June 26, 2014

Sauk Suiattle Indian Tribe
5318 Chief Brown Lane
Darrington, Washington 98241

Attention: Scott Morris, Watershed Manager

Subject: Flood and Erosion Hazard Assessment for the Sauk-Suiattle Indian Tribe Phase 1 Report for the Sauk River Climate Impacts Study

INTRODUCTION

PROBLEM STATEMENT AND STUDY OBJECTIVES

The Sauk-Suiattle Indian Tribe initiated a pilot study to assess the impacts of anticipated climate changes to both tribal infrastructure and the Sauk river ecosystem that supports fish and wildlife critical to the tribe. The Sauk-Suiattle Indian Tribe's homeland encompasses a broad area including the Sauk and Cascade River watersheds in northwestern Washington. The Sauk River is a large meandering alluvial river that flows north into the Skagit River. Sauk River Miles (RM) start at its confluence with the Skagit. The Tribe's reservation is located on an alluvial terrace within the Sauk River valley at RM 14, five miles north (downstream) of Darrington and one mile south of the Suiattle River confluence (Figure 1). In the 1940s the main channel of the Sauk River flowed on the eastern side of the reservation, directly adjacent to current residential housing. This old channel was still active and clearly evident in 1954 (Figure 2). In the last 60 years the river's main channel has been located on the eastern side of the valley but between 1989 and 2013 it has migrated back to the west, toward the reservation, at an average rate of 43 ft/yr (Figure 3). Un-interrupted at this rate, the river would reach housing within 25 years. This could potentially happen much sooner given the old 1940s channel could be rapidly re-occupied by the river (Snohomish County Surface Water Management 2009). The alluvial terrace underlying tribal housing, offices and community buildings is easily erodible and thus at serious risk given the river's tendency to migrate (Figure 3). The Tribe wanted to know whether the warming climate could worsen flood and erosion risks, and whether changes could adversely impact salmon habitat. This report focuses on flood an erosion risks and how they may be impacted by climate change.

Natural Systems Design, Inc. (NSD) prepared this report for the Sauk-Suiattle Indian Tribe as part of the first phase of an interdisciplinary effort designed to contribute critical understanding of Sauk River ecosystem dynamics and sensitivity to climatic changes. The objectives of this report are to: (1) describe the hydrology and geomorphology the Sauk River near the reservation, (2) evaluate available information on potential for climate change to affect future flood flows in the Sauk River basin, (2) document historical changes in river channel and floodplain characteristics of the Sauk-Suiattle Reach, and (3) evaluate the near-term and future threats to tribal infrastructure posed by Sauk River streambank erosion and flooding.

SITE LOCATION AND BASIN CONTEXT

The Sauk River drains a watershed encompassing 732 square miles and is a tributary of the Skagit River in northwestern Washington (see watershed map in Appendix A). The river's headwaters originate on Glacier Peak, a 10,525 foot high stratovolcano, and adjacent mountains in the north Cascades. The Suiattle River

originates from the north and east slopes of Glacier Peak, drains a watershed area of 344 square miles, and joins the Sauk River near River Mile (RM) 13. The drainage area of the Sauk River upstream of the Suiattle River confluence encompasses 314 square miles. The south and west slopes of Glacier Peak drain to the White Chuck River and join with the North and South Fork Sauk Rivers in the Upper Sauk River sub-basin. Clear Creek and Dan Creek are important tributaries joining the Sauk River near Darrington.

The watershed is primarily forested (75%) with about 15% of the area classified as shrub/scrub or grassland, 6% bare ground, 2% snow/ice, 1% water or wetland, and less than 1% developed or agricultural. There are 395 square miles of designated wilderness in the watershed (52% of the total area). 340 square miles were designated as part of the Glacier Peak Wilderness Area in 1964. The remaining areas (55 square miles) were designated in 1984 as part of the Henry Jackson and Boulder River Wilderness Areas.

The Sauk-Suiattle Indian Reservation is located on an alluvial terrace surface within in a broad glacial valley about two miles wide (Figure 1). Tribal lands on and contiguous to the Reservation cover 348 acres, including 40 acres of private residences and community areas. Tribal homes and infrastructure are currently about 1100 ft from the active channel of the Sauk River, separated by forested floodplain (Figure 3). The 4000 ft wide channel-floodplain complex is confined on both sides by Holocene lahar terraces and alluvial fan deposits (Tabor et al., 2002). In addition, the terrace, bed, and bank materials within the Sauk study reach are composed of easily eroded and transported sands and gravels (Tabor et al., 2002). As a result, channel erosion and migration is ongoing, evident in both the historical record and from field examination of existing conditions.

HYDROLOGIC ASSESSMENT

HYDROLOGIC REGIME

Seasonal Patterns of Precipitation and Streamflow

The climate of the Sauk River watershed has a seasonal variability characterized by mild, wet winters and cool, dry summers. Mean monthly temperature at Darrington (elevation 550 feet) ranges from the upper 30s in December and January to the mid-60s in July and August (Figure 4). Precipitation at Darrington averages 81 inches annually, with the majority of precipitation (77%) falling during the period between October and March (Figure 4). Precipitation increases with higher elevations due to orographic effects area averages 125 inches annually over the watershed area.

Winter precipitation generally falls as rain in the lowland areas and transitions to snow at higher elevations. There is an intermediate, transient snow zone in which snowpack persists for relatively short durations and can melt rapidly during rain-on-snow events (Christner and Harr, 1982). Washington State Department of Natural Resources (DNR) has mapped rain-on-snow zones based on average amounts of snow on the ground in in early January, relative to the amount of snow that could easily be melted during a model storm. The DNR map layer for rain-on-snow was overlaid with topographic elevations to evaluate the relative portions of the watershed within each of the three hydrologic zones. Visual interpretation of the rain-on-snow boundaries digitized by DNR yielded an approximate elevation range of 1,300 to 2,600 feet in the Sauk River watershed. In reality, rain-on-snow events occur over a broader range of elevations and fluctuate throughout the winter; however, the threshold values aid in delineating distinct zones based on the prevailing hydrologic regime. GIS analysis of the Sauk River watershed using the USGS 30-meter digital elevation model revealed that 71% of the watershed area is within the snowfall-dominated zone (elevation > 2,600 feet), 12% is within the rainfall-dominated zone (elevation < 1,300 feet), and 17% is within the transitional rain-on-snow zone (Figure 5).

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Streamflow in the Sauk River watershed has a transitional pattern including both rainfall (and rain-on-snow) dominated winter flows and spring/summer snowmelt. Annual hydrographs from gaging stations in the Upper Sauk River sub-basin (#12186000; drainage area = 152 square miles) and lower Sauk River (#12189500; drainage area = 714 square miles) show this seasonal pattern for a representative water year (October 1 to September 30) in Figure 6. A series of winter storms from October to January triggered rainfall, and rain-on-snow, driven peaks in the hydrograph. Flows recede in spring due to a decline in the intensity and frequency of frontal storms. Flows ramp upward in late spring due to snowmelt from the upper watershed with the period of peak snowmelt in June. The comparison hydrographs form the upper and lower segments of the Sauk River show a fairly consistent seasonal pattern despite the 370% increase in drainage area between the two stations.

Flood Frequency and Magnitude

Peak flow data for the U.S. Geological Survey (USGS) gaging station 12189500 near the watershed outlet (drainage area of 714 mi^2) was compiled to analyze the magnitude and frequency of flooding[1]. Data from further upstream on the Sauk near Darrington and above the White Chuck confluence at gaging station 1218600 (drainage area of 152 mi^2) was also analyzed[2]. The USGS maintains a record of the annual maximum instantaneous discharge (annual maximum series) and a partial duration series which includes all flood events exceeding a base discharge of 16,000 cfs. Flood frequency statistics were calculated from the annual maximum series by the procedure in USGS Bulletin 17B[3] for a range of recurrence intervals between 1 and 100 years (Figure 7; Table 1).

Peak flow events in the Sauk River watershed predominantly occur in response to extreme winter precipitation events. Of the 86 year record for USGS gage #12189500, the annual peak flow has occurred during the months between October and January 63 times (73% of all years). The flood of record occurred in October 2003 and was nearly matched several years later in November 2006 (Table 2). There are 10 years (12% of all years) in the annual series in which peak flow occurred during the months February-April. There are 12 years (14% of all years) in which the annual peak flow occurred in response to snowmelt during May or June.   Nine of these years (75%) occurred in the first half of the record period before 1970.

Nearly all of the large peak flows in the Sauk River watershed occur in response to atmospheric river (AR) events. These events, commonly known as a Pineapple Express due to their warm temperatures, are characterized by a narrow plume of moisture-rich air, 400-600 km wide, that delivers large amounts of water vapor from the subtropical latitudes of the central Pacific Ocean to mid-latitude locations along the west coast of the United States (Zhu and Newell, 1998). Neiman et al. (2011) investigated the connection between flooding in western Washington and AR events and reported that all peak flows in the Sauk River watershed with a recurrence interval greater than 5 years (>49,250 cfs at gage 12189500) are caused by AR events for the period 1980-2009. AR driven storm events not only delivered large amounts of precipitation, but were generally accompanied by warm air (7-10^0 F above normal) that increased freezing levels to over 6,000 feet and thus resulted in a much larger portion of the watershed area receiving precipitation in the form of rain as opposed to snow. If the event occurs when there is significant snowpack, the event can

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[1] http://nwis.waterdata.usgs.gov/nwis/peak/?site_no=12189500&agency_cd=USGS&)

[2] http://nwis.waterdata.usgs.gov/nwis/peak/?site_no=12189500&agency_cd=USGS&).

[3] http://water.usgs.gov/osw/bulletin17b/bulletin_17B.html

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deliver even higher amounts of runoff associated with melting snow. Neiman et al. (2011) further concluded that the orientation of low-level winds has an important effect on the amount of precipitation delivered to a particular basin. The Sauk River watershed lies northwest of the Olympic Mountains and due west of the Strait of Juan de Fuca. Any rare AR events hitting the north end of the Olympic Peninsula pass through the Strait directly toward Sauk. Most AR events come from the SW, so they are funneled east of the Olympic mountains and west of the Cascade mountains, flowing over Puget Sound directly toward the high North Cascades and the Sauk. The high Cascades that form the western portion of the Sauk watershed create the highest barrier to ARs moving to northwest, making the watershed particularly susceptible to intercepting these extreme precipitation events.

Table 1. Flood frequency statistics for the Sauk River.

Recurrence Interval (yrs)	Peak Flow (cfs)	
	Sauk River near Sauk (#12189500)	Sauk River above White Chuck (#12186000)
1.01	9,903	3,304
1.5	25,400	7,617
2	31,700	9,565
5	49,250	15,580
10	62,280	20,590
25	80,240	28,220
50	94,680	34,950
100	110,000	42,650

Table 2. Summary of the top ten peak flow events recorded for the Sauk River (at gaging station # 12189500).

Rank	Date	Peak Flow (cfs)
1	10/21/2003	106,000
2	12/26/1980	98,600
3	11/6/2006	86,400
4	11/24/1990	83,400
5	11/27/1949	82,400
6	11/8/1995	79,000
7	11/29/1995	73,600
8	11/10/1990	69,800
9	2/26/1932	68,500
10	12/4/1975	65,300

Land Use Impacts

Timber harvest has been the dominant land use activity impacting the watershed and approximately 17% of the Sauk River watershed has been logged in the historical period (USDA Forest Service, 1996; USDA Forest Service, 2004a; USDA Forest Service, 2004b). The USDA Forest Service has produced a GIS map layer identifying the stand year of origin for forest areas in the within Mt. Baker-Snoqualmie National Forest (map data presented in Appendix A). About 13% of the watershed area mapped in the USFS data has been harvested since 1900 with the most intense harvest activity occurring between the 1940s and 1980s (Table 3). Harvest activities have slowed since the 1980s and commercial thinning is the predominant method currently practiced in the Mt. Baker-Snoqualmie National Forest (USDA Forest Service, 1996; USDA Forest Service, 2004a; USDA Forest Service, 2004b).

Early logging practices were dominated by cutting of shingle bolts that were transported downstream along the river. A railroad was extended up the Stilliguamish River valley to Darrington around 1901 and a spur was extended north from Darrington down the Sauk River valley around 1916 to support logging of the valley bottom and adjacent hillslopes. A railroad line was extended upstream from Darrington around 1923 when a logging camp was established near the confluence with the White Chuck River. The rate of timber harvest began to accelerate in the 1930s and peaked in the1970s. Better logging practices began in the 1990s as a result of the habitat protection for species covered by the Endangered Species Act and the extent of logging has diminished. In the event that extensive clearcut logging occurs again in the watershed, it could aggravate peak runoff, reduce low flows and increase sediment inputs.

Clearcut logging practices and forest roads can alter rainfall-runoff relationships in ways that increase the peak flow magnitude associated with a given amount of precipitation (Jones and Grant, 1996). In estimating peak flow increases in relation to logging activities, it is important to consider how much land is currently logged and how much is in re-growth or successional stages. The peak flow response to timber harvest in smaller tributary subbasins may be significant; however, the magnitude of the response diminishes with increasing watershed area and for higher magnitude (more extreme) storm events (Bowling et al., 2000; Grant et al., 2008; Jones and Grant, 1996). Using data summarizing the peak flow response to harvest in the transient snow hydrologic zone in Grant et al. (2008) and a conservative assumption of 15% cleared area, the upper bound of potential increases in peak flows in the Sauk River watershed is about 10% (and likely within the limits of detection).

Table 3. Summary of timber harvest activity in the Sauk River watershed within Mt. Baker Snoqualamie National Forest (data source: U.S. Forest Service).   Total watershed area is 420,029 acres, total forest area is 366,785 acres. % of total forest area <20 yrs old provides proxy for hydrologically immature area and shows that impact of timber harvest peaked from 1970 to 1990.

Year of Origin	acres	Cumulative area cut (% of forest)	Cumulative area cut (% of watershed)	Cut areas <20 years old as % of total forest area
1910	1,534	0.4%	0.4%	0.4%
1920	1,870	0.9%	0.8%	0.9%
1930	6,810	2.8%	2.4%	2.8%
1940	6,784	4.6%	4.0%	4.2%
1950	5,582	6.2%	5.4%	5.2%
1960	6,079	7.8%	6.8%	5.0%
1970	10,178	10.6%	9.2%	6.0%
1980	7,014	12.5%	10.9%	6.3%
1990	7,987	14.7%	12.8%	6.9%
2000	1,384	15.1%	13.1%	4.5%

HISTORICAL TRENDS IN HYDROLOGIC PROCESSES

Changes in Temperature and Precipitation

Regionally averaged temperatures in the Pacific Northwest have warmed by about 1.3° F since 1895 (Kunkel et al. 2013b). Locally in the Sauk River watershed, the nearest station collecting observations of climatic data is located at the Mt Baker Snoqualmie National Forest Darrington Ranger Station (National Weather Service cooperative network station ID: 451992). The Darrington (located about Sauk RM 22) record is useful in describing climatic conditions given the long period of record (Figure 4); however, there are substantial gaps with missing data that limit use of the Darrington record for trend analysis. There is a long-term record of temperature and precipitation for the climate station at Sedro-Woolley (approximately 30 miles to the northwest in the Skagit River valley) that is part of the U.S. Historical Climatology Network to assist in the detection of climate change.

Mean annual temperature at Sedro Woolley has increased 1.8 °F since 1895 and the trend is significantly different than zero at the 95% level (Figure 8). Annual precipitation totals at Sedro Woolley show considerable variability but no trend during the historical period (Figure 9). The plot showing the cumulative departure from average aids in identifying inter-annual patterns of wet/dry years (Figure 9). Regional precipitation had a sustained wet period (increasing slope in the cumulative departure plot) from 1915 to 1924, then a generally dry period (increasing slope in the cumulative departure plot) from 1925 to 1944. A relatively wet period prevailed from 1945 to 1976. Conditions were then relatively dry in the late 1970s and have since oscillated between wet and dry years with a large range of variability.

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 we are currently within a relatively "cool" PDO regime (Figure 9). 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 and 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 al., 2005; Mote et al., 2008; Mote, 2003; Mote et al., 2005). The observed SWE trend for Miner's Ridge at an elevation of 6,900 feet in the Suiattle River headwaters shows 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) estimate a 16% loss of Cascade spring snowpack over the period 1930-2007 due to historical increases in temperature. Despite a general long term decline in SWE, the recent period since the early 1970s has been characterized by increasing snowpack as temperature trends at the 850 hPa level (roughly 5,000 feet elevation and more representative of conditions where precipitation is falling) have not increased over recent decades despite increasing trends in air temperature recorded at the surface (Stoelinga et al., 2010).

Given that flooding in the Sauk 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 western Washington. Kunkel et al. (1999) describe a modest (but not significant) increase for precipitation totals that exceed a 1-year recurrence interval over western Washington for the period 1931-1996. Madsen and Figdor (2007) analyzed one-day precipitation totals with recurrence interval of 1 year or greater for a large dataset from the National Climatic Data Center (NCDC) and report a 30% increase in the frequency of extreme precipitation for Washington. Mass et al. (2011) analyzed two-day precipitation events along the west coast and identified statistically significant increasing trends in extreme precipitation for the two stations along the Washington coast (Aberdeen and Forks). The observed trend at Aberdeen, a 2.5 inch increase in maximum annual two-day precipitation, is most relevant in that Aberdeen lies along the orientation (southwesterly) that delivers the greatest magnitude AR events to the Sauk River watershed (Neiman et al., 2011; Warner et al., 2012). Dulière et al. (2013) analyzed daily observations from stations in the Historical Climatology Network finding statistically significant increasing in northern Washington (but no significant increase in other portions of the Pacific Northwest) and compared results with simulations generated from two regional climate models (WRF and HadRM). Their comparison suggests that historical trends in precipitation are not associated with global warming but rather driven by natural variability. Regardless of whether historic trends are the result of natural variability, predicted changes due to the warming climate will surpass these historic trends in this century (see sections on *Changes in Streamflow* and *Projected Changes in Streamflow*). Recent work indicates warming temperatures will increase the water vapor content and the precipitation from extreme AR events (99th percentile) will increase by 16-38% by the end of century and increase in frequency by as much as 240% (Clifford Mass, University of Washington, personal communication).

Changes in Glaciers

Glaciers store large volumes of ice and snow in headwater areas of the Sauk River watershed and are an important control on seasonal patterns of streamflow. As of about 2001 there are approximately 12.6 mi[2] of glaciers and permanent snow/ice fields in the Sauk River watershed, about 2% of the total watershed area (Josberger et al. 2007). A large proportion of this snow/ice (9.3 mi[2] or 74% by area) lies within the Suiattle River watershed. The remaining 26% contributes runoff to the Upper Sauk River watershed,

primarily within the White Chuck River subbasin. Other headwaters in the Upper Sauk River watershed, such as the North Fork and South Fork Sauk Rivers, have only small contributions of glacial runoff.

Glaciers are highly sensitive to changes in temperature and precipitation and thus respond to relatively modest changes in climate. The South Cascade Glacier in the headwaters of the Cascade River (adjacent to the northern divide of the Suiattle River watershed) is the most studied glacier in the North Cascades and the monitoring data collected since the 1950s provide the longest running mass balance record in North America for evaluation of glacial response to climate variability and climate change (Josberger et al., 2009). Josberger et al. (2007) estimate a 67% decrease in glacier volume at South Cascade Glacier during the period 1890-2001. The annual net balance has been negative during 39 out of 58 years (67%) during the period 1958-2001. The glacier lost mass from the period 1959-1970, accumulated mass from 1970-1976, and has sustained a negative trend since 1976 (Josberger et al, 2007). Expansion of the monitoring network to measure glacier mass balance over a broader area in the North Cascades shows that there is variation between individual glaciers, however, the general trend toward glacial recession is widespread throughout the region (Granshaw and Fountain, 2006; Pelto and Riedel, 2001; Riedel and Larrabee., 2011). A study of the surface area of 321 glaciers in the North Cascades between 1958 and 1998 showed decreases from -4 to -23 percent, regardless of aspect or elevation (Fountain et al., 2009).

Glacial shrinkage does not occur uniformly; the net mass loss integrates higher rates of summer melting (and longer melt-seasons in some years) with inter-annual climate cycle effects such as the cool-season Pacific Decadal Oscillation (PDO) and ENSO, associated with above average winter accumulations. The data suggest that net gains and losses appear to vary based on the PDO and ENSO inter-decadal cycles into the 1970's. However, the last cool-season PDO, which extended from 1992 – 2005 was not sufficient to offset the warming climate signal. For the years 1998, 2001, 2003, 2004 and 2005, large winter snow accumulations associated with the PDO were overwhelmed by summer melt. If this trend continues, natural variability may become increasingly overwhelmed from climate change effects (Josberger et al, 2007).

