Flood Erosion Hazard Mitigation Evaluation

Upper Sandy River

Clackamas County, Oregon

March 24, 2015

Prepared for:

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1 INTRODUCTION

Natural Systems Design, Inc. (NSD) is pleased to present to Clackamas County Department of Emergency Management this Geomorphic Characterization and basis of design for restorative flood protection within the Upper Sandy River. Our services for this project were completed in general accordance with the scope of work and contract dated January 29, 2014.

The Sandy River watershed in northwest Oregon extends from the west flank of Mount Hood to the Columbia River at Troutdale, Oregon (Figure 1).

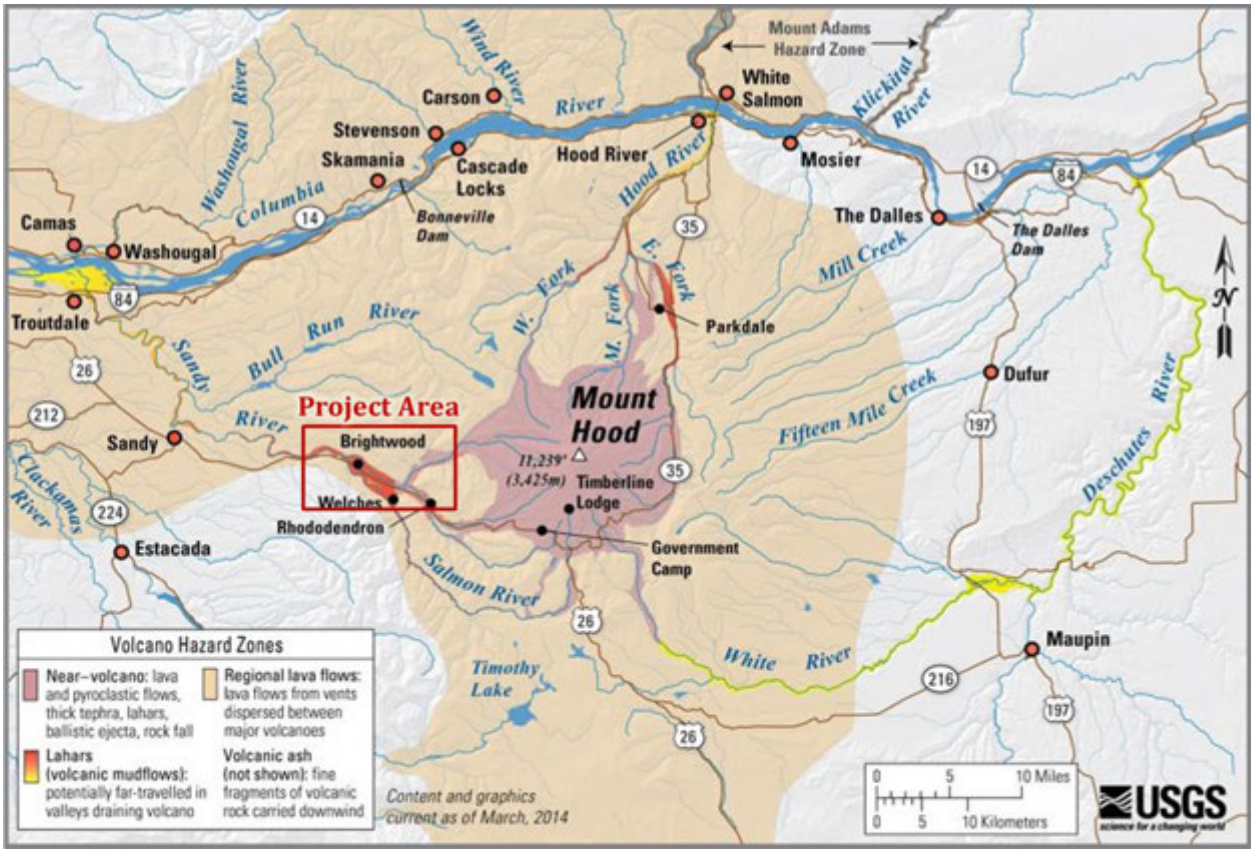

Figure 1. Vicinity Map (USGS Volcanic Hazards Program, 2013)

The Upper Sandy project reach is 10 miles, extending from River Mile 37 (RM 37), just above the Salmon River confluence, to RM 47, just upstream of the Lost Creek confluence. Over the last 50 years the Upper Sandy has experienced several major floods that caused substantial flooding and bank erosion. The flooding of residences, roads and other infrastructure has caused millions of dollars of damage. From 1964 to 2014 the river has experienced 8 of the 10 highest peak flows in its 100 year record of flows. The flood of record occurred in 1964 and eroded over 400 shoreline acres and damaged or totally destroyed roads, bridges and as many as 155 homes (Portland District Post-flood Report July 1966). The three largest flood events occurred in 1964 (61,400 cubic feet per second, cfs), 1996 (48,100 cfs), and 2011 (39,000 cfs).

Based on the complete 100 year record of flows, the 1964 storm had a 0.4% probability of occurring in any given year, equivalent to a 250 year flood event. The flood was extraordinary for the loss of buildings, as described by the Army Corps of Engineers (1966), who reported that "the north bank of the Sandy just upstream from Brightwood showed no indication of buildings, vegetation or topsoil where a group of 40 houses existed prior to the (1964) flood". Although the 2011 flood was smaller in magnitude, about a 33 year flood event, it caused significant erosional impacts along the Upper Sandy shoreline, as well as to public and private infrastructure. During this event, several houses were destroyed due to the erosion of bank soils underlying house foundations, and a half mile section of Lolo Pass Road, which serves hundreds of residents, was washed out.

This report and accompanying maps describe current erosion and flood hazards, the factors influencing these hazards, and a restorative flood and erosion protection strategy for the Upper Sandy River valley.

1.1 PROJECT AREA LOCATION

The Sandy River extends from headwaters on Mount Hood and to the Columbia River (Figure 2).

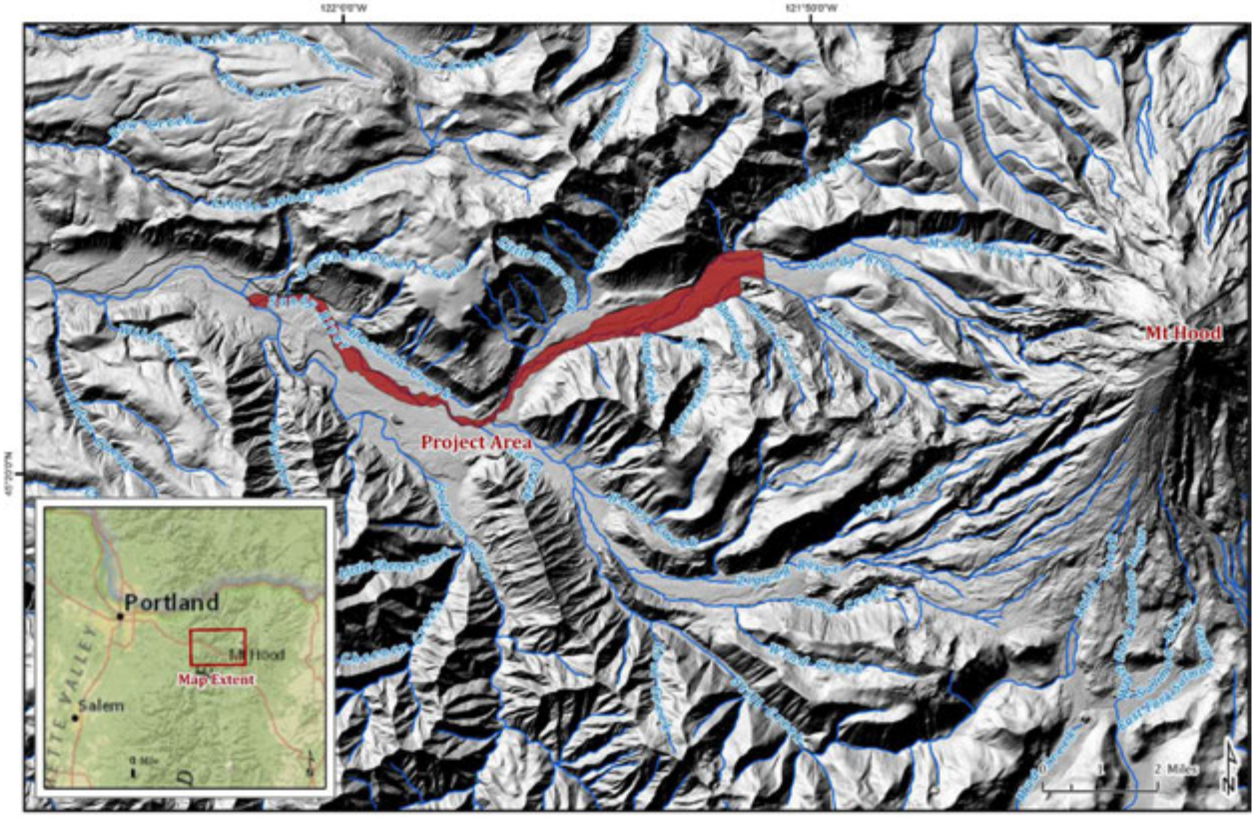

Figure 2. Project Area Map - Upper Sandy River project reach extends from the Salmon River confluence at RM 38 to about RM 49. Data sources: USGS 10m DEM, USGS NHD.

The Upper Sandy River project reach, RM 37-47, includes one of the most developed segments of the entire river valley. The Sandy's largest tributary, the Salmon River enters the river at RM 37.4. Within the project reach two major tributaries enter the River, the Zigzag River at RM 43.0 and Clear Creek at RM 46.6 (Figure 3).

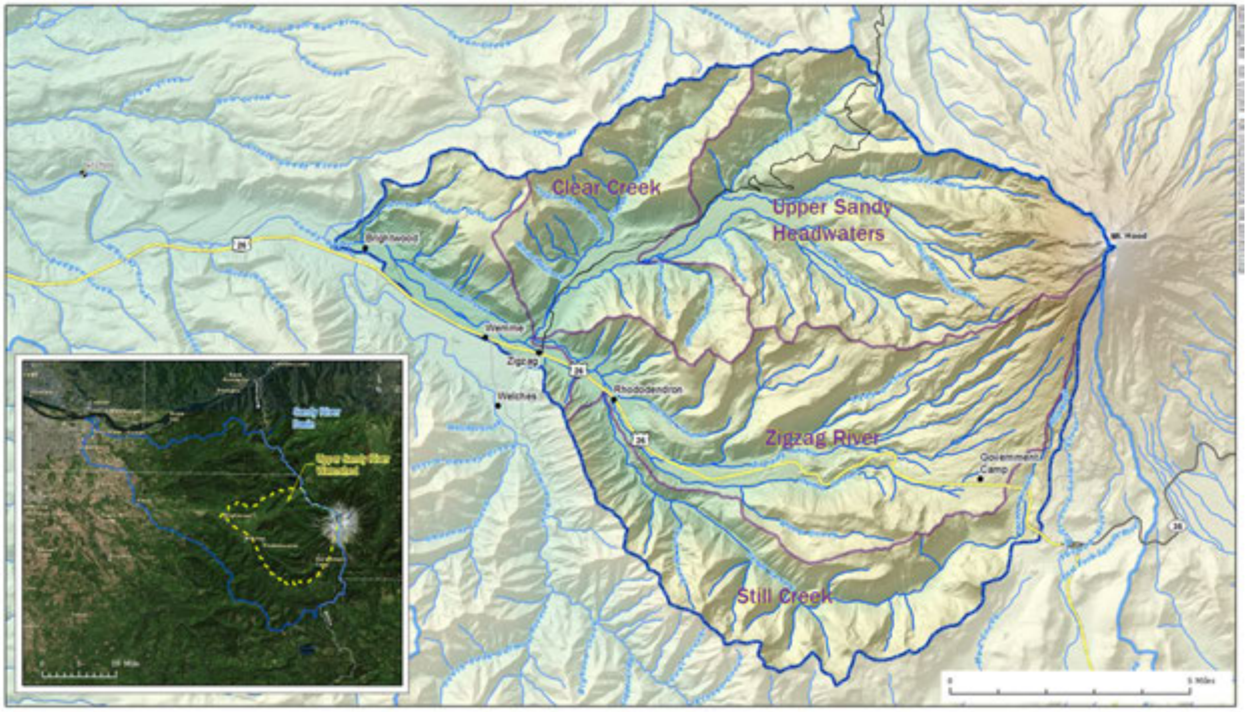

Figure 3. Upper Sandy Watershed with Tributary Basins. Data sources: USGS 10m DEM, USGS NHD, USGS Topographic Maps.

Major roadways situated within the valley include State Highway 26, East Barlow Trail Road (Clackamas County), East Lolo Pass Road (US Forest Service Road 18), East Brightwood Loop Road (County), Mount Hood National Forest Road 18, and East Autumn Lane (County). Two bridges cross the river, the East Brightwood Bridge at RM 38.5 and the East Lolo Pass Road bridge at RM 43.7. East Lolo Pass Road also has a bridge that crosses the Zigzag River at RM 0.1 just above the confluence with the Sandy at RM 43.7. All three of these bridges were destroyed in the 1964 flood.

The river valley bottom is approximately 2000 feet wide, covering over 2020 acres. Within the valley bottom are several hundred residential properties, most of which are privately owned. Development includes several neighborhoods, including the Timberline Rim community (RM 39.2-40.1), the Autumn Lane neighborhood (RM 43.7-44.7), and Zigzag Village (RM 45.1-45.2). Residences in and outside the planned communities are serviced by infrastructure consisting of access roads, residential streets, overhead electrical and other utilities, and the Clackamas County potable water and sewage pipeline crossing at RM 39.5.

1.2 PROJECT OBJECTIVES

The Upper Sandy River encapsulates the complex challenges of managing flood hazards and environmental resources in the montane Pacific Northwest. The 10 mile project reach is located only 15 miles downstream from the river's headwaters on Mount Hood, an active volcano peak 11,239 ft above sea level. The steep gradient, proximity to the large quantities of sediment eroding from the mountain's flanks, and heavy precipitation all make the Upper Sandy valley especially susceptible to flooding and erosion. The Upper Sandy also lies within the high risk zone of catastrophic mudflows associated with Mt Hood eruptive periods (e.g., Cameron and Pringle 1986; Scott et al. 1997; Pierson et al. 2011). Despite these hazards, the Sandy River valley provides the most practical transportation route up the west side of Mount Hood and into central Oregon. State Highway 26 is the principal route from the Portland area, Oregon's largest population center, to Mount Hood and central Oregon communities such as Bend.

Following the 1964 flood, the Upper Sandy was channelized and partly constrained with levees and bank revetments. These actions were followed by a period of extensive development within the valley bottom in the 1970s. This development along the river shoreline has greatly increased the exposure of property owners to flood and erosion hazards. Economic risk and expense increases to the extent that development encroaches into flood and erosion hazard areas. Costs are incurred not only for the construction and maintenance of protection measures, but also from property and infrastructure damages incurred during flood events (English et al. 2011). Development and associated flood protection measures also have severe environmental impacts on other species, particularly with regards to endangered salmonids. The economic and environmental impacts of maintaining development within the Upper Sandy channel migration zone (erosion hazard area) will only be compounded by the occurrence of larger, more frequent extreme floods, as predicted by current climate change models. These issues highlight the importance of finding comprehensive short-term and long-term solutions for managing flood-related erosion risks.

Clackamas County has committed to better understanding the hazards associated with Upper Sandy River flooding, and reducing exposure to these hazards. One of the primary goals in initiating this project is to provide residents and stakeholders with an understanding of flood and erosion hazards and viable flood protection alternatives that better comply with environmental regulations, such as compliance with the Endangered Species Act. This project was funded by a grant from the Federal Emergency Management Agency (FEMA) to assess flood erosion hazards in the upper Sandy River and develop an erosion protection strategy that includes environmentally sensitive, or “restorative” erosion protection measures. Pending additional funding from FEMA, a second phase will involve implementing a demonstration project following the criteria developed in this report.

The specific goals of this study include the following:

1. Assess historic and current river conditions and erosion trends, and identify possible mitigation projects within the project area.
2. Provide the basis of design criteria for methods of bank restoration that include alternatives to ‘traditional’ riprap structures (e.g., FEMA Region 10 circular Engineering with Nature)
3. Identify at least one demonstration mitigation project, described as a composite bank/channel restoration project, as a sustainable and cost-effective approach to improve public safety and overall river balance.

The following chapters of this report summarize the results of a geomorphological investigation, hydrologic and hydraulic modeling, and a strategy for restorative flood protection. Additional information regarding the methods used and details resulting from the analyses is included in appendices to this report. Detailed mapping of geology, historical channel locations, historical airphotos, hydraulic modeling output, and hazard areas is included as Mapbooks within the appendices.

2 HYDROLOGY AND FLOW REGIME

2.1 SEASONAL REGIME

The maritime climate of the western Cascades has seasonal patterns characterized by mild, wet winters and relatively cool, drier summers. Precipitation in the Sandy River Watershed varies from about 78 inches annually in the lower valleys to over 100 inches annually on the upper slopes of Mt. Hood. Fall and winter precipitation accounts for nearly 75% of the annual total (Figure 4a,b).

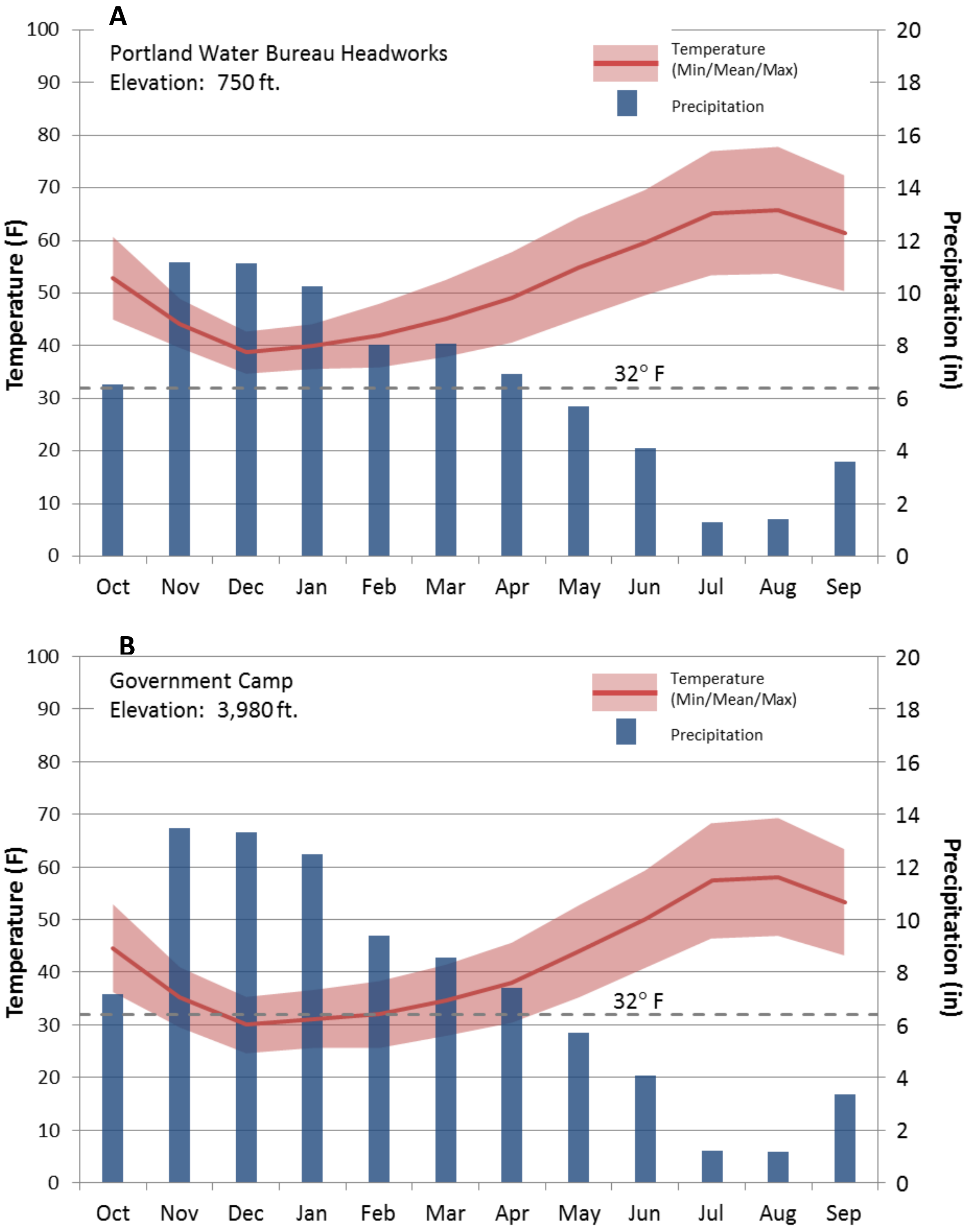

Figure 4A/B. Monthly average temperature and precipitation at the Portland Water Bureau's Headworks site (elev. 750 feet) and Government Camp (elev. 3.980 feet). Data source: NCDC climatic normals (1981-2010).

Winter precipitation generally falls as rain in lowland areas and transitions to snow at higher elevations (Figure 4b). The freezing level elevation fluctuates seasonally as well as episodically, with the passage of frontal weather systems. On average, mean winter temperatures for the months of December through February are around 40° F in the lower basin and drop with increasing elevation to 31° F at Government

Camp (elevation 3,980 feet) (Figure 4b). Higher up the slopes of Mt. Hood at elevation 5,370 feet, the NRCS SNOTEL site (Mt. Hood Test Station) has a mean winter temperature of 29° F. Average snow depth at Government Camp has a maximum value of 45 inches in March and generally melts out by June 1. At the Mt. Hood Test Station SNOTEL site, average snow depth has a maximum value of about 150 inches in April, and generally melts out by July 1, or about a month later than Government Camp.

Streamflow characteristics in the Sandy River display a seasonal regime that begin the water year with low flows in October, that rise in November and remain high through April and May. Stream flows then recede over summer, to an annual minimum in August and September. USGS maintains an active streamflow measurement station on the Sandy River near Marmot (#14137000) that has a period of record dating back to 1912. The gage site at Marmot is located approximately 8 miles downstream of the project area in a confined channel segment near the former site of Marmot Dam (removed in October 2007). Daily streamflow statistics, showing the probability of flows exceeding a given magnitude at Marmot are plotted over the course of a water year in Figure 5.

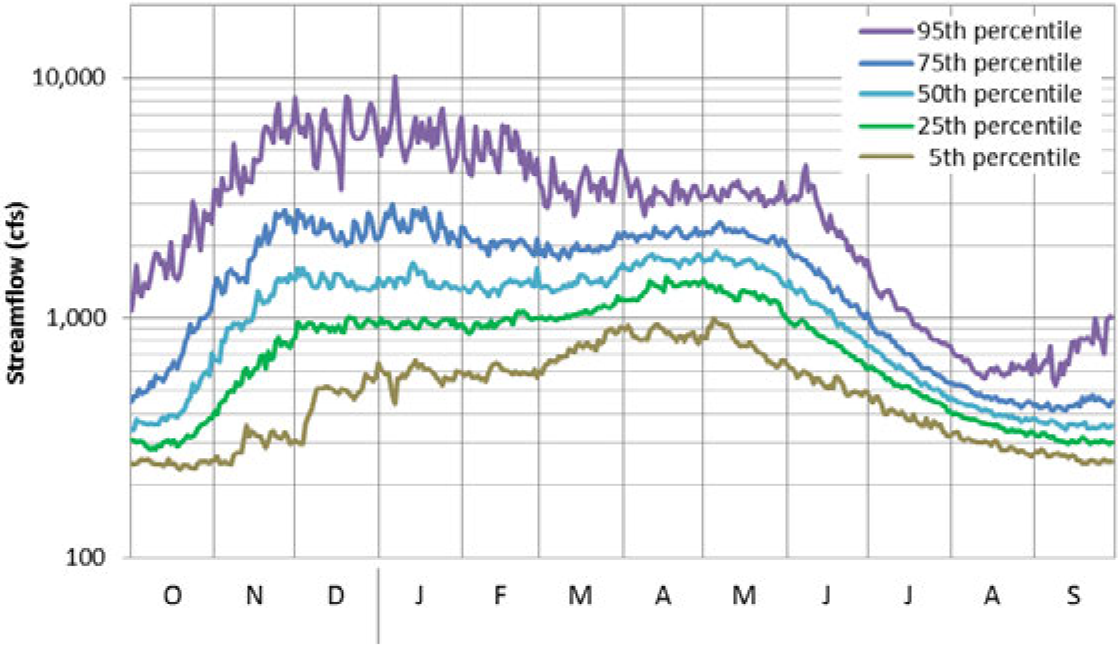

Figure 5. Daily streamflow statistics for the USGS gaging station at Marmot (#14137000); WY 1912-2013.

The period between November and February has the greatest variability, ranging between about 500 and 5,000 cfs, as winter flows are driven by episodic pulses due to storm events. Streamflow in April and May is dominated by snowmelt runoff, with flows that range between 800 and 3,000 cfs, and have median values that are slightly greater than median values in winter. Extreme streamflow values show that the rainfall-driven and rain-on-snow events in winter can be nearly 100% greater than the largest flows during April and May. Summer baseflows typically range between 300 and 500 cfs at Marmot, although late season storm events can increase flow to as much as 1,000 cfs in September.

The U.S. Geological Survey (USGS) has operated additional stream gaging stations in the watershed for shorter periods of time; however direct measurements of flow in the project reaches upstream of the Salmon River confluence is limited. USGS maintained a gaging station at Brightwood (#11373500) that operated during water years 1911-14 and 1927-31. A new gaging station was established in 2013 just upstream of Brightwood at Wemme (#14133450); the station at Wemme reports gage height only for the period 2013-2014. Clackamas County has recently installed flow monitoring locations on the Sandy River at Brightwood Bridge and the E. Lolo Pass Road Bridge and on the Zigzag River at E. Lolo Pass Bridge;

however these data have not been reviewed as part of this assessment. Figure 6 shows a representative hydrograph comparing streamflow at Marmot with streamflow near Brightwood and in a smaller sub-basin (31 mi2) represented by the Zigzag River at Rhododendron (#14131500).

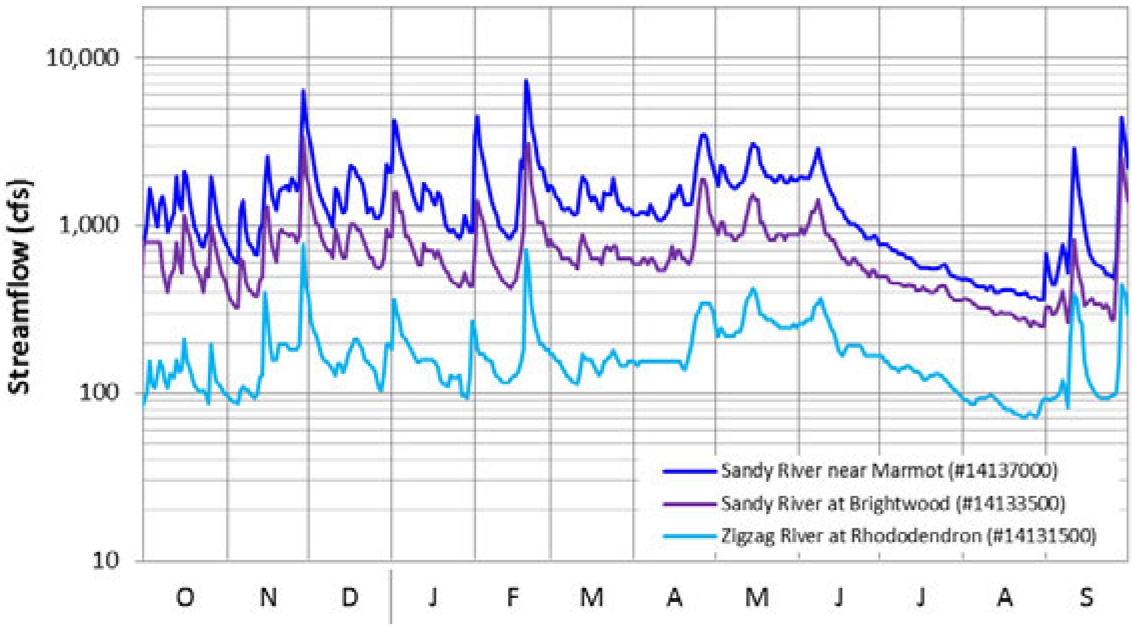

Figure 6. Comparison of three concurrent hydrographs in the Sandy River Watershed for WY 1927. The contributing drainage area is 31 mi^2 for the Zigzag River at Rhododendron (#14131500), increases to 117 mi^2 for the Sandy River above the Salmon River confluence at Brightwood (#14133500), and to 264 mi^2 above the Sandy River at Marmot (#14137000).

The three hydrographs show a similar response to precipitation in the watershed and verify that the long term record at Marmot is representative of streamflow characteristics in the project reach if reduced to account for the upstream decrease in drainage area.

2.2 FLOOD HISTORY

Peak flow data for the USGS gaging station near Marmot (# 14137000) were compiled to analyze the magnitude and frequency of flooding in Sandy River Watershed (Figure 7A, 7B).

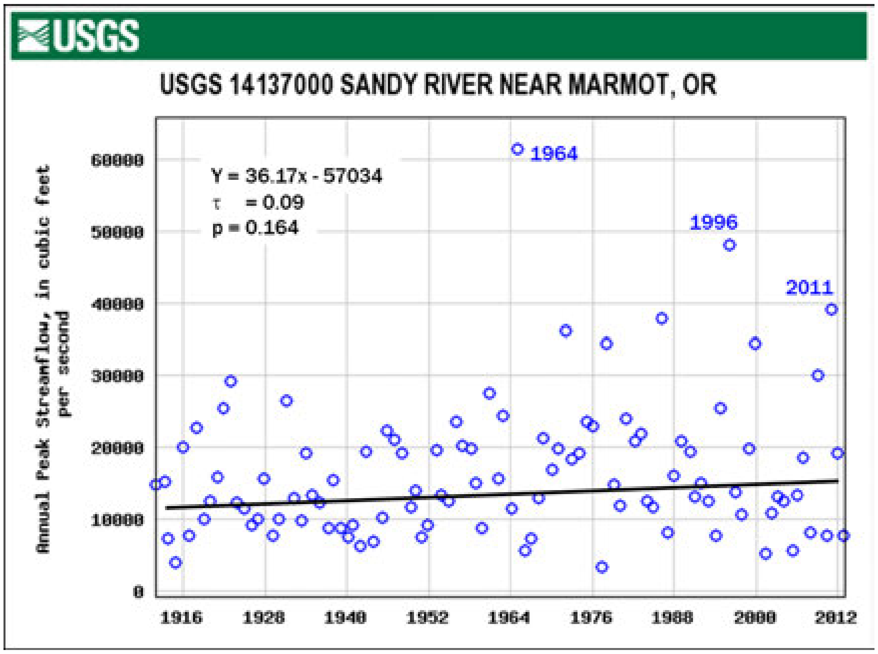

Figure 7A. Annual maximum time series for peak streamflow in the Sandy River at Marmot (WY 1912-2013). The trend line shows an increase in peak flow over the historical period; however the trend is not statistically significant at a 90% (p < 0.1) confidence level.

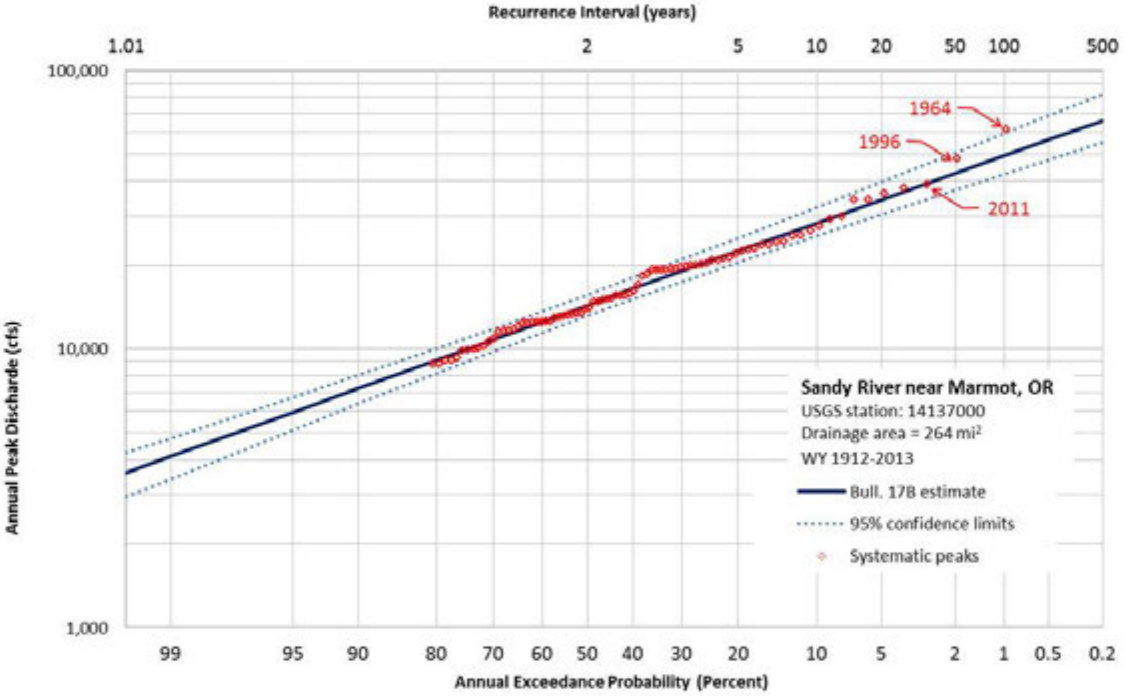

Figure 7B. Flood frequency plot for Sandy River. To determine a flood of a particular recurrence year interval, T, take the reciprocal of the annual exceedance probability (AEP). For example if AEP = 0.01 (1 %), then T = 1/.01 = 100, so an AEP of 1% corresponds to a 100 year flood (1964 flood). An AEP of 2 (1996 flood) corresponds to a 50 year flood. The 2011 flood was about a 30 year flood.

