Module A
Sedimentation Assessment

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SEDIMENTATION ASSESSMENT

EXECUTIVE SUMMARY

The natural sedimentation regime of the East Fork Humptulips and West Fork Humptulips Watershed Administrative Units (E/W Humptulips Watershed) has a fine to coarse sediment ratio typical of other mountainous watersheds on the Olympic Peninsula. Also typical of other watersheds on the Olympic Peninsula, the E/W Humptulips Watershed has a sediment budget that is dominated by inputs from mass wasting and creep processes, with surface erosion contributing a much smaller portion of the total. However, in contrast to other Olympic Peninsula rivers that experience large sediment waves in response to natural disturbance, the East and West forks of the Humptulips River have an unusually high, chronic sediment supply that is punctuated by small, episodic peaks of increased sediment supply in response to limited natural disturbance. The chronic sediment supply is principally derived from the evacuation of glacial valley fill during each peak flow event that causes localized undercutting. This frequent undercutting triggers numerous, small failures along the oversteepened inner gorges and terrace edges. A smaller component of the chronic sediment supply is derived from deep-seated landslides and from the routing of debris fan deposits into the channel network.

Mass wasting processes in response to forest management appear to increase the chronic sediment supply and may also increase the small, episodic peaks that are triggered by larger storm events. The fine to coarse sediment ratio is probably unchanged by increased mass wasting frequency. Mass wasting events that deliver to the channel network initiate on one of three surfaces: 1) on stream-adjacent terrace edges; 2) within small inner gorges in the valley fill material; or 3) on very steep hillslopes, some of which have been glacially scoured. On a site-specific scale, almost all mass wasting events initiate from stream banks, from the walls of small inner gorges, and from small, soil-filled concavities such as bedrock hollows and channel heads. Placement of excess fill, concentration of road drainage, and loss of root strength are the key management-related triggers of mass wasting.

Road erosion is increasing the chronic component of the sedimentation regime and is also increasing the fine to coarse sediment ratio. The East Fork Upper Subbasin receives a low hazard designation, the East Fork Middle, the West Fork Upper, and the Chester Creek subbasins receive moderate hazard designations, and the other five subbasins receive high hazard designations for road erosion. Excess road erosion volumes are caused by certain segments of individual mainline roads (e.g., the 2220, 3000, 3251, 3500, 7500.6, 7940, and

7950 roads) and by secondary and inactive roads in the stream-adjacent and midslope, moderate, high dissection topographic positions.

Management-related mass wasting inputs have not been quantified, so road erosion and mass wasting inputs cannot be directly compared. However, these processes occur throughout the E/W Humptulips Watershed; mass wasting inputs dominate the northern, or headwater, subbasins, while road erosion inputs dominate the southern subbasins. Hillslope surface erosion related to management is everywhere a trivial portion of the sediment budget.

INTRODUCTION

This Sedimentation Assessment combines the watershed analysis assessments for both mass wasting and surface erosion and is designed to address both the State and federal requirements for these two modules. In particular, the Module Questions were drafted to cover all questions asked by the State process in Version 4.0 of the *Standard Methodology for Conducting Watershed Analysis* (State Manual; Washington Forest Practices Board [WFPB] 1997) and by the federal process in the Record of Decision for the Northwest Forest Plan (US Department of Agriculture Forest Service [Forest Service] and US Department of the Interior Bureau of Land Management 1994a, 1994b) and *Ecosystem Analysis at the Watershed Scale: A Federal Guide for Watershed Analysis,* Version 2.2. (Federal Guide; Regional Interagency Executive Committee and Intergovernmental Advisory Committee 1995). See Table A-1 for locations of information corresponding to forms and maps recommended by the State Manual (WFPB 1997). Modifications to the State Manual methodology are described in the responses to individual questions in the Module Questions section.

Table A-1 Guide to products recommended in the State Manual (WFPB 1997).

State Manual product title		Location or corresponding product in this assessment
Form A-1	Mass wasting inventory data	Appendix A-2
Form A-2	Mass wasting map unit description	Appendix A-3 (this assessment delineated geomorphic mapping units rather than mass wasting mapping units)
Form A-3	Mass wasting summary table	Tables A-2 through A-7, pages A-8, A-9, A-11, A-12, and A-18
Form A-4	Summary of mass wasting and surface erosion delivery potential (optional)	Module Question 5, page A-27; Map A-3, Appendix A-1
Map A-1	Landslide inventory	Map A-1, Appendix A-1
Map A-2	Mass wasting map units with potential hazard ratings	Maps A-2 and A-3, Appendix A-1
Form B-1	Hillslope field/photo assessment	Appendix A-2; field observations not formally recorded
Form B-2	Roads calculation spreadsheets	Tables App-A-4-1 through App-A-4-4, Appendix A-4
Form B-3	Road erosion field forms	Not included in report but submitted to Washington Department of Natural Resources (WDNR); see Module Question 6, Step 2, page A-30
Form B-4	Surface erosion summary table	Table A-8, page A-25, and Table A-12, page A-36
Map B-1	Subbasins	Delineated on each of Maps A-1 through A-6, Appendix A-1
Map B-2	Preliminary soil erosion potential	Map A-1, Appendix A-1; did complete surface erosion inventory by photo instead

Table A-1 (continued).

State Manual product title		Location or corresponding product in this assessment
Map B-3	Past 5 years' activities	Map A-1, Appendix A-1; included evaluation of 1993 and 1997 photos
Map B-4	Final soil erosion potential	Map A-3, Appendix A-1; surface erosion usually the result of mass wasting
Map B-5	Road traffic and surfacing	Map A-4, Appendix A-1
Map B-6	Road segment delivery	Map A-6, Appendix A-1

GEOLOGIC OVERVIEW

The core of the Olympic Mountains is uplifting at rates of approximately 1 km per million years (1 mm per year; Pazzaglia and Brandon, in review), and evidence suggests that uplift has actively occurred for at least the past 15 million years, since the late Miocene (Brandon et al. in review). During this time, coastal areas of the Olympic Peninsula appear to have remained at or near present day sea level (Pazzaglia and Brandon, in review). Uplift of the core rocks of the Olympic Mountains is accommodated along a complex fault system. The Southern Fault, which lies to the north of the E/W Humptulips Watershed within the valley of the Quinault River, has accommodated uplift of the southern margin of the Olympic Mountains. Thus, all bedrock exposed in the E/W Humptulips Watershed is part of the peripheral (i.e., coastal) rock assemblage of the Olympic Peninsula (Tabor and Cady 1978).

The bedrock geology of the E/W Humptulips Watershed is almost entirely composed of the Crescent Formation and the related Blue Mountain Unit (Tabor and Cady 1978). The Crescent Basalt (Tcb) and a thickly bedded sandstone facies (Tbmt) outcrop in the headwaters of both the East and West forks of the Humptulips River, while interbedded basalt flows and mudflow breccias of the Crescent Formation (Tcbb) occur throughout the remainder of the E/W Humptulips Watershed (Tabor and Cady 1978). An unrelated and unnamed siltstone and sandstone unit (Tusa) outcrops south of Furlough Creek.

Other lithologies present in the E/W Humptulips Watershed closely resemble their descriptions in Tabor and Cady (1978), but Tcbb is very complex and, in fact, its character is somewhat different from its description in Tabor and Cady. Flow sections in Tcbb are 5 to 15 m thick and are often composed of many, thin flows. In certain outcrops, flows are as thin as 15 cm, and each has a distinct glassy rind on its top surface. Clearly, small, rhythmic extrusions were occurring in a subaerial environment. The larger flow sections are themselves interbedded with pyroclastic sections of 5 to 100 m in thickness. Individual pyroclastic deposits vary from a few centimeters to many meters in depth, and lenses within the ash-dominated material are composed of extremely well sorted lapilli that are subangular in shape and 8 to 10 mm in diameter. In the low mountains north of Donkey Creek between the West and East forks of the Humptulips River, a portion of Tcbb has been rotated to a near vertical orientation. This is exerting a strong influence on erosional processes active in this part of the watershed.

Several times during the Pleistocene, alpine glaciers have developed in the headwaters of the East and West forks of the Humptulips River (Long 1975). The furthest extent of glaciation occurred during the older Wisconsin advance (Long 1975). During this advance, the West Fork Glacier split around a high point of bedrock just south of Donkey Creek. A substantial volume of the ice flowed through a low divide and into the East Fork Valley, joining with the East Fork Glacier (Long 1975). This lobe terminated against the southern hillslope where the East Fork Humptulips River turns toward the west and overrode some low terrain just west of the East Fork Valley. It is unclear whether the headwaters of Chester Creek supported an alpine glacier or whether all the ice in Chester Creek was contributed by the West Fork Glacier, which breached a low divide between the West Fork Valley and Chester Creek. However, the lack of a distinct cirque basin in the headwaters of Chester Creek suggests that the latter hypothesis is more plausible.

In general, hillslope gradient increases and soil depth decreases further up the valleys of the E/W Humptulips Watershed. Hillslopes in the headwaters of both forks have experienced extensive glacial scour. Soils are thin, if present at all, and prominent features such as Colonel Bob display the craggy terrain characteristic of former nunataks, peaks surrounded but not overtopped by glacial ice. Down valley from the headwaters, but north of Donkey Creek, hillslopes are steep (> 65 percent), have soils of moderate depth, and experience shallow mass wasting events in response to natural and anthropogenic disturbance. From Donkey Creek Subbasin south, hillslope gradient varies from steep (> 65 percent) to very gentle (< 20 percent), and soils tend to be quite deep. In this part of the E/W Humptulips Watershed, hillslopes at lower elevation have a thick veneer of glacial till. Mass wasting is rare, even on the steepest hillslopes in the southern part of the watershed.

The valleys of the East and West forks of the Humptulips River have remnant terraces at elevations ranging from the highest glacial outwash surface to just above the modern flood plain. Sediment production through a variety of mass wasting processes triggered by both natural and anthropogenic disturbance is high from stream-adjacent terrace edges and small inner gorges formed as tributary streams downcut through the terraces to reach base level with the mainstem channels.

MODULE QUESTIONS

1. What mass wasting processes are active in the watershed, and how are they distributed across the landscape?

Mass Wasting Inventory

A mass wasting and surface erosion inventory was conducted using aerial photos that span the period from 1950 through 1997. An attempt was made to cover the analysis area in 10-year increments, but this was subject to photo availability and land ownership (i.e., 1950 photos were not available for areas of the Olympic National Forest). In some cases, 1939 photos were used to evaluate mass wasting and surface erosion events that had occurred previously under natural or earlier management conditions. A comprehensive inventory was not conducted with the 1939 photos because of their small scale (roughly 1:30,000), inconsistent lighting, and high distortion away from photo centers. In general, only the larger events that were active around or just prior to 1939 showed up well on these photos.

This analysis inventoried 385 mass wasting and surface erosion events (Appendix A-2). Event number (map label), code (surface erosion or mass wasting), photo years observed, delivery (whether the feature delivered to a stream channel), land use or origin, landslide type, and geomorphic character (landform at origin or initiation area) were recorded. Of the 385 events inventoried, 286 were classified as mass wasting events.