The terminus behavior of 15 glaciers around Glacial Peak have been studied as part of the North Cascades Glacier Climate Project. These glaciers receded a distance of about 1 mile, on average, during the period between the Little Ice Age (ending approx. 1850) and the 1940s (Pelto, 2012). About half of the higher glaciers in the North Cascades experienced a brief period of glacial advance in response to a period of greater winter precipitation and cooler summer temperatures during the middle part of the twentieth century (Hubley, 1956). All of the high elevation glaciers surrounding Glacier Peak advanced during the period 1944-1976 (Pelto and Hedlund, 2001). The lower elevation and more gently sloping glaciers, including Milk Lake, Honeycomb, and White Chuck Glaciers, did not advance during this period and have retreated continuously throughout the last century (Pelto and Hedlund, 2001; Pelto, 2012). All glaciers in the Glacier Peak area have retreated since the 1980s (Pelto, 2012). Glaciers provide a strong signal of climate variability and trends. And glacial recession converts areas previously covered by year round snow to bare ground. Steep slopes of unconsolidated sediment previously covered or buttressed by snow and ice, are exposed to rainfall and higher rates of infiltration that increase the probability of mass wasting and erosion. Unstable slopes can increase the frequency of debris flows which can have catastrophic consequences to headwater streams. Increases in sediment supply and peak flows can lead to channel aggradation and widening that negatively impact salmon habitat by filling pools and side channels, and reducing overhanging cover.

Changes in Streamflow

An inventory of streamflow gaging stations from the USGS National Water Information System in the Sauk River watershed is summarized in Table 4 and plotted on the watershed map in Appendix A. Two USGS gaging stations with long term records of streamflow were selected for further analysis to evaluate historical trends. The gaging station for the Sauk River near Sauk (#12189500) records flow near the

watershed outlet and has a drainage area of 714 mi^2, whereas the station for the Sauk River above the White Chuck River (#12186000) records flow from a subbasin draining 152 mi^2 in the headwaters of the North and South Forks of the Sauk River. The record at #12186000 was truncated to water year (WY) 1929 to match the period of record analyzed for trend at #12189500. There is a third active gaging station at Darrington (#12187500) that operated previously from 1914 to 1932 and was restarted in 2011 as part of the USGS monitoring program in the Sauk River Basin. The period of record at Darrington is not of sufficient length for trend analysis.

NSD analyzed streamflow trends with the Mann-Kendall test; a non-parametric measure of the strength of the relationship between two 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 with the sign of τ indicating the direction of the observed trend. When no trend exists, the expected value of τ is zero.

Streamflow variables evaluated for the two streamflow gaging stations in the Sauk River watershed include:

1. Mean annual flow;

2. Mean winter flow (averaged over the three month period November-January);

3. Mean June flow (representing peak snowmelt runoff);

4. Peak annual flow (annual maximum flood series);

5. Number of flood peaks in the partial duration flood series (all individual flood events exceeding a base discharge of 16,000 cfs at #12189500 and 4,500 cfs at #12186000; excludes multiple peaks associated within a single event); and

6. Minimum annual flow (base flows).

The historical time series of mean annual flow at two USGS gaging stations in the Sauk River watershed show interannual and interdecadal patterns similar to that described above for the precipitation record at Sedro Woolley (Figure 10). Mean annual flows show a slightly increasing trend at both stations though neither trend is significantly different from zero at the 95% level (Table 5). Mean streamflow values for the period November-January, the three most common months for peak flows in both the annual maximum and partial duration flood series, show larger increasing trends that are significant at both stations (Figure 11).

The summer flow regime in the Sauk River has a period of high runoff driven by snowmelt followed by recession of flows in late summer until the return of substantial precipitation in fall. Trends in the mean flow for June, representing the peak snowmelt period, show a general decrease over time with a stronger relationship for the station in the upper watershed (Figure 12). Neither trend for June streamflow is significantly different from zero at the 95% level. The annual minimum flows have the same pattern (decreasing; stronger relationship in the upper watershed) and are not significantly different from zero at the 95% level (Figure 13).

The observed increase in winter streamflow at the Sauk River near Sauk (#12189500) is paired with large and highly significant increases in peak flows. Floods in the annual maximum series for #12189500 increased by 64% over the period of record (Figure 14) and the trend is significantly different from zero at the 95% level. The time series of flood peaks in the partial duration series have a corresponding trend with an 86% increase in the number of flood peaks exceeding the base discharge of 16,000 cfs over the period of record (Figure 15a). Trends for both the annual maximum and partial duration flood series for the station in the upper watershed (#12186000) are also increasing; however, trends at #12186000 have a weaker relationship and lower trend slope compared to #12189500 and the trends in the upper watershed are not

significantly different from zero at the 95% level. Maximum annual peaks for the lower Sauk gage (#12189500) shows a historical increase in flow magnitudes (Figure 15b). Starting in 2014, a simple regression of this trend would predict a 29% increase in average annual peak flow magnitude by 2080 and a 37% increase by 2100. This historic trend may be primarily due to natural variability in atmospheric moisture and how AR events track through western Washington, but it actually under-predicts peak flow increases due to the warming climate that will be discussed below. Another way in which to visualize trends is to calculate flood recurrence curves for different time periods of a flow record. Based on a log-Pearson III (LPIII) distribution, the peak flow record of the same Sauk gage (#12186000) from 1929-1975 predicts a 100 yr recurrence flow (Q100) of about 83,730 cfs. Running the same analysis for the record from 1929-2013 predicts a Q100 of about 111,871 cfs, a 33% increase over 38 years (Figure 15b).   If this historic trend is extrapolated forward from 2014, it predicts a 43% increase by 2080 (Q100=159,494cfs) and a 55% increase by 2100 (Q100=173,925 cfs) (Figure 15b).

Trend analyses based on annual series of streamflow parameters were supplemented with an alternative approach that evaluates the daily record of streamflow to assess trends over time for each date in the calendar year. The approach was developed based on similar analyses from long-term monitoring of ecological research sites by Jones et al. (2012). Results of the two long term records of streamflow in the Sauk River watershed are presented in Figure 16. Overall, there is essentially no significant trend (either increase or decrease) reflecting a change in the timing of streamflow patterns. There are select periods in October and January for which significant increases were detected. Results point to the fact that the most pronounced hydrologic change over the historical record are the increases in peak flows (Figures 14, 15a, 15b), which are more episodic in nature and only show up as outliers in the daily data or get averaged out in the mean annual.

Table 4. Inventory of USGS streamgages in the Sauk River watershed.

Site #	Name	Drainage Area (mi^2)	Period of Record	Years Data
12189500*	Sauk River near Sauk	714	1911-2014	86
12187500*	Sauk River at Darrington	293	1914-32; 2011-14	20
12186000*	Sauk River above White Chuck River	152	1917-2014	90
12189000	Suiattle River near Mansford	335	1938-1949	11
12188400	Suiattle River above Big Creek	307	1970-1979	9
12187000	Sauk River above Clear Creek	259	1910-1913	2
12186500	White Chuck River near Darrington	78	1920-1921	1
12185000	North Fork Sauk River near Barlow Pass	76	1917-1920	3
12185500	South Fork Sauk River near Barlow Pass	33	1917-1931	6
12188500	Big Creek near Mansford	21	1943-1946	3
12185300	Elliott Creek at Goat Lake Outlet	3	1982-1993	11
12189000	Suiattle River near Mansford	335	1938-1949	11

* *indicates the station is Active*

Table 5. Trend statistics for USGS gaging stations in the Sauk River watershed. Positive (negative) values of τ represent increasing (decreasing) trends. Values of τ highlighted in bold are significantly different from zero at the 95% level.

	Period	Sauk River near Sauk (#12189500)			Sauk River above White Chuck (#12186000)		
		τ	p-value	relative change	τ	p-value	relative change
Peak Annual Flow	1929-2013	**0.18**	**0.018**	**+64%**	0.09	0.233	+23%
# Flood Peaks	1929-2011	**0.21**	**0.005**	**+86%**	0.14	0.060	+62%
Mean Winter Flow	1929-2013	**0.18**	**0.014**	**+42%**	**0.15**	**0.041**	**+33%**
Mean Annual Flow	1929-2013	0.07	0.356	+8%	0.03	0.663	+3%
Mean June Flow	1929-2013	-0.04	0.561	-6%	-0.61	0.415	-10%
Min. Annual Flow	1929-2013	-0.02	0.744	-3%	-0.07	0.350	-10%

HYDROLOGIC RESPONSE TO CHANGING CLIMATIC CONDITIONS

Projected changes in temperature and precipitation

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. Mass (2014) reviewed recent model projections and notes that existing models may be too sensitive to greenhouse gas forcing and not fully accounting for natural variability over the Pacific Ocean and thus, over-predicting future increases in temperature (Mass suggests that 2° to 4° F is a more reasonable estimate of projected change over the next century).

The Skagit River Basin Climate Science Report highlights a range of impacts to watershed scale controls such as changes in precipitation, freezing levels, glaciers, and sediment supply that are important factors affecting the ecosystem and human communities in the Sauk River watershed (Lee and Hamlet, 2011). Most relevant to the present study is how future changes in climate may affect flood and erosion hazards in the study reach. The hydrologic mechanisms of primary interest to this study include: (1) climatic changes that increase the relative watershed area for which precipitation falls as rain rather than snow; and (2) increases in precipitation.

Large areas of the Sauk River watershed have transient snow hydrologic characteristics in which winter precipitation frequently falls as snow but then melts during subsequent rain-on-snow events and the cycle repeats several times throughout the season. Watersheds having these characteristics are especially sensitive to changes in climate as the transition between rainfall- and snowfall-dominated zones moves to higher elevations and a larger proportion of the watershed area is effectively contributing runoff during winter storm events (Adam et al., 2009; Elsner et al., 2010; Hamlet et al., 2001; Hamlet and Lettenmaier, 2007). There is a corresponding decline in summer baseflows in such watersheds 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 Sauk River watershed based on the average projected increase in temperature (+ 5.3° F) reported by Mote and Salathé (2010). Previous discussion of the watershed identified transitions between hydrologic zones based on historical data (Figure 5). The projected upward shift in the transient snow zone was estimated from a methodology described by Riedel (2012) 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 29% increase in the rainfall –dominated or transient snow zones that collectively form the effective watershed area during winter storms (Table 6 and Figure 17). These changes have a significant effect on precipitation patterns over the watershed which are graphically depicted in Figure 17. An important consideration, however, is that the boundaries drawn over the hypsometric curve (Figure 5 and 17) are not representative of the freezing/melting levels observed during extreme AR driven precipitation events. These storms were generally accompanied by warm air (7-10[0] F above normal) that increased freezing levels to over 6,000 feet (lower inset in Figure 17) and thus resulted in a much larger portion of the watershed area receiving precipitation in the form of rain as opposed to snow (Neiman et al., 2011). As such, the relative impacts of increasing temperatures on climatic freezing levels are expected to be most pronounced for more moderate magnitude events and may be an important factor driving the trend in mean winter streamflow (Figure 11).

Projections of future changes in precipitation over the Pacific Northwest have a much greater level of uncertainty compared to temperature; model projections range from a 10% decrease to a 20% increase in annual precipitation by the 2080s with ensemble averages around +1 to +2% for the B1 and A1B scenarios (Mote and Salathé, 2010). Changes in the seasonality of precipitation are better resolved with models predicting a general decrease in summer precipitation and increase in precipitation for other months (Mote and Salathé, 2010).

Despite relatively modest projections of change in annual precipitation for the Pacific Northwest, future changes in climate may have large impacts on hydrology of the Sauk River watershed due to changes in the frequency and magnitude of extreme precipitation events that drive winter floods. Empirical data of historical trends are consistent with hypotheses of a warming-induced intensification of the water cycle (Groisman et al., 2004; Huntington, 2006). Climate model simulations indicate a 20-30% increases in water vapor over the continental United States and an acceleration of the water cycle that yields an increase in precipitation during extreme events (Kunkel et al., 2013a). Such warming and increases in water vapor are linked to amplification of precipitation extremes (Allan and Soden, 2008; Min et al., 2011) Further, projected changes in the midlatitude jet stream may affect storm tracks and intensify precipitation in the Pacific Northwest (Salathé, 2006).

Until recently, few studies have investigated how projected changes in climate will affect the processes related to AR storm events. New research, however, suggests that heavy precipitation from AR events will be enhanced under future climatic conditions. Dettinger (2011) evaluated a suite of climate model simulations from the IPCC 2007 report (Randall et al., 2007) for variations of integrated water vapor flux (IWVF) to calculate AR statistics off the coast of California and found that, although average AR statistics do not change, the extremes change dramatically and point to future conditions with higher than historical water vapor transport rates. New research from the University of Washington Mesoscale Analysis and Forecasting Group has used the most recent IPCC climate model simulations (Taylor et al., 2012) to identify projected increases in water vapor approaching the west coast of North America over the next century, increases in the number of AR days, and large increases in precipitation associated with AR events (Mass 2014). Precipitation delivered on days of extreme water vapor flux (associated with ARs) will increase

16-38% and the frequency of these days above the 99th percentile will increase as much as 240% (Clifford Mass, Univ. Washington, personal communication 2014).

Table 6. Projected change in the relative extent of hydrologic zones in the Sauk River watershed based on the dominant form of winter precipitation. The spatial extent of hydrologic zones is mapped in Figure 17.

	Rainfall Dominated	Transient Snow Zone	Snowfall Dominated
Historical	12%	17%	71%
2080s*	32%	26%	42%
Projected Change	**+20%**	**+ 9%**	**- 29%**

*assumes 5.3° F increase in temperature (Mote and Salathé, 2010)
  and 1,500 ft increase in elevation threshold (Riedel, 2012)

Projected changes in streamflow

Streamflow characteristics in the Sauk River integrate the hydrologic effects of upstream controls including climate, geology, and land use. As such, changes in temperature and precipitation described above for the future climate condition are anticipated to drive changes in the hydrologic regime. Key outcomes of this process include changes in the seasonal distribution of flow and changes in the frequency and magnitude of flood flows.

The University of Washington Climate Impacts Group (CIG) developed a comprehensive hydrologic database to support climate change planning and assessment in the Pacific Northwest that 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 Sauk River watershed were downloaded from the project website[4] and evaluated to support assessment of flood and erosion impacts of the Sauk-Suiattle reach.

Selected model output highlighting changes in temperature, precipitation, snowpack, and runoff for the A1B (moderate emissions scenario) are presented in Figure 18. Simulated changes in temperature and precipitation for the Sauk River watershed closely mirror the regional projections described above (warmer temperatures and slightly greater precipitation in winter). The corresponding reduction in SWE in April (peak snowpack) is 52% by the 2080s. Note this is a more dramatic change than that predicted by Stoelinga et al. (2010) for a similar rise in temperature (Stoelinga et al.'s projection would yield a 37% decline in SWE for the same rise in temperature). 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 (35% 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 (73% increase in January streamflow by 2080s).

Geological records from multiple regions have shown a high sensitivity of flood frequency and magnitude in response to relatively modest changes in climate(Knox, 1993; Knox, 2000). The projected climatic changes for the Pacific Northwest in coming decades make transient snow (mixed rain and snow)

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

Natural Systems Design

watersheds such as the Sauk River among the most sensitive to increased flood frequency and magnitude (Hamlet and Lettenmaier, 2007). Assessment of extreme flood events in the CIG study evaluated simulated daily flood statistics at the 20, 50 and 100-year return intervals (Hamlet et al., 2013; Hamlet et al., 2010). The output generated for the Sauk River are presented below in Table 7 and Figure 19 (top graph). The 1-day, 100-year recurrence interval flow is projected to increase 51% by the 2080s. This is greater than the 43% increase predicted from historic trends (see previous section on *Changes in Streamflow*). Even greater increases are projected at lower recurrence interval floods (Table 7). The frequency of extreme events like the 100 yr flood are predicted to increase by as much as 240% (Clifford Mass, Univ. Washington, personal communication 2014).

Table 7. Projected increase in daily flood statistics for the Sauk River near Sauk (#12189500). Data source: Hamlet et al., 2010.

Recurrence Interval (yrs)	Historical (cfs)	2080s* (cfs)	Change
20	28,290	46,230	+63%
50	34,560	54,160	+57%
100	39,960	60,270	+51%

*ensemble average for hybrid delta scenarios (2070-2099)

Hydraulic response to projected changes

NSD ran a hydraulic simulation of the Middle Sauk River to evaluate anticipated increases flood discharge near the Sauk-Suiattle Reservation projected the CIG hydrologic model. Snohomish County provided a copy of the hydraulic model previously developed for the Sauk River Comprehensive Flood/Erosion Control Management Plan. The model is the U.S. Army Corps of Engineers' River Analysis System (HEC-RAS) v4.1.0, a one-dimensional step-backwater hydraulic model. The model domain covered the river segment from the Suiattle River confluence upstream to Darrington. The 100-year peak flood simulation previously developed for the Flood/Erosion Control Management Plan was assumed to represent the present condition. The 100-year peak flow value was then increased by 50% to simulate an increase corresponding to the projected change by the 2080s from the CIG modeling study (Figure 19, top graphic), and consistent with extrapolating historic trends. All else being equal, this increase was shown to produce a 2.4 ft increase in water surface elevation (Figure 19, bottom graphic). This rise will significantly increase flooding and damages to property and infrastructure on the Sauk-Suiattle Reservation. More concerning, the expected increases in the magnitude and frequency of extreme flow events will increase the probability of the Sauk River migrating into the reservation.

HISTORIC CHANNEL CHANGES AND EROSION HAZARD ASSESSMENT

This section presents an assessment of existing geomorphic characteristics and historic channel changes for an approximately 2 mile long segment of the Sauk River upstream of the Suiattle River confluence. The study area is located adjacent to the Sauk-Suiattle Conservation Area, within which the Sauk-Suiattle Indian Tribe has purchased over 250 acres of the floodplain between the Suiattle River and Bryson Road since 2008. The Sauk-Suiattle sub-reach was identified by the Tribe's Natural Resources Department as an important segment of the Sauk River that is sensitive to changes in watershed conditions in terms of risk to habitat and risk to infrastructure. The purpose of the existing conditions assessment is to characterize baseline geomorphic conditions as part of a pilot project that aims to evaluate the potential river channel response to anticipated climate changes in the basin.

The objectives of this phase of the project include identifying the primary mechanisms of channel migration, evaluating river stability over time, and assessing the potential influence of anticipated climate changes on geomorphic processes in the Sauk-Suiattle sub-reach. This initial phase will be expanded in future tasks to collaborate with a multidisciplinary team to construct a conceptual model of the physical and biologic response to changing watershed conditions. The location of the tribe's current reservation poses unacceptable flood risks and land more suitable for development (traditional tribal settlement areas outside any flood or landslide hazard areas) should be secured and developed as soon as possible so that the current reservation can be reforested and retained by the Tribe as a natural resource area.

EXISTING DATA AND PREVIOUS STUDIES

NSD assessed geomorphic conditions for the Sauk-Suiattle sub-reach to compile a summary of physical characteristics describing baseline conditions. Channel and floodplain characteristics were interpreted from a review of GIS data sources and existing information. Data sources compiled for this work are summarized in the list below.

Digital Elevation Models (DEM)
- 2005 Bare Earth LIDAR DEM (6-foot grid cell resolution)
- 2005 Top Surface (First Return) LIDAR DEM
- USGS 1/3 arc-second (10-meter) DEM

Geologic Maps
- Geologic Map Of The Sauk River 30- By 60-Minute (1:100,000) Quadrangle (Tabor et al., 2002)
- GIS database from WA DNR: Digital Geology of Washington State at 1:100,000 Scale, version 3.0
  - Digital version of data mapped by Tabor et al. (2002)
- Geologic Map of the Darrington 7.5-minute (1:24,000) Quadrangle (Dragovich et al., 2002)

Aerial imagery and GIS database of historic channel locations
- Time series of imagery compiled by the Skagit River Systems Cooperative (SRSC):
  - 1949
  - 1964 (not full coverage)
  - 1974
  - 1981
  - 1992
  - 1998
  - 2004
  - 2006

- Additional historic imagery obtained from USGS for the years:
  - 1954
  - 1963

- Recent orthoimagery
  - 2011 (USDA NAIP)

GIS database of historic channel alignments

- GIS polygons produced by the SRSC using the time series of historic imagery 1944-2006

Historic Maps

- 1884 General Land Office Plat Map: Cadastral Survey 33-10E-A, Township 33 North, Range 10 East, Willamette Meridian, WA
- 1899 USGS Topographic Map (1:125,000), Stillaguamish Quadrangle
- 1966 USGS Topographic Maps (1:24,000), Darrington Quadrangle
- 1982 edition (photorevised) USGS Topographic Maps (1:24,000), Darrington Quadrangle

Hydrography

- USGS National Hydrographic Dataset (NHD), streams and water bodies
  - High resolution (1:24,000)
  - Medium resolution (1:100,000)
- FEMA Flood Data (publication date: 1996)

Previous studies

Existing information was reviewed in two technical memoranda describing geomorphic analyses conducted to guide development of the Sauk River Comprehensive Floodplain Hazard Management Plan (Snohomish County Surface Water Management, 2009). In the first study examined channel gradient and width, stream bed grain sizes, sediment transport characteristics, and channel migration patterns were assessed for a 10.5 mile reach between Clear Creek (located upstream of Darrington) and the Suiattle River confluence (DeVries, 2008). The assessment delineated distinct geomorphic sub-reaches and an evaluation of channel stability (aggradation or degradation), based on differeces in stream channel characteristics and channel migration processes The second study (DeVries and Madsen, 2008) assessed avulsion risks in the Sauk from Clear Creek downstream to the Suiattle River confluence. Key findings of these previous studies are summarized as part of the baseline description of existing geomorphic conditions for the Sauk-Suiattle sub-reach.

