placed bank armoring along the HCMZ in between the upstream and downstream boundaries.

11.2 Methodology for Assigning Risk of Erosion along HCMZ Boundary

The following discussion provides an overview of the methodology used to assign the risk of erosion to the HCMZ boundary. A more detailed discussion with additional documentation is provided in Appendix G. The risk of HCMZ expansion was developed using the following three steps:

STEP 1: Assess the likelihood that bank erosion will occur in the future along reaches of the HCMZ boundary (figure 37). Likelihood categories include: very low, low, moderate, high, and actively eroding.

STEP 2: For reaches actively eroding or likely to erode, estimate the potential rates at which bank erosion could progress (figure 38). Potential erosion rate categories include slow, medium, or fast.

STEP 3: Combine the likelihood of erosion and the potential erosion rates to determine the relative risk for expanding the HCMZ boundary (table 11).

11.2.1 Likelihood of Future Bank Erosion

The likelihood of bank erosion along the HCMZ boundary (STEP 1) is primarily dependent upon two main factors: (1) the properties of the material in the bank, and (2) the bank's location relative to existing or potential mainstem and side channel locations of the Hoh River. Bank material properties were subdivided into five categories of erosion likelihood ranging from very little potential to erode, such as bedrock, to a high potential to erode, such as fine-grained glacial outwash.

The general categories of bank material and their associated erosion potential are listed below (see Appendix G for more details on characterization of bank materials):

- Bedrock – Erodibility: VERY LOW
- Human-placed bank protection – Erodibility: VARIABLE
- Alluvial fan deposits – Erodibility: LOW to MODERATE
  Type 1: Steep, alluvial fans located at toe of valley wall with large sized-material (cobble and boulder) – Erodibility: LOW
  Type 2: Alluvial-fan deposits present on terrace surfaces with sand to cobble-sized material – Erodibility: MODERATE
- Alluvial and glacial deposits – Erodibility: MODERATE TO HIGH

Likelihood of erosion is also dependent on whether the main channel or a primary side channel of the Hoh River is currently at or has the potential to flow adjacent to the bank.

The greater the erodibility of the bank material and the greater the chance the river will run against the bank, the higher the likelihood of erosion. For example, if the material in a bank is unconsolidated (loose), glacial outwash (fine sediment that has the potential to be easily eroded) then the bank would have a high potential for erosion. However, the likelihood of erosion would only remain high if the river had a high likelihood of running against the bank in the near future. Historical channel paths and features that may limit channel changes (bedrock, geologic controls, log jams, alluvial fans, etc) were used to estimate the likelihood of potential future channel paths along a given terrace bank.

11.2.2 Potential Rate of Bank Erosion

The potential rate of bank erosion (STEP 2) was determined to assess the relative rate at which a bank might laterally erode. Rates were broken into three categories including slow, medium, and fast. The potential erosion rate is dependent on two main factors: (1) the characteristics of the bank along the HCMZ boundary (bank material, and (2) the vegetation and land use within and on the surface adjacent to the HCMZ. Estimated rates were checked to see if they were reasonable by comparing them to observed historical rates of lateral erosion in areas with similar conditions.

Certain features along the HCMZ boundary may not completely prevent lateral erosion, but at the same time have significant capability to limit the rate at which it occurs. For instance, surfaces along the boundary with old growth forest or large-diameter trees may slow expansion of the HCMZ by providing protection to the eroding bank when the vegetation is at the water surface-bank interface (Beeson and Doyle, 1995). Alluvial fans that provide recurrent additions of sediment can also limit the expansion of the HCMZ boundary, particularly when the sediment is composed of large material (cobbles and boulders). The height of banks along the HCMZ boundary can also limit the rate of lateral expansion because as banks get taller, the rate of expansion often slows due to the increase in bank material volume per unit width (Beeson and Doyle, 1995). This is supported by the historical rates of bank erosion measured along the HCMZ between 1939 and 2002 in the study area. For example, banks along the HCMZ of the Hoh River that are composed of alluvium primarily have heights ranging between 6 to 15 ft, whereas HCMZ banks that are composed of glacial sediments (mostly outwash and lacustrine sediments) have heights >15 ft. Some glacial banks in the study area are over 100 ft high. Although both the alluvial and glacial deposits are unconsolidated and may be easily eroded, the banks composed of glacial deposits would have a slower rate because of their greater height. Human activities can increase or decrease the potential and rate of erosion along the boundaries of the HCMZ. For example, clearing of vegetation within the active floodplain can increase the rate of channel changes, result in higher velocities due to decreased roughness, and ultimately increase the potential for lateral erosion.

11.2.3 Influence from Human Activities

Clearing of vegetation along terrace surfaces can increase rates of HCMZ expansion if the trees are of adequate size to remain stable along the terrace bank rather than being washed downstream, and if the root wads of the tree are within the area of bank that is

being inundated by the river during floods. In the past there has been limited data available to evaluate whether clearing large woody vegetation has an impact on erosion rates. However, some new studies are being done that provide some indication that clearing can increase rates. Beeson and Doyle (1995) documented that of 748 meander bends studied on four stream reaches in British Columbia, bends without riparian vegetation were nearly five times as likely as vegetated bends to undergo detectable erosion during flood events. The erosion measured occurred in alluvial banks and the woody vegetation consisted of mostly cottonwood trees, with some aspen, cedar, spruce and fir trees also prevalent.

Herrera was able to document that old growth trees of at least 21" in stem diameter slow the rate of HCMZ expansion in Olympic National Park reaches (written communication, 2004). Additionally, the data provided in this study may show some indication that clearing of old growth trees along the HCMZ terrace banks adjacent to the river increases the amount of natural HCMZ expansion, although the exact amount of increase caused is not known. Without having any additional information, it was assumed for this risk analysis that terraces bounding the HCMZ that have been cleared of old growth trees could be eroded at a faster rate than areas that have old growth trees. For the Middle Hoh, almost everywhere along the HCMZ boundary has been logged at least once before or since 1939, so all of the terrace banks were assumed to fall into the faster rate of erosion category. Human activities can also decrease the potential for lateral erosion, and restrict the boundaries of the HCMZ, such as where stable, engineered bank protection has been placed along terrace banks. This effect is typically very localized, and only impacts channel processes in the immediate vicinity of the protection. On the other hand, areas that are armored with bank protection are typically composed of glacial or alluvial material and have been actively eroded in the past. If the bank armoring is not stable and is eroded by the river, the bank could be highly susceptible to additional erosion in the future.

11.2.4 Assigning a Risk of Future Erosion

The likelihood of future erosion and the potential rate of that erosion along the HCMZ boundary are combined to create "risk categories". The risk categories are summarized in table 11. The categories are intended to provide a tool for resource decision makers to assess and compare the risk of erosion in various reaches of river. For instance, consider a section of river with a HCMZ boundary assigned a high risk of erosion, but at a slow rate. If some critical infrastructure is located very close to the HCMZ boundary, even a slow rate may become a potential management concern if the likelihood of lateral erosion is high. However, if the infrastructure was located far enough away, even though the likelihood of erosion is high, the fact that the rate is slow may lower the priority of managing for potential erosion. In areas of private property, any loss of land may be considered negative, even if part or all of it is due to natural processes, because the property can not be recovered once it is eroded by the river.

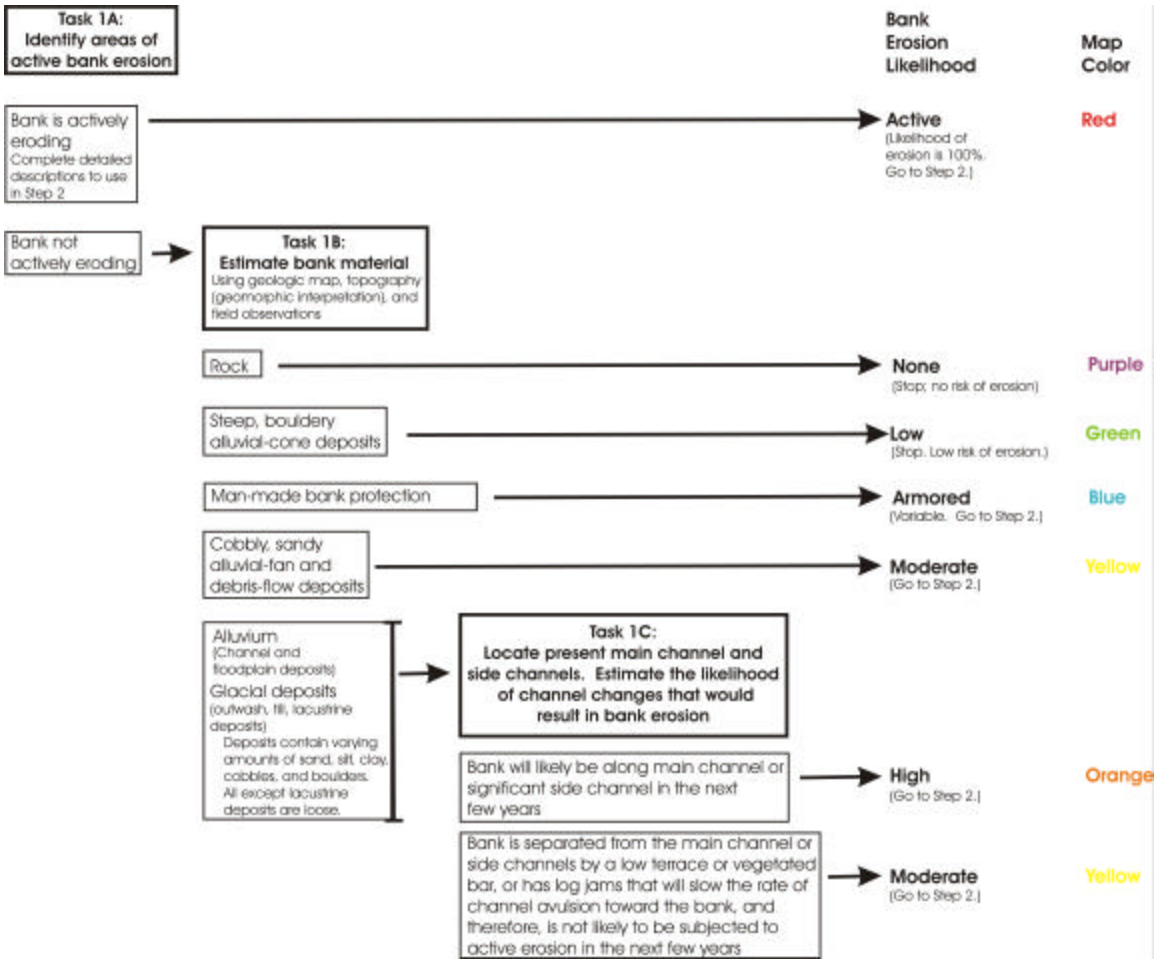


Figure 37. Step 1: Assessment of the likelihood of bank erosion along the HCMZ boundary. Map colors shown refer to colors of risk shown on HCMZ boundary line in aerial photography provided in Attachment 2 of summary report.

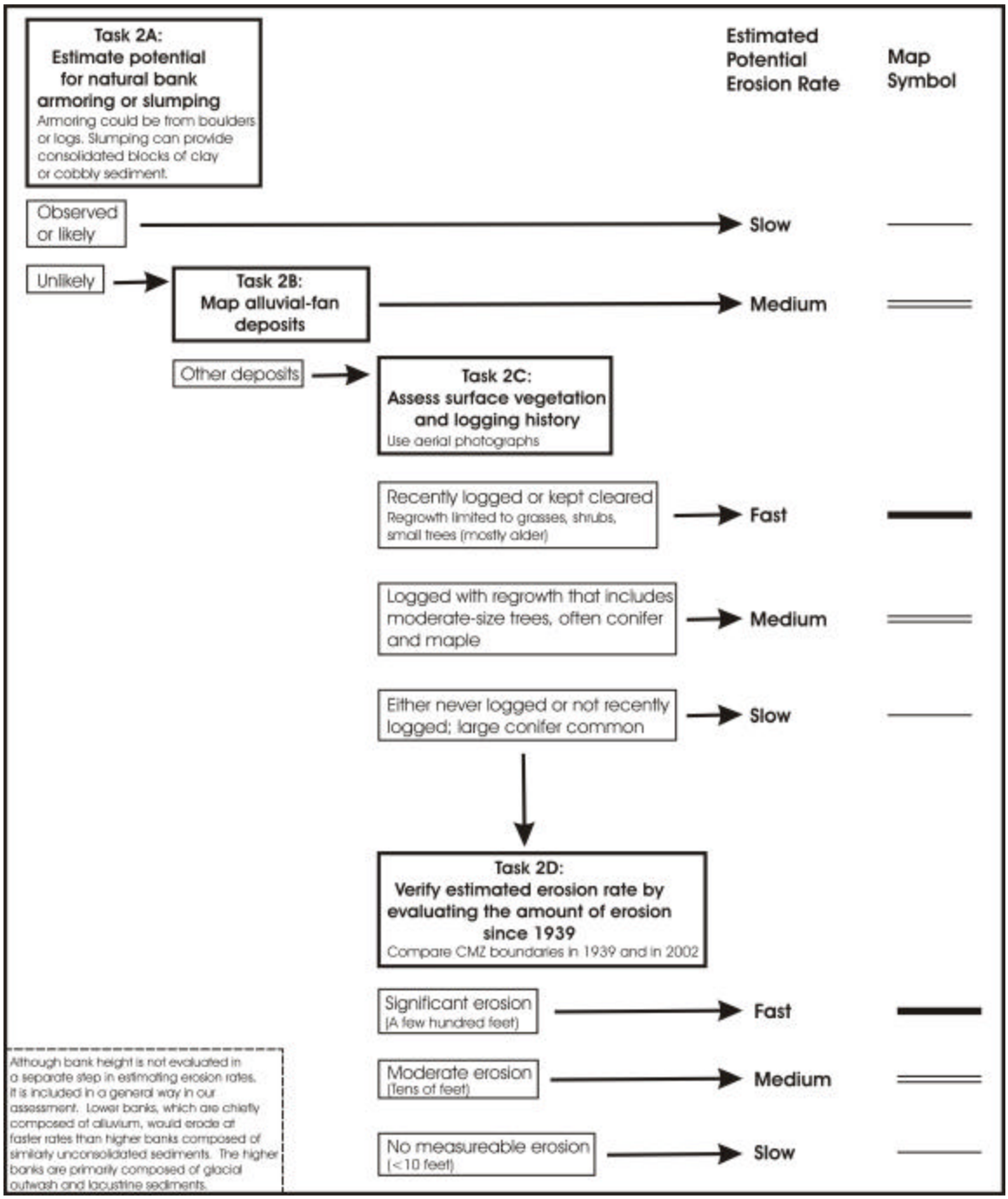


Figure 38. Step 2: Flow chart for determining the potential rates of bank erosion along the HCMZ boundary.

Table 11. HCMZ Boundary Risk Categories Developed From Combining Likelihood for and Potential Rates of Future Erosion

Potential Erosion Rate[2]	Likelihood of Erosion with Present Conditions[1]		
	Active Erosion	**High Likelihood of Future Erosion**	**Moderate Likelihood of Future Erosion**
Fast Rate	**Active_fast:** Evidence for recent lateral erosion[3]; bank has potential to erode several hundred feet over the next several decades	**High_fast:** Terrace bank consists of erodible material and is presently along a main channel, or in an area where a change in channel position is likely and would result in the channel being adjacent to the terrace bank; bank has potential to erode several hundred feet over the next several decades	**Moderate_fast:** Terrace bank is composed of erodible material and is in an area where a change in channel position is possible, but not likely in the near future; bank has potential to erode several hundred feet over the next several decades
Medium Rate	**Active_medium:** Evidence for recent lateral erosion[3]; bank has potential to erode several tens to a few hundred feet over the next several decades	**High_medium:** Terrace bank consists of erodible material and is presently along a main channel, or in an area where a change in channel position is likely and would result in the channel being adjacent to the terrace bank; bank has potential to erode several tens to a few hundred feet over the next several decades	**Moderate_medium:** Terrace bank is composed of erodible material and is in an area where a change in channel position is possible, but not likely in the near future; bank has potential to erode several tens to a few hundred feet over the next several decades
Slow Rate	**Active_slow:** Evidence for recent lateral erosion[3]; bank is not likely to erode more than a few tens of feet over the next several decades;	**High_slow:** Terrace bank consists of erodible material and is presently along a main channel, or in an area where a change in channel position is likely and would result in the channel being adjacent to the terrace bank; bank is not likely to erode more than a few tens of feet over the next several decades;	**Moderate_slow:** Terrace bank is composed of erodible material and is in an area where a change in channel position is possible, but not likely in the near future; bank is not likely to erode more than a few tens of feet over the next several decades;

[1]Terrace bank material for active, high, and moderate erosion likelihood is chiefly unconsolidated and loose sandy, silty, or cobbly sediment. Boulder composition is variable. These sediments are alluvium (channel and floodplain deposits), glacial deposits (outwash and till), and finer sized alluvial-fan deposits consisting of sand and gravel. Where glacial deposits include lacustrine silt and clay, sediment can be consolidated and resistant to erosion. However, banks with this material where seepage is present often fail by slumping and so are unstable.

[2]This is the estimated potential erosion rate assuming that the main channel or a primary side channel, one that carries substantial flow, is adjacent to the terrace bank.

[3] Evidence of recent erosion includes a vertical or overhanging (undercut) bank, exposed roots, lack of vegetation, toppled or disturbed trees (usually alder) or shrubs, slumps, or water issuing from bank, usually just above a clayey silty bed.

12.0 FUTURE CHANNEL MIGRATION ZONE

While not every place on the HCMZ is expected to erode, there are several areas that are more prone to future erosion as a result of the channel running against the boundary. The likelihood of erosion along the HCMZ and the potential rate of that erosion have been estimated in the eight study reaches to help with prioritization of management issues over the next several years (see figures in Attachment 2 of summary report). While some amount of erosion is natural, land use adjacent to the HCMZ boundary can influence and often accelerate the rate of erosion. It is also critical to know where property and infrastructure are at risk for being washed out to help keep residents and critical infrastructure out of harm's way. Therefore, it has also been requested to define the extent of potential erosion areas along the HCMZ over a longer timeframe than what is discussed as the risk assessment in Section 11. While not all the information needed to answer this question is available at the present time, an attempt was made to define the potential "future" HCMZ boundary. The timeframe chosen for the future HCMZ was approximately the next few centuries or until there is a major climate change. A major climate change could induce channel aggradation or degradation and force the evolution of a new channel migration zone.

It is important to note that the future HCMZ includes all areas that have the potential to erode over the next few centuries, but it is not expected that all of these areas would erode. The total amount of area eroded between 1939 and 2002 represents a time period of 63 years. The future erosion areas are typically 4 to 10 times the size of the historical erosion areas. It is difficult to know if the future erosion will occur at the same rates measured between 1939 and 2001, but if it did the estimated future erosion area could account for a time period between 250 to 600 years. Which areas actually erode depends on the alignment of the river channel and the length of time it is present against the HCMZ boundary. Because it is not known which specific areas may erode out of the identified potential future erosion area, all areas estimated to be susceptible to river erosion are included.

12.1 Assumptions Made in Determining Future HCMZ

The first assumption made is that the present land use within the valley and within the HCMZ will not substantially change, particularly in the floodplain and areas adjacent to the HCMZ boundary. This is a critical assumption because such changes could influence the rate and extent of erosion. For instance, if an area along the HCMZ that had never been cleared of old growth vegetation in Olympic National Park was suddenly cleared, it would impact the predicted rates at which that portion of the HCMZ boundary could erode. Another example is that if log jams or vegetation of substantial size were removed within the HCMZ, it could impact the rate of channel migration and the rate at which erosion could occur.

The second assumption made is that the climate and coarse sediment supply to the river would remain relatively consistent. If the sediment load or size distribution supplied to

the river significantly changed, it would impact predicted future channel alignment and form. This would impact the potential for erosion along the HCMZ.

The third assumption made was that the Park and County Roads, and the Rainforest Campground would not limit expansion of the historical channel migration zone. In the past, the river has jeopardized, and in many cases washed away, sections of the Park and County Road and portions of the Rainforest Campground (in addition to private property). In some cases the road was armored and rebuilt back to its original location which kept the HCMZ boundary the same. In other cases, the river washed out the road and the road was rebuilt further away from the river, which allowed expansion of the HCMZ. It is not possible to know which scenario will occur in the future where the road or campground area is jeopardized, so it is assumed that these areas could be eroded. If the terrace surface adjacent to a road or campground is protected before being eroded by the river or rebuilt after erosion, the future channel migration zone would be limited to the present location of this infrastructure.

In areas where bank armoring exists on the HCMZ boundary (including private property), it is assumed that bank protection could be washed out because it is an area where past erosion by the river has been an issue. Where the bank protection is aligned in such a way that the river may be directed at the downstream portion of the bank protection as the channel migrates across the HCMZ, it is particularly subject to being eroded by the river. In property areas that are not armored, it is also assumed that these banks could be jeopardized by erosion from the river. If these banks are armored in the future or current riprap maintained this could change the interpretation of the future HCMZ depending on the stability of the armoring and the potential for the river to wash it out.

12.2 Determining the Future HCMZ

The extent of the future HCMZ boundary at each location was determined by four factors:

1. Likelihood that channel would run against boundary and induce erosion based on historical channel paths and geologic controls at reach boundaries (see Section 11)
2. Historical rates of erosion along the HCMZ with similar characteristics as the area being evaluated. Characteristics used to determine similarity include:
    a. Bank material (alluvium, glacial, alluvial fan, bedrock, etc)
    b. Land use adjacent to bank (cleared, old growth forest, road, etc)
    c. Channel form (multiple channels or single sinuous channel)
3. Potential impacts on expansion of HCMZ including:
    a. Human-placed bank protection along current HCMZ
    b. Areas where HCMZ has been constricted by cutting off or isolating the river from historical active channel or floodplain area
    c. Natural geologic hard points including valley wall, stable reach boundaries, alluvial fans, and bedrock that would limit expansion

4. Sediment transport capacity requirements that would limit the potential length of the channel within a given reach so that the slope would remain steep enough to maintain transport capacity of present sediment load.

The likelihood of the channel running against the bank was determined and incorporated into the risk assessment discussed in Section 11. The historical rates of erosion were used to estimate the potential rate of future erosion. For each area that has eroded since 1939, the maximum lateral erosion width was measured to determine the most conservative (highest amount) of erosion that had occurred. The erosion areas were categorized as to bank material type and what, if any, human activities occurred that may have impacted the erosion rates.

The Hoh River is dynamic and changes alignment frequently. In addition to computing the historical annual rates of erosion, another way to estimate potential future erosion rates would be to divide the maximum erosion distances by the number of years the river ran against the bank to get a potential rate in feet per year. However, with the exception of the reach boundaries, the river will not continually run against the same portion of the HCMZ. This would mean the computed rate would over predict future erosion if extrapolated over a 100-year timeframe. Instead, the average annual rate of erosion was computed by dividing the maximum lateral erosion distance into the HCMZ at each area by 63 years, the period between 1939 and 2002 for which the total erosion occurred. This number better addresses the issue that the channel is not always running against the bank and at least represents the erosion rate over the longest time period available.

There were a total of 19 areas that have eroded between 1939 and 2002 along the HCMZ boundary from which measurements could be made. The maximum lateral erosion distance for each area was measured to represent the possibility that this maximum distance could occur at other locations, although it is unlikely to occur everywhere along the HCMZ. The measured erosion areas occurred over short periods of time (not the entire period between 1939 and 2002) while the river was running against a particular bank. In some cases the river only ran against a HCMZ bank once between 1939 and 2002, and in other cases it ran against it two or more times in this time period. In order to estimate future erosion rates, an assumption was made that the total erosion that has occurred between 2002 and 1939 for a given area would represent the total erosion that could occur in the future over the same period of time. So, rather than dividing the total lateral erosion over the time period it actually occurred, each distance was divided by 63 years (2002 – 1939) to compute the average historical rate of erosion in feet per year for this longer time period (63 years). This rate was used to compute the total erosion that may occur over a long time period into the future. It does not represent the actual rate at which the bank may erode in the future when the river runs against it.

The areas were categorized based on bank material and whether they had direct or indirect human impacts. The distinction between direct and indirect human impacts is important because human activities may influence the rate of bank erosion not only locally on the bank where the activity is occurring (direct), but also in a nearby area on a downstream or adjacent bank from where the activity occurred (indirect). A direct

human impact would be considered to happen directly adjacent to the area that eroded such as clearing of vegetation up to the HCMZ boundary. Of the twelve areas that had direct human impacts, seven of the areas had visible clearing in the 1939 photograph and all but one of the twelve areas had significant clearing evident by the 1960 aerial photograph. An indirect human impact would include an activity such as bank protection or channel constriction in the vicinity of the area that eroded that directed the channel in such a way that it induced erosion on an opposite or downstream bank.

Table 12 shows the range of potential maximum erosion rates computed from historical data for each of the categories. The majority of historical erosion areas (1939 to 2002) occurred in alluvium or glacial banks.

Table 12. Potential future erosion rates along HCMZ boundary categorized by impact from human activities.

Bank Material	Maximum potential future erosion rates (ft/year)[1]		
	No Human Impact	Indirect Human Impact	Direct Human Impact
Alluvium (15 areas)	1.1 to 4.8	6.2 to 6.8	1.0 to 28.1
Glacial (2 areas)	No data	No data	6.3 to 9.5
Alluvial Fan that Extends Into River (2 areas)	3.2	3.3	No data

Rates are based on maximum historical measured rates of lateral erosion along the HCMZ for each erosion area documented between 1939 and 2002.

In areas that have not eroded since 1939, but were estimated to have a moderate or high likelihood of eroding in the future, the data in Table 12 was used to estimate potential future erosion rates based on similarity to the areas that have already eroded. Although there is no evidence of erosion along the banks in these areas since 1939, it is interesting that the HCMZ boundary has evidence of historical meander bends eroding it. This can be seen by the alignment of the boundary that shows curved escarpments where it is likely that the outside of a meander bend expanded the boundary just as has been observed in many areas since 1939. Using the data for alluvial terrace banks was the most straightforward because the majority of banks are low in elevation and of similar composition. Applying the historical rates in glacial banks was more difficult. Each glacial bank had to be evaluated individually based on height, slope of bank, composition of large material in bank, and whether the bank had begun to erode. Glacial banks that are presently eroding are typically less stable than banks that have not begun to erode and still have significant vegetation that helps stabilize the bank. In addition, glacial banks that are presently eroding and are still fairly vertical may continue to erode until a stable slope is achieved, even with additional erosion at the streambank. The potential for an alluvial fan to erode was determined by the distance between the valley wall and the toe of the fan where it extends out into the channel and the size of the source drainage.

In areas that have already eroded since 1939, potential future erosion was estimated based on the existing geomorphic characteristics of the bank. In some cases it made sense to extrapolate the historical rates of erosion into potential future rates. In other cases the

bank has eroded to a point where the existing characteristics and position limit future erosion so a new rate would need to be estimated.

In certain sections there were no physical features that might limit the extent of potential future erosion. In other areas, the future erosion could be limited because of human-placed features, natural constraints, or the need to maintain sediment transport capacity. Human-placed features that were assumed to limit erosion include areas of bank protection. Natural features that would limit or stop additional erosion were the toe of the valley wall, bedrock, higher elevation terraces encountered, and areas along the HCMZ that have resisted erosion since 1939 even when the river was directed straight at them. For some of the areas that have resisted erosion since at least 1939, it is not always known what physical feature of the bank prevents erosion and more detailed bank analysis would need to be done in the field to determine this.

The limitation of sediment transport capacity was more difficult to incorporate. Given that the river must pass through geologic controls at the reach boundaries, it is logical that the river can not flow all the way to the valley edge in every location and still pass through the geologic controls. This is because as the river length increases, the slope of the river decreases. At some point the slope becomes so flat that the river can no longer transport sediment and it will cut itself off. While it is not known what the exact limit is, the HCMZ is widest in Reaches 7 and 8 which may help estimate the limit of potential expansion. If the assumption is made that the reach boundaries also represent vertical as well as horizontal controls on the river, the drop in elevation between boundaries within each reach would be the same over time.

Using this assumption, the slope of the river can be computed and compared based on dividing the drop in elevation from the 2000 survey (or USGS DEM data where survey data was not available) by the channel length as measured from the historical aerial photography. In both Reach 7 and 8, the belt width of the meandering channel has expanded to a point where it is estimated the slope is presently flatter than it has ever been (see table 5). The 2002 aerial photograph indicates that the channel in both of these reaches is nearing a cutoff because it is migrating slightly upstream. If this is the case, the width of the HCMZ may represent a limit on potential expansion of HCMZ in any reach downstream of the South Fork where the discharge is of the same order of magnitude. The current maximum width of the HCMZ in Reaches 7 and 8 is 3300 feet. The largest meander bend amplitude measured since 1939 was 2600 for Reach 8 and 2800 for Reach 7, which is less than the current width. It is unknown exactly what the maximum HCMZ width could be, but the current width may be close to the maximum because each meander bend is ready to cut off. This allows some future expansion but does not go beyond an unreasonable prediction. In the reaches within Olympic National Park, the predicted expansion rates were much lower and limiting channel length was not an issue.

12.3 Limitations on Future HCMZ Estimate

It has been observed that flood peaks have been higher in recent decades and floods greater than the 2-year flood are happening more frequently than they were in the earlier part of the century. It is not known how this may impact future channel migration rates or if this trend will continue, but it is something that should be incorporated into future analyses as more hydrologic data becomes available. Therefore, it is recommended that operation of the current hydrologic gage at the Highway 101 gage be continued in the future to gather more information about floods occurring in the basin.

Another data gap in determining the future CMZ is the identification of additional terrace boundaries between the valley wall and the HCMZ boundary. The significance of identifying these boundaries is that as the HCMZ erodes laterally, if it encounters a higher terrace the rate at which it would continue to erode would likely be slower than the previous rate. Some of these terrace boundaries were mapped, but more exist that were not mapped due to difficult access or excessive vegetation. Light detection and ranging (Lidar) data has proven to be an efficient tool in identifying terrace breaks and their relative heights in similar large river basins with dense vegetation. The accuracy of Lidar data continues to improve as better data processing techniques are being developed, and the cost per square mile goes down with increase in area mapped. Another option would be to continue field investigation to map additional terrace boundaries, but it is often difficult to survey the boundaries due to dense vegetation. Field investigation would most likely require mapping by hand on aerial photography that could be hand drawn into a scaled GIS system, whereas Lidar would already be geo-referenced so mapping could be done in the GIS system.

One of the assumptions made was that the reach boundaries would continue to remain stable over the next 100 years since they have been stable and controlled river position since at least 1891, 1895, or 1918. In some cases this is easy to understand, such as where bedrock forms the boundaries at Spruce Canyon. In other areas it is not obvious from a simple visual observation what is causing the boundary to remain stable. The reason may be the position of the river as it approaches the boundary, or there may be something stabilizing the bank, such as bedrock or a buried log jam that are not visible on the surface. If additional certainty is required, additional investigation at these locations, such as some detailed mapping, could help further evaluate the potential for future HCMZ expansion at these locations. Dating of the channel deposits (e.g., by radiocarbon techniques) at these locations would give some estimate of when the channel abandoned these surfaces and they became terraces. While this may not necessarily be an indication of how long the boundary will be stable in the future, it would provide more information as to the amount of time the active channels have been flowing between the HCMZ boundary.

13.0 OLYMPIC NATIONAL PARK ASSESSMENT

Four of the study reaches (Mount Tom, Hoh Ranger Station, Snider Creek, and Twin Creek Reaches) are within Olympic National Park (see figure 2). In these four reaches, the Hoh River valley is relatively narrow compared to downstream reaches. The valley slopes are steep, and composed of bedrock, colluvium, or alluvial-fan deposits. The HCMZ occupies a significant portion of the valley. Human impacts are minimal, with the exception of the Park Road and the Rainforest Campground facilities. There has been almost no logging and old growth forest covers the majority of surfaces that bound the HCMZ. Overall, the present channel characteristics within Olympic National Park are, in large part, the same as they were in 1939, and probably much earlier.

A summary of the risk (likelihood and potential rate) for lateral erosion along the HCMZ boundary in the Park reaches is provided in table 13 and shown on aerial photography in Attachment 2 of the summary report. There are several sections of the HCMZ boundary that have a high likelihood of eroding, or are already actively eroding. The majority of rates of erosion in the Park reaches fall into the slow category indicating that when the boundaries do erode they erode small lateral amounts relative to downstream Middle Hoh reaches. However, in many cases even a small amount of erosion by the river along the right side of the HCMZ has resulted in damage to the Park Road. Most of the discussion below is focused on issues along the right HCMZ boundary, because no infrastructure or land use is present along the left side. However, the risk of the HCMZ eroding was still determined.

Table 13. Summary of risk categorization for near future along HCMZ Boundary in Park Reaches 1, 2, 3, and 4.

Risk_Rate Lateral Erosion Category	Olympic National Park Reaches	
	Right HCMZ	Left HCMZ
Active_fast	0%	0%
Active_medium	3%	0%
Active_slow	12%	6%
High_fast	0%	0%
High_medium	5%	0%
High_slow	26%	33%
Moderate_fast	0%	0%
Moderate_medium	0%	0%
Moderate_slow	20%	30%
Low (armored)	2%	0%
Low	32%	31%
Very Low	0%	0%

The most extensive human impacts in the reaches within the Olympic National Park are at the Hoh Ranger Station, the Rainforest Campground, and other facilities near RM 37. Another prominent human-generated feature is Taft Pond, which was created by

construction of the Park Road some time between 1950 and 1977. In addition, the Park Road roughly parallels the right HCMZ boundary between the Hoh Ranger Station and the Park Boundary. For the most part, the road has not influenced the Hoh River channel, but because of its position adjacent to the HCMZ boundary, even limited erosion that boundary could have significant impacts on the road and access to Olympic National Park. One area where the Park Road has impacted the Hoh River channel is near the Park Boundary, where the road restricts movement of the channel along the right bank. This section of river is in the Huelsdonk-South Fork Reach, which is mostly outside of Olympic National Park and will be discussed in Section 14.

13.1 Hoh Ranger Station, Campground, and Taft Creek

The Hoh Ranger Station and campground have been constructed on the right side of the river, both within and outside of the HCMZ. The area has been continually subject to erosion and riprap has been the most commonly used method to limit additional loss of land. Another modification is the blocking of an old channel by a campground road (Loop A) that is clearly visible on the 1977 aerial photograph (figure 39). The channel was part of the active channel in 1918 and appears unvegetated on the 1939 aerial photographs and certainly carried higher flows in previous years. However, the channel was not a part of the main active channel in 1939. A meander in the low-flow channel at the head of the blocked channel in 1977 suggests that the river would likely have reoccupied this historical channel path if the road had not been constructed across its entrance.

Artificially blocking the old channel has narrowed the active channel and prevented migration to the right. This constriction of the active channel likely increases velocity and the potential for erosion along the right banks inside the HCMZ that have been armored with riprap. Across from this location the left HCMZ has also been actively eroding since at least 1977 (figure 40). It is unclear if the constriction actually triggered or accelerated the erosion that may have occurred even without this human impact, but the erosion did start at about the same time the channel was blocked. Because the valley on the left side of the river is undeveloped, continued erosion does not pose a risk to private property or infrastructure. For the right side, although the HMCZ boundary is designated as a low risk of erosion, the areas that have been the focus of protection strategies are actually within the HCMZ.

At least two options to minimize threat to infrastructure are possible for the Hoh Ranger Station area. In order to preserve the lower loops of the campground, the riprap and campground road will need to be maintained. If this is done, and the constriction of the channel remains, then erosion of the HCMZ boundary on the left side of the river will likely continue. Another option is to restore the natural channel at this site by restoring its natural width and removing the riprap and lower campground road. This option would require abandonment of the lower loop of the campground. It might also require modification to the riprap placed by the Corps of Engineers along the road at Taft Creek to prevent future erosion of the road.

At Taft Creek, the Park Road acts as a levee and causes a backwater ponding from water flowing down Taft Creek. Although there is a culvert underneath the road, the ponding still occurs, and, creates what is referred to as Taft Pond. There are several older, large diameter trees in the area of Taft Pond that are being inundated with water on a much more frequent basis than they were historically. The exact impact on the trees is not known, but it is likely that if the pond continues they will not be able to tolerate the high water table and may die out. However, it should be noted that biologists have also observed that Taft Pond has created a unique habitat that could be considered valuable to certain aquatic species. If the road is to be maintained at its present location, the riprap along the lower campground road would need to be maintained to prevent the river from reoccupying the 1918 channel path, which would pose a risk of flooding and erosion to the road. If the road were to be moved at Taft Creek northward, it could be moved closer to or just outside the HCMZ boundary to limit impacts on Taft Creek. A bridge or larger culvert for Taft Creek could be built to restore the natural stream channel, and Taft Pond would no longer exist. This would likely reduce the backwater during high flows into the Hoh Visitor Center hiking loop and into the Taft Pond area, but would eliminate the habitat that Taft Pond creates.

13.2 Olympic National Park Road

The Olympic National Park Road is generally located on the terraces that are beyond or at the boundary of the HCMZ. The Olympic National Park Road is adjacent to the right HCMZ boundary in the Snider Creek and Twin Creek Reaches and in the upstream portion of the Huelsdonk-South Fork Reach (figure 41). The Snider Creek Reach between RM 34 and RM 36.5 (Road Mile Post (MP) 3 to 5.8) has a long, straight channel. Within the active channel zone, individual channels have shifted repeatedly and will continue to do so. A persistent point on the left side of the river upstream of RM 36 (Road MP 5) at the upstream boundary of the reach directs flow to the right. This 1895-ft-long section of the right HCMZ boundary is an area of active erosion. Downstream, between RM 36 and RM 35 (Road MP 5 to 4), the active channel is directed toward the left side of the HCMZ. In this section, gravel bars and low terraces are preserved on the right side of the HCMZ. However, during two floods in October 2003, flow was directed into a side channel adjacent to the HCMZ boundary on river right. This caused erosion of a section of the Park Road, which has since been rebuilt. Between about RM 34 and 34.7 (Road MP 3.5 to 4), the active channel is again along the right side of the HCMZ. At the downstream end of the reach, between RM 33.5 and 34 (near Road MP 3), the active channel is no longer straight, but bends to the right and then back to the left. The present low-water channel also curves, so that it is along and actively eroding a 1245-ft-long section of the HCMZ boundary near Road MP 3.

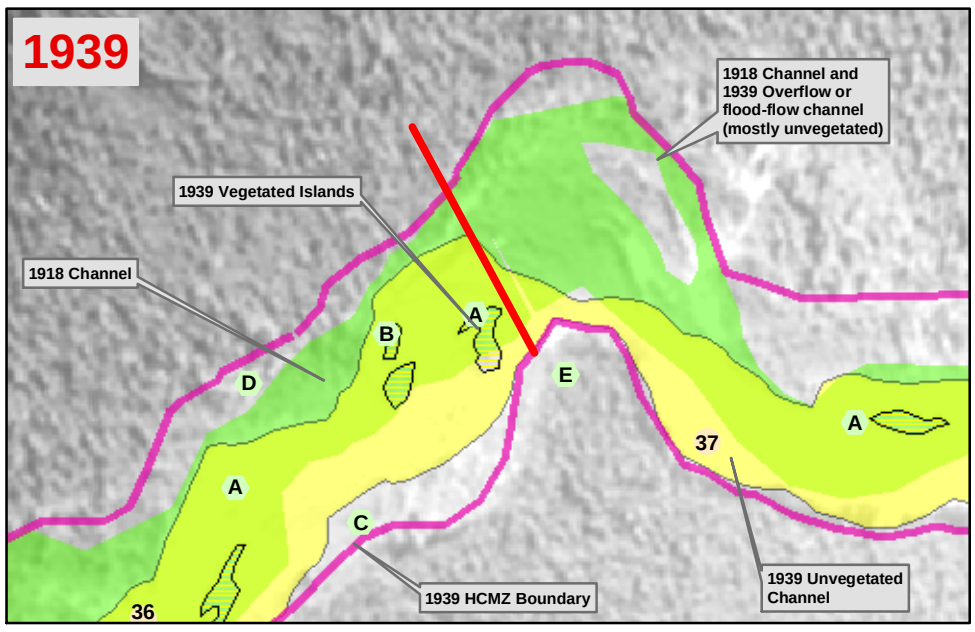
At the upstream end of the Twin Creek Reach, glacial deposits form a ridge about 3.5 km long along the right side of the HCMZ. This ridge, which also forms the valley edge, limits the migration of the active channel to the right. Because the active channel width is restricted at the upstream end, the boundaries of the HCMZ have been fairly stable in this reach. The steep glacial ridge and the Hoh River channel limit the location of the Olympic National Park Road, which is very close to the HCMZ boundary in the upstream

half of this reach. Consequently, even small amounts of erosion of the boundary could have significant consequences for the Park Road. The road has been setback at two locations to the valley edge in this section near RM 33 (Road MP 1.5 and MP 1.7; see figures 3 and 4), and riprap has been added near Road MP 2 (about RM 33.5) and just downstream of Road MP 1 (about RM 31.5) in the upper Huelsdonk-South Fork Reach.

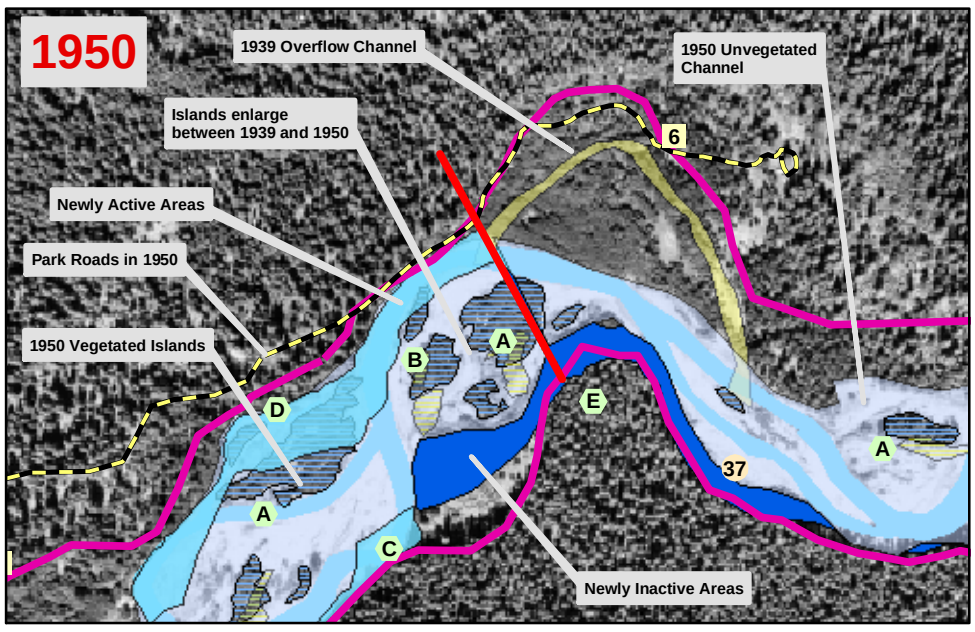
Along the Olympic National Park Road, three sections of the HCMZ boundary are actively eroding: between Road MP 5 to 5.5, near MP 3, and MP 1.5. Erosion will likely continue while the active channel is adjacent to the right HCMZ boundary. The HCMZ boundary between Road MP 3.5 to 4 is not actively eroding, but because the active channel is adjacent to the HCMZ boundary, the likelihood of erosion is estimated as high (figure 41). Because of the proximity of the steep slopes that define the valley edge, the rate of erosion of the HCMZ boundary here is estimated to be slow or medium. However, even a small amount of erosion could adversely affect the Park Road. Moving the road away from the HCMZ boundary, perhaps by 200 ft or to the next terrace, could be considered at MP 3 and between MP 5 to 5.5. This may be difficult in the section near Road MP 1.5, where the road has already been setback, because the road is in between the HCMZ and the steep slope valley edge. During the October 2003 floods, an approximately 150-foot section of the Park Road near MP 5 washed out from river erosion. This area was identified as a high risk of erosion in this study.