Along with mass wasting events, the larger surface erosion events, including road sidecast, were inventoried. Although only mass wasting events are discussed in the answer to Module Question 1, it should be noted that many of the mass wasting events become persistent or chronic surface erosion source areas. This is assumed to be the case in many of those areas where events continue to be visible on successive photo years. Generally, the initial volume resulting from mass wasting is expected to greatly exceed that from subsequent surface erosion. This may be an erroneous assumption for the most persistent events, especially along stream bank areas where undercutting and toe erosion keep slopes active.

Map A-1 (Appendix A-1) shows the location of all of the mass wasting and surface erosion events inventoried within the analysis area. The spatial distribution of these events reflects expected topographic, geomorphic, and geologic conditions. These relationships are discussed below by mass wasting types and processes as well as by subbasin.

Mass Wasting Types and Processes

Mass wasting events, which for the purposes of this document may be collectively termed landslides, have been placed into one of three categories: debris slides, debris flows, and deep-seated failures. The number of landslides by category (or process type) are shown in Table A-2.

Table A-2 Landslide inventory by process.

Process Type	Number of Events	Percentage
Debris Slides	181	64
Debris Flows	94	33
Deep-seated Failures	9*	3

* In addition to these, there are also four, very large, deep-seated landslides mapped as GMU 71 on Map A-2 (Appendix A-1).

Debris slides are shallow, rapidly moving failures that occur near the earth's surface, often at the soil-bedrock interface or along the weathered upper surface of bedrock. As such, stability is strongly related to root strength and slope gradient. Debris slides tend to stop within a few hundred feet unless they reach a steep, concave feature, such as a small channel, and evolve into a debris flow. In the headwaters and some of the upper slope areas, differentiating between snow avalanche and shallow landslide processes is complicated. While differentiating between the two has not been accomplished here, it should be noted that any quantification of sediment yield should address this issue. However, all pathways terminating in debris accumulations or fans, and roads crossing these features, tend to be susceptible to both processes. For the purposes of this analysis, snow avalanches are lumped together with debris slides. Debris slides are called "shallow-rapid" failures in the State Manual (WFPB 1997).

Debris flow is the term used to identify all features that appear to begin as debris slides at a channel head, channel margin, or nearby hillslope and then move into defined channels and progress down the channels a few hundred feet or more. Using State Manual methodology (WFPB 1997), these features would be termed "debris torrents."

The distinction between debris slides and debris flows is important because their impacts on the channel network are often quite different. Many debris slides either fail to deliver to the channel network or deliver relatively small volumes of sediment resulting in limited impacts to short segments of channel. Often debris flows move through first- and second-order channels removing structure (such as large woody debris [LWD] and accumulated colluvial soils stored in these channels) and leaving simplified headwater channels scoured to bedrock. Debris flow scour rates of 8 to 10 m^3 of sediment per meter of channel length have been reported for the Oregon Coast Range (Benda and Dunne 1987), while O'Connor and Cundy (1993) estimated scour rates of 5 m^3 per meter of channel length in the North Fork

Calawah River, and O'Connor (1997) estimated scour rates of 2.5 m^3 per meter of channel length in the South Fork Skokomish River. These values reflect the importance of erosion along the pathway relative to the landslide source area and the significance of differentiating between debris slides and debris flows.

Deep-seated failures are typically slow moving and generally retain much of the vegetation on their surface. Failure planes normally extend below the zone of root penetration and many are thought to be older (pre-existing) features that are periodically active. Because they are often under forest canopy, these areas are easily missed with an inventory based on aerial photos. A number of these features fall within the probable or questionable category, and they are also among the most likely to be under-reported. At least four of these features are large enough to be mapped as landform-scale features and are assigned to geomorphic map unit (GMU) 71 (Map A-2, Appendix A-1).

Distribution of Mass Wasting Features by Subbasin

Table A-3 shows the distribution and density of mapped mass wasting events by subbasin. Subbasins are listed in order from lower watershed to upper watershed areas; they are displayed on Map A-1 (Appendix A-1).

Table A-3 Mass wasting events by subbasin.

Subbasin	No. of landslide events	Drainage density* (mi/mi^2)	Area (acres)	Area (mi^2)	Density ($events/mi^2$)
West Fork Lower	3	5.2	9,152	14.3	0.2
East Fork Lower	5	6.5	9,664	15.1	0.3
Donkey Creek	0	5.3	4,800	7.5	0.0
West Fork above Donkey Creek	7	5.6	9,280	14.5	0.5
East Fork Middle	36	6.4	10,176	15.9	2.3
West Fork above Chester Creek	19	4.6	5,312	8.3	2.3
Chester Creek	59	6.6	6,784	10.6	5.6
East Fork Upper	82	5.9	9,536	14.9	5.5
West Fork Upper	75	6.0	11,712	18.3	4.1

* From Table C-1 (Module C—Hydrologic Change Assessment).

The subbasins listed in Table A-3 can be placed into one of three groups based on landslide density. For each group, the range of landslide densities and a brief character statement are provided below. Grouped in this way, an increasing trend in landslide density from lower and middle to upper or headwater areas is evident.

Group 1: East Fork Lower, West Fork Lower, Donkey Creek, and West Fork above Donkey Creek Subbasins

Landslide densities observed in the aerial photo record within the East Fork Lower, West Fork Lower, Donkey Creek, and West Fork above Donkey Creek subbasins are less than one event per square mile (Map A-1, Appendix A-1). These low densities of landslides reflect that these subbasins are located in the lower areas of the E/W Humptulips Watershed, where hillslope gradients tend to be gentle to moderate and where glacial till and outwash deposits cover much of the landscape.

Group 2: East Fork Middle and West Fork above Chester Creek Subbasins

Landslide densities observed in the aerial photo record within the East Fork Middle and West Fork above Chester Creek subbasins are between two and three events per square mile. These subbasins lie between the lower and upper ends of the E/W Humptulips Watershed and share characteristics with both. Hillslopes in these subbasins are steep and subject to mass wasting, like hillslopes present in the upper subbasins. Extensive glacial valley fill also exists in these subbasins, however, limiting the sources of mass wasting to the upper hillslopes and to inner gorges formed by tributaries that downcut through the valley fill.

Group 3: East Fork Upper, West Fork Upper, and Chester Creek Subbasins

Landslide densities observed in the aerial photo record within the East Fork Upper, West Fork Upper, and Chester Creek subbasins are between four and six events per square mile. These subbasins lie in the headwater areas of the E/W Humptulips Watershed, where the alpine glaciers scoured and oversteepened hillslopes as they grew and flowed towards the lower areas of the watershed. Oversteepened hillslopes extend most or all of the way to the valley floors, and glacial deposition occurs only in limited areas. Hence, much of the landscape in these subbasins is subject to mass wasting, and this is reflected in the moderately high densities of landslides that have occurred in the past few decades.

2. What physical characteristics (landforms) are associated with mass wasting/surface erosion events?

The watershed was divided into GMU following the system developed by Sasich (1994) for the Big Quilcene Watershed Analysis and used by Sasich and Dieu (1995) to evaluate sedimentation for the Sol Duc Watershed Analysis. GMU delineate areas of similar bedrock or environment of deposition or erosion, degree of channel dissection, slope gradient, and active geologic processes. The parameters of delineation, such as hillslope gradient of greater than or less than 65 percent, are chosen to best distinguish areas where mass wasting and surface erosion processes are more active from areas where they are less active. Thus, the watershed can be divided into units that have distinct susceptibilities to and rates or frequencies of erosional processes, as well as distinct sensitivities to natural disturbances and management activities. Considered this way, the watershed can be viewed as coarsely divided by mass wasting and surface erosion hazard.

The watershed was divided into 17 GMU (Map A-2, Appendix A-1). These GMU fall into six broad categories of common geologic histories and geomorphic processes and forms: glacial erosional, glacial depositional, fluvial erosional, fluvial depositional, mass wasting, and inner gorges. The landslide densities for each GMU within the E/W Humptulips Watershed are presented in Table A-4.

Table A-4 Mass wasting by GMU.

Category	GMU	Description	Area (mi.^{2})	No. of landslide events	Landslide density (no. of events/mi^2)
Glacial Erosional	22	Trough headwalls	4.66	17	3.6
	25	Cirques	2.91	11	3.8
Glacial Depositional	34	Moraine, < 40% slopes	15.63	1	0.1
	35	Moraine, > 40% slopes	1.73	2	1.2
	36	Complex glaciated slopes	0.72	1	1.4
	37	Outwash terraces and plains	11.91	12	1.0
Fluvial Erosional Hillslopes	56	Volcanic, moderately dissected, > 65% slopes	26.89	105	3.9
	57	Volcanic, highly dissected, > 65% slopes	9.22	34	3.7
	58	< 65% slopes, weakly dissected	3.30	0	0.0
	59	< 65% slopes, highly dissected	20.16	4	0.2
Fluvial Depositional	60	Post-glacial valley	14.20	9	0.6
Mass Wasting	71	Earth flows/slumps	0.60	4	6.7
	73	Debris flow/alluvial fan deposits	0.30	0	0.0
	77	Convergent headwalls	1.91	28	14.6
	78	Debris flow/debris avalanche tracks	0.86	26	30.2
Inner Gorges*	90	Inner gorges	1.62	14	8.6
	91	Inner gorge/terrace edge landforms in glacial sediment	4.27	17	4.0

* Mass wasting within the inner gorge and terrace edge units (GMU 90 and 91) occurs on steep, channel-adjacent slopes, which are typically well vegetated with large tree species. As a result, it is believed that only the most obvious mass wasting features are inventoried, and it is likely that landslide densities within these areas are undercounted.

The characteristics, active processes, and management concerns for each GMU are described in detail in Appendix A-3. The GMU that are considered to have moderate to high hazard for mass wasting/surface erosion are discussed briefly below.

Mass Wasting Frequency by GMU

Using landslide density values as calculated from the events observed over the entire record of aerial photos (i.e., approximately 50 years), as recommended by Sasich and Dieu (1995) in the Sol Duc Watershed Analysis, the GMU can be divided into low, moderate, high, or very high densities of mass wasting. The definitions used by Sasich and Dieu are as follows:

Low density:	< 2 landslides per square mile
Moderate density:	2 to 4 landslides per square mile
High density:	4 to 6 landslides per square mile
Very high density:	> 6 landslides per square mile

In Table A-5, GMU are grouped into low, moderate, high, and very high landslide densities.

Table A-5 Mass wasting density by GMU.

Density of mass wasting	GMU
Low (< 2 landslides/mi.^{2})	34, 35, 36, 37, 58, 59, 60, 73
Moderate (2 to 4 landslides/mi.^{2})	22, 25, 56, 57
High (4 to 6 landslides/mi.^{2})	91
Very high (> 6 landslides/mi.^{2})	71, 77, 78, 90

Note that the highest densities of landslides within the watershed are concentrated within mass wasting and inner gorge landforms (GMU 70 and 90 series). In other words, 89 of the 277 landslides in Table A-3 (32 percent) are located within 6,118 acres, or 8 percent of the land area. Furthermore, 81 percent of these events delivered to stream channels. Compare these figures to the next highest density of landslides comprising fluvial erosional (hillslope) landforms (GMU 56 and 57)—where 139 of the landslides (50 percent) are located within 23,111 acres or 30 percent of the land area—and glacial erosional units (GMU 22 and 25)—where 28 of the landslides (10 percent) are located within 4,845 acres or 6 percent of the land area.