GEOLOGIC SETTING

The fluvial landforms and geomorphic features in the Sauk River Valley display characteristics reflecting the legacy of glacial, volcanic, tectonic and erosion processes which have shaped the landscape through the Quaternary Period (beginning 2.6 million years ago). Much of the present day topography comprising the Puget Sound Area is a direct product of continental glaciation, which advanced into and retreated from the Puget Lowland several times during the Quaternary Period. Alpine glaciations also sculpted the Cascades. The most recent episode of continental ice sheet advance, known as the Vashon Stade of the Fraser Glaciation, covered the Puget Lowland beginning approximately 18,000 years ago, and ending about 13,000 years before present (Booth, 1987; Porter and Swanson, 1998).   The ice sheet is thought to have been approximately 3,000 feet thick at the present day location of Seattle, increasing to a thickness of over 5,500

feet near the U.S.-Canadian border (Armstrong et al., 1965). Glacial deposits from this time period filled portions of the Lowland and crop out along the Sauk River Valley (Dragovich et al., 2002). Repeated episodes of advancing / retreating glacial ice played a prominent role in the topography the of the Skagit and Sauk River drainage basins.

Historically, the Skagit and Sauk Rivers followed westward and northward flow directions. However, for some period of time during a period of glaciation, drainage from the Upper Skagit Basin was diverted southward into the lower Sauk River Valley by a plug of sediment deposited in the Skagit River Valley near the town of Rockport. Meltwater discharge from the Upper Skagit carved out and enlarged the Sauk valley to the present day size, and captured the lesser Suiattle River discharge, as it flowed south to the location of Darrington, where it joined with the Sauk River and flowed west into the North Fork Stillaguamish Valley. Eventually, the Skagit River cut through the Rockport sediment plug, redirecting the river into its original course and abandoning the lower-middle Sauk River Valley. For a short period after the Skagit left the Sauk valley the Sauk River, and most likely the Suiattle, continued to drain westerly into the North Fork Stillaguamish Valley. Two post-glacial eruptive periods, approximately 12,500 years ago and 5,500 years ago, produced large lahars (volcanic mudflows) originating from Glacier Peak that deposited material in lowland valleys. The lahar deposits blanketed the valley floor in the immediate vicinity of the town of Darrington and diverted Sauk River flow into its modern alignment (Beget 1982, Vance 1957). The Sauk River has since incised through the lahar deposits, leaving terraces that occupy parts of the Sauk River Valley between Darrington and the Suiattle River confluence (Figure 20).

Sediment supply

Alpine glaciers are very effective at eroding mountains and contributing a disproportionate amount of unconsolidated sediment to the watershed. One of the most significant legacies evident in the Sauk Basin is the large amount of sediment that is stored in glaciated areas and available for transport via mass wasting and fluvial conveyance. Sediment sources found in the Sauk headwaters include:

- Quaternary landslide deposits located along valley walls
- Glacial deposits from the Cordilleran Ice Sheet (glacial lake sediments at 3000' elevation
- Recent alpine glacial deposits
- Paraglacial deposits
- The Suiattle formation, a large depositional band of highly erodible fine sediment

Sediment loads in rivers draining glaciated volcanoes have been found to be about an order of magnitude greater than loads in rivers draining non-glaciated mountainous terrain (Czuba et al., 2012; Czuba et al., 2011). Mass wasting and fluvial processes act in concert to efficiently deliver sediment from the upper flanks of volcanoes into downstream rivers. Near the top of the mountain, frequent rockfall and debris avalanches supply colluvium to glaciers surrounding Mount Rainier. These glaciers, in turn, carry sediment downslope within the ice matrix, eventually depositing the load on moraines near the glacier termini. Glacier outburst floods that spawn debris flows are caused by both summer melting and heavy rainfall associated with ARs (Copeland, 2009; Lancaster et al., 2012; Walder and Driedger, 1994); these events carry large sediment loads downstream into the fluvial network. Once in the rivers, large floods transport sediment with the potential to cause localized aggradation and damage roads and bridges (Czuba et al., 2012).

Landuse can also increase sediment production above background levels. Swanson and Dyrness (1975) found that sediment production from large timber clear cuts in the Oregon Cascades can be three times higher than equally sized forested areas, and as much as 5 times higher, depending on the number of access roads included in the area. Other studies have well documented increases in sediment yield due to landslides related to forest clearing (Kitamura and Namba 1981, Tsukamoto 1987, Sidle 1991, Chappell et

al. 2004, Gomi et al. 2004, Constantine et al. 2005). More recent research has shown that sediment production volumes (following the clear cut) decrease substantially after about 25 years of the initial harvest, in response to improved harvesting methods and natural re-vegetation of the clear cut (Imaizumi et al. 2008).

RIVER CHANNEL AND FLOODPLAIN CHARACTERISTICS

The Sauk-Suiattle sub-reach of the Middle Sauk River is characterized by a complex mosaic of alluvial landforms that developed in response to geomorphic processes operating throughout the Holocene period (the 13,000 yr period following the most recent glacial recession) and more recently in response to human land use practices. NSD assessed existing geomorphic characteristics of the study area by reviewing available LiDAR and time series aerial photographs, and compiling field observations and measurements compiled during reconnaissance in November 2012.

The 2005 LIDAR DEM, which presents the most recent topographic surface, was used to identify and measure channel and floodplain characteristics. It is important to note, however, that topographic features within and adjacent to the active channel have changed since 2005. Multiple peak flow events have occurred since the LIDAR data were collected and channel migration has triggered changes in channel pattern, location and sinuosity. The greatest peak flow magnitude during the period since LIDAR data were collected was 86,400 cfs at the gage near Sauk (#12189500); exceeding the 25-year flood recurrence interval event. A total of 12 peak flow events have exceeded the magnitude of a 1.5 year recurrence interval event during this period (approximate bankfull flow moving bedload).

NSD processed the 2005 LIDAR DEM to extract longitudinal and cross-sectional profiles and to derive a relative elevation model (REM) in which ground surface elevations of floodplain, side channel, and terrace areas are expressed relative to the low flow water surface elevation in the main channel (Figure 21). A REM map using the water surface elevation (wsel) of the river's centerline (at time LiDAR was acquired) as the datum for determining relative elevations of the surrounding landscape. The elevation difference of every pixel and the river wsel along a valley cross-section is calculated, producing a map showing how high or low a given location is relative to the river. The REM surface enables detailed mapping of floodplain microtopography for use in assessing landform characteristics.

Regional / Local Context

The Sauk River descends from steep headwater tributaries through a U-shaped valley that opens onto the floor of the former glacial meltwater channel that conveyed the combined flows of the Skagit-Suiattle-Sauk Rivers to the west, currently occupied by the Town of Darrington. From Darrington, the modern day river follows a northwesterly course through the melt water channel to its confluence with the Skagit River. The meltwater channel is broad, measuring from 1 to 1.5 miles wide; the valley floor is confined by Glacier Peak volcaniclastic and lahar deposits primarily along the left side of the valley, and remnants of the lahar combined with alluvial fan deposits along the right side of the valley. Through the U-shaped valley and adjacent to Darrington, the modern active channel is tightly to moderately confined by either the valley width and/or relatively thick terraces formed by lahar deposits (Dragovich et, al, 2002). Downstream of Darrington, from about RM 21 to RM 20 the valley floor broadens markedly and remains relatively constant down to about RM 15, where the active channel corridor goes from about 4200 ft in width to about 2600 ft at RM 14 and becomes confined by lahar deposits (Qvsw) on the Eastside of the valley (Figure 20). The Suiattle River alluvial fan further constrains the active channel corridor width down to about 1200 ft at RM 13.5 and about 600 ft at RM 13.0, reducing corridor to less than 15% of its width above RM 15. The location of the Suiattle–Sauk confluence changes over time depending on the Suiattle's position on its fan. The confluence has been in different locations over a 3700 ft segment of the Sauk, between RM

12.9 to 13.6. The Sauk drops approximately 10.5 ft over this distance. The confluence is currently located at RM 13, but had been located about 2600 ft upstream in 1954, which is why RM 0 for the Suiattle is located at Sauk RM 13.5 (Figure 2). The REM map shows the relic outlet channels of the Suiattle River (Figure 21). Given the Suiattle's alluvial fan has acted to constrain the Sauk's floodplain, the confluence location may influence the local gradient of the Sauk into the project area (Figures 21,22).

Over the length of the drainage basin from the White Chuck River to the Skagit, the valley gradient displays a generally concave profile along the mainstem channel (Figure 22). The channel gradient is about 0.5 percent upstream of Darrington and decreases to less than 0.3 percent through the study reach.

The channel patterns observed in historic aerial photographs are generally consistent with the gradients and topographic/geologic confinement described above. Through the steeper upper U-shaped valley above Darrington (0.5 percent), the active channel corridor is generally straight and narrow with only a few channel sections sufficiently wide to accommodate the development of split flow channels and bars. The channel pattern primarily consists of long arcing bends; the channel has a sinuosity of 1.19, which is relatively low. These conditions indicate that sediment entering the active channel corridor from source areas upstream of, or adjacent to this reach is typically transported through the reach to the melt water valley.

In the wider, lower gradient valley section downstream of Darrington, (<0.3%) the active channel corridor and dominant channel pattern differ considerably. Figure 23 presents a geomorphic map identifying the active channel, the active floodplain, and two terrace surfaces in the study area. The active channel is defined as the composite area occupied by the low flow channel and adjacent un-vegetated bars and low relief alluvial surfaces roughly 4 feet above the low flow water surface. The active floodplain is interpreted as the area adjacent to the active channel, including vegetated bars and alluvial surfaces created by channel migration that are subject to relatively frequent inundation and overbank deposition during peak flows. The floodplain is dissected by side channels and generally conforms to a relative elevation range of 4 to 8 feet above the elevation of the water surface on the REM map (Figure 21). The low terrace surface, elevated approximately 6 to 8 feet above the modern floodplain, occupies a portion of the left side of the valley floor. Smaller remnants of this terrace can be identified as islands of higher ground within the active stream corridor and active flood plain. A terrace is defined as a former floodplain that has been disconnected from the active channel by either uplift or incision. The 6 to 8 foot high terrace may have been an active floodplain in relatively recent history, but the exact timing of its formation and subsequent abandonment is unknown. The low terrace is positioned adjacent to and just above the predicted elevation of the 100-year recurrence interval flood (Snohomish County, 2009). A second terrace surface that is elevated approximately 25 feet above the modern floodplain is also present along the left margin of the valley. The area of this upper terrace, as identified in the LIDAR DEM and REM (Figure 21), conforms to geologic mapping of Holocene lahar deposits (Dragovich et al., 2002); it extends from Darrington to about RM 15 and underlies State Route 530 and the western perimeter of the Sauk-Suiattle Indian reservation.

Through this reach, the active channel corridor is characterized by a multi-threaded channel pattern consisting of a dominant channel flanked by broad gravel bar surfaces, occasional split flow channels (where the dominant channel is bifurcated by bars), and side channels, which often occupy abandoned channels currently separated from the dominant channel by vegetated floodplain surfaces. The dominant channel has the form of large sinuous bends subject to lateral and downstream migration and episodic avulsion. These conditions are driven primarily by the deposition of sediment transported in from the steeper reaches upstream of Darrington. Active deposition in a reach where channel gradient is decreasing will typically promote the formation of multiple relatively shallow channels subject to lateral shifting, abandonment/avulsion, and reoccupation determined by flow displacement and/or deflection caused by channel in-filling and/or flow deflection from new deposition.

As previously described, the Sauk becomes more confined at RM 14 as it approaches the Suiattle River alluvial fan. The Suiattle fan forms a terrace-like surface about 12 ft above the Sauk River from about RM 13.6 to 12.9, confining the Sauk floodplain to about 15% of its upstream width (Figure 21). Given the Sauk's low gradient in this part of its valley and its lateral confinement, it would have been periodically backwatered upstream of the Suiattle during high flows. The segment of the river effected by backwatering would be subject to greater bedload deposition which could trigger periods of accelerated channel migration. The Sauk-Suiattle reservation is located immediately upstream of the Suiattle alluvial fan (RM 14, Figure 21), within the segment of the Sauk that is prone to bed aggradation and channel migration. Predicted increases in peak flows and sediment supply from the Suiattle River are likely to have a more pronounced influence on the Sauk, increasing erosion and flood hazards to the reservation.

As previously mentioned, the active flood plain and two terraces between Darrington and the Suiattle confluence contains privately held timbered land. Most of the timber on the upper and lower terraces, and the west valley wall had been harvested by 1949. In the vicinity of the Reservation and areas north and south of its boundaries, timber was cleared well before 1949 and converted to pasture or crops. Micheli et al. (2003) found that bank erosion rates into agricultural land along the Sacramento river where twice that of forested areas. Abbe et al. (2003) correlated erosion rates along the Queets and Hoh Rivers to the size of forest trees, areas with tree diameters averaging 21 inches or less experienced erosion rates more than twice as high as areas with larger trees. Based on these studies, erosion rates along the Sauk between Darrington and the Suiattle confluence have likely been well above those experienced prior to European settlement. The increase in bank strength attributed to riparian vegetation not only effects bank erosion rates, but the hydraulic geometry of the channel. A loss of bank strength can lead to a wider equilibrium channel (Eaton et al. 2004, Eaton 2006). The loss of mature riparian forests also eliminates the principal source of functional wood material to large alluvial rivers which is primarily recruited through bank erosion (Abbe and Montgomery 2003). Larger trees can slow erosion rates and form critical habitat such as islands and side channels (Abbe et al. 2003, Abbe and Montgomery 2003; Abbe and Brooks 2011).

NSD processed and colorized first return LiDAR data to show the height of the 2005 tree canopy near the Reservation (Figure 24). The map shows that second growth trees (about 55 years old) are roughly 150 feet high or less; trees and shrubs growing on the active flood plain directly east of the Reservation, also from 100 – 150 feet high, grow in a channel that was occupied in 1949 and abandoned sometime prior to 1965, making the trees roughly 40 to 50 years old. Trees of this age, girth and expected root mass, are insufficient to retard bank erosion (Abbe et al. 2003) or create stable snags needed to create logjams that create habitat and influence the river's morphology (Abbe and Montgomery 1996, Abbe and Brooks 2011). Adverse impacts of increasing peak flow magnitude and frequency will be compounded by the lack of mature forests within the Sauk valley (Figure 24). Large scale restoration of mature valley forests will reduce impacts to habitat and infrastructure that are likely to occur from the increasing peak flows associated with the warming climate.

Historic Channel Migration

Review of historic aerial photographs from 1949 to 2011 show that the dominant Sauk River channel and flood plain have been subject to numerous episodes of bank erosion, sediment deposition, channel migration and channel avulsion for many decades to centuries. Over the course of the aerial photographic record (62 years) the changes have also included a shift in overall channel pattern from more dominantly multi-channeled to a more dominantly single-stem system.

Aerial photographs from 1949 to 2011 covering the area adjacent to the Reservation are shown in (Figure 25). The aerial photographs from 1949 to 1981 display the multi-channeled form with relatively sinuous bends. During this time period the bends are very active, undergoing changes in channel location resulting from avulsion, and the growth, migration and bifurcation of bends (1954, 63, 74 and 81) in an active

channel corridor roughly 500 to 800 feet wide. Based on visual observations of this suite of photos, avulsion was one of the dominant channel adjustment processes observed. A major avulsion that occurred just prior to 1962 moved the channel away from the east edge of the Reservation, by cutting off, and completely abandoning a bend that appears to have been migrating westward. Other avulsions are apparent on the 1974 and 1981 aerial photographs. Both lateral and downstream migration of channel bends can also be observed in photographs up through 1981.

Sometime between 1981 and 1992 the character and form of the dominant channel pattern and active channel corridor changed substantially (Figure 25). The 1992 photo shows the channel pattern had already shifted from sinuous multiple channels (anabranching) to a single-stem channel with much lower sinuosity. From 1992 to 2011, the channel pattern has remained more or less the same. Visual comparison of the full suite of time series aerial photographs shows the marked change in channel sinuosity. The loss of mature riparian forests and increasing peak flows both could have contributed to this change in channel planform. The historic reduction in sinuosity may also reflect a period of channel incision within the Sauk, a process that has been documented in the South Fork of the Nooksack Rivers that resulted from historic channel clearing and the loss of functional wood (Natural Systems Design 2013, reports submitted to Lummi and Nooksack Tribes). The reduction in channel length corresponding to lowering sinuosity leads to a steeper channel which increases bed shear stress and channel incision. During a period of incision the river is evacuating bed material faster than it can be replaced. Following any period of incision, a channel will reach a point where it begins to deposit bed material again which initiates lateral migration and gradual creation of a new inset floodplain.

A comparison of channel sinuosity measured from the time series aerial photographs displays the change in channel pattern from 1949 to 2011 (Figure 26); sinuosity was also measured from a 2013 air photo available on the Google Earth Website. In general, the results show that channel sinuosity has decreased over the period of record; from 1.45 and 1.33 during the most active period, to 1.38 and 1.26 between 1981 and 1992, and finally to 1.12-1.14 from 2009 to 2013. The biggest change in sinuosity actually occurred between 2007 and 2009, as the channel pattern changed from multiple shallow bends with short wavelengths, to a pattern consisting of gently curving channel alignments with much longer wavelengths. From 2009 to 2013 channel sinuosity gradually increased from 1.12 to 1.14, describing the development of multiple single stem bends with regular wavelengths and amplitudes extending the full width of the active channel, all of which are migrating in the downstream direction. We believe the trend will be for sinuosity to continue to increase as the river adjusts to historic channel incision by beginning to migrate laterally.

The changes in channel pattern and dominant channel forming process suggest that the channel has been adjusting to changes in local conditions, or to changes in sediment supply or discharge. A possible catalyst for initially high sinuosity and dynamic migration is the Suiattle River alluvial fan, which can be seen on the 1954 aerial photograph (Figure 2) and the Relative Elevation Map (Figure 21). In 1949 and 1954 the entrance point of the Suiattle River into the Sauk River was located farther south (the abandoned channel is visible on the REM, Figure 21). This alignment of the Suiattle would have deposited abundant sediment along the south perimeter of the fan, and could have caused the Sauk to backwater enough to cause the Sauk to drop its sediment load. Although inconclusive, this condition was likely augmented by sediment production generated prior to 1949 by huge clear cuts on nearby portions of the west valley wall and lahar terraces. The combination, these likely conditions, sediment inputs from clear cutting, partial deflection of the active channel and back watering, set up by the Suiattle alluvial fan, would have results in the formation of sinuous bends, and induce dynamic channel migration and avulsion. By 1981 the Suiattle channel shifted northward, and allowed the Sauk to readjust to the new condition.

Channel migration/floodplain dynamics

Channel migration was evaluated for the purpose assessing how the Sauk River will respond and adjust to changes in climate. Rates of migration were estimated for the entire project reach and applied to define 'high and low risk' erosion setback areas in the vicinity of the Reservation. The high risk area is mapped adjacent to the active channel and identifies the area subject to a high probability of bank erosion. The low risk erosion setback is mapped along the outer edge of the high risk area and identifies the area subject to a lower probability that the active bank erosion will actually take place there. Migration rates representative of high and low risk erosion were estimated by starting with a based rate. The base rate is the distance of bank recession measured between dated time-series aerial photographs divided by the number of years comprising the time series period. Analysis of historical airphotos shows that the magnitude and variance of channel migration rates have increased over time. From 1949 to 1974 migration rates averaged about 20 ft/yr, half the magnitude of 40 ft/yr observed between 2004 to 2011 (Figure 27). Bank erosion is a function of the river's ability to move material and the duration which the river attains these conditions. Higher flows typically result in more erosion, just as the duration the river exceeds the threshold at which erosion occurs. To examine this in the Sauk we summed the peak flows exceeding a base threshold flow of 34,770 cfs during a given time period over which erosion was measured and then plotted the result relative to the observed erosion. This was done for annual peaks and partial peaks, both showing a positive correlation (Figure 27). This result demonstrates that if the magnitude and frequency of peak flows increases as predicted from historic trends and climate models, channel migration rates will also increase. This elevates the existing high erosion hazard at the reservation, further demonstrating an unacceptable level of risk to Tribal residents and facilities. Increased rates of channel migration will also adversely impact salmon habitat and inhibit the restoration of mature riparian forests by frequent channel re-occupation.

The *high risk* erosion setback was determined using the average of all historic erosion rates measured within the reach, and treated with an erosion coefficient to account for the sporadic manner in which bank erosion actually takes place. Review of aerial photographs indicated that the channel does not erode a single spot continuously over a given time period, rather, river banks have typically subject to erosion only 10 percent of the time period. The erosion coefficient was obtained by reducing the average migration rate by a factor of 10, (Rapp and Abbe, 2003), and then extrapolated by 100 to reflect a 100 year lifespan of the CMZ. The *low risk* erosion setback was determined using the same approach, but accounts for a lower probability of occurrence. The lower risk area was estimated using the 90th percentile value of the historic migration rates, which is 76 feet per year, to define the low risk buffer width. The calculated average erosion rate and 90 percentile erosion rates, and their corresponding high and low risk setbacks are:

Average Rate: 38 ft/yr - Erosion setback (high risk) = 380 feet (38*(10/100))

90 Percentile Rate: 76 ft/yr - Erosion setback (low risk) = 760 feet 376*(10/100))

High and low risk setback areas, measured from the perimeter of the historic migration zone (HMZ), are shown on the 100 year Channel Migration Zone (CMZ) Map (Figure 28). The CMZ map places the eastern two thirds of the Reservation in the High Risk area, and the western one third in the Low Risk area. Note that the eastern most portion of the Reservation overlaps the abandoned 1949 channel, and therefore lies in the historic migration area, now included in the active floodplain.