13.3 Drainages along the Park Road

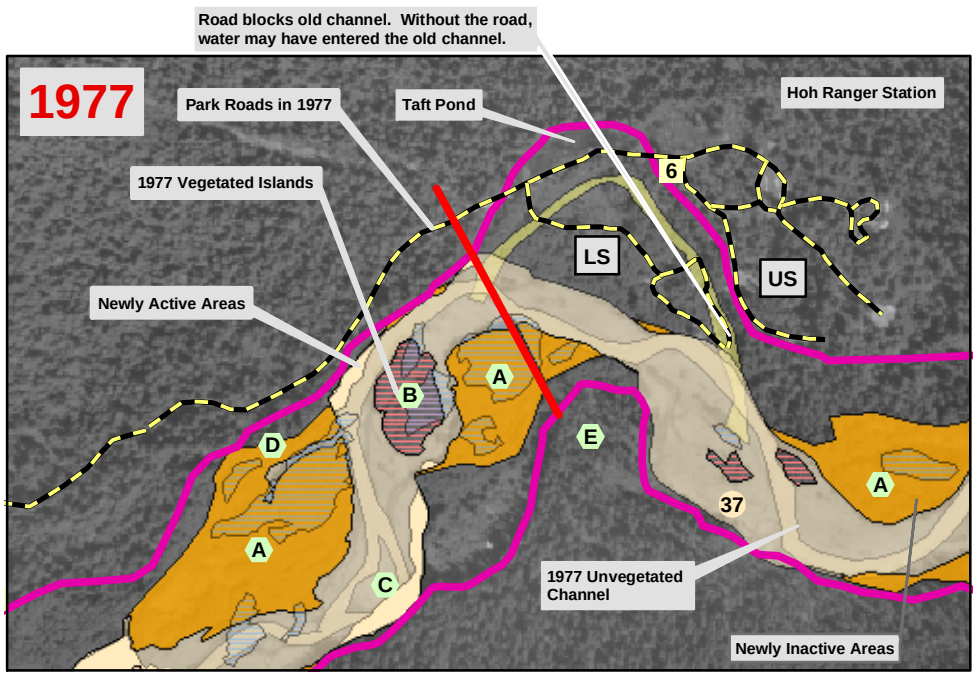
Tributary drainages that cross the Park Road can be a recurrent problem when debris flows occur in the drainages and cannot be effectively passed through the culverts that have been constructed. During the summer 2001, drainages and culverts were examined to identify recent sediment deposits that might indicate unstable conditions where the tributaries intersect the road (figure 42). Some of the culverts were filled or partially filled with sediment, and these may be the ones of most concern. Two culverts along the Park Road had sediment in them: near MP 5.5 at Taft Creek and at MP 0.2 near the Park Boundary. These culverts should be inspected regularly and sediment should be removed when necessary. However, any drainage that has a recent sediment deposit is a site of possible concern. Because we made these observations in 2001, the conditions noted on figure 42 may no longer be present. Another option to consider for management of debris flow crossings would be to replace the culvert with an adequately sized structure that allows for higher volumes of debris flow to be transported under the road and easy clean-out and maintenance when necessary.



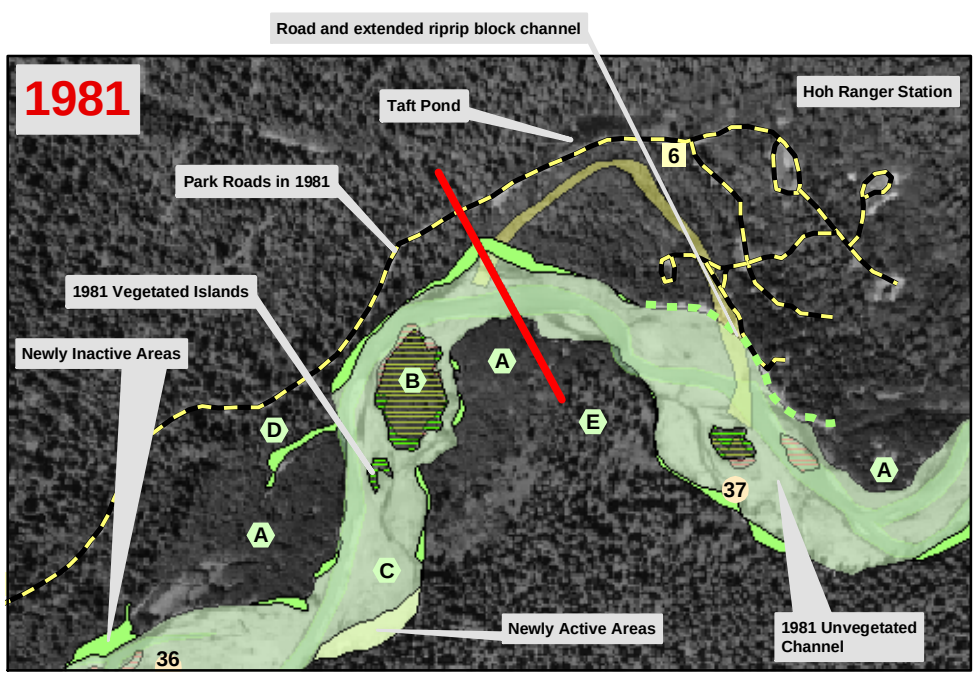
In 1939, neither the campground at Hoh Ranger Station nor the Park Road is present. An overflow or flood-flow channel, which was part of the 1918 channel, is visible in 1939 just downstream from the area of the future Hoh Ranger Station on river right. Because it is unvegetated, the overflow/flood-flow channel likely carried water in 1939, or perhaps 1938.



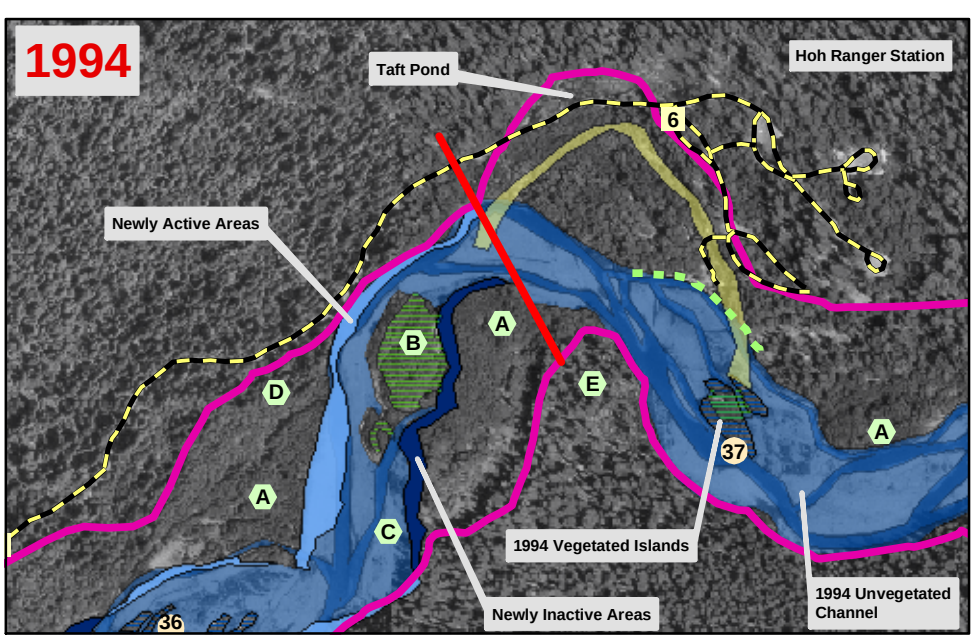
By 1950, work has started in the campground area at the Hoh Ranger Station because logged areas are visible. The Park Road appears to be very narrow and is much less extensive than the present road. Trees are visible in the area that becomes Taft Pond. The 1939 overflow channel appears to have received little recent flow, because the channel is now vegetated. The lack of flow may have occurred naturally, because the main channel is straight and not near the head of the over-flow channel.



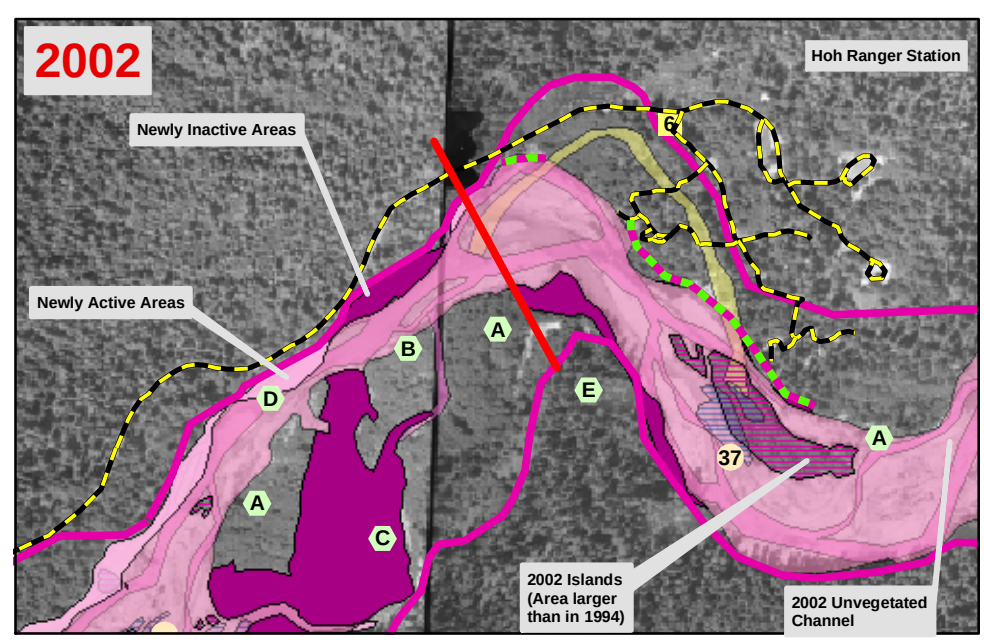
In 1977, the campground is present on an upper surface (US; an old terrace) outside of the HCMZ and a lower surface (LS; the old channel) within the HCMZ. The loop roads in the campground are visible. The road that crosses the head of the old channel (Campground, Loop A) blocks flow into the old channel. A meander in the low-flow and unvegetated channels suggests that the Hoh River might have accessed the old channel in 1977, if the road had not blocked its head. Taft Pond is present. The Park Road appears to be substantially wider than it was in 1950. The Park Road acts as a barrier to flow from the adjacent slope, so that water collects between the road and the slope, creating Taft Pond.



By 1981, riprap has been placed along the the road that blocks the 1939 overflow channel. Riprap extends both upstream and downstream from the channel and bounds the lower campground. The location of the riprap is shown as a dashed, green line within the HCMZ. The low-flow channel has move away from the head of the old channel. Even without the road, flow may not have entered the old channel. Trees in the campground area appear to be larger than they were in 1977 suggesting that logging was not done between 1977 and 1981.



In 1994, the riprap that was visible on the 1981 aerial photograph is still present, but it is covered with trees. More trees have been removed from the campground area.



By 2002, islands have developed along the right side of the HCMZ, and direct most of the flow to the left along the left HCMZ boundary, which is actively eroding (Figure 40).

Letters in light green hexagons show the same localities in all figures: A, Area that was channel in 1939, island in 1950, newly inactive in 1977, and a low vegetated terrace within the HCMZ since 1981; B, Area of persistent islands; C, Area that was part of the channel 1950, but is vegetated and probably a low terrace by 2002; D, Area that was vegetated with trees in 1939, part of the unvegetated channel in 1950 and 1977, vegetated with low vegetation in 1981 and 1994, and part of the unvegetated channel in 2002; E, Area that appears to be resistant to erosion and directs flow to the right (north). The reason for the resistant character of this point is not known.

Numbers in tan circles show river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000.

1,000 500 0 1,000
Feet
N

Figure 39. Changes in the unvegetated channel for time intervals between 1918 and 2002 near the Hoh Ranger Station in Olympic National Park.

Figure 39

Figure 40

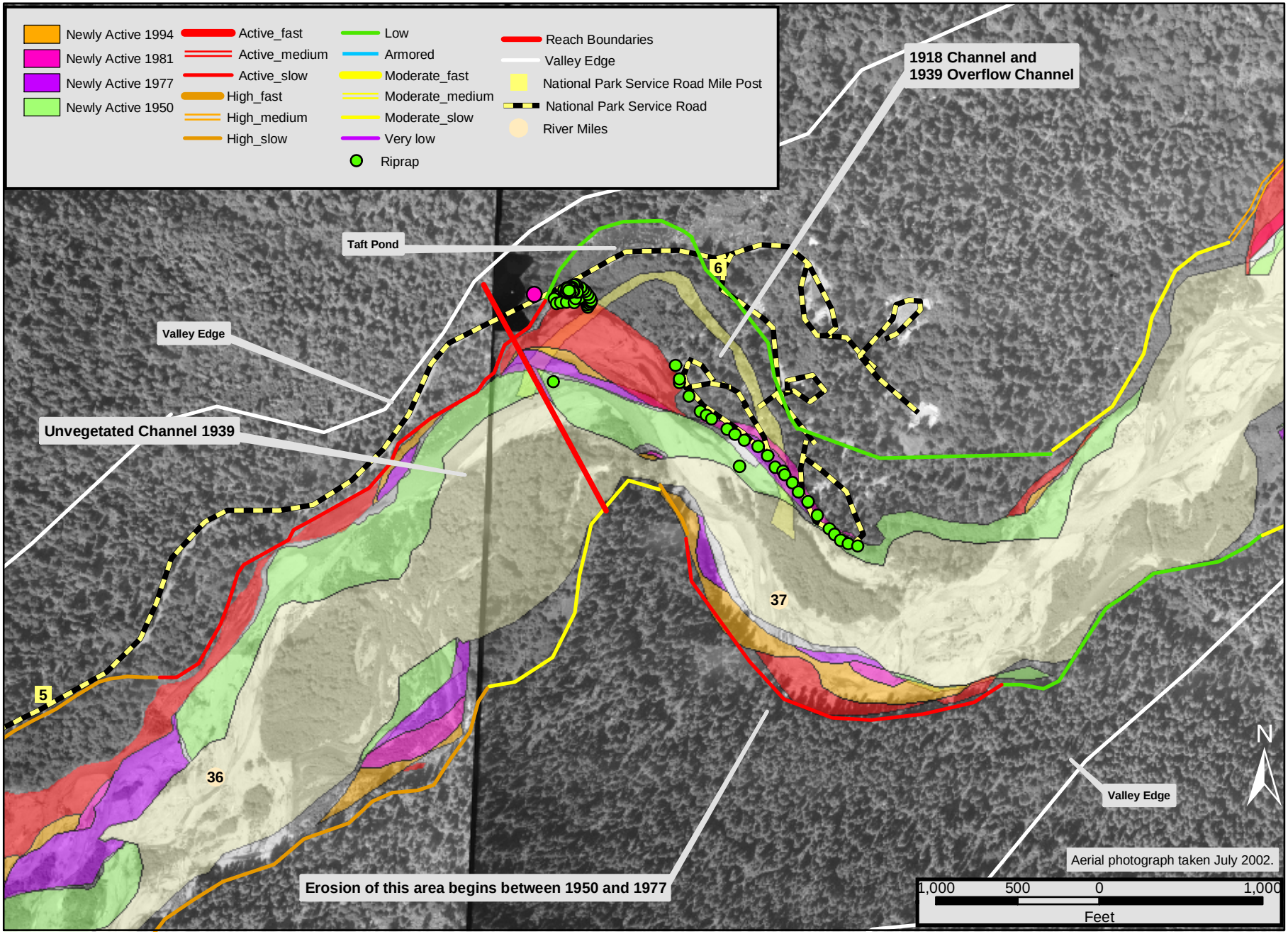


Figure 40. Areas where the unvegetated channel has expanded since 1939 in the Hoh Ranger Station area. The newly active areas are those first visible as part of the unvegetated channel in the year of the photographs as shown and were outside of the unvegetated channel in all previous years. The risk and estimated rate of erosion are shown along the HCMZ Boundary. The actively eroding section of the left HCMZ Boundary near RM 37 began to erode between 1950 and 1977. The lower campground road and riprap along it are within the HCMZ and block flow into the 1939 overflow or flood-flow channel.

Figure 41

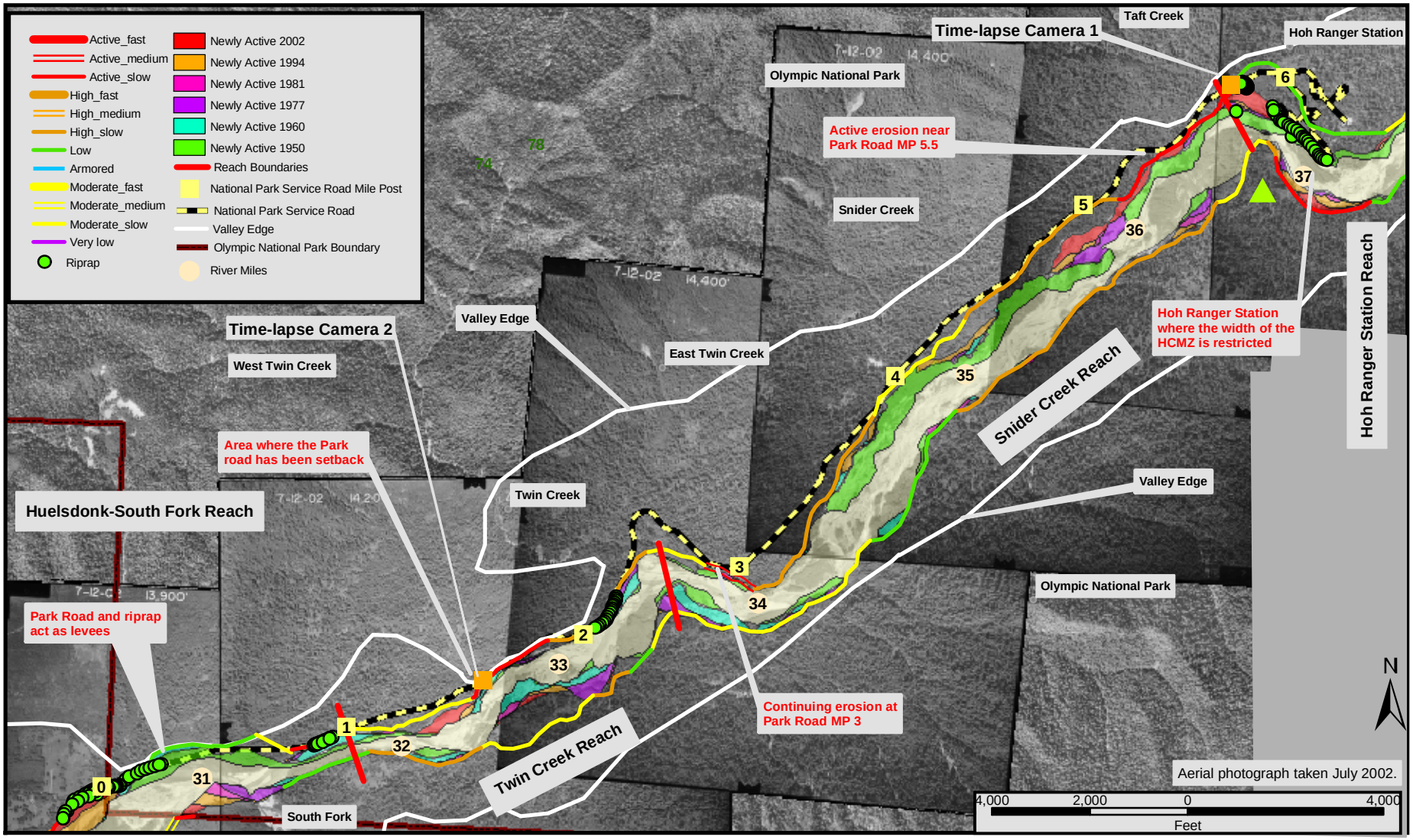


Figure 41. Areas where the unvegetated channel has expanded since 1939 are shown along the Park Road between the Park Boundary and the Hoh Ranger Station. The newly active areas are those first visible as part of the unvegetated channel in the year of the photographs as shown and were outside of the unvegetated channel in all previous years. The estimated risk and rate of erosion along the HCMZ Boundary also are shown for this section. Areas where the Park Road has recently experienced problems are identified by notes in red. The green triangle shows an area that has been resistant to erosion since at least 1939, and, along with riprap on the opposite side of the valley, constricts channel migration. Time-lapse Camera 1 was just downstream of the confluence of Taft Creek and the Hoh River and was looking upstream at the riprap along the right bank. Time-lapse Camera 2, which was located a Park road MP 1.75, was looking upstream at the river channel and erosion of the right bank.

Figure 42

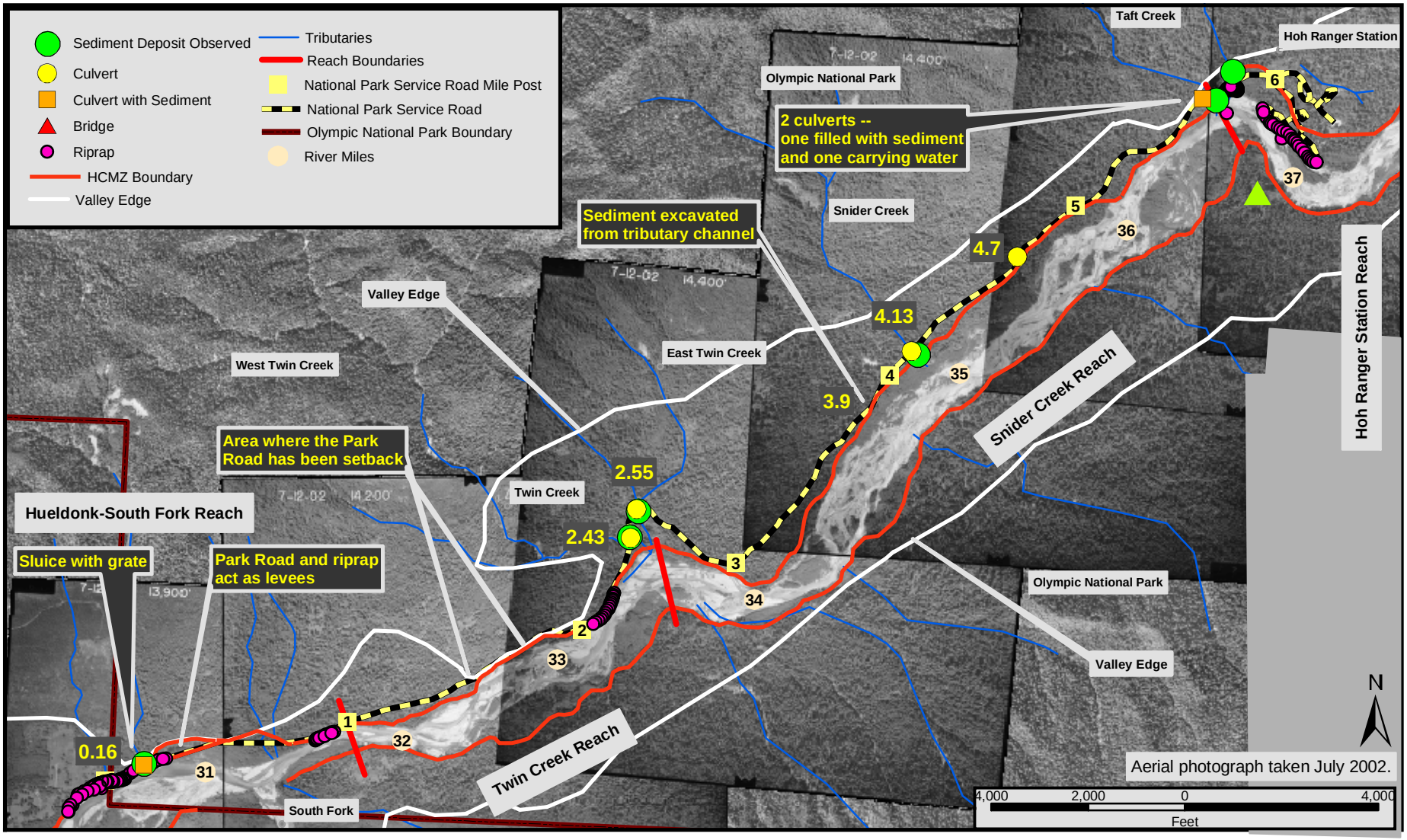


Figure 42. Relatively recent sediment deposits and other features along and near the Olympic National Park Road. The yellow numbers show the road miles along the Park Road. The green triangle shows an area that has been resistant to erosion since at least 1939.

14.0 MIDDLE HOH ASSESSMENT

In the Middle Hoh reaches, alluvium and glacial deposits are present along the majority of the HCMZ boundary. These unconsolidated deposits are eroded by the river at the outsides of meander bends, leaving an irregular configuration of a wider and narrower active channel in areas. The South Fork, the largest tributary of the main Hoh River, enters the main valley near RM 31 at the upstream end of the Huelsdonk-South Fork reach and just upstream of Olympic National Park Boundary (see figure 2). The South Fork has been a significant source of tributary discharge and sediment to the Hoh River. Because of the glaciers in the headwaters of the South Fork and the variability in sediment, the absolute and relative amounts of discharge and sediment supplied by the South Fork vary over time.

In addition to the natural changes that occur in the Middle Hoh relative to the Park reaches, human impacts increase markedly outside of the Park. Many areas downstream from Olympic National Park have been logged (see figure 2). The wider valley and incision into alluvial and glacial deposits have left terraces of several heights adjacent to the HCMZ. The large, flat surfaces are excellent sites for homesteads, some of which were established as early as about 1900. Other activities, such as bank armoring, moving log jams in the river, and blocking or diverting side channels also may have occurred, but are very difficult to document.

The combination of natural processes and human activities in the Middle Hoh has resulted in a wider HCMZ along which unstable boundaries are common. Some sections have eroded markedly since 1939, and other sections have not eroded since 1939 because the river was not observed to run against them. The largest area of lateral erosion of the HCMZ boundary since 1939 occurred at the downstream end of the Willoughby Creek Reach.

A summary of the risk (likelihood and potential rate) for lateral erosion along the HCMZ boundary in the Middle Hoh reaches is provided in table 14 and shown on aerial photography in Attachment 2 of the Summary Report. The risk of erosion categories are fairly evenly spread out along the HCMZ boundaries in the Middle Hoh reaches. There are several sections of the HCMZ boundary that have a fast potential rate of lateral erosion based on clearing of vegetation and measured historical rates of erosion in these areas. All property on either side of the river has a value because it either contains infrastructure, housing, businesses, or is used for timber harvest. Therefore, the risk of erosion will be discussed for both sides of the HCMZ boundary in this section.

Table 14. Summary of risk categorization for near future along HCMZ Boundary in Middle Hoh Reaches 5, 6, 7 and 8.

Risk_Rate Lateral Erosion Category	Middle Hoh Reaches Right HCMZ	Middle Hoh Reaches Left HCMZ
Active_fast	0%	12%
Active_medium	10%	2%
Active_slow	2%	12%
High_fast	13%	12%
High_medium	7%	1%
High_slow	2%	1%
Moderate_fast	11%	11%
Moderate_medium	16%	7%
Moderate_slow	2%	5%
Low (armored)	10%	0%
Low	21%	28%
Very Low	7%	8%

The Jefferson County Road is commonly at risk because of its proximity to the right HCMZ boundary. Sections of the road that are presently vulnerable are near the boundary of Olympic National Park and near Road MP 9.7, both of which are in the Huelsdonk-South Fork Reach, and near Road MP 6.7 in the Morgan's Crossing reach. Even in sections where erosion will likely be minimal or occur at a slow rate, small amounts of erosion could significantly affect the County Road.

14.1 Area near Boundary of Olympic National Park

In the Huelsdonk-South Fork reach, a combination of three factors has resulted in unstable HCMZ boundaries including easily erodible sediment in the HCMZ banks, greater flow and sediment input from the South Fork, and the removal of woody vegetation for homesteads and other development. An area that has been particularly vulnerable to change is at the boundary of Olympic National Park at the upstream end of the Huelsdonk-South Fork Reach. The Park Road between Road MP 0 and 1 and the Jefferson County Road between Road MP 12 and the Park Boundary follow the same alignment and are close to the right HCMZ boundary (figure 43).

The Park Road between the Park Boundary and Road MP 0.5 has been a section with recurrent erosion problems (figure 43). In 1939, the Park Road was adjacent to the HCMZ. But erosion of the active channel along the outside of a meander bend between 1939 and 1950 caused the right HCMZ boundary to erode, and subsequently washed the road out. By 1950 the Park Road had been moved so that it was once again outside of the HCMZ, but closer to the steep slope of the valley edge. By 1960, a slope failure had occurred at the base of the steep slope along which the Park Road was realigned. The slope failure was likely the result of relocating the road closer to the slope. The failure took out a section of the road. By 1977, the road had been realigned to approximately its

position in 1939. However, this realignment placed the road within the expanded 1977 HCMZ and restricted movement of the active channel to river right. By 1981, the active channel moved downstream and began to erode the right HCMZ boundary just outside of the Park and along the Jefferson County Road near MP 12. Downstream of the County Road at Lewis Ranch, erosion occurred between 1981 and 1994, where the surface along the HCMZ boundary had been cleared of trees. The upstream section of Lewis Ranch and the portion of the Jefferson County and Park Roads that have been subject to erosion are now armored with riprap (see figure 44). The section of Lewis Ranch that is armored was partially eroded during an October 2003 flood event, and was again armored following the flood.

Portions of the Park and Jefferson County Roads that are within the HCMZ are slightly raised above the natural terrace surface, making them function as levees during floods. This could increase flood stage of the Hoh River for flows that would otherwise overtop the natural terrace banks and spread out onto the floodplain. However, relative to the active channel the HCMZ is wide in this reach and can convey a large volume of water. The increase in flood stage is likely small relative to the total depth of water in the channel. The Park Road cannot be set back farther without addressing the stability problem of the steep hillslope at this location, which makes alternate management options of the road itself difficult.

Homesteading was observed in a few locations in this area on the cadastral survey maps, and some logging and road building are visible in the 1939 and 1950 aerial photographs. By at least 1977, houses were built within the HCMZ and along its boundary on river left just downstream of the Park Boundary (near RM 30.5). Since at least 1939, the active channel has intermittently flowed along the left side of the HCMZ, and evidence of channels is readily visible on the aerial photographs (figure 43). Between 1939 and 1960, at least one branch of the active channel flowed along this side of the HCMZ. By 1960, the active channel had moved into the middle of the HCMZ. However, between 1977 and 1994, the low-flow channel moved progressively back toward the left side of the HCMZ. By 2002, the low-flow channel had moved back to the right side of the HCMZ. This history of channel movement suggests that the channel will once again occupy the left side of the HCMZ and could affect any development within or along the HCMZ. The left boundary of the HCMZ has been fairly stable since 1939, despite the changes in channel position (figure 44). Portions of the boundary between RM 30 to 31 could erode if the active channel flows along it for a significant amount of time, but since 1939 this has not occurred. Between RM 29 and 30, a large portion of the left HCMZ is composed of alluvial fans that contain large-sized sediment that would be difficult for the Hoh River to erode. For this reason, these sections are categorized to have a low risk of future erosion.

14.2 Area near MP 9.7 Along the Jefferson County Road

At the downstream end of the Huelsdonk-South Fork Reach, the Jefferson County Road near MP 9.7 is adjacent to the HCMZ boundary (figure 45). The active channel curves to the left here, so that the right boundary of the HCMZ is along the outside of a meander

bend. The active channel appears to have flowed along this boundary since at least 1939. The active channel is along the base of a steep, unstable slope composed of glacial deposits. This slope has experienced recurrent slumping, which has impacted the County Road (see figure 9). The slumping may have been initiated by undercutting of the bank by the active channel. In addition, water seeps from the slope and likely contributes to the slope's instability. A separate interim report was prepared to address this site in more detail, but a general overview is provided below (Bureau of Reclamation, 2003).

At least three options could be considered for this section of road, but in order to determine which option is best more information is needed on the mechanisms of slope failure. One option is to move the road up the slope and away from the HCMZ boundary. However, the potential extent of the existing slope failure would need to be determined to examine the potential for initiating slope failure wherever the road would be moved to. Another option is to examine methods for draining the seepage from the slope. If the seepage is a primary contributor to the slumping, then employing drainage methods could be effective in stopping or slowing the slumping. Such methods may be needed to stabilize the slope even in the first option. A third option is to construct log jams in the HCMZ on river right to deflect flow from the slumping bank, and to decrease erosion and increase deposition along the toe of the unstable slope. This option may not stop the slope failures if seepage is its primary cause. If log jams are built downstream of this site, then their influence on erosion of the left HCMZ boundary along Huelsdonk Ranch would need to be considered. Most of the trees along the left terrace have been cleared so Huelsdonk Ranch may be highly susceptible to erosion if the river is directed into it.

14.3 Area near MP 7.7 Along the Jefferson County Road

As the river exits north out of Spruce Canyon, it takes a sharp turn to the west (left) and flows through the Morgan's Crossing Reach. The area directly to the north of the canyon exit has not experienced measurable erosion since 1939, but recently laterally eroded about 90 feet according to Jefferson County personnel observations. The terrace that is eroding contains large-sized sediment and has some woody vegetation on it, but because the October 2003 flood is thought to be the flood of record it may have initiated erosion in many areas that have not seen erosion previously (or at least since 1939). Because this area had not experienced erosion since 1939, and the river has to take a turn to the left to follow the valley alignment it would be anticipated that the potential for additional erosion is limited. However, the Jefferson County Road is now less than a few tens of feet away from the river along at least 1000 feet of the road, and even a small amount of additional erosion could endanger the road. It is recommended that this site be closely monitored for additional erosion and a contingency plan be established if it occurs for the safety of vehicles traveling this direction, particularly at night. Jefferson County has put some bank erosion monitoring pins in at this location to initiate a monitoring plan. Daily monitoring during the winter flood season would be essential, possibly by individuals traveling the road often, such as Olympic National Park service personnel. A setback of the road to the valley edge (about 200 feet) could be considered, but much of the area is wetland due to drainage off the hillside and there may not be room to adequately leave a buffer wide enough that would reduce the risk enough to make the setback worthwhile.

14.4 Area near MP 6.7 Along the Jefferson County Road

In the upstream half of the Morgan's Crossing Reach, the Jefferson County Road is adjacent to the right HCMZ boundary near RM 25 (Road MP 7.5 to 8) and near RM 23.5 (County Site MP 6.7) (figure 46). In the section near RM 25, the HCMZ boundary is nearly coincident with the valley edge. Consequently, the HCMZ boundary has been nearly stable since 1939 and most likely will not erode in the near future. At County Site MP 6.7, erosion of the HCMZ boundary has occurred and continues, even after placement of riprap along the road (see figure 11). A separate interim report was prepared to address this site in more detail, but a general overview is provided below (Bureau of Reclamation, 2003).

At the upstream end of the Morgan's Crossing Reach, the path of the active channel is largely determined by the position of the channel at the mouth of Spruce Canyon. As the active channel exits Spruce Canyon toward the north or right side of the HCMZ, it forms a meander bend (the one near RM 25) to the left as a result of the valley alignment also shifting to the left. Downstream of the left meander, the active channel continues straight down the valley between 1939 and 1950, so that the channel did not flow near County Road Site MP 6.7. By 1950, a left meander in the low-flow channel began to form near the site. Between 1950 and 1977, this meander progressively moved outward toward the County Road Site MP 6.7 (figure 46). Similarly, the two upstream meanders, one along the right side of the HCMZ and one on the left side, had begun to form by 1950 and moved progressively outward.

In 1977, the meander had migrated outward to a point where it was now adjacent to the County Road. The meander has stayed adjacent to the road through 2002. In 1977, a large island and several smaller ones are present in the middle of the active channel near and downstream of County Road at MP 6.7, so that there are two branches of the active channel at this locality (Appendix J). By 1981, the left branch and the area around the islands had filled with sediment and stabilized, so that the left branch only carries water as a side channel. The flow is entirely within the right branch of the active channel, which flows near County Road at MP 6.7.

The meandering of the channel has been affected also by debris flows from Tower Creek, with the latest one visible on 2002 aerial photography. However, no evidence of a debris flow is present on the 1994 aerial photography. It appears that when sediment or debris flows are transported down Tower Creek, the main Hoh River channel cannot immediately transport all of the sediment delivered to the main channel and is temporarily pushed to the south (away from Tower Creek). However, if subsequent floods occur before an additional sediment pulse, then the river will eventually transport the sediment and move farther north. The Tower Creek deposits and valley alignment limit the potential for the channel to flow against, and subsequently erode the right HCMZ boundary between the mouth of Spruce Canyon and the confluence with Tower Creek.

Since at least 1994, the meander at the County Road Site MP 6.7 has been locked into place against the armored bank at the site (figure 47). The armored bank limits the natural downstream and outward progression of the meander bend. However, even without bank armoring, lateral erosion at this location is limited for two reasons. First, the boundary here is a high terrace containing cobble sized sediment that help slow the rate of erosion when the cobbles fall and line the toe of the bank. Second, the alignment of the meander near RM 24 is nearly perpendicular to the valley. When a meander bend reaches this point, the slope becomes flatter making it harder for the river to transport sediment. This usually leads to a cutoff, where the main channel will take an alternate, straighter and shorter path that results in a steeper slope.

A log jam was constructed by Jefferson County about 800 feet upstream of the upstream end of bank armoring at MP 6.7 on the outside of the meander bend (within the HCMZ) in October of 1998. This log jam is still in place as of the writing of this report. Three additional log jams were constructed by Jefferson County in 2003 between this log jam and the upstream end of the bank armoring to try and further protect the road at this site and limit additional erosion from the upstream direction. Unfortunately, in October 2003 potentially the largest flood on record occurred and caused substantial damage to the log jams. Portions of the log jams eroded and were transported at least a few hundred feet downstream and are now present in the active channel.

If a large volume of sediment were to enter the Hoh River and be transported through Spruce Canyon, the sediment deposition could accelerate the potential for a cutoff and cause the channel to migrate back toward the inside of the river bend and follow a straighter alignment similar to the path in 1939 (see figure 46). This would mean that the river channel would cutoff the next downstream meander bend and bypass the County Road at MP 6.7. Existing side channels offer potential paths for the river to cutoff meanders during a flood. In this area, the Clear Creek side channel is a likely cutoff location, because the 1939 historical channel passed through this area (see figures 46 and 44). A natural log jam has formed at the entrance to this side channel, and currently limits the amount of flow and sediment that can enter the side channel (figure 48). However, if a large enough flood were to occur, portions or the entire log jam could be blown out, and the main channel may completely avulse into this channel. Such a new channel position would likely result in an alignment near RM 24 similar to that of the 1939, 1950, or 1960 channels, and the main river channel would no longer be adjacent to County Road Site MP 6.7.

The alignment of the active channel through the downstream half of the Morgan's Crossing reach is dependent upon the approach of the channel from the upstream half. Since the meander at the County Road at MP 6.7 has been locked into place, the Hoh River has been directed straight at the glacial bank on the far left HCMZ boundary near RM 22.5 (see figures 46 and 47). This results in the river being trapped against the left HCMZ boundary all the way to the downstream end of the reach. However, if a cutoff near RM 24 were to occur, the river would likely take an alternate path through the lower reach. Historical channels have passed through almost every location in the active floodplain in the lower half of the reach.

14.5 Area on River Right between RM 21 and RM 23 (Jefferson County Road MP 5 to 6)

Between RM 21 and RM 23, the Jefferson County Road is near the right HCMZ boundary. Between 1939 and 1971, the active channel flowed along at least part of this right boundary (see figure 48). In 1971, the active channel in the lower half of this section consisted of two branches separated by several islands (Appendix J). By 1977, the right branch and the area of the islands had filled and stabilized, so that flow was directed into the left branch and away from the right HCMZ boundary. These conditions remained until about 1994, when a secondary channel developed along the right HCMZ boundary (see figure 48). This channel remains in 2002. At this time, most of the flow is along the left boundary of the HCMZ. However, if the main channel avulses into Clear Creek side channel near RM 24, the downstream section of the right HCMZ boundary probably would receive more flow and would become vulnerable to erosion. Before the channel was directed away from the right HCMZ boundary in 1977 and beginning in 1994, parts of the right boundary were eroded (figure 47). The boundary is composed of poorly consolidated alluvium in low terraces. The surface along the HCMZ boundary has been cleared of trees for development. A short section of the boundary has been armored, which suggests that erosion has threatened the boundary.

One option is to construct log jams in the side channel along the right HCMZ boundary to deflect the river away from the bank if it migrates over to this area. Building the log jams now would allow construction in a relatively dry channel without having to worry about working in the river or diverting it. In order to make this design effective, the approach of the river to this bank would need to be estimated, and the jams may have to be altered or extended if the actual river alignment were different when the river migrates there. Another option is to revegetate the bank along the boundary to facilitate growth of large woody vegetation that may help slow or limit erosion along the bank if the vegetation was not eroded over a long enough period of time. A third option is to move the road farther away from the HCMZ boundary. The surface along the boundary is relatively flat making realignment possible; however, land acquisition and a longer length of road may be required.

14.6 Willoughby Creek Reach

Most areas of the HCMZ in the Willoughby Creek Reach are categorized as having a potential to erode, except where the Hoh River must run straight to enter the Oxbow Canyon (figure 50). This limits the likelihood of future erosion occurring on either of the HCMZ boundaries in the downstream portion of the reach. Two areas at the upstream end of the reach have been resistant to erosion since 1939 even when the river runs against them. One is on river right between RM 20 and RM 21, where the HCMZ boundary coincides with the valley wall. The other is on river left near RM 19.5 just upstream from a long section where the HCMZ is bounded by unstable glacial-lacustrine deposits (Appendix F). These spots are still listed as having a potential to erode because field observations indicated they are likely composed of erodible alluvium. Additional

field work could be done to better understand if there are buried log jams, rock, or other natural features that may explain why they have not eroded since 1939 (figure 50).

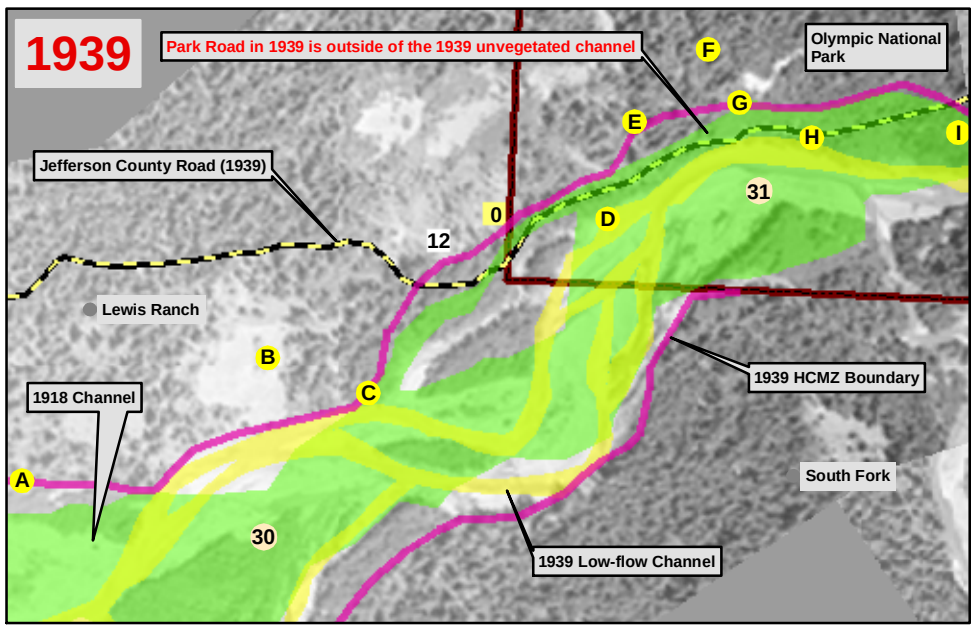
The Jefferson County Road is along the right HCMZ boundary only at the upstream end of the Willoughby Creek Reach, between RM 20 and the upstream end of the reach (Road MP 3.5 to 4.5, figure 50). The road is between the HCMZ boundary and the steep slope of valley edge, which is composed of glacial deposits. The HCMZ boundary adjacent to the section of road has been stable since at least 1939, but the glacial deposits that compose the valley side could be vulnerable to erosion, especially where the slope is not protected. Riprap along the road downstream of MP 4 suggests that erosion occurred or was a threat. Monitoring this section of the road would help determine if erosion is occurring presently. If it is or if it begins, then additional riprap or constructed log jams might prevent continued erosion.