Mass Wasting Processes by GMU Group

Glacial Erosional Landforms

Glacial erosional landforms present in the E/W Humptulips Watershed are cirques (GMU 25) and trough headwalls (GMU 22). The upper slopes and headwater areas include alpine type environments with bedrock exposures, cliff lines, and talus. Many mass wasting features initiate along or at the base of cliff lines or within well-defined bedrock dissections near distinct changes in slope where average gradients are in excess of 85 percent. Slope cross-sections are U-shaped, reflecting toe slope and valley bottom deposition. These characteristics tend to provide a buffer between upper slopes (and mass wasting inputs from hillslope mass wasting) and valley bottom stream channels. Many debris/avalanche chutes terminate in fans or runout zones along valley toe slopes. The bulk of the sediment volume from mass wasting in these landforms does not appear to directly enter the channel network. In addition, it is not clear how many of these features represent or are dominated by snow avalanche rather than mass wasting processes. As a result, direct sediment supply to stream channels from mass wasting within these GMU is expected to be lower than the frequency or density of mass wasting events might otherwise suggest. Where well defined pathways of delivery (e.g., first- and second-order channels) link hillslope areas directly to mainstem and higher order tributary channels, GMU 78, debris flow/debris avalanche tracks, has been mapped to reflect delivery potential. Where fans have formed adjacent to channels, including much of the West Fork mainstem (e.g., Segment W18, Map E-2, Module E—Stream Channel Assessment), stream erosion of these deposits is hypothesized to be a significant source of sediment supply locally.

Glacial Depositional Landforms

There are four GMU in the watershed that fall into the glacial depositional group: GMU 34, 35, 36, and 37. All have relatively deep deposits of glacial material and low densities of mass wasting. One unique aspect of GMU 37 that warrants discussion here is the dramatic way terrace edges within GMU 37 (or neighboring GMU 91) gully in response to focused road drainage. This response to forest practices is addressed in the Causal Mechanism Report for road erosion. Excepting this issue, these GMU are relatively insensitive to natural disturbance and forest practices.

Fluvial Erosional Landforms

Hillslopes upon which fluvial erosional processes are the primary geomorphic agents are classified within the GMU 50 series and subdivided into GMU 51 through 59 based on bedrock type (sedimentary or igneous), slope (< or > 65 percent), and density of dissection (low, moderate, or high). With respect to mass wasting at the landscape scale, there are two distinct classes of fluvial erosional landforms present in the E/W Humptulips Watershed. GMU 58 and 59 have slope gradients of < 65 percent and experience only low densities of landslides (Table A-3). GMU 56 and 57 have slope gradients of > 65 percent and experience moderate densities of landslides. Within GMU 56 and 57, failures are most likely to initiate in locally steep (> 75 percent) concave areas concentrated in and around channel heads and first- and second-order channel margins.

However, other factors such as material properties, structural controls or orientation, stress history, and seepage are not an inherent part of this classification system as usually they cannot be mapped at this level of analysis. Nevertheless, these latter factors may well control local slope stability and the depth and rate of channel incision resulting in locally steep slope gradients. Examples that likely demonstrate the importance of these factors are the Donkey Creek Slide (Event No. 156, Map A-1, Appendix A-1), a large slide which occurred in an otherwise low hazard unit, and Event No. 148, which occurred near the head of Chester Creek in an otherwise low hazard unit. Both were considered to be large and destructive landslides, but both occurred outside of areas that would normally be considered hazardous, at least at the scale we used for this assessment. Investigations at the project or site-specific scale are recommended in these landforms in order to identify and define specific erosion or mass wasting hazards.

Fluvial Depositional Landforms

GMU 60, the post-glacial valley, is the only fluvial depositional landform mapped in the E/W Humptulips Watershed. Essentially, GMU 60 is everything of lower elevation than the surface of the glacial outwash plain (which is mapped as GMU 37) that does not represent a stream-adjacent mass wasting hazard. Thus, GMU 60 includes all post-glacial terraces, terrace edges, and the modern flood plains of the East and West forks of the Humptulips River except those features that are mapped as GMU 91, stream-adjacent inner gorges on the tributaries that cross the valleys and the high terrace edges that overlook the mainstem channels. A low density of landslides occurs within GMU 60. Delivery is unlikely because GMU 60 failures initiate on oversteepened terrace edges that overlook a lower terrace surface.

Mass Wasting Landforms

Across the landscape, there are distinct features with greater surface erosion and mass wasting potential and whose shape and origin are related primarily to mass wasting and erosional processes. These are mapped as the GMU 70 series, mass wasting landforms. Four of these, GMU 71, 73, 77, and 78, have been mapped within the E/W Humptulips

Watershed. The GMU 90 series is similar to the GMU 70 series in that mass wasting is a frequent, land-forming process, but rapid stream incision is a fundamental control on the land-forming processes in the GMU 90 series. Together, the GMU 70 series and 90 series represent a limited land area in the E/W Humptulips Watershed within which occurs the greatest mass wasting frequency. The GMU 90 series is discussed in greater detail in the Inner Gorge Landforms section, below.

GMU 71, Earth Flows/Slumps—GMU 71 comprises delineated polygons of large scale, deep-seated mass wasting features that vary in size from roughly 30 to 140 acres (smaller scale, deep-seated features of a few acres or less are mapped directly on the mass wasting and surface erosion inventory, Map A-1, Appendix A-1). Most landslides of the scale to be mapped as GMU 71 are believed to be either dormant, very slowly moving, or episodic in their movement. Their initiation may have been triggered by glacial erosion or post-glacial fluvial downcutting or may reflect areas of bedrock structural weakness. These areas may behave like areas with high creep rates but often involve a greater thickness of unconsolidated material than is present on an ordinary colluvial hillslope. Midslope benches, surficial expressions of groundwater (e.g., seeps or springs), and high soil moisture may be common features within these areas. Their primary sensitivity to land management activities such as timber harvest and road construction is that their margins tend to be very susceptible to shallow-rapid mass wasting. Where GMU 71 is adjacent to stream channels, inner gorge and stream-adjacent mass wasting is common. Road construction that removes material from the lower area of a deep-seated landslide or concentrates water into a failure plane, head scarp or crack may reinitiate deep-seated movement of these features.

GMU 73, Debris Flow/Alluvial Fan Deposits—GMU 73 represents areas of sediment deposition. As such, GMU 73 indicates where in the watershed mass wasting has been active in the past and where sediment supply has been high. Furthermore, these sediment storage sites often deposit at channel margins and represent a source of coarse and fine sediment for stream bank erosional processes. These features are often adjacent to channels in the Slope Deposit Geomorphic Channel Unit (GCU; compare Map A-2, Appendix A-1, with Map E-2, Module E—Stream Channel Assessment). These streams are considered sensitive to the removal of LWD or riparian vegetation because these features are considered significant in limiting bank erosion and instability of stream-adjacent slopes. Sediment supply to the aquatic system is expected to be higher along channel margins within GMU 73 than from the surrounding hillslope, glacial erosional, and glacial depositional GMU.

GMU 77, Convergent Headwalls—Convergent headwalls are large, commonly teardrop-shaped areas where many steep, first-order channels converge into a single headwater basin, typically ending in a second-order channel that is a well defined debris flow track. These strongly convergent areas concentrate water and colluvial soils on slope gradients that exceed 70 percent. (Similar-shaped features at lower slope gradients that do not show the frequent mass wasting history typical of GMU 77 are mapped as part of the GMU 50 series.) Convergent headwalls typically extend to the ridgetop. Bedrock hollows at channel heads and the margins along channel edges are particularly prone to frequent shallow failures. Activities that remove root reinforcement of the soil (such as timber harvest), concentrate water (such as road construction and possibly timber harvest operations), or increase the volume of fill within depressions and channel head areas decrease slope stability and contribute to slope failures in this landform.

GMU 78, Debris Flow/Debris Avalanche Tracks—This landform consists of steep first- and second-order channels, channel heads, and oversteepened channel edges that have a history of failure that is evident in the photo record. In the West Fork Upper and East Fork Upper subbasins, frequent snow avalanching is likely and, within some of these polygons, may be the primary process of formation. Frequent scour, lack of old vegetation, and debris accumulations at the toe are typical of these areas. The edges of GMU 78 are typically delineated on the hillslope by a slope break; geomorphically, the margins are similar to small inner gorges. After a debris flow is initiated (commonly from a bedrock hollow) and travels down the debris flow track, subsequent failures are initiated as a result of undercutting along the channel margins. Areas delineated as GMU 78 occur throughout the steeper hillslope areas and are therefore concentrated in the upper subbasins. Convergent headwalls (GMU 77) typically deliver to the larger order channels within the channel network via a debris flow track, and it is likely that a debris track exists below each convergent headwall. Landslide densities are very high (Table A-4), which is to be expected since we conservatively mapped sites for which failure occurrence or signature was observed during the period of photo record. Other debris flow tracks for which we did not observe a history of failure may exist within GMU 22, 25, 56, and 57; these should be mapped as field work is done in these GMU or as failures are observed on future photo series.

Inner Gorge Landforms

In the E/W Humptulips Watershed, inner gorge landforms are mapped as GMU 90 and 91. They are closely related to mass wasting landforms. Inner gorge features or valley inner gorges are erosional features "formed primarily through mass wasting triggered by channel downcutting, lateral cutting, oversteepening and/or undercutting of the slope" (Haskins et al. 1996). There may be a bedrock material or structural weakness that further influences slope stability and locations where these features are likely to form. Inner gorge failures are commonly of a shallow-rapid nature, usually occurring as debris slides. Deep-seated rotational slumps or translational slides occasionally occur.

GMU 90, Inner Gorges (Bedrock)—As mass wasting events are frequent on unmanaged slopes in GMU 90, it is expected that these areas are very sensitive to management activities (most of the areas mapped as GMU 90 in the watershed are unmanaged). Clearcut harvest just upslope of these features may have influenced slope movement/instability in Phillips Creek (Chester Creek Subbasin) and in the East Fork Upper Subbasin. Presumably this slope movement would be related to an increase in water supplied to inner gorge slopes (as ground or surface water). GMU 90 is a significant source of natural sediment production.

GMU 91, Inner Gorge/Terrace Edge Landforms in Glacial Sediment—GMU 91 exists throughout the watershed where stream channels have incised through valley-filling glacial deposits. Along mainstem segments (on one or both sides), GMU 91 occurs where the stream flows against and undercuts a high terrace edge. The large eroding bank along the West Fork just upstream of the Forest Service Road 22 bridge (T21N, R09W, NW 1/4 of Section 21) is a good example of this. Many of these features are persistent for decades.

Along tributary streams, GMU 91 occurs where downcutting or channel incision through valley bottom glacial deposits have occurred and where the gradient has adjusted to accommodate the elevation difference between the tributary channels draining the hillslope areas and the mainstem channels. Thus, GMU 91 is closely associated with Terrace Transition GCU channels (compare Map A-2, Appendix A-1, with Map E-2, Module E—Stream Channel Assessment). An excellent example of a GMU 91 inner gorge on a tributary to the mainstem occurs at lower Pete's Creek in the West Fork Upper Subbasin.