FUTURE EROSION HAZARDS

The erosion rates used to delineate the Channel Migration Zone map are derived from historic and recent aerial photographs. As such, these rates reflect only past conditions. Although past conditions include channel responses to past storms driven by atmospheric rivers and other high stage flow and sediment

transport events, the period from 1949 to 2013 was not dominated by the effects of projected significant glacier melt-off, increasing air temperatures and AR events associated with climate change.

The review of historic empirical data and climate model predictions indicate trends in conditions that will affect future channel forming processes and promote erosional hazards within the middle Sauk River Valley. Most important, and possibly irreversible in the short term, is the trend of increasing air temperatures, which will, in turn, drive the elevation of freezing level higher and increase the total area subject to rainfall and rain-on-snow-events. By itself, this single change in climate (increase in air temperature) will have a profound effect on future flooding. These changes are graphically shown in Figure 20; projected changes suggest that between now and 2080 more than half the snow zone area will be lost, and rainfall and rain-on-snow area will double. Figure 17 displays the increase in the size of the drainage basin upon which precipitation will fall as rain. These conditions will generate larger peak flows in winter and increase both the frequency and magnitude of flood events. In addition to these projected changes, storms driven by atmospheric rivers are predicted to increase in both frequency of occurrence and magnitude.

The projected increases in the magnitude and frequency of substantial flood events will increase the intensity and extent of erosion throughout most of the watershed, and in the area adjacent to the Reservation. Higher peak flows, and longer flow durations, will be expressed through the Middle Sauk Valley in terms of increased flow velocities, and subsequently, as increased erosion potential. Figure 27 displays the correlation between median rates of bank erosion measured from time series aerial photographs, and the sum of peak flow events greater than the base discharge. The migration rate/discharge graph shows that past migration rates increase linearly with increasing discharge; this strongly indicates that the projected increase in future peak flows will drive much high rates of erosion and channel migration than have occurred previously.

Increased peak flows, accompanied by higher rates of erosion and channel migration will have profound effects on the channel pattern, the active channel corridor, and the active flood plain. The exposure of large sediment sources from the recession of alpine glaciers, mass wasting, and erosion of the channel perimeter will increase the supply of sediment available to high stage flows. Once this material reaches fluvial conveyance zones, waves of material are likely to affect channel capacity downstream, further increasing the frequency and magnitude of flooding, and alter the pattern and stability of the channel. Channel aggradation from deposition of large sediment loads, may result in a braided system with several rapidly migrating/avulsion prone channels. However, the current form of the channel is more likely to continue its evolution towards a rapidly migrating single-stem river capable of eroding the active floodplain and lower terrace.

For either of the scenarios described above, Sauk River migration will eventually re-grade the valley floor and Holocene landforms, including the alluvial fan deposits upon which the Reservation is located. Presently, there are virtually no erosion-resistant hard points, such as stable log jams or old growth riparian trees, currently residing within the active channel corridor or floodplain capable of protecting the Reservation from the river. This condition is a result of changes in land cover from past timber harvests. The younger riparian forest currently in place lacks both the size and maturity to withstand the erosion associated with flood flows. These immature trees are subject to undermining from bank erosion, and are highly unlikely to survive long enough to reach full maturity.

Given the projected conditions above, the Reservation is subject to immanent risk from future flooding and channel migration. Further loss of the riparian forest, coupled with increasing peak flows, flooding, and rates of erosion will eventually result in the loss of the remaining portions of the floodplain, and expose the low terrace to erosion. The channel migration zone will need to be extended west of State Route 530 and in some places as far as the valley wall. The movement of the channel, by lateral migration and/or avulsion,

will damage infrastructure, including Bryson Road, and State Route 530, which provides access to the Reservation, as well as all residential roads within the Reservation.   Aquatic habitat will also be damaged substantially. Habitat can be damaged from scour of the channel floor due to increased discharge, aggradation of the channel floor, active channel reworking resulting from migration, and increased water temperature from loss of riparian vegetation and increased air temperatures.

The Sauk-Suiattle Reservation, including residential housing and tribal administrative offices are at serious risk from flooding and erosion. The Reservation lies within the channel migration zone of the river, and will suffer catastrophic losses when the river channel moves into developed areas. The probability of the Reservation flooding is currently greater than 1 percent and within the next 80 years the magnitude of flooding is expected to increase 50% and the frequency more than double. Currently the river is migrating toward the Reservation slough and this 1949 river channel will certainly be re-occupied by the river in the near future. The Tribe currently have no defenses to stop the river from migrating into residential housing and Tribal offices (Figure 29). The visualization in Figure 29 offers a realistic scenario of the risk the Reservation faces even without climate change. Because of the warming climate this scenario is much more likely and poses an unacceptable level of risk to the Sauk-Suiattle Tribe over the next several decades. Severe and irretrievable damages, and possible loss of life, are an inevitable consequence of failing to move residents and facilities out of their current location. The cost of moving development to safer ground will only increase with time, and it is recommended that planning begin immediately to identify safe locations for the Tribe's long term welfare. Existing developed areas can be restored in a manner consistent with natural resource objectives of the Tribe.

CLOSING AND LIMITATIONS

NSD has prepared this report for the Sauk-Suiattle Indian Tribe, their authorized agents and regulatory agencies responsible for the project. Within the limitations of scope, schedule and budget, our services have been executed in accordance with generally accepted practices for hydrology and geomorphology in this area at the time this report was prepared. The conclusions, recommendations, and opinions presented in this report are based on our professional knowledge, judgment and experience. No warranty or other conditions, expressed or implied, should be understood.

We appreciate this opportunity to be of service to the Sauk-Suiattle Indian Tribe for this project and look forward to continuing to work with you. Please call if you have any questions regarding this report, or if you need additional information.

Sincerely,

Natural Systems Design, Inc.

Tim Abbe Ph.D., P.E.G., P.H.G
Principal Geomorphologist

Mary Ann Reinhart, P.G., M.S.
Senior Geomorphologist

Shawn Higgins, M.S.
Project Geomorphologist

ATTACHMENTS:

Figure 1. Topographic map of the Sauk River valley.

Figure 2. 1954 aerial imagery of the Middle Sauk River.

Figure 3. 2011 aerial imagery of the Middle Sauk River.

Figure 4. Monthly temperature and precipitation at Darrington.

Figure 5. Hypsometric curve of the Sauk River watershed.

Figure 6. Hydrographs showing seasonal patterns of flow.

Figure 7. Flood frequency curves for the Sauk River.

Figure 8. Annual temperature at Sedro Woolley, WA.

Figure 9. Annual precipitation at Sedro Woolley, WA and PDO.

Figure 10. Historical trends in mean annual streamflow.

Figure 11. Historical trends in winter (Nov-Jan) streamflow.

Figure 12. Historical trends in June streamflow.

Figure 13. Historical trends in minimum annual streamflow.

Figure 14. Historical trends in the annual maximum flood series.

Figure 15. Historical trends in the partial duration flood series.

Figure 16. Historical trends in the daily streamflow record.

Figure 17. Projected changes in hydrologic zones.

Figure 18. Simulated hydrologic changes for the Sauk River.

Figure 19. Hydraulic simulation of projected 100-year flood.

Figure 20. Geologic Map of the Sauk River valley.

Figure 21. Relative Elevation Map (2000 LIDAR DEM).

Figure 22. Longitudinal profile of the Sauk River.

Figure 23. Geomorphic map of the Sauk-Suiattle reach.

Figure 24. Tree canopy height in the Sauk-Suiattle reach.

Figure 25. Historical aerial imagery of the Sauk-Suiattle reach.

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Figure 26. Historical changes in channel sinuosity.

Figure 27. Channel migration rates.

Figure 28. Preliminary channel migration zone delineation.

Figure 29. CMZ and simulated channel migration scenario.

Appendix A. Map Spplenment

1. Shaded relief map of the Sauk River watershed.
2. Map of the stand year of origin for forests in Mt. Baker-Snoqualmie National Forest
3. Relative Elevation Map and aerial image of the Sauk-Suiattle reach.
4. Comparison of historic (1949) and recent (2011) Orthoimagery.

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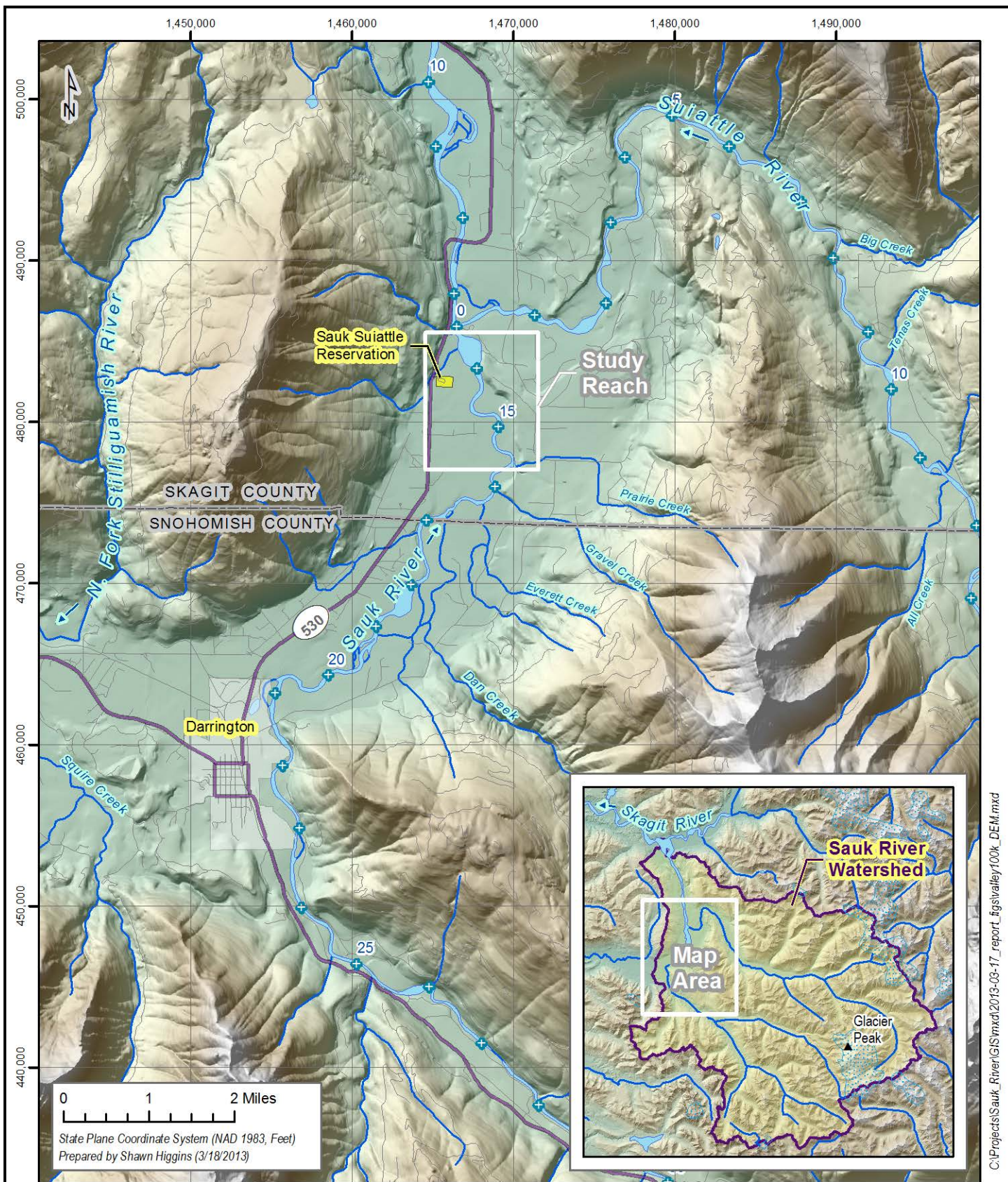
FIGURE 1 – Topographic map of the Sauk River valley.

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FIGURE 2 – 1954 aerial imagery showing anabranching channel of Middle Sauk

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FIGURE 3 –2011 aerial imagery of the Middle Sauk River.

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Darrington Ranger Station
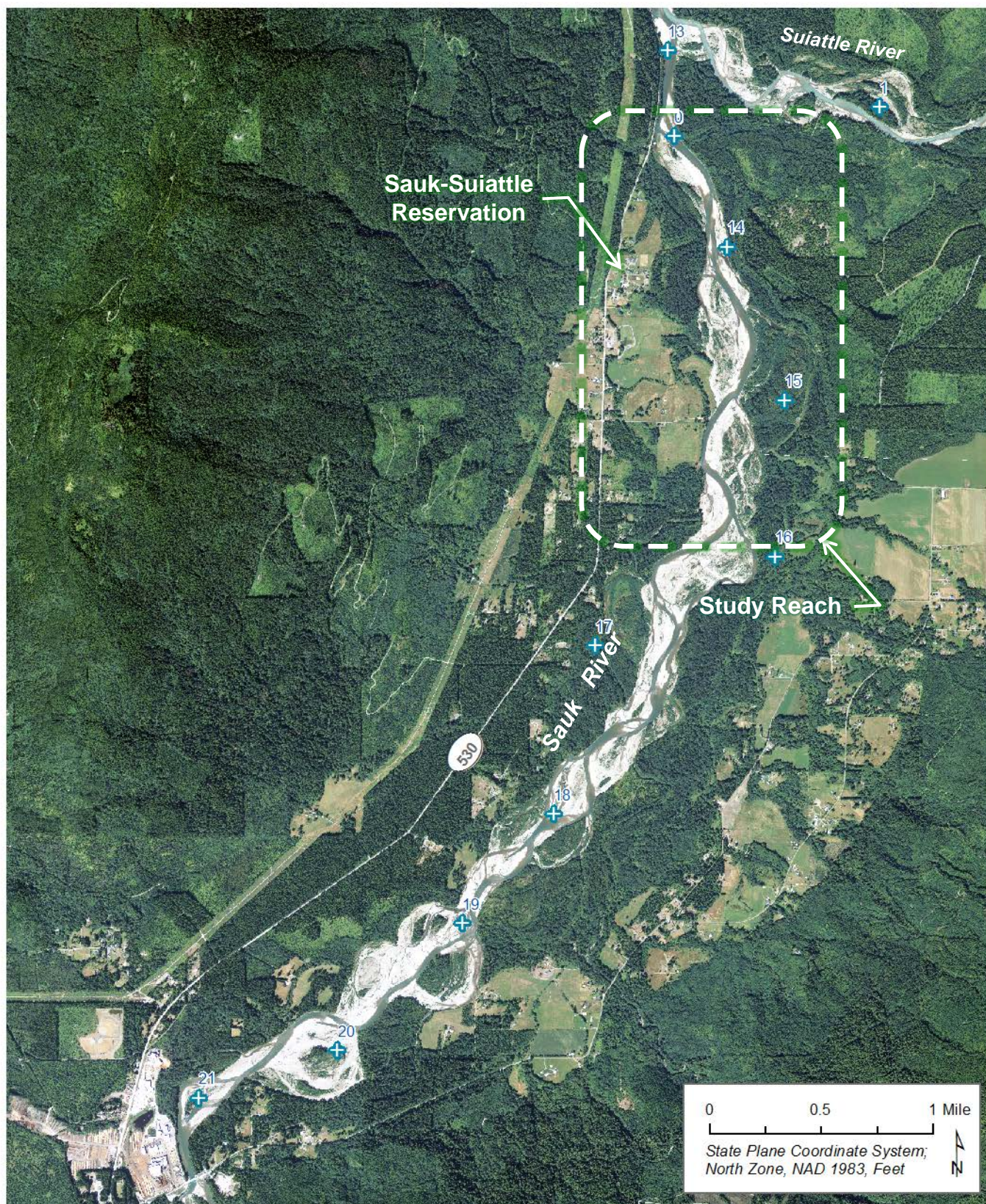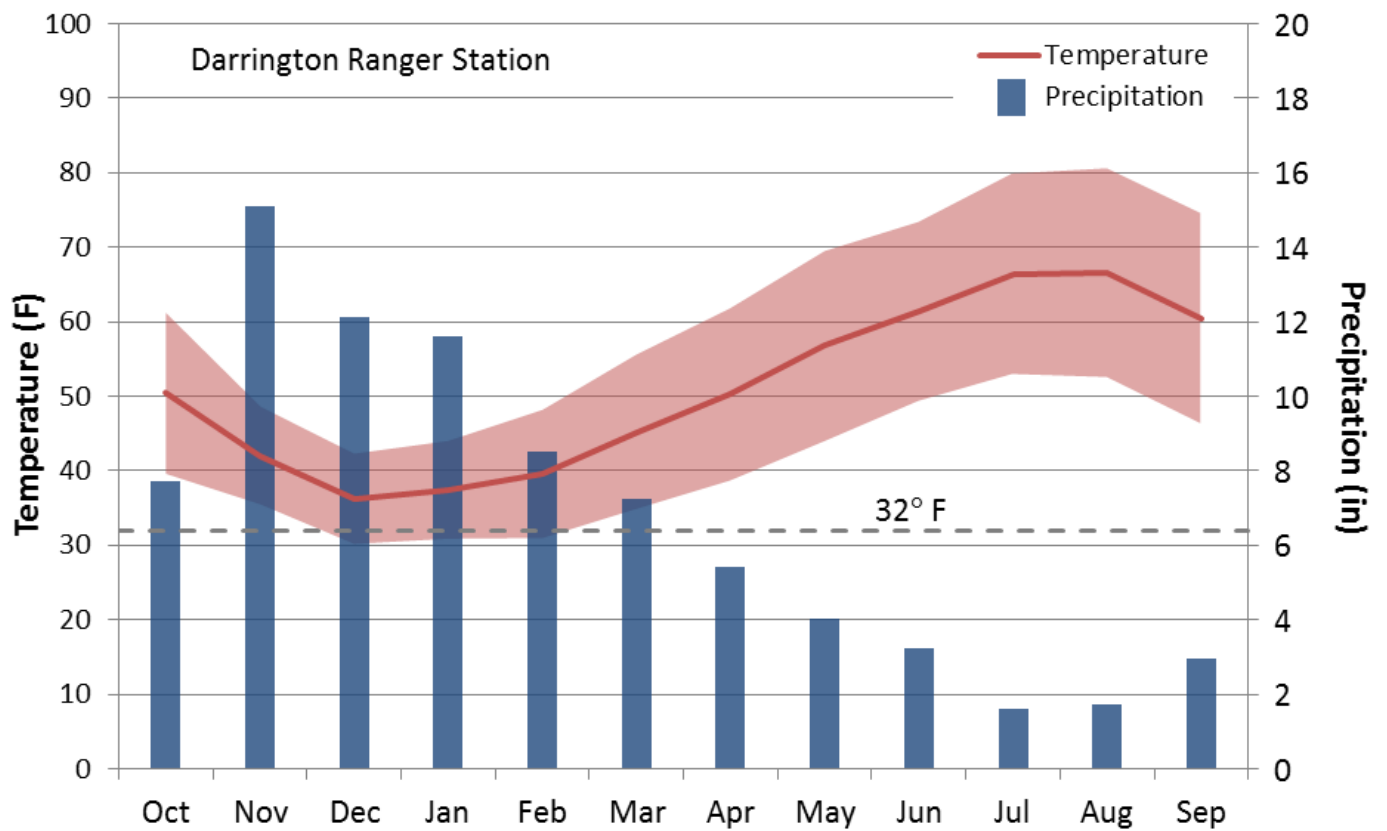
1971-2010 Climatic Normals
Source: National Climatic Data Center

FIGURE 4 – Monthly temperature and precipitation at Darrington.