The largest floods recorded during the period of record are ranked below in Table 1.

Table 1. Summary of the top ten peak flow events recorded for the Sandy River at Marmot (# 14137000).

Rank	Date	Peak Flow (cfs)
1	December 22, 1964	61,400
2	February 07, 1996	48,100
3	January 16, 2011	39,000
4	February 23, 1986	37,800
5	January 20, 1972	36,200
6	December 02, 1977	34,500
7	November 25, 1999	34,400
8	January 02, 2009	30,000
9	January 06, 1923	29,200
10	November 24, 1960	27,500

Peak flow events in the Sandy River watershed predominantly occur between October and March with nearly 70% of the flood peaks in the annual maximum series occurring during the three month period from November to January. Nearly all of the large floods in the Sandy River watershed are associated with atmospheric river (AR) events, commonly known as a Pineapple Express in the Pacific Northwest. These storms are characterized by a narrow plume (~250-350 miles wide) of moisture-rich air that deliver large amounts of water vapor from the subtropical latitudes of the central Pacific Ocean to mid-latitude locations on the west coast of the United States, from California to Washington (Zhu and Newell, 1998). Neiman et al. (2011) investigated the connection between ARs and flooding in the Pacific Northwest and reported that all peak flows with a recurrence interval greater than 5 years are caused by AR events for the period studied (1980-2009). AR driven storm events not only deliver large amounts of precipitation, but are generally accompanied by warm air (7-10° F above normal) that increases freezing levels to over 6,000 feet and thus results in a much larger portion of the watershed receiving precipitation in the form of rain as opposed to snow.

Table 2. Flood frequency statistics calculated for the USGS gaging station for the Sandy River at Marmot (#14137000), WY 1912-2013 and estimated statistics for ungagged reaches in the project area upstream of the USGS gage.

Recurrence Interval (yrs)	Peak Flow (cfs)			
	USGS Gage At Marmot	above Salmon River	above Zigzag River	above Clear Creek
1.01	4,110	2,100	1,020	700
1.5	11,390	5,820	2,820	1,920
2	14,340	7,320	3,550	2,420
5	22,470	11,470	5,560	3,800
10	28,390	14,500	7,030	4,800
25	36,410	18,590	9,010	6,150
50	42,750	21,830	10,580	7,220
100	49,390	25,220	12,220	8,340

Flood frequency statistics were calculated from the annual maximum series by the procedure in USGS Bulletin 17B for a range of recurrence intervals between 1 and 100 years (Table 2, Figure 7B).

The Christmas Flood of December 1964 was the largest flood recorded in the historical period (~250 yr flood, Figure 7B) and caused widespread damage to property and infrastructure in the Sandy River Watershed. The event began with a blast of cold arctic air from British Columbia interacting with a maritime air mass moving in from the Pacific resulting in new snowfall over the watershed including 10 inches of snow in the valley at Brightwood and 18 inches of snow at Government Camp. Temperatures began to rise on December 19th and 20th and snow turned to rain. The weather station at Government Camp (elevation 3,980 feet) reported a daily high temperature of 48° F at on December 22nd. Following 9 inches of rain over two days, the formerly 55 inch deep snowpack at Government Camp, was reduced to only 6 inches in three days (from December 20th – 23rd). Observations of frozen ground suggest that infiltration would have been limited, and likely increased runoff. Snowmelt totaling 4 inches of water equivalent, enhanced the rainfall runoff to produce a total of 13 inches of runoff. Snow pillow measurements from an elevation of 5,500 feet showed that slopes at higher elevation with deeper snowpacks were more effective at absorbing the initial rainfall and yielded less than 5 inches of total runoff despite receiving over 9 inches of precipitation (Waananen et al., 1971). Streamflow in the Sandy River began to rise rapidly on December 21st and reached a peak discharge of 61,400 cfs on the afternoon of December 22nd. This magnitude has an estimated recurrence interval of greater than 200 years and is more than double the previous flood of record in 1923, 55 years prior to the Christmas Flood. During this flood, large quantities of sediment were mobilized and transported; however, no sediment data are available.

Similar conditions to the 1964 event prevailed in February 1996 to produce another large flood that again triggered widespread channel migration, erosion, and damage to property and infrastructure in the Sandy

River Watershed. The early part of the winter had been wet, but generally warm with little to no snow accumulation at Government Camp in mid-January. A series of colder storm events delivered large amounts of snow over the last two weeks of January, resulting in 15 inches of precipitation and a snowpack accumulation of over 90 inches at Government Camp. Several days of very cold temperatures, between January 30th and February 3rd, froze soils over most of the watershed. Then, on February 3rd, an atmospheric river transporting warm, moist air from the topics moved over western Oregon and delivered prolonged, heavy rainfall. Accompanying high temperatures of 46° F at Government Camp (elevation 3,990 feet) and 41° F at the Mt. Hood Test Site SNOTEL station (elevation 5,370 feet) were recorded on February 7th. During this AR event, the snowpack at Government Camp was reduced from 74 inches on the 3rd to 30 inches on the 8th. Measurements of snow water equivalent at Government Camp were not available. Data from the Mt. Hood Test Site SNOTEL station show that 8 inches of precipitation fell on February 6th and 7th, the snowpack compressed from 107 to 86 inches (net change of -21 inches), and snow water equivalent increased by 4 inches. The data shows that, similar to 1964, deep snowpacks in the upper basin absorb precipitation and moderate the amount of water available as runoff, whereas shallow snowpacks at lower elevations are not effective at absorbing precipitation and contribute to enhanced runoff due to rapid melting. Streamflow in the Sandy River increased sharply to a peak of 48,100 cfs, just under the estimated 100-year flood, around 11 PM on February 7th.

The most recent flood event to cause widespread damage on the Sandy River occurred in January 2011. The two day precipitation total at Government Camp was 6 inches on January 16. The maximum temperature reached 44 degrees F at both Government Camp and the Mt. Hood Test Site SNOTEL station despite the nearly 1,400 foot rise in elevation. The snowpack at Government Camp was 34 inches on January 12 and reduced to 19 inches following 2.5 inches of rain on January 13-14, then further reduced to 12 inches following heavy rainfall on the 16th. At the Mt. Hood Test Site SNOTEL station, 7 inches of precipitation fell in the two day period on January 15th and 16th, the snowpack compressed from 78 inches to 70 inches (net change of –8 inches) and the snow water equivalent remained nearly constant resulting in 7 inches of runoff (Figure 8a,b).

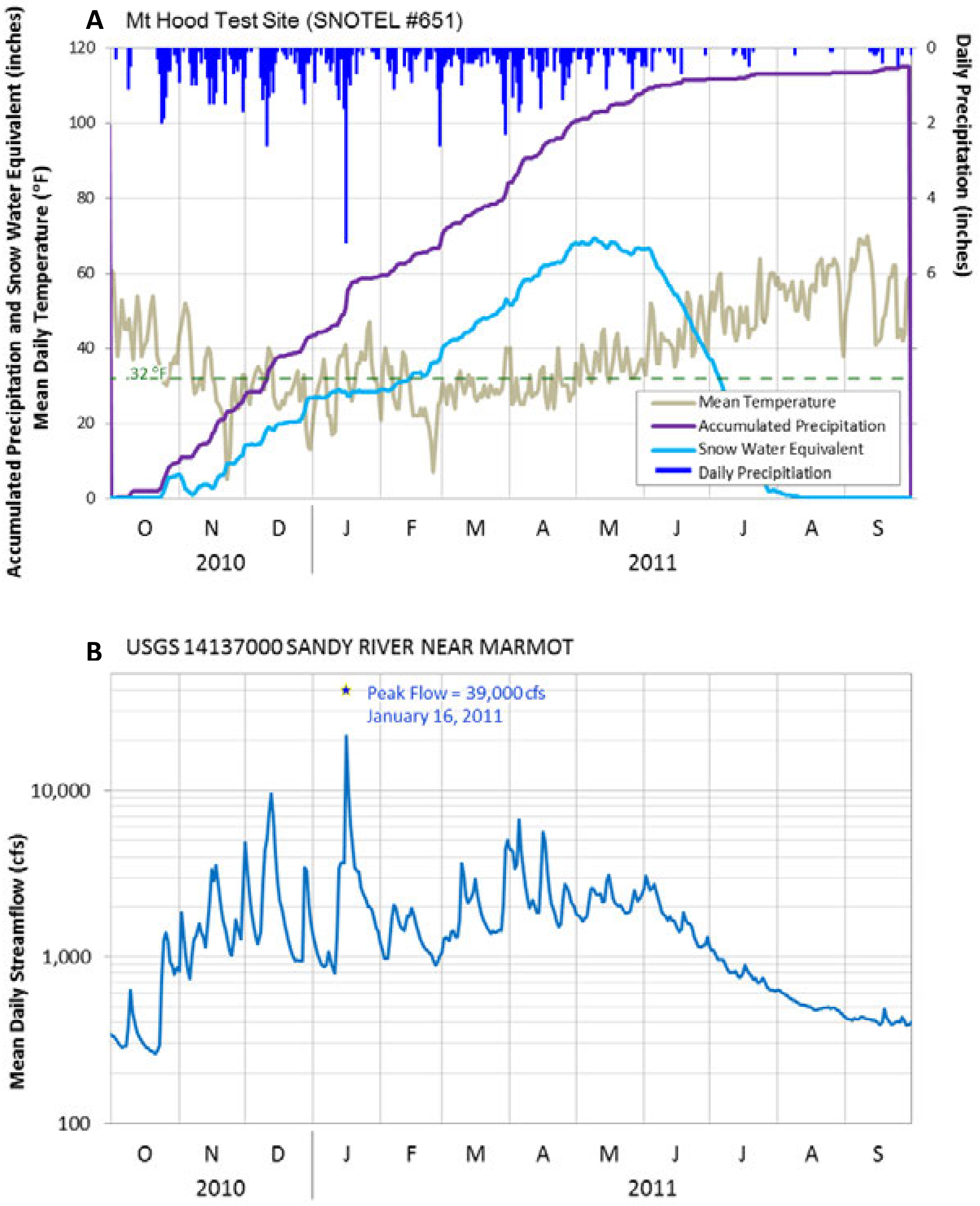

Figure 8A/B. Annual time series of temperature, precipitation, snow water equivalent and streamflow for WY 2011. Temperature and precipitation data from Mt. Hood Test Site (SNOTEL; elevation 5,370 ft). Streamflow data from USGS gaging station #14137000 on the Sandy River near Marmot.

Runoff volumes were again enhanced from the mid-elevation areas in the TSZ. Streamflow in the Sandy River began rising sharply late in the day on the 15th and peaked mid-afternoon on January 16th at 39,000 cfs, an estimated flood event magnitude between 25- and 50-year recurrence interval.

2.3 HYDRAULIC MODEL RUNS FOR 2- AND 100-YEAR STORM FLOWS

NSD utilized an existing HEC RAS (v. 4.1.0) hydraulic model to evaluate hydraulic parameters within the study area (STARR 2013). The HEC RAS model was developed using the U.S. Army Corps of Engineers (Hydraulic Engineering Center River Analysis System, HEC RAS). The HEC-RAS model covers a 14-mile long segment beginning near Alder Creek at RM 331 and extending upstream beyond the confluence with Lost Creek near RM 47 (Figure 2, Appendix Mapbook 1).

HEC-RAS solves a one-dimensional (1D) energy equation that averages hydraulic parameters over a cross-sectional area then solves for continuity between successive cross-sections along the study reach. The model for this project was composed of 226 total cross-sections with 185 cross-sections along the main stem channel and an additional 41 cross-sections incorporated along split flow reaches. Model geometry integrated topographic survey data collected in the active channel area with elevations from a LiDAR-based (Laser Illuminated Detection And Ranging) Digital Elevation Model (DEM) in the overbank areas. STARR (2013) simulated steady flow profiles for the 2- and 100--year recurrence interval peak flows with model inflows at Alder Creek, Salmon River, Zigzag River, Clear Creek, and the headwater tributaries above Clear Creek, using values based on a flood frequency analysis of the USGS gage near Marmot (#14137000) and application of a drainage area ratio to account for downstream changes in flow (Table 1). Model parameters representing roughness, expansion/contraction losses, and ineffective flow areas were unchanged from the original model as documented by STARR (2013).

Model output for the 2-year and 100-year storm flows, including velocity, flow depth and boundary shear stress, are presented in a series of 6 mapbooks 1-6, found in the Appendices of this report.

2.4 HISTORICAL CLIMATE TRENDS

Regionally averaged temperatures in the Pacific Northwest have warmed by about 1.3° F since 1895 (Kunkel et al., 2013). Temperature at the NWS station at the Portland Water Bureau's Headworks site has warmed slightly more than the regional average (1.8° F). Long term patterns of climatic variability in the western United States are closely associated with decadal scale changes in the Pacific Ocean as measured from the Pacific Decadal Oscillation (PDO). The historical record has oscillated between 20-30 year PDO regimes, characterized as "cool" or "warm" with key transitions, or shifts, in PDO occurring around 1925, 1945, and 1977 (Mantua and Hare, 2002; Mantua et al., 1997). The prevailing trend of recent years suggests that we are currently within a relatively "cool" PDO regime. Long term patterns observed within the historical record of precipitation closely mirrors historical fluctuations in PDO. Cool phases of the PDO are strongly correlated with cooler temperatures, greater precipitation, and increased flood risk in the Pacific Northwest. These correlations are strengthened during periods in which the PDO is in phase with the shorter term fluctuations in the El Niño/Southern Oscillation (ENSO) (Hamlet and Lettenmaier, 2007). Lee and Hamlet (2011) describe a twofold increase in precipitation anomalies during years in which the PDO and ENSO are in phase.

The amount of precipitation falling as snow and stored in headwater subbasins has changed in association with modest increases in temperature. Observed trends in snow water equivalent (SWE) show a general decline of 15-35% in the Cascades with some locations having lost over 40% SWE since 1950 (Hamlet et

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[1] RM references use the measurement system derived from USGS topographic maps.

al., 2005; Mote et al., 2008; Mote, 2003; Mote et al., 2005). Observed SWE trends in the North Cascades at elevations above 6,900 feet show an 11% decline for the period 1950-2006 (Mote et al., 2008). Accounting for natural variability driven by circulation over the North Pacific Ocean, Stoelinga et al. (2010) estimated a 16% loss of Cascade spring snowpack over the period 1930-2007 due to increases in temperature. Furthermore, Jackson and Fountain (2007) measured historical glacier fluctuations at Mt. Hood noting a terminus retreat of 1,600-2,300 feet and a 35-40% reduction of glacier area for the period 1904-2007.

Given that flooding in the Sandy River watershed is predominantly controlled by AR driven precipitation events, a key question regarding hydrologic impacts of climate change is centered on changes in extreme precipitation. Previous studies of regional precipitation trends have reported increases in extreme precipitation over the western Cascades. Madsen and Figdor (2007) analyzed one-day precipitation totals with a recurrence interval of 1 year or greater for a large dataset from the National Climatic Data Center (NCDC). They report a 30% increase in the frequency of extreme precipitation for Washington State. Mass et al. (2011) analyzed two-day precipitation events along the west coast, and found an increasing trend in extreme precipitation for the Oregon coast at Tillamook. Recent work indicates warming temperatures will increase the water vapor content and the precipitation from extreme AR events (99th percentile) by 16-38% by the end of century, and that these extreme events will increase in frequency by as much as 240% (Clifford Mass, University of Washington, personal communication).

Streamflow trends in the Sandy River display historical changes in response to the observed 20th century warming. Jefferson (2011) evaluated the sensitivity of 29 watersheds to recent warming in the Pacific Northwest, including the Sandy River at Marmot. This study noted a statistically significant increase in winter flows, with a concurrent decreasing trend in spring streamflow. NSD analyzed streamflow trends with the Mann-Kendall test; a non-parametric statistical measure of the strength of the relationship between two selected variables. Kendall's rank correlation coefficient (τ) is well suited to this application because it is not sensitive to the effect of skewness, or extreme values, which are typical of hydrological data (Helsel and Hirsch, 2002). Values of τ range between -1 and +1, where the negative or positive sign of τ indicates the direction of the observed trend. When no trend exists, the expected value of τ is zero. The observed trend for peak flow at Marmot has a τ value of 0.07 indicating a slight increasing trend; however the observed trend is not statistically significant at a 90% confidence level (Figure 7A).

Note that the length of the historical record used in estimating flood frequency has a substantial impact on the calculations of this increasing trend. For example, comparing the latter half of the historical record (1963-2013) to the first half of the record (1912-1962) shows a 70% increase in the magnitude of the 100-year flood.

2.5 IMPACTS OF CLIMATE CHANGE ON HYDROLOGIC PROCESSES

Geological records from multiple regions have shown a high sensitivity of flood frequency and magnitude in response to relatively modest changes in climate (Knox, 2000; Knox, 1993).The warming of global surface temperatures over recent decades, primarily due to burning of fossil fuels, has already triggered a wide array of impacts to the environment and our society that are projected to accelerate in the coming decades (Melillo et al., 2014). Mote and Salathé (2010) analyzed climate model simulations for two scenarios, A1B (moderate emissions increase) and B1 (low emissions) from the Intergovernmental Panel on Climate Change (IPCC) 2007 report (Randall et al., 2007) and projected an increase in mean annual temperature over the Pacific Northwest of 6.1° and 4.5° F, respectively, based on ensemble averages. The overall range of model predictions for these two scenarios was between 2.8° and 9.7° F and averaged 5.3° F over the next century.

The distribution of subbasin areas over which winter precipitation falls as rain, as opposed to snow, is an important control on the hydrologic regime in the Sandy River watershed. Subbasin areas at higher elevations that are cold enough for snowpack accumulation during winter, store precipitation seasonally until temperatures increase in spring and water is released as snowmelt runoff. These high elevation areas form a snowfall dominated zone (SDZ), with moderated runoff processes during winter and sustained baseflows during spring and early summer. Low elevation areas form a rainfall dominated zone (RDZ) in which runoff from winter precipitation is quickly routed through the drainage network, contributing to episodic flood pulses in the watershed. Between the rainfall dominated and snowfall dominated portions of the watershed is an intermediate, Transient Snow Zone (TSZ) in which snowpack persists for relatively short durations and can melt rapidly during rain-on-snow events. Snowmelt concurrent with heavy, prolonged rainfall is an important process, contributing to flooding in areas downstream of the TSZ (Harr, 1981). Along western slopes of the Oregon Cascades, the TSZ generally spans elevations ranging between 1,500 and 3,900 feet (Christner and Harr, 1982). In the Upper Sandy River Watershed the TSZ encompasses 63% of the total area. An additional 33% of the watershed is at higher elevations, in the snowfall dominated zone, and a relatively small portion (4%) lies within the rainfall dominated zone (Figures 9 and 10).

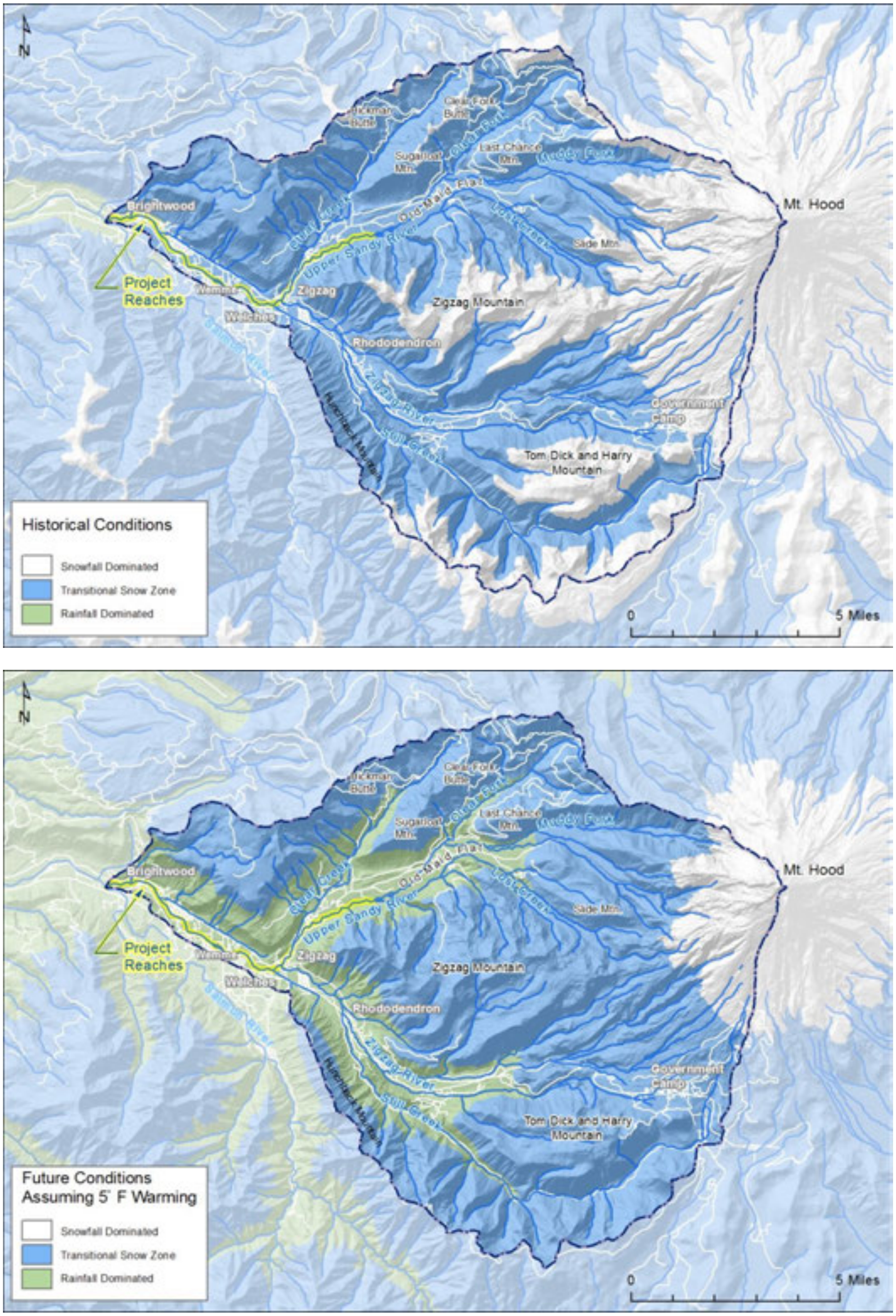

Figure 9. Map of hydrologic zones in the Upper Sandy River Watershed based on the dominant form of winter precipitation and the projected change in elevation thresholds by the end of the 21st century under the A1B emissions scenario.

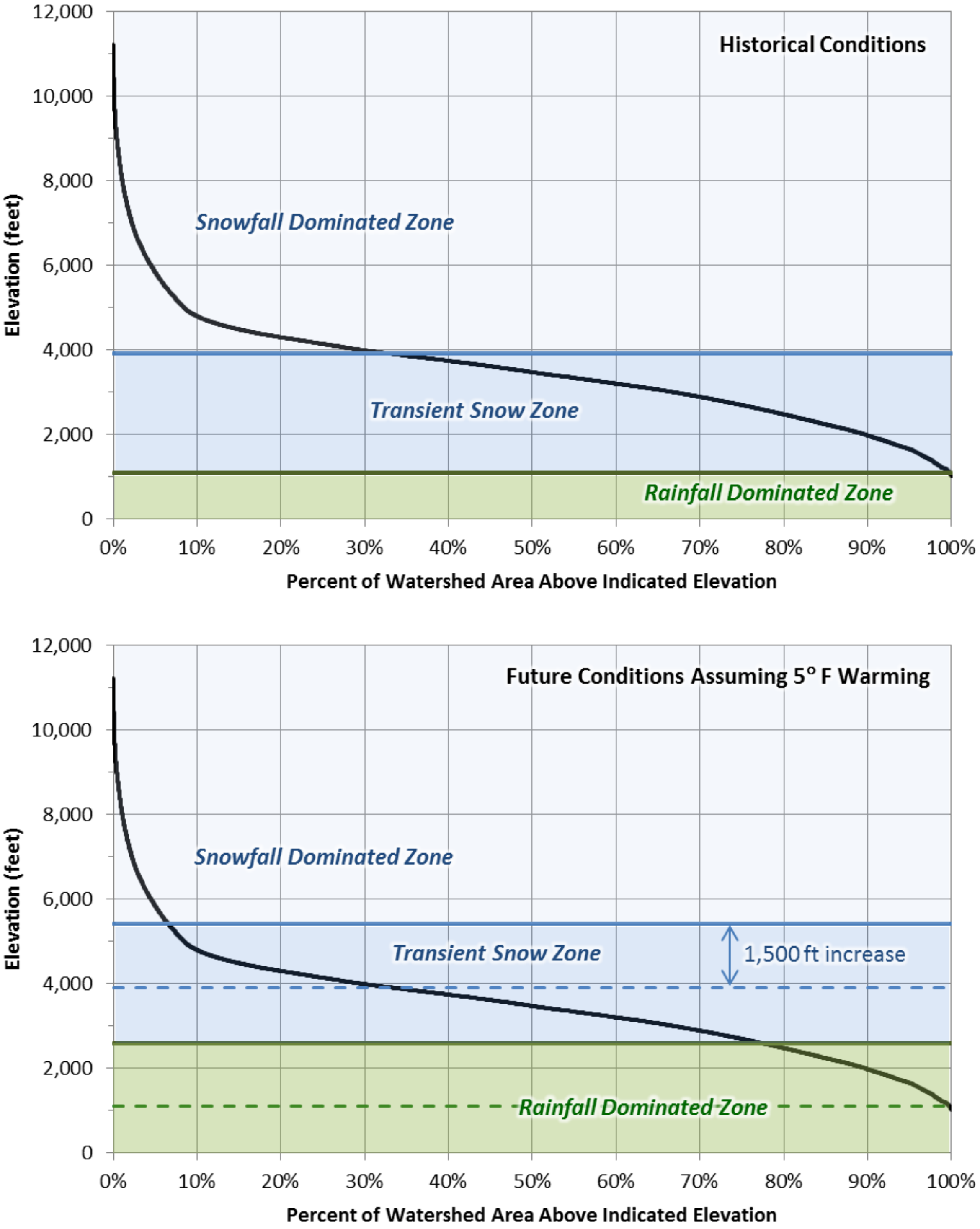

Figure 10. Hypsometric curve showing the range of elevations in the Upper Sandy River Watershed. Elevation thresholds delineate the relative land areas in hydrologic zones characterized by dominant winter precipitation and the projected increase in the contributing watershed area for rainfall, and rain-on-snow, generated floods under future conditions assuming a 5° F increase in temperature.

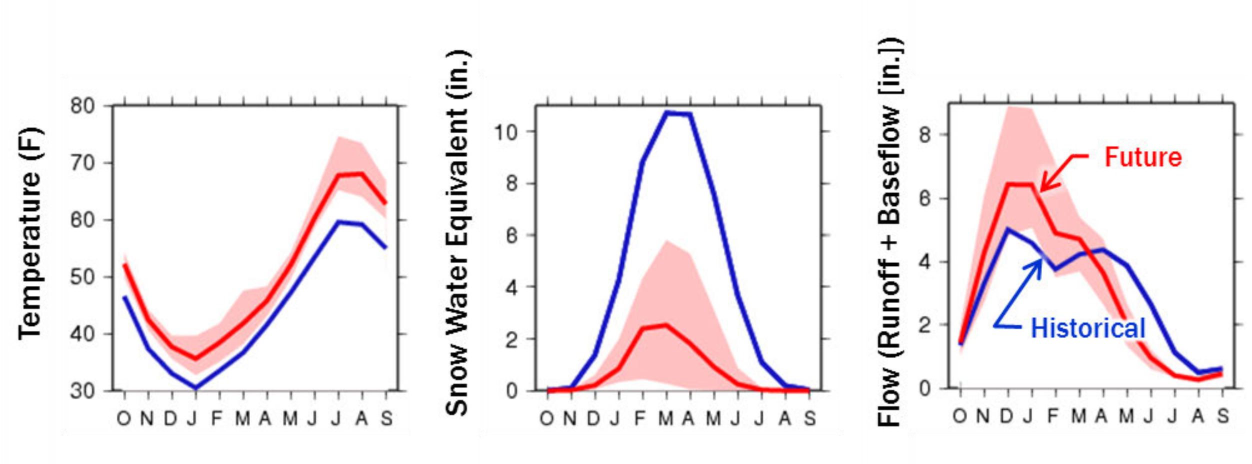

Figure 11. Simulated changes in temperature (left), snowpack (center), and runoff (right) for the Sandy River Watershed. The blue line shows the historical average and the red line shows the ensemble average from 10 climate models. The pink shading shows the range of estimated future conditions derived from the 10 climate models. Figures were downloaded from the Columbia Basin Climate Change Scenarios Project website at http://warm.atmos.washington.edu/2860/.

Watersheds having a large percentage of land area in the TSZ are especially sensitive to changes in climate. The transition between rainfall- and snowfall-dominated zones is predicted to move to higher elevations where a larger proportion of the watershed area would contribute runoff during winter storm events (Adam et al., 2009; Elsner et al., 2010; Hamlet et al., 2001; Hamlet and Lettenmaier, 2007). In these types of watersheds, there is also a corresponding decline in summer baseflows, as the relative amount of precipitation stored in snowpack declines with increasing temperature (Casola et al., 2009; Hamlet et al., 2005; Stoelinga et al., 2010).

NSD evaluated the anticipated change in relative land areas within rainfall-dominated, snowfall-dominated, and transient snow zones for the Sandy River watershed based on the average projected increase in temperature (+ 5.3° F) reported by Mote and Salathé (2010). The upward shift in the transient snow zone was estimated from a methodology described by Riedel (2011) in which the projected temperature increases are transformed to elevation values by applying an adiabatic lapse rate of 3.5° F/1,000 ft. This approach predicts an upward shift of 1,500 feet by the 2080s and results in a 27% increase in the rainfall–dominated and transient snow zones that collectively form the effective watershed area during winter storms (Table 3 and Figure 10).

Table 3. Estimated change in the distribution of hydrologic zones for the Upper Sandy River Watershed assuming 5° F increase in temperature for the period 2070-2099 (2080s).

	% watershed area		Relative Change
	Historical	2080s	
Snowfall Dominated	33%	7%	-27%
Transient Snow	66%	71%	4%
Rainfall Dominated	0%	23%	23%

These changes will have a significant effect on precipitation patterns over the watershed (Figure 9) and the seasonal timing of runoff from headwater regions. The headwaters presently characterized by deeper snowpacks in the snowfall-dominated zone, will transition to transient snow characteristics in future decades.

The University of Washington Climate Impacts Group (CIG) developed a comprehensive hydrologic database to support climate change planning and assessment in the Pacific Northwest. This database downscales output from global climate models and simulates future watershed conditions within a variable infiltration capacity (VIC) hydrologic model (Hamlet et al., 2013). Data and figures of model output for the Sandy River watershed were downloaded from the project website2 and evaluated to support assessment of flood and erosion impacts of the project reach.

Selected model outputs, highlighting changes in temperature, snowpack, and runoff for the A1B (moderate emissions scenario), are presented in Figure 11. Simulated changes in temperature and precipitation for the Sandy River watershed closely mirror the regional projections described above, with warming winter temperatures and slightly increasing winter precipitation. The corresponding reduction in SWE in April (peak snowpack) is 83% by the 2080s. Most striking in the model output from CIG, is the projected change in the seasonal distribution of runoff. Summer flows during the snowmelt period peak earlier and are much lower than the historical average, showing a 63% decline in June streamflow by 2080s. Conversely, winter streamflows are projected to increase over time as the effective basin area increases with rising freezing levels and increased winter precipitation, or a 40% increase in January streamflow by 2080s.