Terrace edges exist along the lower slopes and valley floors of the mainstem valleys throughout the E/W Humptulips Watershed. However, only those terrace edges that are adjacent to active channels and have potential to deliver to the aquatic system (channel network) are included within this GMU.

The terrace edges and inner gorges mapped as GMU 91 are formed in glacial deposits, principally outwash, that are at or near their angle of repose. Landslide densities are high (Table A-5) and, in fact, are probably much higher than indicated by the mass wasting and surface erosion inventory because many small failures that are not visible on the aerial photos have been observed during site visits. Root strength is considered an important stability factor because observed failures are shallow in nature. Toe slope stream erosion or loss of vegetation can lead to instability that, in many examples, has been persistent and slow to recover. Eroding banks occur naturally at the outside of meander bends and have persisted throughout the photo record; many are obvious on the 1939 photos.

3. By landform, what are the important triggers of mass wasting events?

Most mass wasting events initiate in small, concave areas of those GMU with moderate, high, or very high densities of landslides. Of the inventoried shallow-rapid failures (debris flows + debris slides), 52 percent initiated within first-order channel heads, headwalls, or concave slope areas (Table A-6). Another 35 percent initiated at a stream bank, along channel margins, or within inner gorges. Only about 13 percent of the inventoried shallow-rapid mass wasting events initiated on planar or convex slopes that were not also stream-adjacent; few of these failures evolved into debris flows and delivered sediment to the channel network.

Table A-6 Landslide number and percent by slope form of initiation point.

Landslide location	Number	Percent of total
First-order channel heads, headwalls, and concavities	149	52
Stream bank, channel margins, and inner gorges	100	35
Planer hillslope areas	33	12
Convex hillslope areas	2	< 1

In the discussion that follows, each group of landforms or GMU is evaluated briefly with respect to hazard locations and triggering mechanism. Emphasis is placed on landforms with moderate or high mass wasting frequency. Table A-7 shows general triggering mechanisms associated with mass wasting events by GMU.

Table A-7 Mass wasting triggering mechanisms by GMU.

			Triggering mechanism		
GMU	Description	No. of events in data set*	Timber harvest	Roads	Natural
22	Trough headwalls	17		47%	53%
25	Cirques	11	18%	27%	55%
34	Moraine, < 40% slopes	1	100%		
35	Moraine, > 40% slopes	2	100%		
36	Complex glaciated slopes	1	100%		
37	Outwash terraces and plains	4	25%	50%	25%
56	Volcanic, moderately dissected, > 65% slopes	105	23%	68%	9%
57	Volcanic, highly dissected, > 65% slopes	34	6%	21%	73%
58	< 65% slopes, weakly dissected	0			
59	< 65% slopes, highly dissected	4		100%	

Table A-7 (continued).

GMU	Description	No. of events in data set*	Triggering mechanism		
			Timber harvest	Roads	Natural
60	Post-glacial valley	9	22%	56%	1%
71	Earth flows/slumps	4		25%	75%
73	Debris flow/alluvial fan deposits	0			
77	Convergent headwalls	28	11%	32%	57%
78	Debris flow/debris avalanche tracks	26	4%	73%	23%
90	Inner gorges	14	21%		79%
91	Inner gorge/terrace edge landforms in glacial sediment	17	35%		65%

* There is a discrepancy in the data set. Only 277 of the 286 mapped landslide features are displayed in this table. It is not clear where the error exists, although it is expected to be an artifact of GIS processing related to mass wasting polygons that intersect more than one GMU. Specifically, single landslides were assigned to the GMU containing the initiation point of the slide. This was done to avoid double-counting landslides as they traveled through lower GMU. No serious errors in interpretation are expected to result from this GIS artifact because 97 percent of the total population of inventoried landslides are included.

Glacial Erosional Landforms (GMU 22 and 25)

GMU 22 and 25 contain a moderate density of mapped failures and a delivery rate to the stream network of 55 to 60 percent. Over half of the failures are of natural origin, associated with very steep upper slopes (in excess of 85 percent). These natural failures most often occur within dissections and well-defined debris flow and snow avalanche pathways. Lower slope areas have few failures and tend to be depositional rather than source or initiation areas. The exception to this occurs along the banks of second- to fourth-order channels where debris deposits or colluvial soils have accumulated along stream margins; here shallow landslides and bank erosion exist. Failures associated with roads are typically the result of fill placement (especially sidecast) and undercutting (cutslope construction) on very steep slopes, in excess of 85 percent. Concentration of water from road drainage is an important contributing factor.

Slopes greater than 85 percent are believed to be susceptible to shallow mass wasting associated with loss of root strength resulting from timber harvest because of the combination of very steep slopes and a shallow soil mantle. Failures associated with an increase in water resulting from timber removal (peak flow effects) may be a factor, but no direct evidence of this was observed. However, it is possible that any increase in peak flows could result in increased stream bank cutting at the lower areas of these GMU along mainstem and lower tributary channel margins.

Glacial Depositional Landforms (GMU 34, 35, 36, and 37)

These landforms all have a low density of mapped mass wasting features. With the exception of GMU 36 (complex glaciated slopes), these are lower slope and valley bottom areas with glacial (including fluvial-glacial) deposition. The areas most susceptible to mass wasting are associated with well-defined channel margins and terrace edge landforms where local steepening of slope occurs. Within these local steep areas, many of which were caused by channel or stream incision (and are at or near the steepest stable angle for that material), loss of root strength is likely a significant contributor to slope instability. Though infrequent, all of the mapped failures within GMU 34, 35, and 36 have been associated with clearcut timber harvest. However, most deliverable failures in glacial materials will initiate within areas delineated as GMU 91.

An unusual situation exists for GMU 37. Gullying or channel incision has occurred from concentration of road drainage. Examples may be found along the Newbury Creek Road where the road exists near a terrace edge or other distinct change in slope.

Fluvial Erosional Landforms (GMU 56, 57, 58, and 59)

GMU 56 and 57 are landforms with a moderate density of mass wasting features. The highest frequencies of mass wasting occur along channel margins and at first-order channel heads where slopes exceed 75 percent. GMU 58 and 59 have low densities of mass wasting. No landslides are mapped within GMU 58 (this is the landform characterized by slopes generally less than 55 percent). For both of these GMU, landslide initiation points are expected to have slope associations similar to those of GMU 56 and 57 (i.e., local slope increases around channels). However, the occurrence of landslides is much less frequent because of the lower slope gradients present in GMU 58 and 59.

First- and second-order channels, channel heads, and local slope concavities (e.g., bedrock hollows) within GMU 56 and 57 have a high sensitivity to road fillslope construction and drainage diversion or concentration by roads, especially where slopes exceed 75 percent. Many of the inventoried, road-related failures are believed to have resulted from these factors, especially where sidecast construction practices were used. Other factors that are expected to be significant include culvert plugging and drainage rerouting during storms and deteriorating organic materials buried in or supporting sidecast material. Most road failures initiated within concave landforms such as bedrock hollows or channels, but some road failures initiated on planar and convex slopes. Within these GMU, road-related landslides account for 60 percent of the total inventoried landslides.

Timber harvest activities have been associated with a comparatively smaller number of failures in these GMU and account for a number of landslides approximately equal to the number observed to occur under natural conditions. Non-road-related slope failures are associated with locally steep slopes, in excess of 75 percent, in and around concavities. Sixty percent of failures related to timber harvest occurred along steep stream banks and channel margins. All harvested areas where failures were observed to occur included areas of clearcut harvest. Loss of root strength is believed to be the primary trigger; however, the frequency of failures along channel margins may indicate that peak flows or increased runoff are factors associated with stream undercutting of these slopes. Note that non-road-related failures within these GMU are located primarily within the rain-on-snow precipitation zone (compare Map A-1, Appendix A-1, with Map C-2, Module C—Hydrologic Change Assessment).

Fluvial Depositional Landforms (GMU 60)

Loss of root strength and introduction of excess water, such as by the channeling of road drainage, will trigger small debris slides and gullying of terrace edges within GMU 60. However, delivery of sediment to the channel network or a wetland is unlikely because terrace edges with delivery potential have been mapped as GMU 91.

Mass Wasting Landforms (GMU 71, 73, 77, and 78)

GMU 71, earth flows/slumps, are often old or ancient features that are no longer actively sliding on their deep failure plane. Road construction practices that load slopes (filling), undercut slopes (especially around toe slope areas), or concentrate or re-direct water, and timber harvest activities that increase the available water flowing into the body of the slide or in streams marginal to the slide, thus causing erosion or undercutting, could decrease stability and initiate motion of all or a portion of the mass. However, initiation of deep-seated motion has rarely occurred in response to forest practices and has not been observed to occur in the E/W Humptulips Watershed. Because the depth to the slide plane typically exceeds rooting depth, root strength is not considered a primary trigger of deep-seated motion.

However, these features experience a significant number of shallow failures (Table A-4). Slope instability is generally restricted to margin areas such as the head scarp, side scarps, and toes. Side scarps and toe areas are especially sensitive where they are adjacent to stream channels. Because the underlying material has been broken up and moved in the past, critical slope gradients are often lower in this GMU than in GMU where ordinary colluvial soils are present. Margins of these features where slopes exceed 65 percent are the primary areas of concern and are likely to be responsive to both timber harvest and road construction.

GMU 73, debris flow and alluvial fans deposits, have a low density of mapped landslide initiations because these features represent areas of deposition. Where GMU 73 exists adjacent to streams, toe slope erosion and instability could and does occur (most events have been identified as surface erosion rather than mass wasting sites). Therefore, activities that increase runoff, such as channeling road runoff or increasing peak flow hazard by timber removal upslope in sensitive areas, could initiate or sustain erosion in these areas.

GMU 77, convergent headwalls, are highly sensitive to both roading and timber harvest. These landforms concentrate water on steep slopes and contain many steep, channelized initiation points (e.g., channel heads and bedrock hollows). Any activities that increase or concentrate water can further decrease slope stability. The concentration of drainage from roads is an important landslide trigger, as is the oversteepening of slopes by the application of excess sidecast. The proportion of landslides in this GMU triggered by roads is surprisingly low but appears to reflect the reluctance of forest managers to build roads on this obviously unstable ground. Although the effects of hydrologic response and root strength are difficult to separate because they usually occur together, many convergent headwalls are within the rain-on-snow zone, and increases in runoff or groundwater levels are potentially an important trigger.

GMU 78, debris flow/debris avalanche tracks, are highly sensitive to roading and timber harvest. While most areas of GMU 78 are unmanaged, slopes in the West Fork Upper Subbasin have been heavily managed (both timber harvest and roading) and are, or have been, quite responsive. All of the triggers discussed above for GMU 77 are valid for GMU 78 as well. In addition, because this GMU incorporates well-defined debris flow pathways, a common failure mechanism is undercutting by debris flows (additional small failures and persistently eroding channel and channel margins are often mapped as part of the original failure). Debris flows initiated within or passing through this GMU can create a chronic condition of failure from channel edges within this GMU.

Inner Gorge and Terrace Edge Landforms (GMU 90 and 91)

The data in Table A-7 suggest that mass wasting in inner gorge and terrace edge landforms is not associated with roads. However, no roads are present within these GMU. It is likely that these features are preferentially avoided as road locations because of difficulty of construction and mass wasting potential.