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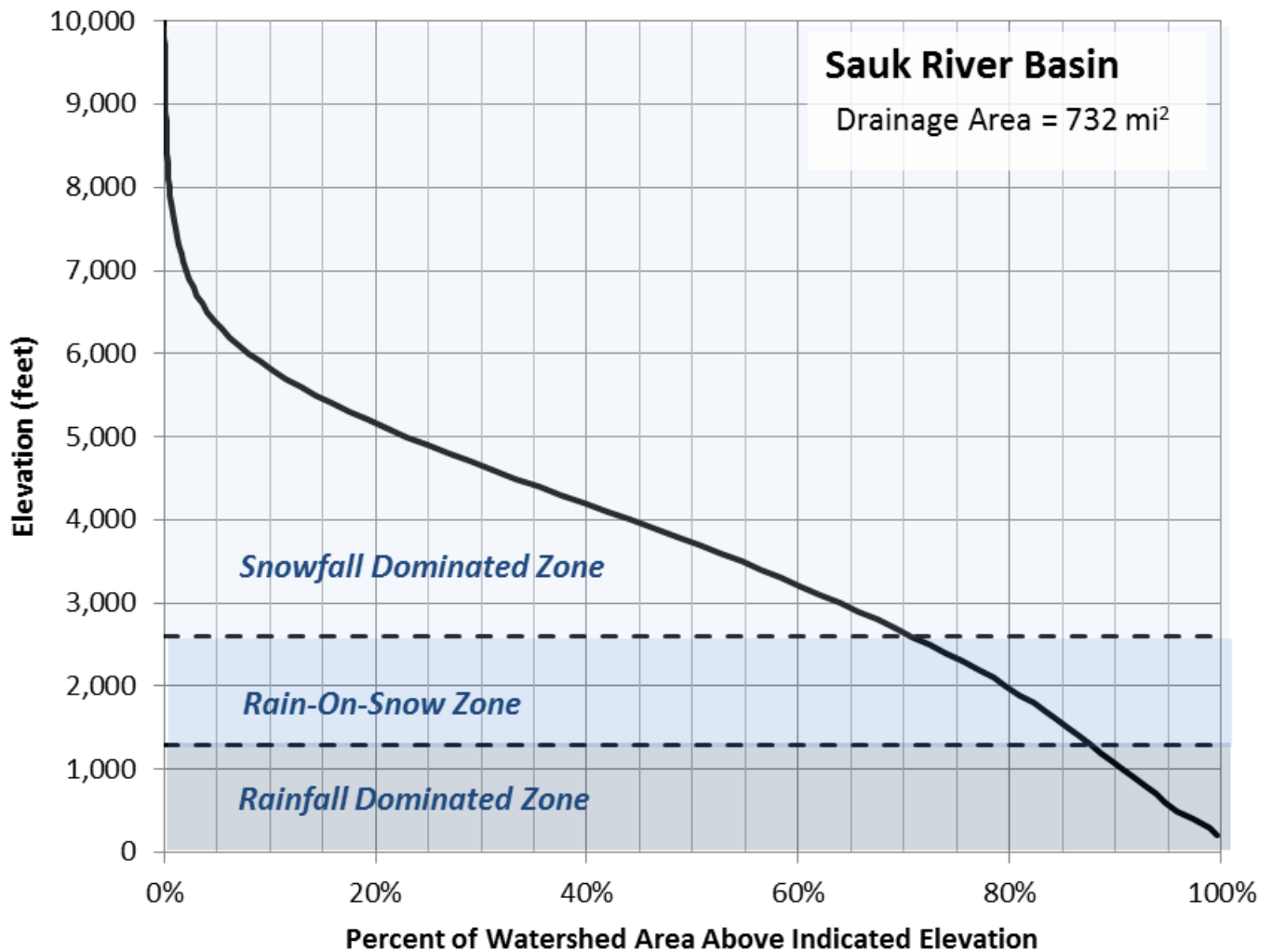
Hypsometric curve derived from USGS 10 m DEM.
Transition elevations between hydrologic zones defined by
WA DNR (1991) rain-on-snow model.

FIGURE 5 – Hypsometric curve of the Sauk River watershed.

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FIGURE 6 – Hydrographs showing seasonal patterns of flow.

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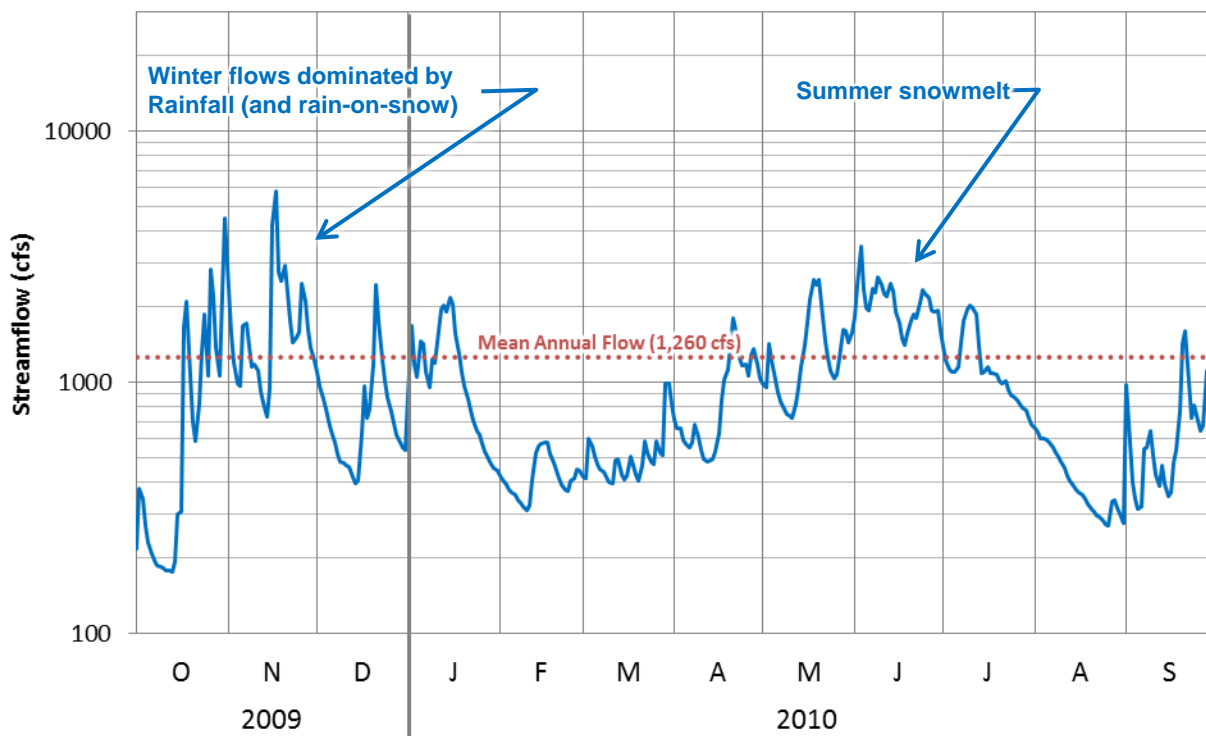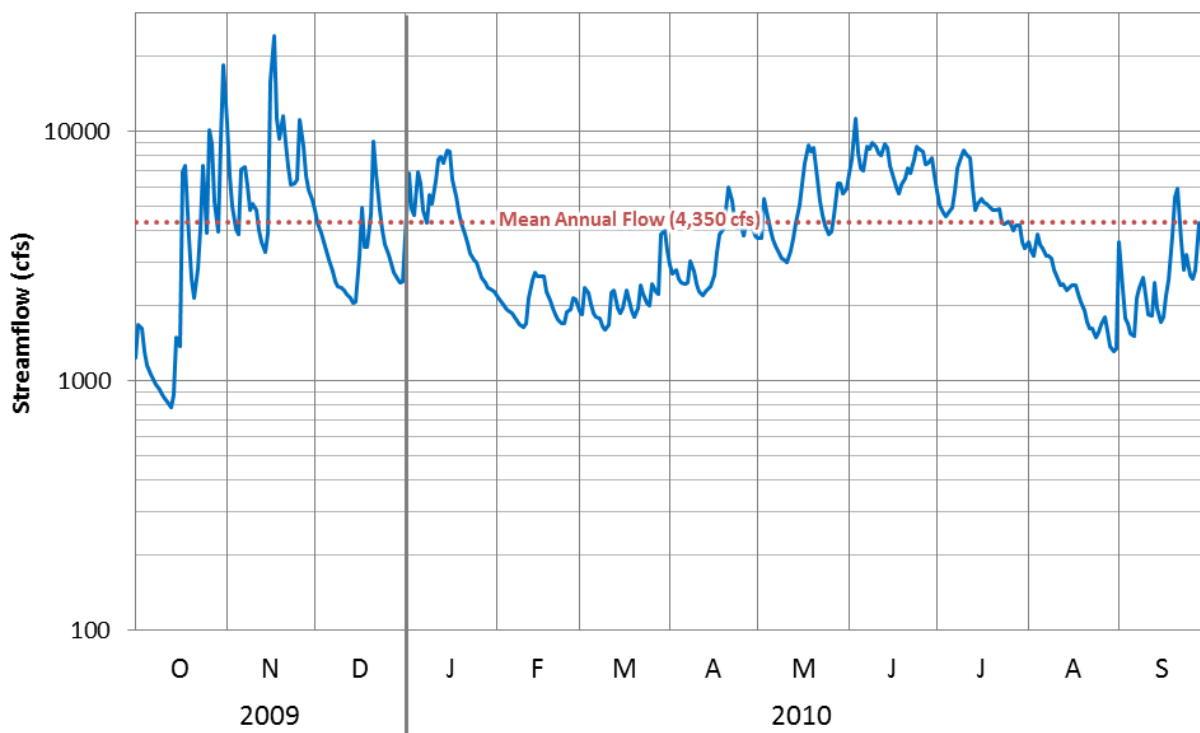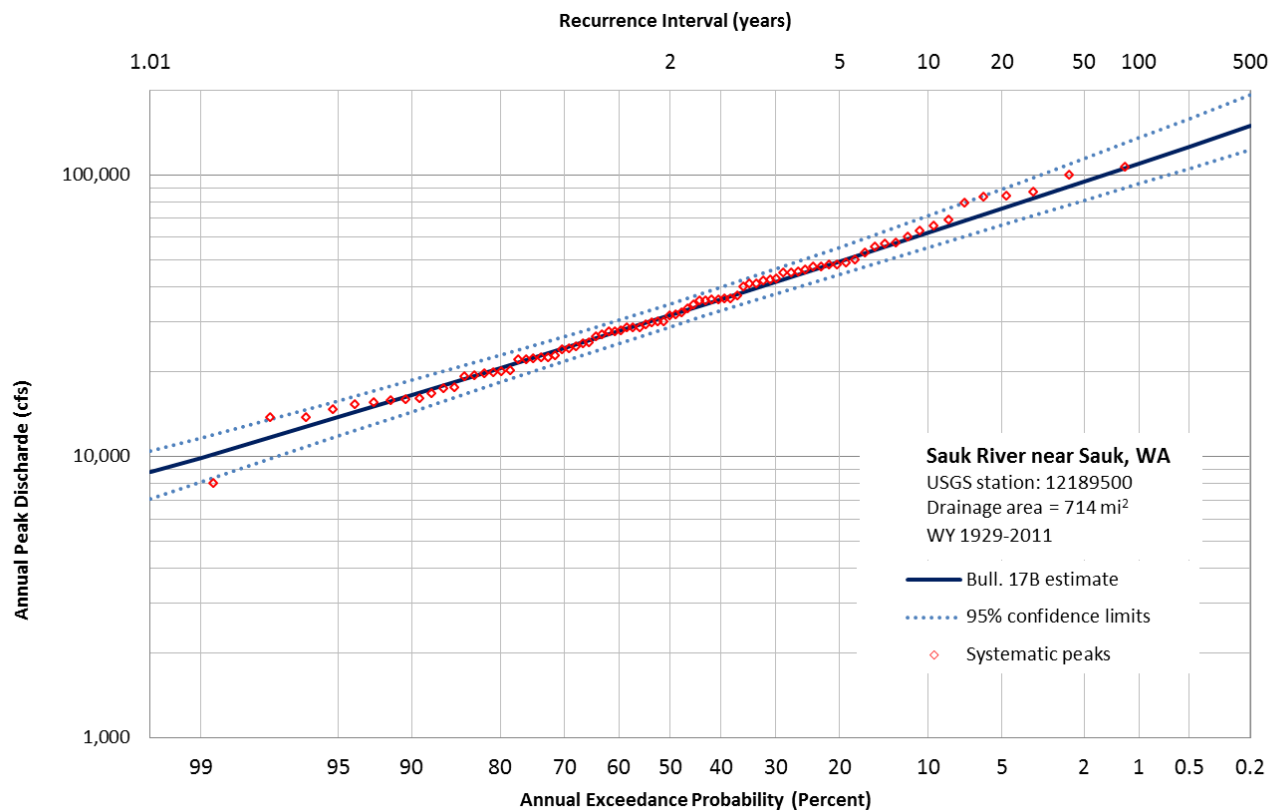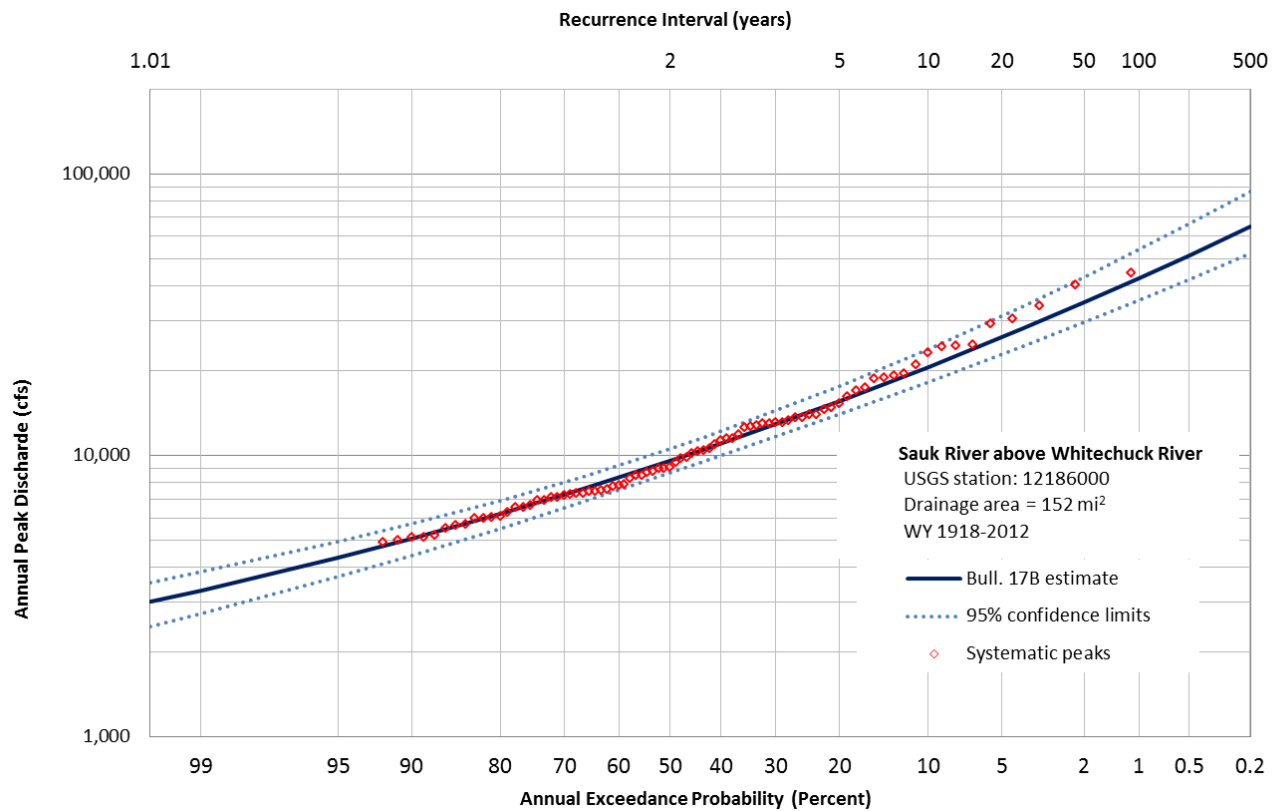
FIGURE 7 – Sauk River flood frequency curves at gages 12186000 & 12189500.
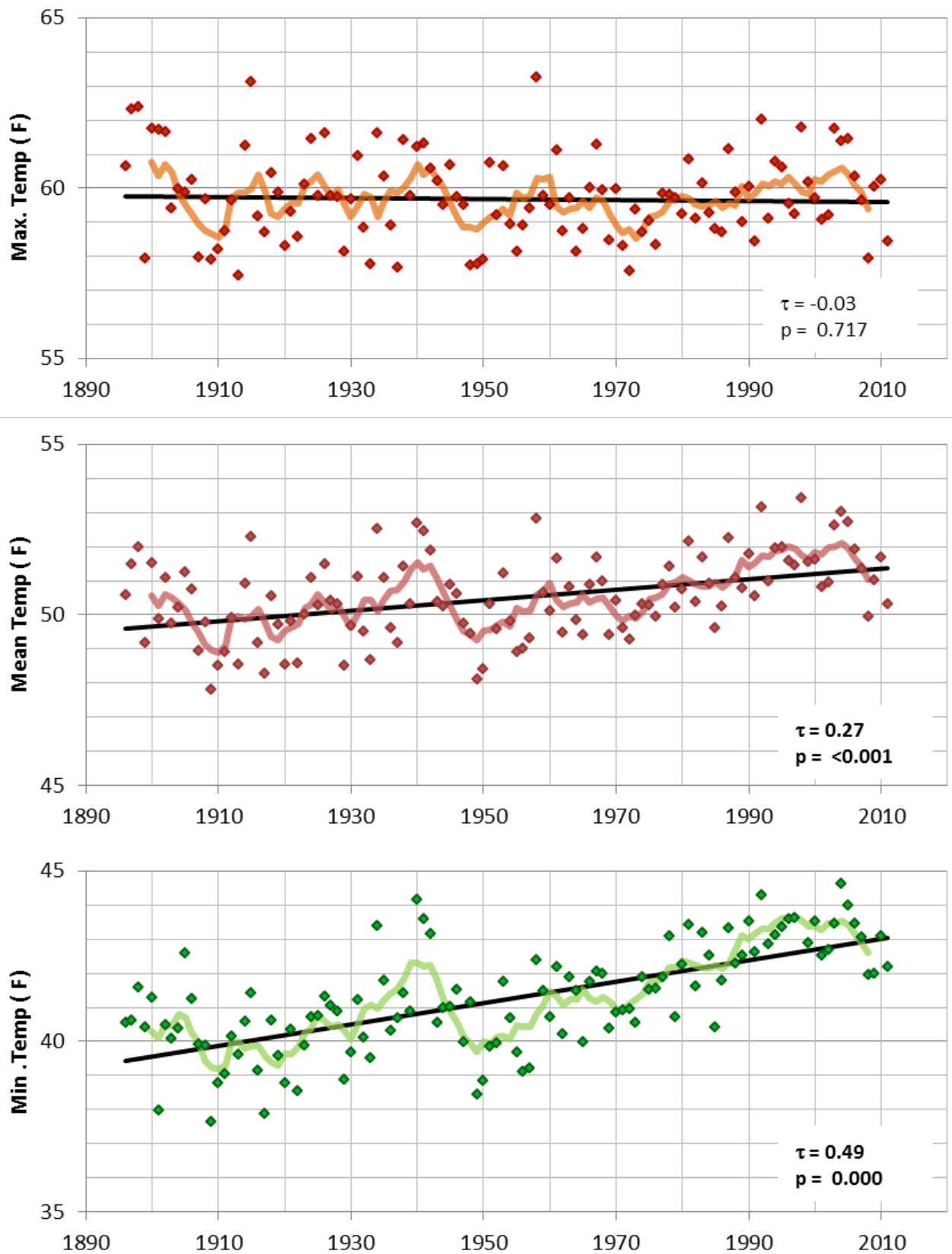
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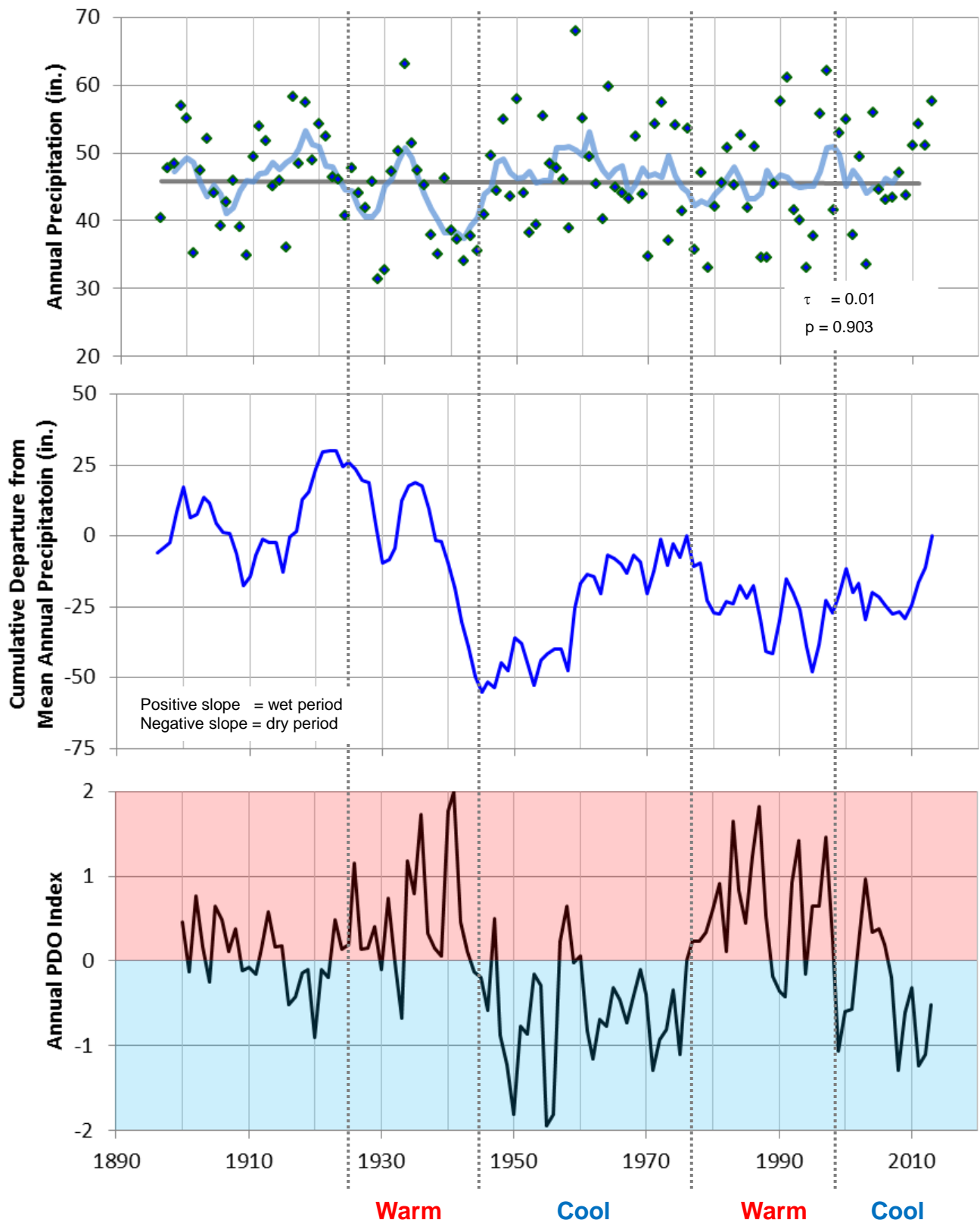
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FIGURE 8 – Annual temperature at Sedro Woolley, WA.