A cutoff of the meander present in 1939 occurred some time before 1950 between RM 19 and 20 (figure 49). The cutoff resulted in extensive erosion of the right HCMZ boundary, which is composed of unconsolidated alluvium. A homestead was present on the right bounding terrace in 1939, and the surface had been cleared of woody vegetation. This is the largest lateral extent of area eroded along the HCMZ boundary within the eight study reaches. About half of the erosion at this location occurred between 1939 and 1950 (figure 50). Additional area was eroded between 1950 and 1960, and small areas have continually eroded during each time interval examined since 1960 as the river meander has migrated outward (to the north) and downstream. Currently, there is no infrastructure or roads at this site and the right terrace area that remains has some large woody vegetation on it. It is predicted by this study that the current meander will cutoff and that the potential for extensive lateral erosion at this area in the near future is small. Over the long term, it is predicted that some additional erosion could occur along the HCMZ boundary in this area. However, the erosion is predicted to be limited because the meander can not migrate much farther to the north (into the terrace) and still maintain the ability to transport sediment.

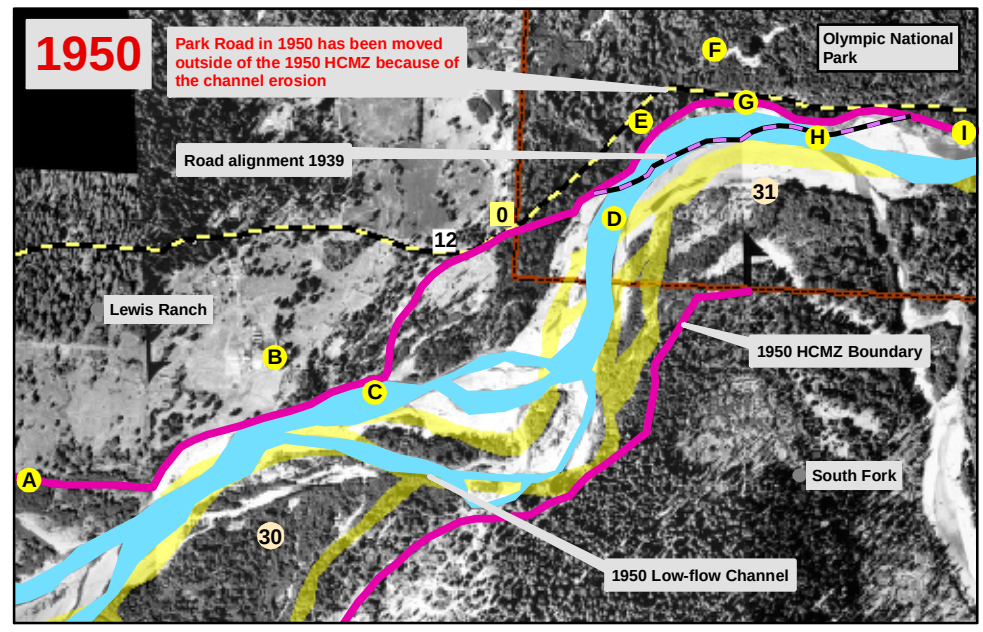
A 3240-ft-long section of the left HCMZ boundary near RM 19 is actively eroding as a result of being on the outside of a meander bend (figure 50). The land being eroded has been used for timber harvest activities in the past. The high, steep bank is composed of unconsolidated glacial and lacustrine deposits and has eroded back to an angle of repose in most areas. The meander that now erodes this bank was initially formed after the cutoff that occurred between 1939 and 1950 in this reach. The meander has progressively migrated outward and downstream into this left HCMZ bank since that time (Appendices A and J). The erosion is caused not only by river erosion, but also by seepage flows that drain from this high steep bank. The bank is very unstable as indicated by gullies eroded into the bank and blocks of sediment that have toppled from the exposure. The active erosion on this bank will likely continue whether the river is running against it or not, but the current position of the river does cause additional erosion at the toe. The existing slope of the bank and its position along the valley edge suggest that the lateral extent of future erosion is limited. In addition, the river meander is predicted to a cutoff, which would move it away from the left HCMZ boundary.

14.7 Drainages along the Jefferson County Road

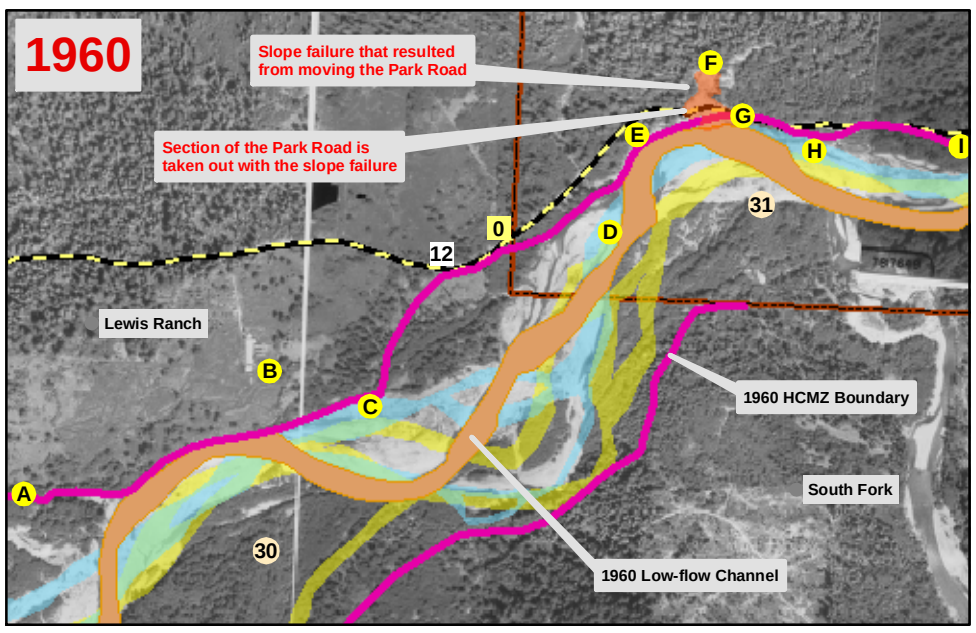
As noted for the Park Road, drainages that cross a road can be a recurrent source of problems when they have debris flows that can not be effectively passed through the road crossing. During observations made in the summer of 2001, it was noted that two culverts along the County Road contained recent sediment deposits: one at MP 4.2 and one at MP 9.7 (figure 51). These culverts should be inspected regularly, and any sediment deposits should be removed after tributary floods. An additional location that has been a management concern for local residents is along the alluvial fans in the vicinity of drainages on Huelsdonk Ridge. These drainages have had an increase in debris flows and flooding as a result of mass wasting initiated on the hillslopes by clear cutting (Logan, 1991). Logan suggests that it may take at least 50 to 60 years of successive tree growth to provide a root system that has the potential to begin stabilizing these soils and limit additional sediment from being unnaturally delivered to these tributaries. Additional study would need to be undertaken to look at management options for this complex large-scale problem to reduce the impacts to local residents in this area. As with the Park Road, another option to consider would be to replace the culvert with an adequately sized structure that allows for higher volumes of debris flow to be transported under the road and easy clean-out and maintenance when necessary.



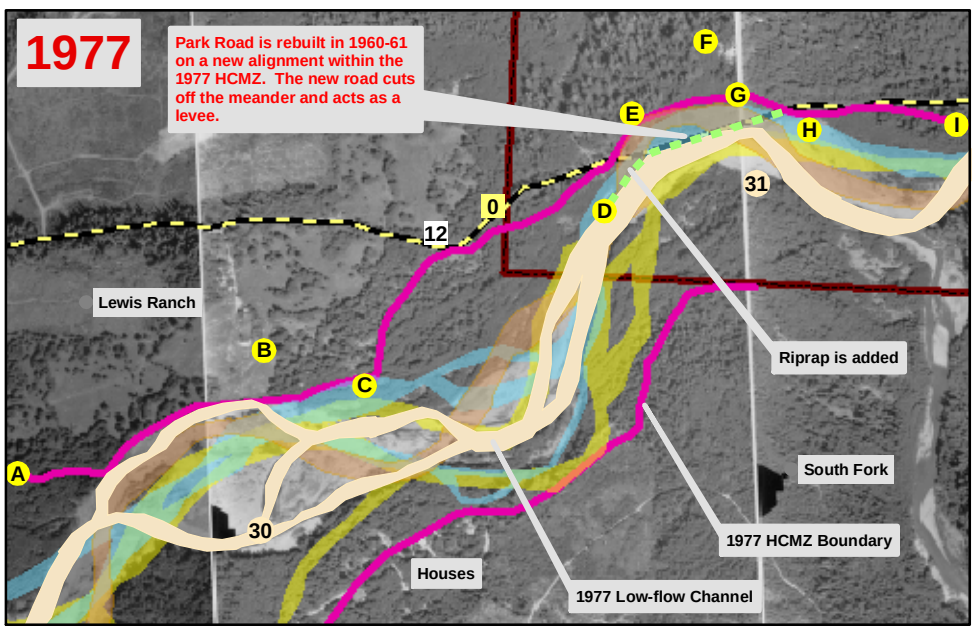
In 1939, the low-flow channel is along the right HCMZ boundary between Localities D and H. The Olympic National Park Road between these two localities is along, but outside of, the 1939 unvegetated channel.



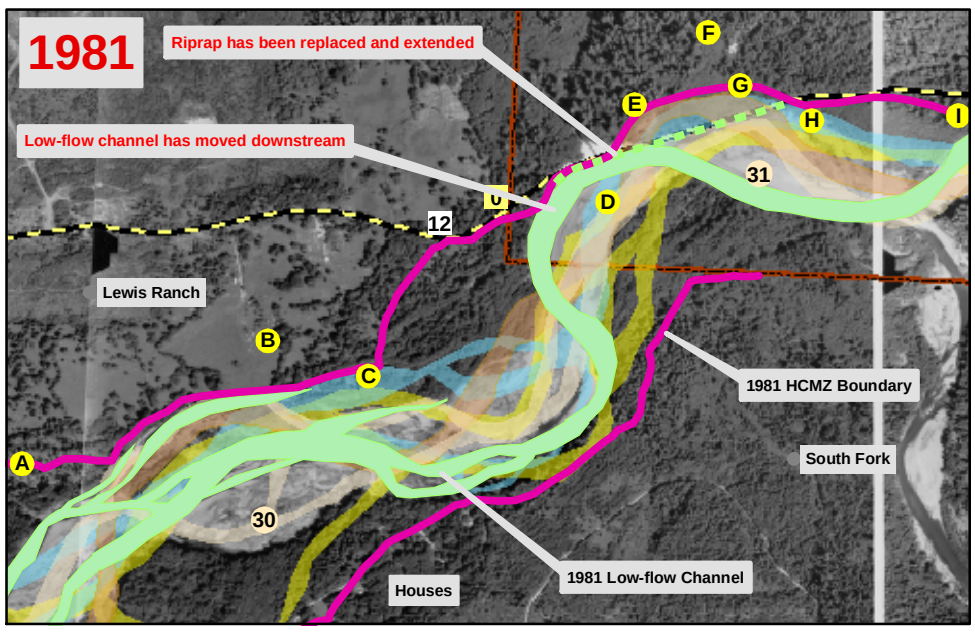
In 1950, the low-flow channel has eroded the right HCMZ boundary between Localities D and H. The low-flow channel and HCMZ boundary are now between Localities E and G. The Park Road has been relocated and moved outside of the newly expanded HCMZ. The alignment of the Park Road in 1939 is shown between Localities D and H for comparison.



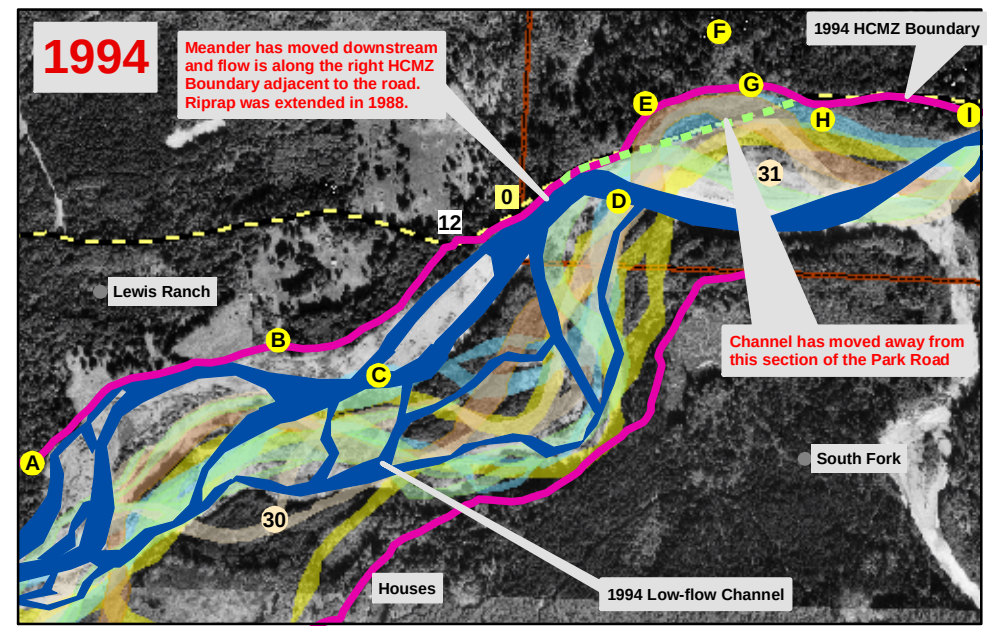
By 1960, a slope failure has occurred at Locality F, just upslope from the section of the Park Road that was relocated outside of the HCMZ by 1950. Realignment of the Park Road, along with the location of the low-flow channel along this bank, likely contributed to the slope failure. The slope failure removed a section of Park Road between Localities E and G. The low-flow channel has eroded slightly farther to river right in this area since 1950.



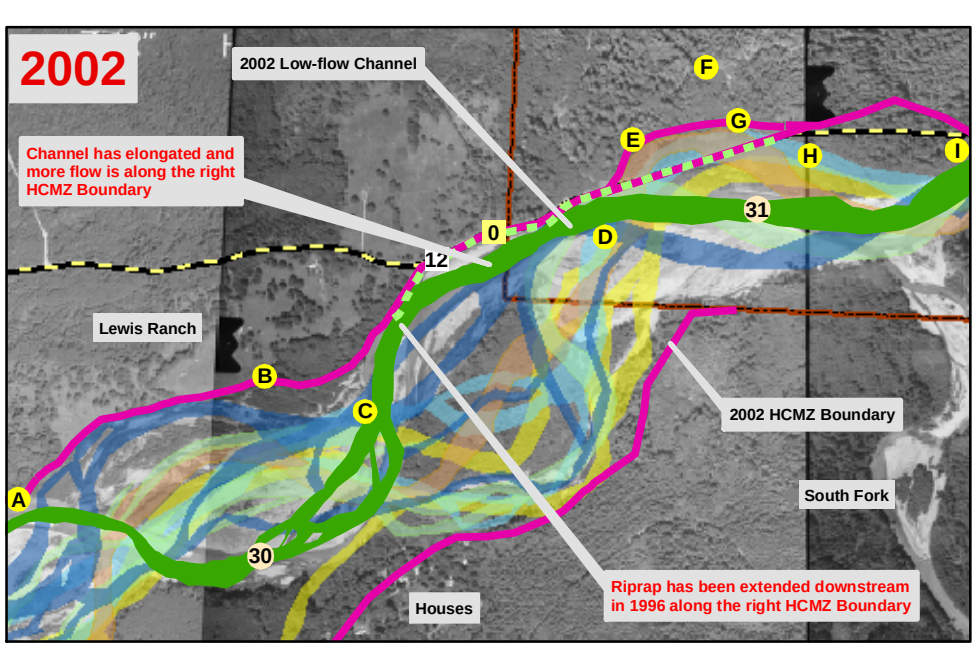
By 1977, the Park Road has been rebuilt away from the steep slope that failed, but within the HCMZ. The new road alignment is nearly the same as it was in 1939. Riprap has been added along the road and extended downstream to Locality D. When the road was is this position in 1939, it was outside of the HCMZ. Now it is within theHCMZ, and it cuts off a meander of the active channel, restricts meander migration, and acts as a levee. Houses have been built near the left HCMZ Boundary.



By 1981, the meader that was between Localities D and H has moved dowstream along the right HCMZ boundary. Riprap has been replaced and extended downstream along the right HCMZ boundary, in order to protect the boundary from erosion along this new location of the low-flow channel.



By 1994, the low-flow channel has moved farther downstream along the right HCMZ boundary near Locality D. By this time, the right HCMZ Boundary has eroded from Locality C to Locality B. This is along the Lewis Ranch, an area that has been cleared of trees since at least 1939.



By 2002, the low-flow channel is more elongated and has moved farther downstream along the right HCMZ Boundary. Riprap has been extended even farther downstream along the HCMZ Boundary outside of Olympic National Park and along Lewis Ranch.

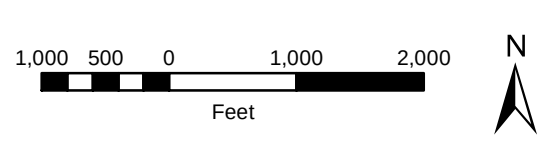


Figure 43. Changes in the low-flow channel for time intervals since 1918 for a section of the Huelsdonk-South Fork Reach near the boundary of Olympic National Park and just downstream of the South Fork confluence. Yellow circles with letters show the same localities in all of the figures. River mileages are based on a river survey conducted in 2000.

Figure 43

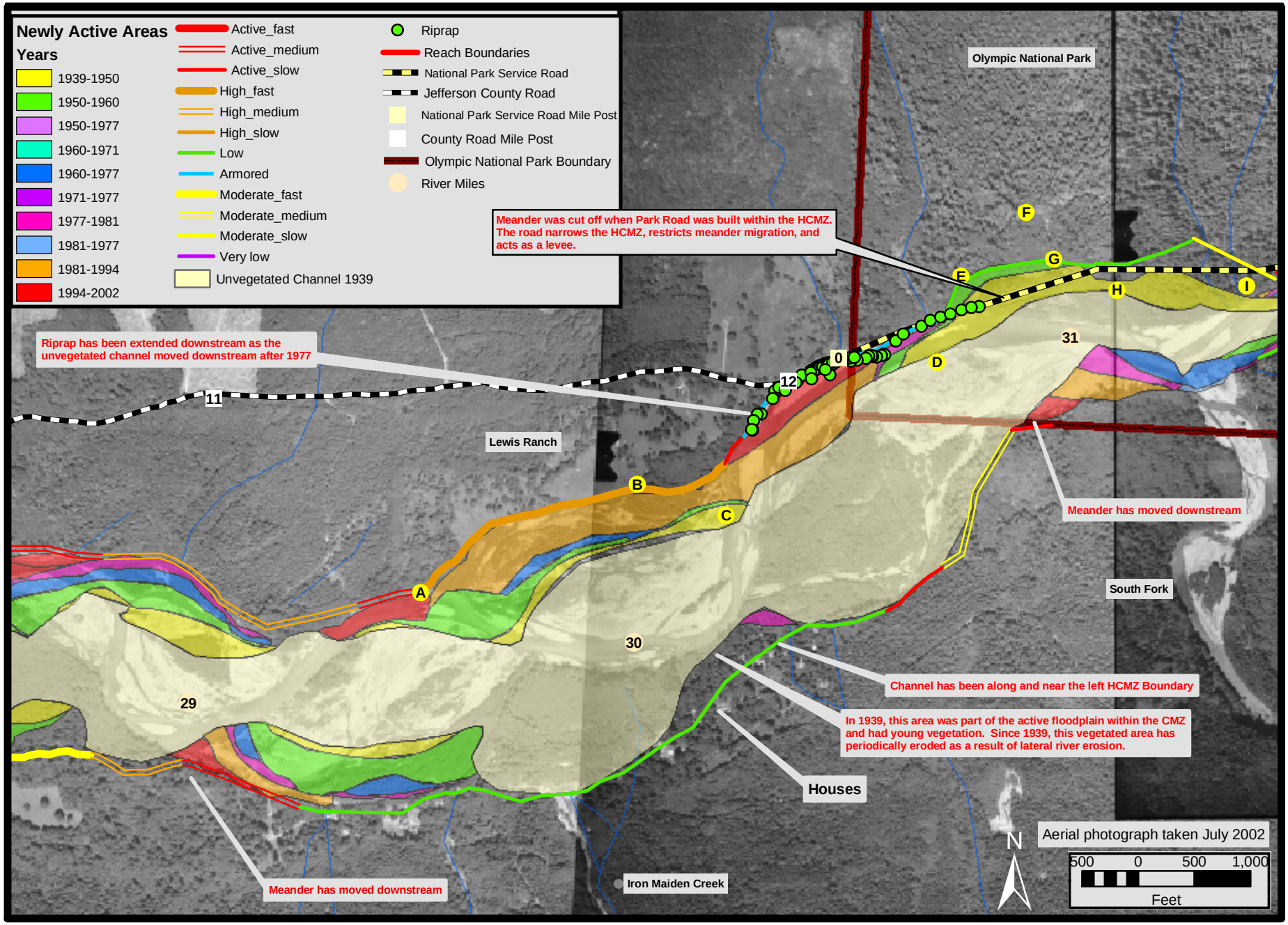


Figure 44

Figure 44. Areas where the unvegetated channel has expanded in the upper part of the Huelsdonk-South Fork Reach near and downstream of the boundary of Olympic National Park. The newly active areas are those first visible as part of the unvegetted channel in the year of the photographs as shown and were outside of the unvegetated channel in all previous years. The risk and rate of erosion are shown along the HCMZ Boundary. The history of the area at the Park Boundary is shown in Figure 40. The letters in yellow circles show the same localities as those shown in Figure 43.

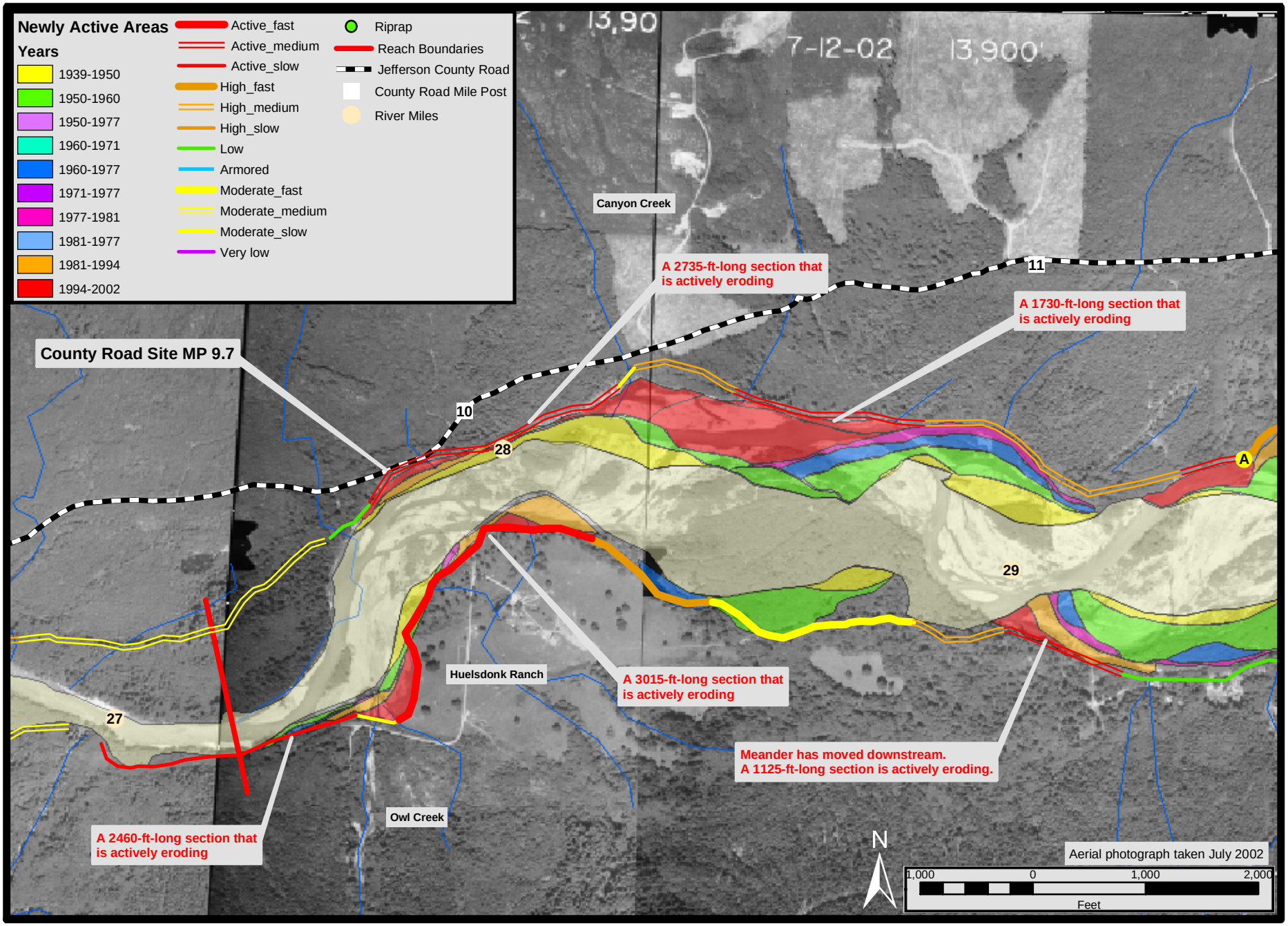
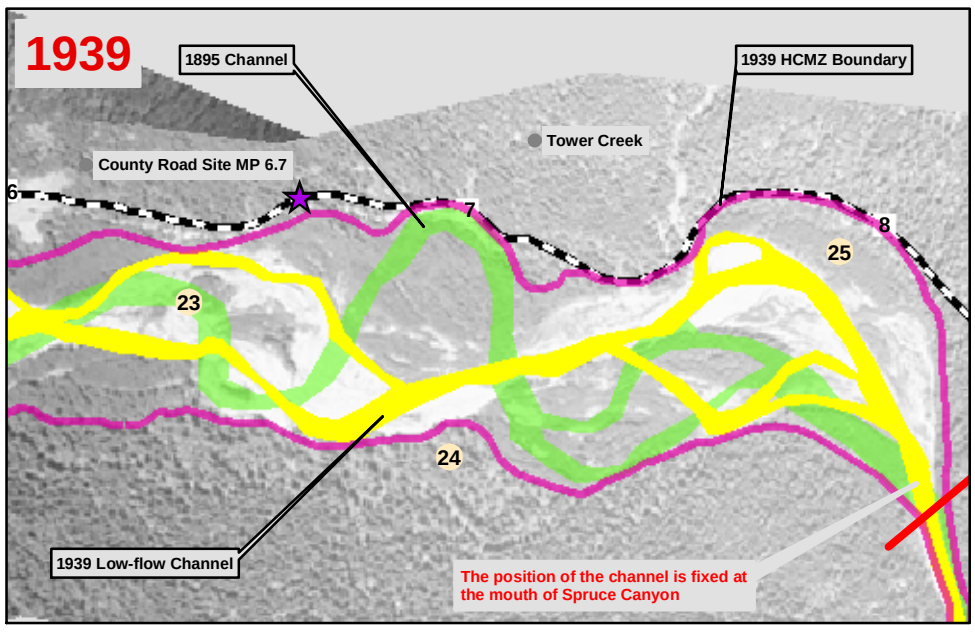
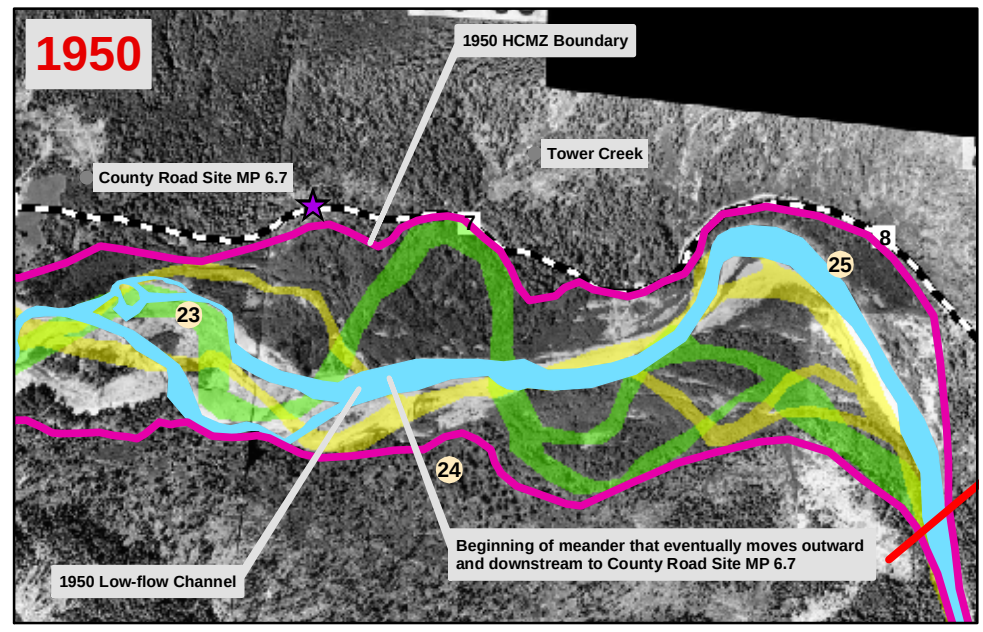


Figure 45

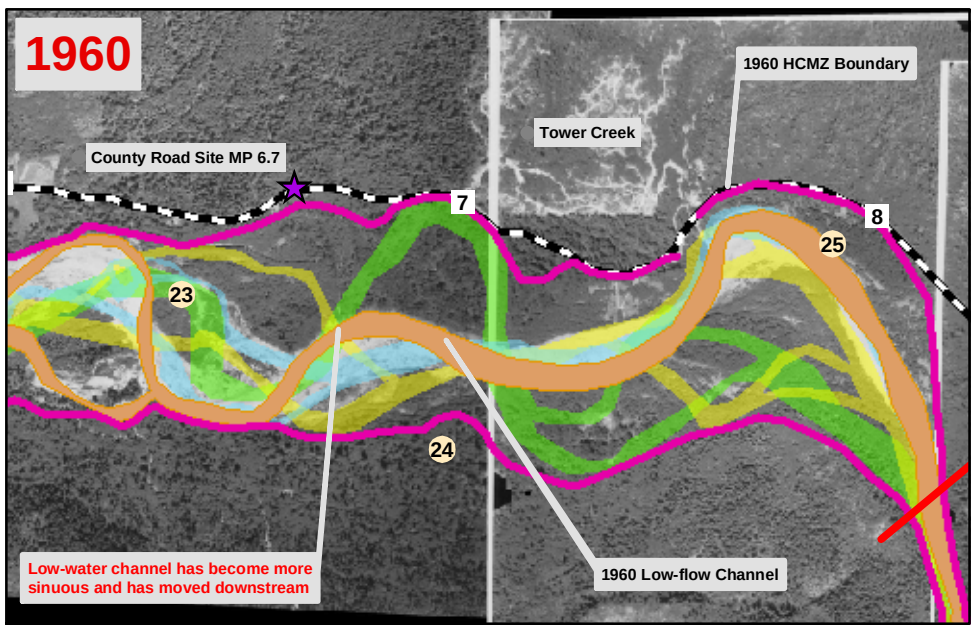
Figure 45. Areas where the unvegetated channel has expanded in the lower part of the Huelsdonk-South Fork Reach near County Road Site MP 9.7. The newly active areas are those first visible as part of the unvegetated channel in the year of the photographs as shown and were outside of the unvegetated channel in all previous years. The risk and rate of erosion are shown along the HCMZ Boundary. The history of the area is shown in Appendices A and J.



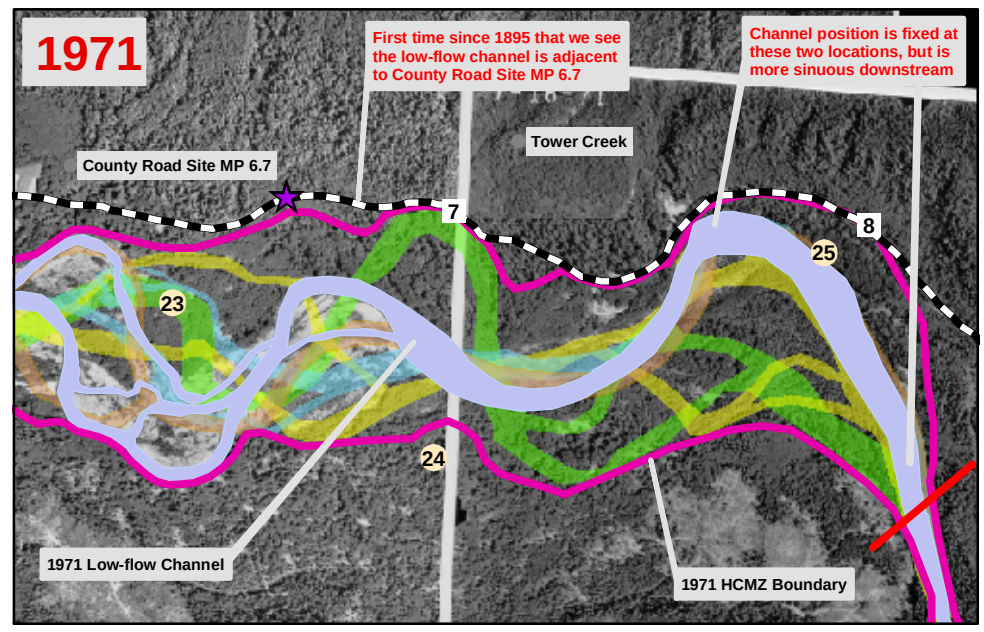
In 1895, a meander in the channel was at it maximum extent on river right upstream of County Road Site MP 6.7. In 1939, the low-flow channel was not near County Road Site MP 6.7. The channel was more braided and straighter than it is in subsequent years as shown on the available aerial photographs.



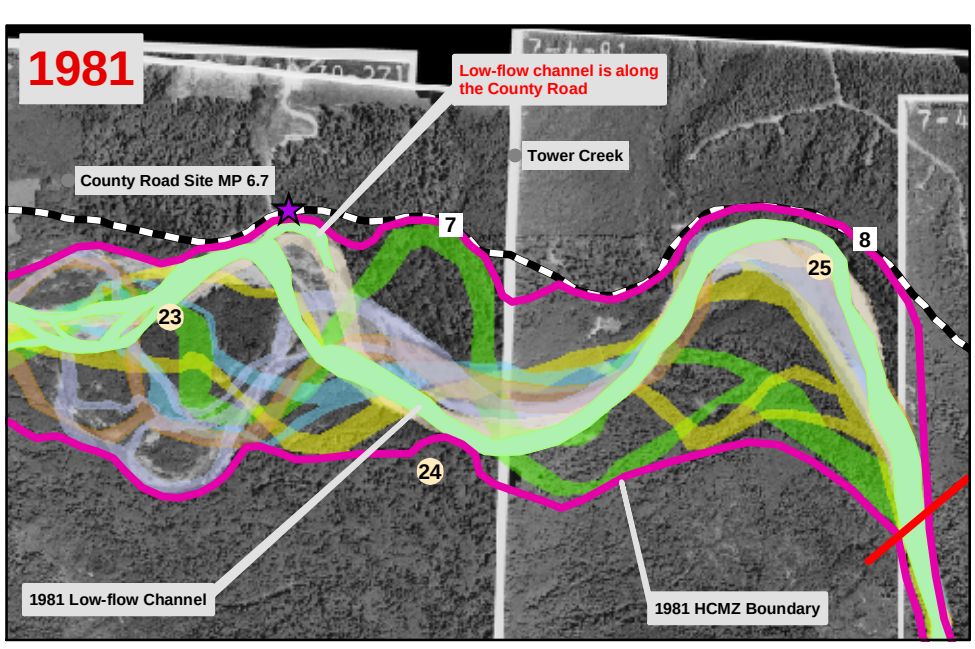
By 1950, the meander in the low-flow channel that will eventually move outward to flow along County Road Site MP 6.7 has just begun to develop near RM 24. The meander near RM 25 has moved outward since 1939.



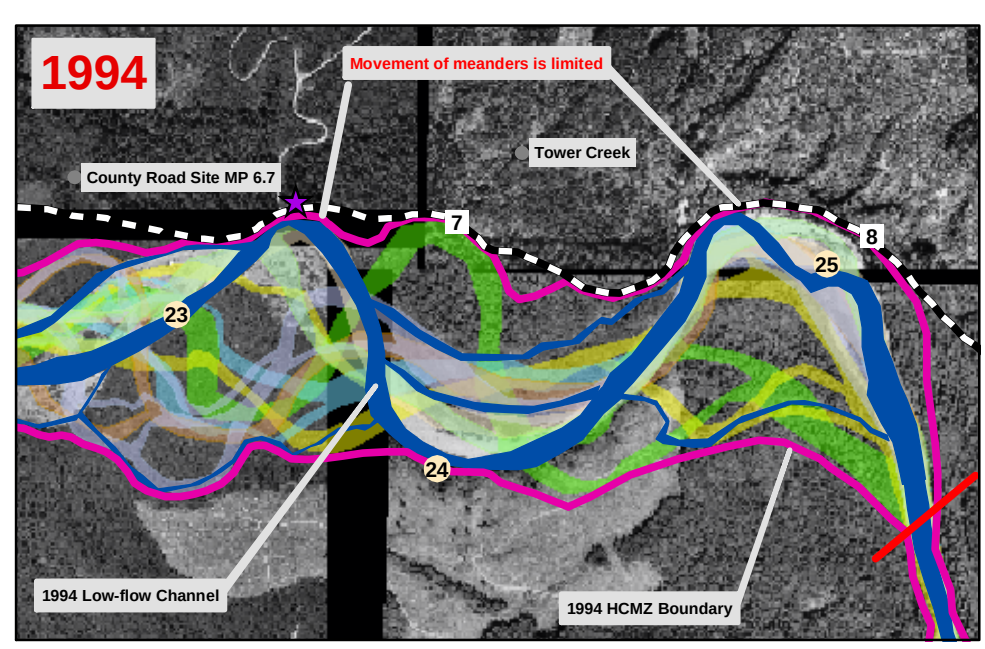
In 1960, the meanders in the low-flow channel at RM 25 and between RM 23 and 24 have moved outward, and the low-flow channel is more sinuous than it was in 1950.



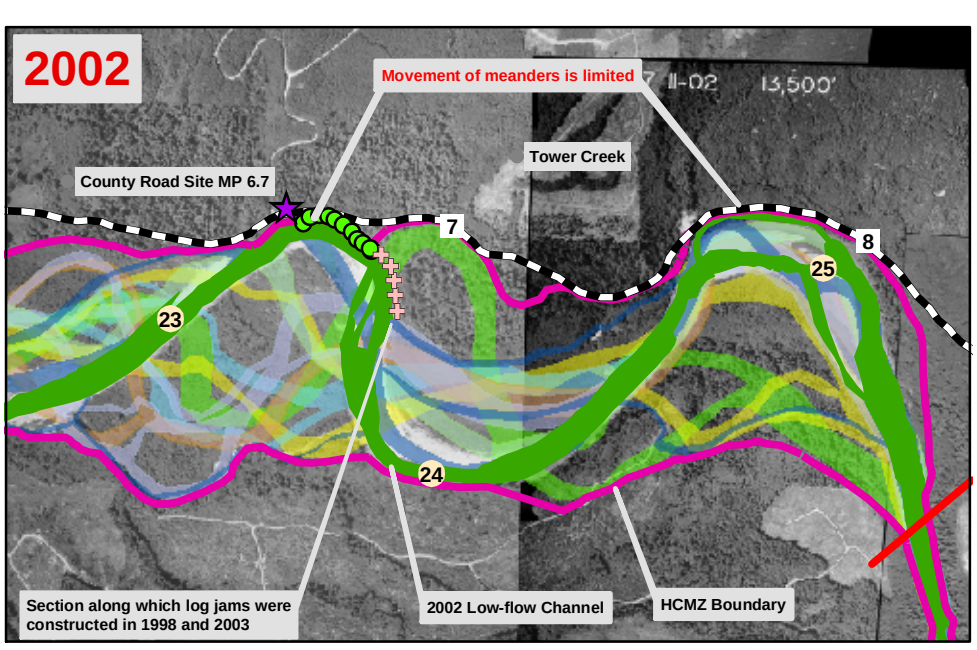
By 1971, the meander between RM 23 and 24 has moved outward to flow along the HCMZ Boundary at County Road Site MP 6.7. The meander stays approximately in this position to at least 2002 because meander movement is limited by the County Road.



By 1981, the meander at County Road Site MP 6.7 has moved outward only slightly since 1971.



By 1994, movement of the two meanders on river right, one near Tower Creek and one at County Road Site MP 6.7, is limited by the County Road and (or) the valley edge.



By 2002, riprap has been added to County Road Site MP 6.7. The two meanders on river right are still locked into their positions as they were by 1994.

1,000 0 1,000 2,000
Feet

N

Figure 46. Changes in the low-flow channel for time intervals since 1895 for a section of the Morgans Crossing Reach between RM 23 and RM 25, including County Road Site MP 6.7.