GMU 90 has a high frequency of mass wasting and is directly connected to third- and higher-order channels. Slopes often exceed 85 percent and are naturally very unstable. Removal of vegetation and subsequent loss of root strength would be expected to increase the naturally high failure rates. Failures in Phillips Creek and the East Fork Upper Subbasin have occurred just downslope of large clearcut areas and may be associated with hydrologic response (increases in runoff or shallow groundwater) following removal of the trees. There are no roads within this GMU, but it is expected that midslope roads within this GMU would have numerous stability problems. However, well-engineered road crossings should be stable as they are in GMU 91. Practices of cutting, filling, drainage re-routing, and concentrating water would all create potential stability problems.

Like GMU 90, GMU 91 has a high frequency of natural mass wasting. In addition, many events recorded in the mass wasting and surface erosion inventory (Appendix A-2) have been mapped as surface erosion features. In fact, they probably represent a combination of surface erosion and debris sliding. These tend to be large and persistent features, and re-vegetating these slopes seems to take more time than it does on failures that occur on other hillslope areas (Appendix A-2). Persistence of these sites to remain bare may be related to continual stream cutting at the toe of these slopes, so alterations in stream flow or channel position (lateral shifting) may play a role in the healing process. Where these slopes have been clearcut, persistent erosion and mass wasting have been common on slopes exceeding 80 percent. Root strength is a significant contributor to slope stability, and loss of root strength is expected to be a significant trigger. The persistence of failures and large stream cut banks in unmanaged areas may indicate that changes involving an increase in stream flow (concentrating drainage from roads and decreasing hydrologic maturity in sensitive areas by removing vegetation) may have a significant effect on the stability of and sediment production from these areas. As in GMU 37, runoff from roads at or near the terrace edge can initiate large-scale gullying or rapid channel incision.

4. What areas of the landscape are susceptible to surface erosion from either natural processes or management activities?

Methods

We delineated surface erosion events—those unvegetated, eroding areas that are not permanent features of the landscape and that initiated by surficial, not mass wasting, processes—on Map A-1 (Appendix A-1). We recorded the apparent land use or origin of each event (i.e., the trigger) and whether or not the sediment appeared to deliver to a channel (Appendix A-2). Thus, we have information about the historic and current causes and delivery mechanisms of surface erosion. We identified the GMU that are most susceptible to surface erosion by using the Geographic Information System (GIS) to analyze the correlation of surface erosion events with GMU (Map A-2, Appendix A-1). These methods for evaluating surface erosion hazard are distinct from the methodology recommended by the State Manual (WFPB 1997) but have been used in several previous watershed analyses (e.g., Sol Duc Pilot [Sasich and Dieu 1995], North Fork Calawah [Dieu and Shelmerdine 1996], E/W Dickey [LaManna et al. 1998]).

Landscape Distribution

Hillslope surface erosion is distributed in a predictable pattern across the E/W Humptulips Watershed (Map A-1, Appendix A-1). In the southern half of both the East Fork and West Fork watersheds, surface erosion occurs where the mainstem is actively eroding into a high terrace. In the northern half of both watersheds, surface erosion occurs in the headwater areas of small tributaries. This pattern reflects the fundamental geologic differences between the northern and southern ends of these watersheds. In the southern end of each watershed, gentle hillslopes drain to low-gradient mainstem rivers that receive more sediment than they can effectively transport. In response to this sediment load, the mainstem channels experience significant channel migration and, hence, terrace erosion. At the northern end of each watershed, steep hillslopes that experience shallow-rapid landslides and subsequent surface erosion drain to narrow, confining valleys that contain moderate-gradient streams with effective sediment transport mechanisms and limited channel migration.

Distribution by GMU

In the past half century, hillslope surface erosion has occurred to < 0.1 percent of the area within each of the following GMU present in the E/W Humptulips Watershed: 22, 34, 35, 36, 37, 58, 59, 71, and 90 (Table A-8). With the exceptions of GMU 22 and 90, these GMU are low-gradient landforms that are unlikely to experience hillslope erosion, and it is not surprising that the results of the aerial photo inventory demonstrate that hillslope surface erosion is an insignificant process in these GMU. GMU 22 actually experiences very significant surface erosion because portions of the GMU have sheer rock cliffs and talus slopes (see Appendix A-3 for more information). However, we chose not to map these large, chronically unvegetated, natural areas as surface erosion events. Instead, we limited the identification of surface erosion events in this GMU to areas that appeared to be newly eroded. GMU 90, inner gorges, of which only 139 acres are mapped in the E/W Humptulips Watershed, is likely to experience surface erosion in response to either natural or anthropogenic disturbance because of the presence of oversteepened slopes (see Appendix A-3) but by coincidence of the low acreage has not during the period of photo record.

Table A-8 Surface erosion events, acres, and percentages, by GMU.

GMU	No. of events*	Acres	Percentage of GMU area
22	3	1.47	0.05
25	5	4.99	0.27
34	5	0.48	—
35	2	0.70	0.06
36	0	0.00	—
37	9	2.60	0.03
56	38	38.66	0.22
57	15	17.85	0.30
58	0	0.00	—
59	1	0.95	—
60	26	16.50	0.18
71	0	0.00	—
73	2	10.15	5.26
77	6	4.23	0.34
78	7	8.34	1.51
90	0	0.00	—
91	28	45.25	1.67

* GIS analysis of events per GMU divides and double counts events that lie across two GMU; this totals 147, rather than the actual 99 events delineated on Map A-1.

Five GMU have experienced modest surface erosion (0.1 to 1.0 percent) in the past half century: GMU 25, 56, 57, 60, and 77. GMU 60, the post-glacial valley, contains oversteepened terrace edges that are not stream-adjacent and, thus, were not mapped as GMU 91. These edges, created as the post-glacial river downcut through soft glacial sediment, are sensitive to disturbance and experience hillslope surface erosion under full canopy. The other four GMU contain oversteepened colluvial hillslopes that will erode in response to mechanical disturbance and increased surface runoff. However, the majority of surface erosion in these four GMU occurs on the scars of mass wasting events. As mass wasting events are mapped separately, this fact is not reflected in the surface erosion data. However, for purposes of management, we are concentrating our understanding on the identification of triggers. Thus, we are most concerned with surface erosion that initiated as such, because it is this occurrence that we can manage for in the future.

Not including extensive surface erosion after mass wasting initiations, two GMU have experienced hillslope surface erosion over greater than 1 percent of their area: GMU 78 and 91. Polygons of GMU 78, debris flow/debris avalanche tracks, delineate the common pathways through which debris flows reach lower tributaries from headwater initiation sites. Polygons of GMU 91, inner gorges/terrace edge landforms in glacial sediments, delineate stream-adjacent, oversteepened slopes within the post-glacial valley (GMU 60). These landforms experience surface erosion (and mass wasting) in response to stream or debris flow undercutting and all manner of natural and anthropogenic disturbance.

Finally, GMU 73 has experienced hillslope surface erosion over 5.26 percent of its area. Polygons of GMU 73, debris flow/alluvial fan deposits, delineate the locations of landscape-scale deposition that occurs through a variety of processes. When deposition has been recent, as noted by Event No. 194 (Map A-1, Appendix A-1), surface erosion will occur for a period of years until vegetation is established. These areas are not necessarily sensitive to disturbance; surface erosion happens when deposition occurs in response to disturbance of the areas that deliver to this GMU. Therefore, this unusually high percentage of eroding surface area is a natural circumstance.

Triggers and Delivery

Ninety-nine surface erosion events are delineated on Map A-1 (Appendix A-1) and recorded in Appendix A-2. Of these, 57 events appear to have delivered sediment, and 42 events do not appear to have delivered sediment, to a waterbody. As isolated surface erosion events that do not deliver sediment to the channel network or a wetland are of little interest to forest managers, only the delivered events will be discussed in detail.

Thirty-nine natural events occurred, and all delivered to the channel network (Table A-9). Thirty-four of these are recorded as occurring on stream banks (i.e., terrace edges), and another three are recorded as occurring along channels or inner gorges. It is clear that natural surface erosion in the E/W Humptulips Watershed is dominated by stream-adjacent undercutting processes driven by peak flows or the passage of debris flows.

Table A-9 Surface erosion events by trigger and delivery.

Trigger	No. delivered	No. not delivered	Total
Natural	39	0	39
Harvest	3	5	8
Road construction:			
Fillslope	15	33	48
Cutslope	0	3	3
Landing	0	1	1
Total	**57**	**42**	**99**

Forty-eight of the observed surface erosion events were occurrences where excessive sidecast was pushed downhill of a newly constructed midslope road; 15 of these occurrences appeared to deliver sediment to a channel or wetland (Table A-9). An evaluation of the recorded data for the 15 events reveals that two, eight, one, three, and one events were first observed on the 1950, 1968, 1972, 1977, and 1982 aerial photos, respectively. As no such occurrences were observed on aerial photos of the 1990s, we believe that the forest managers of today are in compliance with Washington Forest Practices or are practicing appropriate best management practices (BMPs).

Eight surface erosion events occurred in response to harvest; three of these events appeared to deliver sediment to a waterbody (Table A-9). These three events, Nos. 131, 163 and 257, were first observed in either the 1968 or the 1977 aerial photos, and all three occurred within an inner gorge feature (Map A-1, Appendix A-1; Appendix A-2). Protection of inner gorge features from management-related disturbances will be provided through mass wasting prescriptions. Surface erosion unrelated to mass wasting processes within inner gorges has been such a rare occurrence in the E/W Humptulips Watershed that separate hillslope erosion prescriptions cannot be justified.

Conclusions

Hillslope surface erosion unrelated to mass wasting events is not a significant process in the E/W Humptulips Watershed except on naturally unvegetated slopes in the headwaters. Most natural surface erosion events occur in the stream-adjacent environment and are triggered by undercutting during peak flow events or the passage of a debris flow. Instances of management-related surface erosion events have been rare, especially in the past two decades, and do not require special consideration such as a watershed analysis prescription.

5. Where in the watershed does delivery of mass wasting/surface erosion events to the fish-bearing stream network represent moderate and high hazard?

Mass wasting hazard calls were developed through team consensus at Synthesis and are presented in detail in the Synthesis Matrix (included in this watershed analysis). Hillslope surface erosion calls were not made because surface erosion occurs so rarely, except as a natural process, as to constitute a low hazard to the entire fish-bearing stream network.

The mass wasting potential or likelihood of a landform experiencing mass wasting in response to disturbance, which we think of as "pure" hazard, must be evaluated from the viewpoint of channel vulnerability to determine the real hazard to public resources such as fish and water quality. This latter hazard, sometimes called the "T/F/W" hazard after the Timber/Fish/Wildlife Agreement, is defined as the "likelihood of adverse change and deliverability" (State Manual, WFPB 1997) and takes into account mass wasting volumes, channel response, and routing effects.