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FIGURE 9 – Annual precipitation at Sedro Woolley, WA and PDO.

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FIGURE 10 – Historical trends in mean annual streamflow.

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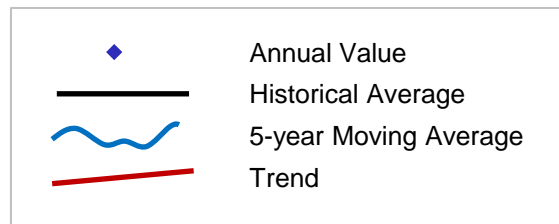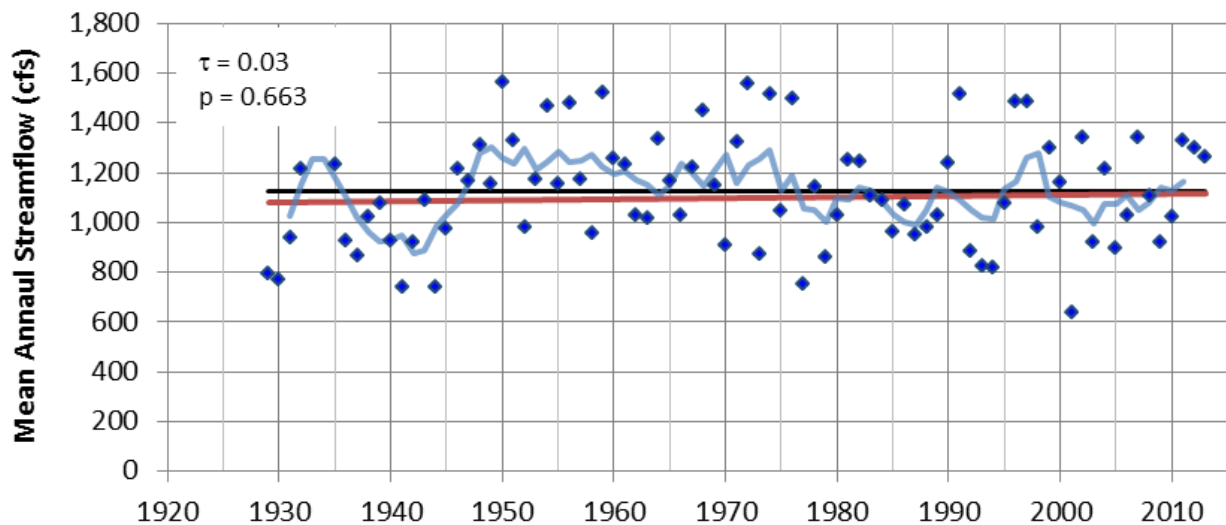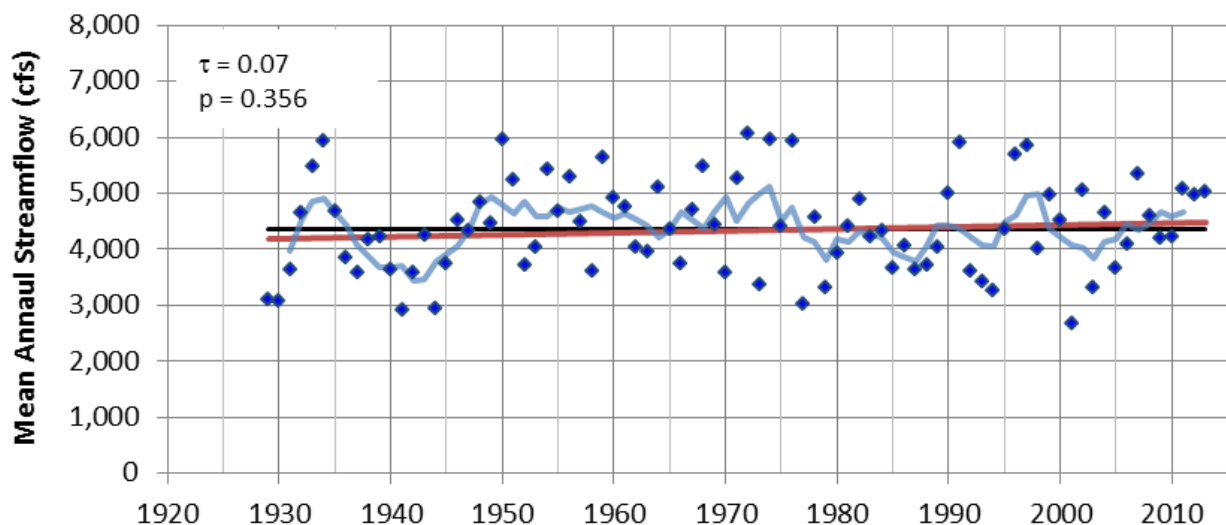
Winter

Sauk River above White Chuck (#12186000)
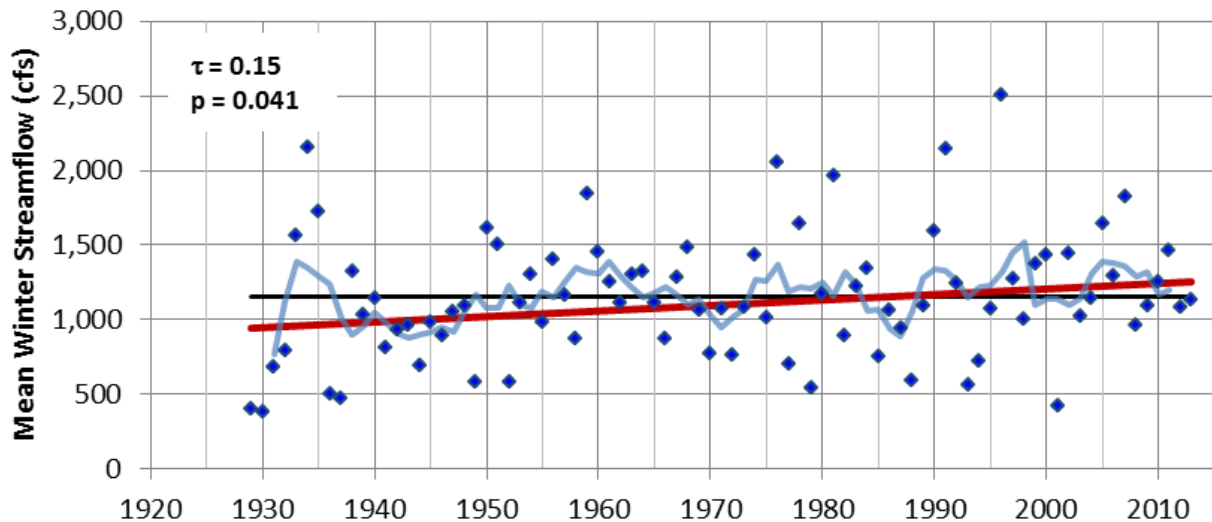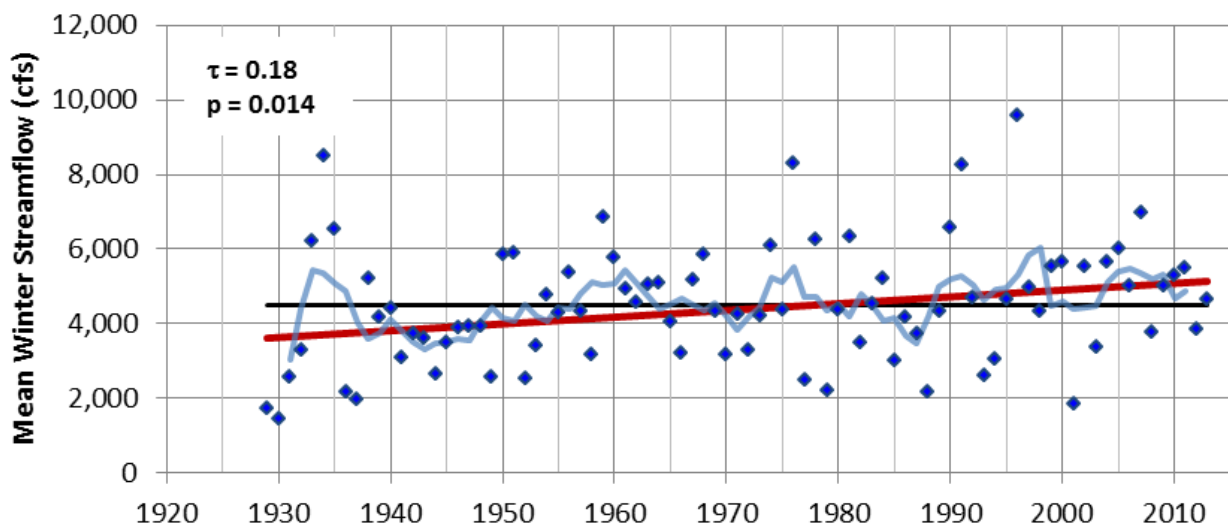
τ = 0.15
p = 0.041

Sauk River near Sauk (#12189500)

τ = 0.18
p = 0.014

FIGURE 11 – Historical trends in winter (Nov-Jan) streamflow.

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FIGURE 12 – Historical trends in June streamflow.

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Minimum Annual Flow

Legend:
- Annual Value
- Historical Average
- 5-year Moving Average
- Trend

Sauk River above White Chuck (#12186000)

τ = -0.07
p = 0.350

Sauk River near Sauk (#12189500)

τ = -0.02
p = 0.774

FIGURE 13 – Historical trends in minimum annual streamflow.

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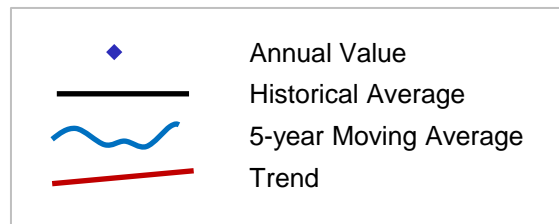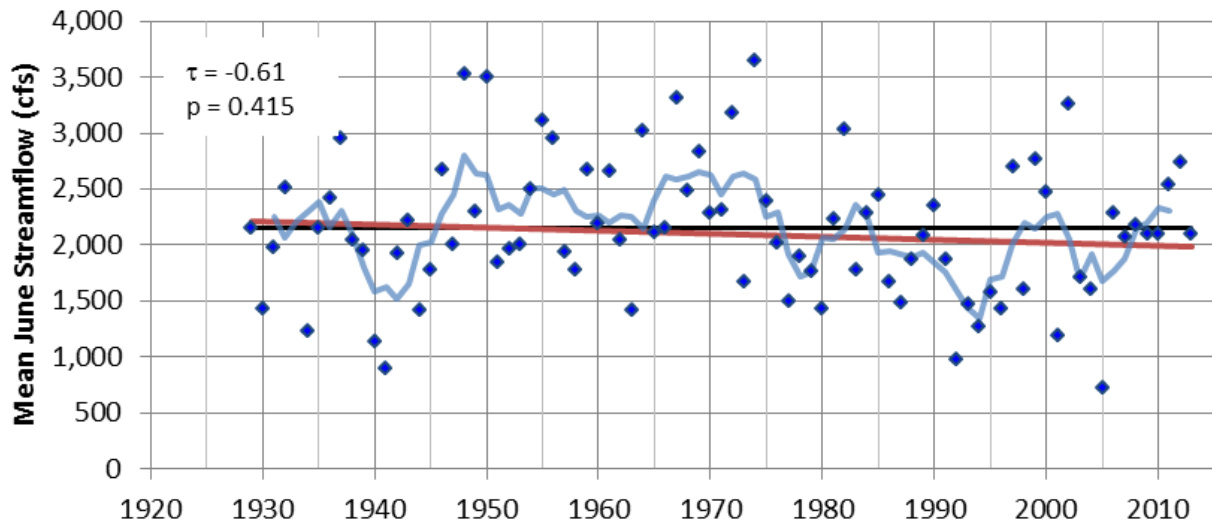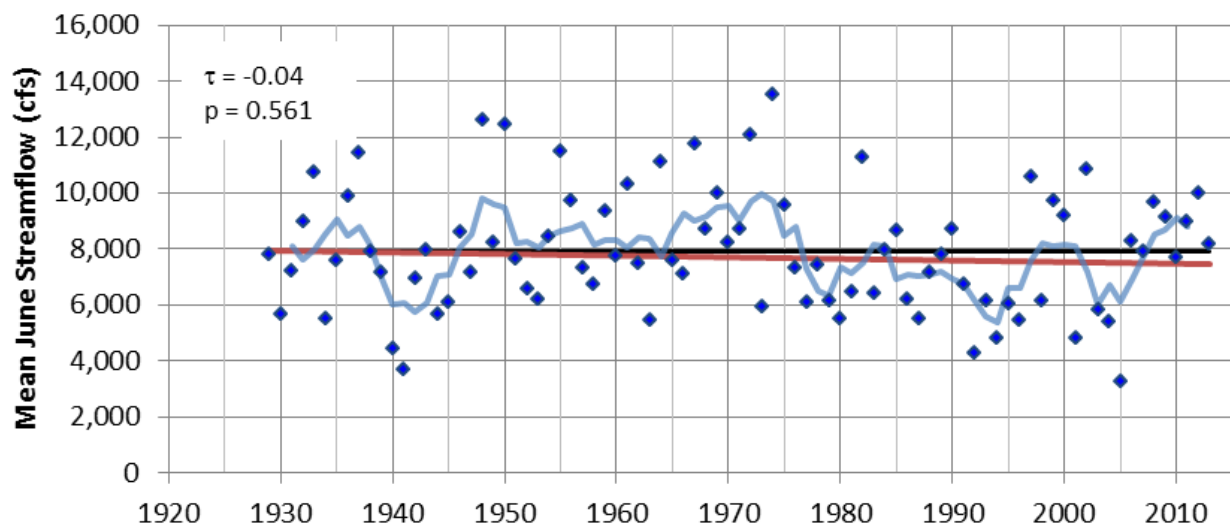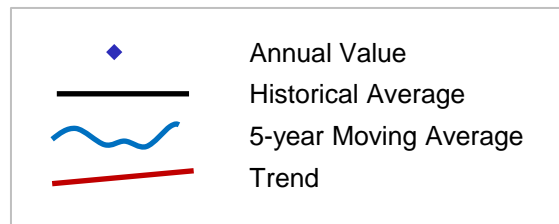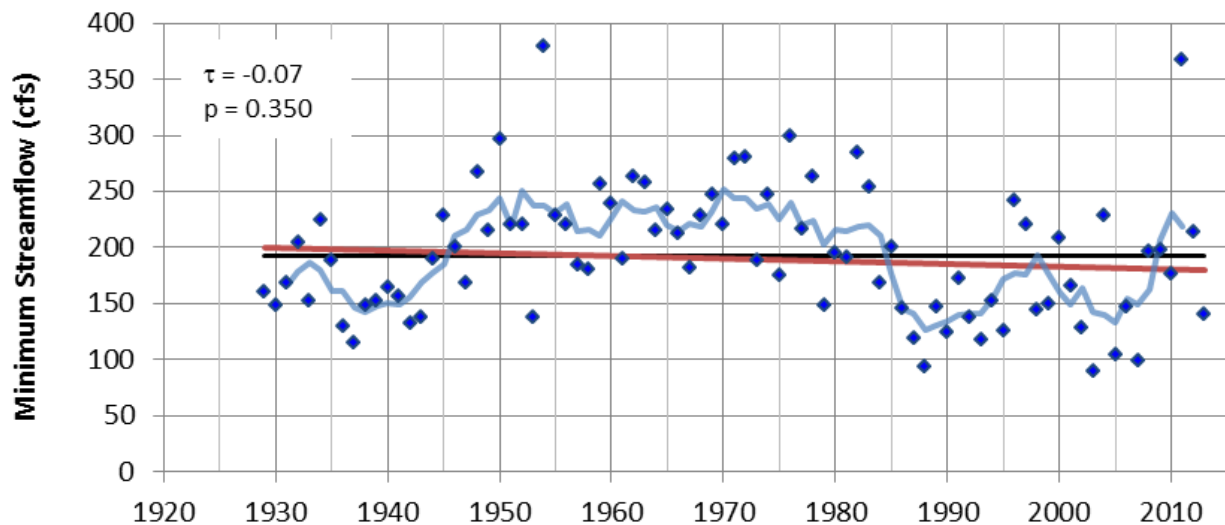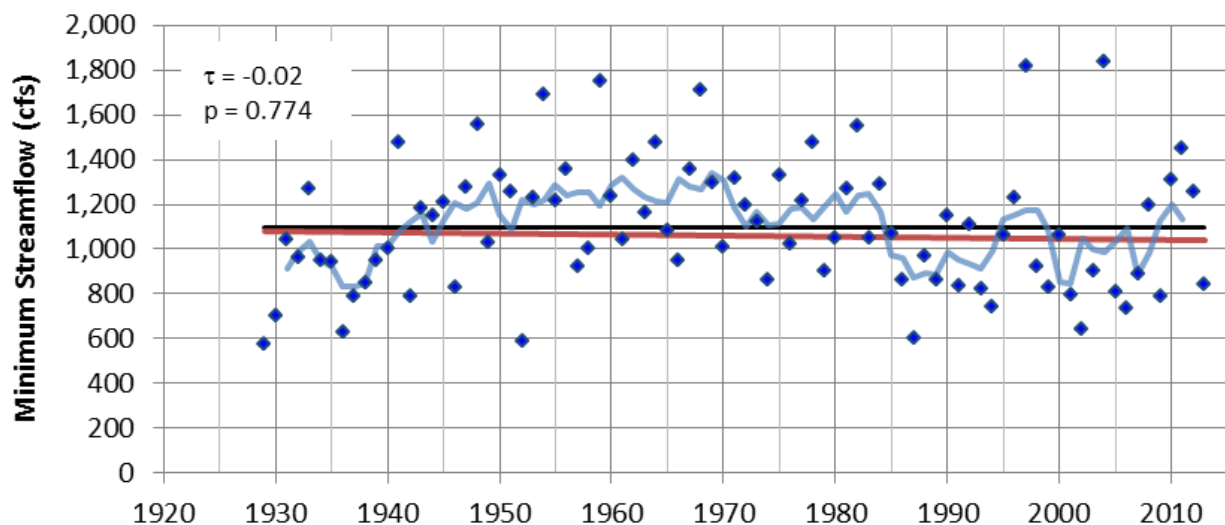
Peak Flow (Annual Maximum)

Sauk River above White Chuck (#12186000)
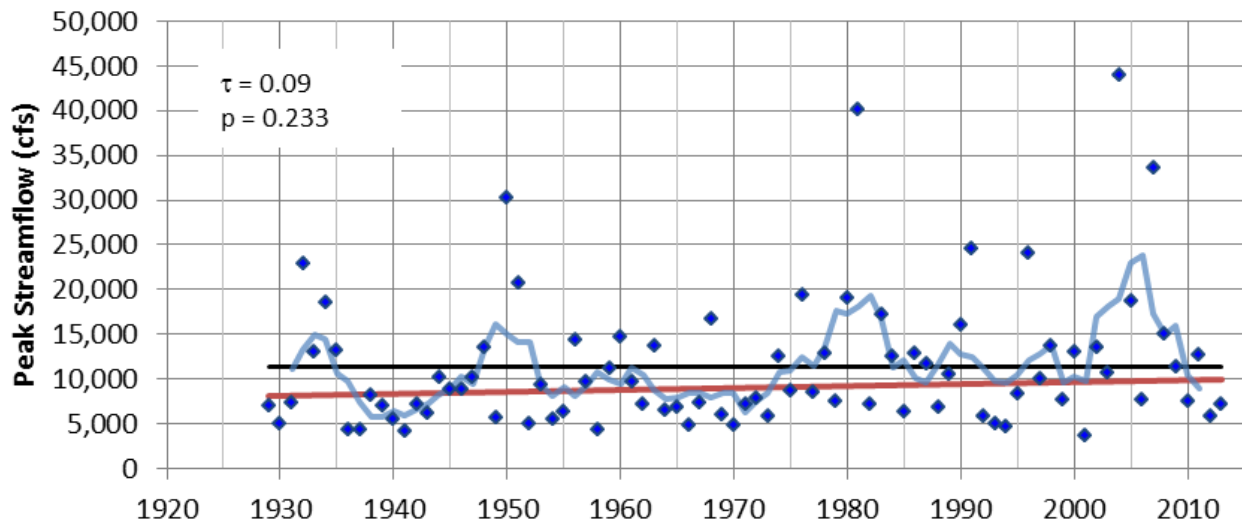
$\tau = 0.09$
$p = 0.233$

Sauk River near Sauk (#12189500)

$\tau = 0.18$
$p = 0.018$

FIGURE 14 – Historical trends in the annual maximum flood series.