In combination with the effect of higher freezing level elevations, the projected increase in the frequency and intensity of atmospheric rivers is likely to amplify the trend toward increasing peak flows in future decades. The frequency of extreme events, like the 100 year flood, is predicted to increase by as much as 240% (Warner et al., 2014). The projected climatic changes for the Pacific Northwest in coming decades make transient snow (mixed rain and snow) watersheds such as the Sandy River among the most sensitive to increased flood frequency and magnitude (Hamlet and Lettenmaier, 2007). Assessment of extreme flood events in the CIG study simulated daily flood statistics at the 20, 50 and 100-year return intervals (Hamlet et al., 2013; Hamlet et al., 2010). The outputs generated for the Sandy River are presented below in Table 4. The 1-day, 100-year recurrence interval flow is projected to increase 19% by the 2080s.

Table 4. Projected increase in daily flood statistics for the Sandy River. Data source: Hamlet et al., 2010.

Recurrence Interval (yrs)	Historical (cfs)	2080s* (cfs)	Change
20	22,800	28,100	24%
50	27,100	32,800	21%
100	30,500	36,400	19%
*ensemble average for hybrid delta scenarios (2070-2099)			

Additionally, glacial recession induced by the warming may pose another hazard in the Upper Sandy River, due to increased sediment supply and debris flows. As permanent snow cover recedes on the flanks of Mt. Hood, unconsolidated sediment on steep slopes will be exposed directly to rainfall and surface erosion such as gully development. The retreat of glaciers within the headwaters of the Upper Sandy and Zigzag watersheds exposes areas with slope angles higher than the thresholds for debris flow initiation, the probability of these events occurring increases (Legg et al. 2014). Rain on snow events have been correlated

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[2] http://warm.atmos.washington.edu/2860

to headwater erosion in Western Oregon (Harr 1981). Therefore, increasing the frequency and magnitude of rain on snow events on Mount Hood will contribute to greater sediment supply. This pattern will increase the quantity of sediment delivered to the river, which could accelerate channel migration rates. For example, the Upper Sandy River above RM 48 (upstream of Muddy Fork Bridge) experienced a major flood event sometime between 2005 and 2010, probably in 2006. This event more than doubled the unvegetated channel width and left boulder deposits suggesting it may have been the result of a debris flow event (Figure 12).

Figure 12. Old Maid and Timberline Lahar Deposits. The cut bank is located on the left bank downstream of the Zigzag confluence at RM 42.3. This site is one of only a few where the river has exposed and is currently eroding the Timberline lahar deposit. As the Timberline erodes, the Old Maid lahar is undermined and fails.

3 GEOMORPHIC SETTING

3.1 CURRENT CONDITION

Drainage basin development and channel behavior evolve and develop under the influence of numerous basin and reach scale factors and processes. Basin topography, proximity to water, sediment sources, and the history and evolution of the basin all influence current channel form and behavior.

The Upper Sandy River project area extends about 10 miles upstream from the Salmon River confluence, from about RM 37.5 to RM 47.5, although for the purposes of this geomorphic characterization the river was qualitatively evaluated all the way upstream to its sediment source areas.

When viewed in plan form, the Upper Sandy River channel follows a southwest trend from its sediment source area down to the Zigzag River confluence. The lower half follows a northwest trend from the Zigzag confluence to the Salmon River confluence. The upper portion of the Sandy River has a steeper average gradient than the lower portion, as seen in the Valley Profile (Figure 13).

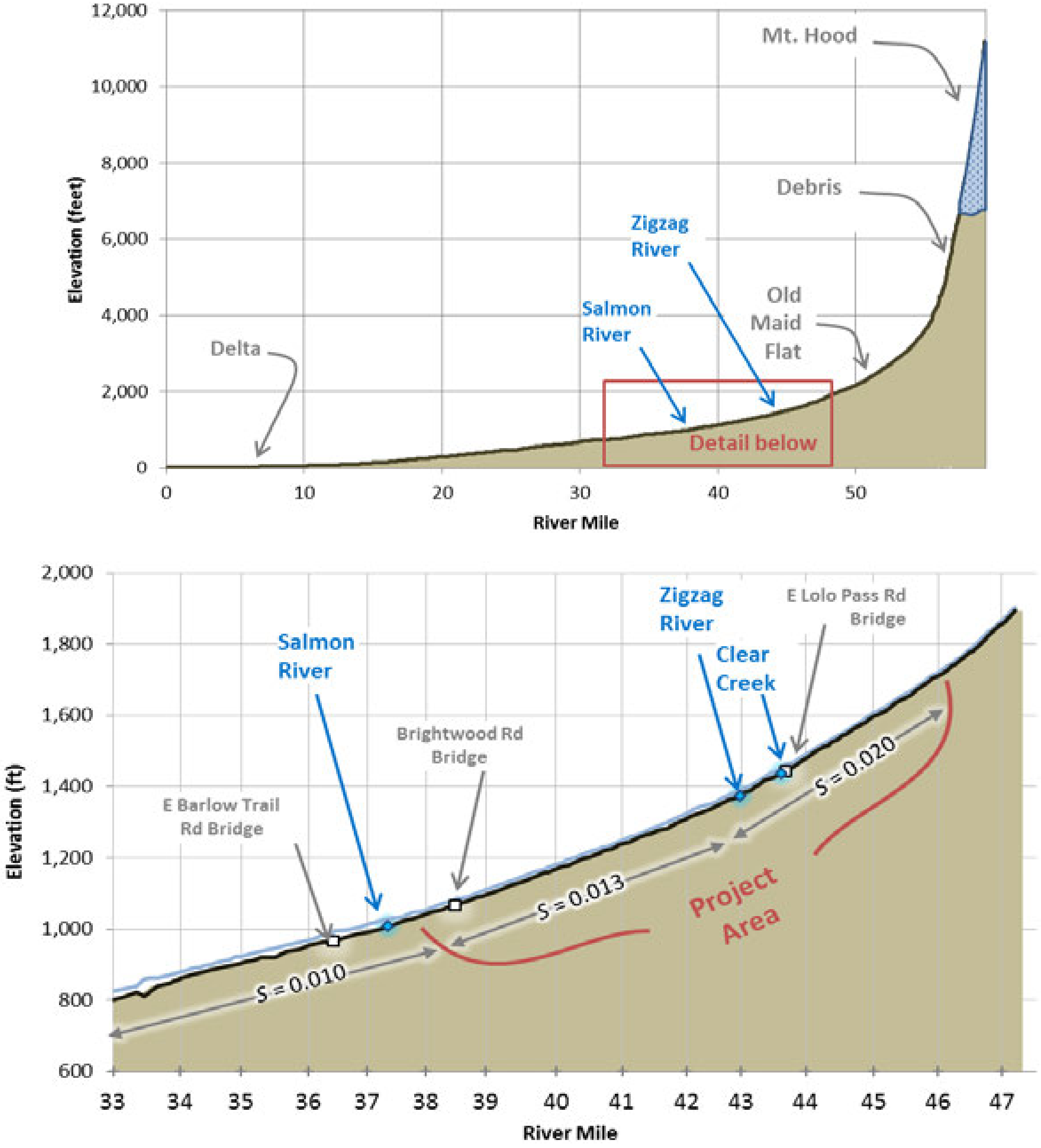


Figure 13. Valley Profile - The project area is situated roughly 10 miles from the Sandy River source area on Mt Hood. Average valley gradients through the project area range from 2 percent above the Zigzag River to 1 percent. at the Salmon River confluence.

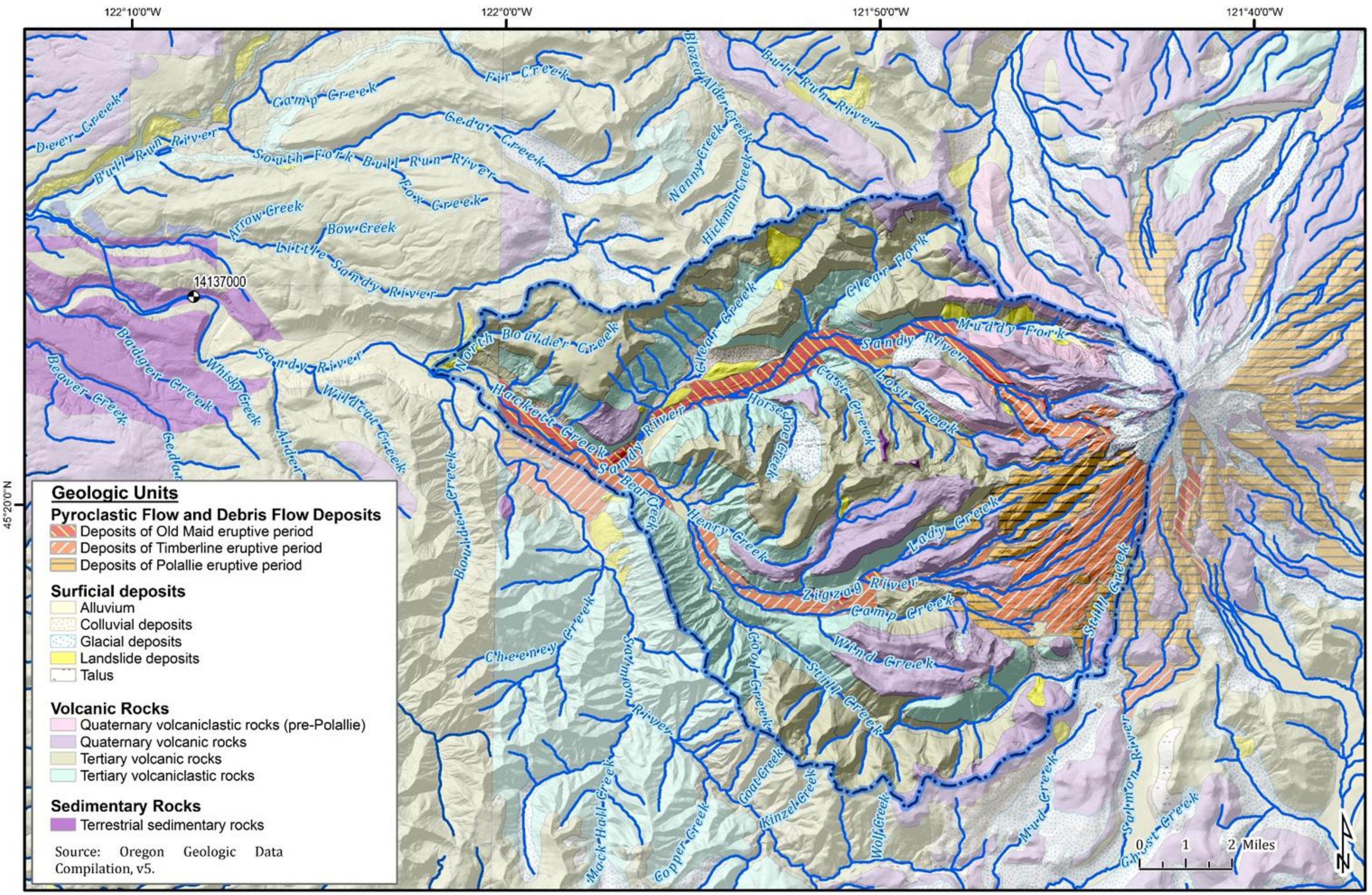
The upper valley floor is very broad and bounded at the edges by steep to moderately graded valley walls. Throughout the upper valley, the active Sandy River channel is a primarily braided system consisting of 2 or 3 shallow channels separated by unvegetated to vegetated gravel bars. The braided channel form extends from sediment source areas on the mountain to about RM 44.1, where it transitions to a single stem channel with meander bends that extend to and beyond the downstream end of the project reach at the Salmon River confluence. Topographic features described are most easily observed on the Relative Elevation Maps (see REM Mapbook 7), provided in the Appendix.

Throughout the northeast trending section, the valley floor is composed of an active river channel bounded by a low elevation terrace, which is in turn is bounded by a higher elevation terrace that extends to the valley walls (See REM Mapbook 7). The terraces are vegetated by evergreens and deciduous shrubs and bush.

The geomorphic landscape features defining the gross topography of the valley bottom are products of recent watershed- and reach-scale processes; however, they also reflect the history and evolution of the valley. In the case of the Upper Sandy River, its history has had great influence on present day channel behavior.

3.2 GEOLOGIC HISTORY AND VALLEY EVOLUTION

The Sandy River is underlain by a geologic sequence of Mt. Hood Volcanic rocks, lahar and mudflow deposits, and alluvial fan and streambed materials. The distribution of these materials is provided in Figure 14 (Sherrod, D.R. and W.E. Scott. 1995).



Source: Oregon Geologic Data Compilation, v5.

Figure 14. Geology Map. Base map data from: USGS Mt. Hood (1983) and Oregon City (1982) Quadrangles.

The Sandy River sediment source areas are located high on Mt. Hood, a volcano that has been active as recently as 200 years ago.

The Sandy River valley has been carved from Mt. Hood volcanic bedrock by alpine glaciers that have come and gone over the last 60,000 years. Mt. Hood volcanic rocks primarily consist of Andesitic lava flows roughly (65 to 2 million years old). These rocks are generally very hard and impermeable. Lava flows consist of molten rock that flows down the mountain until it cools to form hard volcanic rock. These rocks are exposed at the ground surface along the north and south valley walls, and possibly along the north bank of the Sandy River channel a short distance upstream of the Zigzag River confluence. Although most of the major mountain building lava flows ceased roughly 7,600 years ago, the mountain has been active, producing numerous small eruptions of lava, pyroclastic flows and lahars (Scott et al. 1997). Lahars are viscous mudflows composed of volcanic ash, cinders, and silt- to sand-sized rock fragments, mixed with water, that originate near volcanic vents. Compared to lahar deposits, volcanic rocks are very resistant to erosion. Many of the more recent lahar events in the last several thousand years flowed down existing river valleys, partially to completely filling the valley.

Lahars move extremely rapidly down the mountain, catastrophically impacting anything in their path. Sedimentary deposits left behind these events are composed of silt to large boulders, and are very permeable and sensitive to erosion. The most recent lahar flows occurred 1,700 and about 200 years ago. The 1,700-year-old event, called the Timberline Lahar, originated at Crater Rock on the upper southwest slope of Mt. Hood, and flowed down both the Zigzag and Sandy River valleys (Figures 14, 15, and 16) all the way to the Columbia River (Cameron and Pringle. 1986; Pierson et al. 2011). The most recent lahar event, the Old Maid Lahar, occurred only 200 years ago, and also originated from Crater Rock, but flowed down and inundated only the Sandy River valley. Due to its age, and thus it's longer period of compaction, the Timberline lahar deposit is somewhat more resistant to erosion than the Old Maid lahar deposit.

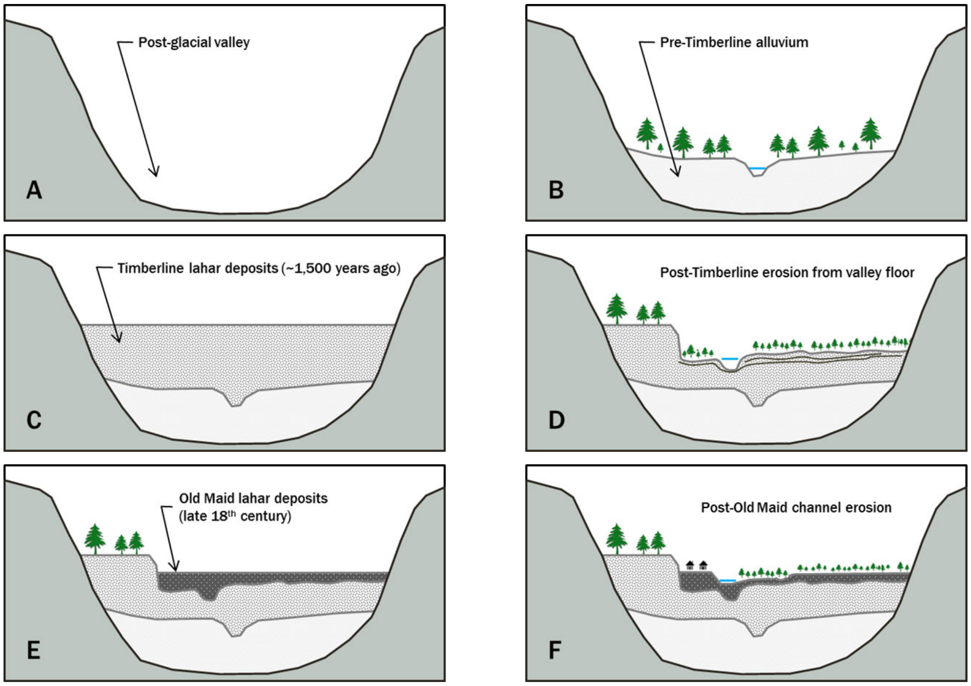
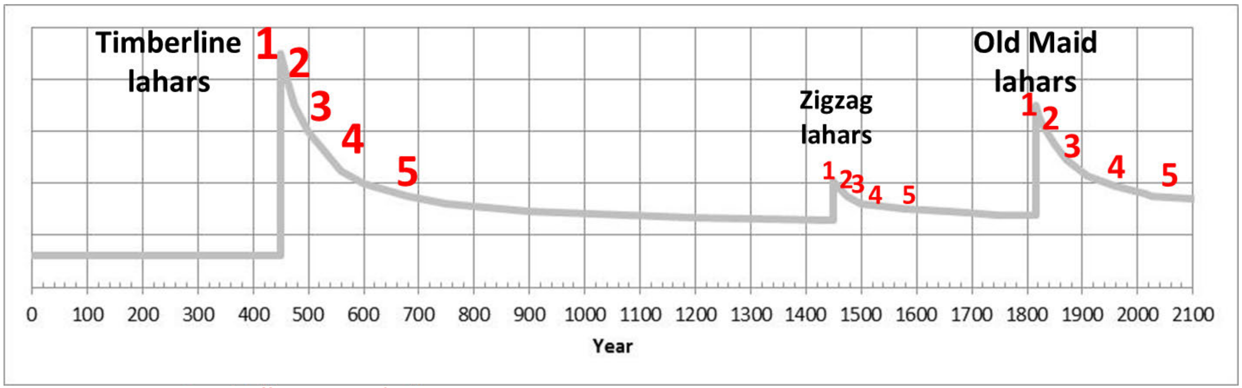


Figure 15. Watershed Scale Valley Responses to Lahars - The effects of Timberline and Old Maid lahars on the Upper Sandy River valley begin with sketch C, which depicts how the mudflow buried the valley floor to depths up to 100 feet. Over the course of next 1,500 years, the river channel cut downward and widened the floodplain, creating terraces composed of Timberline lahar (D). The Old Maid lahar buried the active channel and floodplain, but not the high Timberline terraces about 200 years ago, forcing the process of incision and channel/floodplain widening to start over again.

Years before Present	Eruptive Period	Deposition in Upper Sandy
180-270	Old Maid	~27 ft deep burying old cedar forests
400-600	Zigzag	only found in Upper Sandy above Lost Creek and in Zigzag valley
1400-1800	Timberline	terraces 27-36 ft above current river much larger event than subsequent events.



1 **Valley aggradation**
2 **Wide braided channel**
3 **Rapid channel incision**
4 **Channel widening**
5 **Slowing incision, valley widening with channel migration**

Figure 16. Sequence of elevation changes over time.

These two events have exerted profound influence on Sandy River valley evolution and channel behavior over the last 1,700 years. Following each lahar event, the river reformed at the surface of the lahar and began to cut downward through the sediment layer (Pierson et al. 2011) (Figure 15 and Figure 16). As it cut downward, the channel also eroded sidewalls composed of lahar deposits, creating space for the development of alluvial floodplains and more complex channel patterns.

Alluvium is loose sediment transported by moving water. In the Upper Sandy River, the alluvium comprising the stream bed is derived from volcanic rock fragments, lahar deposits, and reworked alluvium from upstream river reaches. Stream bed materials are more sorted than lahar deposits, with coarse sediments, representing bedload deposits, and fine grained sediments, representing overbank floodplain deposition.

As the Sandy River's alluvial landscape evolved post-lahar event, the channel continued to cut downward as it migrated back and forth laterally across the valley, further widening the floodplain by eroding the mostly fine sediment of the lahar deposit. Over time, this process resulted in a landform consisting of two broad, flat topped terraces separated from one another by the incising river channel. The river channel would have continued to cut downward until it reached the pre-Timberline elevation, which is a likely point of channel stability. However, when the Old Maid Lahar event occurred it partially filled the valley, leaving only the two Timberline terraces outstanding, forcing the river to reform at the top of the new deposit to begin the whole process over again (Figures 14, 15, and 16). This time the resulting landform consisted of two differently elevated terraces; the higher, 1,700 yr-old, Timberline terraces and the lower, 200 yr-old, terraces composed of Old Maid lahar deposits. These topographic features are most easily viewed on the REM Mapbook 7.

3.3 EVOLUTION OF THE UPPER SANDY RIVER CHANNEL

If no other major depositional events were to occur in the valley, the river would continue downcutting to a stable elevation (the pre-Timberline elevation), where further incision would cease. In the last 200 years, since the Old Maid Lahar event, several small lahars and numerous debris flows consisting of eroded volcanic and lahar sediments have coursed down the mountain slopes, and through the Zigzag and Sandy River valleys. With each event, the elevation of the river bed increases by some amount, changing local and sometimes reach-scale channel gradient, forcing the river to adjust. Clearly, the repetitive history of smaller lahars and debris flows coursing through the river valley has had an enormous effect on the evolution and development of the Upper Sandy River channel. Each lahar, and even the smaller debris flows, has reset the developmental processes of the river, constantly forcing the river into an unstable state that produces lots of erosion and sediment transport.

Channel form has evolved in response to changes in local/reach scale valley gradients and the amount of loose sediment the stream has to work through. Changes in channel dimensions and function generally follow the succession of evolutionary phases shown on Figure 17.

Figure 17 shows the various phases of channel response to a sedimentation event large enough to aggrade (raise the elevation) of the channel floor. These aggradation events could occur at a watershed scale such as the Old maid Lahar event or at a very local scale resulting from a debris flow. The sequence of channel responses to aggradation (phase 1) shown in the diagram begins with channel braiding (phase 2), which naturally occurs whenever the sediment supply exceeds the transport capacity within a given segment of the river. Channel braiding is followed by rapid channel incision (phase 3), which occurs as the channel attempts to cut down through the sediment to readjust to the downstream base level (pre-sedimentation elevation). Channel form during Phase 3 downcutting is typically a mostly straight to gently curved single stem channel. As the channel incises it widens (phase 4). Finally, as the channel gets close to the pre-sedimentation elevation it enters phase 5, where incision slows and the channel form evolves to migrating meander bends that eventually widen the valley bottom. Sandy River channel conditions observed in historic aerial photographs and during field reconnaissance indicate the upper portion of the channel is in phase 2 (braided) and the lower portion varies between Phases 3 and 4, depending on the volume of sediment entering this river section with large storm events. To summarize, a general model of channel evolution is presented as a series of stages starting with the pre-disturbance condition, followed by channelization and incision, then further incision and widening, then aggradation and widening, and finally a stage of "quasi-equilibrium" (Figure 17) (Schumm 1999; Simon and Hupp 1987; Simon and Rinaldi 2006).

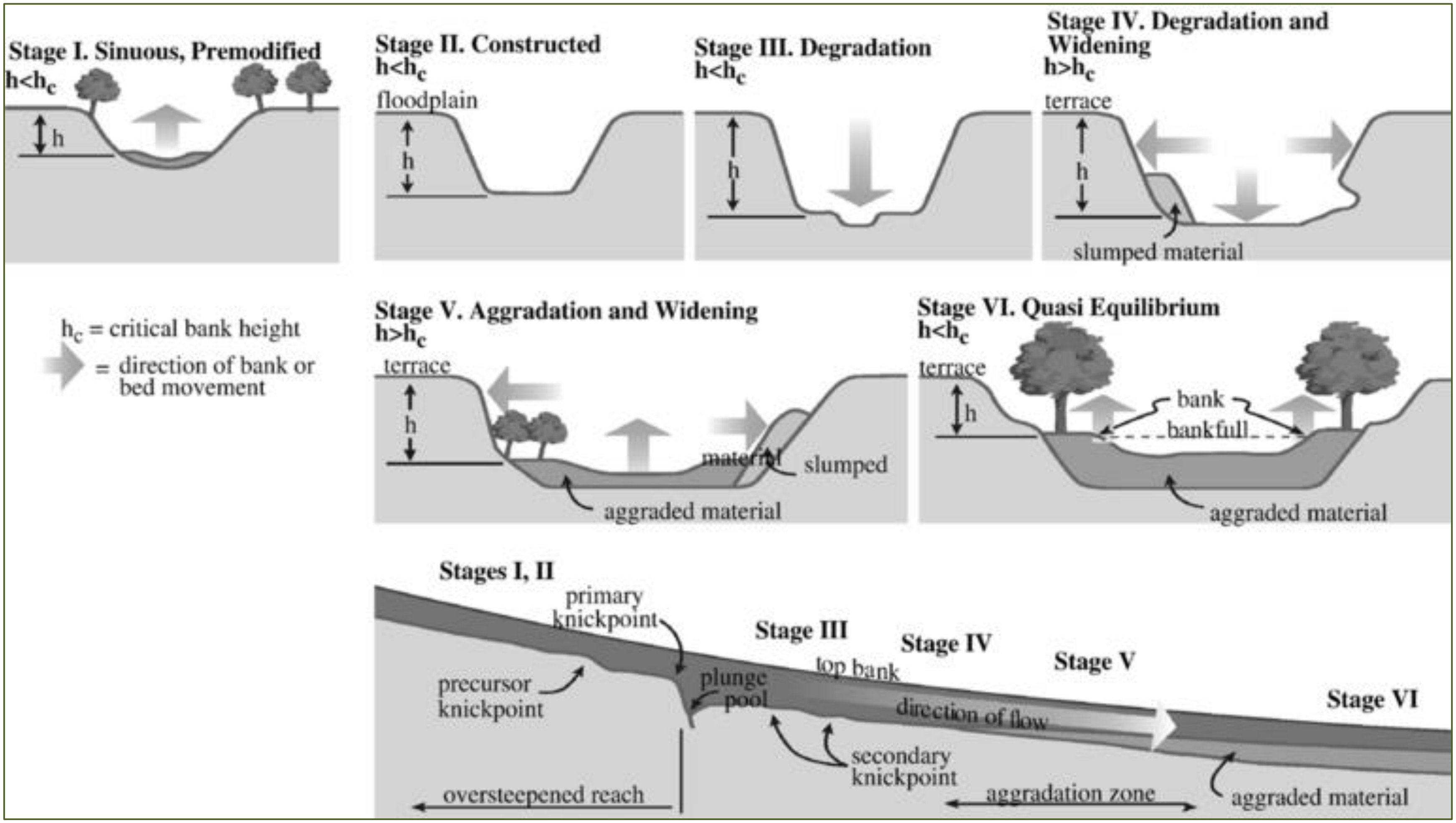


Figure 17. General sequence of stages associated with channel incision (from Simon and Rinaldi 2006).

The watershed scale river valley evolution can be seen in a review of historic maps and available historic aerial photographs. The earliest GLO survey maps from 1873 and 1882 (Figure 18) show a generally straight to gently curving single stem channel with no islands.

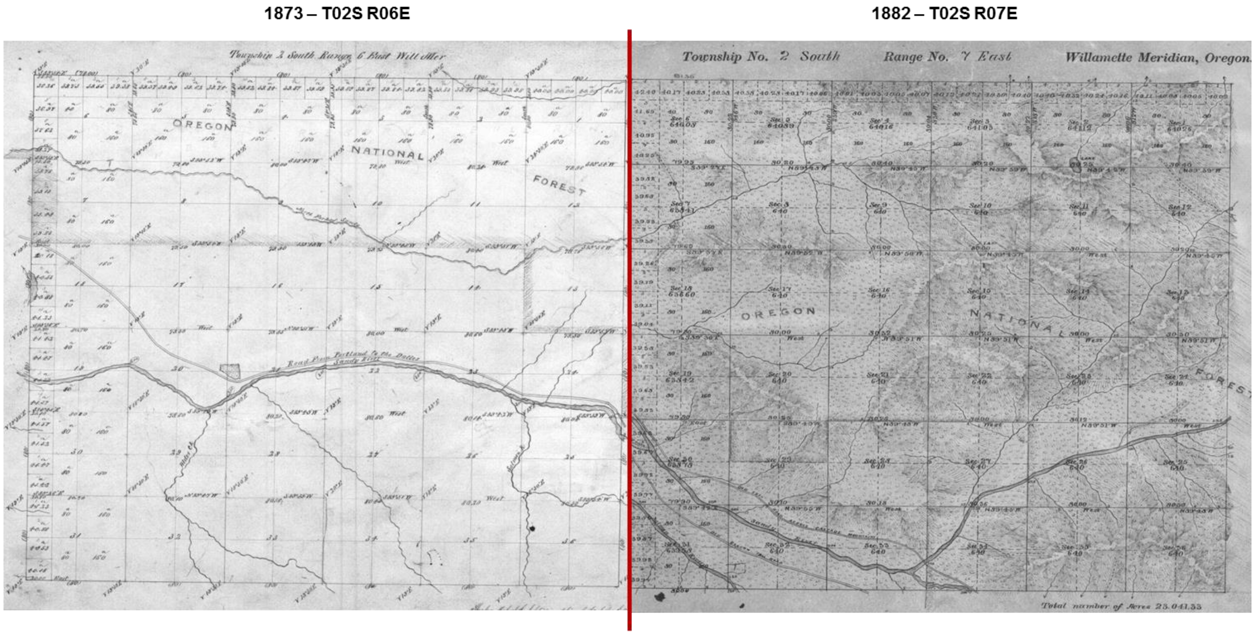


Figure 18. General Land Office Survey Maps for1873 (left) and 1882 (right).

From the late 1800s to 1914 and 1952 (1914 and 1952 Appendix Mapbooks 8 and 9), the channel pattern downstream of the Zigzag confluence remain much the same; generally straight single stem channel segments with occasional bends and several islands that appear to split flow within the lower half of the project area. The historic record, which began roughly 100 years after the occurrence of the Old Maid Lahar, suggests the lower portion of the channel (downstream of Zigzag confluence) was in a state of incision through the lahar deposit. During this same period, the channel upstream of the Zigzag confluence was subject to the most notable changes in channel form, where bend amplitudes just upstream of the Zigzag confluence increased considerably. The changes in channel form recorded in the Old Maid Flats portion of the river are the result of numerous, periodic episodes of smaller scale geological processes capable of bringing large volumes of sediment in from upstream sources. These processes include landslides, debris flows, and debris torrents, all of which are composed of reworked sediments derived from stockpiled lahar deposits on valley walls high in the watershed. Sediments produced from these processes are typically transported downstream by high stage flows and deposited on the Old Maid Flat area as bars and alluvial plains. From there, sediment can be mobilized and transported further downstream by storm flows with sufficient transport capacity, which of course can vary widely depending on the magnitude of the storm event.

The channel pattern throughout the entire project area changed dramatically from its 1952 form during a major storm in 1964. The event was the largest on record, estimated to have been equivalent to a 250 year storm event, with a peak flow of 63,000 cfs. During this storm, the active channel widened almost everywhere by a factor of 2 or 3, eroding river side terraces and alluvial banks and increasing the channel corridor width from a minimum of 150 to 200 feet up to 1,000 or 1,200 feet. Everything within the expanded channel corridor was destroyed. In response to these landscape scale changes, the channel pattern also changed: the previously single stem channel form became a multi-channeled braided system, the amplitudes of pre-storm bends increased and new bends developed, the sinuosity of the entire channel increased, and completely new channels cut through forested areas abandoning the previously occupied channel (a process called avulsion). Pre- and post-1964 event changes are shown in the Mapbook 10 entitled 1961 – 1965 imagery – pre and post 1964 flood imagery.

The February 1965 imagery provides enough visual detail to suggest that, following the 1964 storm event, channel forming processes transitioned from channel down cutting (incision) and minor widening, to channel braiding and/or migration of newly formed bends. The formation of braided and migrating meander bend channel forms both require specific conditions including an abundance of sediment and highly erodible river banks.

Following the 1964 flood event, channel pattern and form were further altered by the Army Corps of Engineers when they mechanically cut a preferred alignment for the post-1964 channel and then constructed levees and revetments to constrain portions of the channel. Treatments conducted by the Corps involved dredging out the 1952/1961 channel pattern and regrading both left and right bank alluvial plains to smooth surfaces (Figure 19, courtesy of Raymond Arrigotti).

Figure 19. Army Corps of Engineers Bull Dozers Re-Grading the 1964 Channel. Following the 1964 flood the ACOE mechanically graded over the active channel to recover the pre-'64 single stem channel. The re-grading straightened and shortened the 1964 channel, increasing the channel gradient in the process. Note the large proportion of fine grained materials comprising the flood deposits. Photos courtesy of Raymond Arigotti.