GMU 56, 57, 71, 90, and 91 were identified as having moderate mass wasting potential, meaning that mass wasting events are likely to be small or to occur infrequently. Some polygons or areas of GMU 56, 57, 71, 90, and 91 were determined to have high T/F/W hazard because mass wasting events initiated within these areas would be likely to deliver directly to a GCU with high vulnerability to coarse sediment. For example, in Table 25 of the Synthesis Matrix, polygons of GMU 91 are determined to represent high hazard because they deliver directly to the Low-gradient Pool/Riffle GCU, which is highly vulnerable to coarse sediment inputs. Other polygons or areas determined to be high hazard would be likely to deliver to a GCU that was not highly vulnerable itself to coarse sediment but that would quickly route the sediment into a highly vulnerable GCU. For example, in Table 24 of the Synthesis Matrix, polygons of GMU 91 are determined to represent high hazard because they deliver directly to the Terrace Confined GCU, which is only moderately vulnerable to coarse sediment inputs, but the delivered sediment will then route quickly into the highly vulnerable Low-gradient Pool/Riffle GCU. If mass wasting events from a polygon or area of a GMU deliver to a GCU of low or moderate vulnerability and are not routed or are only slowly routed to a more vulnerable GCU, then the T/F/W hazard was determined to be moderate rather than high. An example of this type of hazard determination can be seen in Table 6 of the Synthesis Matrix, where polygons of GMU 91 deliver to the Flood Plain Migration GCU. Examine Maps A-2 and A-3 (Appendix A-1) to observe how polygons or areas of these GMU have been assigned either moderate or high hazard.

Other GMU have the potential to yield very large volumes of sediment where mass wasting occurs. Typically, these are the same landforms that have developed effective routing mechanisms into the channel network, so delivery of sediment is likely to be direct and absolutely overwhelming to any GCU. GMU 77, convergent headwalls, and GMU 78, debris flow/debris avalanche tracks, have these characteristics, and all polygons of these GMU have been identified as representing high hazard.

Riparian Reserve Recommendations

GMU 77, 78, 90, and 91 are moderate and high mass wasting hazard landforms with a high efficiency of sediment delivery. They are expected to be quite sensitive and responsive to management activities, such as road construction and timber harvest, as well as to natural disturbances such as wildfires and large storms. These GMU are proposed for inclusion in the Riparian Reserve system on federal lands based on a designation of unstable and potentially unstable slopes.

GMU 90 and 91 and the high hazard margins of deep-seated landslides (margins of GMU 71) are susceptible to shallow mass wasting and sensitive to management activities. These are areas not well identified by the slope morphology model. Fortunately, on federal lands (where these GMU are located), these areas fall within the Riparian Reserve system as defined by site potential tree height and stream class. Any proposed changes to Riparian Reserve boundaries in these areas must also take into account the GMU boundaries. In other words, if reductions in Riparian Reserve boundaries are proposed at the project scale, they should not extend inside of the moderate or high hazard GMU boundaries until such boundaries have been located on the ground during evaluation by a qualified geotechnical specialist.

6. What are the approximate volumes of sediment inputs from natural background (i.e., creep) and road erosion? Are there moderate or high hazards to fish habitat or water quality from road erosion inputs?

Methods

Evaluation of potential impacts from road erosion was done following the methods described in the State Manual (WFPB 1997) with minor modification. There were five steps to the evaluation. First, natural or background inputs of fine sediment were estimated for each subbasin. Second, maps that delineate road surfacing and traffic and topography were made. Third, the 3000, 3251, and 7950 mainline roads, the 2220, 7500.6, and 7940 secondary roads, and selected segments of the remaining roads, representative of the types delineated on the maps made in Step 2, were surveyed for erosion and delivery. Fourth, the volume of sediment that is eroded from the road prism and the fraction of this that is delivered to stream channels were estimated for each surveyed road segment. Fifth, total road erosion inputs per subbasin were calculated by extrapolating the values of the representative road segments and adding the values for the 2220, 3000, 3251, 7500.6, 7940, and 7950 roads.

Step 1: Natural Background Inputs

Natural background inputs can be estimated by a simple cross-sectional area, calculated from soil depth and stream channel length, multiplied by a creep rate. When following the State Manual methodology (WFPB 1997), soil depths are assigned by soil type. In a somewhat different approach, soil depths were assigned to each GMU with consideration of both average depths for the soil types present and field observations of the GMU. Thus, built into the calculations are the evaluations of slope gradient, the degree of dissection, and the mass wasting history, factors that also influence soil depths. Soil creep rates were assigned to each GMU: 2 mm/year for GMU with slopes that are usually > 30 percent; 1 mm/year for GMU with slopes that are usually < 30 percent. The creep rates and

30 percent threshold are from the State Manual methodology, but slope assignment by GMU rather than directly by topography simplifies the GIS work and may more accurately delineate areas with distinct creep rates by averaging the overall gradient of a slope rather than so rigorously separating areas of distinct creep rates by the 30 percent threshold. GIS personnel provided a spreadsheet containing stream length per GMU per subbasin, and the calculations were completed on this spreadsheet (Table App-A-4-1, Appendix A-4). Soil depths and creep rates assigned to each GMU are evident in Table App-A-4-1. As suggested by the State Manual, a specific gravity for soil of 1.5 was used in the calculations.

Step 2: Development of Maps

After completing initial field work and evaluating aerial photos, and while working closely with landowner representatives from Rayonier, the WDNR, Olympic Resources Management, and the Olympic National Forest, two maps were developed. Distinct traffic levels (e.g., mainline, inactive) and surfacing (e.g., > 6 inches of gravel, 2 to 6 inches of gravel) were delineated on Map A-4 (Appendix A-1). Mainline roads receive frequent, heavy log truck and dump truck traffic; secondary roads receive occasional log truck and dump truck traffic; inactive roads receive frequent light vehicle traffic; and abandoned roads receive occasional light vehicle traffic, if any. In general, mainline and secondary roads have unvegetated treads; inactive roads have unvegetated or only lightly vegetated tire tread surfaces but may have vegetation on the road crown; and roads classified as abandoned have highly variable amounts of vegetation, from light grass to large trees.

The topographic position (e.g., ridgetop, midslope, stream-adjacent) of each road segment was delineated on Map A-5 (Appendix A-1). Stream-adjacent roads are those that lie parallel to and within 200 feet of a stream for greater than 0.25 mile. Stream-adjacent roads are expected to have very high sediment delivery to the channel network. Valley bottom roads lie on very flat topography and rarely cross streams; they are expected to have very low sediment delivery to the channel network. Ridgetop roads lie on or near a ridgetop and rarely cross streams; they are also expected to have very low sediment delivery to the channel network. Three distinct categories of midslope roads were delineated. Midslope roads on low-gradient hillslopes (usually less than 35 percent) with few stream crossings (i.e., low dissection) are expected to have limited sediment delivery to the channel network and no mass wasting potential. Midslope roads on moderate-gradient hillslopes (< 65 percent) with many stream crossings (i.e., high dissection) are expected to have high sediment delivery to the channel network and limited mass wasting potential. Midslope roads on steep-gradient hillslopes (> 65 percent) with many stream crossings are expected to have high sediment delivery to the channel network and may have significant mass wasting potential.

Step 3: Selection and Inventory of Road Segments

Erosion surveys of road segments were conducted in three ways. First, the 3000 (continuation of the East Humptulips County Road), the 3251, and the 7950 mainline roads, and the 2220 (Newbury Creek Road), the 7500.6, and the 7940 (Rainbow Creek Road) secondary roads were continuously surveyed. This was done because erosion rates of mainlines, and to a lesser extent of secondary roads, are so great that even small errors caused by extrapolation from surveys of other road segments (because of small changes in delivery between the surveyed and unsurveyed roads) can cause large errors in the final results. Second, road segments about 1 mile long representative of other road types were surveyed. Road segments surveyed were carefully selected to best represent a road type created by the combination of characteristics on Maps A-4 and A-5 (Appendix A-1; e.g., an inactive, stream-adjacent road), but road types whose erosion rates could be easily derived from another survey were not surveyed. For example, because of the similarity between inactive and abandoned roads in most factors except traffic, erosion from an abandoned, stream-adjacent road can be derived using the survey from an inactive, stream-adjacent road by changing the traffic factor from 1 to 0.05. Third, many abandoned roads were briefly visited. A short segment of each of these was walked to evaluate the condition of the drainage structures and to evaluate whether the road represented any significant source of sediment. The objective of these surveys was to develop an overall picture of the condition of abandoned roads throughout the watershed so as to portray accurately the hazard they represent.

Road erosion inventories and the abandoned road surveys were done on a modified version of Road Erosion Field Form B-3 from the State Manual (WFPB 1997). Photocopies of the actual field inventory forms are attached to copies of this report submitted to the WDNR for peer review; others may request photocopies from Dieu.

Step 4: Calculation of Erosion Rates for Reference Roads

We created two spreadsheets, each somewhat modified from that provided at the WDNR Watershed Analysis Certification Training (Tables App-A-4-2 and App-A-4-3, Appendix A-4). For the shorter surveys of representative segments, Table App-A-4-2 was used to calculate tons/mile/year (instead of tons/acre/year as is done exactly following State Manual methodology [WFPB 1997]), a value to be extrapolated to other segments of the same road type. Using Table App-A-4-3, we calculated tons/drainage structure/year for the 2220, 3000, 3251, 7500.6, 7940, and 7950 roads. (Drainage structures include ditch outs, cross drains, water bars, culverts, and bridges.) This is a useful way to calculate the long, continuous surveys for mainline and secondary roads because the value for an individual drainage structure can be assigned to the subbasin within which the drainage structure lies. Furthermore, values of tons/drainage structure/year allow an engineer to evaluate where additional cross drains will be most effective at reducing the overall delivered erosion from a road. All constants used in the road calculations are taken from the State Manual.

Step 5: Final Calculation by Subbasin

The E/W Humptulips Watershed was divided into nine subbasins; these are clearly delineated and labeled on Map A-4 (Appendix A-1).

The continuous mainline and secondary road erosion surveys were split into subbasins by determining where the subbasin boundaries lie with respect to individual drainage structures. As subbasin boundaries are, by definition, high points in the topography, each individual drainage structure clearly lies within a subbasin. The tons/drainage structure/year values for all drainage structures in a subbasin were added to get a total value for the 2220, 3000, 3251, 7500.6, 7940, and 7950 roads. The values contributed to each subbasin from the continuous road surveys are apparent in the far right column of Table App-A-4-3 (Appendix A-4).

For the remaining road segments, GIS personnel provided the total length of each road type in each subbasin. Road types represent a combination of attributes delineated on Maps A-4 and A-5 (Appendix A-1). The different road attribute combinations that exist in each subbasin are presented in Table App-A-4-4 (Appendix A-4). Table App-A-4-4 was used to calculate the total erosion from roads within each subbasin other than from the mainline and secondary roads that were continuously surveyed. This was accomplished by extrapolating from the representative surveyed segment (or from the value calculated by modifying a factor used in the calculation of an appropriate survey) for a distinct road type to all miles of the road type by using the tons/mile/year value.

Finally, the totaled values obtained from the mainline and secondary roads were added to the results in Table App-A-4-4 (Appendix A-4) to arrive at the total delivered road erosion value for each subbasin.