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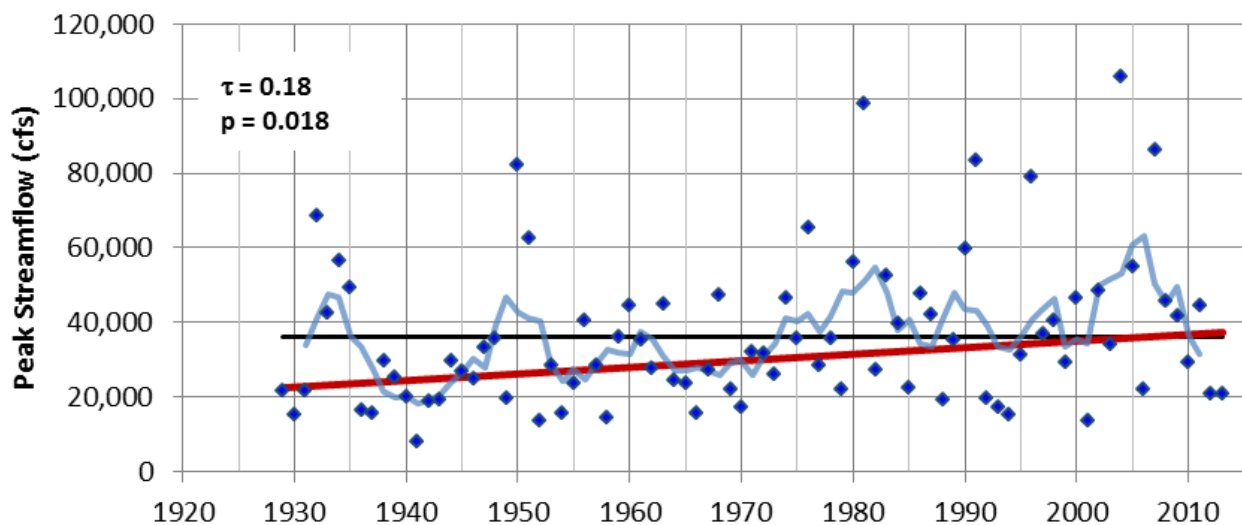
Peak Flow (Partial Duration Series)
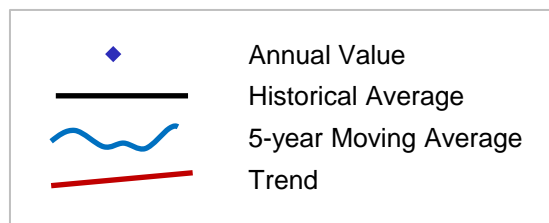
Sauk River above White Chuck (#12186000)
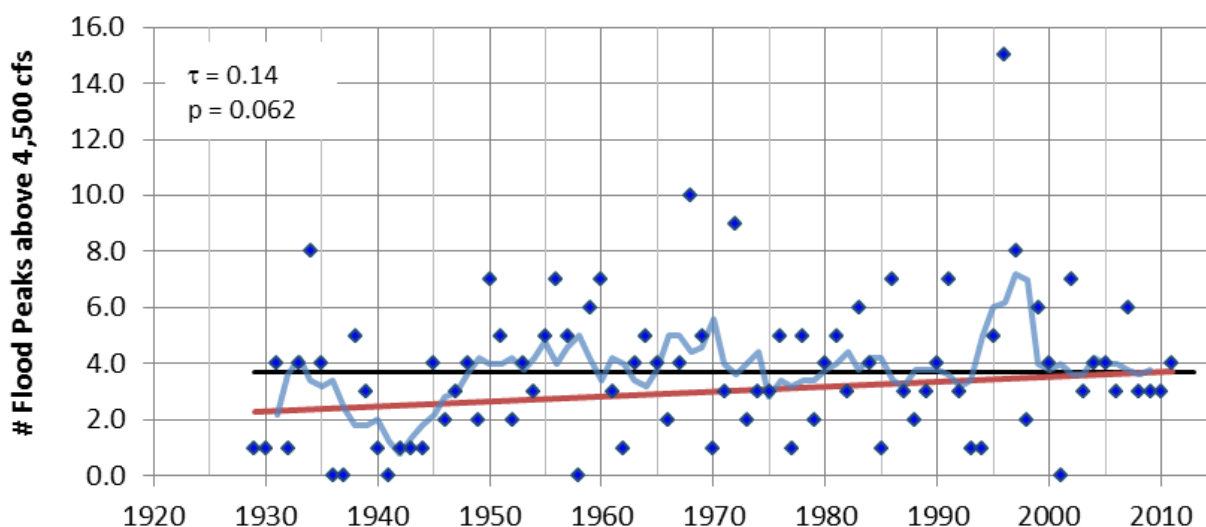
τ = 0.14
p = 0.062

Sauk River near Sauk (#12189500)

τ = 0.21
p = 0.005

FIGURE 15a – Historical trends in the partial duration flood series.

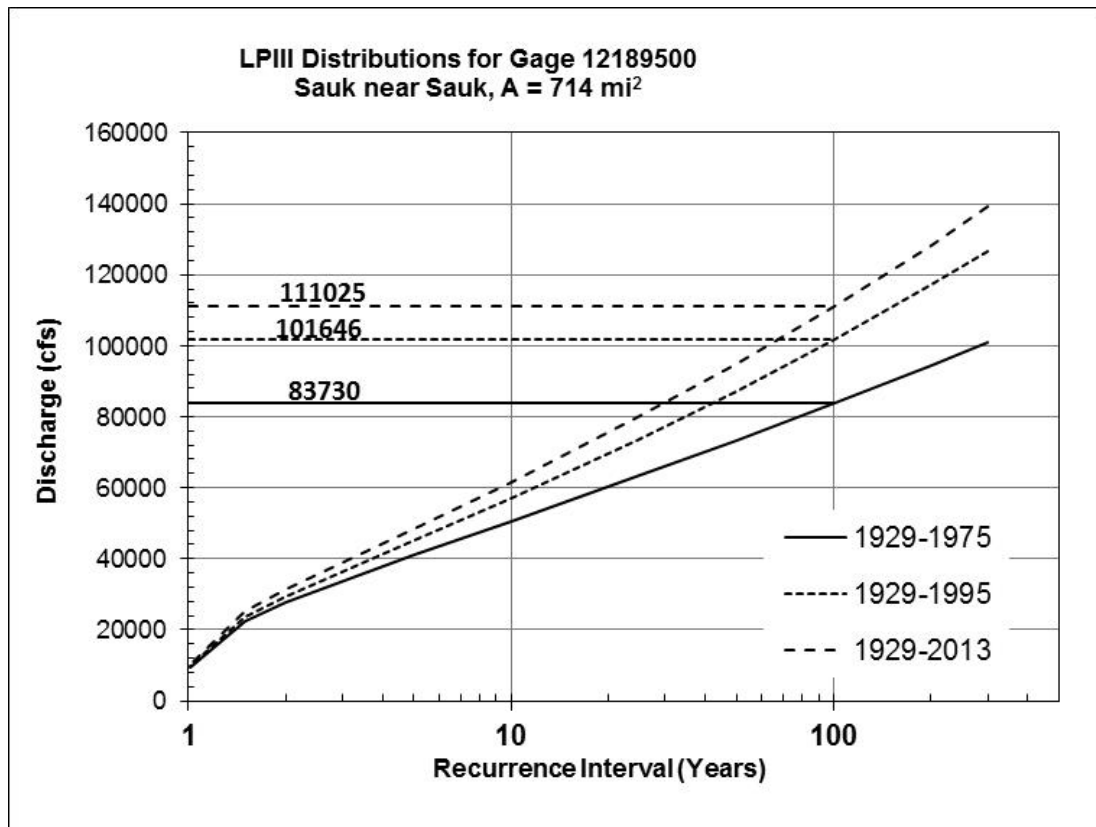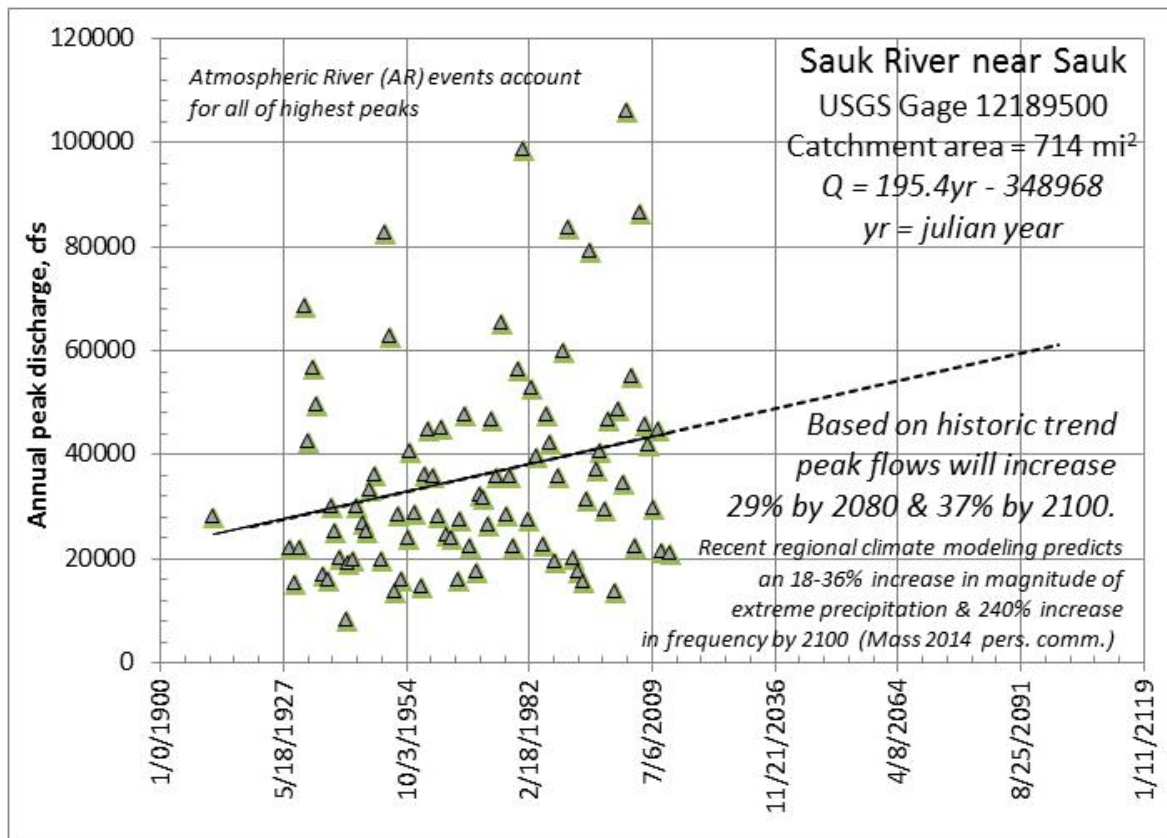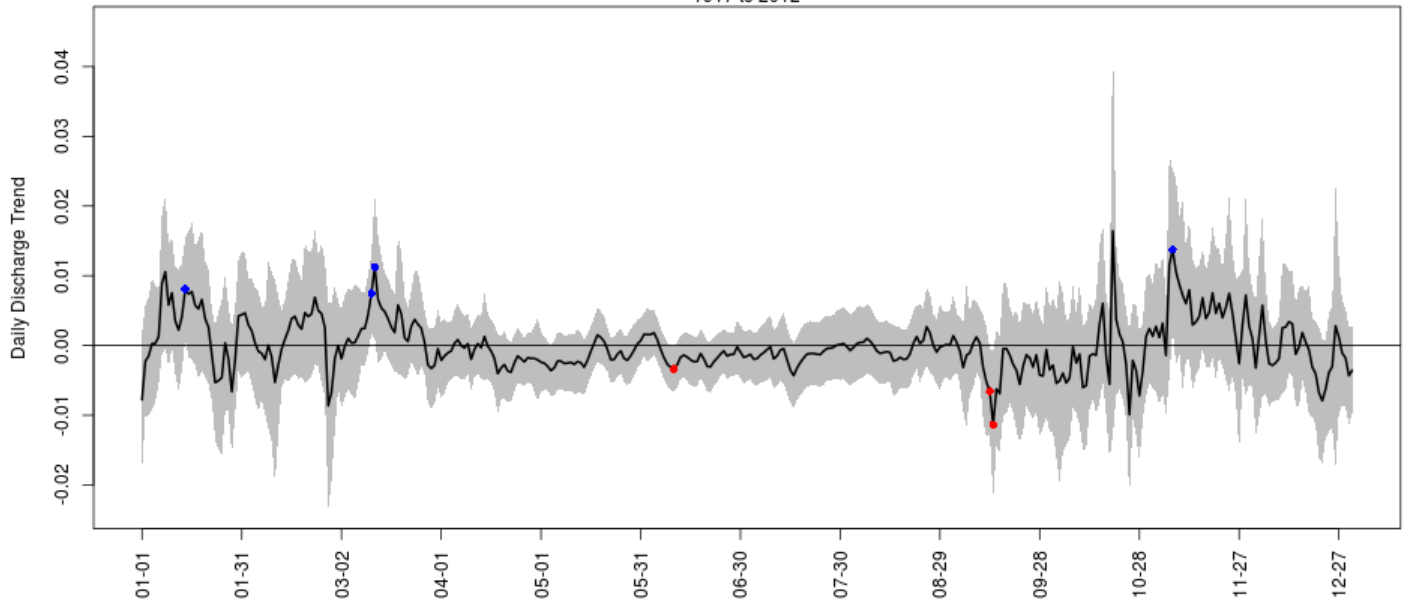**Flood and Erosion Hazard Assessment
for the Sauk-Suiattle Indian Tribe**
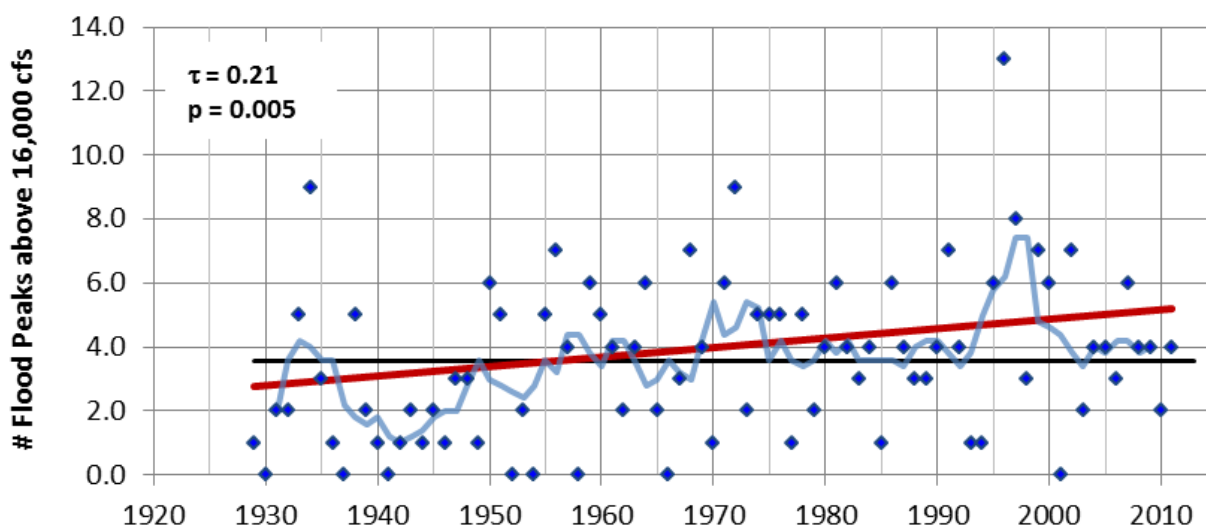
FIGURE 15b – Historic trend in annual peak flows (top) and changing flood recurrence curves through time showing increase in the 100 yr flood discharge (bottom).
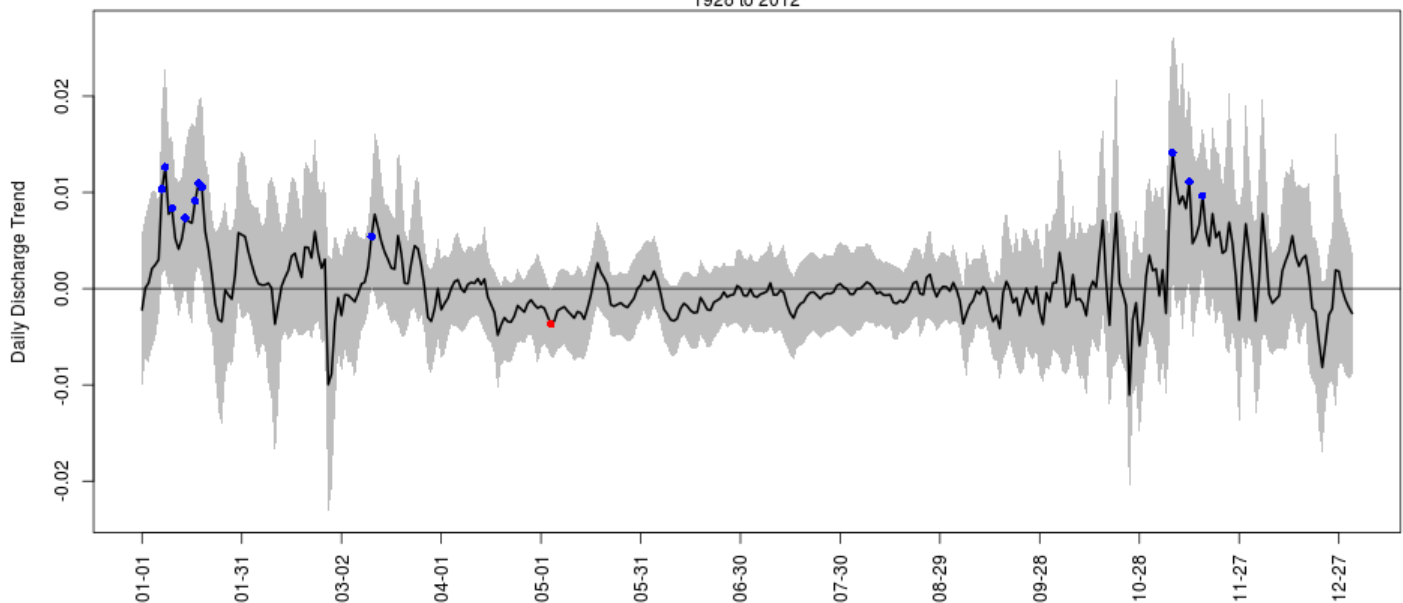
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Trends derived from the daily records of stremflow at USGS gaging stations. The black line is the trend line and a positive trend value corresponds to an increase in flow over time for that date. Conversely, a negative trend value corresponds to a decrease in flow over time for that date. The gray envelope is the 95% confidence interval. Blue/Red dots represent a trend that is significantly different than zero at the 95% level. Analysis methods are based on an approach described by Jones et al. (2012).

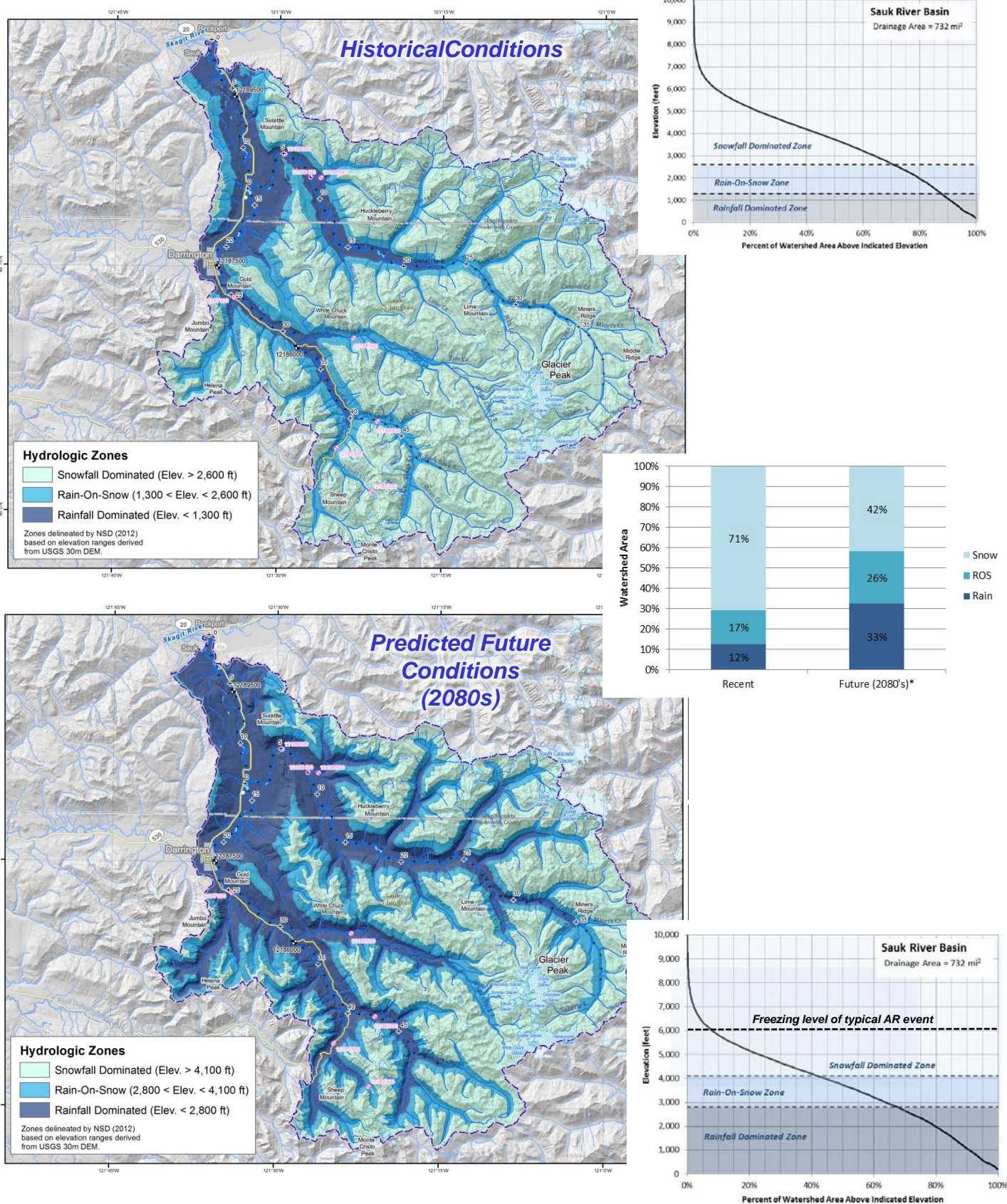FIGURE 16 – Historical trends in the daily streamflow record.