This action cut off bends formed in 1964, which straightened and lengthened the dominant channel, and substantially reduced channel sinuosity. The changes in channel form resulting from Corp treatments can be seen in the Mapbook 11 entitled February 1965 – August 1965 Imagery. Channel realignments having the greatest impact on future channel function and performance include channel lengths extending from RM 39 to RM 39.5 (see at the top of page 2 of Mapbook 11) where a new levee cut off a channel formed in 1964, and from RM 39.5 to RM 40.3, where a another new levee cut off an avulsion channel. At both of the leveed sites the river was moved back into the 1961 channel. Other sites where substantial actions were taken include RM 40.0/40.1, at RM 41.6 and RM 42.4 where the river was pushed back to the pre-1964 channel, and the right side of the river was regraded. In the area of the Zigzag confluence, and from RM 43 to RM 43.3, the river channel was also re-graded. Rather than straightening the channel by cutting off the bends, the bend amplitudes were shortened by 100 to 200 feet. In addition to altering the channel pattern and locally constricting it, all woody debris was removed from the active channel from the Salmon to the Zigzag confluences.

From 1970 to 1994 (1970 and 1994 Appendix Mapbooks 12 and 13) most of the graded areas reclaimed by the Corps had become vegetated and the channel may have incised a bit. Most of the changes observable from the aerial photographs include minor bank erosion due to channel migration, reoccupation of the 1964 channel at RM 38.0, and a channel avulsion at RM 44.25 where the channel moved away from Lolo Pass Rd. Note that the 1994 Appendix Mapbook 13 displays an increase in the number of residential houses and other structures, many of which are located within or immediately adjacent to the 1964 active channel area regraded by the Corps.

From 1994 to 2008 both channel width and bend migration increased substantially in areas most severely graded by the Corps (see 1994, 2005, 2008 Appendix Mapbooks 13, 14 and 15). Most of the observed changes reflect the response of the channel to the 1996 storm, which was estimated to be slightly less than the 100-year storm event (storm event with 1% probability of occurring in any given year). Review of aerial photos dated 2000, available on the Google Earth website show that the channel widened by a factor of 1.5 to 2 throughout the project area. In the vicinity from RM 39.8 to RM 40 the bend migrated northeast, out of the Corp alignment and into the left river bank now occupied by the Timberline Rim community. All bends from RM 40.3 to RM 41.4 and from 42.2 to RM 43 have also migrated out of the Corps alignment, creating a more braided form with increased bend amplitudes and sinuosity. Upstream of the Zigzag confluence, the bends re-graded by the Corps increased in amplitude and migrated southeast back into the 1964 channel.

The channel continued to evolve from 2008 to 2012 (2012 Appendix Mapbook 16) with the most significant areas of change occurring in response to the 2011 storm event. This storm caused substantial erosional damage along channel banks and, in some areas, threatened the total loss of several residential structures. It is worth noting that the evolution of the channel followed in suit with the changes observed after the 1964 and 1996 storms, based on 1970 and 2005 aerial photographs, respectively. The channel sections subject to the greatest changes in active channel width are the areas most affected by the Corps actions following the 1964 event (see channel traces in Figures 20a/b and 21a/b).

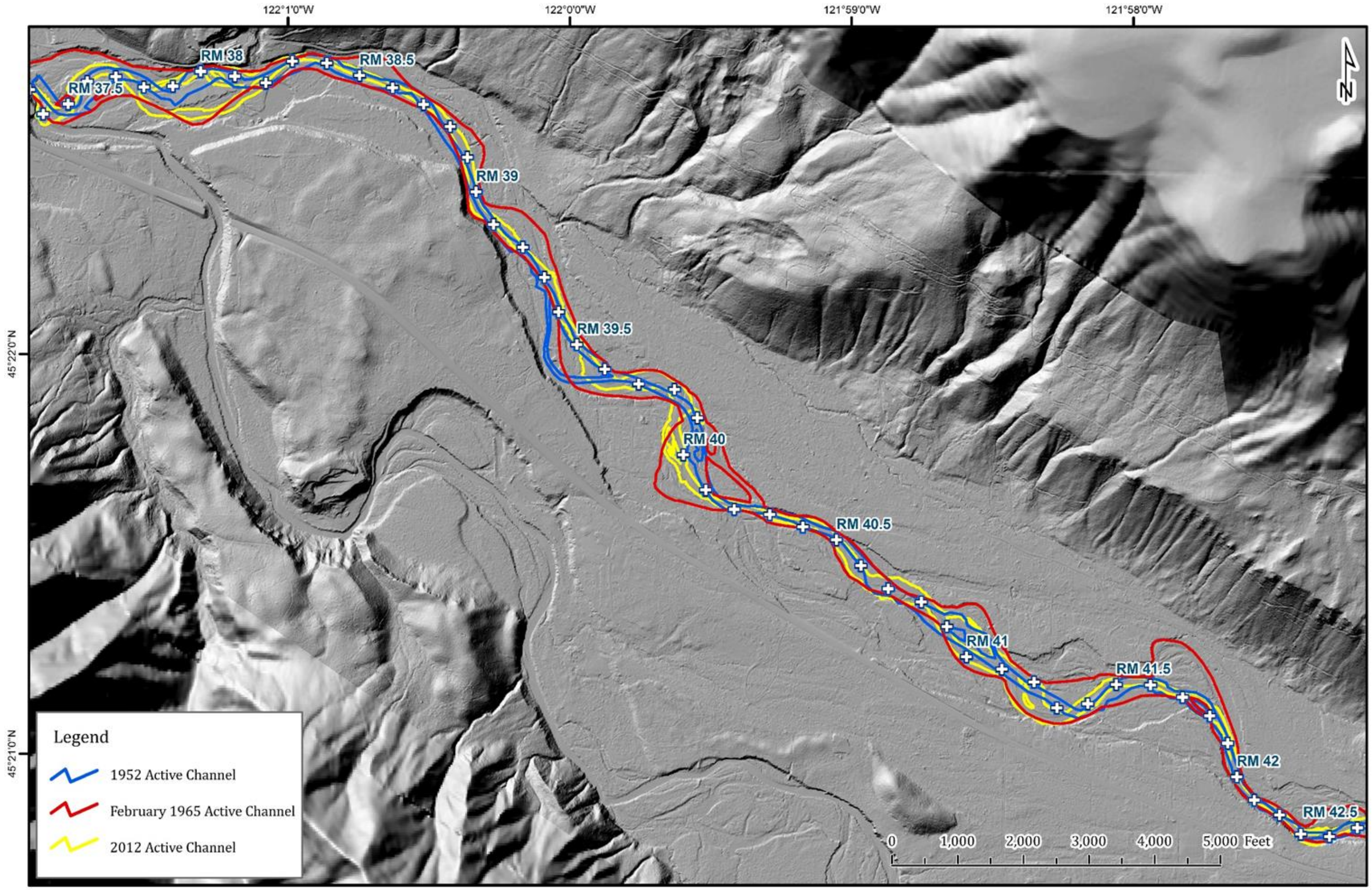


Figure 20A. 1952, February 1965, and 2012 Channel Traces. Channel traces digitized from aerial photographs show how the channel width expanded in response to the 1964 storm. The 1952 channel is representative of the pre-1964 channel. Note that the 1964 channel width increased 2 to 3 times the 1952 width. The 2012 channel reflects channel responses to ACOE channel re-grading since 1965. Data sources: USGS 10m DEM, DOGAMI LiDAR (2013), NSD 2014.

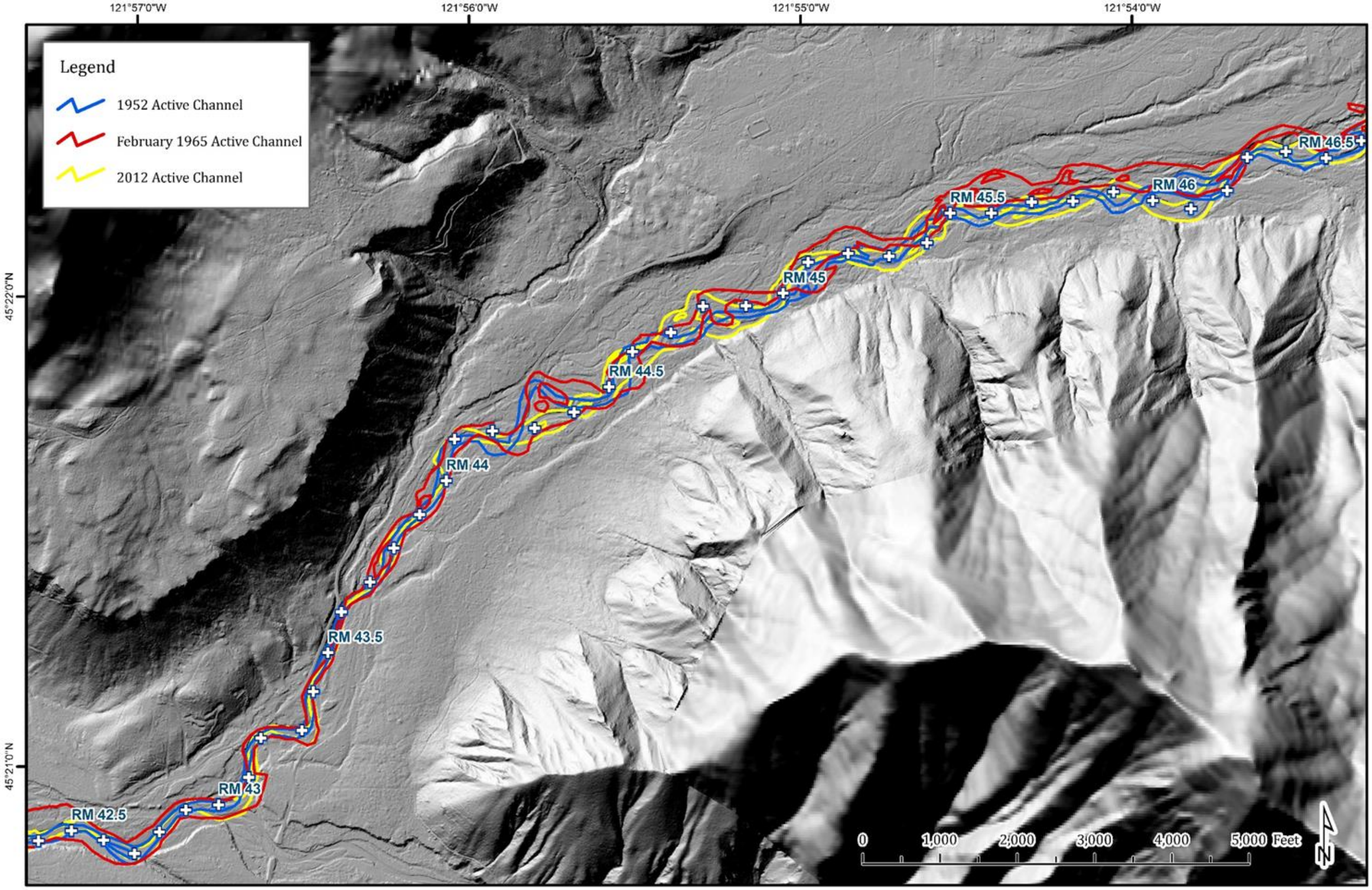


Figure 20B. 1952, February 1965, and 2012 Channel Traces. The digitized channel traces display channel responses to the 1964 storm event, and to sediment deposition generated by large storms and debris flows since 1964. Note the avulsion between RM 44.3 and RM 44.4. Data sources: USGS 10m DEM, DOGAMI LiDAR (2013), NSD 2014.

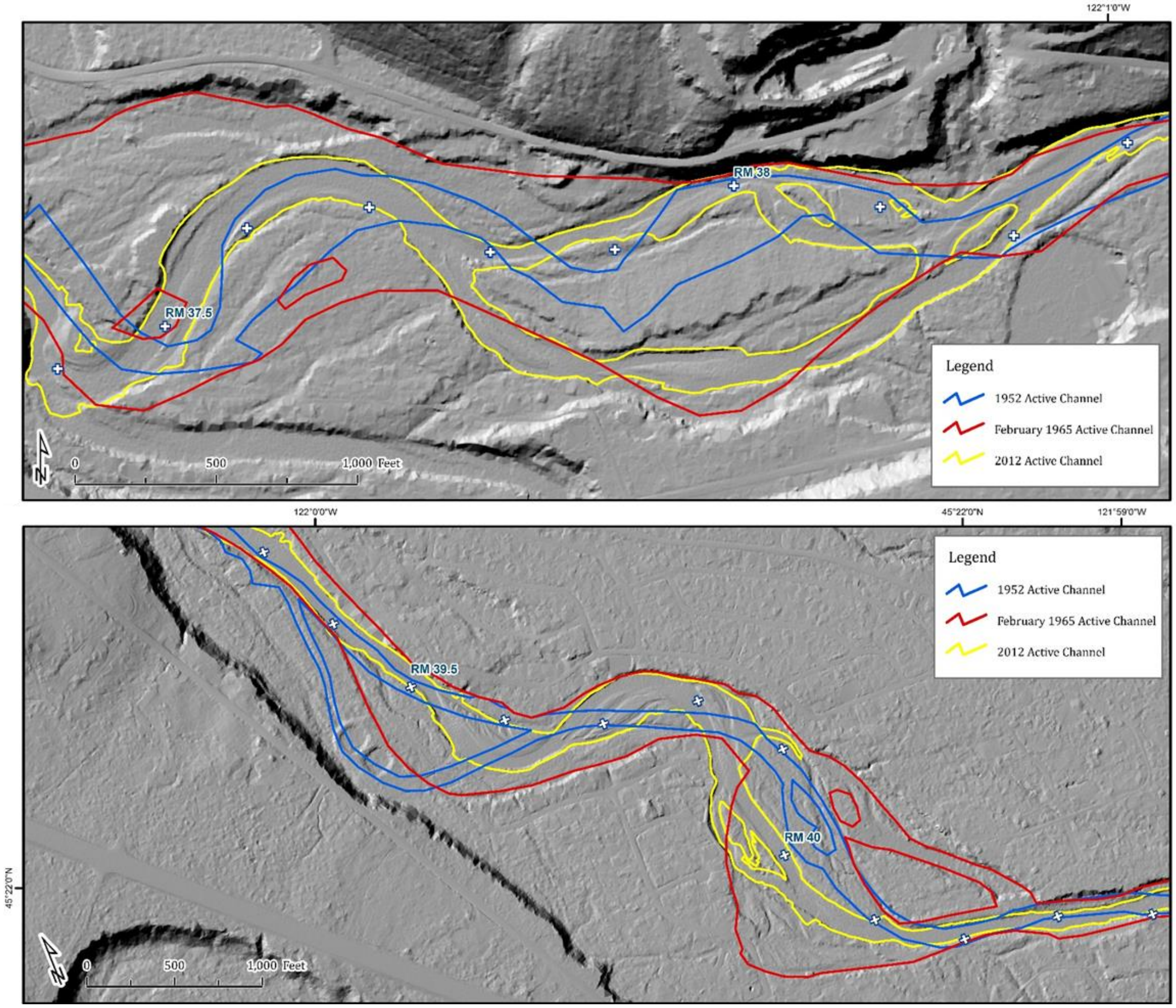


Figure 21A. 1952, February 1965 and 2012 Channel Traces. Digitized channels show how the pre-1964 channel widened in response to the 1964 storm event. At each location the ACOE re-graded the 1964 channel area and moved the river back into the 1952 alignment and location. Both sites have experienced substantial migration as the river moves to reclaim the re-graded portions of the 1964 channel some of which are now developed, and recover some of the sinuosity lost to the Corp actions. Data sources: DOGAMI LiDAR (2013), NSD 2014.

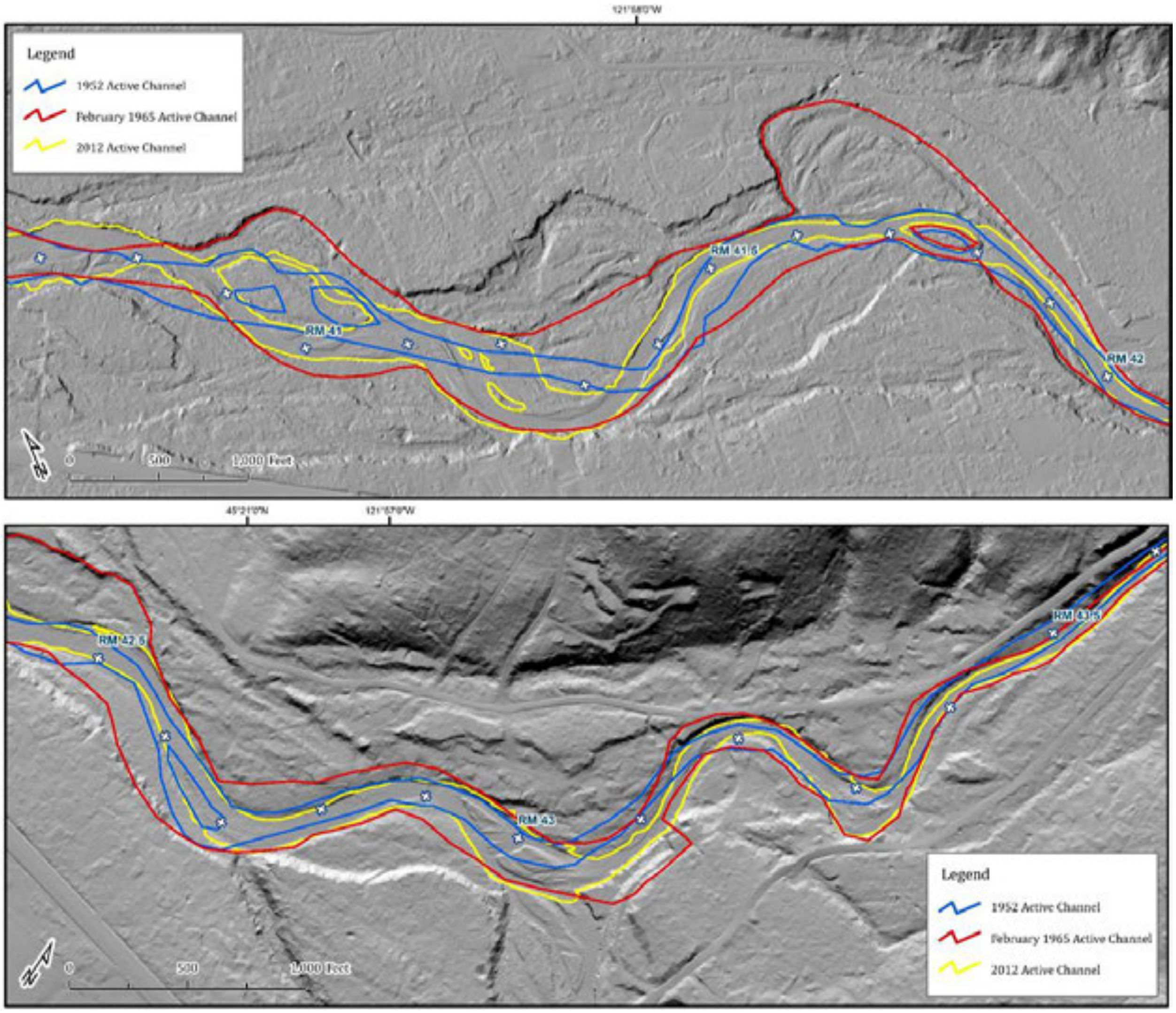


Figure 21B. 1952, February 1965 and 2012 Channel Traces. Digitized channels show how the pre-1964 channel widened in response to the 1964 storm event. At each location the ACOE re-graded the 1964 channel area and moved the river back into the 1952 alignment and location. Both sites have experienced substantial migration as the river moves to reclaim the re-graded portions of the 1964 channel some of which are now developed, and recover some of the sinuosity lost to the Corp actions. Data sources: DOGAMI LiDAR (2013), NSD 2014.

3.4 CHANNEL FORM AND PROCESSES

The preceding section described the evolution of the channel as it responded to the Old Maid Lahar and the three biggest storm events of the last 50 years. One of the more important lessons learned from review of the aerial photographs was that, while the channel is widening almost everywhere within the project area, the expansion of the active channel is most pronounced in the areas re-graded by the Corps following the 1964 flood event. At these sites, the active channel is widening in response to the formation of bends cut off or truncated by Corps actions. In several places, the river has reached the edge of the 1964 active channel and is now eroding into high banks composed of Old Maid lahar deposits, and in some areas, the Timberline Lahar (Figure 12).

However, channel widening is also occurring in response to the formation of vegetated bars (islands) stable enough to split flow and stand up to the force of the river at the 33 year flood event of 2011. Vegetated islands downstream of the Zigzag confluence are located at RM 38.1, 39.5, 40.0 40.1, 41, 41.8. Upstream of the Zigzag River, several more vegetated islands appear to be developing within the braided portion of the river. This channel type, called anabranching, consists of two or more channels separated by vegetated islands. In well-established anabranching rivers the islands can persist for decades or centuries and are at approximately the same elevation as the surrounding floodplain (Bridge 1993). The relatively rapid evolution of the river from the single thread channel of the USACE to one comprised of meander bends with anabranching and braided areas can be explained in part the river's gradient, discharge and the median grain size of the bed material, all of which play important roles in channel form (straight, anabranching, braided). The variation in channel with channel gradient and grain size /discharge is shown in Figure 22.

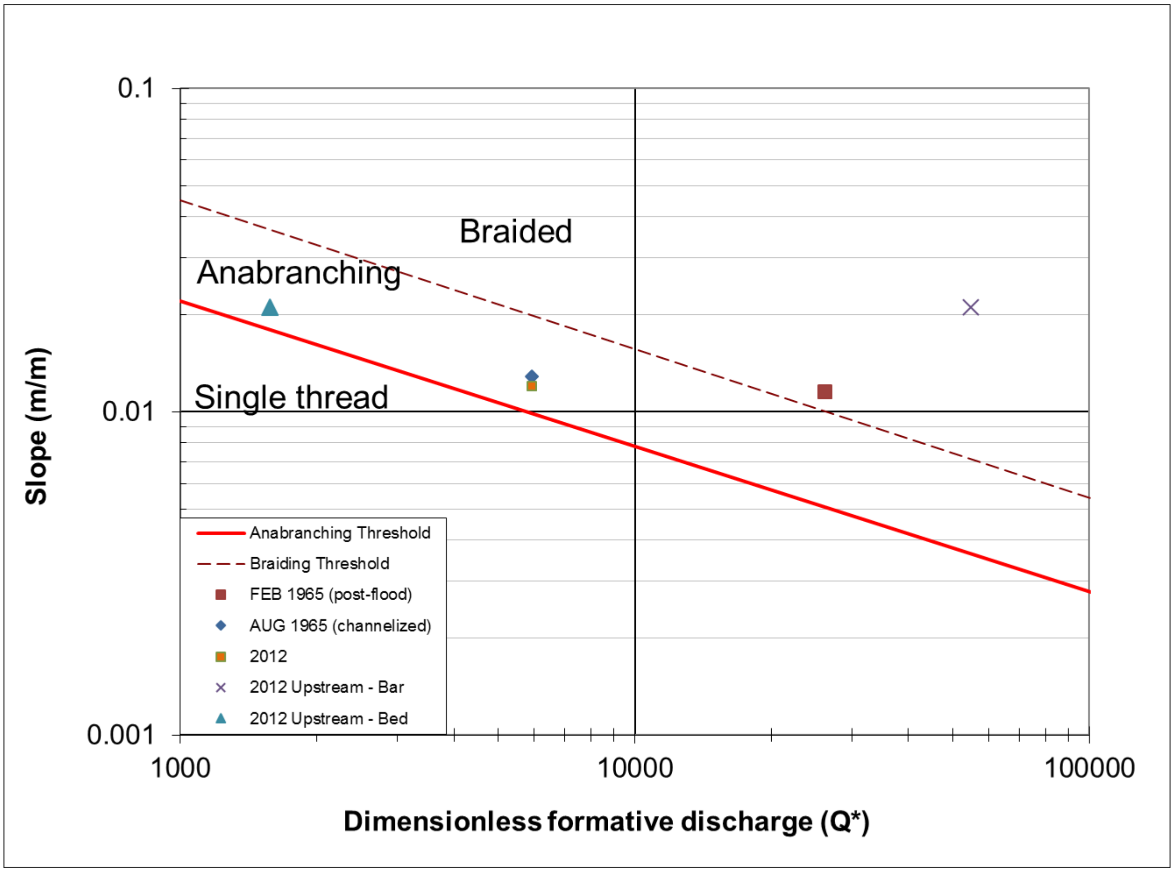


Figure 22. Anabranching Threshold for Sandy River. After Eaton et al. 2010.

Following the method of Eaton et al (2010), aggraded segments of the upper project area plot as a braided channel (2012 Upstream-Bar, Figure 22). Plotting up this same segment using the D50 of the 2012 incised channel, the river plots in the anabranching domain (Figure 22). Immediately following the December 1964 flood the Sandy below the Zigzag River confluence plots up in the braided channel domain due to the assumption it had a smaller D50 (Figure 22). The channelized 1965 and 2012 channel both plot well within the anabranching domain, indicating that the river is unstable as a single thread channel (Figure 22). This analysis shows that restoration and management of the river should focus on allowing the river to adjust to a morphology based on its formative discharge, bedload characteristics and gradient.

As discussed previously, Upper Sandy River dynamics are primarily driven by three major elements: large peak flows, abundant sediment, and steep channel gradient. There are many other elements and processes that contribute to the river’s dynamic behavior, including the sensitivity of river banks to erosion, the plan form of the channel, how constrained the river channel is by levees, revetments and natural pinch points, and the size and breadth of floodplains, among others.

The Sandy River banks are composed of mud flow deposits and sediment derived from the mud flows, and are, therefore, highly sensitive to erosion. The river has been able to substantially erode its banks during large flood events, causing permanent recession of the banks from as little as a foot or two, to more than 100 feet at a time, depending on the magnitude of the storm event. The processes typically associated with the bank erosion include, at a minimum, channel widening associated with channel incision, and channel migration, which is defined as the physical movement of the river channel across a floodplain. Channel migration usually takes place along river bends, where the outside bank of the river erodes while a gravel bar develops on the inside bank of the bend, called the point bar. Migration is an important natural process by which the stream flow expends energy by eroding the stream banks, and increasing the width of the active flood conveyance corridor. When migration is prevented, less flow energy is used, and more energy is focused on the river bed resulting in scour, or passed downstream.

For the purposes of this project, it is important to understand the mechanics of migration and, more importantly, the length scales of migrating bends. Throughout the project area, channel widening and migration can be initiated wherever sediment is deposited as bars on the river bed during a large storm event. The resulting topography causes small to large changes in local flow patterns. As the bar grows, it deflects or steers increasing portions of the flow around the bar towards the adjacent river bank. The growing bar extends into the channel and compresses flow against the outside bank of the bend, where flow velocity is also fastest, causing bank erosion. This hydraulic condition results in slower velocity along the inside bank of the bend, promoting the deposition of sediment on the bar. As the point bar grows both the bend radius and the channel length (circumference around the bend) increase. Channel lengths comprising the erosional portions of migrating meander bends vary roughly from 700 feet (upstream of the Zigzag confluence) to 1,250 feet at the downstream end of the project area. Keeping in mind that the erosion prone channel length of any bend is in constant flux, changing as the bend it develops over time and with changes in upstream and downstream channel form, the eroding portion of the bend at Timberline Rim (Timberline bend) is about 1,060 feet long. The ‘Timberline bend’, (shown in lower image of Figure 21A and Figure 23), has been the most active bend in the project area.

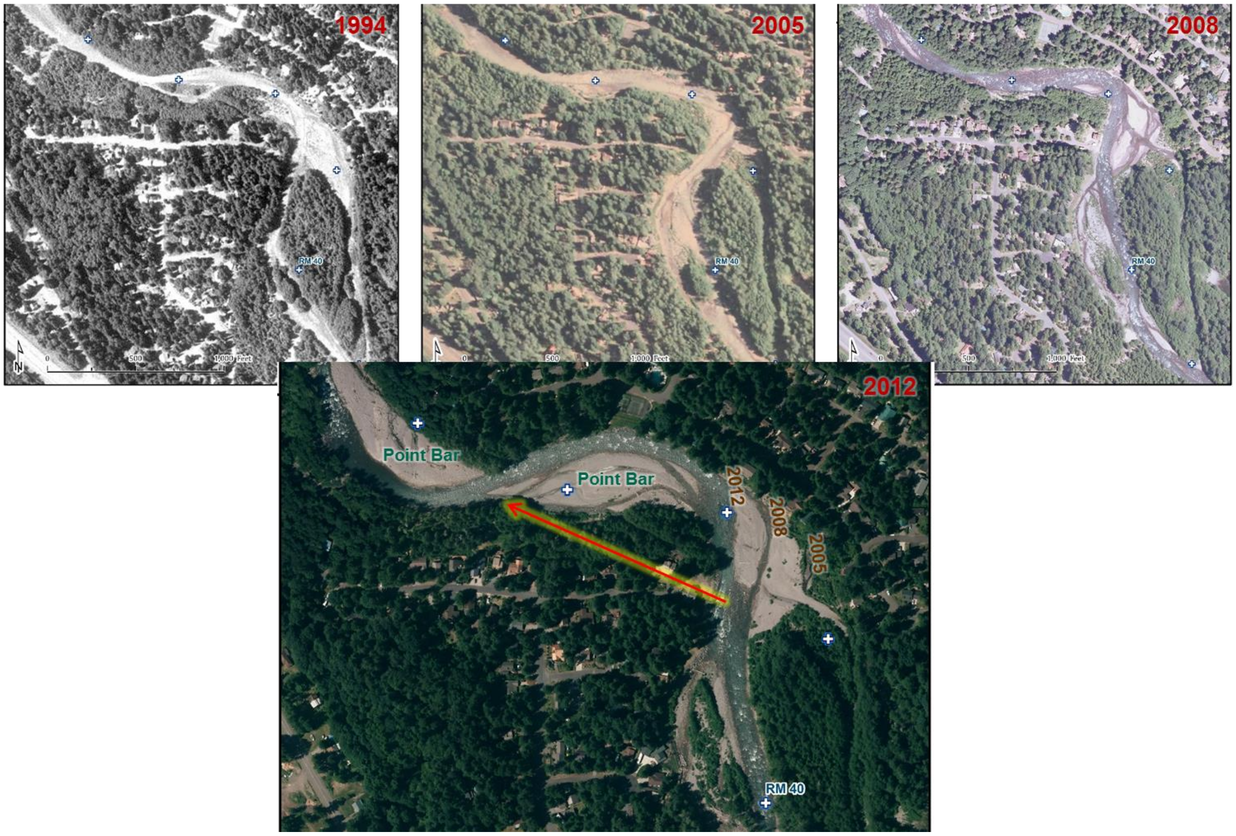


Figure 23. Timberline Rim Channel Migration. This group of air photos shows the lateral and downstream migration of the large bend adjacent to the Timberline Rim community. Note the remnant channel traces showing the distance of migration from 2005 to 2008 to 2012. Note also the size of the bend relative to property plats. Data sources: University of Oregon Libraries, USDA NAIP.

Figure 23 shows not only the continued evolution of the bend from 1996 through 2012, but also the length of the eroding bank relative to the total channel length, and the direction of bend migration over that time period.

The process promoting the development of braided channels is similar to bar formation. Braided channels and their associated bars are more typically associated with higher channel gradient, and a supply of sediment that exceeds the transport capacity of the flow. Braided channel systems consist of multiple, relatively shallow channels separated by un-vegetated, relatively loose gravel/cobble bars. At bankfull flows, the braids coalesce into a wide shallow channel (thus very different than an anabranching channel). Both the bars and channel alignments are unstable and subject to frequent mobilization and reorganization during any flow capable of entraining bar and bed materials. When large volumes of bedload are transported into a segment of the river that doesn’t have the capacity to move the material the channel aggrades and widens. Channel braiding is indicative of a bedload supply that exceeds the river’s transport capacity.

The channel upstream of the Autumn Lane residential community (above RM 45) is braided and reflects the high supply of coarse sediment the channel receives from upstream. This area is prone to major vertical fluctuations in the river bed, aggrading or degrading by 6-10 feet. The channel width has increased substantially during each major storm event in the last 60 years, sometimes by factors of 2 or 3, depending on sediment volumes entrained by the storm flows. This process was recorded on aerial photographs dated 2005 and 2010 (Figure 24).