Results

Natural Background Results

Natural background rates, in tons/year for each of the nine subbasins, are presented in Table A-12. Values range from a high of 1,109 tons/year in the East Fork Middle Subbasin to 334 tons/year in the Donkey Creek Subbasin. The wide range of natural background rates reflects the ranges in several characteristics of the subbasins. Obviously, the acreage of each subbasin is reflected in the natural background rates (e.g., 10,195 acres in the East Fork

Middle Subbasin versus 4,801 acres in the Donkey Creek Subbasin). However, the difference in natural background rates for the two subbasins is not simply a difference in acres. The East Fork Middle Subbasin yields 0.109 tons/acre/year while the Donkey Creek Subbasin yields 0.070 tons/acre/year. In part, the difference in natural background rates is controlled by the channel density (6.36 miles/square mile versus 5.27 miles/square mile, respectively). Geology also exerts some influence. Specifically, as the proportion of the low-gradient GMU (e.g., 34, 37, and 60) increases, the tons/acre yield decreases. Therefore, yield tends to be lower in the southern subbasins for two reasons: increased proportion of low-gradient GMU and decreased channel density.

Road Survey Results

As described in detail in Step 3 in the Methods section, above, three different types of road erosion surveys were conducted in the E/W Humptulips Watershed. Certain mainline and secondary roads were continuously surveyed. Segments of roads representing a particular traffic/topographic combination were surveyed so that these results could be extrapolated to the extended road network. Abandoned roads were examined to understand how they were different from inactive roads and to verify that they were not causing significant sediment production by a process not observed on inactive roads (i.e., numerous culverts becoming plugged and causing the road ballast to erode).

Continuous Surveys of the 2220, 3000, 3251, 7500.6, 7940, and 7950 Roads—The estimates of surface erosion are presented in tons/drainage structure/year for the continuously surveyed segments of the 2220, 3000, 3251, 7500.6, 7940, and 7950 roads in the E/W Humptulips WAU in Appendix A-4. These results are summarized by road and subbasin in Table A-10.

Table A-10 Summary of road erosion derived from the 2220, 3000, 3251, 7500.6, 7940, and 7950 roads

Subbasin	2220 Road	3000 Road	3251 Road	7500.6 Road	7940 Road	7950 Road	Total
East Fork Upper	—	—	—	—	—	—	—
East Fork Middle	—	—	—	—	—	—	—
East Fork Lower	—	605	136	—	—	—	741
West Fork Upper	—	—	—	—	—	—	—
West Fork above Chester Creek	—	—	—	—	—	—	—
Chester Creek	45	—	—	—	—	—	45
West Fork above Donkey Creek	627	—	—	—	0	—	627
Donkey Creek	—	142	—	—	29	—	171
West Fork Lower	—	0	—	37	—	384	421
Total	**672**	**747**	**136**	**37**	**29**	**384**	**2,005**

Representative Surveys of Other Road Segments—One or more surveys of representative inactive and secondary road segments were conducted for each of the six topographic and construction classifications. The actual surveyed segments are noted on Map A-5 (Appendix A-1). These data were used to calculate the fine sediment derived from road erosion and delivered to the channel network in tons/mile/year. These results were modified to derive road erosion values for topographically equivalent roads classified as abandoned. The road erosion values that were extrapolated to all unsurveyed road segments are presented in Table A-11.

Table A-11 Values in tons/mile/year extrapolated to unsurveyed road segments.

	Aban-doned, > 6"	Aban-doned, 2–6"	Inactive, > 6"	Inactive, 2–6"	Asphalt inactive	Secondary
Valley Bottom	0.00	0.00	**0.00**	0.00	---	0.00
Midslope, < 35%, Low Diss.	2.19	2.37	3.30	5.16	---	**14.47**
Midslope; < 65%, High Diss.	12.57	13.34	17.22	24.98	**1.55**	**67.93***
Midslope, > 65%, High Diss.	3.93	4.08	**4.78**	6.20	---	13.29
Ridgetop	0.67	0.83	**1.65**	3.30	---	**0.00**
Stream-adjacent	17.50	19.68	**30.58**	52.38	**19.06**	**129.78**

Bold values are calculated from actual surveys; non-bold values are derived.

* Value averaged from surveys of 3000.7 and Sec. 32, 29, 18 roads.

With respect to the results of previous watershed analyses, there were two surprising results for the E/W Humptulips Watershed road erosion calculations. First, all roads that fall into the midslope, moderate-gradient, high dissection category except asphalt roads appear to cause significant (> 10 tons/mile/year) contributions to the channel network. The values for inactive and abandoned roads were created by modifying the calculations of two surveys conducted on secondary roads and may be artificially high because the tread widths were not corrected for the lower levels of traffic. However, field observations suggest that many of these road segments (i.e., inactive and abandoned roads of midslope, moderate-gradient, high dissection topography) have high delivery because there are numerous stream crossings per mile and few cross drains or other relief mechanisms. In fact, the number of stream crossings per mile of road in this topographic category is unusually high in the E/W Humptulips Watershed because many of the moderate-gradient hillslopes have a thick veneer of glacial till, notorious for having a high density of small streams. Therefore, our confidence in the absolute values is moderate, but our confidence in the belief that these roads are delivering significant volumes of sediment to the channel network is high.

Second, this is the authors' first experience with calculating values for an asphalt mainline road (the Donkey Creek–South Boundary Road), and the results suggest that the use of a high traffic factor for asphalt roads produces erroneous values. Specifically, with a mainline traffic factor, 153 tons/mile/year were calculated to be delivered to the channel network from the stream-adjacent portion of the Donkey Creek–South Boundary Road. As the asphalt surface produces almost no sediment, and as the cutslope and fillslope are densely vegetated, this is an absurd result. To avoid labeling a very environmentally sound road as a hazard, we chose to use the inactive traffic factor and calculate values that more reasonably represent the true sediment production and delivery from the Donkey Creek–South Boundary Road. These values are presented in Table A-11 in the "Asphalt inactive" column.

It is not surprising that stream-adjacent roads of all traffic levels are delivering significant sediment contributions to the channel network. Almost all roads that parallel streams in an immediately proximal position have very high delivery.

Also, despite the initial prediction of high delivery, it is not too surprising that road segments in the midslope, steep-gradient, high dissection category are delivering only modest amounts of sediment to the channel network. In the E/W Humptulips Watershed, many of these segments lie near ridgetop on well-drained colluvial soils, above the point where headwater areas accumulate sufficient water to cause the formation of channels. The value for secondary roads in this topographic category was created by calculation from a survey of an inactive road without corrections for likely differences in tread width. The value is probably somewhat low but of little consequence to the overall subbasin totals because very little length of secondary road is in this topographic category.

Surveys of Abandoned Roads—The authors and two contractors who assisted with the field work made numerous field observations of abandoned roads. Several conclusions can be drawn from these observations. One, abandoned roads vary considerably in quantity of tread vegetation, from a little grass on the crown of the road to large trees across the entire road tread. Where tread surfaces are bare, they are usually well armored with coarse rock. Where this is not the case, the road segments were mapped into the 2 to 6 inches of gravel category (Map A-4, Appendix A-1). Two, although slight slumping of old road prisms is not uncommon, complete washouts and landslides originating from abandoned road prisms are rare except from those segments categorized as lying on midslope, steep, high dissection topography. Obviously, abandoned roads in this topographic category need to be carefully evaluated for mass wasting potential. Three, many of the road segments that were long ago abandoned are actually places of net deposition of sediment. Through natural forest sedimentation processes (e.g., bioturbation and creep), and through cutslope ravel as the oversteepened surface lays back to the natural angle of repose, sediment is building up on the abandoned road tread.

Road Erosion by Subbasin

The total sediment yield from roads to channels is summarized in Table A-12. These values are the sums, per subbasin, of the continuously surveyed roads, presented in Table A-10, and of the representative surveys or derived values presented in Table A-11 as they have been extrapolated to the miles of each road type. The actual calculations are presented in Table App-A-4-3 (Appendix A-4).

Table A-12 Summary of road erosion results.

Subbasin	Road density (mi./mi.^{2})	Road erosion yield (tons/year)	Natural background yield (tons/year)	Percent of background	Hazard call
East Fork Upper	1.62	308	730	42	Low
East Fork Middle	3.19	830	1,109	75	Moderate
East Fork Lower	5.38	1,308	856	153	High
West Fork Upper	1.28	538	924	58	Moderate
West Fork above Chester Creek	3.01	428	344	124	High
Chester Creek	3.17	483	758	64	Moderate
West Fork above Donkey Creek	3.02	780	825	95	High
Donkey Creek	5.23	792	334	237	High
West Fork Lower	5.05	889	673	132	High
Total or (Average)	**(3.29)**	**6,356**	**6,553**	**(97)**	**High**

Volumes of road-derived sediment vary from 308 tons/year in the East Fork Upper Subbasin to 1,308 tons/year in the East Fork Lower Subbasin. Several factors are influencing the road erosion yields of the nine subbasins. There is some correlation between road erosion yield and road density. Specifically, the three subbasins with road densities greater than 5 miles/square mile, the East Fork Lower, West Fork Lower, and Donkey Creek subbasins, have three of the five highest road erosion yields. However, the East Fork Middle and the West Fork above Donkey Creek subbasins have road erosion yields in the same range as the three subbasins with road densities greater than 5 miles/square mile but have road densities just over 3 miles/square mile. The other two subbasins with road densities just over 3 miles/square mile also have high road erosion yields, although significantly lower than the previously mentioned five subbasins. As all four of the subbasins with road densities of just over 3 miles/square mile and high road erosion yields lie somewhere between the headwaters and the confluence of the East and West forks, it seems likely that topography is exerting influence on the delivery mechanisms. In fact, as will be discussed below, midslope roads on hillslopes of moderate gradient are contributing very significantly to the road erosion yields of the central subbasins. The West Fork Upper Subbasin has an unusually high road erosion yield for a subbasin with a road density of 1.28 miles/square mile. This appears to be driven by the predominance of highly dissected topography and the presence of long lengths of stream-adjacent road. Finally, absolute size of a subbasin is exerting little influence on its road-derived sediment. For example, there is less than 10 percent difference in the acreage of the East Fork Upper and East Fork Lower subbasins (9,555 acres versus 9,677 acres, respectively).

Road Erosion Hazard

Hazards calls for fine sediment derived from road erosion take into account the volume of fine sediment entering the channel network of a subbasin as compared with the natural background sediment yield, the sensitivity of the GCUs within the subbasin, and water quality. With the creation of the new Water Quality Module (WFPB 1997), the sensitivity of other water bodies such as lakes and wetlands is also considered. Basic (default) hazard calls are established as follows: High hazard is concluded when road erosion exceeds 100 percent of the natural background yield (i.e., more than doubles the sediment input to the channel network); Moderate hazard is concluded when road erosion is between 50 and 100 percent of the natural background yield; and Low hazard is concluded when road erosion is less than 50 percent of natural background yield. However, careful consideration of such issues as confidence in the assessment and sensitivity of the GCUs within a subbasin may cause a moderate call to be adjusted to either a high or a low call. High hazard calls remain high regardless of GCU sensitivity because of concern for water quality degradation.

The three subbasins with road densities of > 5 miles/square mile, Donkey Creek, West Fork Lower, and East Fork Lower, each receive a high hazard call (see Table A-11). The percentages over natural background for these three subbasins are not unusually high when compared with the results of other watershed analyses, although 237 percent for the Donkey Creek Subbasin is certainly cause for grave concern. Of the four subbasins with road densities of just over 3 miles/square mile, the West Fork above Chester Creek and the West Fork above Donkey Creek subbasins receive high hazard calls, and the East Fork Middle and Chester Creek subbasins receive moderate hazard calls. These road densities are somewhat lower than road densities that typically lead to moderate or high hazard calls, but as discussed above, the prevalence of midslope roads in the central portions of the E/W Humptulips

Watershed appears to cause unusually high delivery. That the West Fork Upper Subbasin receives a moderate hazard call from a road density of 1.28 miles/square mile is very exceptional; again, this appears to be caused by unusually effective delivery mechanisms. Only the East Fork Upper Subbasin receives a low hazard call.