Figure 46

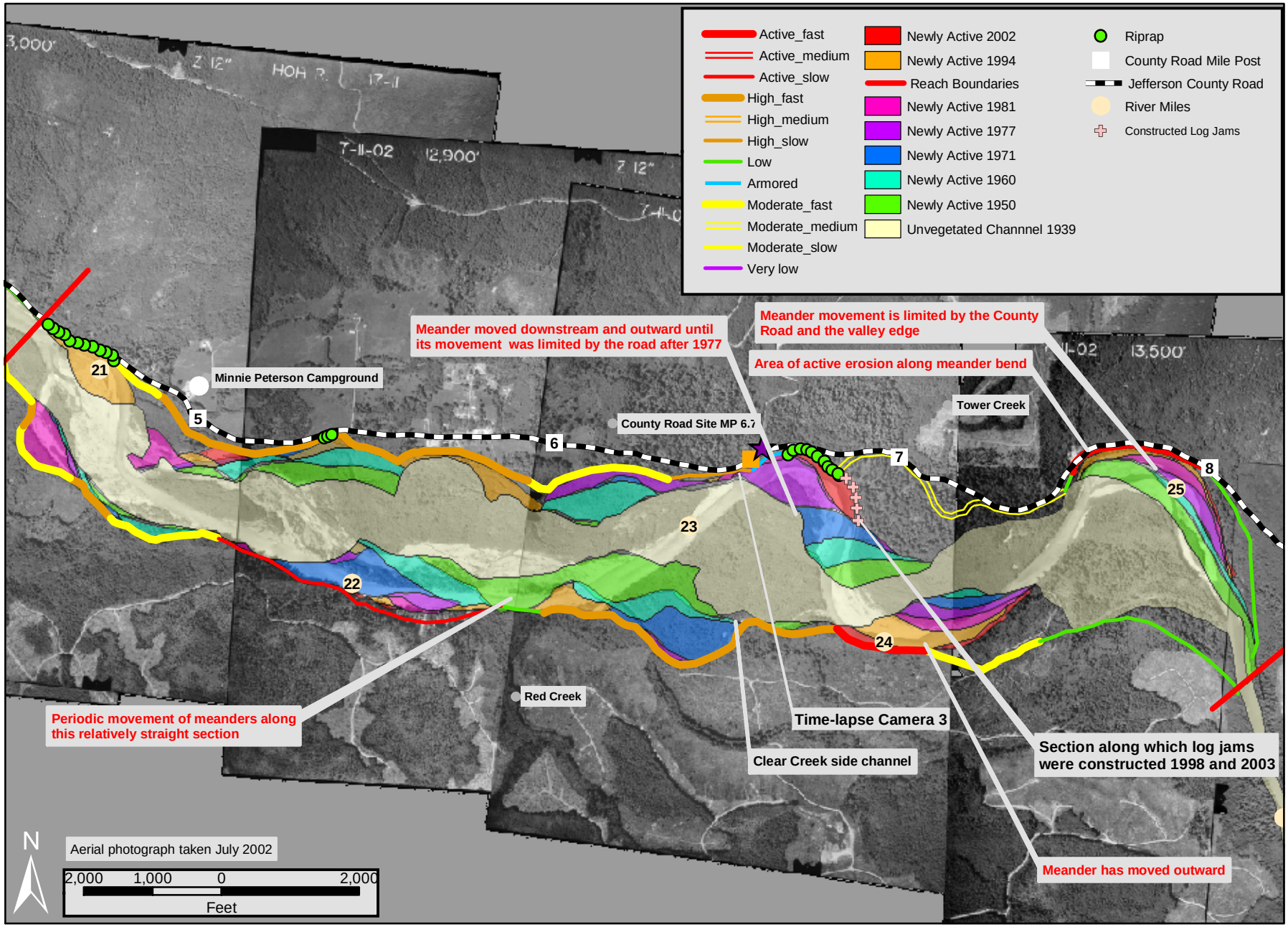
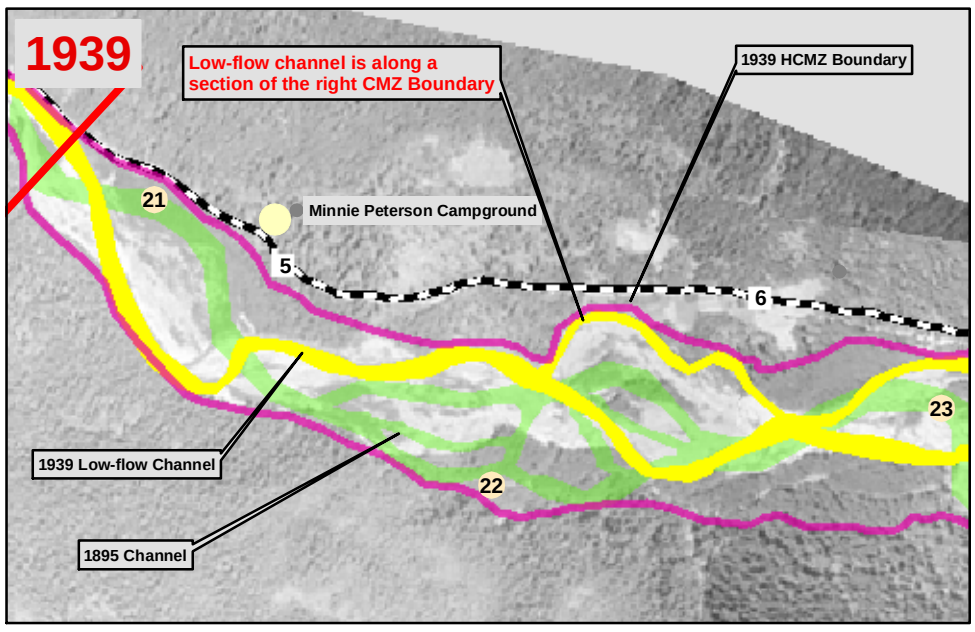
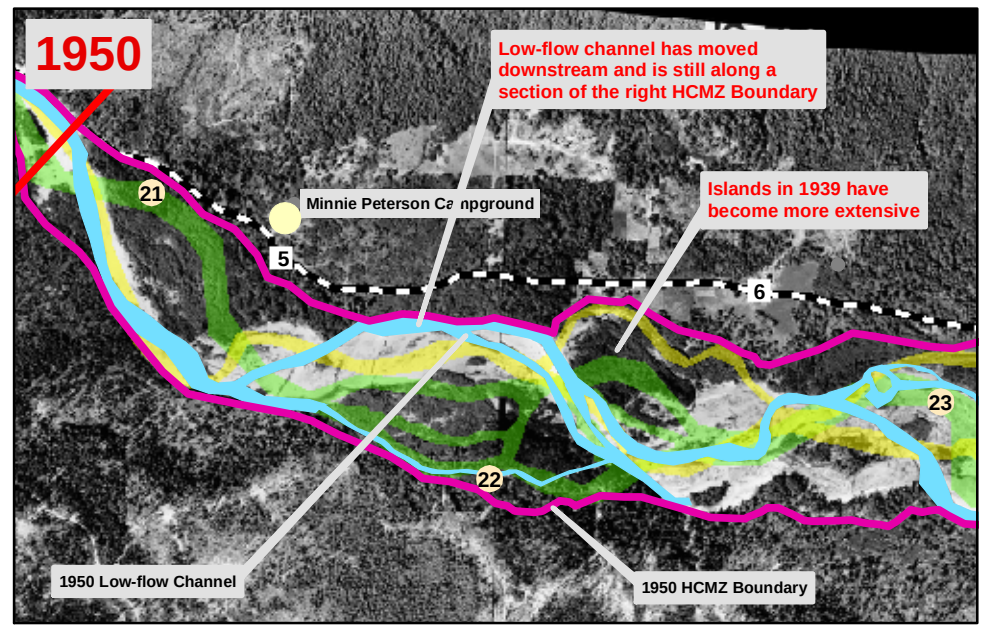


Figure 47

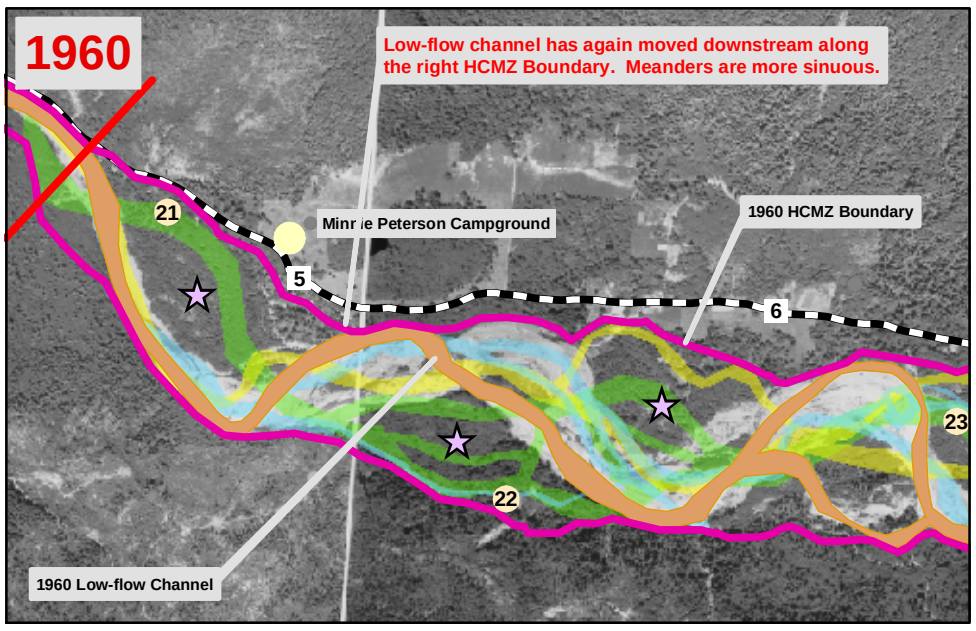
Figure 47. Areas where the unvegetated channel has expanded since 1939 in the Morgans Crossing Reach. The newly active areas are those first visible as part of the unvegetated channel in the year of the photographs as shown and were outside of the unvegetated channel in all previous years. The risk and rate of erosion are shown along the HCMZ Boundary. Time-lapse Camera 3, which was at MP 6.7, was pointed looking upstream at the extensive riprap along the right bank.



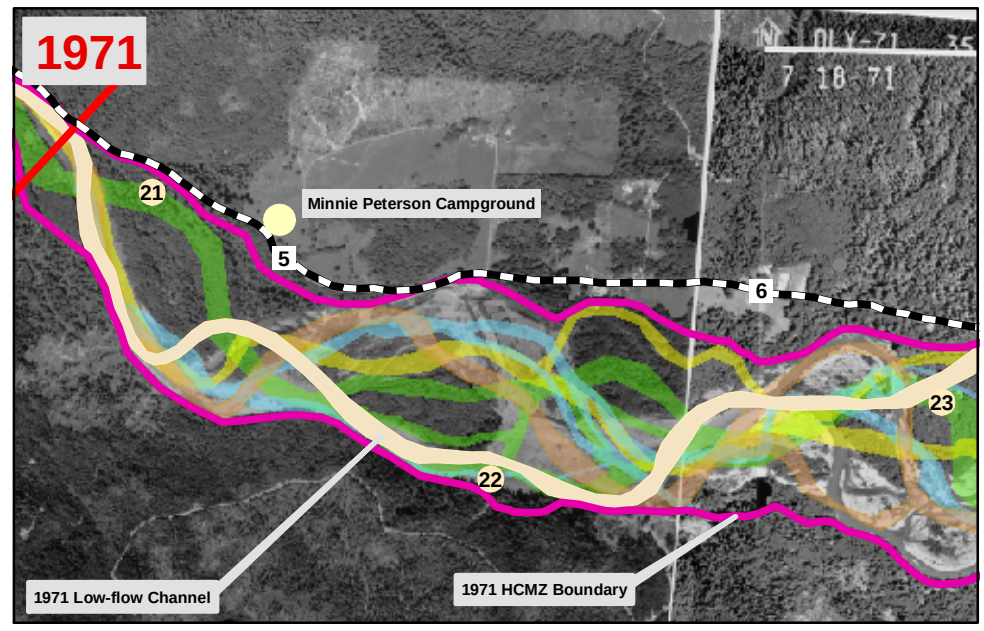
In 1939, the low-flow channel is along a section of the right HCMZ Boundary. Note that part of the surface outside of the right HCMZ Boundary has already been cleared of trees.



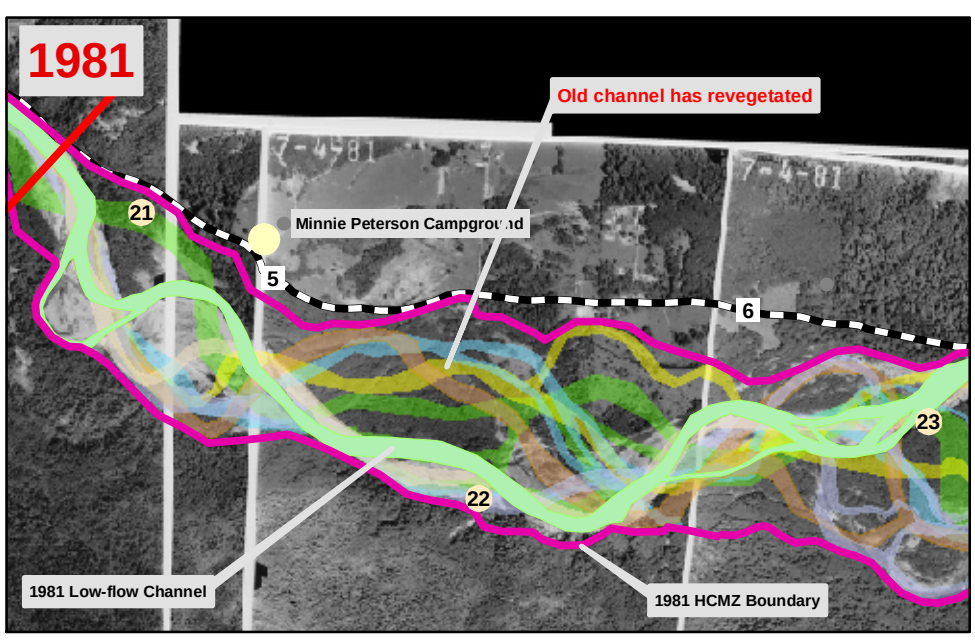
By 1950, the low-flow channel along the right HCMZ Boundary has moved downstream near RM 22. Additional logging of the surface north of the Hoh River has occurred since 1939.



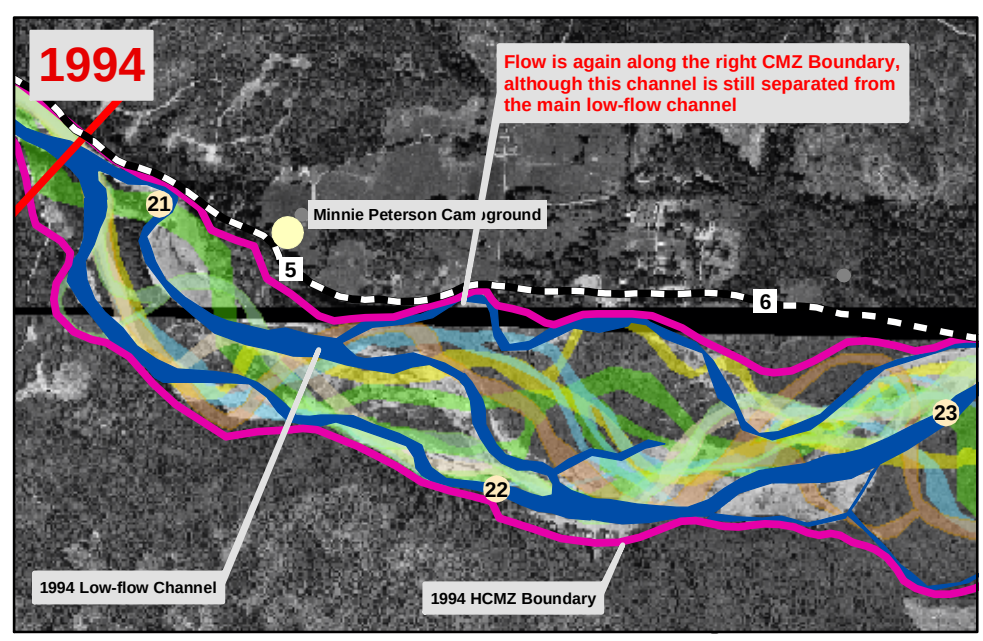
By 1960, the low-flow channel has moved farther downstream to near RM 21.5 and has become more sinuous. Areas indicated with stars were islands within the unvegetated channel that are outside of the channel (probably low terraces) by 1960 (Appendix J).



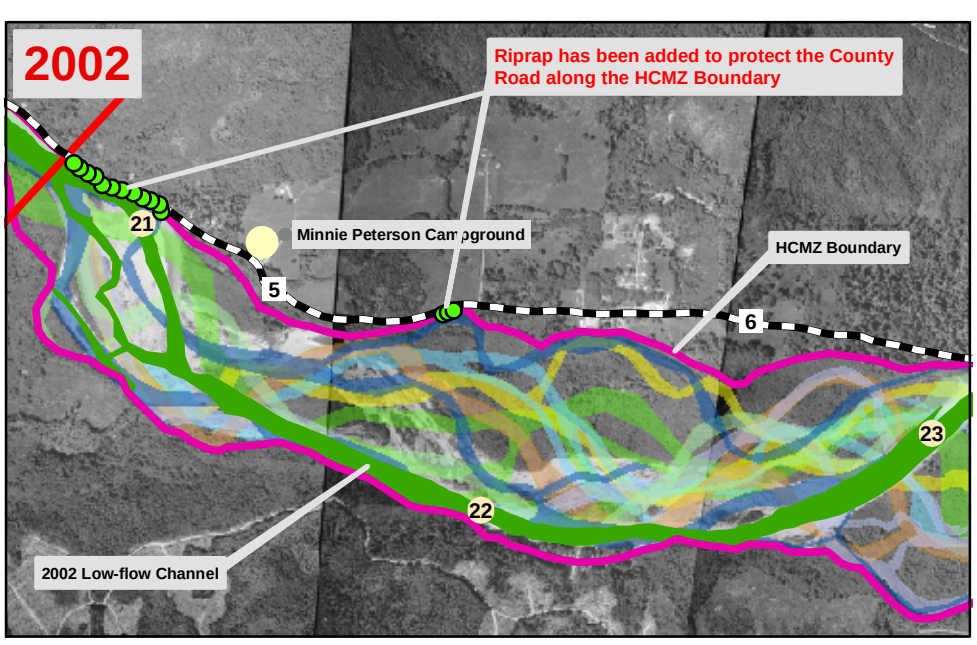
By 1971, the low-flow channel is primarily along the left HCMZ Boundary The channel along the right boundary between County Road MP 5 and 5.5 does not appear to carry much, if any, flow at this time.



In 1981, the low-flow channel remains along the left HCMZ Boundary. The channel on the right has revegetated.



By 1994, a portion of the low-flow channel has re-occupied a channel along the right HCMZ Boundary. Most flow still appears to be in the channel along the left HCMZ Boundary.



By 2002, riprap has been added along two sections of the Jefferson County Road, near MP 5.5 and near MP 4.5. The riprap at MP 5.5 may have been added about 1994, when the low-flow channel was along this boundary. By 2002, the low-flow channel has moved away from this boundary to the left side of the HCMZ.

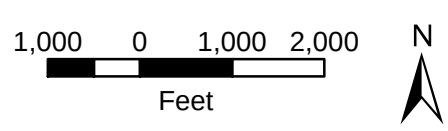
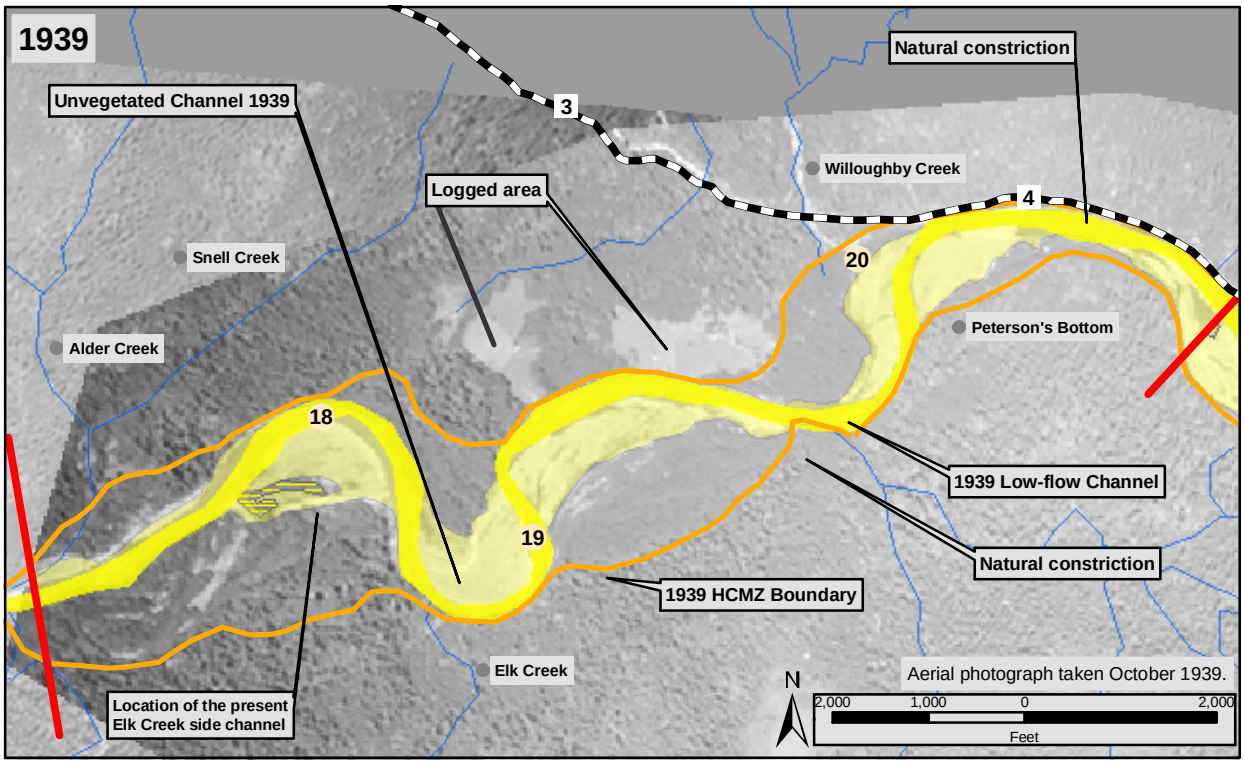


Figure 48. Changes in the low-flow channel for time intervals since 1895 for a section of the Morgans Crossing Reach between Jefferson County Road MP 5 and MP 6, RM 21 to 23.

Figure 48



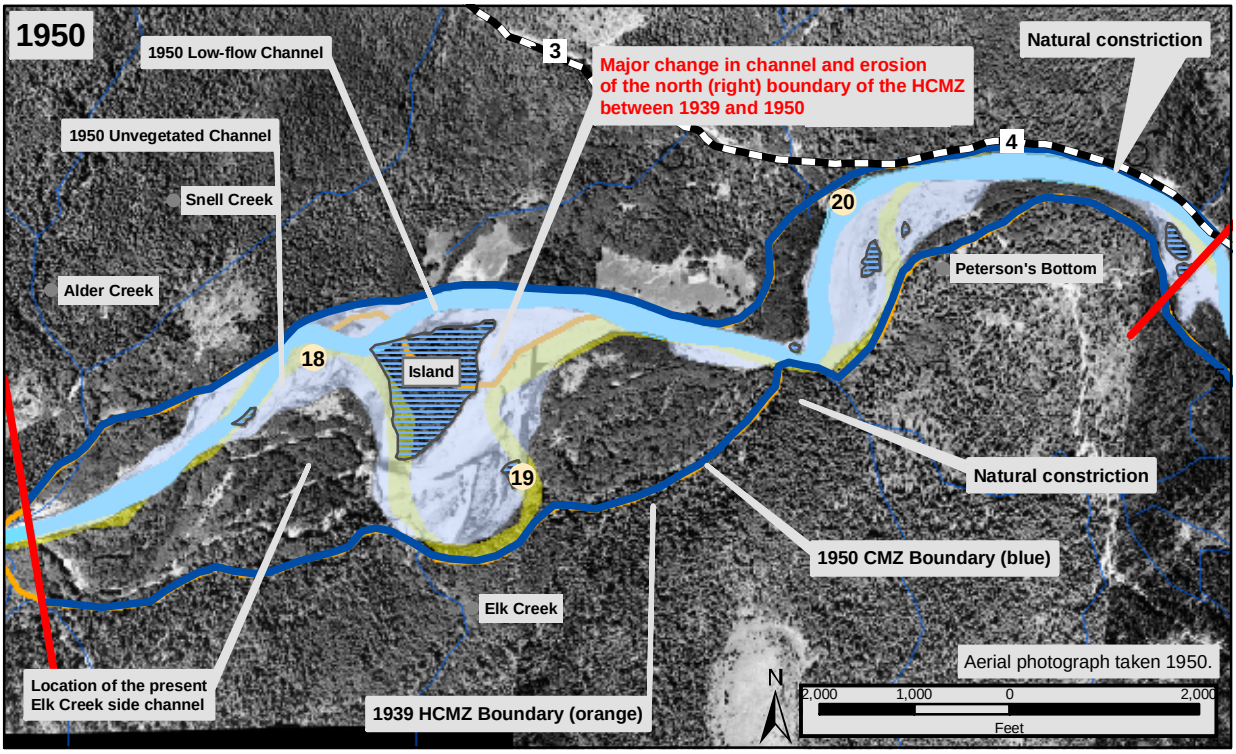


Figure 49. Changes in low-flow and unvegetated channels between 1939 and 1950 in the Willoughby Creek Reach.

Figure 50

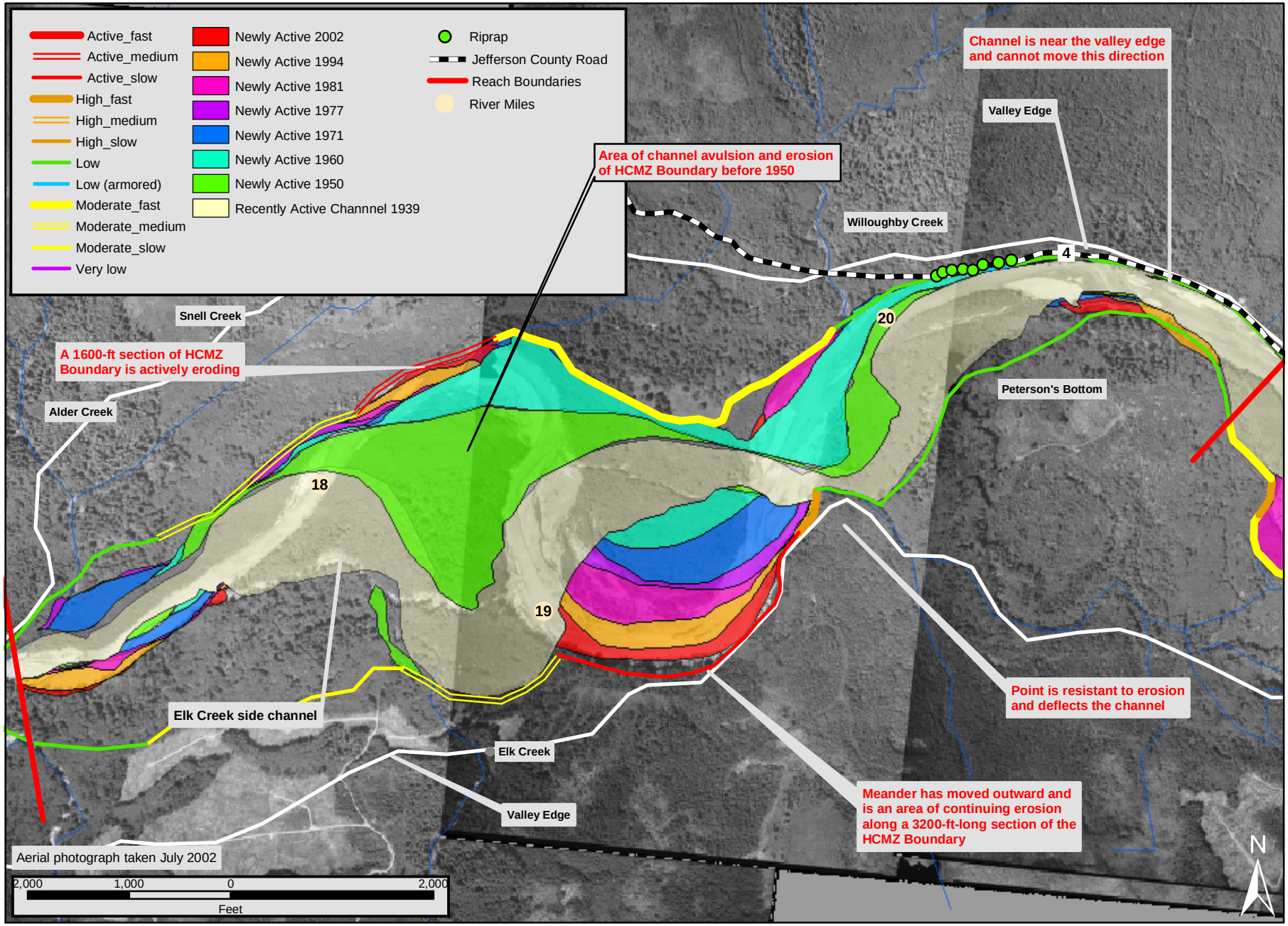


Figure 50. Areas where the unvegetated channel has expanded since 1939 for Willoughby Creek Reach. The newly active areas are those first visible as part of the unvegetated channel in the year of the photographs as shown and were outside of the unvegetated channel in all previous years. The risk and rate of erosion are shown along the HCMZ Boundary.

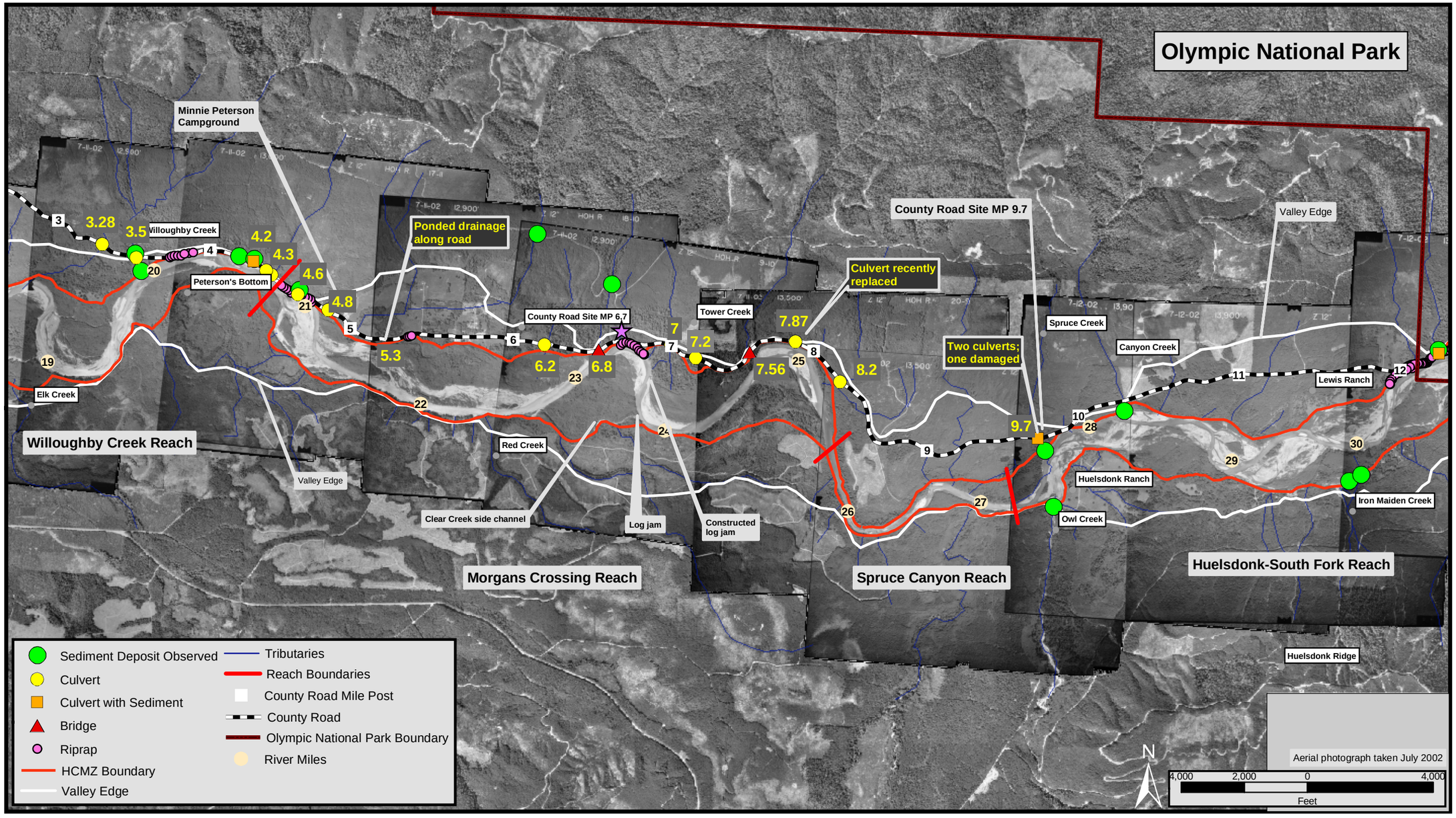


Figure 51. Relatively recent sediment deposits from tributary drainages and other features along and near the Jefferson County Road between MP 3 and MP 12 at the boundary of Olympic National Park. Yellow numbers show road miles along the County Road. The conditions of the road and culverts that are noted here are based on observations made in 2001 and may not reflect present conditions. However, the areas that experienced problems in 2001 could be areas with continuing problems that require maintenance.

15.0 MANAGEMENT CONSIDERATIONS FOR RIVER EROSION AREAS AND ROAD CROSSINGS

Some general management considerations are provided in this section to deal with areas of erosion along the river and road crossings, but more detailed data collection and analysis is recommended for developing a management strategy at any specific location. Additional management strategies for areas currently at risk in the Park reaches will be provided in a separate report by Herrera Environmental Consultants (in progress).

If it is desired to mitigate for the impacts of existing riprap on aquatic habitat, one possible mitigation strategy would be to install engineered log jams along the riprap to deflect the river away from the bank and encourage sediment deposition in the eddy downstream of the log jam. The gravel bar formed downstream of the log jam can grow vegetation and can provide a more natural buffer between the river and riprap. In addition to providing some habitat restoration, this would also provide additional protection against bank erosion and reduce the risk of future erosion. Construction of the log jam would have relatively little risk in endangering the protected road or property because even if the log jam were to wash out, the road and property would still be protected by riprap.

One of the best ways of protecting the road from stream bank erosion is to align the road on a terrace farther away from the river near the valley wall. Care must be taken to insure that the road is not so close to the valley wall that landslides become a hazard to the road. However, the road can't always be setback and stream bank protection is sometimes required. Riprap can be an effective material to prevent bank erosion if properly designed, but it also prevents or limits riparian forest vegetation from growing along the banks. Riparian forests provide a root structure to the stream bank and a potential source of large woody debris during future bank erosion. This impact of riprap can be reduced by building a rough and irregular alignment to the bank protection, which will create eddy and sediment deposition zones. These sediment deposition zones will eventually support riparian vegetation. Stream bank erosion often occurs along the outside of a meander bend. If riprap is placed along a smooth curvilinear alignment, then it will tend to lock the position of the meander bend, and channel thalweg, in place and prevent its migration downstream. The construction of a rough and irregular alignment of bank protection will also help to avoid locking the meander bend and channel thalweg in place. The constructed bank protection should be irregular enough to create eddies and sediment deposition zones, but the bank protection should not cause the river channel to abruptly change course in a tight radius of curvature. Such a design will likely fail.

There are two areas of armored banks located within the HCMZ. At the Park Boundary, the road crosses an old meander bend near the valley wall. This segment of road is armored with riprap. Although this bank armoring has limited the lateral migration of the river channel, it has not caused the river to follow any course that it had not previously followed during the past century. The road cannot be setback at this location because of the landslide hazard that was experienced back in 1960 when this was tried. At the Rainforest Campground, a large portion of the armored bank is within the HCMZ and

this does constrict the channel and impact river processes. This activity may have increased the extent of erosion on the opposite left HCMZ boundary, but there is no infrastructure or human use of the left terrace. Management will need to evaluate whether to continue to maintain the Taft Pond, which was created by the road because it acts like a dam to Taft Creek. Presently, Taft Creek passes under the road through a culvert and then though a rock fish ladder to the Hoh River. Although this pond is not natural, it may provide certain aquatic habitats and aesthetic values.

Boundaries of the HCMZ that have a high risk of future erosion should be monitored where infrastructure or property could be damaged. Bank protection that is constructed prior to severe erosion could be done with less impact than bank protection that is constructed on an emergency basis and can incorporate habitat restoration goals where appropriate. Perhaps the biggest benefit to constructing the protection ahead of severe bank erosion is the ability to work under relatively dry conditions. Under such conditions, it would be easier to integrate features that enhance natural habitat such as engineered log jams into to the bank protection design.

Alluvial terrace banks along the HCMZ boundary where trees have been cleared would benefit from a long-term strategy of planting native trees that can one day grow to an old growth forest. While large trees would take several decades to become established, over the long-term, they would help slow the rates of terrace bank erosion along the HCMZ boundary and provide a potential source of large woody debris. Although trees could help stabilize surface erosion on glacial banks, most glacial banks are much taller than the root structure of trees, so the root structure would not help to prevent erosion at the river level. However, large old growth trees that fall into the river during terrace bank erosion may help to deflect the river velocities away from the toe of the eroding bank. Landslide areas along the river may be impacted by stream bank erosion at the toe of the landslide. In many cases, groundwater flow encountering an impermeable layer on a steep slope is the primary cause of the landslide. Engineered drainage paths, stabilization of the toe of the landslide, or structures that deflect the river away from the landslide may help limit additional erosion.

Areas impacted by tributary debris flows may have different management approaches depending on what structures or property are at risk, such as a road or residents living on a debris fan. Where there is only a road crossing, bridges or box culverts with metal grates at the road surface could be installed. Debris could be cleaned from the box culverts after a debris flow by opening the grates on the road surface. These types of crossings provide an easy way to clean out the channel after debris flows and limit the potential for the road being shut down due to plugging. In areas where there are residential properties, sediment from the debris flows and flood runoff can both be a continuing problem. In some cases, the occurrence and frequency of debris flows has been exacerbated by logging and the associated road building activities. This type of complex problem would likely take several decades to re-establish hillslope stability even if no further logging is done. Structures present may have to be relocated off the debris fan to avoid the potential hazards.

16.0 CONCLUSIONS

This report presents a geomorphic reach analysis between river miles 17 to 40 (Oxbow Canyon to Mount Tom Creek) of the Hoh River. The study was initiated at the request of the Hoh Tribe to provide a better overall understanding of river processes, and how human activities and development within the Middle Hoh valley over the last century may have altered those processes. Additionally, resource managers at Jefferson County and Olympic National Park indicated that it would be useful to have an assessment of both historical and potential future erosion areas along infrastructure and property that are at risk from river erosion. Historically damage of property has been addressed on an emergency basis as the damage occurred, but resource managers have expressed an interest in developing a long-term strategy that would work with and limit the impacts on river processes while maintaining protection of critical property and infrastructure.

16.1 Historical and Future Channel Migration Zone Boundaries

The channel migration zone includes the river channel, side channel, and floodplain areas bounded by terraces. The terrace surfaces are abandoned floodplains, formed at a time when the river channel was at a higher elevation. The floodplain is formed and reworked by migration of the river channel.

Available data and analysis were sufficient to delineate the historical channel migration zone (HCMZ) that represents a timeframe between 84 to 111 years before 2002, depending on the reach (see Attachment 2 of summary report). The oldest set of maps documents the position of the Middle Hoh River in 1891 or 1895 and the Upper Hoh River within Olympic National Park in 1918. These maps were found to be generally accurate and compared well with the historical aerial photography. These early maps (1891, 1895, and 1918) are believed to represent a dynamic river channel position and alignment under fairly natural conditions when there was only limited logging or other impacts associated with human activity that would affect river processes.

Examination of historical channel behavior was the basis for delineating the potential risk and rate of terrace bank erosion over the next several years along the 2002 HCMZ, and for delineating the future channel migration zone boundary. The risk analysis shows which terrace banks, along the 2002 HCMZ boundary, are most likely to erode in the near future. The risk analysis also indicates, if the terraces did erode, at what rate they might erode based on several factors including bank material, vegetation presence, and channel position. The risk of terrace bank erosion, and expansion of the HCMZ, was considered highest whenever the main river channel could flow against the terrace. Existing side channels and overflow channels already convey water during floods and offer a path of least resistance when the existing bankfull discharge is exceeded. These channels were identified as having the highest risk of capturing the main channel in the near future. In some locations, this would result in the main river channel flowing against the terrace banks of the HCMZ boundary. Some of these side and overflow channels have log jams blocking their entrance that limit the amount of water, sediment, and wood that can enter these channels. The risk that the log jams will be blown out

during a flood, and that the main channel will then move into the side channel, depends on both the stability of the log jam and the direction the river attacks the log jam.

The future channel migration zone boundary shows all terrace areas adjacent to the 2002 HCMZ boundary that may be subject to river erosion over the next two to three centuries (see Attachment 2 of summary report). Each of these terraces areas have the potential to erode and become the future channel migration boundary based on historical river positions and rates of erosion. However, the total potential erosion area shown includes more areas than could possibly erode in the next few centuries based on historical rates of erosion (assuming hydrology and sediment loads do not significantly change in the future). This conservative approach was taken to document all terrace areas where river where erosion could occur.

The boundaries of the HCMZ are fairly well defined from the numerous maps and aerial photographs that span the 20th Century. The risk and rate of where terrace bank erosion will expand the HCMZ boundary in the near future have less confidence than the delineation of the historic boundary. However, the future risk and rate of erosion are based on historical assessment of channel changes, erosion rates, and physical constraints on the river. The future HCMZ requires the greatest amount of judgment and has the least certainty.

16.2 Comparison of Olympic National Park to Middle Hoh Reaches

The majority of the Olympic National Park study area (Reaches 1 through 4) have consistently had more complex and braided channel patterns since 1939 and, on average, wider active channel widths than the Middle Hoh study area (Reaches 5 through 8). However, there are a few relatively short sections in the Park that do have single meandering channels. Reaches 5, 7 and 8 in the Middle Hoh were generally found to have single meandering channels, except for short cutoff periods, since the late 1800's.

There is an abundant source of large woody debris within the Olympic National Park reaches because the steep and forested valley walls are relatively close to the active river channel. In addition, logging has not occurred within the Park so the trees tend to be older and have larger diameters than they do in reaches downstream. The large, old growth woody debris is not easily transported by the river in the Park and, therefore, increases the channel roughness. This large woody debris can act locally as hydraulic controls creating river pools or deflecting the flow into multiple channels.

River flow increases downstream from the confluence with the South Fork, so logs with larger diameters are needed to maintain stable log jams within the active channel area. However, there are fewer sources of large trees available for recruitment in the reaches downstream from the South Fork confluence to create stable log jams. The alluvial and glacial terrace surfaces that from the boundary of the HCMZ in the Middle Hoh reaches have been logged at least once over the last century. The Hoh River downstream from the South Fork also tends to have only one low-flow channel rather than the complex patterns observed in the Park. When a large portion of the flow is concentrated into one

channel, the transport capacity of both sediment and wood increases because the river stage and velocity increase relative to a reach where the flow is split into several channels. Both of these factors limit the amount of large wood that may be currently recruited and remain stable in the Middle Hoh reaches.

Only a few vegetation patches within the HCMZ in the Middle Hoh reaches have remained stable since 1939. These vegetation patches were noted to contain large diameter trees during site visits. This provides some evidence that old growth trees can help to slow or limit the rate and extent of river channel migration. Another explanation could be that these patches have buried log jams at their base that help to keep the area from being washed out by the river. Virtually no vegetation patches within the HCMZ of the Park reaches were observed to be stable since 1939. It was also found that the entire HCMZ area is more frequently reworked by the river in the narrower Park reaches than in the Middle Hoh reaches.