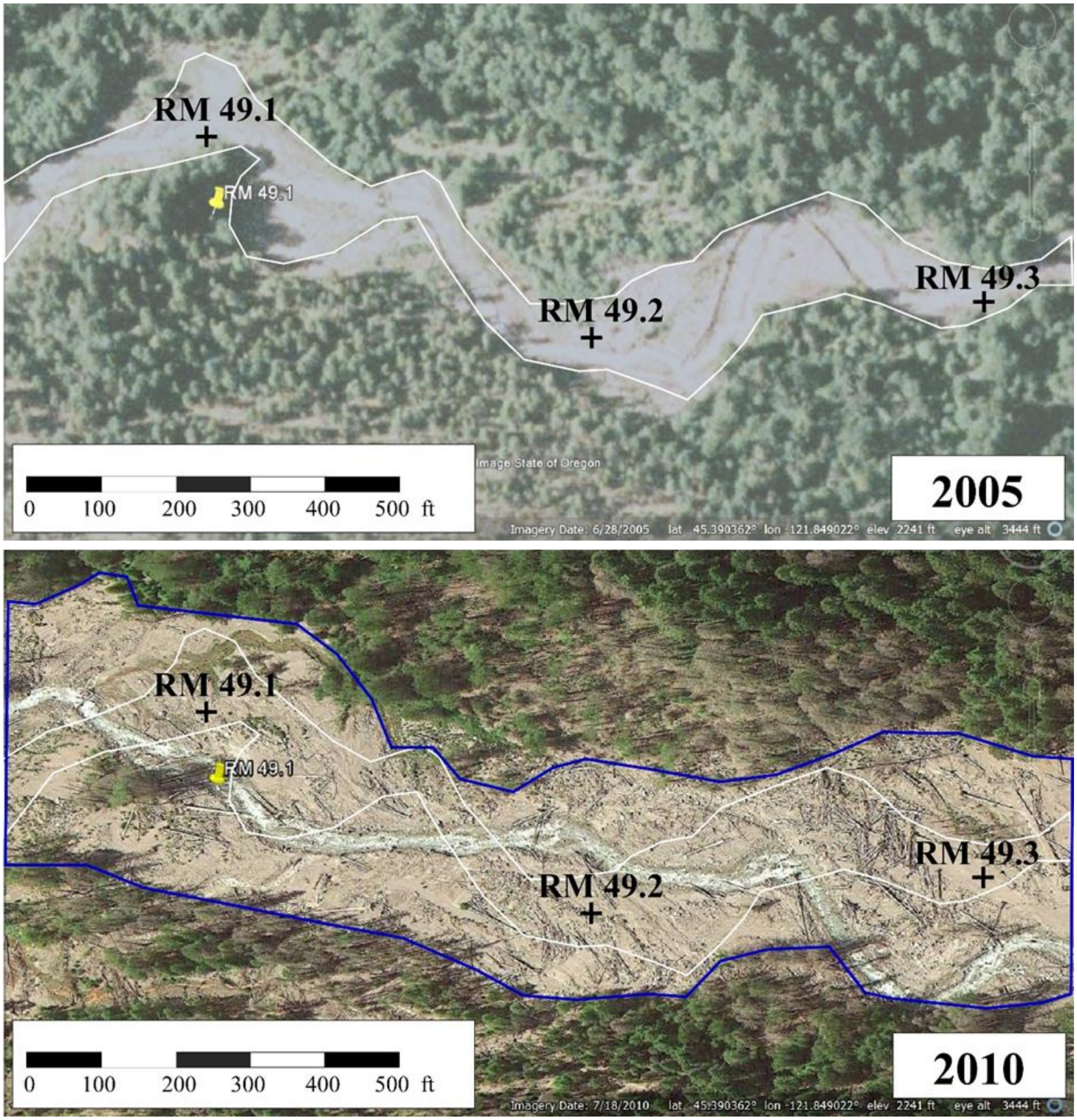
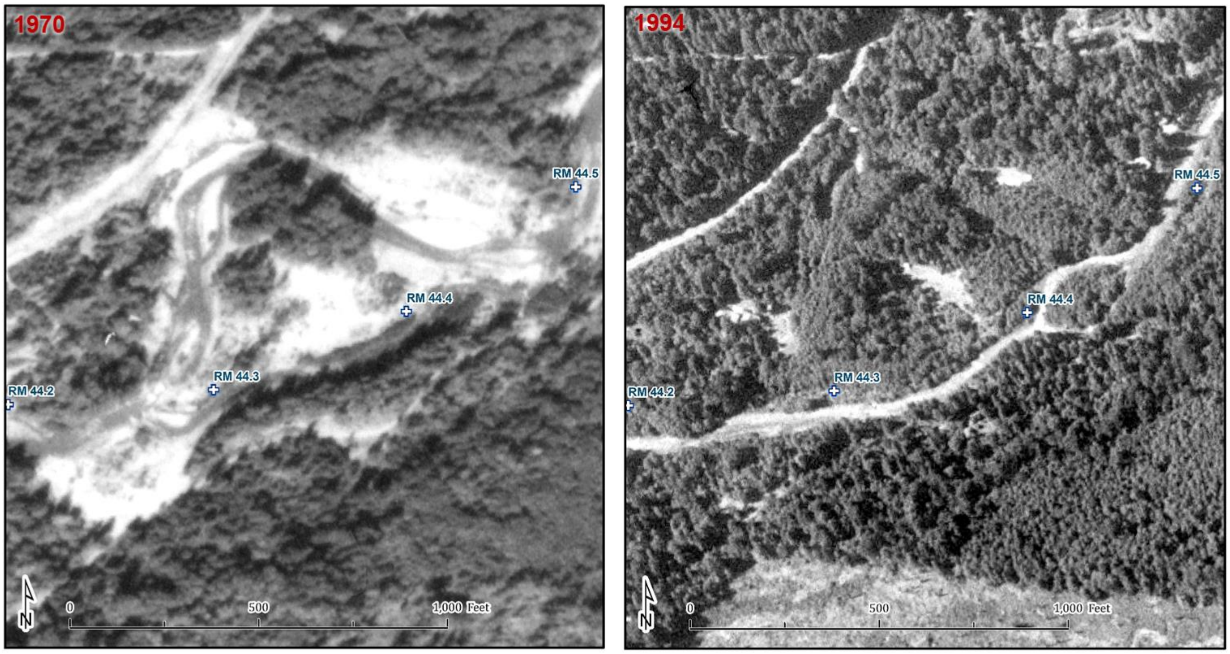


Figure 24. Channel expansion in Upper Sandy around RM 49 (about 1.2 miles upstream of Muddy Fork Bridge, above the project area). This dramatic response probably occurred in the flood of 2006. Boulder deposits in the channel and the severity of the changes indicate it may have been run out of a large debris flow

Channel avulsion is a form of migration where the river abandons its current channel to occupy a newly formed, or older abandoned channel (Figure 25).



1970 1994

Figure 25. 1970 / 1994 Avulsion. An avulsion took place sometime between 1970 and 1994 in the Old Maid Flats area been RM 44.2 and RM 44.4. The large bend, active in 1970, was cut off and abandoned by 1994. Although avulsions like this can occur in the course of a single storm event, this one probably occurred over several years. Data sources: University of Oregon Libraries.

The avulsion can take place abruptly, during a single storm event or gradually over a period of several storm events. Avulsions occur when the current channel fills with sediment, or when flow is diverted out of the main channel by some combination of sediment and large woody debris whose volume is sufficient to obstruct flow. A key point here is that channel migration and avulsion are both driven, in large part, by river discharges strong enough to move sediment and erode banks; the presence of erodible bank soils; and deposition of sediment and large tree snags on the channel floor and bar surfaces.

Channel behavior in the upstream braided and downstream meander bend river sections is fueled by an abundance of sediment in transport during large storm events. In general, a large proportion of the incoming sediment is deposited on the Old Maid Flats area, accounting in large part for the frequent changes in channel planform and periodic avulsions. Currently, the actively migrating meander bend section of the river is also fueled by sediment deposition, although by comparison, it currently receives smaller sediment volumes than the Old Maid Flats.

It is important to recognize the current sediment supply and transport regime in the lower river section is not a constant and could change at any time. Substantial active channel widening occurred during the 1964 storm event, and it will happen again with the next significant storm event, which is almost assured given the expected effects of climate change on the Sandy River watershed (see Section 2.4). It can also occur with the next lahar large enough to flow downstream of the Salmon River confluence. The Old Maid lahar took place a mere 200 years ago, and the mountain is still an active volcano. The only valid questions regarding the repeat occurrence of either event are when, and at what magnitude.

3.5 BED AND BANK MATERIALS AND SEDIMENT TRANSPORT

Bank erosion driven by any process or mechanism is dependent not only on sediment supply and stream discharge, but also on the sensitivity of bank soils to erosion.

Streambed Composition

The stream bed throughout the project area is composed primarily of coarse gravel, cobbles and boulders. The project team collected sediment point count data to better describe grain size diameters and to help understand when stream bed materials are likely to be entrained into transport. A plot of sediment grain size analyses is provided in (Figure 26).

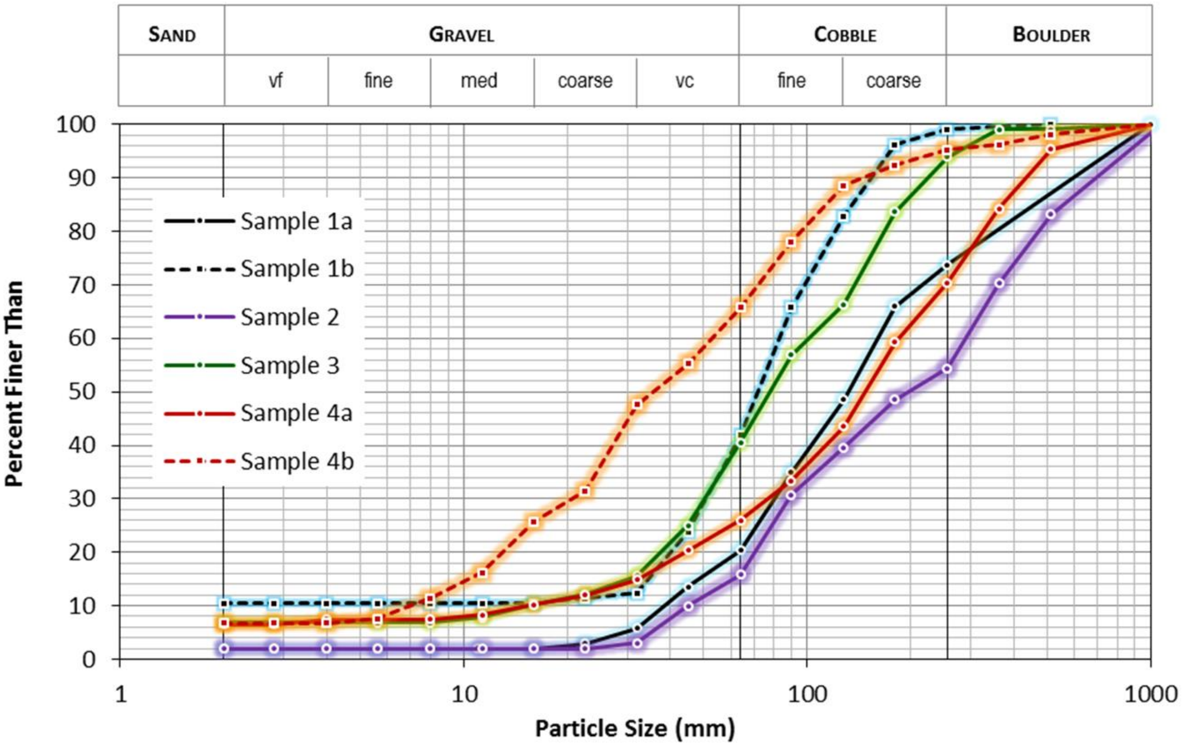


Figure 26. Sediment Grain Size Distributions. All samples were collected as point counts. Point count samples 1a and 1b were conducted at RM 39.65; Sample 2 at RM 41.3; Sample 3 at RM 40.3, and Samples 4a and 4b at RM 44.9.

In the old Maid Flats area, sediment comprising the active portion of a new channel cut in 2011 (Figure 27a) during an avulsion event ranges from very coarse gravel to cobbles and boulders with sand.

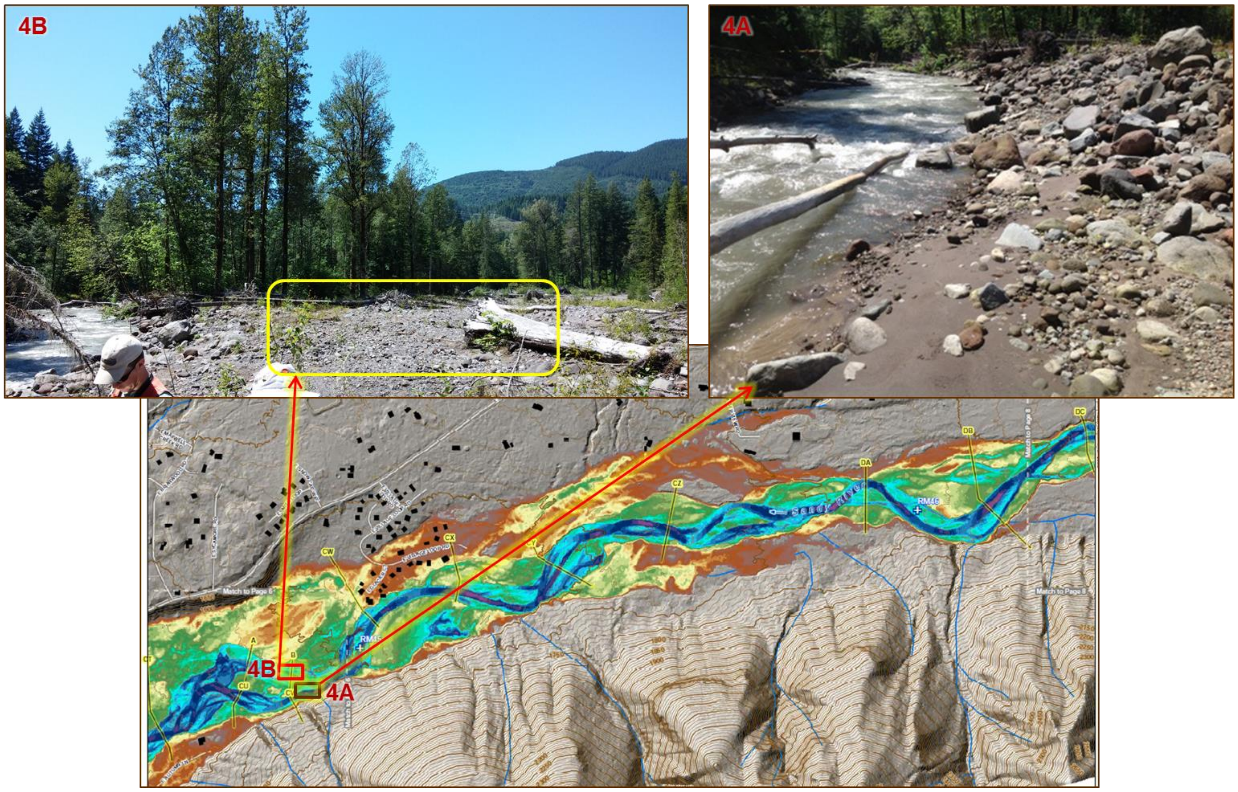


Figure 27A. Grain Size Sample Locations 4A and 4B. Point counts comprising these samples were conducted at RM 44.9 from the edge of the active channel (Sample 4A) and the surface of and abandoned channel (Sample 4B). Note the finer grained composition of Sample 4B, which is more characteristic of sediment transported via debris flows.

The adjacent channel, abandoned in that same event, is composed of much finer sediment (Sample 4a) ranging from fine gravel to fine cobbles with sand and occasional boulders. Sediment comprising the abandoned channel is indicative of the large sediment volumes transported in from upstream, which inundated and widened the braided channel sections within the Old Maid Flats.

Downstream from the Zigzag confluence, in the region upstream and downstream of Timberline Rim, the river bed composition is very coarse, ranging from coarse gravel to coarse cobbles and boulders with varying amounts of sand. The grain size plots for samples 3, 2, 1a and 1b are shown in Figure 26 and the location of Sample 1b, which is representative of bedload in transport, it shown in Figure 27b.

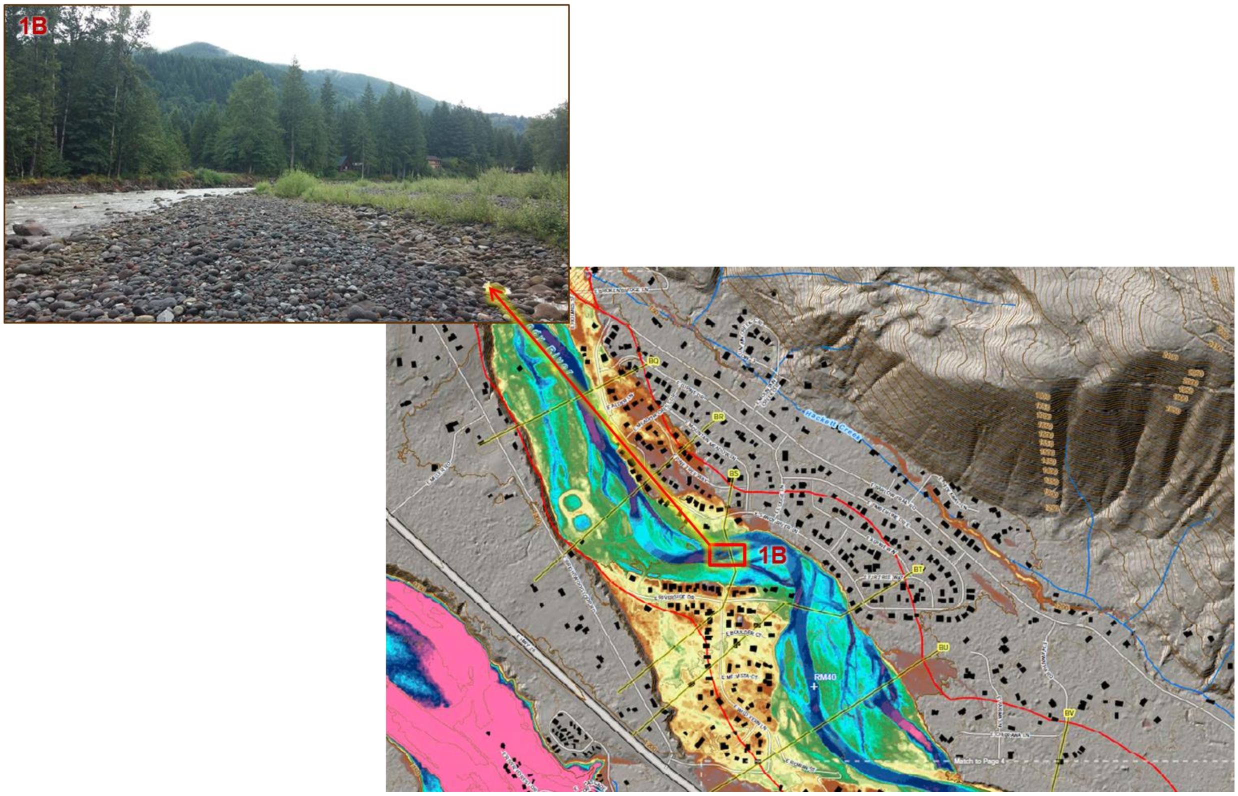


Figure 27B. Sample 1B was collected from the surface of a gravel bar located just downstream of the Timberline Rim tennis court. Sampling from the surface of the bar is typically representative of bedload in transport at flows overtopping the bar surface.

Bank Soils

River bank soils throughout the project area are relatively consistent. Banks along both sides of the river typically consist of Old Maid Lahar sediment. The Old Maid Lahar unit is composed of sand sized ash and cinder, and rock fragments ranging from coarse sand to boulders, although the sand sized material is by far the largest component of the total sediment volume. Because the lahar is only 200 years old, and because it is composed of granular sediment, it is porous, permeable to water and very sensitive to erosion by moving water. The Old Maid Lahar overlies the older Timberline Lahar (1,700 years old), and in some places, both units are exposed in tall river banks (Figure 12). The Timberline unit contains approximately the same grain size distribution as the Old Maid unit, but it is older by several hundred years and is therefore is more compacted and consolidated. In theory, the compaction may render it more resistant to fluvial erosion; however, there is no factual data to support that notion. Some hill slopes composed of Timberline overlain by the Old Maid lahar unit are highly sensitive to erosion. Figure 28 displays an outcrop containing both lahar units where both lahar units are being eroded by the river and mass wasting processes (groundwater infiltration, internal friction angle of material, and gravitational forces).

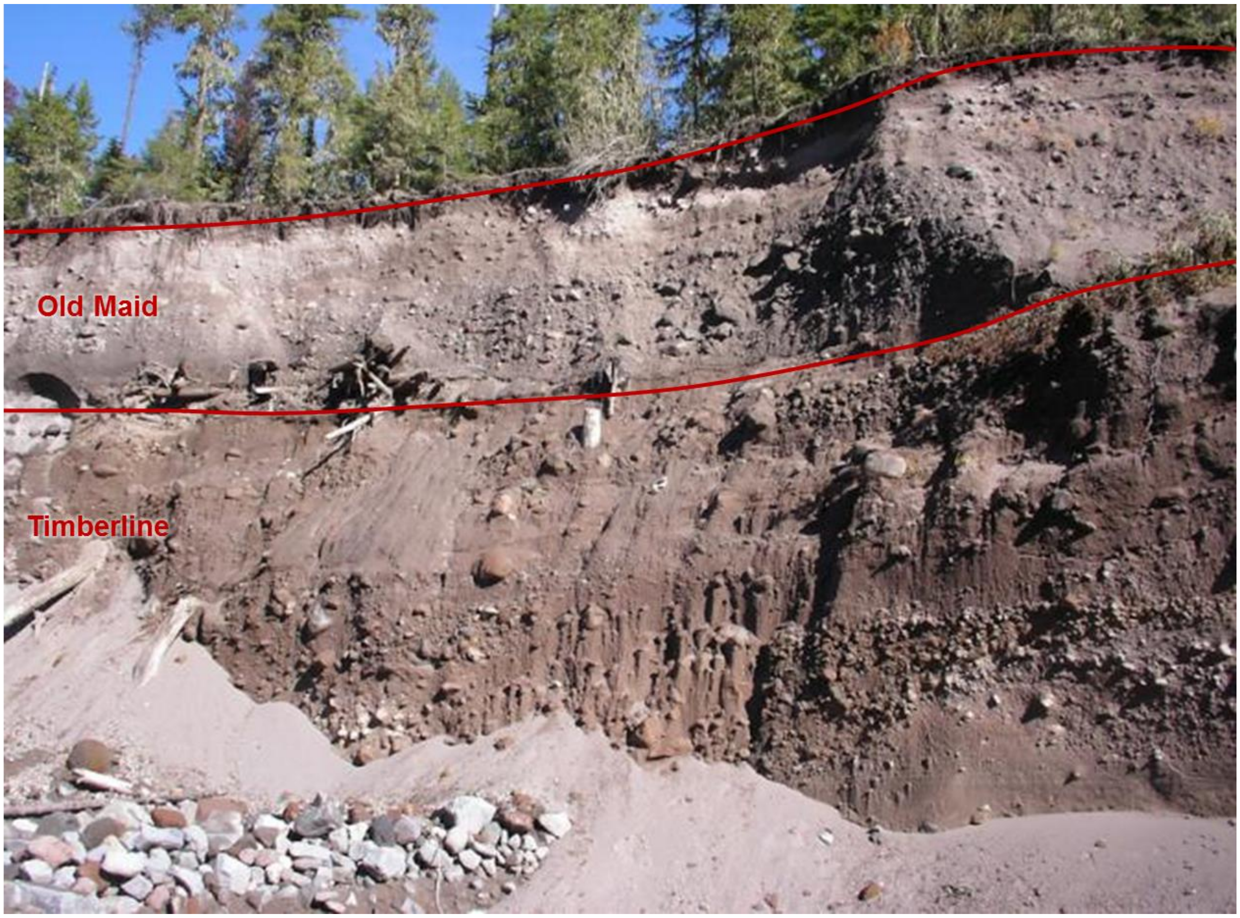


Figure 28. Old Maid and Timberline Lahar Deposits. A slope face composed of a thick Timberline lahar deposit overlain by the Old Maid lahar deposit. The slope face is set well back from the river. The lahar unit have been exposed by hillslope weathering processes. Note the collection of woody debris at the top of the Timberline lahar, buried by the Old Maid unit, suggesting the former presence of running water.

Comparison

Compared against river bed materials, the river banks are much more susceptible to fluvial erosion. River bed materials form somewhat of an armored surface that requires substantial velocity to initiate erosion. Stream bed armoring is a frequent result of streams where flow velocities are fast enough to mobilize sand and gravel sized materials but not cobbles, leaving behind an armored bed composed of large gravel, cobbles and boulders. During most flow stages, even as flow levels rise, the near bed velocity is not high enough to begin eroding the bed, but is more than sufficient to erode banks composed of Old Maid Lahar. The exact flow velocity needed to erode the stream bed is difficult to predict, since it depends largely on the distribution of grain sizes and how densely they are packed together. Based on the large quantity of large cobbles and boulders comprising the river bed throughout the project area, bed erosion is likely to take place only when flow velocities near the channel floor exceed 12 ft/s or greater (Figure 29). Flow conditions such as this typically occur only once or twice a year.

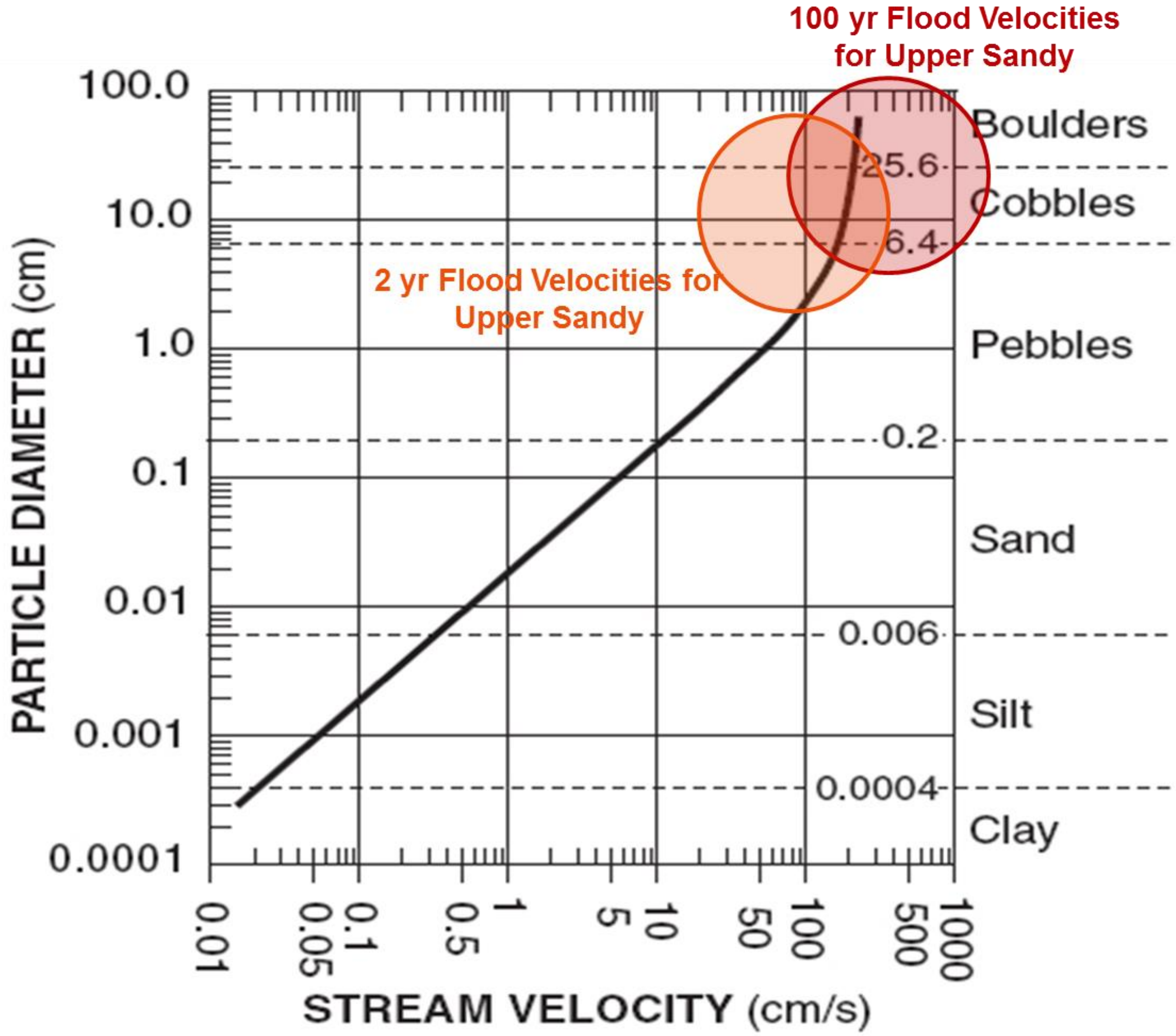


Figure 29. Relationship between flow velocity and average (D50) minimum stable particle size. This graph displays the median grain diameters stream flow can transport during the 2-year (large cobbles) and 100-year (cobble to boulders) recurrence interval storm flows. After Peter Mulroy 2012.

Given the high near-bed velocity required to erode the river bed and the high sensitivity of bank soils to erosion, it's clear that the project area river banks are subject to erosion during less than bank full flows, which can occur several times a year. Bank soils are also vulnerable to erosion over longer periods during any storm flow. The only requirement for erosion of most bank sections within the Upper Sandy is that the water surface elevation be in direct contact with exposed soils.

4 EROSION HAZARD RISKS AND THE CHANNEL MIGRATION ZONE

The project goals established for this study in Section 1.2 of this report focus on:

1. Assessing historic and current river conditions and erosion trends as an approach for identifying possible mitigation projects within the project area.

2. Provide the basis of design criteria for methods of bank restoration that include alternatives to 'traditional' riprap structures (e.g., FEMA circular Engineering with Nature).
3. Identify at least one demonstration mitigation project, described as a composite bank/channel restoration project, as a sustainable and cost-effective approach to improve public safety and overall river balance.

Identifying bank erosion mitigation projects requires identification of areas subject to current and/or future erosion risks. In the Upper Sandy River the high risk areas are those subject to aggressive channel migration and periodic episodes of active channel widening associated with significant storm events or volcanic mud flows.

Maps projecting the future channel migration zone (CMZ) offer the most effective vehicle for identifying such risks. The CMZ defines the probable extent of migration over the course of a specified period of time. The width of the estimated CMZ is based on historic rates of migration. The CMZ should be sufficiently wide to accommodate future migration and channel widening.

For the purposes of this project, the project team used existing CMZ maps prepared by the Oregon Department of Geology and Mineral Industries (DOGAMI) in 2011. The maps were modified to incorporate the most recent aerial photographs and LiDAR (2013). The results of CMZ modifications are shown in the Sandy River Mapbook 17 entitled 'DOGAMI and NSD CMZ

For the DOGAMI study, English et al. (2011) analyzed high resolution LiDAR topography and mapped historical channel changes from 1955-2009 to delineate the Channel Migration Zone (CMZ) for the Sandy River upstream to the confluence with Clear Creek. The methodology references an approach by Rapp and Abbe (2003) developed for similar applications in Washington State. The CMZ attempts to delineate an area potentially subject to channel processes over a time period 100 years into the future. The approach delineates the following zones within the CMZ:

1. **Historical Migration Zone** (HMZ): combined extent of mapped channel areas 1955-2009;
2. **Avulsion Hazard Zones** (AHZ): areas outside of the HMZ that are at risk of channel occupation (e.g., secondary channels, relict channels, and floodplain swales);
3. **Erosion Hazard Areas** (EHA): areas outside of the HMZ and AHZ which may be susceptible to toe erosion and/or mass wasting initiated by fluvial processes (e.g., undercutting of steep slopes).
4. **Disconnected Migration Areas** (DMA): areas within the EHA that are isolated from the CMZ by the presence of man-made structures that prevent channel migration (e.g., rock revetments).

The Rapp and Abbe (2003) approach is summarized as:

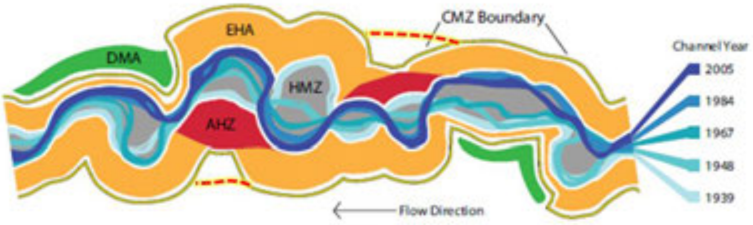
$$CMZ = HMZ + AHZ + EHA - DMA.$$

As part of the Phase 1 assessment in preparation for Clackamas County, NSD compiled the GIS database from English et al. (2011) to overlay the CMZ boundaries on Relative Elevation Maps (REM) and other basemap information at a scale of 1:6000 (1 inch = 500 feet). NSD developed a series of map annotations and recommendations for CMZ map revisions based on field observations, hydraulic, and geomorphic analyses. Key findings of our review are summarized below and referenced in a Mapbook 18 entitled Draft Annotated CMZ Maps).

4.1 KEY FINDINGS

The selected approach has been the most widely applied methodology for CMZ delineation in Pacific Northwest Rivers and is appropriate for the intended application. Our review finds that English et al.'s (2011) map series presents a relatively accurate representation of channel migration hazards in the Sandy River valley and is a substantial contribution to guide planning efforts for management of flood and erosion hazards. The list below notes key findings and comments noted during our review to support recommendations for map revisions to improve the delineation of channel migration and erosion hazards.