Although five subbasins receive a high hazard call for road erosion, and three receive a moderate hazard call, the overall road erosion yield for the E/W Humptulips Watershed is slightly less than 100 percent of natural background (see Table A-12). This means that excess road erosion inputs are spread somewhat evenly throughout the watershed and that, unfortunately for forest managers who must pay the costs of road maintenance, many segments of road are significantly contributing to the total yield. The roads and road categories in each subbasin that are most significantly contributing to the total road yield are listed in Table A-13 and depicted on Map A-6 (Appendix A-1). Effective evaluation of these roads followed by careful application of BMPs to reduce either production of sediment or delivery of sediment to the channel network are necessary to reduce the road erosion yields to levels that are unlikely to cause detectable water quality changes (i.e., below 50 percent of the natural background yields).

Table A-13 Roads and road categories causing moderate or high hazard, by subbasin.

Subbasin	Roads and road categories most significantly contributing to volumes of road erosion causing moderate or high hazard
East Fork Upper	None.
East Fork Middle	All inactive (> 6") and mainline roads in the stream-adjacent topographic position, and all inactive (> 6") and secondary roads in the midslope, moderate, high dissection topographic position.
East Fork Lower	3251 Road, 3000 Road, all roads in the stream-adjacent topographic position, and all inactive (> 6") and secondary roads in the midslope, moderate, high dissection.
West Fork Upper	All inactive (> 6") roads in the stream-adjacent topographic position and all inactive (> 6") and secondary roads in the midslope, moderate, high dissection topographic position.
West Fork above Chester Creek	All secondary roads in midslope topographic positions, and all inactive (> 6") roads in the midslope, moderate, high dissection topographic position.
Chester Creek	Newbury Creek Road (2220), and all abandoned (> 6"), inactive (> 6"), and secondary roads in the midslope, moderate, high dissection topographic position.
West Fork above Donkey Creek	Newbury Creek Road (2220).
Donkey Creek	Rainbow Creek Road (7940), 3000 Road, all inactive (> 6") and secondary roads in the stream-adjacent topographic position, and all inactive (> 6") and secondary roads in the midslope, moderate, high dissection topographic position.
West Fork Lower	7950 Road, 3500 Road from the 3000 to the 3500.2, 7500.6 Road where it lies in the stream-adjacent topographic position, all inactive (> 6") and secondary roads in the stream-adjacent topographic position, and all secondary roads in the midslope, moderate, high dissection topographic position.

7. What are the relative contributions of coarse and fine sediment from mass wasting, hillslope erosion, and road erosion?

Natural Regime

Our evaluation indicates that the natural sedimentation regime of the E/W Humptulips Watershed is chronically high, with a small overprint of additional sedimentation triggered by natural disturbances. We have documented evidence of a chronic, high sediment load by recording the continuous occurrence of channel migration during the past several decades along extensive reaches of the East Fork and West Fork mainstems (see Map E-3 and relevant text in Module E—Stream Channel Assessment). Active mainstem channel migration provides a positive feedback mechanism because it causes the erosion of high terrace edges during each peak flow event. In addition, the lower reaches of the tributaries have incised into the glacial valley fill and created oversteepened inner gorges that are experiencing small, frequent failures in response to peak flows. Delivery of sediment from the lower reaches of the tributaries to the mainstems occurs efficiently in the high-gradient Terrace Transition GCU (see Map E-2, Module E—Stream Channel Assessment). These terrace edges and inner gorges, delineated as GMU 91 (Map A-2, Appendix A-1), are the most significant source of the chronic sediment load. GMU 71, earth flows/slumps, and GMU 73, debris flow/alluvial fan deposits, are other key components of the chronic sediment budget. In essence, these GMU represent processes (i.e., slow, deep-seated earth movement and temporary storage of mass wasting events) that feed or meter sediment from the hillslope into the lower channel network. Other hillslope processes, such as creep and surface erosion, further contribute to the chronic sediment load.

Overprinted onto this chronic, high sediment load are small spikes of increased sedimentation in response to natural disturbances. Wildfires and windstorms have infrequently affected small areas of the E/W Humptulips Watershed in the past several centuries (see Module B—Vegetation Assessment for details). Probably, these disturbances have resulted in small sediment pulses that have originated in a localized area and then attenuated as they reached the mainstem to which the area is tributary. Large storm events have likely caused increased sedimentation across the entire watershed, but a lack of evidence for large-scale sediment waves in the channel network suggests that these pulses are quite small with respect to the chronic sediment load (see Module E—Stream Channel Assessment). The small sediment pulses are derived from GMU 71, 73, and 91, which undoubtedly experience elevated rates of mass wasting and sediment movement in response to large storm events. GMU 56, 5 7, 77, 78, and 90 also experience elevated rates of mass wasting and contribute to a storm-driven sediment pulse, but valley storage is quite efficient in many of the tributary reaches that are upstream of the mainstem valleys, protecting the mainstems from these sediment pulses.

The proportions of fine and coarse sediment derived from the natural regime are not known, but certain statements can be made about the individual sources. Inputs from GMU 91, one of the largest sources, are dominated by glacial outwash that is quite variable in character (i.e., clay deposits, thick sand lenses, and well-sorted gravel layers are each present in many outcrops) but on average probably provides more coarse than fine sediment to the channel network. However, colluvial soils within the Tcbb lithology (Tabor and Cady 1978) and soils derived from glacial till (GMU 34 and 35, Map A-2, Appendix A-1) are dominated by fine sediment and also provide significant inputs to the channel network. Overall, the proportion of fine to coarse sediment present in the natural regime is probably similar to that of other watersheds on the Olympic Peninsula.

Forest Management Effects

Through increased mass wasting frequency, forest management elevates both the chronic and episodic signatures of the natural sedimentation regime. Timber harvest and road building on unstable slopes increase the frequency of shallow landslide events in GMU 56, 57, 77, 78, 90, and 91. Loss of cover and root strength in GMU 91 elevates the chronic signature for a period of years or even decades through the occurrence of small debris slides and subsequent surface erosion. Peak flow increases in the rain-on-snow zone, although small, may be elevating sediment production from GMU 91 for a period of years after timber harvest, further exacerbating the chronic signature. Under a managed regime, increased landslide frequency in GMU 56, 57, 77, 78, and 90 will occur in response to significant storm events and will contribute to both the chronic and episodic portions of the natural sedimentation regime. This response to timber management is felt throughout the E/W Humptulips Watershed but most strongly in the northern subbasins and in the mainstem rivers.

Sediment derived from road erosion is increasing the chronic portion of the natural sedimentation regime; it is also increasing the ratio of fine to coarse sediment. The road erosion and natural background calculations indicate that, on average, roads are contributing almost as much sediment to the channel network as are natural creep and bank erosion processes (Table A-12). Although sediment production through natural and management-related mass wasting processes has not been quantified, it is clear that road erosion is a significant portion of the total sediment budget. Furthermore, since road-derived surface erosion consists almost entirely of fine sediment, road erosion must be increasing the natural proportion of fine to coarse sediment. Road erosion occurs throughout the lengthy wet season and is not particularly elevated by individual storm events; hence, it is a chronic sediment source overprinted on the natural regime. In general, road erosion is greatest in the southern subbasins (Map A-6, Appendix A-1).

Hillslope surface erosion in response to forest management, except where it occurs in response to mass wasting events, is a trivial component of the overall sediment budget in the E/W Humptulips Watershed. It is unlikely that hillslope surface erosion in response to forest management is significantly increasing or altering the natural sedimentation regime.

Conclusions

The natural sedimentation regime of the E/W Humptulips Watershed has a fine to coarse sediment ratio typical of other mountainous watersheds on the Olympic Peninsula. Also typical of other watersheds on the Olympic Peninsula, the E/W Humptulips Watershed has a sediment budget that is dominated by inputs from mass wasting and creep processes, with surface erosion contributing a much smaller portion of the total. However, in contrast to other Olympic Peninsula rivers that experience large sediment waves in response to natural disturbance, the East and West forks of the Humptulips River have an unusually high, chronic sediment supply that is punctuated by small, episodic peaks of increased sediment supply in response to limited natural disturbance.

Mass wasting processes in response to forest management appear to increase the chronic sediment supply and may also increase the small, episodic peaks that are triggered by larger storm events. The fine to coarse sediment ratio is probably unchanged by increased mass wasting frequency. Road erosion is increasing the chronic component of the sedimentation regime and is also increasing the fine to coarse sediment ratio. Management-related mass wasting inputs have not been quantified, so road erosion and mass wasting inputs cannot be directly compared. We can assert that both processes occur throughout the E/W Humptulips Watershed; mass wasting inputs dominate the northern, or headwater, subbasins, while road erosion inputs dominate the southern subbasins. Hillslope surface erosion related to management is everywhere a trivial portion of the sediment budget.

8. What are the likely near-future trends in mass wasting frequency and surface erosion volume (specifically road erosion) in the watershed?

Likely near-future trends in mass wasting frequency are variable across the E/W Humptulips Watershed. In the southern subbasins (i.e., Group 1 subbasins as identified in Module Question 1), mass wasting frequencies have been fairly constant and low for several decades. This trend is likely to remain unchanged in the foreseeable future because the mass wasting hazard present in GMU 91, which is the majority of the unstable land in these subbasins, will be protected by the Federal Riparian Reserve Strategy or identified and mitigated on State, County, and private lands as forest engineers follow the E/W Humptulips Watershed Prescriptions and the Washington Forest Practices Rules. In the northern subbasins (i.e., Groups 2 and 3 subbasins), mass wasting frequencies have been moderate to high and increasing over the past two or three decades. Numbers of failures triggered within harvested areas should be decreasing as young forests grow and root strength returns to unstable slopes. However, if preventative steps are not taken on aging, sidecast-constructed roads in these subbasins, failure frequencies from road-related triggers will continue to rise for another two or three decades. As road-related failures tend to be larger and more destructive than most harvest-related failures, without preventative steps there will be an overall increase in sediment yield from mass wasting processes in the northern subbasins.

The likely near-future trend of road erosion volumes across the entire E/W Humptulips Watershed is one of a decreasing nature. There will be less harvest on State, County, and private lands because the end of the second rotation is near. The WDNR Habitat Conservation Plan requires that substantial road maintenance be accomplished on State lands. The Forests & Fish Legislation, currently being drafted into new Washington Forest Practices Rules, requires the same on County and private forestland. The E/W Humptulips Watershed Prescriptions will focus these efforts where road maintenance is most needed. On federal lands, traffic levels have been on a decreasing trend, as have road maintenance activities. While a lack of road maintenance may lead to increased mass wasting frequency from midslope roads on unstable slopes, it will lead to decreased surface erosion on other roads as all components of the road prism revegetate. Furthermore, from both active road decommissioning and from neglect, there will be fewer accessible roads on federal lands. Each of these factors will decrease the overall road erosion volumes.

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