16.3 Erosion of Historical Channel Migration Zone Boundary Since 1939

Of the total HCMZ area that has eroded between 1939 and 2002, 86% (278 acres) was composed of alluvial material. Both the right and left HCMZ boundaries have the same proportions of alluvial banks both inside and outside of the National Park. The glacial deposits make up the majority of remaining terrace erosion areas and there is a greater proportion in the Middle Hoh reaches than in the Park reaches. The glacial deposits are much more variable in their composition than the alluvial deposits, and they erode by a combination of processes including river erosion at the toe of the terrace and slope failure due to headward erosion and seepage through the bank. Therefore, even when the river is not running against the glacial terraces, these terraces may still continue to have slope stability problems.

About one-third of the left and right HCMZ bank length has eroded in the Middle Hoh reaches. Inside Olympic National Park, about one-fourth of the left HCMZ bank length has eroded, but only 10% of the right. The total area of bank erosion since 1939 was approximately 6 acres per mile for the four reaches within Olympic National Park (total of 47 acres) and 23 acres per mile for the reaches downstream from Olympic National Park (total of 276 acres), almost four times as much. Expansion of the HCMZ is a natural process for the Hoh River given its physical setting and presence of glacial and alluvial terrace banks. The reason for the greater erosion area in the Middle Hoh reaches, relative to the Park reaches, can be attributed to increases in flood magnitudes, differences in channel form, and increases in human disturbance.

River erosion is directly related to the size and frequency of floods. A small subset of overlapping gage data from the Hoh River near Mount Tom, the South Fork, and at the Highway 101 Bridge was available. A comparison of this data and evaluation of increase in drainage basin size in the downstream direction indicates that flood magnitudes in the Middle Hoh may be two to three times that of floods in the Park dependent on the contribution of runoff from the South Fork drainage. More gage data and analysis are needed to validate this statement.

Based on two USGS gages that provide discharge records in the study area, the average annual flood peak and the 2-year flood peak have both increased on the Hoh River in the study area since 1927. Between 1927 and 1971, the 2-year flood peak was exceeded between 18 and 50 percent of the years, but since 1971, the 2-year flood peak has been exceeded in 70 percent of the years. In Reaches 7 and 8, the fastest rate of channel migration occurred during the period 1977 to 1981 when the 25-year flood was twice exceeded. This indicates that the higher magnitude floods that are now occurring can cause greater rates of channel migration and subsequently greater amounts of lateral expansion of the HCMZ. However, the largest total area of measured erosion along the HCMZ boundary occurred in Reach 8 between 1939 and 1960, prior to the increased flooding.

While larger flows can initiate higher rates of channel migration and bank erosion, they are not the only factor causing higher rates of terrace bank erosion in the Middle Hoh reaches relative to the Park reaches. A change in channel form from multiple channels with a steeper slope, more woody debris and roughness in most of the Park reaches to a more sinuous channel with a flatter slope and less wood in the Middle Hoh reaches also plays a role (Spruce Canyon, Reach 6, is the exception). These factors are important because the majority of erosion occurs along the outside of meander bends or along terrace banks that line active, side, and overflow channels. In Reaches 7 and 8 the upstream-most meander bend of the active channel has only been cutoff twice over the roughly hundred years of historic channel positions documented. Reach 5 is a transition reach with some areas of meandering channels and some areas of braiding. The cycle of meander bend migration and cutoff in Reach 5 is slightly faster than it is in Reaches 7 and 8. Within the Olympic National Park reaches, the multiple channels change more frequently, but the rate of terrace bank erosion is slower than the Middle Hoh reaches. This means that the river channel in the Middle Hoh reaches continues to erode terrace banks for a longer period of consecutive time and causes the HCMZ boundary to expand at a greater rate than in the Park reaches.

Accelerated erosion rates are expected to occur when the banks have less resistance to erosion. Riparian trees, tree roots, and large woody debris are some of the principal material properties resisting bank erosion. Additionally, large cobbles that fall in as a result of bank erosion and line the toe of the bank have also been observed to limit expansion of the HCMZ in the Park. Herrera (2004) found that in the Park reaches, trees of at least 21 inches in stem diameter can help slow the rate of bank erosion and typically remain stable near the erosion area when they do fall into the river. The reaches in Olympic National Park have less discharge than the reaches downstream from the confluence with the South Fork River, which would mean shallower water depths and less ability to float away the large woody debris. This indicates that a larger diameter log is needed to remain stable in the river channel downstream from the South Fork confluence. The removal of riparian forest and large woody debris along the terraces in the Middle Hoh reaches has reduced the recruitment of large woody debris to the channel and eliminated old growth vegetation along the terrace banks of the HCMZ.

Measurements of natural erosion rates to evaluate the impact of logging terrace surfaces in the Middle Hoh were not possible, but by normalizing the changes in slope and discharge, erosion areas in the Park reaches could be used for comparison. All of the areas where HCMZ expansion was measured since 1939 in the Middle Hoh had been logged prior to the river running against the bank. Although prior to disturbance, the older cadastral survey maps did not have a clear definition of the terrace boundaries, and, therefore, could not be used to determine natural erosion rates of the Middle Hoh HCMZ. There are a few undisturbed erosion areas within the Park reaches that do have a single meandering channel eroding the alluvial terrace bank. These undisturbed areas were used to develop a natural rate of erosion for the Middle Hoh by normalizing the naturally occurring changes in discharge and slope between the two study areas. There are 14 comparable areas (4 within the Park reaches and 10 within Middle Hoh reaches) where an alluvial terrace bank was eroded along the outside of a meandering channel bend. For each of these 14 areas, the average erosion rate was computed over the period from 1939 to 2002 and normalized by the maximum erosion rate. The total stream power (2-year discharge multiplied by the average hydraulic slope) was computed for each reach and normalized by the maximum stream power. The normalized erosion rate was then divided by the normalized total stream power. Although there were several assumptions made for the input data, the computations indicate that on average half of the terrace bank erosion that occurred in the Middle Hoh reaches cannot be explained solely by changes in discharge, channel planform, or longitudinal slope. This indicates that logging of the alluvial terrace surfaces bounding the HCMZ has resulted in an additional amount of erosion in the Middle Hoh that otherwise would not have occurred.

16.4 Impacts of Increased Sediment Supply from Human Activities

A review of literature on the Middle Hoh reaches indicate that mass wasting events along the valley walls have increased in area and frequency since 1939 as a result of logging activities (Parks, 1999; Powell, 1999). While the exact increase in frequency and area are not known, the additional mass wasting would be expected to episodically increase the amount of fine and coarse sediment delivered to the main river channel. In comparison, it was found that the number of mass wasting areas in Olympic National Park have only increased by less than 5 percent since 1939, and the amount of bank erosion is relatively small compared to the total HCMZ area. No significant change in channel morphology has been observed in the Park reaches since 1939, which would indicate that the upstream sediment supply has been in balance with the hydraulic capacity of the river channel to transport sediment. Our study found that the amount of terrace bank erosion per unit river length is greater for the Middle Hoh reaches than for the Park reaches. This means that larger amounts of fine and coarse sediment are contributed to the river from HCMZ expansion in the Middle Hoh reaches.

An increase in the supply of fine sediment to the Hoh River would increase suspended sediment concentrations and turbidity, but would not cause aggradation in the main river channel. While fine sediment is easily transported downstream through the main river channel, it may deposit in slow velocity areas, such as the forested floodplain and side-channel eddies, which may adversely impact aquatic habitat. Some recent studies of side

channel sediment composition support this, but the longevity of the impact in relation to the frequency of mass wasting events is not known.

A large increase in the supply of coarse sediment to the Middle Hoh reaches from the increased frequency of mass wasting and HCMZ expansion could lead to riverbed aggradation and ultimately change the meandering channels to a braided channel planform. However, no significant changes in river planform were observed over the 20th Century that would be associated with riverbed aggradation. The river planform through the Middle Hoh reaches has been consistently meandering. Reach 5 is a transitional reach that is generally meandering but also exhibits some of the braiding characteristics of the Park reaches.

The consistency of the river planform through the Middle Hoh reaches indicates that the sediment transport capacity of the Hoh River is generally in balance with the upstream sediment supply. The increases in coarse sediment supply to the Middle Hoh reaches has not been great enough to cause changes in river planform. There is a gradual reduction in slope in the downstream direction of the study area, which could cause a gradual reduction in transport capacity in the downstream direction. However, this appears to be balanced by the increase in river flow from downstream tributaries, especially the South Fork Hoh River. Visual observations confirm that sand to cobble-sized sediment is transported through all study reaches and even to the river mouth. Sensitivity testing of stream power (the balance of water flow or velocity and channel slope) indicated that the transport capacity of the Park reaches is nearly equivalent to the Middle Hoh reaches. The exception is Reach 6, through Spruce Canyon, which has higher sediment transport capacity than any of the other study reaches because it is constricted by bedrock on either side of the river. Stream power analyses help support the conclusion that the increases in coarse sediment loads from mass wasting and terrace bank erosion are likely small relative to the total sediment transport capacity.

16.5 Summary of Potential Management Concerns

Of the 6 miles of Park Road, 0.88 road miles (15 percent) are protected by riprap, which armors the adjacent river bank. Approximately 0.24 miles of the river bank armoring is located along portions of the road that coincide with the HCMZ terrace bank at Road Miles 0.8 and 2.2. The armoring of terrace banks (such as at road miles 0.8 and 2.2) does not limit the channel from migrating to where it has historically been. However, the riprap provides less roughness and vegetative cover than a naturally forested river bank and the riprap prevents the potential recruitment of large woody debris. The remaining 0.64 miles of armored river bank are within the HCMZ at the Park Boundary and near Taft Creek. Additionally, two areas of the Park Road, at MP 1.5 and 1.7, have experienced active erosion, but these sections of road were setback to the valley wall rather than armoring the bank.

There are 3 additional locations along the Park Road that were identified to be at risk in the near future that total 0.4 road miles:

1. 500 ft of bank immediately downstream from the existing bank protection at Park Road MP 0.8;
2. 1,250 feet of eroding bank along 680 feet of road near Park Road MP 3.0;
3. 1,900 feet of eroding river bank along 850 feet of road downstream of Taft Creek near Park Road MP 5.5

The remaining 4.7 miles of Park road are set back far enough away from the river that erosion is not likely. Together, the previously armored sections of river bank and the potential future erosion sections amount to 22 percent of the total Park Road that either have required management action or may require action in the future. Some conceptual ideas for protecting the Park Road from future terrace bank erosion are presented in Section 15.0 and in a separate document that is to be completed by Herrera Environmental Consultants.

Of the 12 miles of County Road, 5 areas totaling 1.2 miles (10 percent) of right HCMZ terrace boundary have been armored. Reclamation (2003) prepared a specific report related to the active erosion of the terrace bank at County Road MP 6.7. Additionally, a landslide area near County Road MP 9.7 endangers the road. There are two large glacial landslide areas on the left HCMZ that will continue to contribute sediment to the river as long as the river runs against them, but these terrace banks have not been armored. Future river bank erosion is likely at Lewis Ranch and Huelsdonk Ranch, and along the County Road between MP 5 and 6. Some conceptual ideas for protecting the County Road and private property from future terrace bank erosion are presented in Section 15.0.

Debris flows from tributary streams can cause damage to roads and private property. Debris flows on tributary channels do occur naturally, but they can also be initiated by logging activities. As a result of increased debris flows in many of the Middle Hoh tributaries, the alluvium in these steep tributary channels has been eroded away and as a result the fish habitat has been destroyed (Kennard, 1999; Hatten, 1991). Additionally, mass wasting on hillslopes is thought to increase the volume and frequency of debris flows beyond natural levels (Logan et al, 1991). Where debris flows encounter road culverts, debris deposition can plug the culverts and force additional debris to flow over, and sometimes erode, the road. Some conceptual ideas of alleviating problems from debris flows are described in Section 15.0.

Logging of terrace surfaces adjacent to the river has reduced the ability of the Middle Hoh reaches to recruit large, old growth woody debris as it erodes the HCMZ. A reduction in large woody debris in the channel over time would reduce the amount of fish habitat created by the wood, particularly along the low-flow channel.

17.0 RECOMMENDATIONS FOR FUTURE STUDIES

Some additional studies could be considered which would build upon the work described in this report. Collection of extensive topographic data of the river valley would help delineate the location and extent of the terraces in the Hoh River valley. This would also provide an important baseline dataset to monitor future channel changes and terrace bank erosion. Lidar data have been recently collected on the Elwha, Dungeness, and Quinault Rivers and successfully used to develop detailed topographic data in large, vegetated reaches where other techniques (photogrammetry or ground survey) are not feasible. A typical product given the vegetation constraints in this area would be a 6x6 foot grid, which would be sufficient for delineating terrace breaks.

The first terrace adjacent to the active channel or floodplain (HCMZ boundary) was generally delineated with a good degree of confidence in the Middle Hoh reaches, but the Park reaches were more difficult to access and in places some assumptions had to be made. Detailed topographic data would improve the accuracy of the delineated HCMZ boundary. This information could also be utilized to improve the prediction of potential expansion of the HCMZ and the boundary of the future channel migration zone. This is because the potential rate of future expansion is typically reduced as the river runs into progressively higher terraces. Only limited delineation of terraces outside of the HCMZ was possible for this study because of the lack of extensive, detailed topographic data for the river valley. Detailed topographic data could also be utilized in the evaluation of future management alternatives, such as road setbacks.

One of the assumptions made was that the reach boundaries would continue to remain stable over the next 100 years since they have been stable and controlled river position since at least 1891, 1895, or 1918. In certain areas it is not obvious from a simple visual observation what is causing the boundary to remain stable. The reason may be the position of the river as it approaches the boundary, or there may be something stabilizing the bank, such as bedrock or a buried log jam that are not visible on the surface. If additional certainty is required, additional investigation at these locations, such as some detailed mapping, could help further evaluate the potential for future HCMZ expansion at these locations. Dating of the channel deposits (e.g., by radiocarbon techniques) at these locations would give some estimate of when the channel abandoned these surfaces and they became terraces. While this may not necessarily be an indication of how long the boundary will be stable in the future, it would provide more information as to the amount of time the active channels have been flowing between the HCMZ boundary.

Additional studies could focus on integrating the geomorphic information provided in this report with historical and present studies related to fisheries habitat. Studies related to the impact from mass wasting on tributary channels would also provide valuable information for fishery habitat assessments that this study did not address.

Monitoring of terrace bank erosion, river channel position, and hydrology of the river would be useful to verify predictions and refine methodologies used in this study. This would help improve techniques utilized in future studies on the Hoh River and other

similar river systems. Monitoring data might include items such as aerial photography, continued river gage operation at Highway 101 location, additional river gage locations in the Middle Hoh or Park reaches, observance of debris flow occurrence, observance of large woody debris, and topographic surveys using Lidar and/or bathymetric measurements.

As part of a separate research effort, a meander model was developed and, then calibrated for Reach 7 of the Hoh River based on the historical meander migration that has occurred between 1950 and 2002 (Randle, 2004). The initial results of the research model were very positive in that its predictions of meander migration matched well with actual historic data in Reach 7. This research model could be further applied to the more sinuous reaches of the Hoh River (e.g. Reaches 5, 7 and 8) to develop future predictions for various potential hydrologic, land use, and river conditions. If future monitoring data of the river channel and terrace bank erosion could be collected in conjunction with this effort, the capabilities of the research model to make predictions could then be further tested and improved. One example might be using the model to predict the maximum lateral extent of meander migration (future CMZ) if a road were setback and the present bank armoring removed. Another example would be to use the model to predict the impacts of engineered log jams placed in the river.

18.0 REFERENCES

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19.0 GLOSSARY

active channel – The unvegetated channel that conveys the majority of the river's bed-material load. Does not include overflow or side channels.

active floodplain – The zone of active channel, side channels, overflow channels and intervening surfaces that receive some flow at annual intervals. It is synonymous with present floodplain.

aggradation – Deposition of sediment.

alluvium – Sediment deposited by flowing water.

bank-full channel – The channel that holds the bank-full flow or discharge.

bank-full flow – The flow that fills the active channel to the incipient point of overtopping the banks. It is the flow that causes the majority of channel changes and sediment transport over a long period of time. It is usually determined from field observations. It often is called the effective discharge and channel-forming discharge.

bar – Accumulations of bedload (sand and gravel) that are deposited along or adjacent to a river as flow velocity decreases. If the sediment is reworked frequently, the deposits will remain free of vegetation. If the surface of the bar becomes higher than the largest flows, vegetation stabilizes the surface making further movement of the sediment in the bar difficult.

bed-material – Sediment that is preserved along the channel bottom and in adjacent bars.

bedload – The sediment that is transported intermittently along the bed of the river channel by creeping, rolling, sliding, or bouncing along the bed. Typically includes sizes of sediment ranging between coarse sand to boulders.

channel deposits – Sediment that is deposited in the channel as flow subsides.

coarse sediment – Boulders to coarse sand; sizes that are usually transported as bedload and are too large to be deposited outside of the channel on the floodplain by overbank flow.

control point – A survey station that provides horizontal or vertical position data, or both, that can be identified on aerial photographs and used to ortho-rectify the photographs or to correlate data.

D_{50}– The median particle-size diameter for a sediment sample, such that 50 percent of the sample is larger than this value.

debris flow – A moving mass of rock fragments, soil, and mud, more than half of the particles being larger than sand size.

discharge – The volume of water in a river that flows through a given cross section of the river channel per unit time. In the United States it is usually measured in cubic feet per second (ft^3/s).

effective discharge – The discharge that transports the most sediment over a given time interval. It is often referred to as the discharge that is the most effective in shaping and maintaining the form of the channel.

fine sediment – Fine sand, silt, and clay; sizes that can be transported as suspended sediment and are often deposited outside of the active channel in areas of low velocity.

floodplain – The zone interpreted on the basis of geomorphic characteristics characterized by presence of riparian vegetation, unweathered sediment, and relatively low surfaces immediately adjacent to the active channel that are periodically inundated by flood flows.

Holocene – The geologic time interval between about 10,000 years ago and the present.

hydraulics – The physical laws governing water movement.

large woody debris – Logs, branches, and other large pieces of trees that are transported by the river during high flows and are often deposited on gravel bars as flow velocity decreases.

levee – A natural or artificial embankment that is built along a river channel margin; often constructed to protect an area from flooding or confine water to a channel. Often referred to as a dike.

loess – A deposit of wind-blown silt.

longitudinal bar – An elongated gravel bar that extends along and roughly parallel to a relatively straight section of river channel. It grows in a downstream direction, with its steep side toward the channel bank and with a narrow trough between the bar and the bank.

low-flow channel – The channel that carries water during times of low flow. It tends to follow the deepest part of the channel.

mass wasting – General term for the dislodgement and downslope transport of soil and rock under the influence of gravitational stress (mass movement). Often referred to as shallow-rapid landslide, deep-seated failure, or debris flow.

mid-channel bar – A ridge-shaped or somewhat arcuate-shaped gravel bar that is preserved between branches of a low-flow channel.

fluvial geomorphology – The study of river channel geometry and planform, and how it changes over time.

ortho-rectified photograph – An aerial photograph that has been corrected for the geometries and tilt angles of the camera when the image was taken and for topographic relief using a digital elevation model, flight information, and surveyed control points on the ground.

overbank deposits – Fine sediment (fine sand, silt, and clay) that is deposited outside of the channel on the floodplain or terrace by overbank flow.

overflow channel – A channel, often adjacent to the active channel, that carries water only during high flows (floods) . It can be dry for much of a year, but receives flow frequently enough that it is generally unvegetated. It is synonymous with flood-flow channel.

channel planform – Characteristics of the river channel that determine its two-dimensional pattern as viewed on the ground surface, aerial photograph, or map.

Pleistocene – The geologic time interval between 1.6 million years ago and 10,000 years ago.

point bar – A sand or gravel bar that is deposited at the inside of a meander bend as a result of secondary currents related to changes in velocity at a bend in the channel. It is usually found where sediment is supplied from upstream, so that the bar grows in the downstream direction as sediment continues to be added to the inside of the bend.

Quaternary – The geologic time interval between 1.6 million years ago and the present. It includes both the Pleistocene and the Holocene.

riparian – The area in or along the edge of the river channel. It often refers to habitat or vegetation.

riprap – Large angular rocks that are placed along a river bank to prevent or slow erosion.

river mile (RM) – The distance in miles measured along the centerline of the river channel upstream from the mouth or other established point of origin (e.g., confluence).

rock flour – Finely comminuted, chemically unweathered material, consisting of silt- and clay-sized angular particles of rock-forming minerals, chiefly quartz, formed when rock fragments are pulverized while being transported or are crushed by the weight of superincumbent material. The term is most commonly applied to the very fine powder

that is formed when stones embedded in a glacier or ice sheet abrade the underlying rocks, and that is deposited as the matrix in till or in outwash deposits.

scour – Local erosion of sediment from the channel bed caused by high velocity.

side channel – A secondary channel that nearly always carries flow and is located in the active floodplain and may be fed from groundwater or tributaries much of the time.

channel sinuosity – The ratio between the length of the channel, as measured along the centerline of the channel, to the centerline length of the valley. For this study, the ratio was measured between the length of the channel and the centerline of the future channel migration zone. The higher the sinuosity value, the more curving the channel pattern.

stage – The height of the water surface above the channel bed; referenced either by depth or to a vertical datum.

suspended-sediment load – The fine sediment (fine sand, silt, and clay) that is transported in suspension above the channel bed. It is the sediment that is light enough to be transported in suspension much of the time, in contrast to the bed load that is primarily moved along the bed.

terrace – A relatively stable, flat surface formed when the river abandons the floodplain that it had previously deposited. It often parallels the river channel, but is high enough above the channel that it rarely, if ever, is covered by water and sediment. The deposits underlying the terrace surface are alluvial, either channel or overbank deposits, or both. Because a terrace represents a former floodplain, it can be used to interpret the history of the river.

transport capacity – The ability of the river to move sediment. It depends upon channel gradient or slope, discharge, size of the available sediment, and channel form (e.g., width, depth, roughness).

transverse bar – A gravel bar that extends roughly perpendicular across the direction of flow. It is often associated with split, branching flow and can create steps in the channel bed.

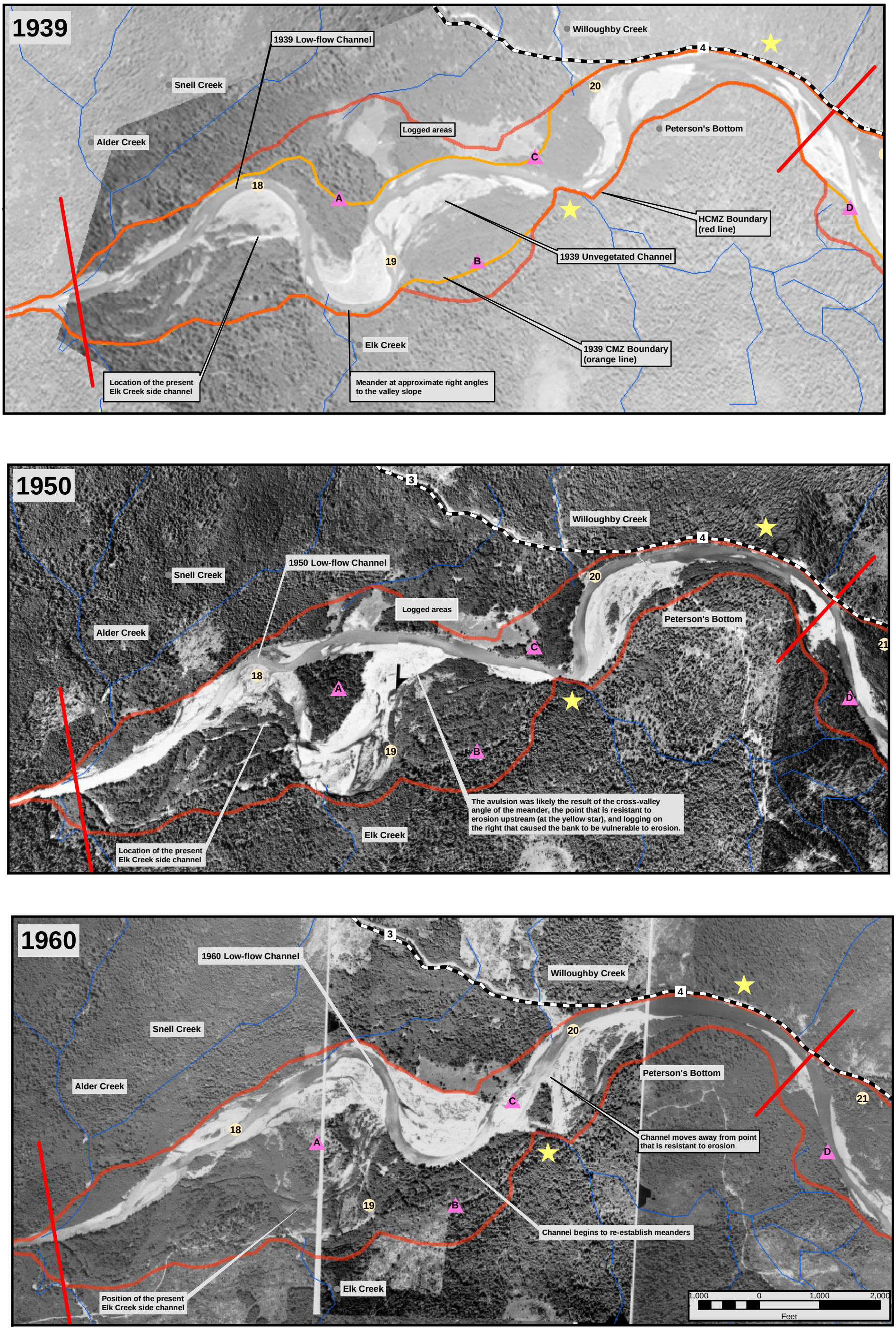
Appendix A.
Historic Channel Changes from 1939 to 2002

This section provides historical aerial photographs and the HCMZ boundary for each of the eight study reaches between 1939 and 2002.

Table A-1. Aerial Photography and Maps Acquired and Rectified to Same Scale for Geomorphic Study

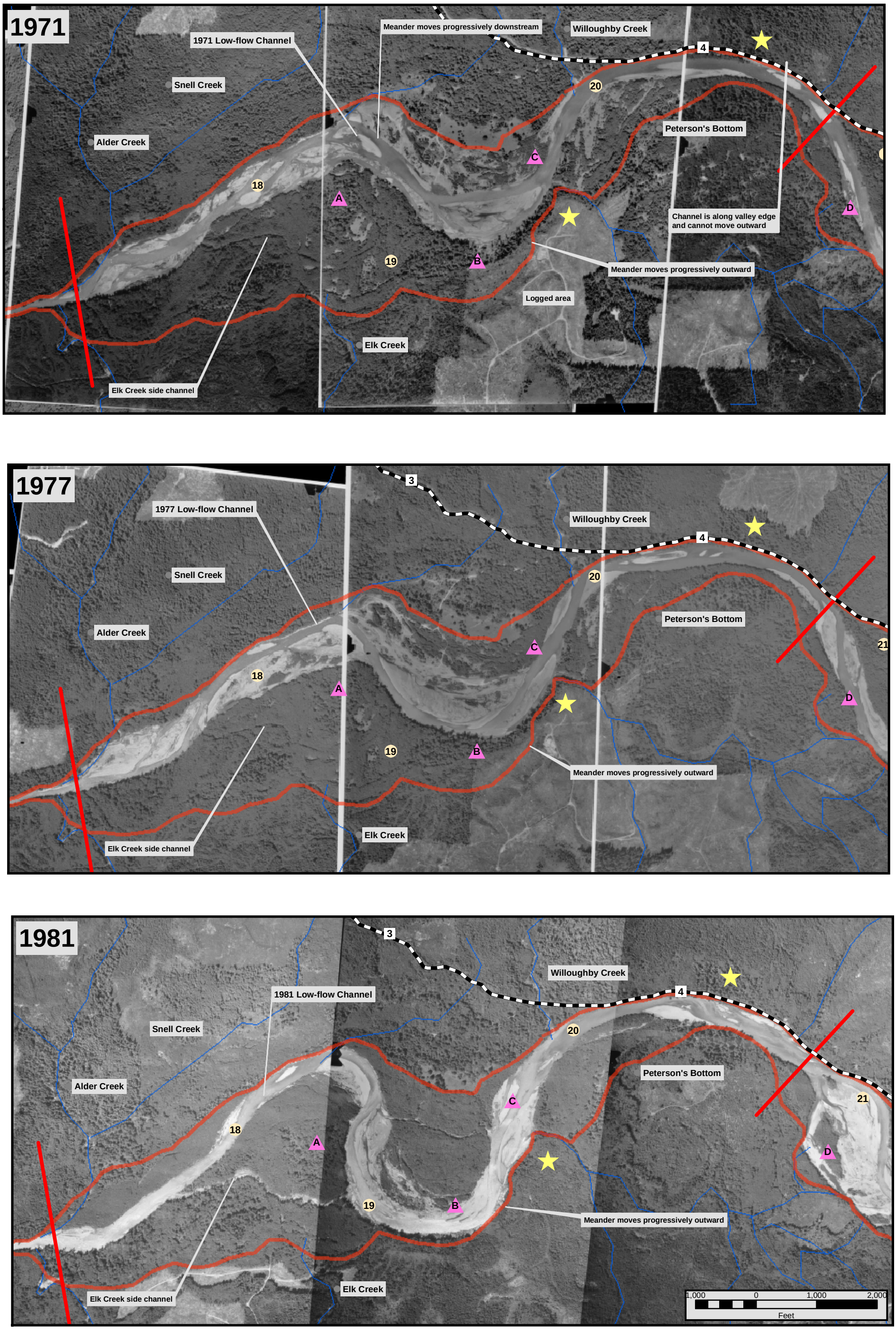
Photograph or Map Date	Scale	Area Covered from mouth (RM 0) to Mount Tom Creek (RM 40)[1]	Type	Source	Project	Reach Rectified in GIS
1891, 1895, or 1918	1:31,680	Mouth to RM 40	Cadastral Survey Maps	BLM	-	RM 17 to 40
10-12-1939	1:125,000	Mouth to RM 40	Black & white	USGS National Archives (Wallace Aerial Surveys)	GS-J	RM 0 to 40
1950-51	1:12,000	Mouth to RM 38	Black & white	BERRY (Univ. of Washington)	M49-13	RM 17 to 38
1960	1:12,000	Mouth to RM 35	Black & white	WDNR[2]	WWJC6000	RM 17 to 35
8-9-1971	1:12,000	Mouth to RM 27	Black & white	WDNR	OLY-71	RM 17 to 27
7-22-1977	1:12,000	Mouth to RM 38	Black & white	WDNR	OL-77	RM 17 to 38
7-4 & 9-4, 1981	1:12,000	Mouth to RM 38	Black & white	WDNR	OL-81	RM 17 to 38
1987	1:24,000	Mouth to RM 40	Quad Map (DRG[3])	USGS	-	RM 0 to 40
1994	1:24,000	Mouth to RM 40	Black & white orthophoto	USGS	-	RM 0 to 40
7-28-1998	1:12,000	Mouth to RM 31	Color	Hoh Tribe	Quillaute-Hoh	Photos Not Rectified
7-8-2001	1:32,000	Mouth to RM 40	Black & white orthophoto	DNR	OLQT00	RM 0 to 40
7-10 to 7-12, 2002	1:12,500	Mouth to RM 40	Color	Sound Aerial Survey	HOH R	RM 17 to 40

[1]ONP Boundary located at RM 31; [2]WDNR is Washington Department of Natural Resources Photo and Map Sales; [3]DRG is digital raster graphic (scanned USGS quadrangle map)



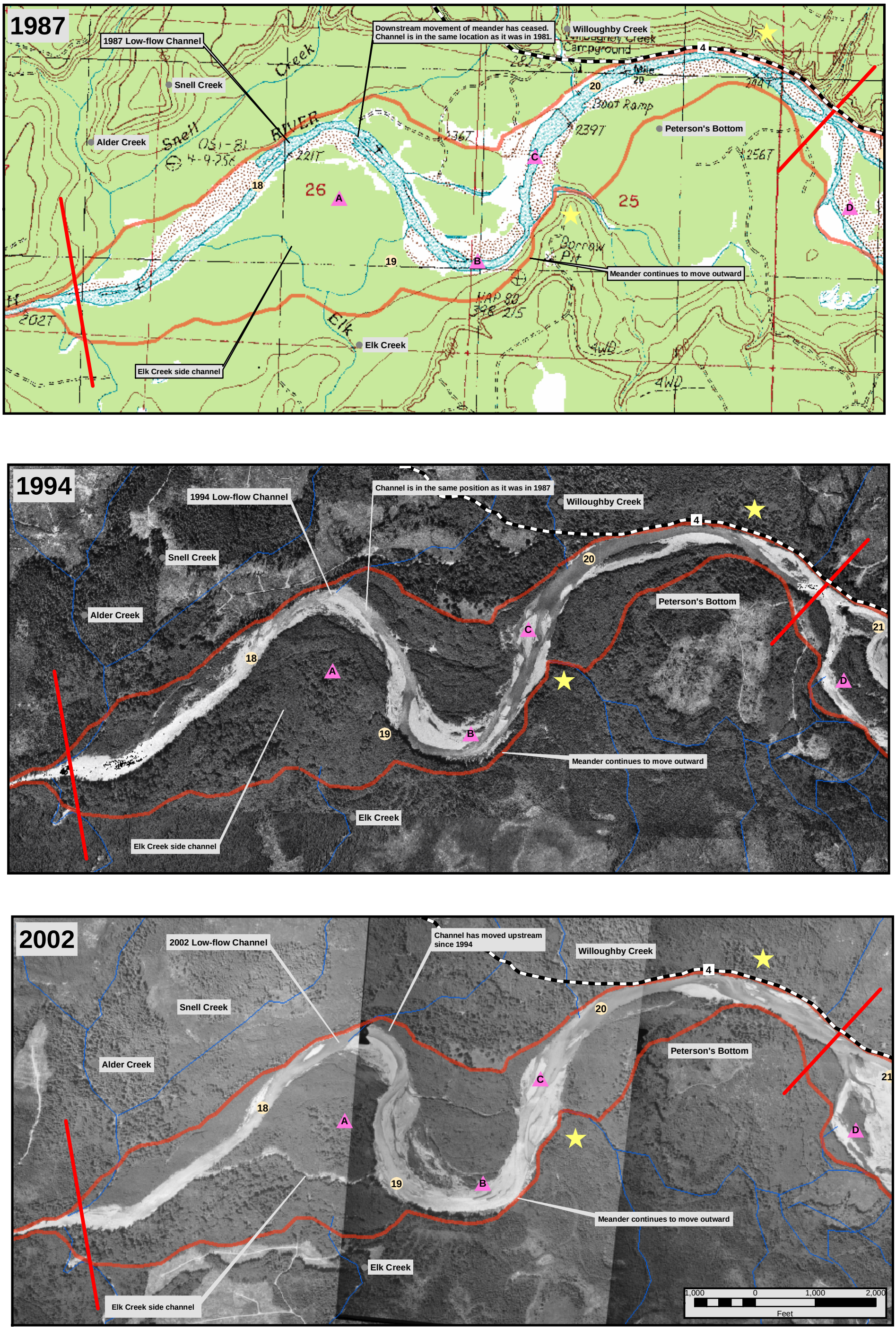
Yellow stars show the two areas that have been resistant to erosion since 1939. Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. Mileages are based on a channel survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.1. Aerial photographs taken in 1939, 1950, and 1960 for the Willoughby Creek Reach.



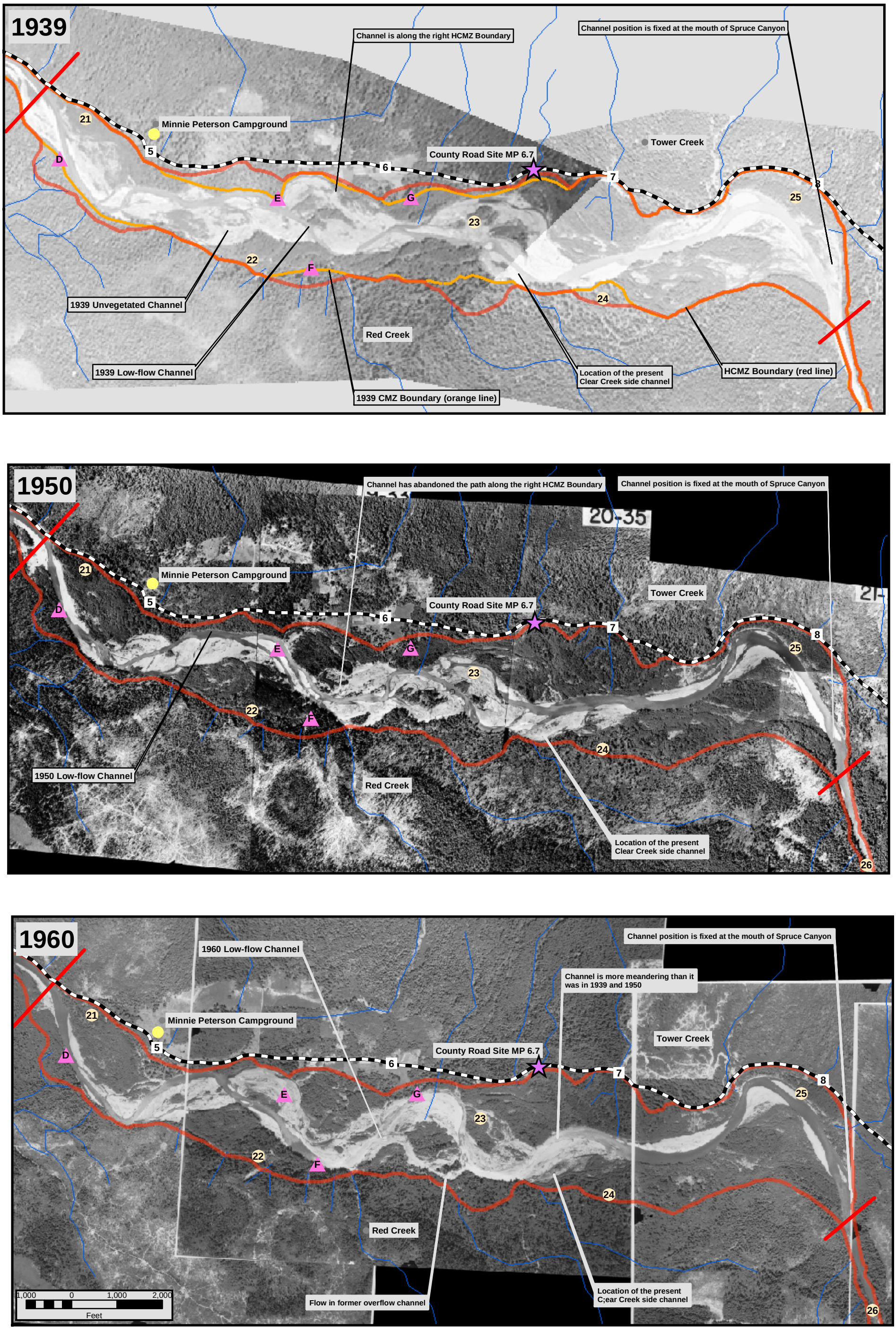
Yellow stars show the two areas that have been resistant to erosion since 1939. Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. Mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.2. Aerial photographs taken in 1971, 1977, and 1981 for the Willoughby Creek Reach.



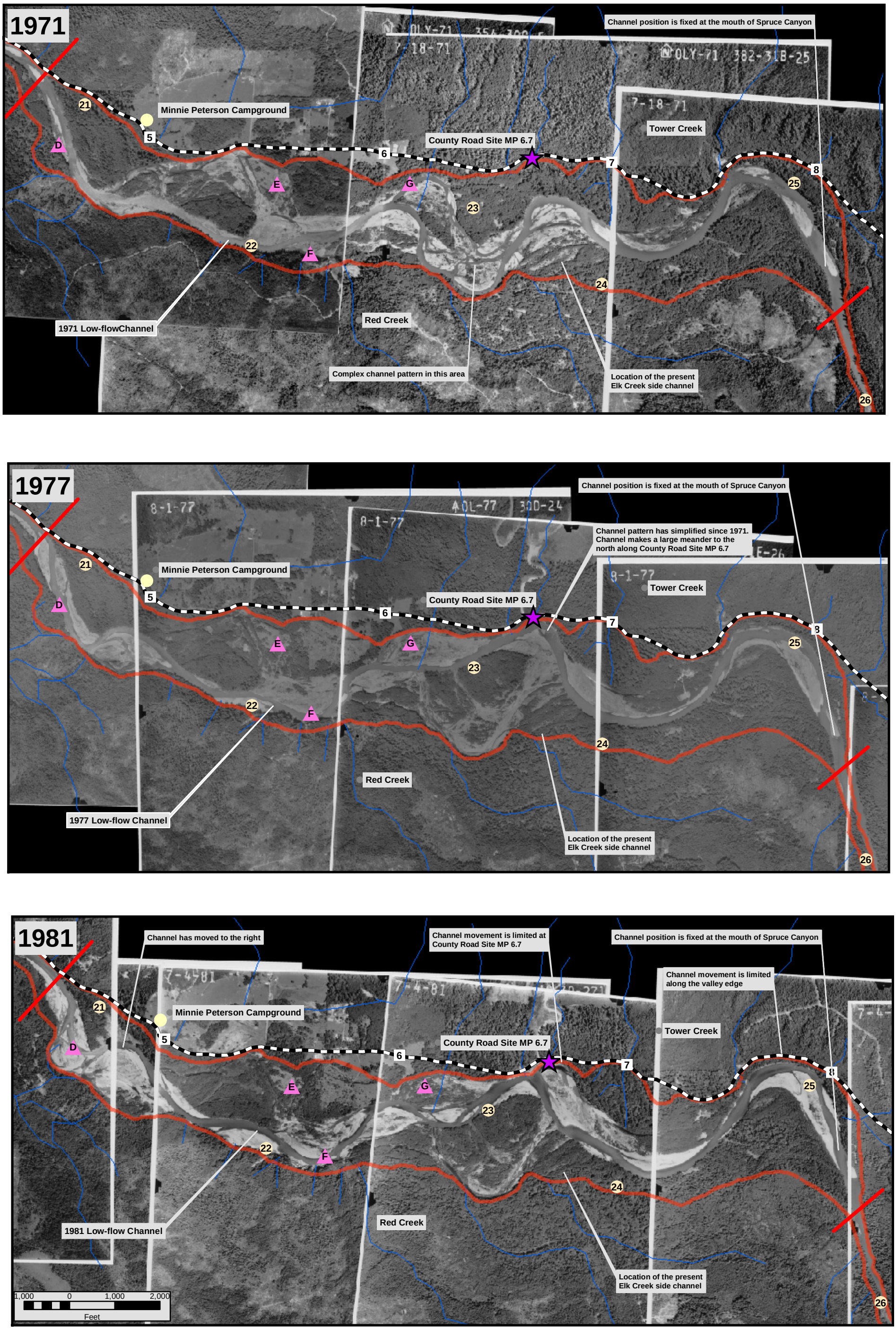
Yellow stars show the two areas that have been resistant to erosion since 1939. Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. Mileages are based on a channel survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.3. Topographic map from 1987, and aerial photographs taken in 1994 and 2002 for the Willoughby Creek Reach.