1. The HMZ delineated by English et al. could be expanded with information compiled as part of the NSD's Phase 1 assessment showing a broader corridor of channel occupancy over the historical record. Topographic mapping based on a 1914 USGS survey shows the channel historically occupied portions of the valley presently outside of the active channel (see map sheet 3, area B, for example). Furthermore, imagery compiled by Clackamas County for the period immediately after the December 1964 flood shows multiple areas that blew out in 1964 which are not shown in the delineated HMZ. Also, localized areas that experienced substantial erosion in January 2011 are not shown in the present HMZ (see map sheet 2 at Timberline Rim where HMZ would be wider if accounting for 2011 migration). These additional data sources were digitized by NSD for inclusion as part of HMZ mapping to best delineate channel migration hazards along the Sandy River
2. There are multiple avulsion pathways not specifically identified in the mapped AHZ. Additional avulsion pathways are called out on the annotated map series with red arrows. Many of these are relatively short secondary channels in the active floodplain that can rapidly become part of the active channel when flows are redirected by bank erosion and/or wood recruitment during flood flows (see map page 3; area B). Also, noted in our review is a relatively long, abandoned channel, which is a potential avulsion pathway that would yield a substantial shift in the river morphology upstream of Timberline Rim (see map page 4; areas A-C). Note that rivers such as the Sandy are susceptible to large pulses of sediment that can produce localized aggradation and engage portions of terrace surfaces presently above the active channel. Rapp and Abbe (2003) found vertical streambed fluctuations of up to 2 meters in mountain drainage basins of the Pacific Northwest. As such, abandoned channels identified on low terrace features adjacent to the active channel were flagged as potential avulsion pathways in our review and included in the modified CMZ.
3. The technical approach applied by English et al. (2011) deviated from the methodology published by Rapp and Abbe (2003) in areas adjacent to AHZs. The conceptual graphic of CMZ delineation from English et al. (2011) is pasted below. Note that EHA is applied as a setback distance from the edge of the HMZ. The CMZ graphic is annotated with dashed red lines to show how the width of the CMZ is increased when the EHA is applied as a setback distance from the edge of the AHZ, as described by Rapp and Abbe (2003). We incorporated this revision into the modified CMZ to provide sufficient setback distance from the AHZ to limit future erosion hazards.



CMZ = HMZ + AHZ + EHA - DMA

4. Multiple locations in the valley are delineated by English et al. (2011) as disconnected migration areas, or DMA, where portions of the erosion hazard area, or EHA, are isolated from the active stream corridor by an existing road. Many of the roads used as boundaries for the DMA are setback short distances from the HMZ or AHZ and are not presently subject to toe scour. As the river migrates over time, however, it will eventually erode the alluvial material or lahar deposit underlying the road. By identifying these areas as DMA, it is assumed there is commitment to armor that road with sufficient protection from erosion into the future. Note, however, that past events in the upper Sandy River have eroded into segments of E Lolo Pass Road and E Barlow Trail Road. From this historic pattern, it can be assumed there are areas within the Sandy River Valley noted as DMA that may actually be at risk to channel migration hazards. Identifying these areas as DMA may provide a false sense of security to landowners with residences on the landward side of existing roads.

4.2 FINAL CMZ MODIFICATIONS

The final CMZ encompasses the adjusted historic migration zone (HMZ), which now includes 2011 and 2012 active channels, all potential avulsion channels (AHZ) and an increased erosion hazard area (EHA). The EHA was increased to better account for rapid migration and channel widening that occurred during the 1964 storm event, as well as the 1996 and 2011 storm events. On average, the adjusted CMZ is about 2,000 feet wide throughout the project area. The EHA is based on several factors; migration recorded since the 1970 aerial photograph was taken, the tendency of river bends to migrate downstream as well as laterally, and potential for rapid widening of the active river channel with the next significant, 75 to 100 year recurrence interval, storm event, or a storm event.

The consistency of the CMZ width throughout the project area, even in places that have shown little or no migration and channel expansion, is intended to account for future variability, as seen in the historic record. At present, the Upper Sandy River is very young, only 200 years old, and will be subject to extreme swings ranging from incision to channel widening as the channel continues to respond to the Old Maid Lahar, and to large sediment loads.

Based on the results of the erosional processes within the project area, a list of erosion hazard sites is provided in Table 5.

Table 5 High Risk Sites in Upper Sandy River Project Area

RM	BANK	ISSUE
37.5-37.9	Left	Properties at western portion of E. Salmon St. lie on low-lying alluvial surface between Sandy River (north) and Salmon River (south). This area is at severe risk of Sandy River avulsing into the Salmon River. Given risk of erosion and flooding, properties lying below the high terrace, on E. Brightwood Loop Road, should be considered for acquisition.
37.9-38.0	Left	Properties on high terrace, north of E. Brightwood Loop Road, are at high risk of erosion due to current migration of Sandy River to the south.
37.95-38.05	Right	Sandy River has moved to the toe of the hillslope along north side of the valley, below E. Barlow Trail Road. Depending on bedrock conditions, the river poses a risk to road.
38.20-38.24	Left	Erosion along left bank of the river poses imminent risk of channel avulsion into large gravel pits south of the river. An avulsion will result in the river impinging upon the high terrace along E. Brightwood Loop Road.

38.50	Both	Brightwood Bridge poses severe constriction to the river. This bridge was destroyed in December 1964 and the crossing should be widened substantially to improve flood conveyance and channel processes.
38.70-38.72	Left	Properties lying within historic channel migration zone are at high risk of erosion and flooding.
38.64-38.71	Right	E. Barlow Trail Road lies within the high erosion risk area. The potential future restorative flood protection measures needed to protect road could further exaserbate risks to properties on left bank at RM 38.70-38.72.
38.90-38.91	Right	Properties along E. Relton Lane lie within high erosion risk area. This area was where 40 homes were washed away in December 1964 flood.
39.20-39.30	Right	Properties along E. Holmes Road lie well within historic channel migration zone and avulsion pathway.
39.30	Left	Property located along edge of 1914 channel and current avulsion pathway where there is a high risk of the river moving into this channel upstream at RM 39.6.
39.44-39.51	Right	Properties located along the eroding right bank at imminent risk.
39.51-39.63	Right	While not in an area currently subject to erosion, properties along right bank remain in high risk area.
39.63-39.91	Right	These properties lie along a right bank area that is currently eroding and includes some low-lying properties subject to flooding.
39.60-40.05	Left	Properties are in an area of high risk of erosion, particularly those located north of E. Riverside Drive. Eastern most properties, at the upstream end, lie within an area where the river experienced dramatic widening in December 1964 flood.
40.05-40.10	Left	Northern portion of E. Rowan St. lies within a high erosion and flood risk area. Abandoning this street will remove constraint, currently limiting flood protection opportunities.
40.10-40.45	Left	Properties along left bank lie within high risk erosion zone and constrain channel migration zone.
40.10-40.30	Right	Properties situated on top of high terrace, along the avulsion channel that formed in December 1964 and was cut-off with a levee early in 1965. Opening the levee plugging the channel will result in substantial flood protection improvement to left bank residents downstream but poses unacceptable risk to properties on the right bank high terrace. Acquisition of a few properties on the right bank high terrace alleviates this risk and offers one of most significant opportunities within the Upper Sandy for restorative flood protection.
40.60-40.80	Left	Properties within high risk erosion area (100 ft within historic migration zone).
40.78-40.83	Right	Properties at downstream (west) end of E. Polly Ave lie on eroding high terrace and are at imminent risk of erosion.
41.00	Right	Homes at south end of E. View Ave and E. Winnie Road are located in potential avulsion pathway.
41.00-41.10	Left	Homes along E. Jerry’s Lane lie within historic channel and inside high risk erosion zone.
41.10-41.30	Right	Homes at south end of E. Winnie Road and large portions of E Lost Shelter Road, E. Roaring River Road, and E. Brook St. are located in potential avulsion pathways
41.15-41.40	Left	Erosion of high bluff may need to be addressed given river is within 200 ft of business along Highway 26. Homes at west end of E Emigrant Trail lie with high risk erosion area.
41.56-41.80	Left	Properties within high erosion risk area, including those in the upstream (eastern) portion of E. Emigrant Trail.
41.80-42.00	Right	Properties along E. Chinquepin Drive lie within high erosion risk area along severely constrained segment of the river.
42.10-42.24	Right	Small group of properties within high erosion area south of E. Sundance Road severely constrain migration zone.
42.26-42.41	Left	Properties on eroding high bank at imminent risk of erosion.
42.40-42.65	Left	Properties lie within high erosion risk area.
42.60-43.16	Right	Properties lie within high erosion risk area. Homes south of E. Alpine North Court are particularly susceptible given current erosion trends and location opposite Zigzag River confluence.

42.80-42.90	Left	Properties on high bluff at west end of E. Skookum Lane lie along potential avulsion pathway and erosion area.
43.10-43.25	Left	Properties at upstream (north) end of E. Rockwood Creek Lane lie with historic channel location and area of high erosion risk. This area is where the river channel has been constrained against north (right) side of valley where damage to E. Barlow Trail Road requires additional bank protection. Acquisition of properties on left bank are needed before restorative flood protection measures can be implemented to protect E. Barlow Trail Road.
43.25-43.37	Right	Properties lie within an area of both high erosion and flooding risk. Acquisition of properties would significantly improve flood conveyance and habitat conditions within this constrained reach of the river.
43.30-43.65	Left	Properties west of E. Lolo Pass Road are at high risk of erosion due to severely constrained channel migration zone. Currently, the river is constrained along E. Barlow Trail Road, posing chronic maintenance problem for the road. Potential future restorative flood protection methods to protect road would put properties on left bank at even higher risk. Given location of E. Barlow Trail Road at toe of valley hillslope, properties on left bank are limiting condition.
43. 63-43.85	Right	E. Lolo Pass Bridge imposes severe constriction on river and requires major expansion to improve flood conveyance.
43.95-44.05	Right	Properties at high risk to flooding and bank erosion due to constrained channel migration zone.
43.70-44.70	Left	Properties along E. Autumn Lane are at high risk to erosion and flooding due to constrained channel migration zone.
44.15-44.60	Right	Properties between Lolo Pass Road and the river lie within high risk channel migration zone where the river is subject to major vertical and horizontal fluctuations in river bed. The river near RM 44.36 is where the historic channel came right up to Lolo Pass Road. This relic channel remains an avulsion pathway.
45.08-45.21	Right	Zigzag village development properties along E. Glacier Court and lower E. Village Loop Road are at high risk of erosion. Two homes were destroyed in 2011 flood and purchased by Clackamas County.
45.7-45.8	Right	Properties at south end of E. Glacier View Road lie within high risk of erosion where the river is subject to rapid vertical and horizontal changes.
46.3-46.6	Right	Properties along southern portion of E. Cold Springs Road lie within an area with a high risk of erosion, and is most unstable portion of Upper Sandy study area.

5 RESTORATIVE FLOOD PROTECTION STRATEGY

5.1 SUMMARY OF FLOOD HAZARD ISSUES

The Upper Sandy River has a long history of large storm events that have caused substantial flooding and bank erosion throughout the upper river corridor, upstream of the Salmon River confluence. The flooding of residences, roads and other infrastructure has caused millions of dollars of damage. In the last 50 years (1964-2014) bank erosion has claimed over 400 acres along the ten mile project reach of the Upper Sandy (RM 37.5-47.5), damaging or destroying roads, bridges, and homes. The U.S. Army Corps of Engineers reported that 155 homes were completely destroyed in the Sandy basin in the December 1964 flood.

> *"the north bank of the Sandy just upstream from Brightwood showed no indication of buildings, vegetation or topsoil where a group of 40 houses existed prior to the (1964) flood." - U.S. Army Corps of Engineers Portland District Post-flood Report July 1966.*

The 2011 flood caused significant erosional impacts along the river's shorelines, as well as to public and private infrastructure in developed areas (Figure 30, courtesy The Oregonian).

Figure 30. Home damage along the Upper Sandy River due to erosion in 2011 along right bank at Zigzag Village development, RM 45.1. Like much of Upper Sandy, the bank is composed of fine sediment that is more easily eroded than the coarse material of the river bed. Photo credit: *The Oregonian* newspaper.

A critical fact that elevates erosion risks in the Upper Sandy is that many of the river's banks are comprised of poorly consolidated deposits primarily composed of sand, which are more easily eroded than the river's own bed of cobbles and boulders (Figure 30). Channel migration is a natural process and the Upper Sandy is gradually reclaiming the valley it had prior to being filled by the Old Maid mudflow, or lahar, 200 years ago. As the river expands its floodplain, energy is more effectively dispersed, which has several important benefits such as increased flood storage, slower erosion rates, and more salmon habitat. The 1964 flood resulted in a major expansion of the channel's area and left the river with more channels, an increase in total channel length, lots of wood and a finer bed texture; all of which significantly improve salmon habitat (Figure 31).

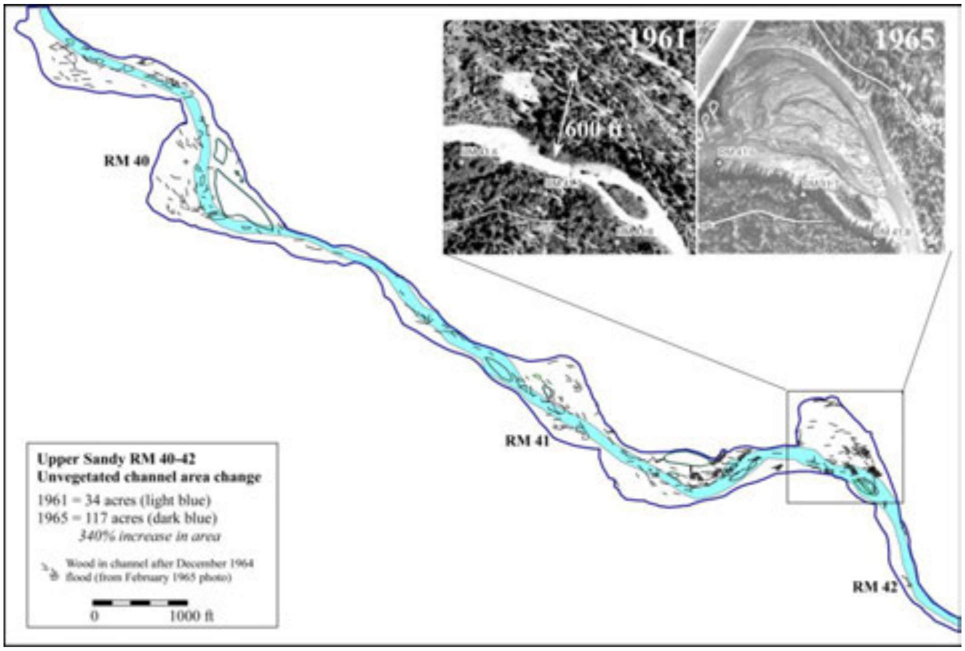


Figure 31. Upper Sandy RM 39.8 to 42.0 showing the 340% expansion of the channel area after the December 1964 flood. The channel enlargement left behind a much more complex multi-thread morphology, a finer substrate and lots of wood. Inset photos show river at RM 41.7 where river moved over 600 ft to the north. After the flood the U.S. Army Corps of Engineers removed all the wood, constructed levees and re-established the river to an excavated channel in the 1961 alignment.

This response was seen to a lesser degree after the 2011 flood (Figure 32).

Figure 32. Upper Sandy RM 44.1 Lolo Pass Road washout in 2011. The channel moved through the road adding over 60 ft to its migration zone. The flood left a net increase in the quantity of wood in the channel which added additional flow resistance and enhanced fish habitat. Historic confinement and wood clearing has concentrated the river's energy and severely limited the formation of beneficial salmon habitat. Providing the river with more room to move and implementing flood protection measures that focus on energy dissipation will not only improve habitat but reduce long-term flood protection costs. In this case the road was rebuilt in its pre-existing location.

After the 1964 flood the U.S. Army Corps of Engineers diked and channelized the river into a single channel within its pre-flood alignment. This concentrated the river's energy and unfortunately gave a false sense of security to adjacent homeowners. The river's natural tendency is to migrate and re-establish a larger floodplain. Damages to roads and bridges from erosional forces cause temporary road closures and diversions, and other infrastructure inspections, and repairs. Efforts to protect property and infrastructure by constraining the river can pose chronic maintenance costs and catastrophic risks. These actions also adversely impact critical habitat for endangered salmon species.

Hydraulic modeling of current conditions shows that mean flood velocities decrease in sections of the river with greater inundation widths (Figure 33).

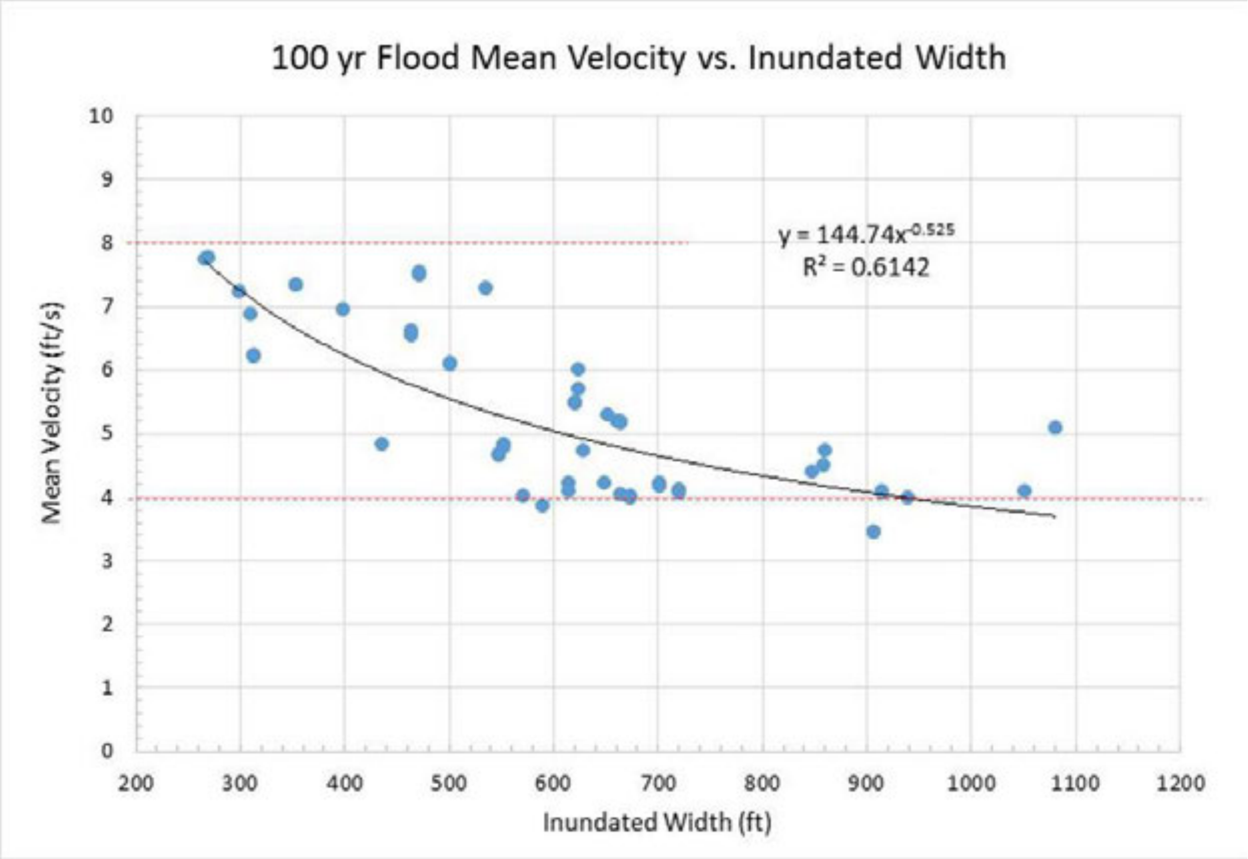
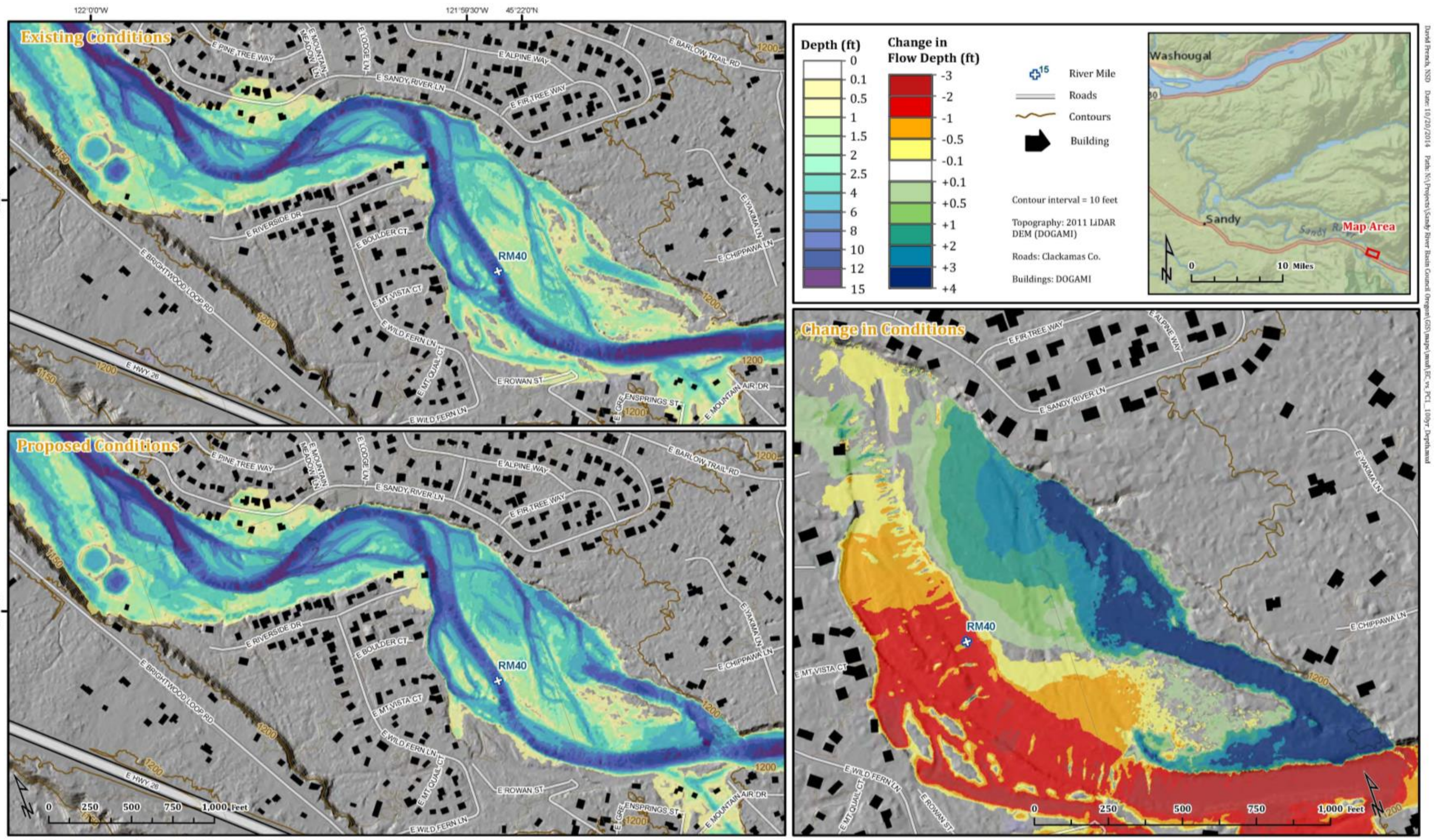


Figure 33. Output from HEC-RAS hydraulic model showing how mean velocities during the 100 yr flood decrease as a function of the inundated (floodplain) width, showing an approximately 2-fold drop when it reaches 900-1100 ft in width. This provides guidance for a minimum zone in which channel migration can be manage

This data indicates that 900-1100 feet is a minimum zone for accommodating channel migration. Detailed modeling of the river between RM 39.5 and 40.4, in the Timberline Rim community, shows that widening the floodplain by re-engaging a relic channel that had formed in the December 1964 flood, and had subsequently been diked off in 1965, delivers significant flood protection benefit to residents along the south side (left bank) of the river (Figure 34a, b).

Specifically, the model results predict lower flood depths and velocities within the existing channel by removing the right bank levee and increasing conveyance. In addition, these reductions in flood depths and velocities lower the shear stress acting on the river bed, which reduces the river's sediment transport capacity.



Sandy River Basin Watershed Council Restorative Flood Response Design Project

Change in Flow Depth during 100 year Event for Proposed Alternative 1

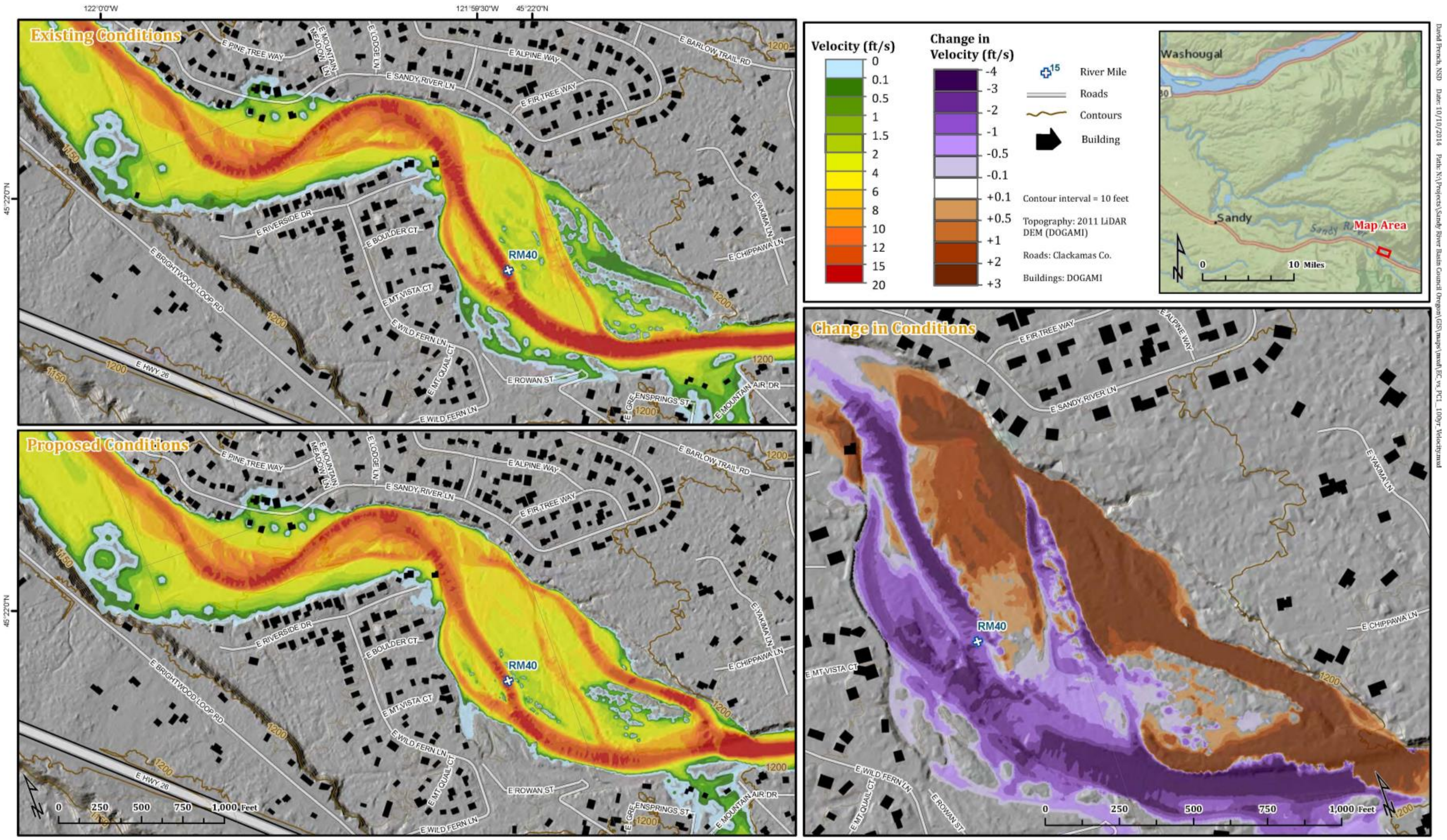
Hydronia RiverFlo-2D hydraulic model results for 100 year flow event (22,420 cfs) under existing and proposed alternative 2 conditions. Change in conditions derived from difference between proposed and existing.

Lambert conformal conic projection, NAD 1983
State Plane Coordinate System (OR North Zone)

Sandy River Basin Watershed Council

Natural Systems Design

Figure 34A. Illustration of how widening the cross-sectional area available to flood flow will diminish flow depths. Timberline Rim community from RM 39.4 to 40.4, river flows from lower right to upper left. The upper left image is output from a two-dimensional hydraulic model showing the 100 year flood inundation depths under existing conditions. The lower left image is inundation depths if right bank levee was removed and the river re-engaged to a side channel it carved in the December 1964 flood. The lower right image shows the difference, illustrating a three foot reduction in depths in much of the river. Giving the river more space reduces the extent of inundation along the left bank.



Sandy River Basin Watershed Council Restorative Flood Response Design Project

Change in Flow Velocity during 100 year Event for Proposed Alternative 1

Hydronia RiverFlo-2D hydraulic model results for 100 year flow event (22,420 cfs) under existing and proposed alternative 1 conditions. Change in conditions derived from difference between proposed and existing.

Lambert conformal conic projection, NAD 1983
State Plane Coordinate System (OR North Zone)

Figure 34B. Model output for the 100 year flood showing changes in velocity. By removing the levee and engaging the 1964 side channel flow is distributed into an additional channel and maximum velocities throughout the reach are reduced. This diminishes the river's erosive energy and size of rock it can move. Allowing the river to widen its floodplain provides direct benefits to flood protection and enhancing fish habitat.

Figure 35. The Upper Sandy has a very high sediment transport capacity, leaving a coarse river bed comprised of large cobbles and boulders. The larger boulders reflect the size of rock needed to be stable. View from left bank at RM 40.65, July 2014, flow is from right to left.

Currently the Upper Sandy is characterized by a coarse boulder substrate (Figure 35). The larger boulders left in the river after it has eroded into mudflow deposits offer a clue to the size of rock needed to withstand the forces imposed by flood flows. Hydraulic model results indicate that the river can move boulders up to 40 inches in diameter during floods, so the size of rock needed for defensive measures should be 60 inches or greater. Model results also show that when the flood inundation width is increased from 300 ft to 1100 ft, there is a 5-fold reduction in the particle size mobilized under the mean velocity (averaged across the wetted channel area). With more room to expand the river bed ends up with a finer bed material that is more beneficial to spawning salmon.

The historic channel migration zone defines the area that the river has carved out over time and can correspond to the floodplain area. When a river is confined to a small portion of its historic migration zone it is likely to experience very rapid migration when it breaks out of its confinement, as has happened in the Upper Sandy. In an unconstrained river, the rate at which the historic migration widens over time gradually diminishes as a result of the greater frictional resistance the river experiences due to a longer channel, wider floodplain, riparian vegetation and wood material. Different portions of the Upper Sandy project area have had very different patterns of channel movement over the last two hundred years. Upstream of RM 47 the river has moved across its entire valley. This is attributed to several things:

1. the closer proximity to Mt. Hood subjects this stretch of the river to more frequent events, delivering large quantities of sediment. For example, the outflow of a debris flow in 2006 dramatically widened the river channel but, only affected areas upstream of Muddy Fork Road bridge (RM 48).

2. the area upstream of TM 47 is subject to large vertical fluctuations in river bed elevation, which drives rapid channel migration,
3. the lack of development has left the river unconstrained since historic times.

Moving downstream from RM 47, the zone of debris flow hazards is not left behind. However, the probability of debris flow occurrence is reduced since only bigger, less frequent events reach further downstream. Development within the channel migration zone begins to be more pronounced at RM 45.2, at Zigzag Village, and at RM 44.7 the river becomes constrained by development adjacent to E. Autumn Lane on the left (SE) and development off Lolo Pass Road on the right (NW). Here, large areas of development lie well within the CMZ, specifically within the high hazard area (defined as the width of the historic migration zone plus a 100 ft buffer, Sandy Risk/Hazard Mapbook 19). From RM 44.7 to the Lolo Pass Road bridge, the width of the historic migration zone decreases from approximately 600-800 ft down to less than 200 ft. The decrease is largely a result of the bridge, which constricts the river to a 60 ft wide channel, a ten-fold decrease. The erosion risk presented by such a constriction was made evident after the December 1964 flood, which not only destroyed the bridge but carved channels around both sides of it, increasing the floodplain width over 300%. The bridge was rebuilt in its original configuration in 1965. The bridge and subsequent development downstream of it, have certainly limited the natural expansion of the historic migration zone. The bridge, developed properties, and most of the valley are underlain by highly erodible mudflow deposits that extend from the Zigzag River confluence (RM 43.0) upstream to RM 43.8. This entire area is very susceptible to channel migration as reflected by the erosion that occurred during the 2011 flood along the left bank, at RM 43.3, destroying a house. In this same location, the river is currently threatening Lolo Pass Road.

Downstream of the Zigzag River, the valley bottom widens and is comprised of both mudflow deposits, channel deposits laid down prior to the survey of historic maps (1873/1882, 1914), and channel deposits within the historic migration zone. The REM maps of the valley clearly illustrate that the river carved a much larger portion of the valley bottom after the Old Maid mudflow (circa 1800) than reflected in the historic migration zone. Development in this portion of the river has not only extended well into areas the river has been in the last 200 years, but into the historic migration zone (last 100 years). The river presently is not only migrating across the areas it has been, but it continues to carve into the mudflow deposits that make up the high terraces along the valley margins, as it continues to recover from the Old Maid mudflow.

Property damages along the Upper Sandy can be attributed to several key facts:

- The river's erosive power exceeds the resistance of bank materials. During a flood the river can move boulders up to 4 ft in diameter. The river's power is reflected in the large cobbles and boulders comprising its bed, smaller material is washed away.
- Most of the river's banks are comprised of smaller material and thus easily eroded. The two primary bank materials along the Upper Sandy consist of:
    - Mudflow deposits associated with two Mt. Hood eruptive periods, the larger Timberline deposits about 1700 years ago and the Old Maid deposits about 200 years ago. These mudflows filled the entire valley and, in places, form high banks well above any flood levels. While these deposits include large boulders, they consist primarily of mudflow material and thus, despite their height, are easily eroded. As the river migrates laterally into these deposits it reclaims its original valley, increasing floodplain area and channel length.
    - Alluvial sediment was deposited by the river as it eroded mudflow deposits. This sediment is unconsolidated and can easily be remobilized by the river. Since these deposits were laid down

by the river in the last two hundred years, they underlie low lying surfaces within the valley, including flood prone areas.

In summary, the Upper Sandy's erosive power is greatest where it is confined by high banks and constrained to a single, straight channel The wider the river's floodplain, the greater the flood conveyance and energy dissipation, which in-turn can allow the river channel to increase its length by forming a more sinuous path and creating secondary channels. The natural valley widening that has taken place since the Old Maid mudflow has been slowed by historic actions to constrain the river and armor its banks.

Bank protection measures must not only address the river's ability to move large boulders, but also its tendency to scour its bed during very large storm events, thereby undercutting even the most formidable defenses. Given more space, the river would have considerably less erosive power; in other words, as high water spreads out over floodplains it slows down. Trees further slow the water and their roots hold the underlying soil together (e.g., Tsukamoto 1987; Sidle 1991) and increase the strength of river banks to resist erosion (Eaton et al. 2004; Eaton 2006; Simon and Collison 2002; Simon et al. 2006; Konsoer 2014). And when banks erode, fallen trees can form logjams that further diffuse the river's energy and even protect some areas of the floodplain from erosion (Abbe et al. 2003; Konsoer 2014). A broader vegetated floodplain, with log jams, would also afford valuable benefits for fish and wildlife habitat.

Providing the river with sufficient space lowers risks, allows for more economical and effective flood defenses, enhances fish and wildlife habitat, and improves aesthetic and recreational opportunities. Thus the principal element of an effective flood protection strategy should be to provide the river with space to accommodate channel migration and flood conveyance (Figure 36). Please refer to Appendix 19, Risk Hazard Mapbook to view high resolution risk maps.

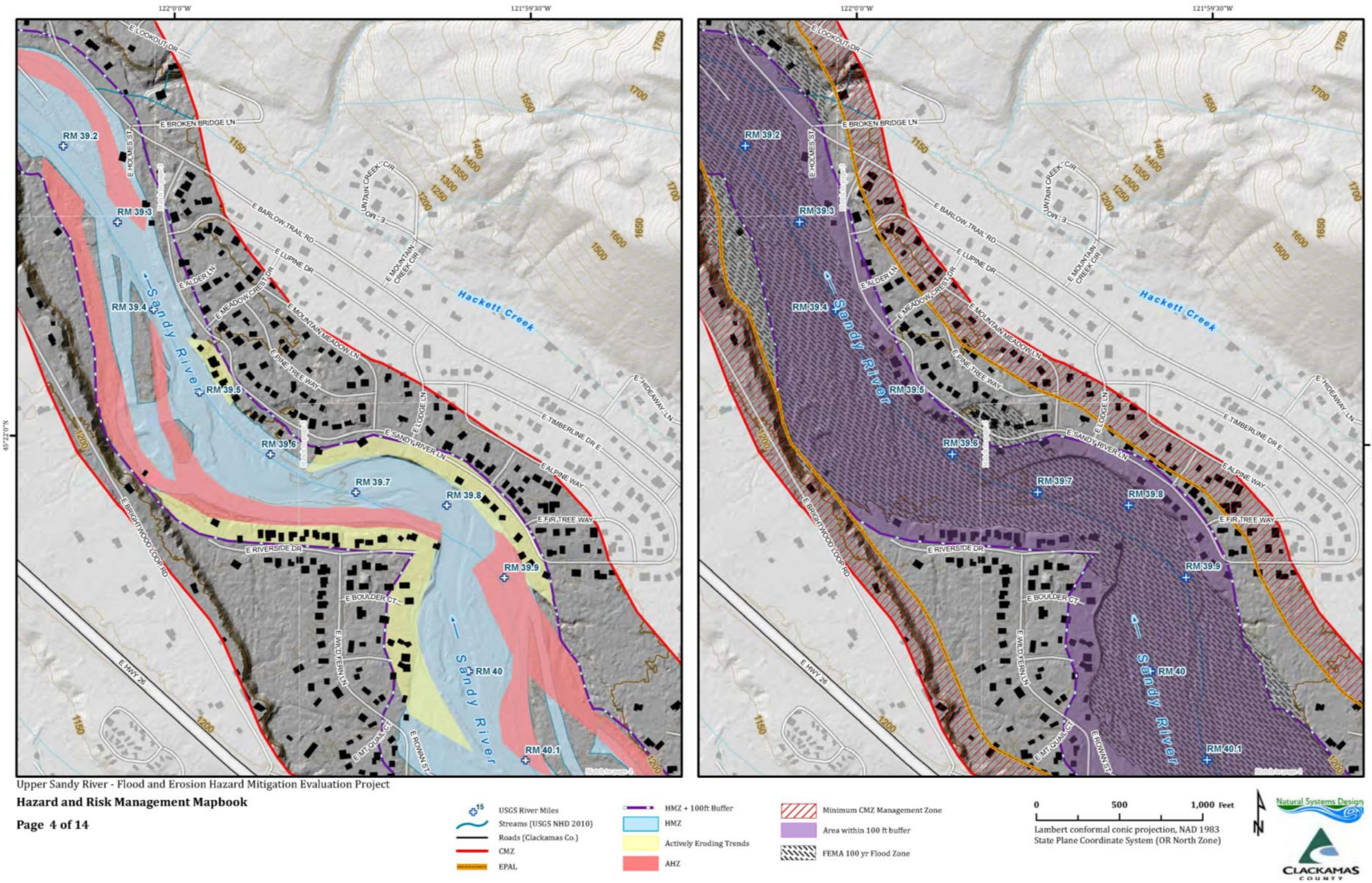


Figure 36. Maps from Risk and Hazard Mapbook prepared for Upper Sandy showing flow and erosion hazard areas, including channel migration zone (Appendix 19). The map on the right also presents an “emergency protection action line” (EPAL) that identifies boundaries of area in which channel migration can be managed.

5.2 PROBLEMS WITH TRADITIONAL FLOOD PROTECTION SOLUTIONS

Attempts to increase river bank stability by armoring river banks have had limited success. Typically, these measures don't extend deep enough into the river bed to prevent the armored bank from being undermined by the river, or to keep the armoring material from being moved by the river. Armoring can also increase flow velocities along the bank, further aggravating erosion by increasing basal shear stress at the bank toe. Armoring also confines the river, which sustains or enhances the river's high erosive power. For these reasons, armoring some areas can also have unintended adverse impacts on nearby areas. Where the river has been able to migrate and establish wider floodplain areas, its erosive power diminishes significantly.

Decisions to restrain the river at specific locations can have far-reaching effects on river behavior, flow velocity, and erosion across the river and downstream. For example, when a levee or bank protection measure is constructed from riprap, or some similar hard material, it usually extends into the active channel, taking up valuable cross sectional area. In other words it narrows or constricts the active channel. High energy flow deflecting from a hardened bank can result in increased velocity (especially at high bank full flows). Substantial erosion effects may be seen well downstream of the treated bank, resulting in the loss of shoreline property, channel floor incision and substantial damage to aquatic habitat. Specifically, erosion and scour of the stream bed surface can alter both the composition of the stream bed and the overall channel geometry, incising and simplifying the channel by smoothing out pools and riffles. Such conditions are known to damage or completely eliminate in-channel fish habitat and prevent it from forming.

Traditional flood protection directly conflicts with the laws passed in the last 40 years to protect our environment and quality of life. The collapse of the Pacific Northwest's iconic salmon fisheries has led to major changes in the regulations governing how rivers are managed, including flood protection measures. In the Sandy River, where the entire basin is the focus of habitat restoration efforts for Salmon and Steelhead listed under the Endangered Species Act (ESA), agencies and residents alike should recognize two effects of hardened banks; they create absolutely no habitat value, and they adversly affect downstream shoreline and riverbed conditions. Salmon and Steelhead require diverse and complex habitat, sometimes referred to as habitat complexity. Complex habitat includes deep pools, log structures in the water to provide feeding grounds and areas for hiding and rearing young, and for adult fish to hide from swift-moving currentsduring storm events..

5.3 UNDERLYING PRINCIPLES OF RESTORATIVE EROSION PROTECTION MEASURES

The primary causal factor of stream bed and bank erosion, assuming that channel perimeter soils are sensitive to erosion, is direct exposure to high velocity flow. At the most fundamental level it is important to understand that the velocity of water flowing over a streambed or adjacent to a bank is not uniform everywhere within the water column, and that the velocity at the boundaries is affected by several factors. For any water depth, flow velocities are typically fastest at the top of the water column and lowest at or near the bed or bank surfaces. Graphing velocity as a function of the distance from a river bank will typically take a parabolic shape, with velocity going to zero at the bank boundary and increasing quickly with distance from the bank. Slower near-bank velocities correlate to lower shear stresses acting on the bank, which reduces the potential for erosion.

Other factors affecting flow velocity that are important to restorative erosion prodection include channel roughness and riparian and bank vegetation. In general, the greater the roughness value of the boundary, the greater will be the distance from it where flow velocity are slow. (Figure 37).

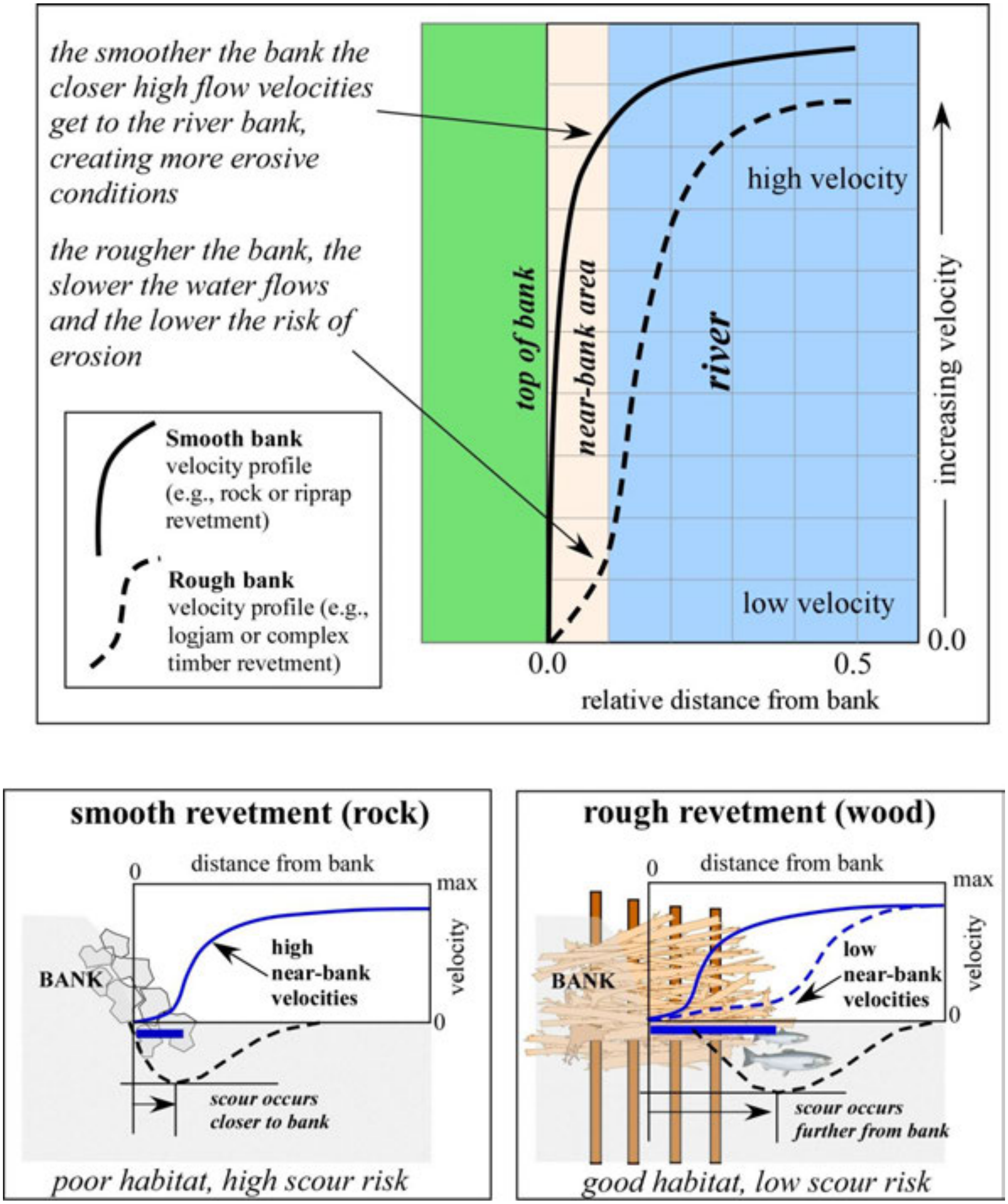


Figure 37. Illustration of how rougher banks reduce river velocities near the bank. Traditional bank protection tends to create a smooth bank where high flow velocities hug the bank (solid lines above). Where banks are roughened near-bank velocities are reduced (dashed lines), diminishing the risk of erosion and improving salmon habitat. T. Abbe.

Wood materials, whether living stems or fallen trees, are effective in increasing the roughness value of stream banks and reducing near-bank flow velocity, shear stress, and the erosive energy acting along the bank. Roughness also increases secondary flow cells or vortices along the bank, which further act to reduce high velocities along the bank (Knight et al. 1992; 1994; Blanchkaert et al. 2010; Meile et al. 2011; Konsoer 2014).

Increasing the density of riparian trees typically lower the rate of river migration, resulting in narrow, deep channels with greater relief (Gran and Paola 2001; Micheli et al. 2003; Abbe et al. 2003; Eaton 2006). Vegetation also increases soil cohesion and thus increases bank strength and resistance. Bank erosion rates along forested banks have been found to be 50-90% lower than un-forested banks (Thorne and Furbish 1995; Micheli et al. 2003; Abbe et al. 2003; Konsoer 2014). Abbe et al. (2003) found that erosion rates were dependent on tree size, which was attributed to the fact that larger trees are more likely to form stable rougheness elements with longer residence times than smaller trees. Konsoer (2014) found that tree snags situated along banks comprise primary roughness elements responsible for major changes in flow patterns along eroding banks. Flow patterns and erosion rates were compared to two similar meander bends of the Wabash River in Illinois, one with a smooth bank along agricultural land, and the other along forested land. The rougher bank was subject to more pronounced secondary flow vórtices, which slowed near-bank velocities and pushed the river's primary current further away from the bank (Figure 38), whereas the smoother bank erodes at a rate 17 times faster than the rough bank (Konsoer 2014).

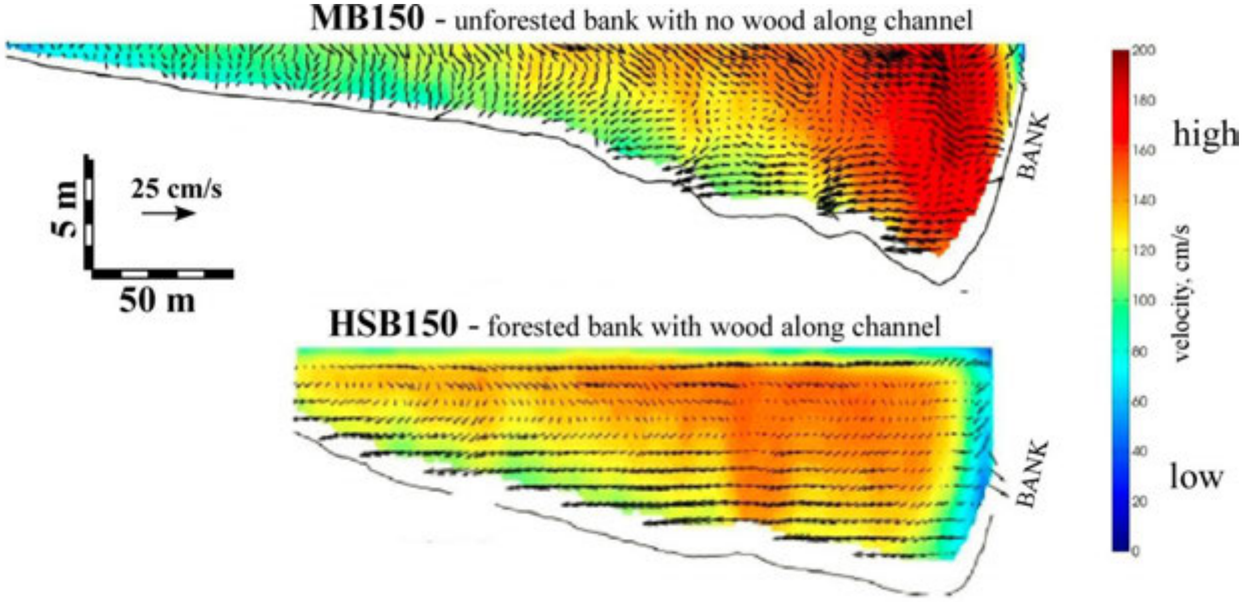


Figure 38. Flow velocity fields around two bends of Lower Wabash River, Illinois. Cross-section MB 150 is downstream of meander apex with relatively smooth bank, HSB72 is cross-section in similar location of bend where there are snags along the bank. The roughness created by the snags along HSB72 slows down velocities near the bank. Erosion rates at HSB72 are 17 times less than MB 150 (Konsoer 2014).

The slow velocities and abundant cover found in rough complex banks are ideal refugia for juvenile salmon, both from high flows and predators. Gran and Paola (2001) found that riparian vegetation increased the variance in flow directions and could increase scour depths by increasing down welling. Scour is the principal failure mechanism of most bank protection, particularly rock revetments. Once undermined, toe rocks simply roll away and compromise the entire revetment. Thus any bank protection should either be deeply embedded into the river bottom or have a self-settling design that allows it to sink into the bed while still armoring the bank. Given that the Upper Sandy channel is still cutting down (incising), scour will become an even greater risk in the future. Roughened banks can induce down welling that increases scour depths, but because these structures occupy a larger footprint, they push the scour further away from the bank where it isn't a problem (Figure 37). This is particulary important since the formation of deep scour pools beneath complex cover also creates ideal salmon habitat. By managing rivers with forest buffers and rough banks we not only reduce channel migration rates but also create more physically diverse and productive habitat benefiting fish and wildlife.

5.4 A RESTORATIVE FLOOD PROTECTION STRATEGY

A basic strategy for long-term flood erosion protection, that will also benefit fish and wildlife, was developed using the information learned about Upper Sandy River's channel migration and floodplain evolution, including the role of in-stream and floodplain roughness elements. A similar strategy has been implemented in the Upper Quinault and Upper Puyallup Rivers in Western Washington.

The plan first addresses the need to provide the river with sufficient space within an established River Management Corridor (RMC). Connecting rivers to forested floodplains helps to store flood waters and decrease flood peaks downstream (e.g., Anderson 2006; Thomas and Nesbit 2006). Within the central portion of the RMC, migration of the main river channel is acceptable (Figures 39, 40).

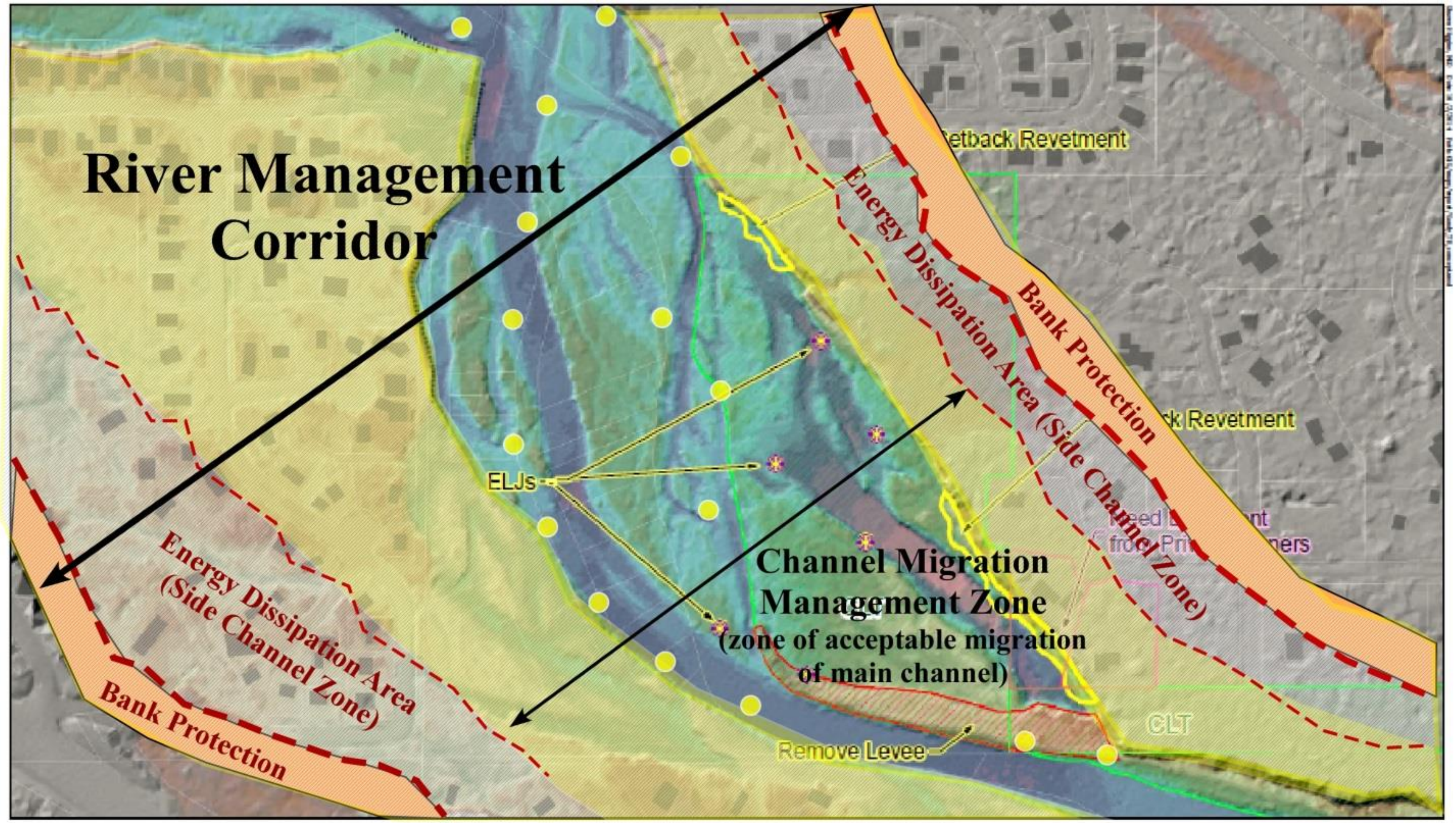


Figure 39. Spatial elements of long-term restorative flood protection strategy in the Upper Sandy River. Any land within the channel migration zone (CMZ) is at risk of erosion. Measures to limit channel migration will be most effective where the river has already established a wide floodplain or where land has been set aside to accommodate future erosion (~900-1200 ft in width). When bank protection is needed it should consist of methods that dissipate energy and create beneficial salmon habitat

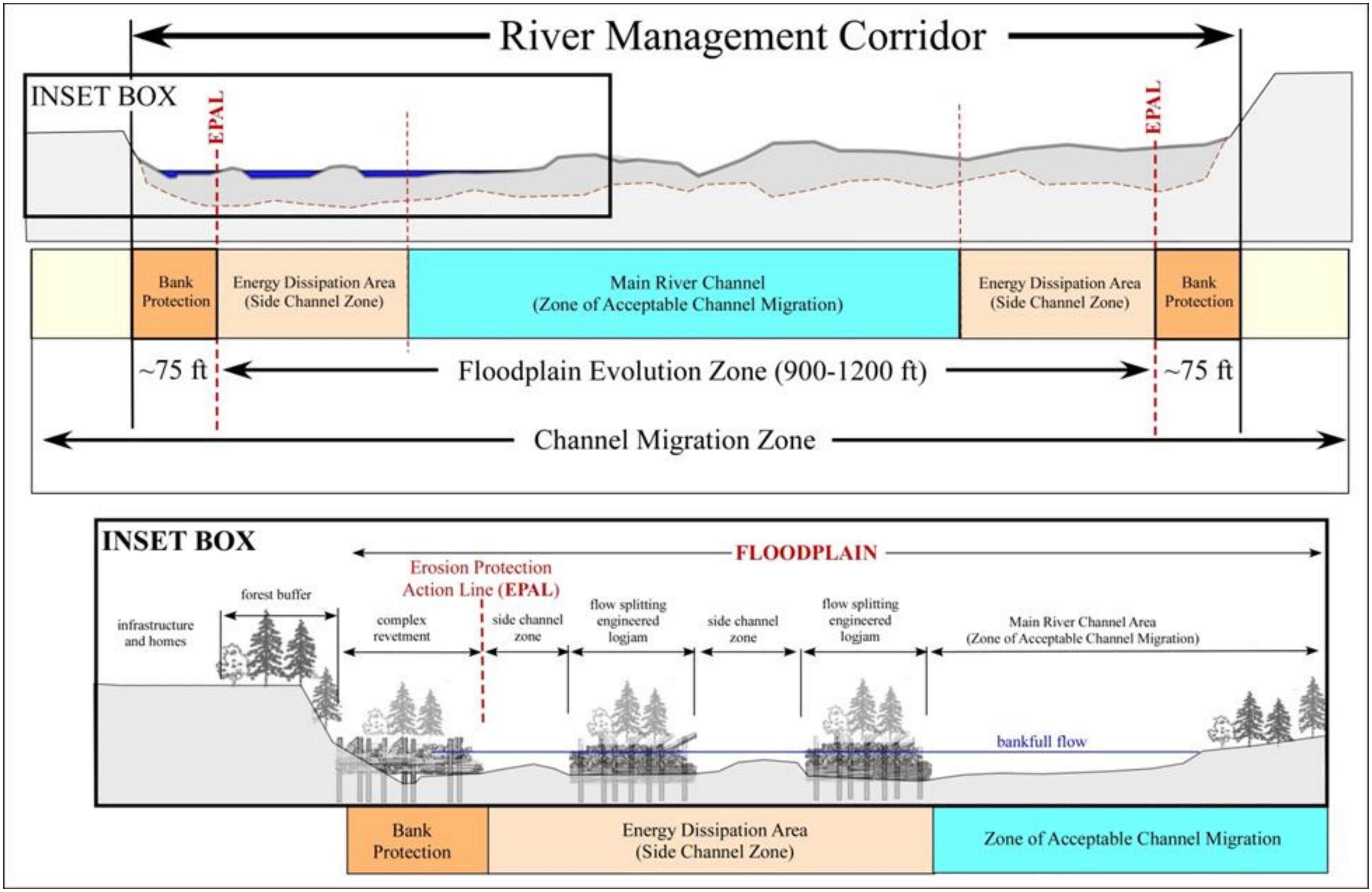


Figure 40. Conceptual valley cross-section illustrating river management corridor (RMC) erosion protection strategy within a channel migration zone (CMZ). The RMC is an area within the valley should be set aside to allow for natural channel migration and flood conveyance. At the margins restorative flood protection measures focus on dissipating energy but allowing flood conveyance in the form of less erosive side channels. The final line of defense should be roughened revetments that increase bank resistance, further reduce the river's energy and

The second basic element of the plan is to dissipate the river's energy as it approaches the margins of the RMC by splitting the main river channel into smaller side channels. Logjams also contribute to spreading flow out onto floodplains and increasing storage by raising water elevations (Abbe 2000; Brummer et al. 2006; Montgomery and Abbe 2006). This dissipation is accomplished using engineered logjams that emulate island forming natural logjams common in Pacific Northwest rivers (Abbe 2000, Abbe and Brooks 2011).

The third element of the plan is to establish a line of defense at the RMC (Figures 39, 40). This is where restorative bank protection measures should be implemented that further dissipate energy, protect the bank, and enhance fish habitat. Unlike traditional protection measures, such as rock (riprap) revetments that are relatively smooth, the preferred bank protection measures should be rough, complex, structures per the underlying principles of the previous section. The recommended future restorative flood protection strategy is summarized below:

1. **Give the river space**
    a. Establish a minimum River Management Corridor (RMC) of 900-1200 feet for acceptable channel migration and flood storage (Figure 40).
    b. Bank protection measures should not be installed where they would limit RMC to less than 900 ft without exceptional circumstances. The RMC is the area within the Erosion Protection Action Line (EPAL) on Clackamas County maps.
    c. Infrastructure and structures within the RMC (and EPAL) should be relocated to safer areas outside the channel migration zone (CMZ).
    d. Flood protection actions require a community approach and should not be undertaken on a property by property basis.
2. **Use structures that dissipate the river's energy**
    a. Allow natural logjams to form within the RMC to help dissipate the river's energy by splitting the main channel into smaller side channels and create beneficial salmon habitat.
    b. Construct flow splitting structures that break-up the main channel into smaller "side" channels before it reaches an area of concern. This can be done with an array of island forming engineered logjams (ELJs). This 'side channel zone' provides flood conveyance and habitat but keeps the highest energy of the river at bay.
3. **Build salmon friendly bank protection**
    a. Encourage and preserve mature riparian forests along the margins of the RMC to slow erosion rates.
    b. Where the river absolutely cannot be permitted to go, construct stable bank protection consisting of rough structures that dissipate energy and create habitat.
    c. Complex "rough" structures that reduce near-bank velocities and strengthen banks enough to resist the erosive power the river imposes during extreme floods.

An example layout using this strategy was developed for the Upper Puyallup River, which drains the western flank of Mt. Rainier, WA, and constructed in 2013 (Figure 41).