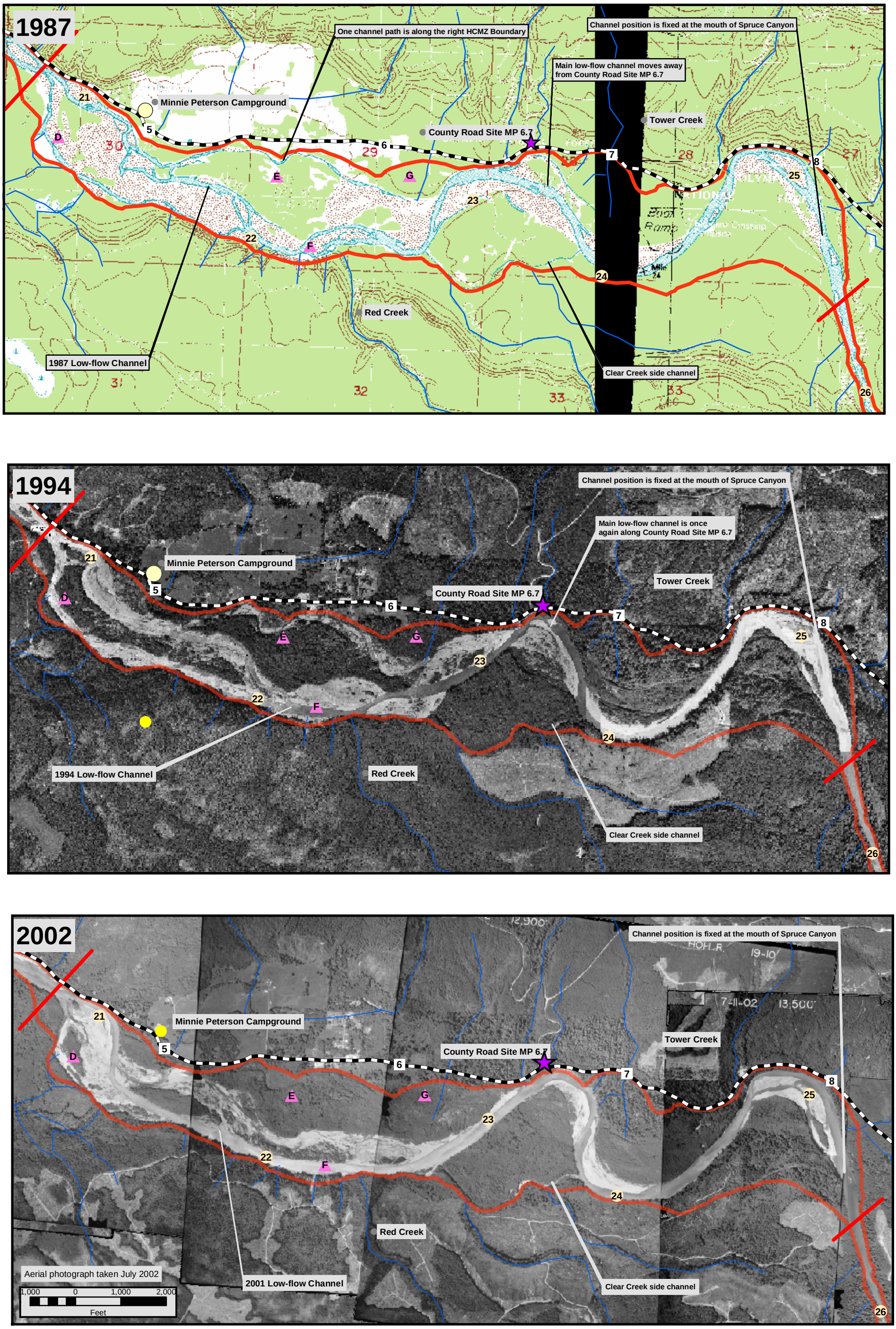
Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. Mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.4. Aerial photographs taken in 1939, 1950, and 1960 for the Morgans Crossing Reach.



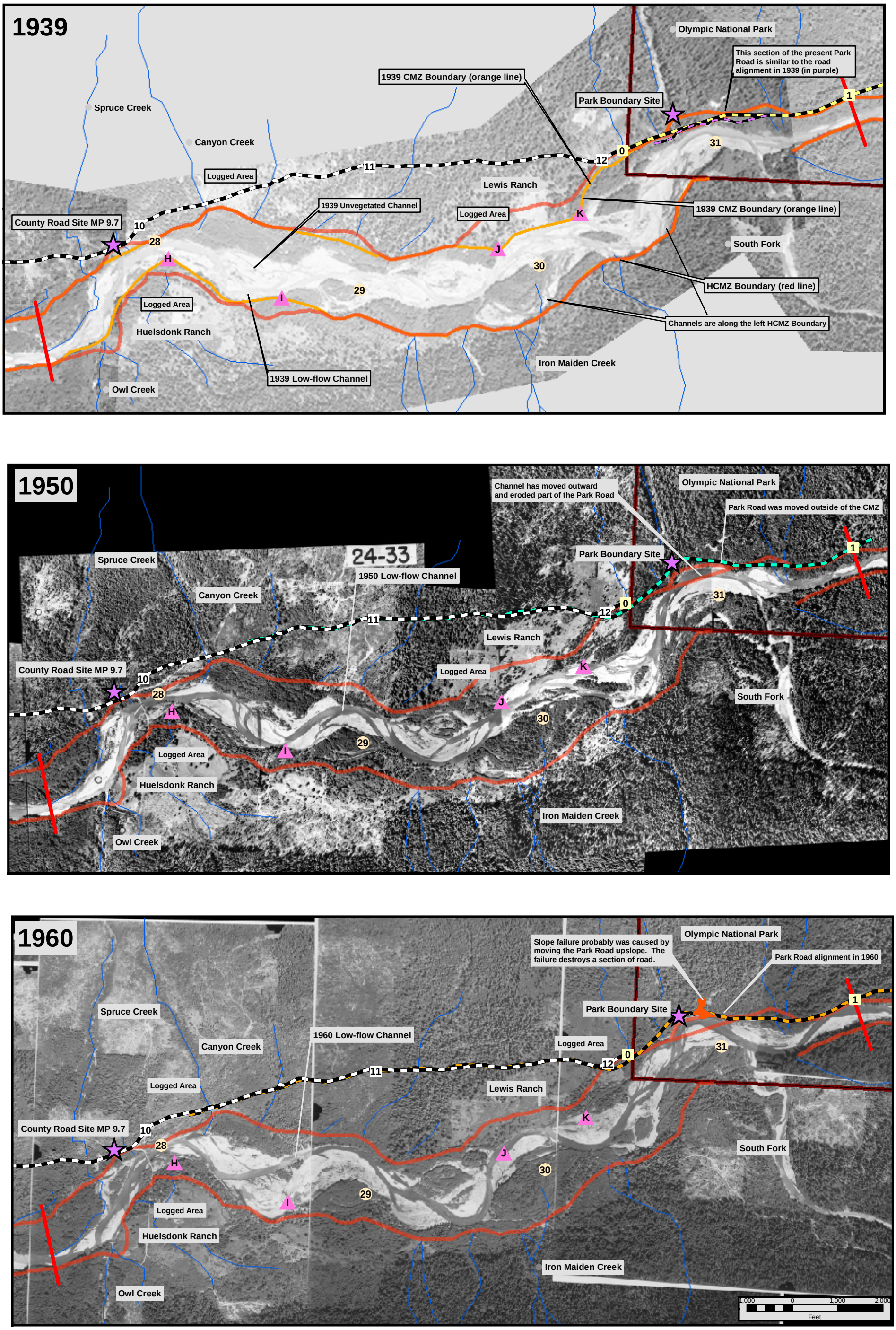
Letters in the pink triangles indicate the same localities in all of the figures. Numbers in the tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.5. Aerial photographs taken in 1971, 1977, and 1981 in the Morgans Crossing Reach.



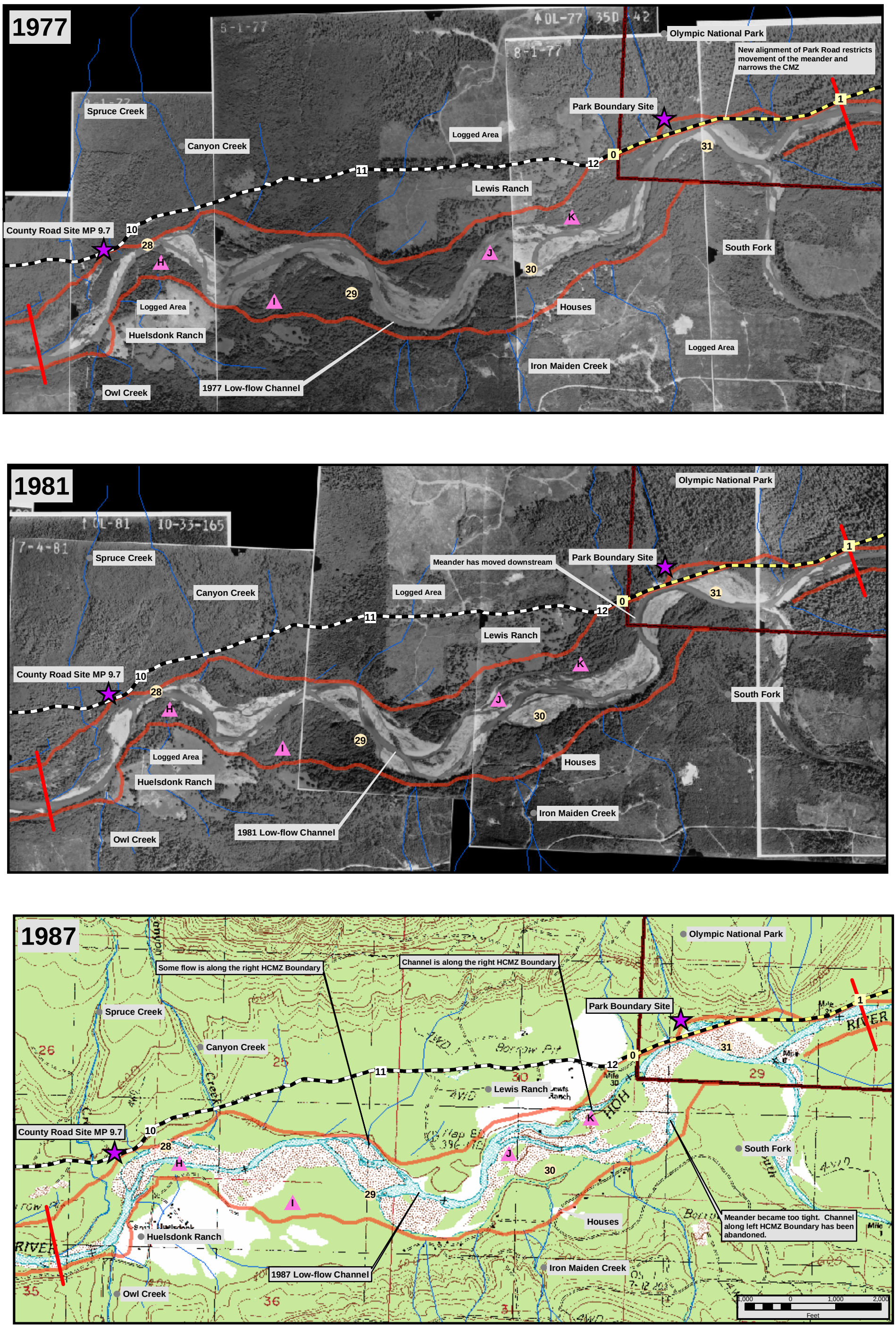
Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. Mileages are based on a channel survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.6. Topographic map dating from 1987, and aerial photographs taken in 1994 and 2002 for the Morgans Crossing Reach.



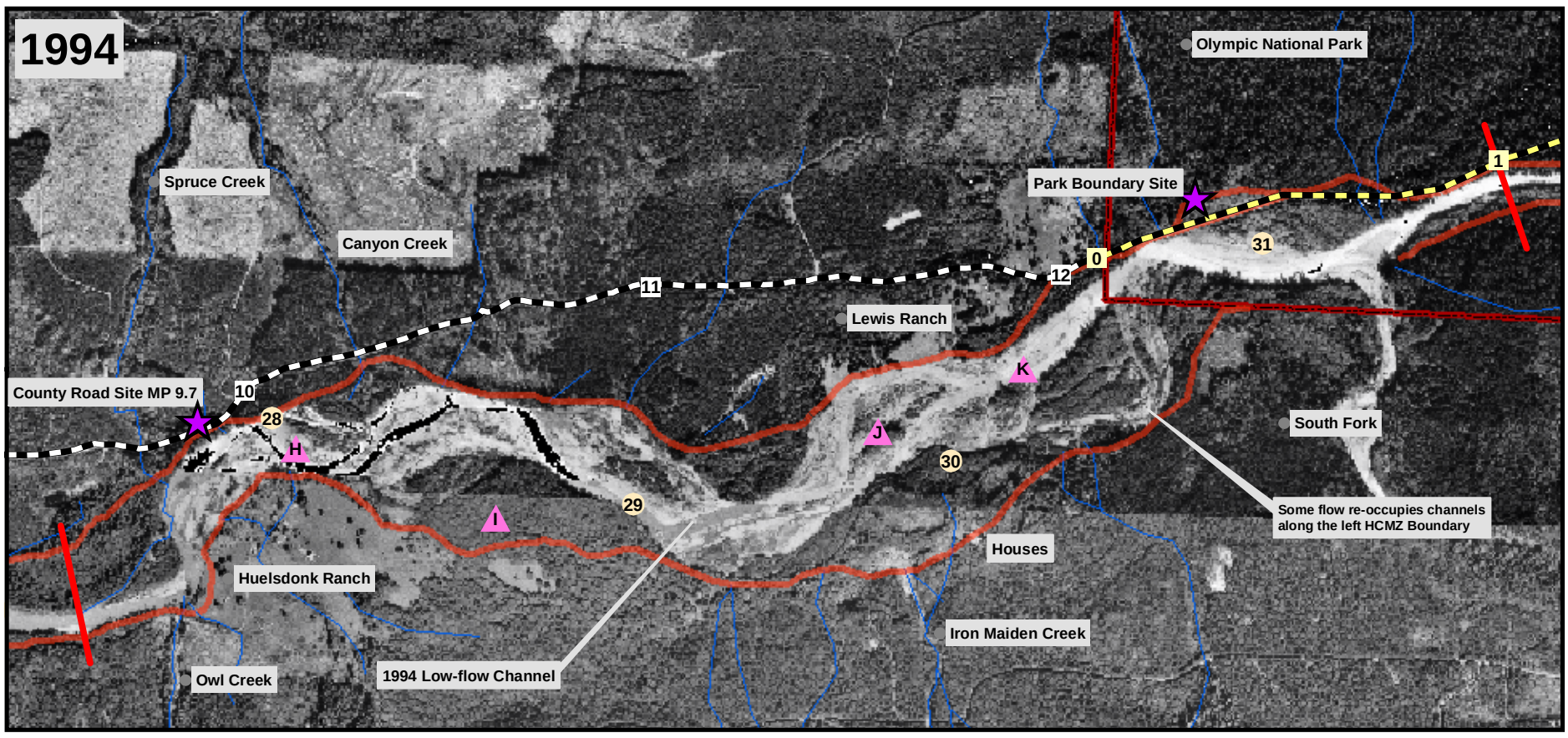
Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

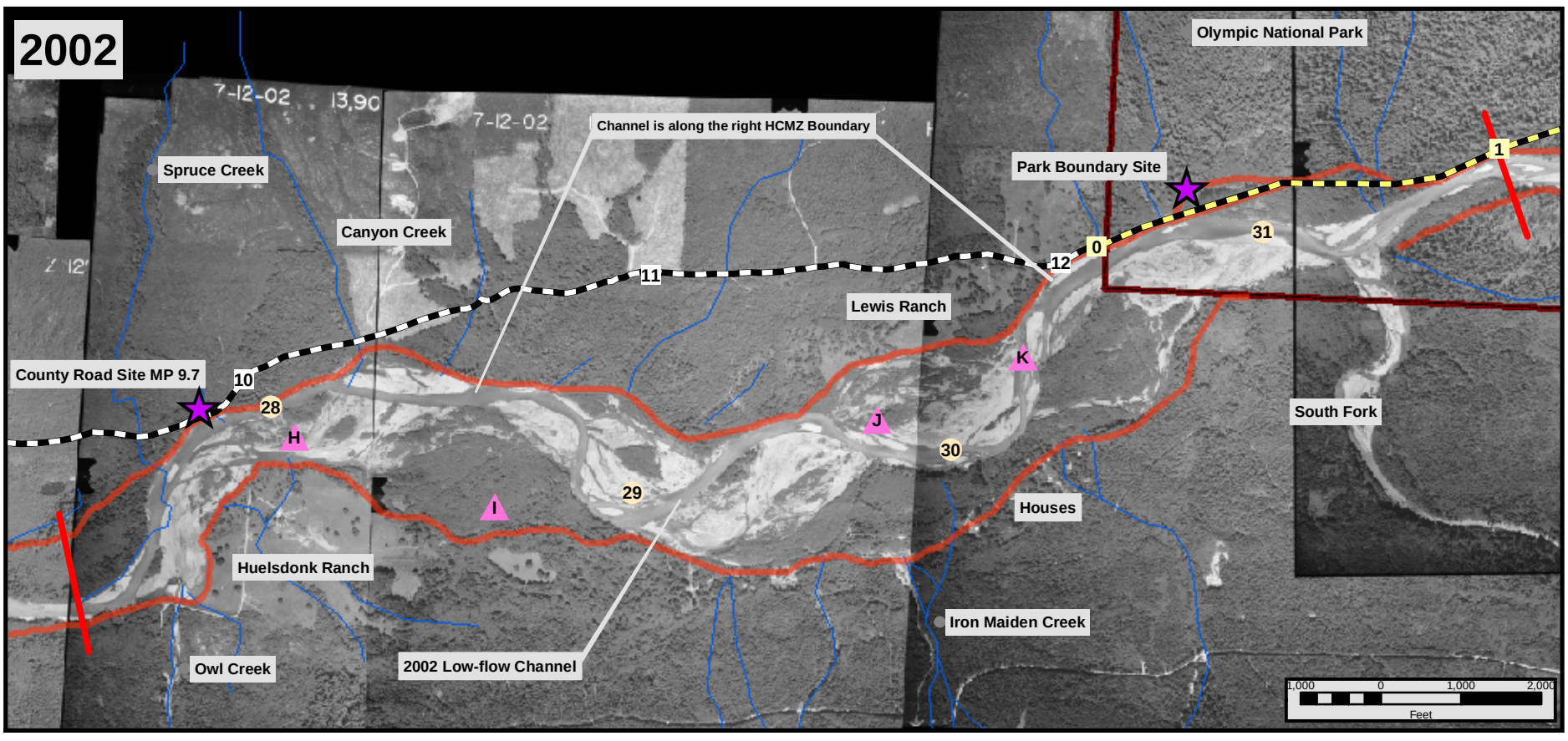
Figure A.7. Aerial photographs taken in 1939, 1950, and 1960 for the Huelsdonk-South Fork Reach.



Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

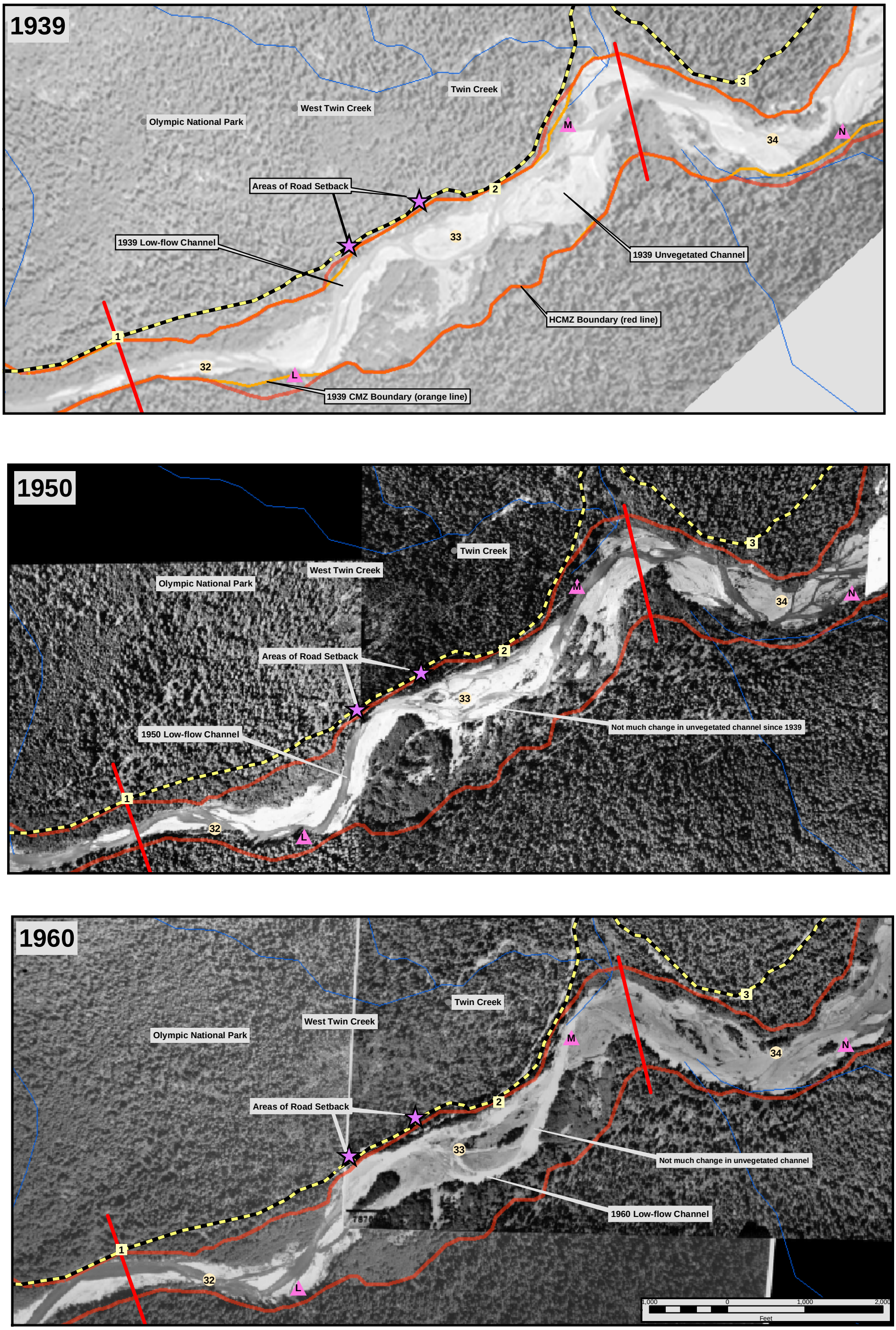
Figure A.8. Aerial photographs taken in 1977 and 1981, and a topographic map dating from 1987 for the Huelsdonk-South Fork Reach.





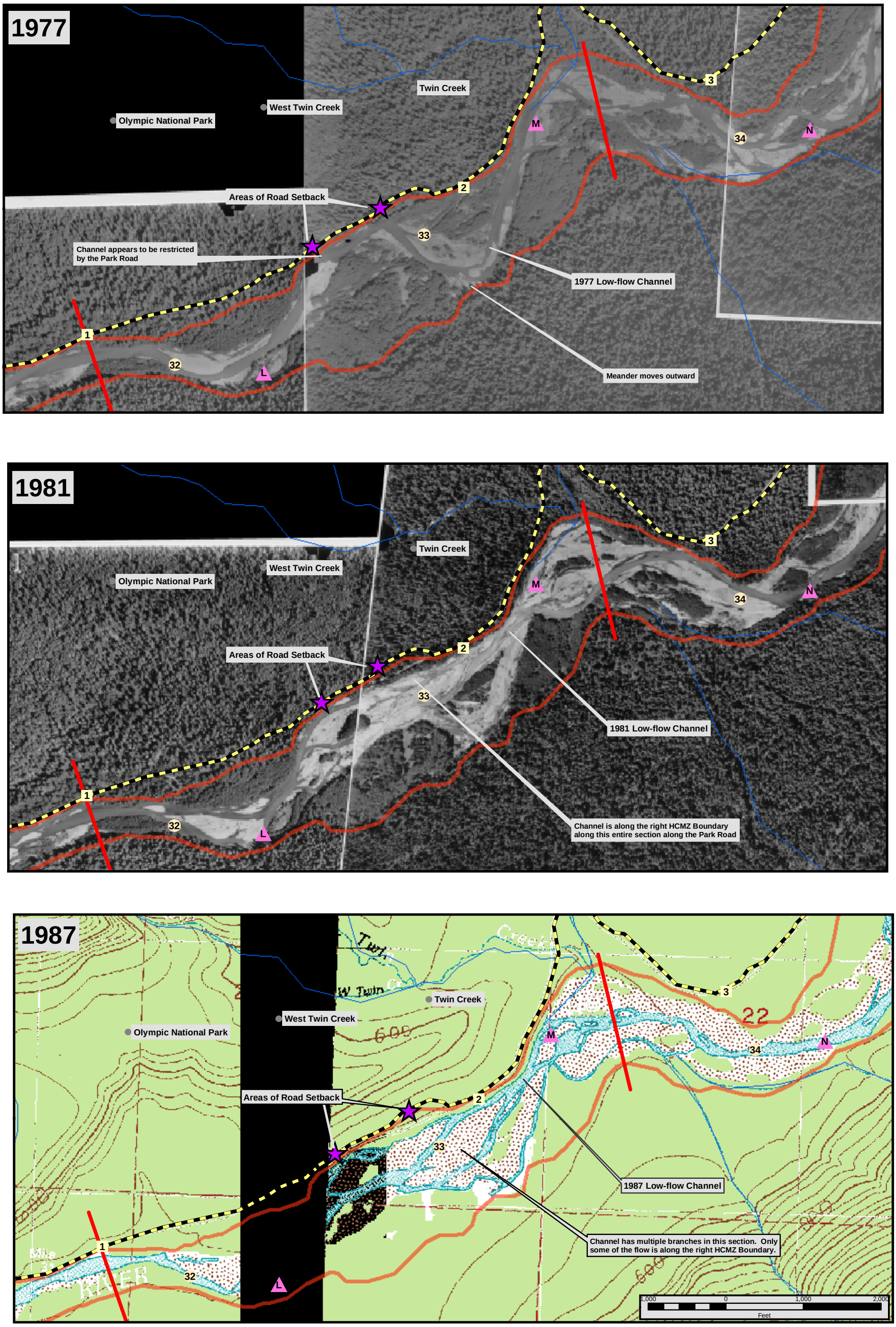
Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.9. Aerial photographs taken in 1994 and 2002 for the Huelsdonk-South Fork Reach.



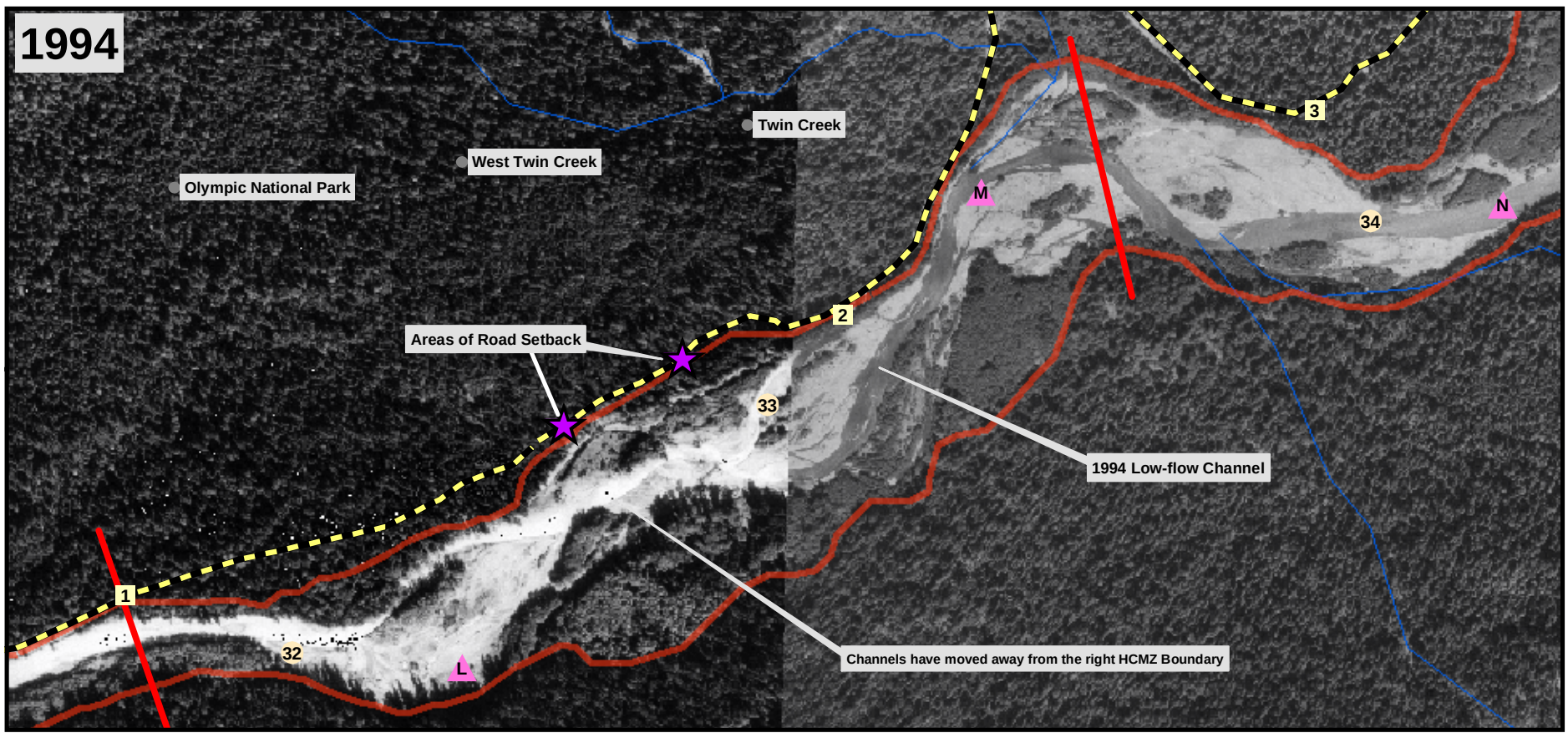
Letters in the pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

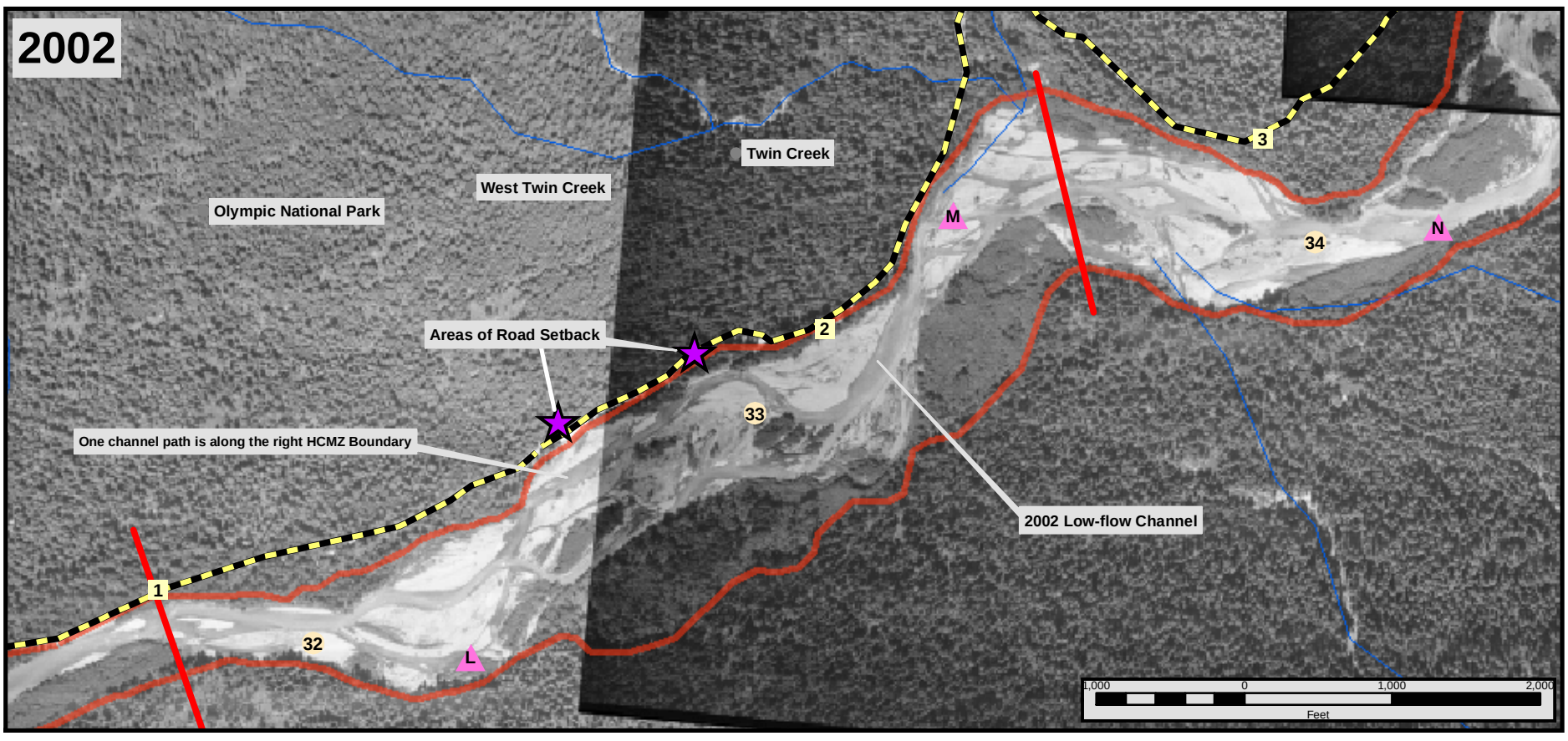
Figure A.10. Aerial photographs taken in 1939, 1950, and 1960 for the Twin Creek Reach.



Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

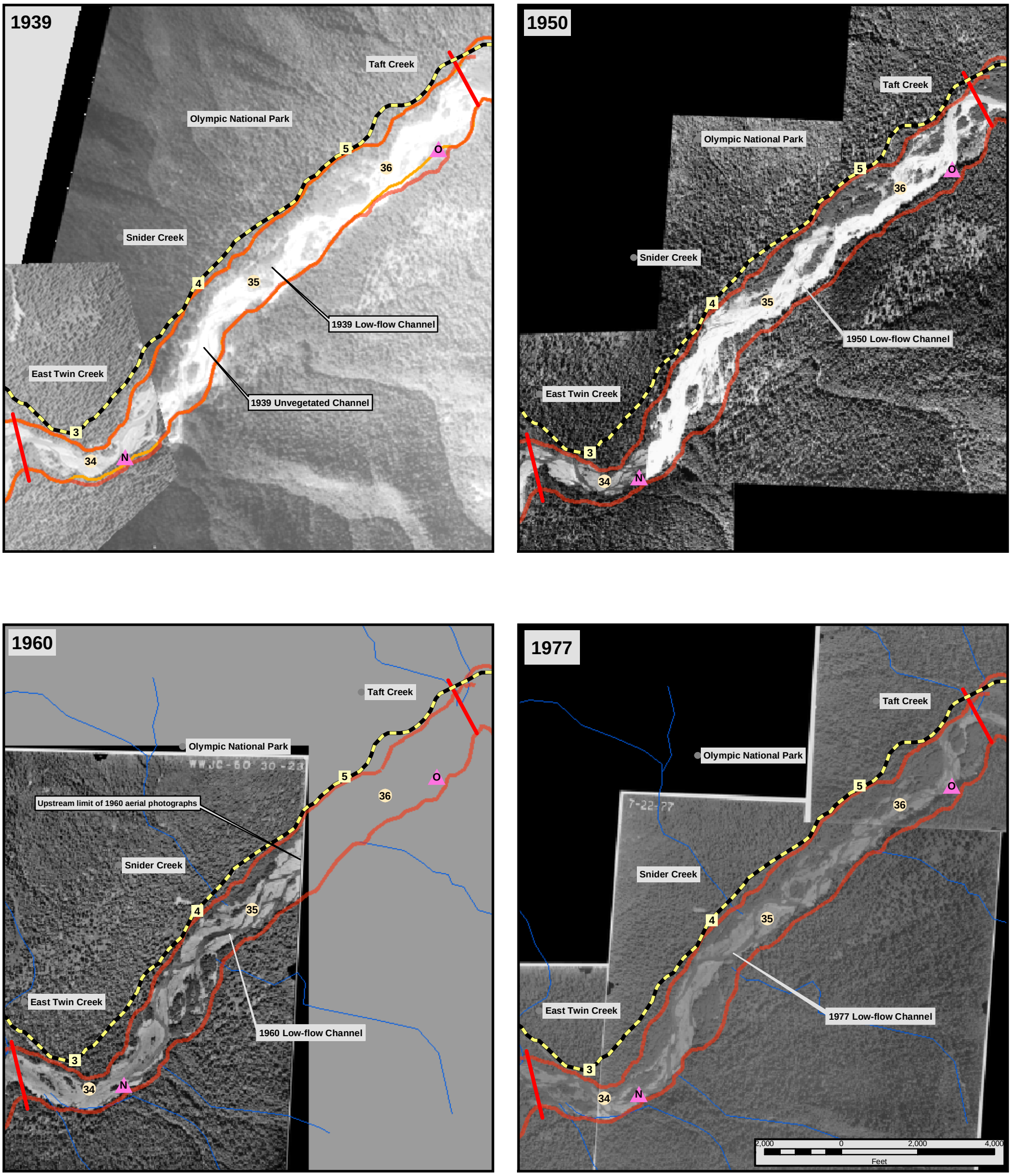
Figure A.11. Aerial photographs taken in 1977 and 1981, and a topographic map dating from 1987 for the Twin Creek Reach.





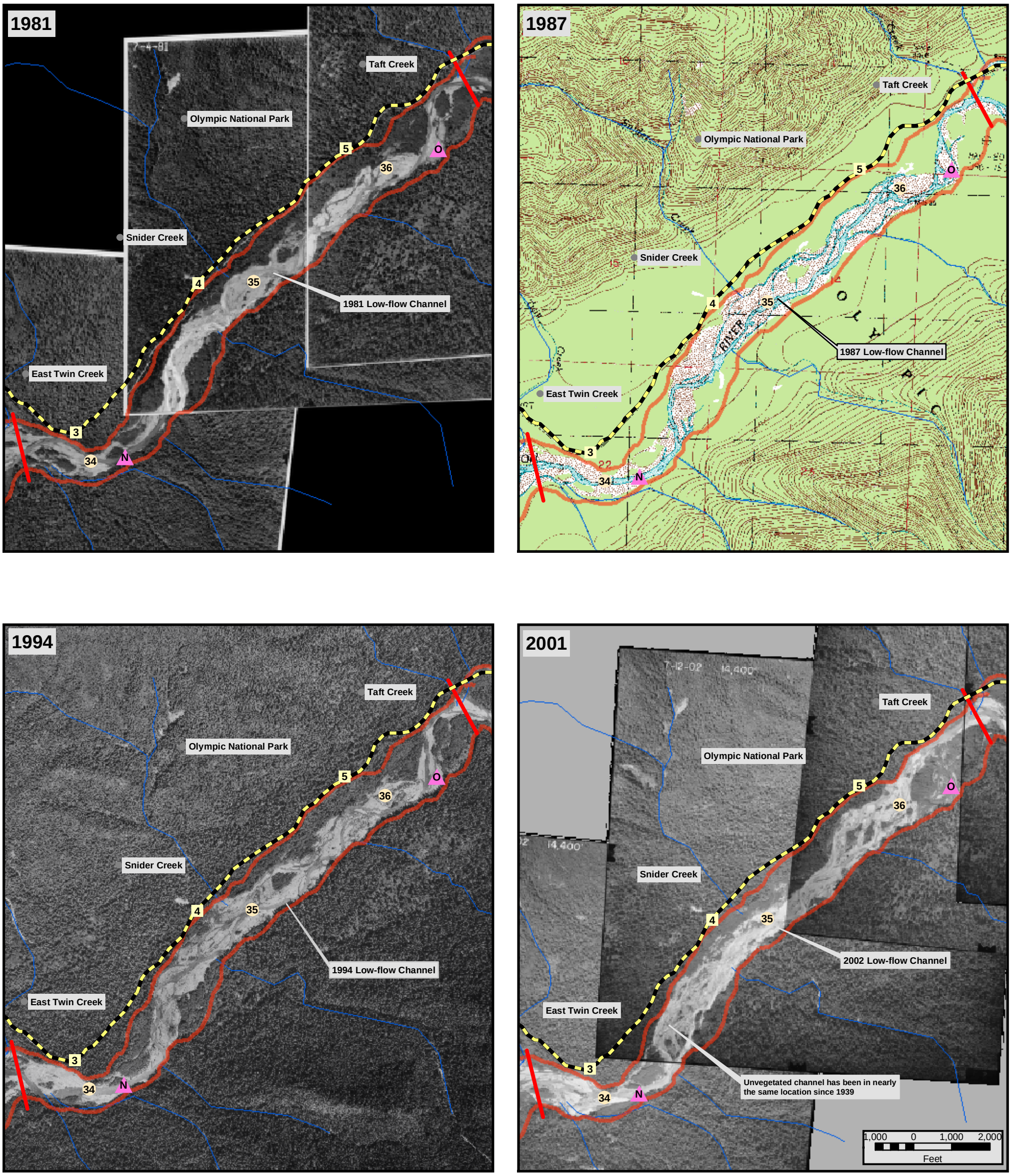
Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.12. Aerial photographs taken in 1994 and 2002 for the Twin Creek Reach.



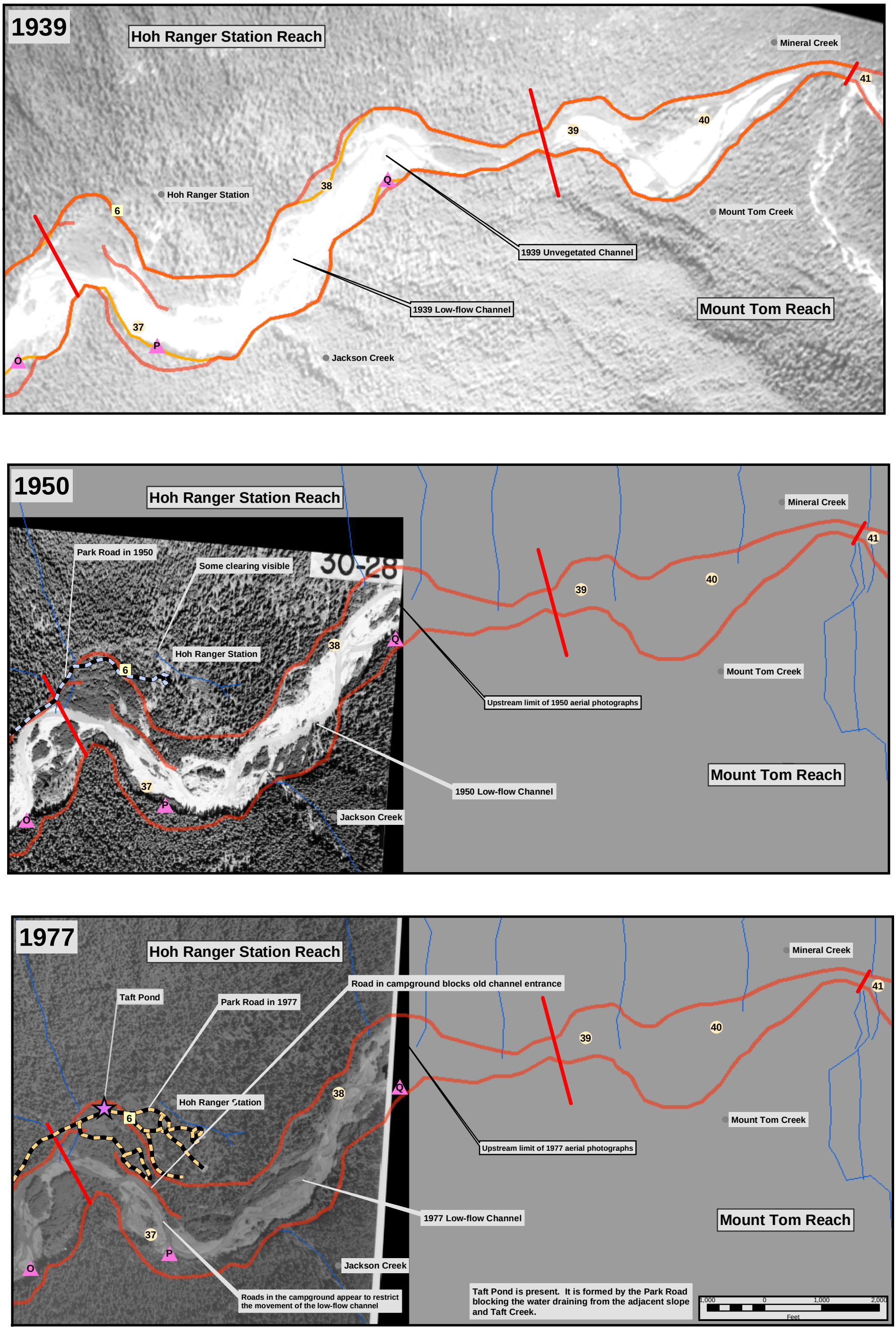
Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.13. Aerial photographs taken in 1939, 1950, 1960, and 1977 for the Snider Creek Reach.