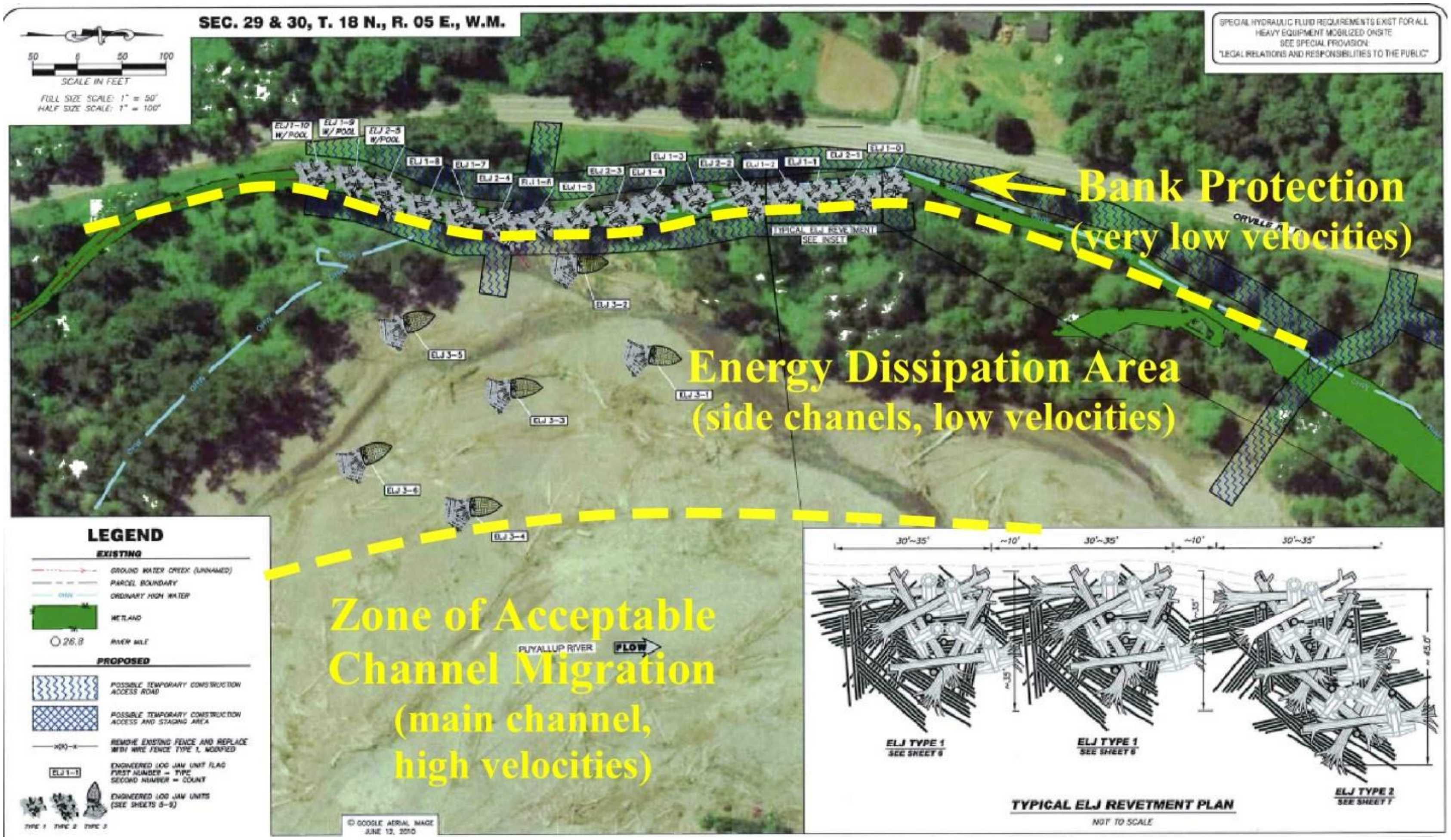


Figure 41. Example of a bank protection strategy illustrated in Figure 19. This design was done to protect a county road along the Upper Puyallup River. The river drains the western flank of Mount Rainier. Six engineered logjams were constructed in the energy dissipation area, a portion of floodplain that had previously been eroded by the river. The ELJs will establish forest islands and side channels that create salmon habitat while keeping the main channel away from the road. Bank protection was near the road consisted of a complex revetment of timber ballasted with 8 ton concrete jacks that emulate the function of wood while ensuring the structure has the needed resilience and longevity (inset in lower right). Project design by NSD and Pierce County Public Works built in 2013

The project included an array of ELJs on the margin of the zone of acceptable main stem channel migration and a complex revetment bank protection near an important county road. A forested buffer was left intact between the bank protection and road. The ELJs within the energy dissipation area form islands that split flow into smaller side channels and deflect the main channel away from the road (Figure 42) (Abbe et al. 2003; Abbe and Brooks 2011).

Figure 42. The Upper Puyallup project during high flow in 2014 looking upstream at two of engineered logjams (ELJs) in the energy dissipation area (side channel zone). View is from complex timber revetment on Upper Puyallup River's left bank. The ELJs are splitting flow into smaller channels before the flow reaches the bank. The ELJ is one of six forming an array of structures to keep the main channel from approaching the bank. Photo by Tom Nelson.

As vegetation matures on the islands they help to restore the forested floodplain and associated wetlands and side channels.

The construction of ELJs is of critical importance in any river, particularly one as powerful as the Upper Sandy. The typical approach focuses on building a deep foundation that prevents the log structure from being undermined and provides resistance to sliding and buoyancy. This type of construction requires extensive excavation and dewatering which can be challenging and expensive (Figure 43).

Figure 43. Example of engineered logjam that doesn't have self-settling elements of previous examples. This structure is deeply embedded into the river so that it can withstand scour without being compromised. Note people on right side of the structure. Pit is 16 feet deep and timber posts extend deeper. Elwha River 2014.

New approaches to building ELJs have been developed to reduce construction impacts and costs by using deformable self-settling designs. These techniques are dependent on ballast that weighs down the timber without being washed away. Two basic options that have been used for self-settling structures:

1. interlocking ballast elements (e.g.,dolosse) that don't require cable or chain
2. ballast (e.g., rock) collars that require cable or chain.

The first technique uses ballast elements that have a complex interlocking shape to better emulate the shape of natural snags. One such ballast element that has been used for over 70 years in coastal defenses are concrete jacks called dolosse (plural for "dolo") first developed in South Africa and apparently meaning "knuckle bone". Dolosse are interlocked to key structural logs within the ELJ to ensure the structure remains stable even if undermined. One advantage to a dolo-log structure is they can be constructed in deep water by attaching individual dolosse directly to logs (using rope or chain) and lowered into the river (Figure 44a).

Figure 44A/B. Using a combination of timber and dolosse has been used in Washington State as a more restorative alternative to traditional measures to protect levees and roads. The dolosse are eight ton un-reinforced concrete jacks that provide a complex interlocking shape emulating the function of natural snags. The top photo (a) shows how a dolo and attached log can be easily lowered into place and avoid expensive dewatering. Using the dolosse with logs creates a complex structure as shown in bottom photo (b) that can settle if undercut by scour, but without the need of rock or cable. The structures can be designed with lots of wood so the dolosse aren't even visible. Since they are self-settling, these structures don't need to be deeply excavated into the river bed as rock revetments or ELJs constructed only using timber (Figure 42, 43). Photos are of complex revetment built to protect a levee along the Lower Puyallup River in Fife, WA.

Concrete is an inert artificial rock so it is physically no different than using imported rock commonly used in both bank protection and river restoration projects. Since dolosse are un-reinforced, they have no internal rebar. To improve the aesthetics of dolosse they have been given bark textures and colored brown using inexpensive non-toxic water based stains (see brown dolo being lowered into place in figure 45).

Figure 45. Construction of ELJ using 8 ton dolosse in Upper Puyallup (same structures depicted in Figure 40). The dolosse offer an interlocking ballast the structure can settle into river bed if undermined without coming apart. This means the structures don't require as much excavation, lowering construction impacts and costs. Dolosse are covered with alluvium and wood so they are barely visible in completed structure. View is looking upstream into core of the structure.

A dolo-log structure is a wood structure with only enough dolosse to ensure the desired stability. The volume of wood in a completed structure should be more than twice the volume of concrete and have a cumulative wood surface area more than ten times the concrete surface area. The large surface area of wood is easily attained by incorporating large numbers of small logs within the structure. The combination of logs and dolosse is ideal for creating complex rough revetments (Figure 44b). Since the large old-growth snags that played a critical role influencing the morphology and ecology of northwest rivers (e.g., Abbe 2000; Abbe and Montgomery 2003; Brummer et al. 2006; Montgomery and Abbe 2006; Collins et al. 2011) are no longer available, viable alternatives are needed to restore our rivers. Dolosse offer one possible means of emulating the functions old-growth snags once provided in creating stable flow obstructions capable of capturing mobile wood material and forming logjams that created islands, side channels, pools and cover.

The second self-settling option, ballast collars, consists of two rocks each weighing 2 tons or more attached to one another by a segment of steel cable or chain several feet long. The collars are placed with one rock on either side of key structural logs. This way if the log is undermined it simply settles into the scour hole. Using this approach logs are first laid down and then draped with the rock collar. The technique is not as well suited for deep water placements (as the dolo-log option) unless the rock collars are securely locked completely around the log and lowered into place as a complete unit. Since the rock collars hang beside or beneath the attached log, they can be positioned out-of-sight and have little aesthetic impact (Figure 46).

Figure 46. Example of an engineered complex timber revetment bank protection creating a rough shoreline very different than traditional rock revetments found along Sandy River. The structure along the South Fork Nooksack River in northwest Washington is stabilized with timber piles and rock collars (no dolosse). Structure was built in 2011 by Lummi Indian Nation.

Complex timber revetments using rock collars such as depicted in Figure 46 have performed well in achieving the dual goals of protecting river banks which creating beneficial fish habitat. In the long-term, the wood lying above the base flow water level will break down, leaving the rock collars which will no longer provide the same function since the wood they secured was the essential roughness element. The dolosse offer a distinct advantage with regards to longevity since they will continue to provide roughness and trap wood coming down the river.

The design of bank protection measures such as complex timber revetments (whether using dolosse or rock collars) should focus on creating stable roughness elements that rapidly slows down water velocities and dissipates the river's erosive energy. The structures also strengthen the bank, making it more resistant to erosion. The low velocity and abundant interstitial area within a complex wood structure is ideal for juvenile salmon seeking refuge during floods and cover from predators year-round. Adjacent pools are ideal resting areas for adult salmon who may use nearby gravel deposits for spawning.

In summary, there are two primary approaches to ensuring the stability of in-stream structures:

- Deeply embedding the structure into the river, using piles or excavating a deep pit during construction (Figure 43)
- Creating a self-settling structure that sinks into the river bed when scour occurs. This approach requires ballast such as rock collars or large concrete jacks that interlock with the timber that won't roll away (Figures 44-46).

The fish and wildlife benefits of implementing this restorative flood protection strategy can also bring benefits for people. With more space the Sandy River will develop a more sinuous channel (bends), more side channels, more pools, and home to lots more fish. These changes add length to the river, which reduces its gradient and adds roughness, both of which reduce the river's erosive energy. Additional energy dissipation occurs because of more logjams in the river. These attributes will completely change the character of the river. Much of the Upper Sandy is comprised of a relatively simple boulder bedded channel in which deep pools and spawning gravels are rare. Once allowed to migrate and increase its channel length, the river will develop a finer texture and deep pools that won't just benefit salmon and otters, but will create wonderful summer swimming holes, sunny gravel bars, and great fishing (Figure 47).

Figure 47. Illustration of how river restoration doesn't just benefit salmon, but also people. The photos above are looking upstream at same site before and after restoration of the Mashel River in Eatonville, WA. In 2006 a rock revetment was replaced by a series of engineered logjams. The logjams formed deep pools where none had previously existed and created greater textural variance in the channel. Over 400 juvenile salmon were documented in each of the ELJ pools and during the summer the pools became popular swimming holes for Eatonville residents.

A final but important note concerns volcanic hazards and the impacts resulting from the warming climate, as described earlier in this report. With regards to volcanic hazards, all but the highest terraces of the Upper Sandy lie within areas that can be impacted by mudflows originating on Mt. Hood. Thus the primary recommendation of this study, to move people and infrastructure out of harm's way and give the river more space, will only help reduce the damages associated with volcanic hazards. Climate changes have already begun to increase temperatures, which are resulting in more rain and less snow falling within the Sandy watershed. Even relatively small climatic changes can have major impacts to flood severity (e.g., Knox 1993; see main climate discussion of this report). Permanent snow cover is decreasing, exposing large areas of unstable sediment deposits on the upper flanks of Mt. Hood. In addition, the magnitude and frequency of atmospheric river storm events hitting the Pacific Northwest are predicted to increase. This combination of factors will increase flood magnitudes, 100 year floods are also predicted to increase in frequency by 20% in the next 50 years (Hamlet et al. 2013). These changes in snowpack and storm events exacerbate flood and erosion problems. Imminent volcanic hazards, along with ongoing climatic changes, highlight the importance of implementing a comprehensive plan to protect people and the environment.

5.5 IMPLEMENTING RESTORATIVE FLOOD PROTECTION

Collaborative actions between private landowners, non-governmental conservation organizations, land trusts, and local, county, state and federal agencies are required on the Sandy River to reduce risk to people, positively influence our ecosystems particularly for sensitive species, and acknowledge the impacts of our actions on those around us. Multiple landowners must work together in order to create long-term change that saves human lives, enhances the watershed ecosystem and reverses the current potential for catastrophic damages.

Solving flooding and erosion problems in the Upper Sandy River can be done in ways that also enhance fish and wildlife habitat and the quality of life for people living in and visiting the valley. While a relatively small number of landowners may be impacted in any given flood, a large portion of the community will be impacted over time. Developing an effective and economical flood protection strategy involves everyone in the community, including frequent visitors such as those passing though on highway 26. The safest approach to living with natural hazards is to live outside the hazard area. This is the first and most important action. Property within flood and erosion hazard areas is unsafe for permanent dwelling, but it is outstanding for fish and wildlife and recreation. Landowners within hazard areas should consider working with public agencies and land trusts to sell their land or relocate to safer areas. In areas where enough space can be put aside for the river, infrastructure and property on high ground within the outer portions of the CMZ can be protected. It should be noted that any flood protection is a large undertaking involving major public works projects. Actions taken by individual landowners won't stop the river from moving elsewhere. Individual actions can also adversely impact other landowners and limit the development of long-term solutions that benefit the entire community and the valley.

Large portions of the Sandy River Valley have already been purchased and are being managed for conservation. As part of the Marmot Dam removal in 2007, Portland General Electric donated 1500 acres to the Western Rivers Conservancy (WRC). The WRC has committed to acquiring 4500 acres to create a continuous river corridor along thirteen miles of the Sandy River to create a wild river sanctuary (http://www.westernrivers.org/projectatlas/sandy-river/). The Columbia Land Trust (CLT) acquired 30 acres of floodplain in 2007 within the Upper Sandy (RM 40.1) adjacent to the Timberline Rim Community. Restoration led by the Sandy River Basin Watershed Council (SRBWC) is proposed for this site that will improve floodplain connectivity. Land Trust and Conservation organizations such as the WRC, CLT and SRBWC all work closely with landowners, Clackamas County, and State and Federal agencies and can be valuable partners in land acquisitions that will create a more sustainable river corridor in the Upper Sandy. We recommend that Clackamas County and the Sandy River Basin Partners (http://www.sandyriverpartners.org/contact.html) work together with local communities to develop a strategy for establishing a Upper Sandy River Migration Management Corridor that will reduce exposure to flood and erosion risks and sustain fish and wildlife habitat.

The use of FEMA acquisition funding has been used in multiple locations throughout the country. Some examples of those include:

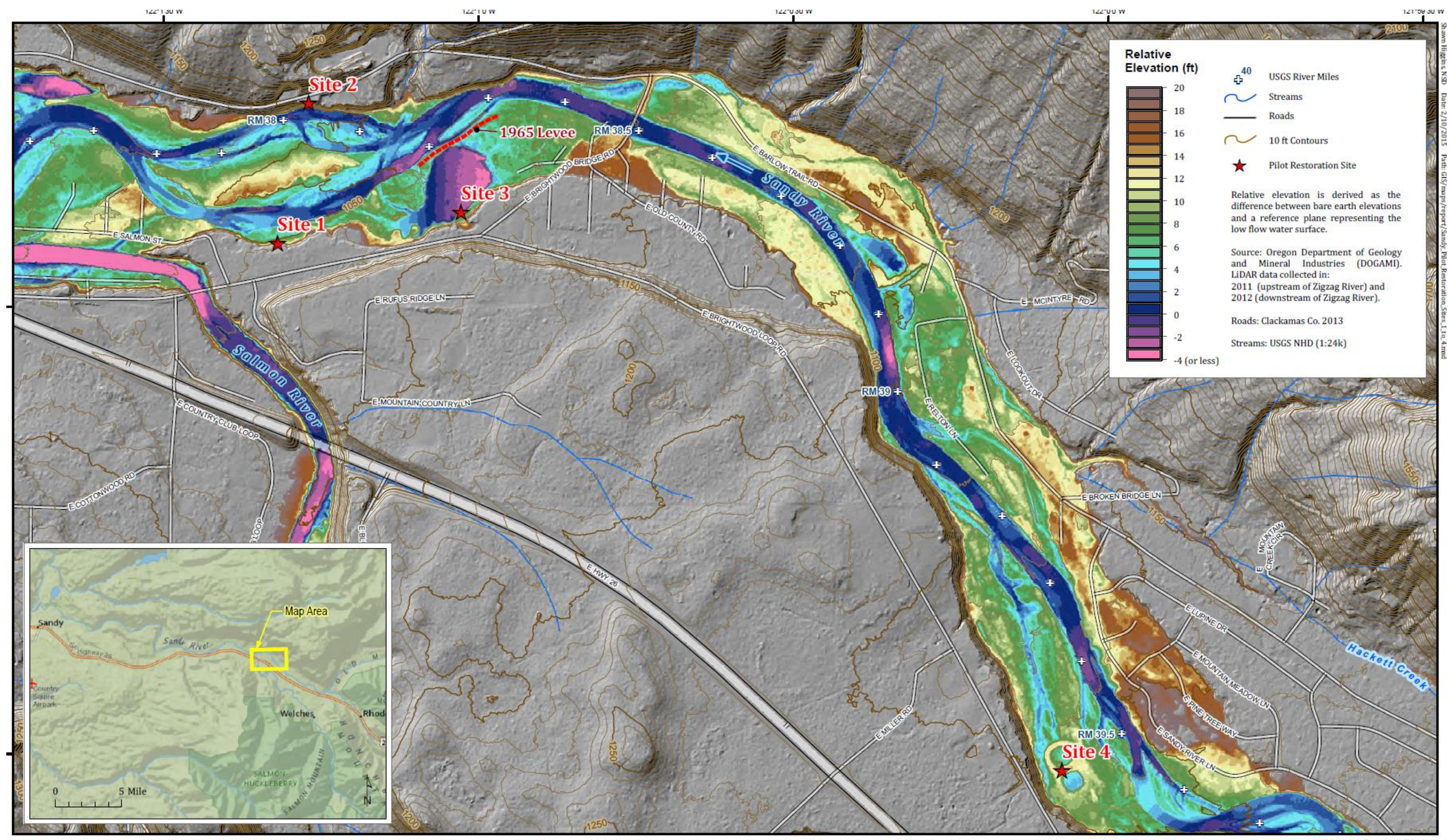
- City of Austin, TX- Onion Creek Flood Protection Program- The Army Corp of Engineers in partnership with the City of Austin has purchased more than 300 of the properties prior to a major flood event in 2013.
- Charlotte-Mecklenburg (North Carolina) Storm Water Services has purchased more than 325 flood-prone houses, apartment buildings and businesses in more than a dozen neighborhoods along various creeks in the flood zone. With this effort, more than 600 families have been moved out of the highest-risk sections of local floodplains.
- Johnson Creek- Portland, OR- The strategy in determining the properties to purchase in the Flood Protection District identified target areas based on three priorities. The identified properties were consistent with the Johnson Creek Resource Management Plan objectives, the properties were affected by repeated flooding and the area where the property was located had a significant biological resource that could be saved or built upon.

5.6 POTENTIAL FUTURE RESTORATIVE FLOOD PROTECTION PILOT PROJECTS

As part of the scope of this study, a list of potential future pilot project sites that include some or all of the elements in the restorative flood protection strategy was created. These sites will be evaluated and prioritized in the next phase of this project. Site characteristics considered include:

1. Locations close to the Erosion Protection Action Line (EPAL) near the margin of the channel migration zone (CMZ).
2. Locations in potential avulsion pathways where the river is actively moving toward.
3. Locations where historic levees can be removed to increase channel length and flood storage.
   Locations within the CMZ where protection is needed to protect critical infrastructure and where the minimum recommended channel migration management zone of 1100 feet can be secured through property acquisition.

The six sites were identified for possible future pilot projects where elements of the restorative flood protection strategy can be implemented (Figure 48a,b).



Upper Sandy River - Flood and Erosion Hazard Mitigation Evaluation Project
Restorative Flood Protection Pilot Project Sites
Sites 1 - 4

Lambert conformal conic projection, NAD 1983
State Plane Coordinate System (OR North Zone)

Natural Systems Design
CLACKAMAS COUNTY

Figure 48A Potential future restorative flood protection pilot

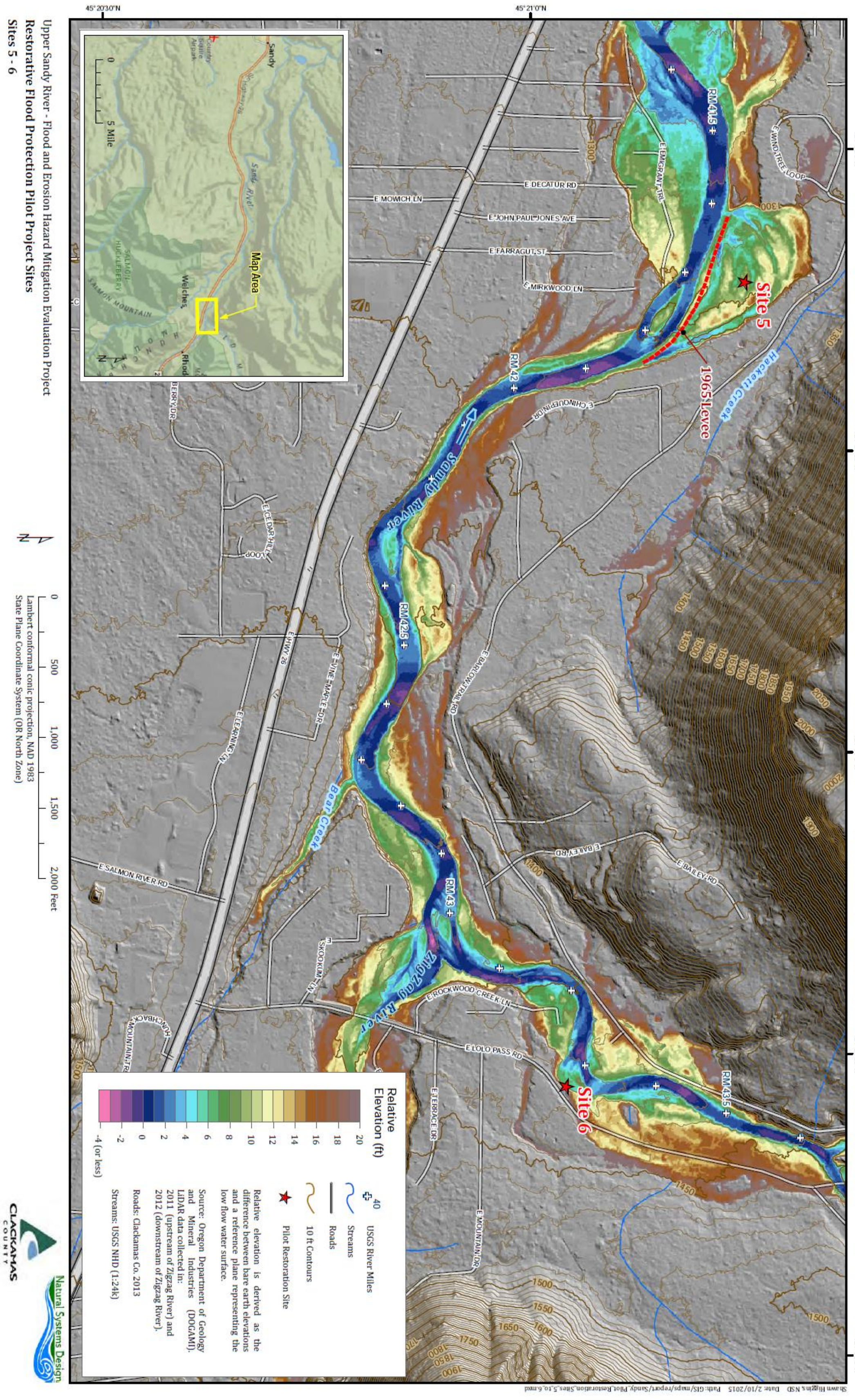


Figure 48B Potential future restorative flood protection pilot

The strategy can ultimately be applied to the entire ten mile study reach, but the six pilot project sites simply highlight locations where channel migration poses a more immediate risk to infrastructure.

The first two sites are located in a reach (RM 38.0) where the river has already established an active migration zone and where the current floodplain is close to the minimum recommended width of the river management corridor (RMC).

The third site (RM 38.2) is in a location where the 1965 levee is likely to breach and send the river into some old gravel pits (currently forming ponds). The site remains undeveloped and once the levee is breached, it will meet the minimum recommended RMC width. Neither of the first three sites are likely to have any impacts on existing homes, nor will they require removal or relocation of existing infrastructure or land acquisitions (Figure 49).

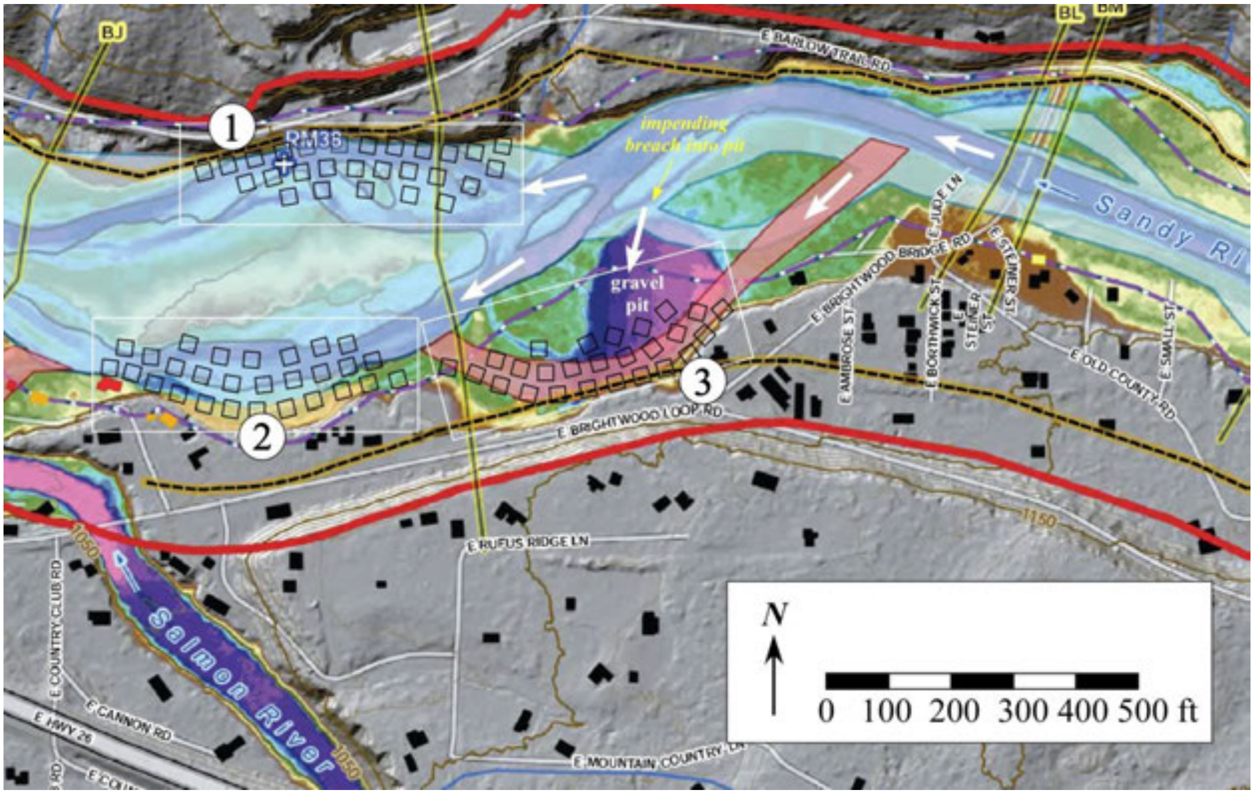


Figure 49. Example of possible future bank protection layouts for recommended pilot project sites 1, 2 and 3. Sites 1 and 2 are segment of the river where it has established an active channel migration and floodplain width close to the minimum needed and thus are sites where actions could be taken immediately. Site 3 is located in segment of the river still constrained by a levee, but the levee has begun to fail and it is likely the river will break into the gravel pit and flow south toward E. Brightwood Loop Road. When the river occupies the gravel pit it will more than double its active migration zone.

The fourth site (RM 39.5) will require relocation of an existing pipeline crossing beneath the river and county wastewater pump station that is located in the middle of the abandoned 1914/1952 river channel. The existing road is not protected from river erosion and is at risk of significant damage from both flooding and future channel migration. The river has been migrating toward the facility since the 1970s or 1980s, and this process has included the development of a small side channel near the apex of the meander bend (RM 39.55), which currently conveys water toward the maintenance road even at low flows. These conditions are expected to continue, and are likely to expose the pipeline along the south bank (left), and threaten the existing maintenance road and wastewater pump station. If the maintenance road is protected from future erosion by conventional hardscaping, it will likely deflect or steer flow across the channel toward private residential properties located on the right bank. Conversely, relocating the county infrastructure and building an array of complex wood structures to protect the high bluff along E. Brightwood Loop Road will allow the river to access its historic (1914/1952) channel, doubling the area of acceptable channel migration without structures, and help reduce the threat the river currently is imposing on the right bank at RM 39.5, where the river is actively migrating into several home sites.

Pilot project site number five (RM 41.6) is located along the north (right) side of the river, where the river migrated about 600 ft during the December 1964 flood to form a large meander (Figure 31). After the flood in 1965 a levee was constructed that cut-off the meander and a large portion of floodplain. Removing all, or portions of, this levee will open up a large area for flood storage and channel development. Restorative flood protection measures can be taken along the northern margin of the meander to ensure E. Barlow Trail Road and homes on the high terrace are protected. This project may entail acquisition of property or conservation easements, but is unlikely to have any adverse flood impacts due the large area of floodplain that will be reconnected.

Pilot project site six (RM 43.3) is located upstream of the Zigzag River confluence in a portion of the river floodplain constrained between E. Barlow Trail Road to the northwest and Lolo Pass Road to the southeast. During the 2011 flood, the river washed out a house on the left (SE) bank and nearly took out Lolo Pass Road. The home site was acquired by Clackamas County and what remained of the house was removed. Currently the left bank remains unprotected, putting Lolo Pass Road at serious risk. If re-locating Lolo Pass Road further to the southeast is not possible, restorative bank protection could be implemented but the structures would have to be built within the existing cross-section of the river which, will inevitability increase flood water elevations upstream of the project. Given that two home sites on the right (NW) bank immediately upstream are currently situated within the 100 yr flood inundation zone, it is likely that acquisition of the properties will be required to implement the project, but will help to better achieve the goals of the restorative flood protection strategy. A summary of the recommended pilot project sites is provided below.

Upper Sandy Restorative Future Potential Future Flood Protection Pilot Project Site Summaries

SITE 1			
RM	VALLEY SIDE	LANDMARKS	SITE
37.90-38.05	South	E. Brightwood Loop Rd immediately upstream of E Salmon St.	Anabranching reach with minimum migration management zone of about 800 ft. Southern channel is close to EPAL at base of high terrace.

SITE 2

RM	VALLEY SIDE	LANDMARKS	SITE
37.95-38.08	North	E Barlow Trail Road downstream of North Boulder Creek	Anabranching reach with minimum migration management zone of about 800 ft. Northern channel is at EPAL at toe of valley hillslope & road grade

SITE 3

RM	VALLEY SIDE	LANDMARKS	SITE
38.10-38.25	South	Toe of high terrace between gravel pit and E. Brightwood Bridge Rd, directly across river from North Boulder Creek	Anabranching reach where left (south) bank levee constrains migration management zone (MMZ) to about 425 ft. River is eroding levee and avulsion into gravel is imminent. Once into the pit, the MMZ will double in width, but the river channel will be directed right into terrace below E. Brightwood Bridge Rd. Implementing protection strategy prior to avulsion will better safeguard the road and allow for restoration of large portion of the valley.

SITE 4

RM	VALLEY SIDE	LANDMARKS	SITE
39.46 39.58	South	Site of current Clackamas County wastewater pump stationat toe of high terrace below E. Brightwood Loop Road	Anabranching reach that was constrained to single channel and has been widening over last several decades, threatening homes and resulted in several replacements of county wastewater pipeline crossing. Decomissioned wastewater treatment ponds are located in 1914 river channel. Currently the river is migrating to west toward the 1914 channel and has already formed new overflow channels along county maintenance road. Recommend removing at-risk county facilities, implementing restorative flood protection to give the river more space, and help reduce active erosion along right bank at RM 39.47 where several homes are at high risk.

SITE 5			
RM	VALLEY SIDE	LANDMARKS	SITE
41.60 41.82	North	Site of major expansion of channel meander resulting from December 1964 flood southwest of E Barlow Trail Road. Meander was cut-off by levee constructed in 1965	The 1965 levee constrained MMZ to less than 200 ft and cut-off over 700 ft that had opened up as a result of 1964 flood. Removing 1965 levee would immediately open up substantial flood storage and channel migration area. Restoration flood protection measures may be needed along North terrace margin

SITE 6			
RM	VALLEY SIDE	LANDMARKS	SITE
43.27 43.33	South	Site where E Lolo Pass Road is currently at imminent risk.	Site located well inside CMZ and protecting E Lolo Pass Road will require acquisition of E Cedar Point Court properties on north side of river off E Barlow Road. Home on left bank immediately downstream was acquired by Clackamas County after being damaged in 2011 flood. Properties immediately upstream along left (south) bank and along E. Rockwood Creek Lane should be considered for acquisition to expand MMZ.

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7 APPENDICES

7.1 GIS Mapbooks