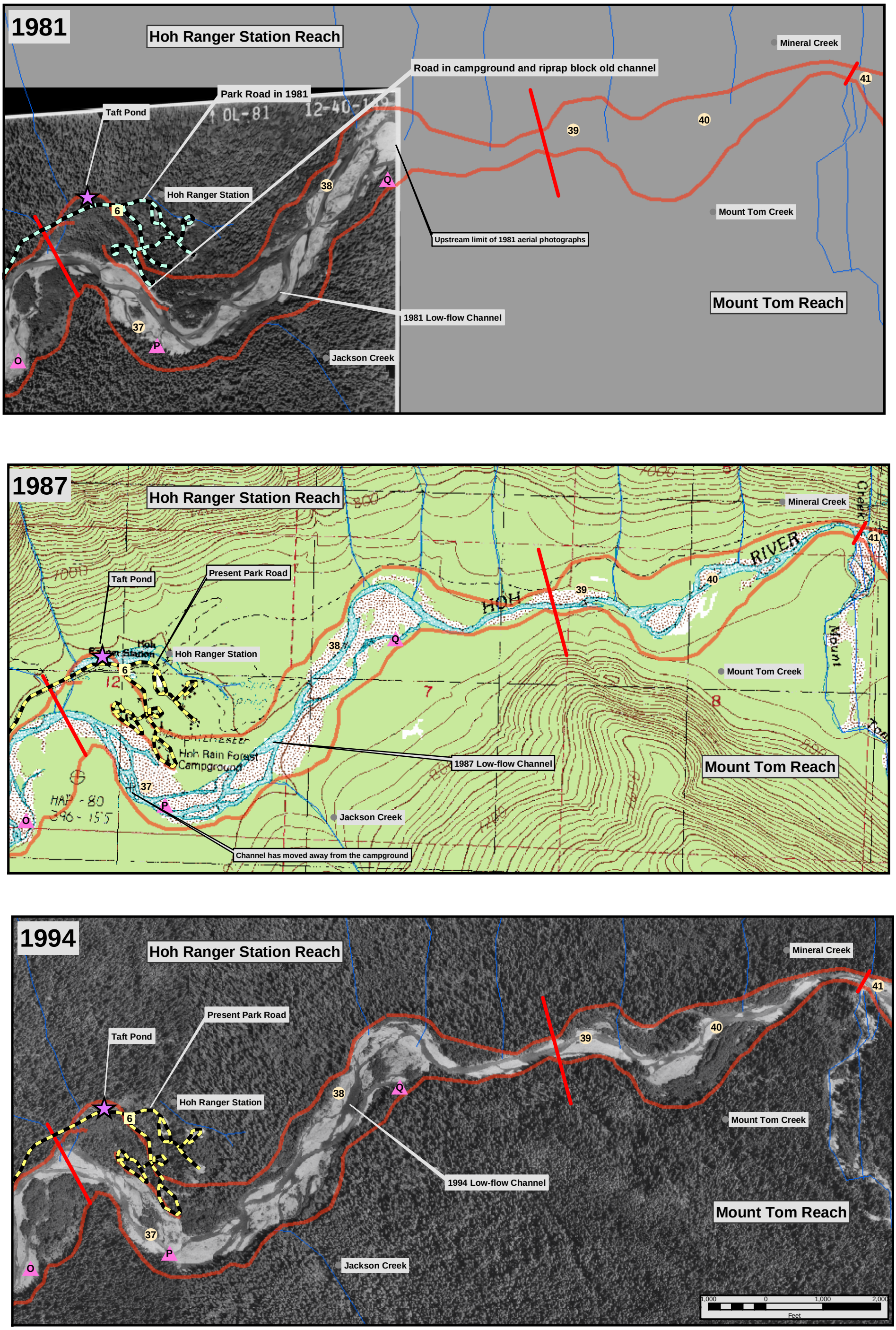
Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.14. Aerial photographs taken in 1981, 1994, and 2002, and a topograhic map dating from 1987 for the Snider Creek Reach.



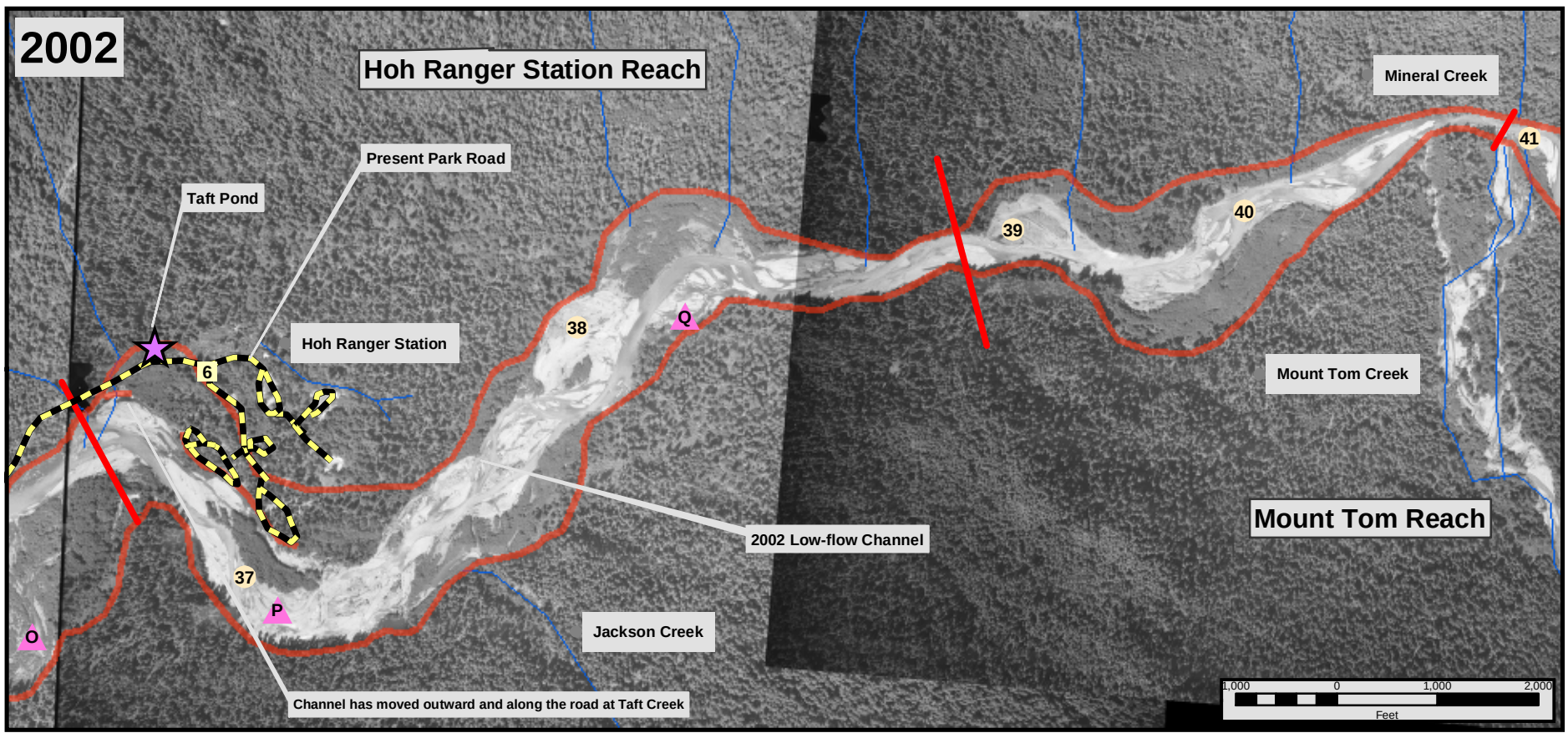
Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.15. Aerial photographs taken in 1939, 1950, and 1977 for the Hoh Ranger Station Reach.



Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Figure A.16. Aerial photographs taken in 1981 and 1994, and a topographic map dating from 1987 for the Hoh Ranger Station and Mount Tom Reaches.



Letters in pink triangles indicate the same localities in all of the figures. Numbers in tan circles are river miles from the mouth of the Hoh River. River mileages are based on a river survey conducted in 2000. Red line on both sides of the channel is the HCMZ Boundary.

Explanation of Symbols Used in Appendix A

- HCMZ Boundary
- Tributaries
- Reach Boundaries
- National Park Service Road Mile Post
- National Park Service Road
- County Road Mile Post
- Jefferson County Road
- Park Road in 1950
- Park Road in 1977
- Park Road in 1981
- Location Points
- River Miles

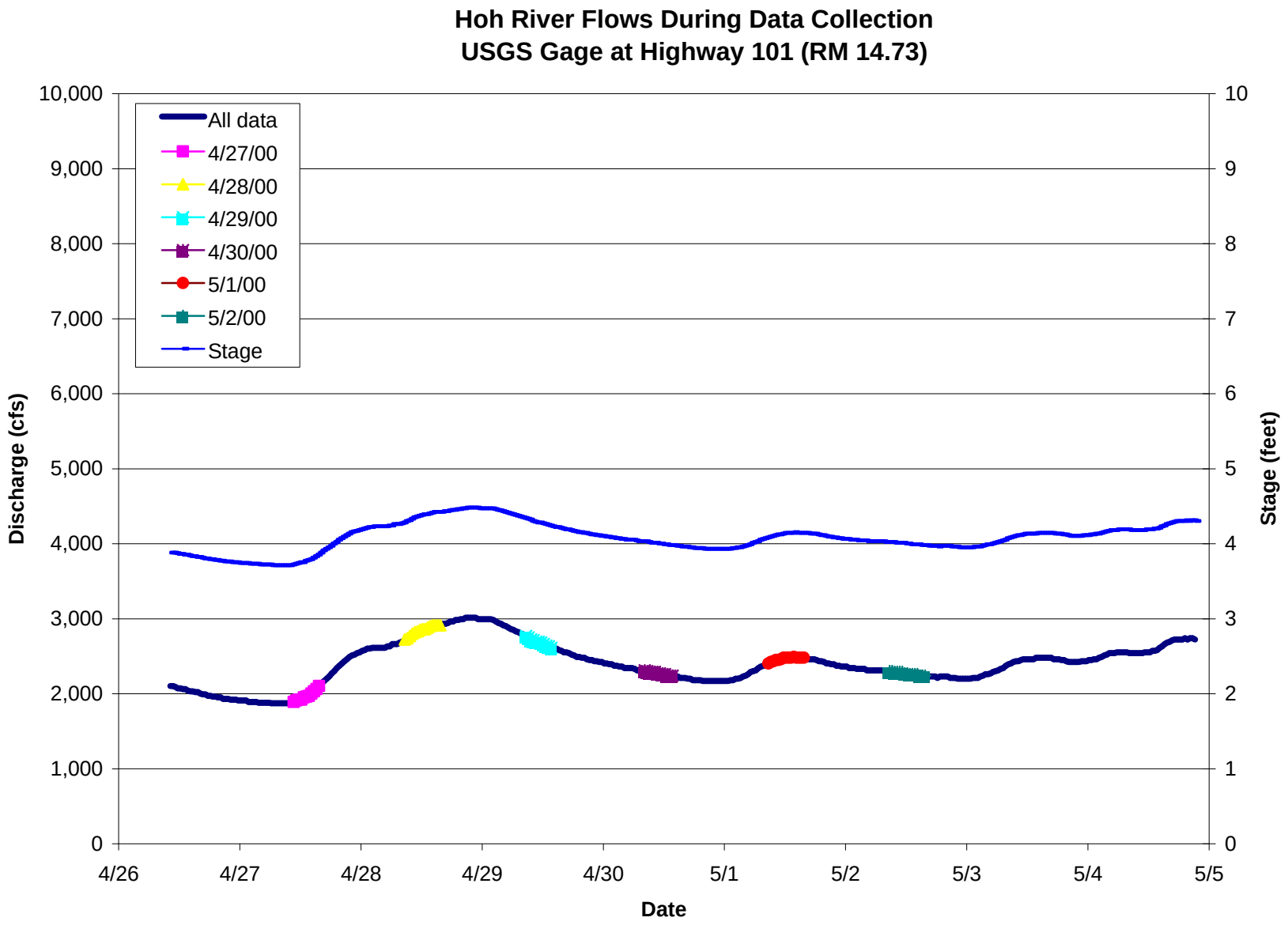
Figure A.17. Aerial photograph taken in 2002 for the Hoh Ranger Station and Mount Tom Reaches.

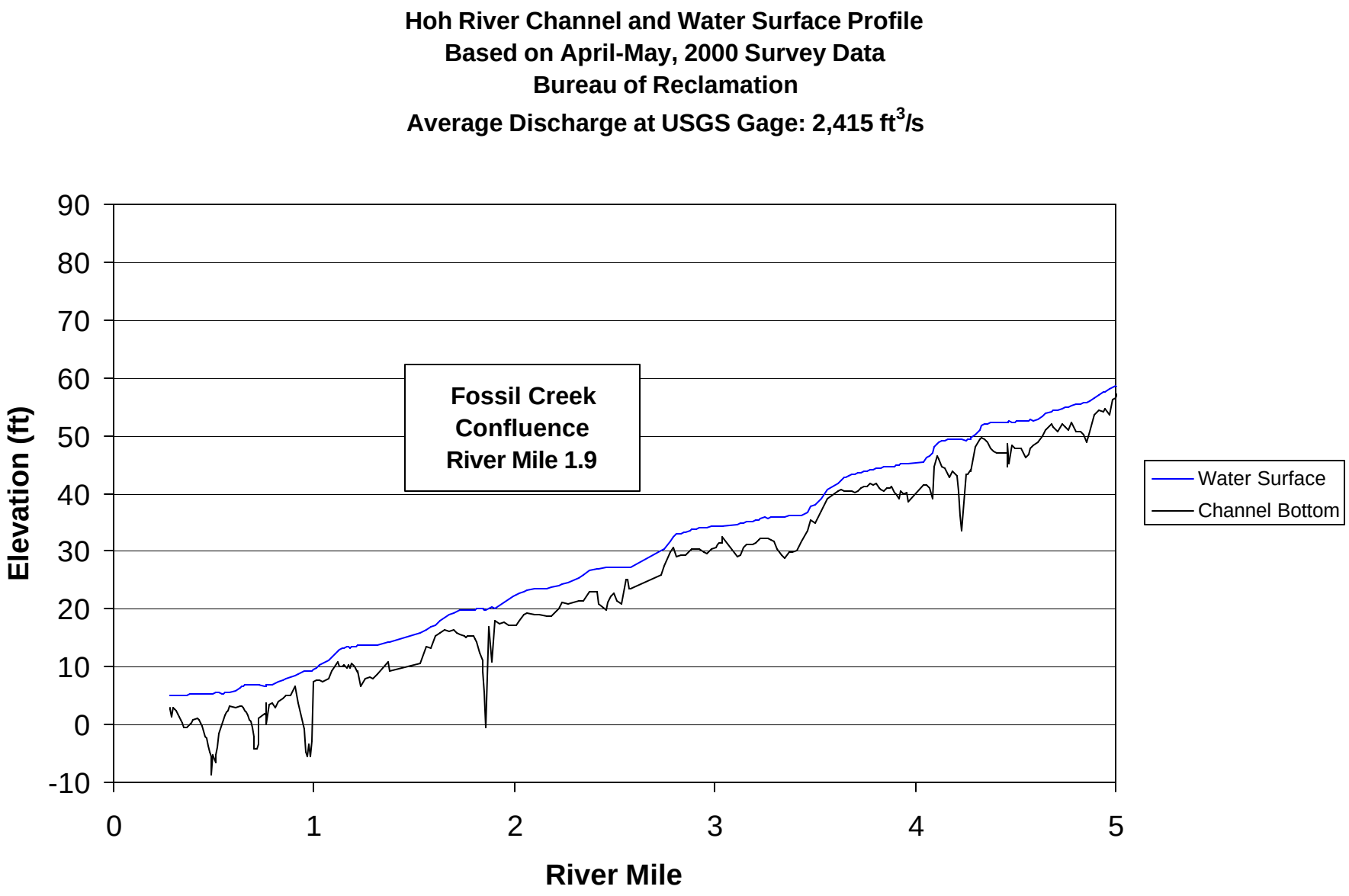
Appendix C.
Profiles of Channel Bottom and Water Surface.

The following appendix presents longitudinal profiles of the measured channel thalweg and water surface elevation for river mile 31 to the mouth where survey data was collected in April and May of 2000.

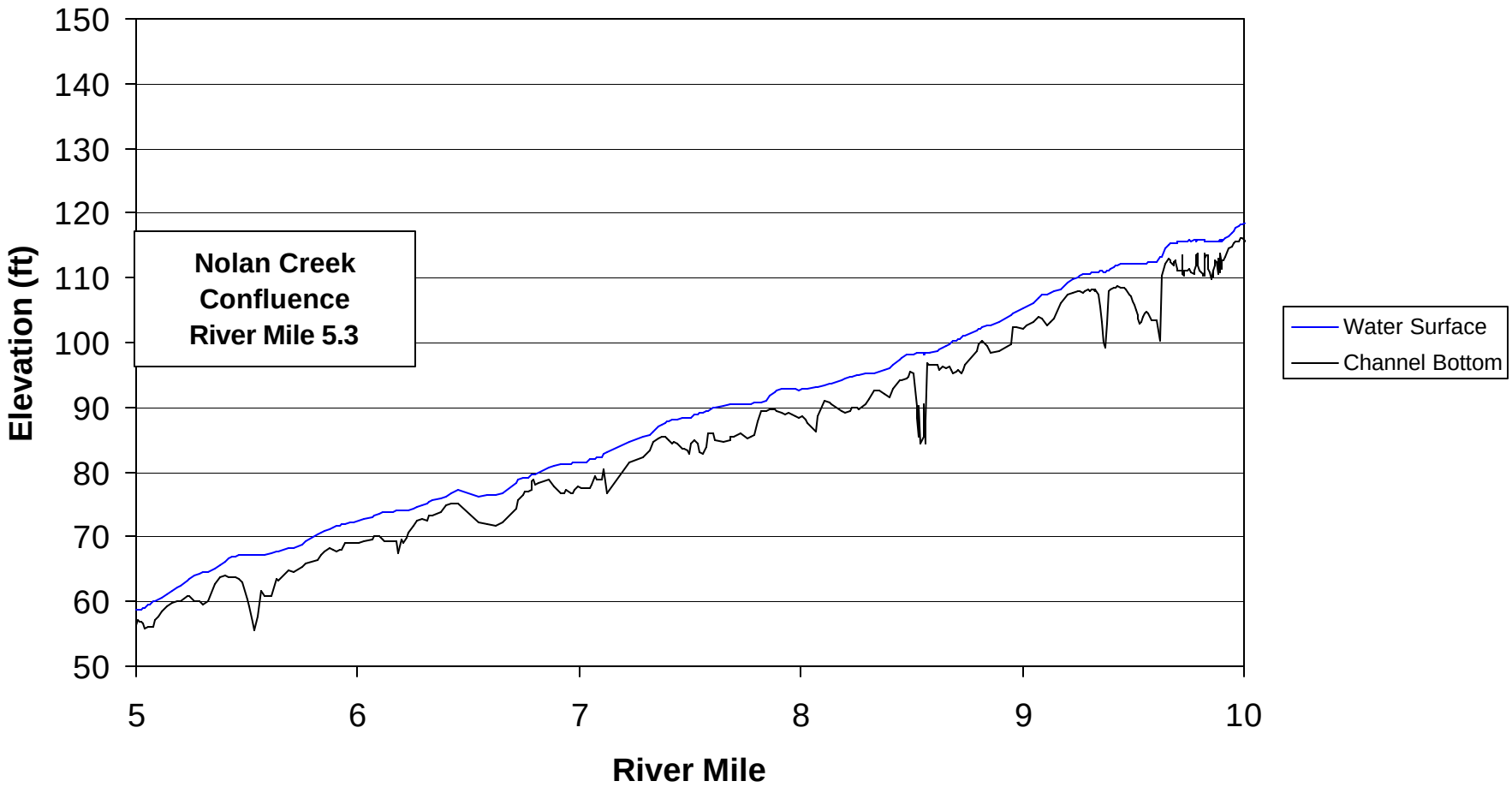
Channel Survey Data Information

Dates of Survey:	4/27/00 to 5/2/00
Projection:	Washington State Plane North, Horizontal: NAD83 and Vertical: NGVD88
Units:	Feet
Equipment:	Trimble 4800 and 4700 GPS Total Station Innerspace Depth Sounder
Control Network	Established by Bureau of Reclamation Ephrata Survey Crew Contact: Cory Stolsig (509) 754-0252
Data Processing	Arc Shape Files and ASCII Text Files Contact: Jennifer Bountry, Bureau of Reclamation, Denver, CO (303) 445-3614
Data Collected	Channel Bottom (Depth) Water Surface Elevation Left (LWE) and Right Water's Edge (RWE) Gravel Bar Topography

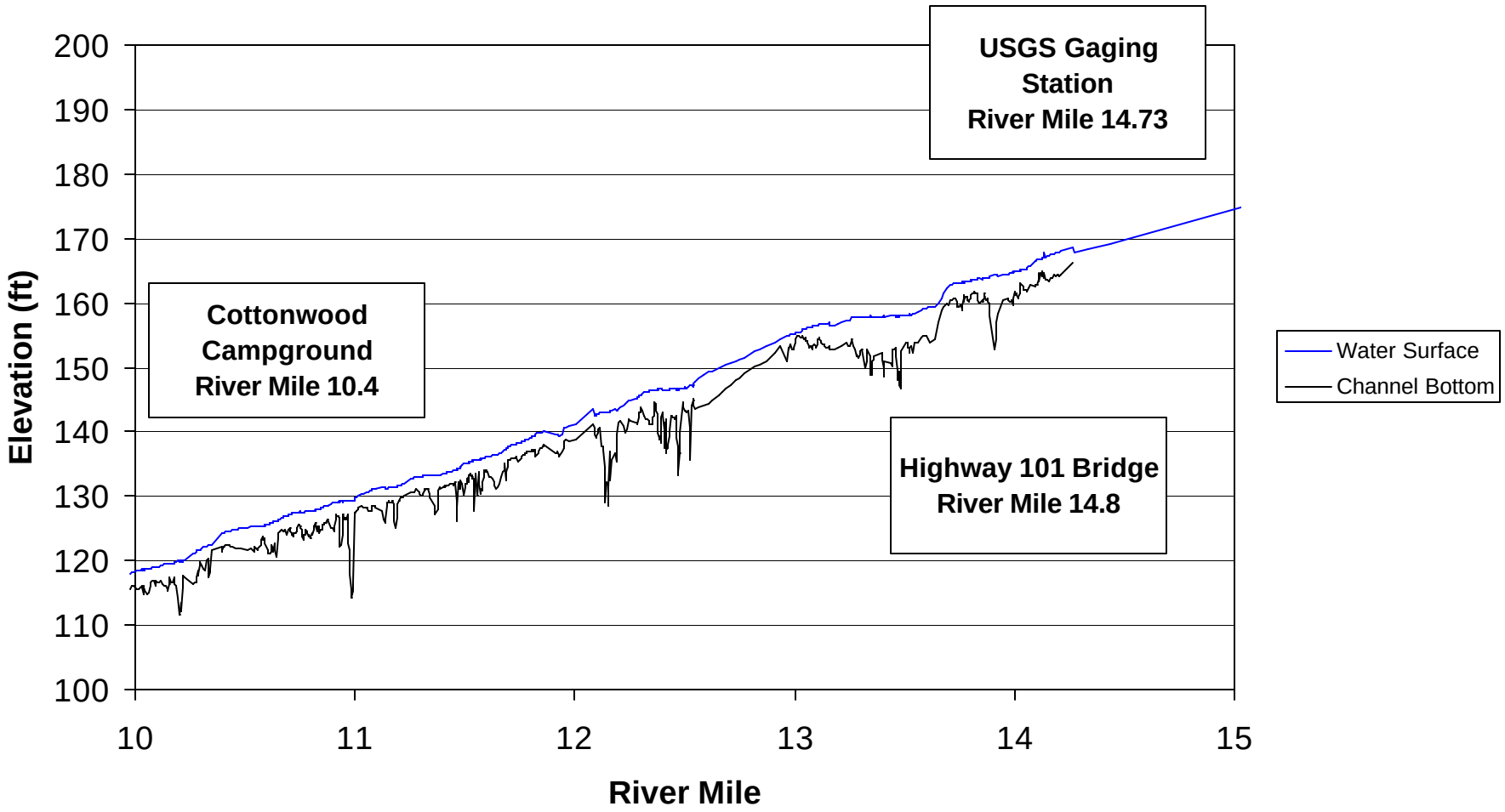

Hoh River Flows During Data Collection
USGS Gage at Highway 101 (RM 14.73)
All data
4/27/00
4/28/00
4/29/00
4/30/00
5/1/00
5/2/00
Stage
Discharge (cfs)
Stage (feet)
Date
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
10
9
8
7
6
5
4
3
2
1
0
4/26
4/27
4/28
4/29
4/30
5/1
5/2
5/3
5/4
5/5

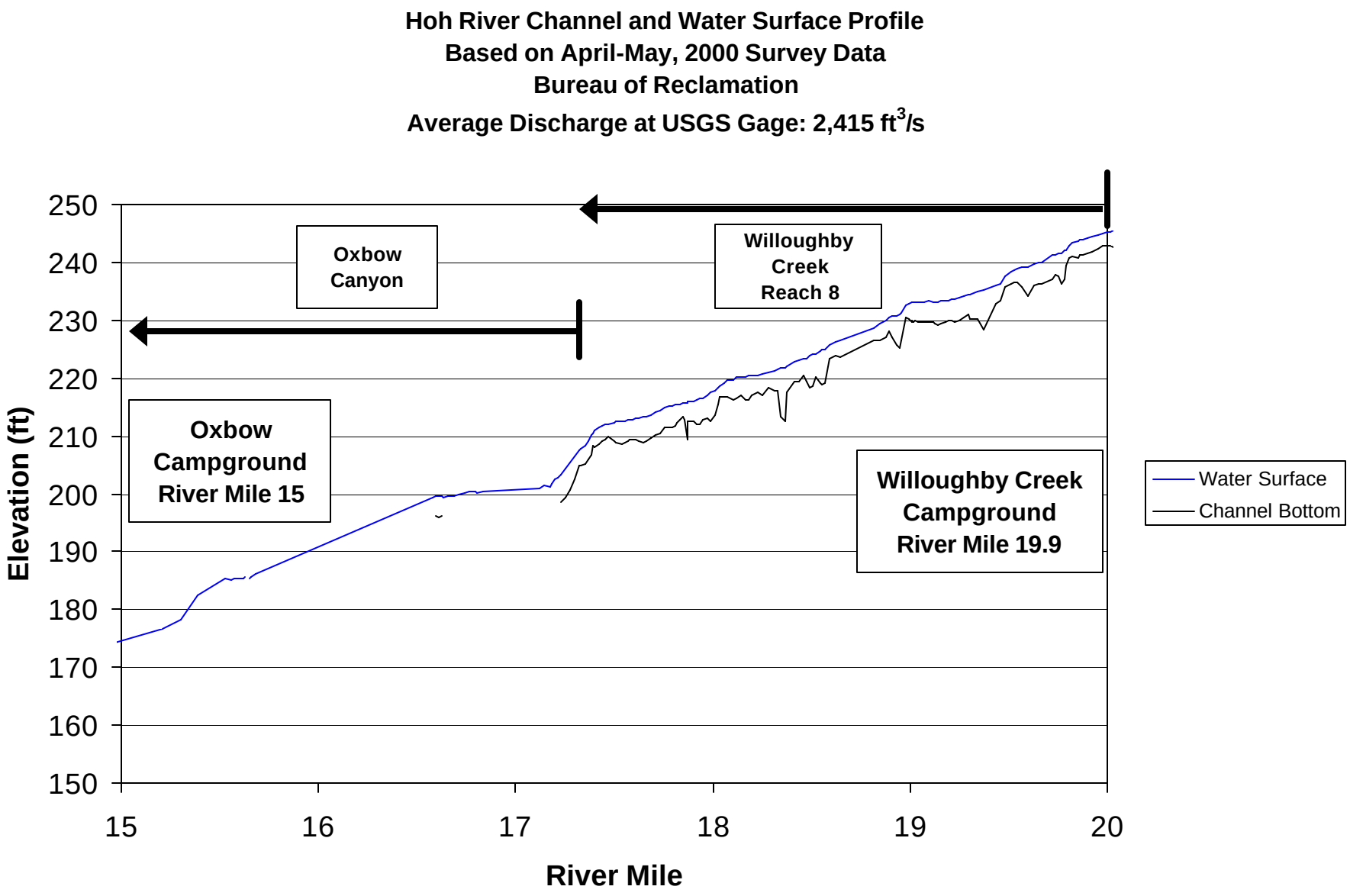

Hoh River Channel and Water Surface Profile
Based on April-May, 2000 Survey Data
Bureau of Reclamation
Average Discharge at USGS Gage: 2,415 ft3/s
Fossil Creek
Confluence
River Mile 1.9
Elevation (ft)
90
80
70
60
50
40
30
20
10
0
-10
0
1
2
3
4
5
River Mile
Water Surface
Channel Bottom

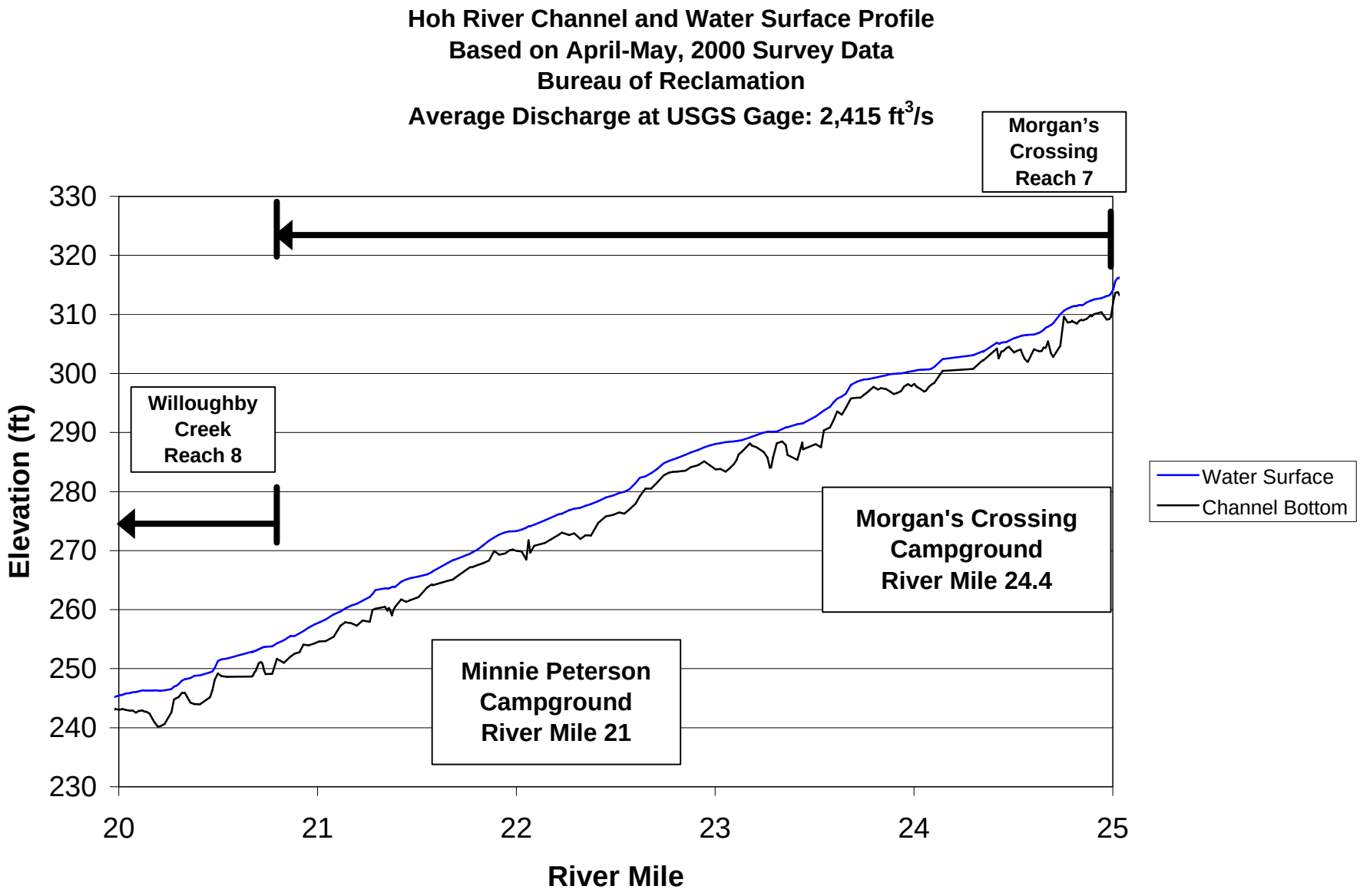
Hoh River Channel and Water Surface Profile
Based on April-May, 2000 Survey Data
Bureau of Reclamation
Average Discharge at USGS Gage: 2,415 ft^3/s

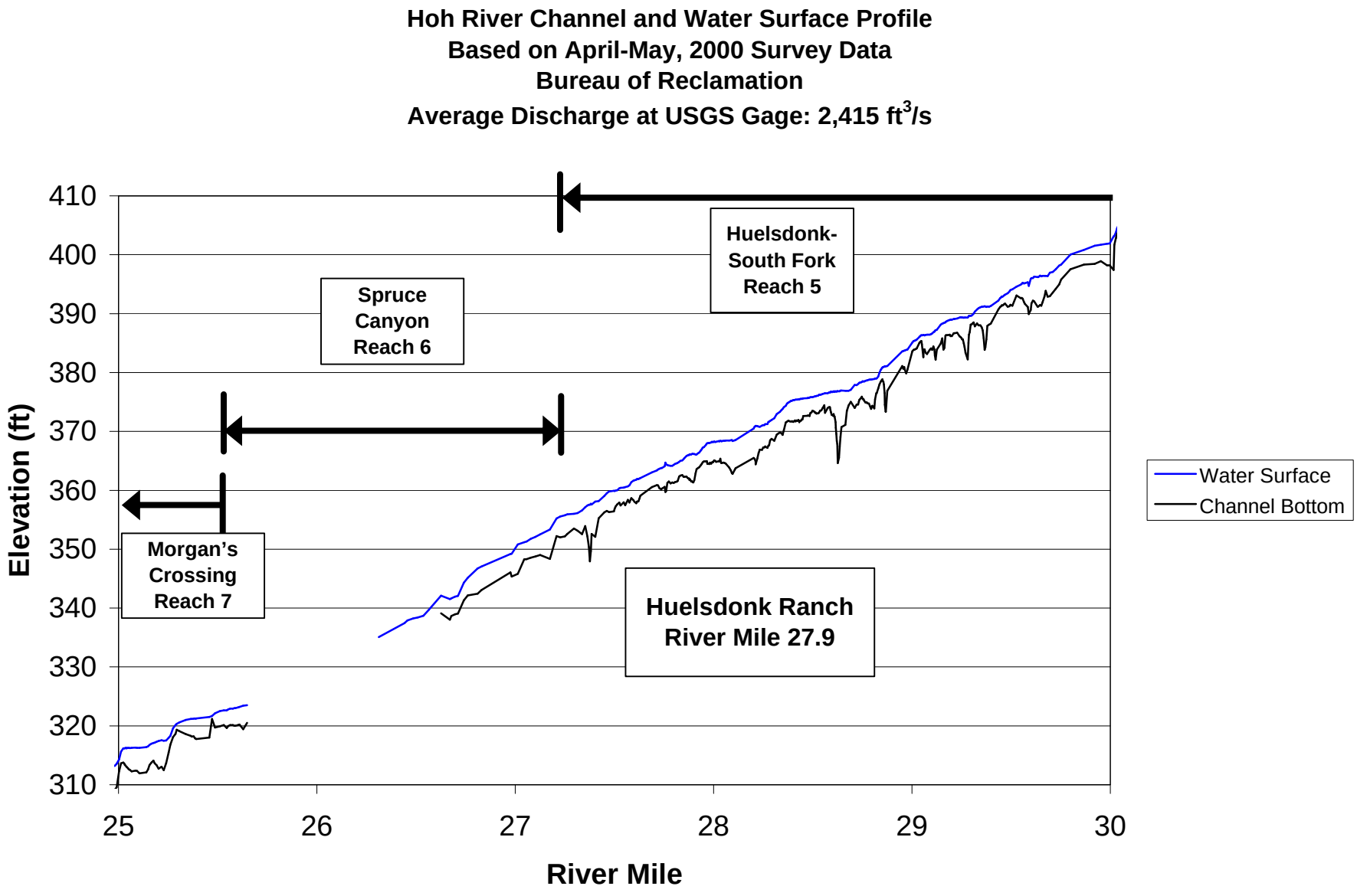


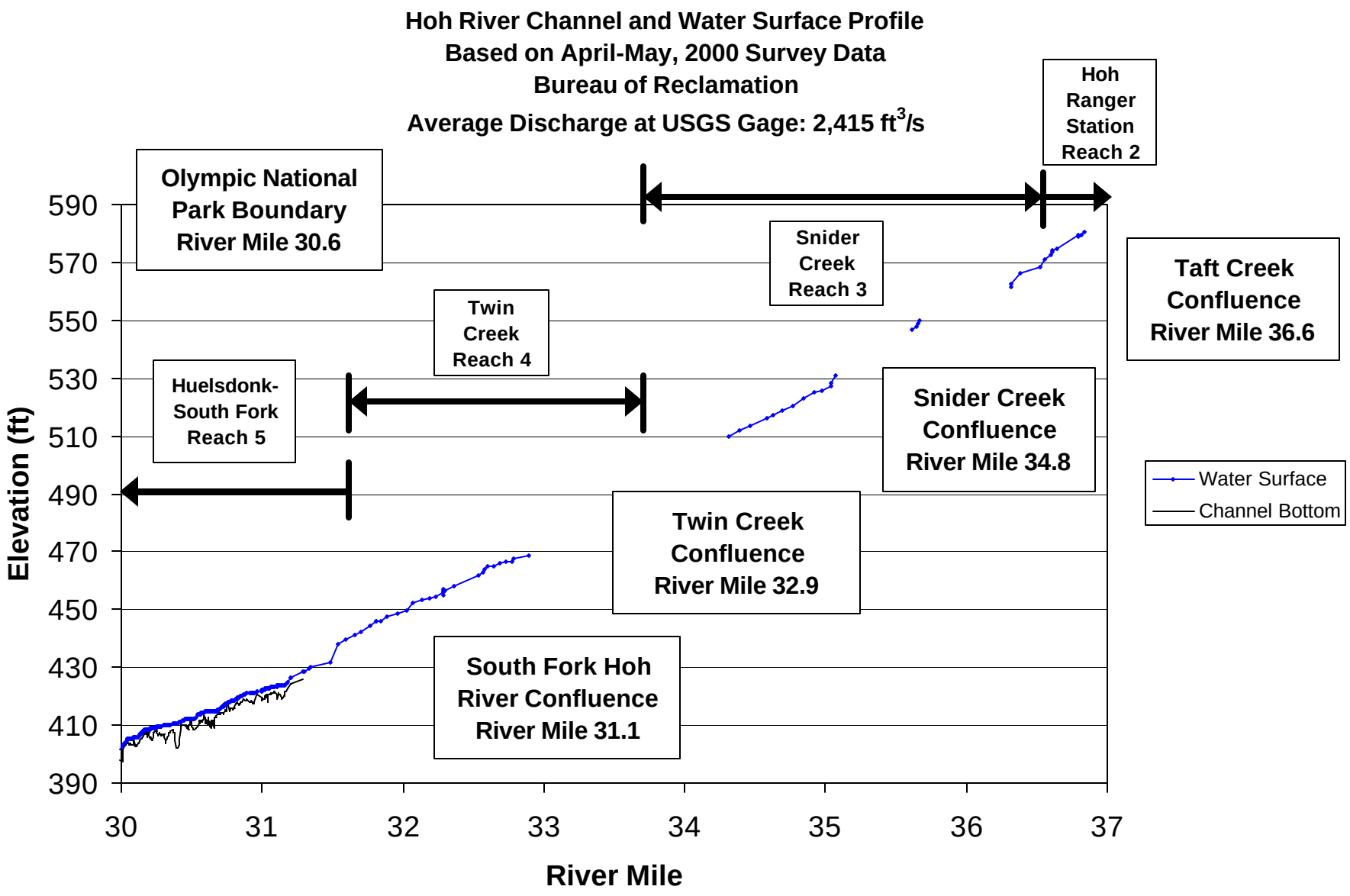
Hoh River Channel and Water Surface Profile
Based on April-May, 2000 Survey Data
Bureau of Reclamation
Average Discharge at USGS Gage: 2,415 ft^3/s




Hoh River Channel and Water Surface Profile
Based on April-May, 2000 Survey Data
Bureau of Reclamation
Average Discharge at USGS Gage: 2,415 ft3/s
Oxbow Canyon
Willoughby Creek Reach 8
Oxbow Campground River Mile 15
Willoughby Creek Campground River Mile 19.9
Water Surface
Channel Bottom
Elevation (ft)
250
240
230
220
210
200
190
180
170
160
150
15
16
17
18
19
20
River Mile


Hoh River Channel and Water Surface Profile
Based on April-May, 2000 Survey Data
Bureau of Reclamation
Average Discharge at USGS Gage: 2,415 ft3/s
Morgan's Crossing Reach 7
Willoughby Creek Reach 8
Morgan's Crossing Campground River Mile 24.4
Minnie Peterson Campground River Mile 21
Water Surface
Channel Bottom
Elevation (ft)
330
320
310
300
290
280
270
260
250
240
230
20
21
22
23
24
25
River Mile


Hoh River Channel and Water Surface Profile
Based on April-May, 2000 Survey Data
Bureau of Reclamation
Average Discharge at USGS Gage: 2,415 ft3/s
Huelsdonk-South Fork Reach 5
Spruce Canyon Reach 6
Morgan's Crossing Reach 7
Huelsdonk Ranch River Mile 27.9
Water Surface
Channel Bottom
Elevation (ft)
River Mile
410
400
390
380
370
360
350
340
330
320
310
25
26
27
28
29
30


Hoh River Channel and Water Surface Profile
Based on April-May, 2000 Survey Data
Bureau of Reclamation
Average Discharge at USGS Gage: 2,415 ft3/s
Hoh Ranger Station Reach 2
Olympic National Park Boundary River Mile 30.6
Snider Creek Reach 3
Taft Creek Confluence River Mile 36.6
Twin Creek Reach 4
Huelsdonk-South Fork Reach 5
Snider Creek Confluence River Mile 34.8
Twin Creek Confluence River Mile 32.9
South Fork Hoh River Confluence River Mile 31.1
Water Surface
Channel Bottom
Elevation (ft)
590
570
550
530
510
490
470
450
430
410
390
30
31
32
33
34
35
36
37
River Mile

Appendix F.
Bank Descriptions along the Hoh River collected during August 2002 Field Work.

Coordinates are in Washington State Plane North 1983 Feet.

Reach	Huelsdonk-South Fork	Huelsdonk-South Fork	Huelsdonk-South Fork	Huelsdonk-South Fork
GPS Point	1: N 856122 E 314111	None (near 1)	2: N 856059 E 314026	3: N 853617 E 312660
Location	Bank along side channel within HCMZ; near site of the Crippen homestead	Bank along side channel within HCMZ; near site of the Crippen homestead	Bank along side channel within HCMZ; near site of the Crippen homestead	Bank within HCMZ along main channel and just downstream of a side channel
Erodibility	High	Moderate	Low	High
Relationship to HHCMZ or geologic boundaries	Bank along surface (low terrace) within HCMZ	HCMZ boundary	HCMZ boundary	Bank along surface (low terrace) within HCMZ
Date described	8/1/02	8/1/02	8/1/02	8/1/02
Bank	Left	Left	Left	Left
Landform	Low terrace within HCMZ	High terrace	High terrace	Low terrace within HCMZ
Relationship to channel	Along a side channel	Along a side channel	Along a side channel	Along outside of meander of main channel
Bank height (ft; m)	3.5; 1	8; 2.5	15; 4.5 (est.)	7.3; 2
Bank material	Overbank sand and silt over channel-fill cobble gravel	Overbank cross-bedded sand and silt about 3.5 ft (1 m) thick over channel-fill cobble gravel	Fluvial sand about 3.5 ft (1 m) thick over channel-fill cobble gravel	Overbank sand and silt about 1 m thick over channel-fill cobble gravel
Consolidation	Loose	Loose	Loose	Loose
Slope (degrees)	Mostly near 90	90 for the sand and silt (upper half of bank); 25 to 45 for the cobble gravel	25-45	90 for the sand and silt; 25 to 45 for the cobble gravel
Dominant vegetation	Mixed: Alder, cottonwood, spruce, maple 3-3.5 ft (1 m) dm	Mixed: Cedar, maple, sitka spruce stump 16.5 ft (5 m) dm (est. 300 yrs old)	Mixed: Includes large cedar 16.5 ft (5 m) dm, ferns	Alder or mixed: Hemlock, cottonwood 1.5 ft max dm
Human features and activities	Clear cut about 10 yrs ago, but not to edge of surface; clear cut earlier	Logged as indicated by stumps	Clear cut to edge	None
Roots	Fine and medium roots cover >50% of bank	Medium roots cover >50% of bank	Medium roots cover >50% of bank; grass and shrubs growing on bank	Fine roots cover about 10% of bank
Protection	LWD along about 50% of bank; shrubs growing along bank	LWD along bank	LWD (large logs); sand deposited by side channel protects lower half of bank	LWD along <10% of bank
Evidence of active landslide	None	None	None	None
Evidence of active erosion	None	Bank has overhanging, undercut roots; bank is in part vertical	None	Bank is undercut, and roots are exposed; erosion indicated by aerial photographs
Other notes	Channel through surface is coho spawning habitat	Surface above bank could be part of the 100-yr floodplain	Side channel has deeply incised into terrace; terrace about 6 ft (2 m) high is inset along higher terrace	Bank was eroded about 40 ft (12 m) during winter 2001-2002. Horizontal distance to bank from observation site is 4 ft (1 m)

Reach	Huelsdonk-South Fork	Huelsdonk-South Fork	Huelsdonk-South Fork	Huelsdonk-South Fork
GPS Point	4: N 850618 E 312343	5: N 849087 E 310892	None	6: N 847317 E 312796
Location	Bank along main channel between two sections that have eroded since 1939	Bank along a terrace along a side channel	Bank downstream of riprap in Lewis Ranch area	Bank along upstream-most exposure of glacial deposits
Erodibility	High	Moderate	High to moderate	High
Relationship to HHCMZ or geologic boundaries	HCMZ boundary	HCMZ boundary	Bank along surface within HCMZ	HCMZ boundary
Date described	8/1/02	8/1/02	8/1/02	8/1/02
Bank	Right	Left	Right	Right
Landform	Terrace defining HCMZ boundary	Terrace defining HCMZ boundary	Low terrace in floodplain within HCMZ	Remnant of glacial deposits defining HCMZ boundary
Relationship to channel	Along a straight to slightly curving section of the main channel; at outside of meander	Along a side channel with water flowing in two directions	Along main channel	Along outside of meander bend of the main channel
Bank height (ft; m)	6.5; 2 (est.)	6.5; 2 (est.)	3.5-6.5; 1-2 (est.)	40; 12
Bank material	Overbank sand and silt about 3-4 ft (1-1.25 m) thick over channel-fill cobble gravel	Overbank sand and silt	Overbank sand and silt about 0.5 m thick over channel-fill cobble gravel	Sand and silt about 2 ft (0.5 m) over glacial cobble gravel over about 10 ft (3 m) of "blue" lacustrine silt and clay
Consolidation	Loose	Loose	Loose	Consolidated for silt and clay; loose for cobble gravel and sand and silt
Slope (degrees)	90 for the sand and silt; 25 to 45 for the cobble gravel	25 to 45		90 for the sand and silt (upper part); 25 to 45 for the cobble gravel (middle part); 45 to 90 for silt and clay (lower part)
Dominant vegetation	Mixed: Mostly hemlock 2-3 ft (0.5-1 m) dm; ferns; alder along bank immediately adjacent to channel and on adjacent downstream surface of same height	Mixed: Alder, large hemlock, vine maple	Mixed: Alder, spruce, maple	One line of shore pine about 1 ft dm; remnant of 200-ft-wide (60 m) RMZ left after logging
Human features and activities	None	Houses on surface, but not visible from bank	Clear cut on surface in area of ranch, but not to edge of surface	Clear cut now near edge; original 200-ft (60-m) RMZ has mostly eroded
Roots	Fine and medium roots cover about 10% of bank	Medium roots cover about 25% of bank	Medium roots cover about half of bank	Fine roots cover <5% of bank
Protection	LWD along 20% of bank (bank is mostly exposed)	LWD along <10% of bank	LWD along about 50% of bank	None
Evidence of active landslide	None	None	None	Slumps, disturbed vegetation; water issues from bank
Evidence of active erosion	Bank is undercut, and roots are exposed; recently toppled trees along bank and channel	Bank is undercut; trees from surface have toppled into channel	Bank is undercut, and roots are exposed	Bank is undercut and roots are exposed; trees have recently toppled into channel from top of bank
Other notes	Side channel enters just upstream bank; bank upstream has eroded	HCMZ boundary needs to be moved to this location	Logs are present on top of bank	Upstream a slightly lower surface is 25 to 30 ft (7.5-9 m) high

Reach	Huelsdonk-South Fork	Huelsdonk-South Fork	Huelsdonk-South Fork	Spruce Canyon
GPS Point	7: N 845303 E 313139	8: N 842942 E 311921	9: N 842373 E 310375	11: N 836027 E 311374
Location	Bank in glacial deposits just downstream of the mouth of Canyon Creek	Bank just upstream of the mouth of Spruce Creek	Bank along glacial deposits just downstream of Owl Creek	Bank near mouth of Spruce Canyon
Erodibility	Moderate	Moderate	Moderate	Low
Relationship to HHCMZ or geologic boundaries	HCMZ boundary	HCMZ boundary	HCMZ boundary	HCMZ boundary; surface above within 100-yr floodplain
Date described	8/1/02	8/1/02	8/1/02	8/1/02
Bank	Right	Right	Left	Left
Landform	Remnant of glacial deposits defining HCMZ boundary	Probably an alluvial fan	Remnant of glacial deposits	Remnant of glacial deposits over rock?
Relationship to channel	Along a now-abandoned thread of main channel	Along outside of meander bend of a channel that carries about half of the main-channel flow	Along outside of meander bend; at junction of main and secondary channels	Along straight section of main channel
Bank height (ft; m)	25; 7.5	8.5-10; 2.5-3 (est.)	16.5; 5 (est.) for height of slumps along bank	40; 12 (est.)
Bank material	Glacial cobble gravel over "blue" lacustrine silt and clay	Channel-fill deposits of cobble gravel alternating with thin beds of fluvial sand and silt	Glacial cobble gravel over about "blue" lacustrine silt and clay at base of slope	Glacial cobble gravel over rock?
Consolidation	Consolidated for silt and clay; loose for cobble gravel	Loose	Loose for cobble gravel; consolidated for silt and clay	
Slope (degrees)	25 to 45 for most of cobble gravel; 90 for silt and clay and in places for cobble gravel	90 for upper 75% of bank; 25 to 45 for lower 25%	25 to 45 for most of bank	45
Dominant vegetation	Conifer: Spruce, shore pine, hemlock most with about 1 ft (0.3 m) dm	Mixed: Hemlock, cottonwood; alder on bank immediately adjacent to channel	Alder, grass in slumped areas; a few large conifers higher on bank	Conifer: Mostly hemlock
Human features and activities	Upper Hoh Road is visible through trees, but is not adjacent to bank	Upper Hoh Road is visible through trees, but is not adjacent to bank	Huelsdonk Ranch is upstream	Clear cut, but not to edge of surface; 200-ft (60-m) RMZ still preserved
Roots	Medium roots cover <5% of bank	Fine roots cover about 25% of bank; roots also in layers buried within sediments in bank	Bank is vegetated	Bank is covered with vegetation
Protection	LWD; trees have toppled onto bank from top of bank	LWD along <5% of bank	A few alders have toppled onto bank; none large enough to offer protection from erosion	None
Evidence of active landslide	Slumps, disturbed vegetation	None	Slumps, disturbed vegetation	None
Evidence of active erosion	Bank has overhanging, undercut roots	None	Roots are exposed	Eroded roots
Other notes	Main channel used to be along this bank on an outside bend of a meander; now a gravel bar is preserved at base of bank; bar has extended down-stream since 2001; now main channel is on opposite side of bar	A sequence of debris-flow deposits (poorly sorted) is exposed; debris-flow deposits interfinger with fluvial cobble gravel; bar that was present along bank in 2001 is gone by 2002	Upstream-most exposure of glacial deposits on the left bank	Although 10-12 ft (3-3.5 m) above low-water channel, surface is overtopped by floods; surface has overbank sand and silt

Reach	Morgan's Crossing	Morgan's Crossing	Morgan's Crossing	Willoughby Creek
GPS Point	13: N 829850 E 314946	14: N 830129 E 314744	17: N 823715 E 313034	18: N 813002 E 314625
Location	Bank where riprap along Upper Hoh Road has been eroded	Bank just upstream of bank described at WP13	Bank just downstream of Red Creek	Bank across from Schmidt bar
Erodibility	High to moderate	High to moderate	Low?	Extreme to high
Relationship to HHCMZ or geologic boundaries	HCMZ boundary	Inside HCMZ	HCMZ boundary	HCMZ boundary
Date described	8/2/02	8/2/02	8/2/02	8/2/02
Bank	Right	Right	Left	Left
Landform	Remnant of glacial deposits along HCMZ boundary	Alluvial bank within HHCMZ	Remnant of glacial deposits along HCMZ boundary	Remnant of glacial deposits along HCMZ boundary
Relationship to channel	Along outside of meander bend of main channel	Along outside of meander bend of main channel	Along straight section of main channel	Outside of meander bend of main channel
Bank height (ft; m)	31; 9.5	10.5; 3	142; 43	50-55; 15-16.5
Bank material	Sand and silt over channel-fill cobble gravel cut into "blue" channel or delta cross-bedded sands	Overbank sand and silt about 3 ft (1 m) thick over channel-fill cobble gravel	Tan and gray sand/silt/clay over cobble gravel inter-fingered with gray sand/silt/clay over gray cross-bedded, coarse and medium sand	Glacial cobble gravel 5-10 ft (1.5-3 m) thick over cross-bedded sand (75% of bank) over "blue" lacustrine silt and clay (at very base only)
Consolidation	Consolidated for silt and clay; loose for cobble gravel and sand and silt	Loose	Consolidated for clay and silt; loose for sand/silt/clay and cobble gravel	Loose for sand and cobble gravel; consolidated for silt and clay
Slope (degrees)	90 for most of bank	90 for the sand and silt (upper part); 25 to 45 for the cobble gravel (lower part)	90; 25-45 at base of bank or at drainages	90 at very top (cobble gravel); 45-90 for middle (sand); 25-45 near base (silt and clay)
Dominant vegetation	Mixed: Spruce, hemlock, shore pine; 2 ft (0.5 m) max dm	Mixed: Large alder, hemlock, spruce	Conifer	Conifer
Human features and activities	Probably clear cut because trees seem to be too small for a surface this high; Upper Hoh Road and riprap	Upper Hoh Road on surface	None	Entire surface logged; no large trees now
Roots	Fine and medium roots cover <5% of bank	Fine roots cover <5% of bank	Medium roots cover <5% of bank; grass and shrubs growing in part of bank	Fine and medium roots cover <5% of bank
Protection	Riprap on bank just upstream of this locality	LWD along about 50% of bank; just downstream of Jefferson County's engineered log jam	None	Trees (small diameters) have toppled onto bank, but none are large enough to offer protection from erosion
Evidence of active landslide	None	None	Yes, at drainages; none along vertical portions of bank; water exiting from bank	Slumps, disturbed vegetation; water exiting bank
Evidence of active erosion	Bank is undercut, and roots are exposed; known erosion from aerial photographs	Bank is undercut, and roots are exposed	None	Bank is undercut, and roots are exposed
Other notes	Bank has eroded about 120 ft (36.5 m) since 1939. Horizontal distance to bank from observation site is 219 ft	Bank here is all alluvium in contrast to its continuation downstream (see WP13)	Colluvial cones cover base of slope; some "blue" silt and clay near base of slope; bank has benches that are capped by fine-grained deposits (silt); bank has a high risk for continued landslides	Main channel is actively eroding into the sloping surface of the ridge of glacial deposits; much of the bank is composed of sediment that is sandy and very loose; bank has been eroding; oxidized sand and gravel beds

Reach	Willoughby Creek			
Waypoint	19: N 810465 E 317175			
Location	Bank along glacial deposits			
Erodibility	High			
Relationship to HHCMZ or geologic boundaries	HCMZ boundary			
Date described	8/2/02			
Bank	Right			
Landform	Remnant of glacial deposits along HCMZ boundary			
Relationship to channel	Along outside of meander bend of main channel			
Bank height (ft; m)	25; 7.5			
Bank material	Sand over glacial cobble gravel over about 8 to 12 ft (2.5-3.5 m) of “blue” lacustrine silt and clay			
Consolidation	Consolidated for silt and clay ; loose for cobble gravel and sand			
Slope (degrees)	90 for most of the bank			
Dominant vegetation	Alder, grass; a few aligned hemlock that were part of RMZ			
Human features and activities	Clear cut; original 200-ft (60-m) RMZ now is one-to-two trees wide			
Roots	Fine and medium roots cover <5% of bank			
Protection	None			
Evidence of active landslide	Water issues from bank			
Evidence of active erosion	Bank is undercut (silt and clay at water line) and roots are exposed; lots of erosion since 1939 indicated by aerial photos; erosion indicated by thin band of RMZ that remains			
Other notes	One log is buried within a gravel channel cut into the fine-grained glacial deposits; log is about half way down bank vertically; log extends over low-water channel; could this log be dated?			

APPENDIX G:
ADDITIONAL DETAIL ON METHODS USED TO ASSESS THE RISK OF CHANNEL MIGRATION ZONE EXPANSION

Expansion of the HCMZ is a natural process that results from a continually changing, dynamic river channel. In addition to delineating the HCMZ, the risk of expansion along the HCMZ boundary was identified to help provide a useful tool for understanding which areas along the HCMZ boundary are most likely to erode and how quickly. While expansion of the HCMZ is natural, the rates of expansion can be drastically different in areas where development has occurred. Areas where human impacts may be accelerating the rate of expansion were also incorporated into the risk assessment. The risk of HCMZ expansion was developed using the following three steps:

STEP 1: Assess the likelihood that lateral bank erosion will occur along reaches of the HCMZ boundary (categorized from very low potential to erode to actively eroding)

STEP 2: For reaches actively eroding or likely to erode, estimate the potential rates at which lateral bank erosion could progress (slow, medium, or fast)

STEP 3: Combine the likelihood of erosion and the potential erosion rates to determine the relative risk for expanding the HCMZ boundary

The likelihood of lateral bank erosion (STEP 1) is primarily dependent upon two main factors: (1) the properties of the material in the bank, and (2) the bank's location relative to existing or potential mainstem or side channel locations of the Hoh River. Bank material properties were subdivided into five categories of erosion likelihood ranging from very little potential to erode, such as a bedrock outcrop, to a high potential to erode, such as fine-grained glacial material. Likelihood of erosion is also dependent on whether the main channel or a primary side channel of the Hoh River is currently or has the potential to flow adjacent to the bank. The greater the erodibility of the bank material and the greater the chance the river will run against the bank, the higher the likelihood of erosion. For example, if the material in a bank were loose (fine sediment that has the potential to be easily eroded) then it would have a high potential for erosion. However, the likelihood of erosion would only remain high if the river had a high likelihood of running against the bank in the near future. Historical channel paths and features that limit channel changes (bedrock, log jams, debris flows, etc) were used to estimate the likelihood of potential future channel paths along a given terrace bank.

The potential rate of bank erosion (STEP 2) was determined to assess the relative speed at which a bank might erode if erosion was initiated from the Hoh River flowing adjacent to the bank. Rates were broken into three categories including slow, medium, and fast. The potential erosion rate is dependent on two main factors: (1) the properties of the material in the bank, and (2) the vegetation and land use on the surface within and adjacent to the HCMZ. In some cases, bank height also affects the potential rate of lateral erosion assigned because there is more material to erode when the bank is higher.

1.1 STEP 1: Assess the Likelihood of Erosion of the HCMZ Boundary

Assessment of the likelihood of bank erosion along the HCMZ boundary was accomplished through four basic tasks (see figure # in main report).

TASK 1A: Identify areas of active bank erosion along the HCMZ boundary.
For remaining banks along the HCMZ boundary that are not actively eroding, the following tasks were completed.

TASK 1B: Estimate the erodibility of bank material along the HCMZ boundary.

TASK 1C: Estimate the potential for main or side channels to flow against the HCMZ boundary.

TASK 1D: Assign a likelihood of erosion based on results from Tasks 1B and 1C.

1.1.1 TASK 1A: Map Actively Eroding Terrace Banks

The first task was to identify banks along the HCMZ that are actively eroding. Because actively eroding terrace banks pose the most immediate risk for expansion of the HCMZ, they were mapped in a separate category and have the most detailed information. Actively eroding terrace banks were initially identified in the office using aerial photography and subsequently verified during a field trip in August 2002. The characteristics of the actively eroding banks were described and are included in Attachment F. Evidence for active erosion includes an adjacent river channel, a vertical or overhanging (undercut) slope, exposed roots, a lack of vegetation, toppled or disturbed trees (usually small alder) or shrubs, slumps, or water seeping from the bank (often just above silty clay beds).

Many of the actively eroding banks are located on the outside of present meander bends of the main Hoh River channel. Most of these banks are composed of loosely consolidated alluvial deposits or glacial deposits. The most unstable active banks are predominantly loose sand. Other actively eroding banks include some clay and silt beds, along which sediment is recurrently slumping.

1.1.2 TASK 1B: Estimate Terrace Bank Material Erodibility

For the remaining terrace banks along the HCMZ boundary without obvious evidence for active erosion, the second task was to estimate the bank material to help determine the potential erodibility. Bank material was estimated using field observations, a published geologic 1:125,000-scale map (Tabor and Cady, 1978), and 1:24,000-scale topographic maps to interpret geologic deposits and related geomorphic features such as alluvial fans.

Because the Hoh River has downcut through Pleistocene glacial deposits and Pleistocene and Holocene alluvial deposits, sediment in the banks is quite variable, both vertically and laterally. We have tried to assess the dominant characteristics for the terrace banks in these deposits that would serve as the best indicator of erodibility. The bank material was broken up into the following categories described below.

Bedrock – Erodibility: VERY LOW

Banks that are composed of naturally formed bedrock. Along the entire study area, two areas of bedrock are present: one in Spruce Canyon in Reach 6 and one in Oxbow Canyon, just downstream of Reach 8. Banks composed of bedrock are generally stable, limit channel migration, and have essentially very little chance for measurable erosion during the next several decades.

Alluvial fan deposits – Erodibility: LOW to MODERATE

Two types of alluvial fan deposits were observed in the study reach (Harvey, 1997). The two types were not distinguished for mapping of bank categorization, but were incorporated when determining the potential for future lateral erosion. For each alluvial fan deposit, recent sediment deposits that reached the Hoh River channel were mapped where observed during field investigations. Sediment deposits that reach the river channel can limit lateral erosion of the HCMZ depending on the size of material, the frequency of occurrence, and the process initiating the sediment transport. Estimating the frequency of occurrence and characterizing the origin of the sediment deposit were beyond the scope of this study, but could include a range of processes from debris flows to reworking of bed-material during flood events. Generally speaking, debris flows have the capacity to carry larger sized sediment due to slurry type transport as opposed to capacity limited transport of flood events (limited by slope and discharge).

> **Type 1: Steep, alluvial fans located at toe of valley wall with large sized-material (cobble and boulder) – Erodibility: LOW**
>
> Alluvial deposits that are associated with steep alluvial fans, contain cobble and boulder-sized material, and generally drop right into the active channel or flood plain without crossing any terrace surfaces. They are present at the mouths of tributaries that drain steep rock slopes immediately adjacent to the Hoh valley. Steep alluvial fans were observed along the HCMZ boundary on the Hoh River upstream of the confluence with the South Fork Hoh River in Reaches 1 through 4.
>
> These steep alluvial fans are not very likely to be eroded by the Hoh River, and are categorized to have a low likelihood of erosion. Although unconsolidated, the large cobbles and boulders in the fans are difficult for the river to transport, especially with the reduced flow upstream of the confluence with the South Fork of the Hoh River.
>
> **Type 2: Alluvial-fan deposits present on terrace surfaces with sand to cobble-sized material – Erodibility: MODERATE**

Other alluvial-fan deposits develop as tributaries along the Hoh River drop off the steep valley wall onto terrace surfaces before reaching the active flood plain of the Hoh River. The alluvial fans are formed from sediment transported down the tributary channel and deposited where the tributary slopes flatten. As one channel fills with sediment, the tributary channel will shift to another location. Over long periods of time, the various channel positions and sediment deposits form the "alluvial fan", with the widest portion of the fan at the confluence with the Hoh River. These deposits are often found at the mouths of larger tributaries downstream of the South Fork, where the valley is relatively wide, primarily in Reaches 5, 7, and 8. Alluvial-fan deposits located on terrace surfaces are generally composed of finer-sized material (sand, gravel, and cobble) and have flatter slopes than the steep alluvial-fan deposits.

Because of the finer-sized sediment and flatter slopes in the Type 2 alluvial-fan deposits relative to those of the Type 1 steep alluvial-fan deposits, these deposits are assumed to be more easily eroded by the Hoh River and are assigned a moderate (instead of low) likelihood of erosion. These areas are not assigned a high likelihood of erosion because pulses of sediment periodically transported down the channels limit the likelihood of lateral erosion, even if the sediment sizes are small relative to the steep alluvial fans found in the upper watershed.

Human-placed protection – Erodibility: VARIABLE

Terrace banks along the HCMZ that are protected through man-made activities, including riprap, engineered or placed logs, and road embankments. Where stable, engineered bank protection has been placed along terrace banks the potential for lateral erosion would be low and the bank armoring would restrict the boundaries of the HCMZ. This effect is typically very localized, and only impacts channel processes in the immediate vicinity of the protection. On the other hand, areas that are armored with bank protection are typically composed of glacial or alluvial material and have been actively eroded in the past. If the bank armoring is not stable and is eroded by the river, the bank could be highly susceptible to additional erosion in the future. Because many of the armored banks in the Hoh valley have been at least partially eroded in the past following installation of the bank armor, we generally assumed these banks could be eroded and the channel migration zone could expand. In a few locations, alluvial banks have been protected that are within the HCMZ rather than on the boundary. In these cases, the bank protection was identified along with the natural boundary of the HCMZ and the material that composes it. Similarly, these areas were not assumed to limit potential future migration.

Alluvial and glacial deposits – Erodibility: MODERATE TO HIGH

The remaining banks are composed of alluvial and glacial deposits. Most of the alluvial deposits are associated with terraces of the Hoh River and its major tributaries. Alluvial deposits associated with terraces consist of both fine-grained (clay, silt and fine sand) flood plain deposits and coarse-grained (coarse sand, gravel and cobble) channel deposits. Often both are present in one bank, with flood plain deposits a few feet thick overlying coarser channel deposits.

The glacial deposits are present throughout the valley and are associated with high surfaces and ridges. The glacial deposits include mostly outwash deposits that are composed of loosely consolidated sand, silt, cobbles, and boulders, as well as lacustrine deposits, which are thin to thick beds of compact silt and clay. The lacustrine beds act as a barrier to downward water movement, so that water is forced to flow laterally along these beds until it reaches the bank. The outward-flowing water contributes to slumping of the sediment in the bank.

Except for the fine-grained glacial lacustrine sediments, the alluvial and glacial outwash deposits are primarily loosely consolidated, relatively fine-grained, and are easily transported by the Hoh River. Thus, the potential for erodibility of these banks is high. For banks that include a substantial amount of lacustrine sediment, the potential for erosion is dependent upon the exact composition of the deposits and the amount of and location of seepage from the bank. These banks often fail by slumping and the disturbed sediment, especially if silt-sized, may be easily removed by the Hoh River. If the slumped sediments are primarily clay, then they may remain in consolidated blocks that can armor the bank and limit the rate of further erosion.

1.1.3 TASK 1C: Identify Potential Future Channel Positions

Although terrace bank material is important in assessing the likelihood that a bank could erode, banks that are composed of loose, easily eroded sediment may be stable if the Hoh River channel is not in contact with the bank. Thus, the likelihood of erosion must also include estimating the potential for future channel locations to be against the HCMZ boundary. The greater the potential for the channel to flow against a bank composed of erodible material, the higher the likelihood the bank will be eroded.

Future positions of the main channel were evaluated based on existing and historical channel positions. Existing channel positions give an indication of which direction the channel is headed. For instance, if an existing channel contains a meander bend, the channel is likely to continue eroding the outside of the meander bend while gradually shifting the meander in the downstream direction. Eventually, the meander planform will become perpendicular to the valley and a sudden change in channel position (avulsion) will be likely. Historical channel positions suggest potential locations for the channel avulsions. Often an existing unvegetated overflow or a vegetated side channel that already contains water during high flows is a likely candidate for the channel to avulse to since a flow path is already established. Side channels that have large stable log jams at their entrances have some protection from the main channel avulsing into them, but eventually may be subjected to the log jam being blown out. A few banks may never be subjected to the river running against them even if they are composed of highly erodible materials. This is because in certain reaches geologic features such as bedrock canyons or debris flows limit potential channel paths as the river transitions from one area to the next.

1.1.4 TASK 1D: Assign the Likelihood of Erosion

Likelihood of erosion categories include very low, low, moderate, high, and areas that are already actively eroding. For the very low potential category, boundaries were composed of bedrock and were not dependent on whether the channel runs against the bank. For low, moderate, and high likelihood of erosion categories, the rating was assigned based on a combination of the potential for bank erosion and the potential for the channel to run against the bank in the next several years to decades. Terrace banks that are currently along the present main channel, or an active side channel, were typically observed as actively eroding unless the bank material was composed of bedrock or stable human-placed protection.

Terrace banks along the active flood plain where the main channel is progressing toward them were rated as having a high likelihood of being subjected to erosion. Terrace banks along smaller side channels that are beginning to convey flow or areas where historical channels have existed are also interpreted as having a high likelihood of the channel running against them in the near future. Banks that are protected from present channels by vegetated bars or surfaces that include only small, discontinuous flood channels of limited extent are the less likely to be adjacent to the main channel or a primary side channel during the next few years. Thus, banks in these locations are thought to have a moderate likelihood of erodibility because it may be a longer time before the river flows against them. Terrace banks that have not had flow against them for very long time periods due to geologic features that limit potential channel paths are rated as having a low likelihood of erosion.

1.2 STEP 2: Estimation of Potential Lateral Erosion Rates

Once the likelihood for erosion of the terrace banks bounding the HCMZ was determined, the potential rates of lateral bank erosion were estimated for those banks in the active, high, and moderate likelihood to erode categories. For terrace bank erosion in the low and very low categories, erosion rates were not estimated. Lateral erosion rates were identified as slow, medium, or fast using four tasks:

TASK 2A: Estimate the potential for natural bank armoring or slumping
TASK 2B: Map alluvial-fan deposits
TASK 2C: Assess the vegetation and logging history for the surfaces above the banks
TASK 2D: Compare the present HCMZ boundary with the HCMZ boundary in 1939

1.2.1 TASK 2A: Estimate the Potential for Natural Terrace Bank Armoring or Slumping

The first task was to determine which terrace banks in the moderate, high, and active likelihood categories had natural bank armoring that would result in a slow rate of erosion. The tendency for a bank to become naturally armored is primarily a function of bank material. On the basis of field observations, three main types of material seem to

provide natural armoring: boulders, blocks of consolidated clay, and large logs. The large logs are chiefly those that have fallen onto the bank from the surface above the bank. The availability of large logs is a function of the vegetation on the surface above the bank, which is discussed in Section 1.2.3 (Step 2C).

If the content of boulders in an alluvial or glacial deposit is high enough, then periodic undercutting of the finer sediment by the Hoh River as it flows along the terrace bank will leave boulders on the bank that are too large for the Hoh River to transport. The boulders often become concentrated along the toe of the bank, where they protect the bank from additional erosion. Similarly, if a significant number of large blocks of compacted clay are present on the bank, usually from slumping, then the blocks can act as armoring and also limit the rate of erosion.

1.2.2 TASK 2B: Map Alluvial-fan and Recent Sediment Deposits

Most terrace banks composed of alluvial-fan deposits contain enough large rocks to slow the rate of potential erosion by the Hoh River. Further, recurrently active sediment waves that reach the main channel (through either debris flow or bedload transport processes) also slow erosion of the adjacent banks, because the sediment deposit provides additional material that must be eroded. A contributing factor is the slope of the alluvial fan away from the valley wall. The steeper the slope the more expansion of the HCMZ boundary is limited due to increasingly larger volumes of material that reach the main river channel.

1.2.3 TASK 2C: Assess the Vegetation and Logging History for the Surfaces above the Banks

Of the terrace banks that do not have a tendency to become armored, the surface vegetation is an important factor in determining the potential erosion rate. Surfaces that have large diameter trees tend to have a slower rate of erosion because as the banks become undercut by the river, the larger trees have substantial roots that protect the bank and limit erosion, or the tree may fall against the bank providing natural armoring. Beeson and Doyle (1995) documented that of 748 meander bends studied on four stream reaches in British Columbia, bends without riparian vegetation were nearly five times as likely as vegetated bends to undergo detectable erosion during flood events. For example, the largest amount of lateral bank erosion observed between 1939 and 2002 on the Hoh River was 1500 feet along a bank just upstream of the entrance to the Oxbow Canyon that had been logged and developed in 1939. On the other hand, the majority of ONP has not been subjected to logging or development, and lateral terrace bank erosion has not been significant. The present vegetation and logging and development history were interpreted from aerial photographs ranging from 1939 to 2002 (see Table 3).

Surfaces that have been recently logged or are kept clear (e.g., by development, for pasture) were categorized as fast potential erosion rates. The grasses, shrubs, and scattered trees provide few roots to stabilize sediment in the terraces, and do not provide large enough logs to armor the banks.

Banks along terraces that have been logged, but have at least moderate-size trees at this time are estimated to have a medium erosion rate. The exception is terrace banks that are composed of loose sand and are a few tens of feet high. These high banks may not receive much benefit from the tree roots or the potential effects of log armoring. Thus, these banks are estimated to have fast, rather than medium, erosion rates.

Banks along terraces that are covered with thick stands of large trees are estimated to have slow erosion rates. These are surfaces that have never been logged, mostly in ONP, or surfaces that were logged so long ago that the large trees have reestablished. The trees on these surfaces are large enough and prevalent enough that their roots can provide some stability to the bank sediments and any trees that fall onto the bank will be large enough to provide armoring.

Even in areas of large-diameter trees (where erosion rates are otherwise slow), terrace banks composed primarily of loose silt and that are a few tens of feet high are thought to have a medium potential erosion rate. This is because of the high erodibility of the sediment and the height of the bank, which limits the effectiveness of roots and logs for slowing erosion.

1.2.4 TASK 2D: Verify Rates by Comparing the Historic and 1939 CMZ Boundaries

Verification of the assigned potential erosion rates was accomplished by comparing the locations of the HCMZ boundary in 1939 and in 2002. For terrace banks that have eroded during the last 63 years, the total area and average yearly rate of erosion were approximated. In general, terrace banks assigned a fast erosion rate should have on the order of hundreds of feet of erosion. Terrace banks with a medium erosion rate should have on the order of several tens of feet of erosion. Finally, terrace banks with a slow erosion rate should have on the order of less than10 feet of erosion. Potential erosion rates were adjusted where significant evidence suggested a different rate than previously assigned.

A few exceptions existed where historical erosion did not tell the whole story. For instance, in some areas the HCMZ terrace bank has only just recently been exposed to the river flow and has not been subjected to erosion in the past. These areas must rely on the bank properties and potential channel path assessments to assign potential rates of erosion. Comparison of more recent aerial photography from 1994, 2001, and 2002 provides some indication of the potential rates of erosion for these banks that are actively eroding. In other cases, areas along the HCMZ that had once been cleared of vegetation have already eroded at a fast rate, but remaining large diameter trees on the edge of the logged area may limit the rate of any additional erosion now that the logged area has eroded.

1.3 STEP 3: Assign a Risk of Terrace Bank Erosion Based on Likelihood and Rate Categories

For the banks bounding the HCMZ with at least a moderate likelihood of erosion, the likelihood for erosion and the potential rate of that erosion are combined into risk categories (see Table # in main report). The purpose of integrating the categories is to not only see which areas are most likely to erode over the next several years to decades, but also to estimate at what rate they might erode relative to other areas along the HCMZ boundary. For instance, a given reach may have several areas of high likelihood or actively eroding banks, but knowing which banks might erode the fastest helps prioritize the risk. On the other hand, a reach in ONP may have all banks categorized as slow rates of erosion due to large diameter trees, but knowing which areas have the highest likelihood to erode next is important in understanding the risk of erosion. The risk of erosion is of particular concern in areas where it is desired to protect and manage property and infrastructure. The categories are mapped with a combination of colors and line patterns along the HCMZ boundary on aerial photography.

Terrace banks bounding the HCMZ with Likelihood-Rate categories of Active-fast, Active-medium, High-fast, and High-medium are the areas that we think are the most likely to be eroded at the fastest rate during the next few years. These banks are shown on figures in this report by red (Actively Eroding) and orange (High Likelihood), thick (Fast Rate) and double (Medium Rate) lines. These terrace banks often are composed of loose alluvial or glacial deposits and are bounding terraces that have been logged recently or are kept clear of trees. These banks are primarily in Reaches 5, 7, and 8, where channel changes between 1939 and 2002 are the greatest.

Terrace banks in these same reaches that are composed of alluvial-fan deposits are interpreted to have only a moderate likelihood of erosion and potential slow rates if erosion does occur. This is because of the coarser, cobble-sized material in these deposits and the continuing additions of sediment being transported down the tributary during runoff events.

Steep alluvial fans with large sized-material (cobble and boulder) are thought to have a low risk of erosion during the next several years. These banks are located primarily within ONP (Reaches 1, 2, 3, and 4). Where the banks bounding the HCMZ are bedrock, as in Spruce Canyon (Reach 6) and downstream of Reach 8 in Oxbow Canyon, the likelihood of erosion during the next few years to decades is assumed to be very low.

Appendix H:
Hoh River Historic Aerial Photographs and Map Geographic Transformation

This data set is a compilation of historic World BIL image files, covering a portion of the Hoh River in western Jefferson County, Washington from the river's mouth to approximately river mile 40 inland. These images were created by the United States Bureau of Reclamation, Denver Technical Service Center, Remote Sensing and Geographic Information Group.

Scanned historic aerial photo sets were acquired for the study area. Image dates for the historic photos include 1939, 1950-51, 1960, 1971, 1977, 1981, 1994, 1998, 2001, and 2002 (see Table 5 in main report).

The historic scanned images were geo-referenced and rectified to horizontal control points that were derived from a 3' pixel resolution Digital Ortho Photo (DOQ) mosaic which was developed and provided by the Washington Department of Natural Resources. The DOQ source date for when the aerial photographs were flown is July 8, 2001 as referenced by the Washington Department of Natural Resources Photo and Map Sales Office. The horizontal datum for the rectified images is Washington State Plane North, NAD1983, feet.

The input historic photo scans were geo-referenced using ESRI software. Control point values were transferred from an image point on the DOQ (example: road intersection, tree) to the same image point on the scanned photograph. The image processing software rectifies the photo-image to fit the DOQ using a first-order transformation.

Root mean square (RMS) errors were documented for approximately 20 percent of the transformations. RMS values ranged from 1.5 feet to 198.6 feet. Relative spatial accuracy of the output images is a function of a variety of factors and varies from one image to another. One of the main factors influencing spatial accuracy is the amount of vertical terrain variation that occurs within the bounds of each image. Images that represent earth features in more undulating terrain (mountains, canyons, etc.) will generally be less accurate. Another major factor specific to this study area is the overall lack of visible control points, especially in the upper reaches of the study area. Budget concerns did not allow vertical control to be considered in this effort. However, a vertical control component would most likely improve the overall output accuracy of transformation process. The DOQs meet National Map Accuracy Standards, however the resulting images may not meet NMAS. The largest RMS errors were associated with the 1939 aerial photographs, which were high in elevation and did not have the same equipment capabilities as modern aerial photography does. The 1939 aerial photographs are visibly not to the exact same scale as the 2001 DOQs, and good judgement must be used in mapping features from the digital versions of these photographs. The remaining historic aerial photographs had lower RMS values, but care must still be taken in mapping from these photographs in areas where the scales may be slightly off. GIS mapping for this project took these factors into consideration.

A 1st order transformation using the Georeferencing toolbar in ArcMap 8.03 was also used to rectify the original land survey maps of the Hoh River showing the river position from surveys in 1891, 1895, or 1918 depending on the reach. The USGS 1:24k Digital

Raster Graphics were used for control because the survey maps contain the original section and township boundaries that are identified in the USGS quadrangle maps. A minimum of five control points were used on each historic map. The cumulative RMS error for each historic map was no more than 5 feet in both the easting (X) and northing (Y) directions.

Table H-1. Aerial Photography and Maps Acquired and Rectified to Same Scale for Geomorphic Study.

Photograph Date	**Scale**	**Area Covered from mouth (RM 0) to Mount Tom Creek (RM 40)[1]**	**Type**	**Source**	**Project**	**Reach Rectified in GIS**
10-12-1939	1"=2 miles	Mouth to RM 40	Black & white	USGS National Archives (Wallace Aerial Surveys)	GS-J	RM 0 to 40
1950-51	1:12,000	Mouth to RM 38	Black & white	BERRY (Univ. of Washington)	M49-13	RM 17 to 38
1960	1:12,000	Mouth to RM 35	Black & white	WDNR[2]	WWJC6000	RM 17 to 35
8-9-1971	1:12,000	Mouth to RM 27	Black & white	WDNR	OLY-71	RM 17 to 27
7-22-1977	1:12,000	Mouth to RM 38	Black & white	WDNR	OL-77	RM 17 to 38
7-4 & 9-4, 1981	1:12,000	Mouth to RM 38	Black & white	WDNR	OL-81	RM 17 to 38
1987	1:24,000	Mouth to RM 40	Quad Map (DRG[3])	USGS	-	RM 0 to 40
1994	1:24,000	Mouth to RM 40	Black & white orthophoto	USGS	-	RM 0 to 40
7-28-1998	1:12,000	Mouth to RM 31	Color	Hoh Tribe	Quillaute-Hoh	Photos Not Rectified
7-8-2001	1:32,000	Mouth to RM 40	Black & white orthophoto	DNR	OLQT00	RM 0 to 40
7-10 to 7-12, 2002	1:12,500	Mouth to RM 40	Color	Sound Aerial Survey	HOH R	RM 17 to 40

[1]ONP Boundary located at RM 31
[2]WDNR is Washington Department of Natural Resources Photo and Map Sales
[3]DRG is digital raster graphic (scanned USGS quadrangle map)

Appendix L.
Terrace Dating in the Hoh River Basin.

Table L-1. Comparison of Terraces Characteristics Described for the Hoh River and the South Fork

For main Hoh River (Fonda, 1974)					For a 1,000-m-long (3300 ft) study reach on the South Fork (Swanson and Lienkaemper, 1982)						
Surface or Terrace	**Height Above Low-flow Channel**	**Vegetation Community**	**Estimated Age**	**Source of Age Estimate**	**Surface or Terrace**	**Height Above Low-flow Channel**	**Vegetation Community**	**Estimated Age**	**Source of Age Estimate**	**Continued Flooding**	**Primary Erosion Process**
Alder Flat	About 1 m (3.3 ft)	Alder; will gradually be dominated by sitka spruce and bigleaf maple	65 to 75 yrs	Tree size	**Surface 1**	Up to 1 m (3.3 ft)	Alder			Yes	Surface scour (newly emergent gravel bars)
					Surface 2	1.5 to 2 m (5 to 6.6 ft)	Alder	30 yrs	Alder up to his age; trees likely date time of establishment of vegetation	Yes	Surface scour
First Terrace	2 to 3 m (6.6 to 10 ft)	Bigleaf maple, black cottonwood	400 yrs	Correlation to trees sampled on till on Mt. Rainier and correlated to glacial advance between 1540 and 1635	**Surface 3**	About 2 m (6.6 ft)	Alder, spruce, sitka spruce	>100 yrs	Tree age; trees likely date time of establishment of vegetation	Yes; overbank deposition	Bank undercutting; Channels along back edge of surface
					Surface 4	About 3 m (10 ft)	Spruce, western hemlock	>258 yrs	Spruce and hemlock are up to this age, based on sample of 20 trees; includes old-growth, open-grown spruce and hemlock; trees provide minimum age only	Yes; overbank deposition	Bank undercutting; whole trees fall into river; channel along back edge of surface
Second Terrace	About 5 m (16.5 ft)	Western hemlock, sitka spruce; bigleaf maple in small numbers	>500 to 600 yrs	Sitka spruce trees are at least this old; then correlates the tree age to the 1217 to 1364 ice advance on Mt. Rainier	**Surface 5**	About 5 m (16.5 ft)	Spruce, western hemlock	>266	Spruce and hemlock are up to this age, based on a sample maximum age in a sample of 20 trees; many large down boles in advanced stages of decay suggest surface is likely substantially older the oldest living trees; trees provide minimum age only	No	Bank undercutting; Whole trees fall into river
Third Terrace	15 to 20 m (49.5 to 66 ft)	Western hemlock	No estimate; original valley fill, which is described at till		**Not described**						