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FIGURE 17 – Projected changes in hydrologic zones due to warming climate.

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Simulated Hydrologic Parameters for Scenario A1B (moderate emissions)
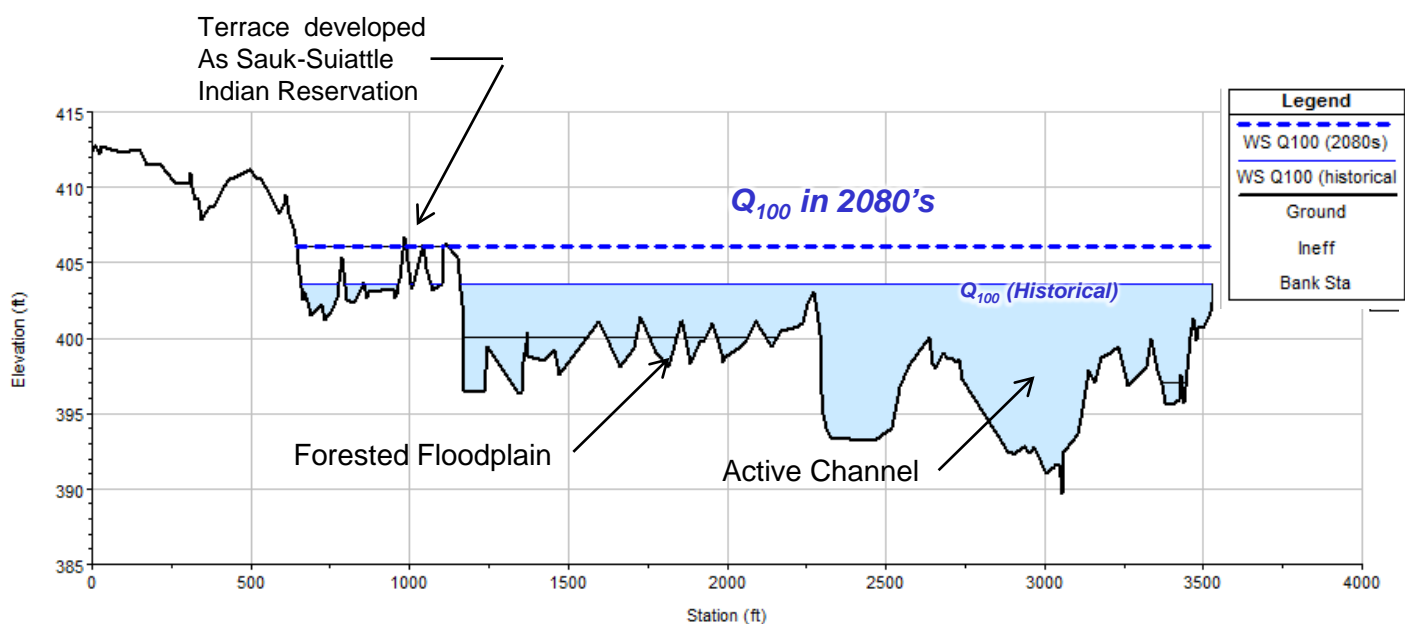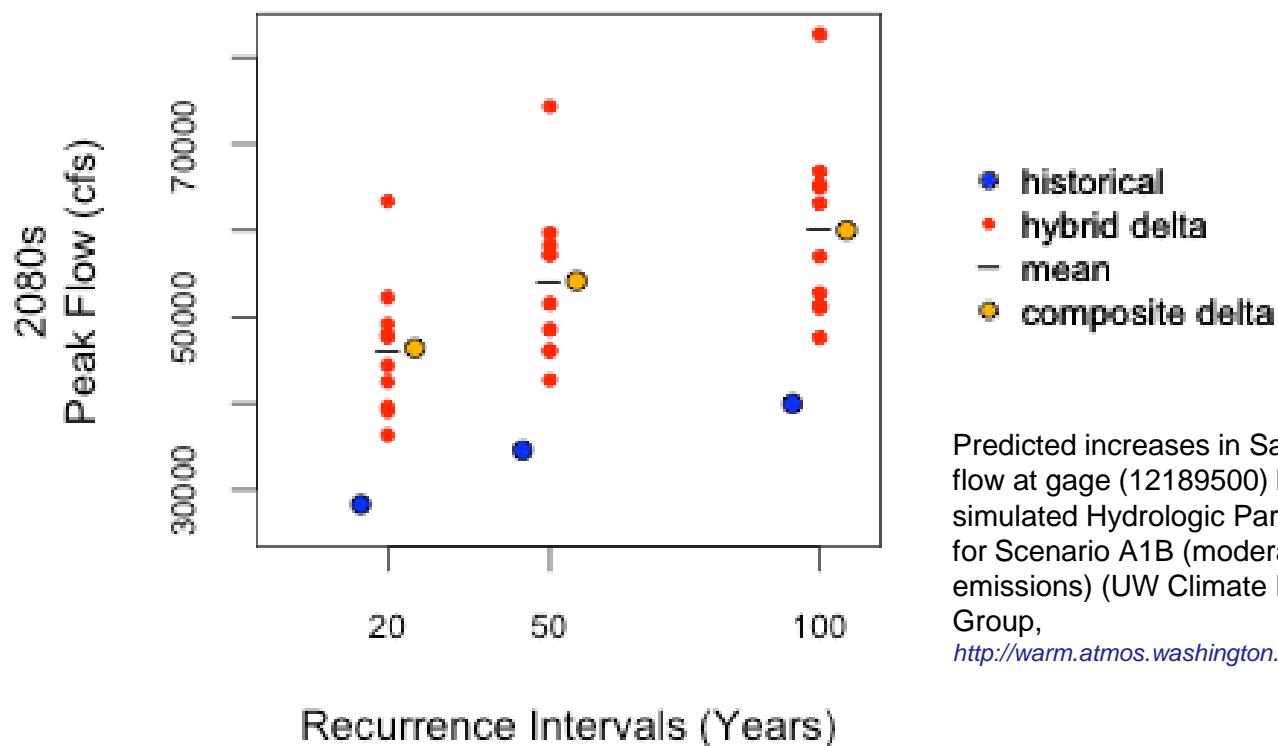Sauk River near Sauk (#12189500)
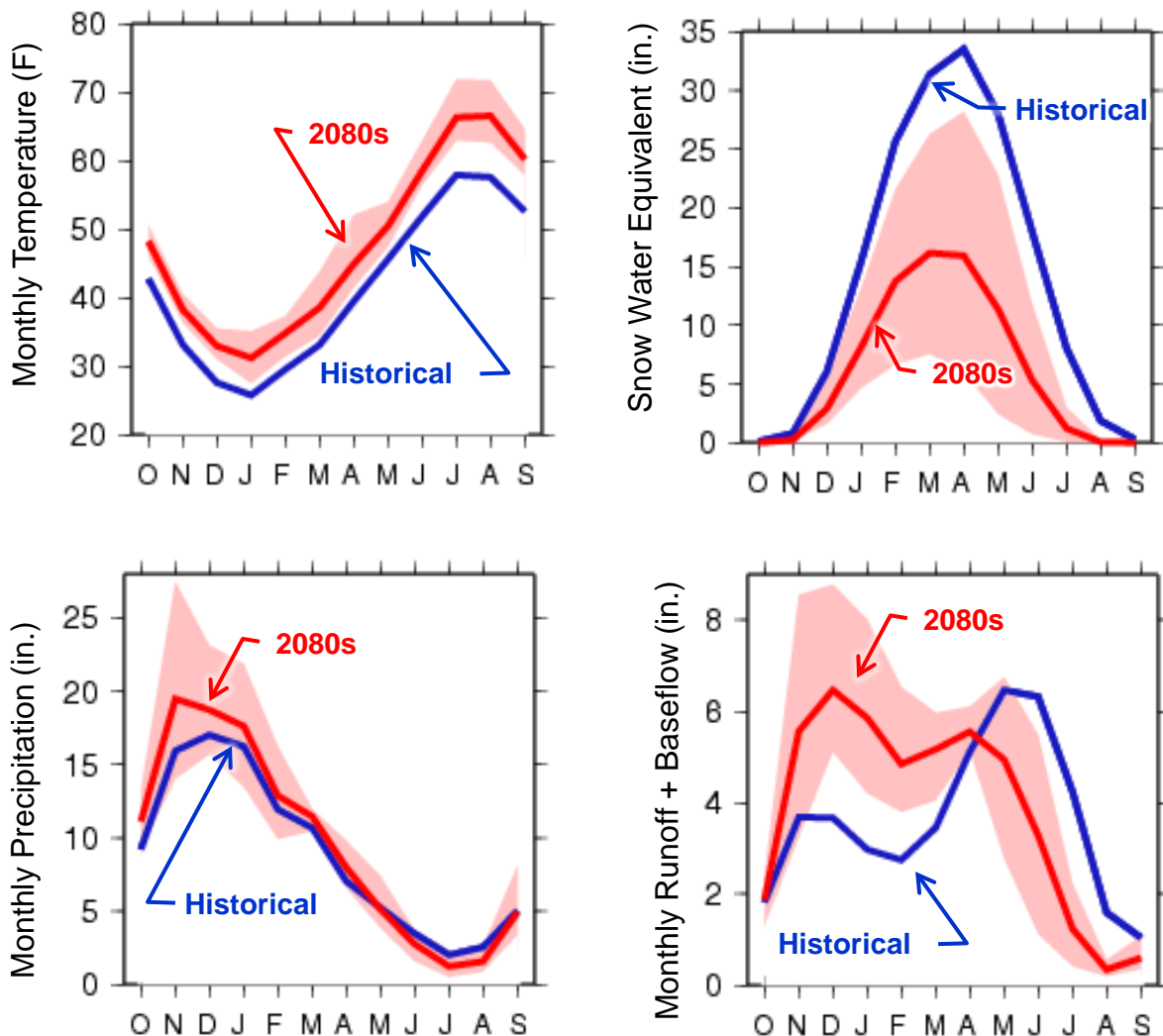
Data source: Hamlet et al. (2010)

Projected values for the 2080s represents the period 2070-2099.

Figures downloaded from the Columbia Basin Climate Change Scenarios Project website at http://warm.atmos.washington.edu/2860/. These materials were produced by the Climate Impacts Group at the University of Washington in collaboration with the WA State Department of Ecology, Bonneville Power Administration, Northwest Power and Conservation Council, Oregon Water Resources Department, and the B.C. Ministry of the Environment.

FIGURE 18 – Simulated hydrologic changes for the Sauk River.

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Predicted increases in Sauk peak flow at gage (12189500) based on simulated Hydrologic Parameters for Scenario A1B (moderate emissions) (UW Climate Impacts Group, *http://warm.atmos.washington.edu/2860/.*

- Hydrologic model simulations by the UW Climate Impacts Group predict an increase in peak flow magnitudes in response to anticipated climate change.

- Ensemble mean of climate projections yields 50% increase in discharge of 0.01 probability peak flow (100 yr flood) for the A1B (moderate emissions) scenario by the 2080's.

- Hydraulic model simulations of existing and future (2080's) peak flow magnitudes for a 100-year recurrence interval event predict a 2.4 foot increase in the Sauk-Suiattle subreach.

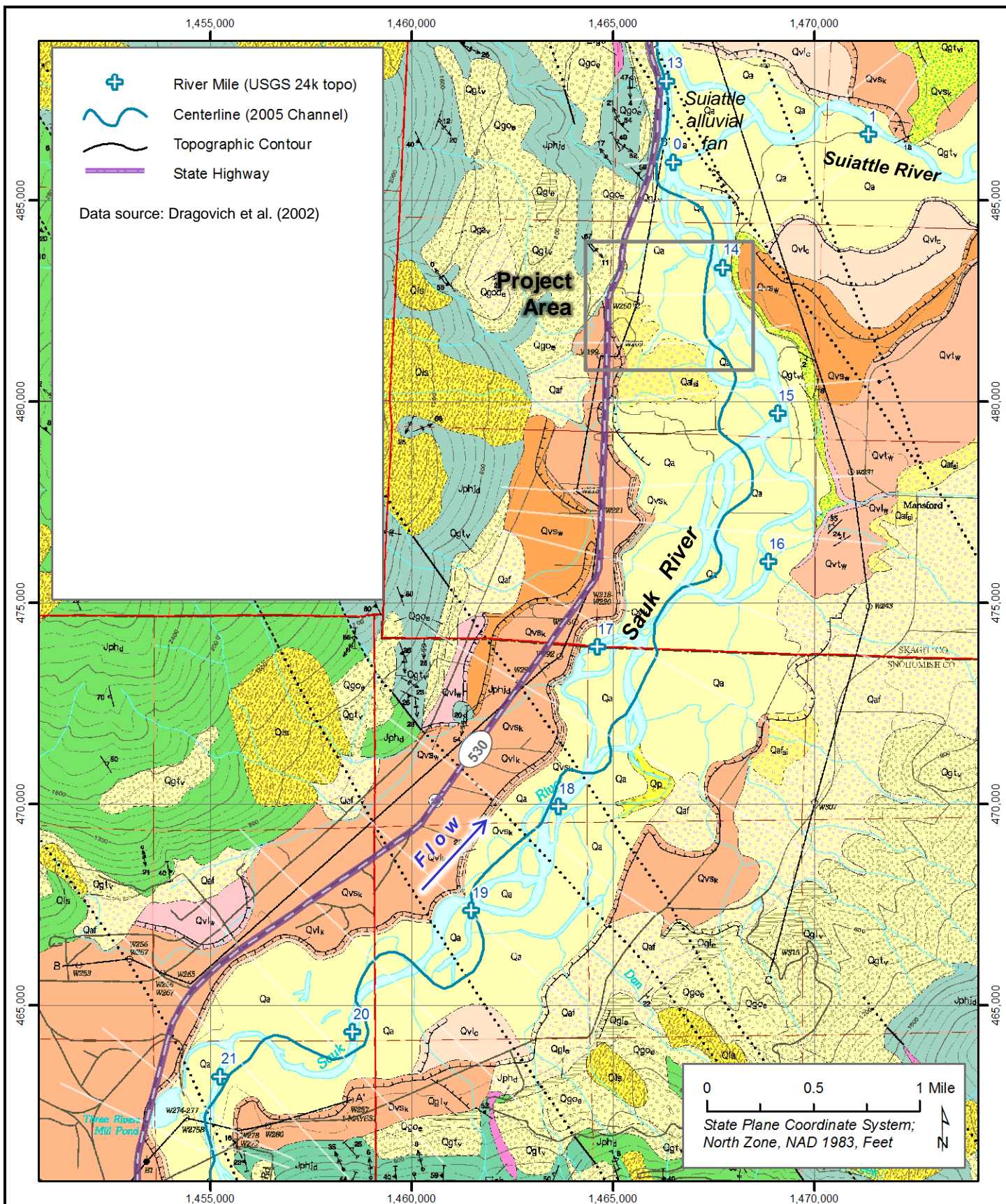FIGURE 19 – Hydraulic simulation of projected 50% increase in100-year flood.

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FIGURE 20 – Geologic Map of the Sauk River valley.

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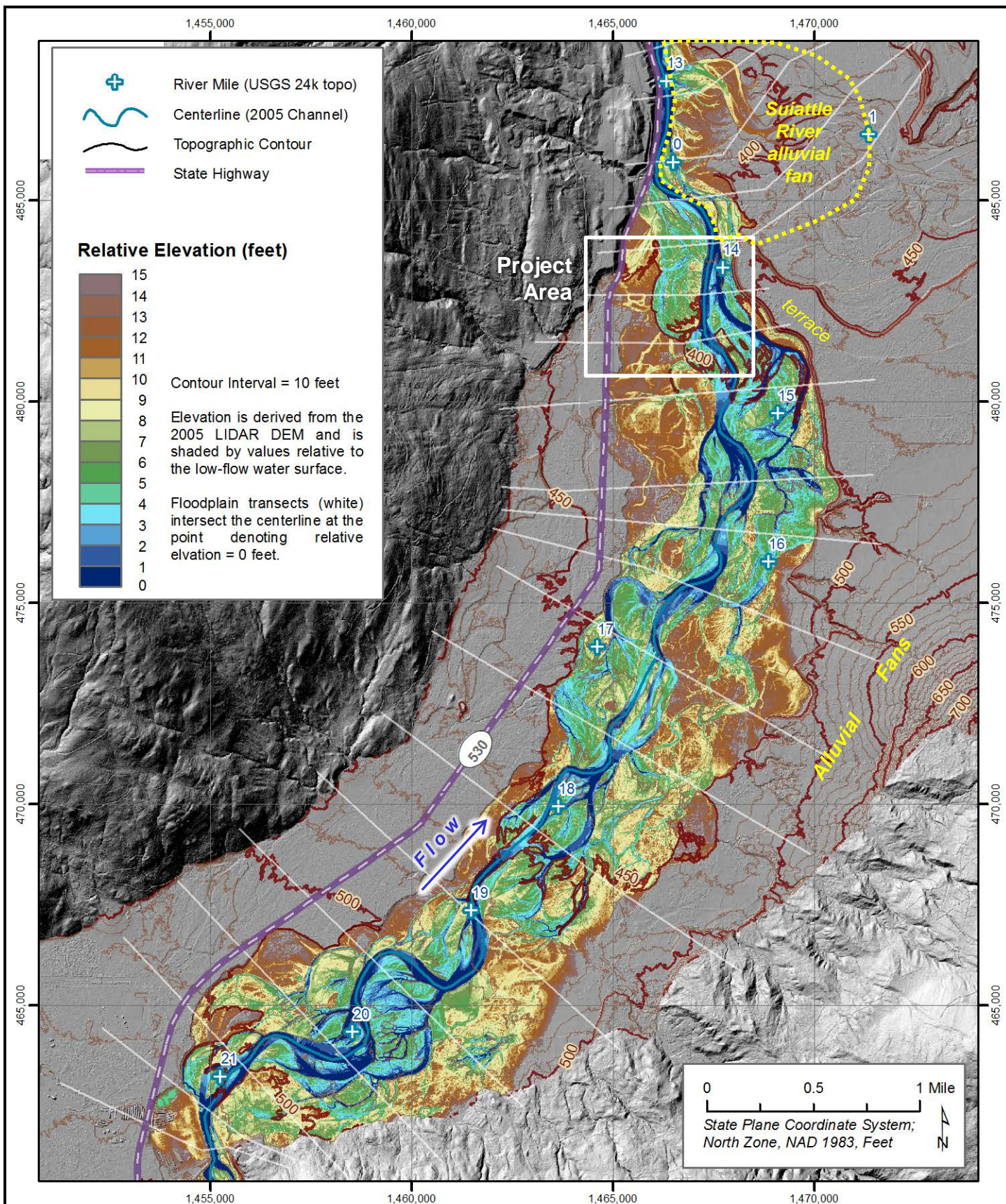P.O. Box 15609
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Relative Elevation (feet)

Legend:
- River Mile (USGS 24k topo)
- Centerline (2005 Channel)
- Topographic Contour
- State Highway

Contour Interval = 10 feet

Elevation is derived from the 2005 LIDAR DEM and is shaded by values relative to the low-flow water surface.

Floodplain transects (white) intersect the centerline at the point denoting relative elevation = 0 feet.

Relative Elevation scale: 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0

Project Area

Suiattle River alluvial fan

terrace

Alluvial Fans

Flow

530

State Plane Coordinate System; North Zone, NAD 1983, Feet

0   0.5   1 Mile

FIGURE 21 – Relative Elevation Map (2000 LIDAR DEM).

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FIGURE 22 – Longitudinal profile of the Sauk River.

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FIGURE 23 – Geomorphic map of the Sauk-Suiattle reach.

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Legend

- ✚ 1000   Stationing (feet)
- 〜   2011 Channel Alignment
- 〜   Topographic Contour
- —   Roads

Tree Canopy Height

- > 150 ft
- 100-150 ft
- 50-100 ft
- 15-50 ft

source: 2005 LIDAR DE< Canopy height derived as the difference between first return and bare earth surfaces.

River stationing measured upstream from the confluence with Suiattle River along centerline of 2011 channel alignment.

0   1,000   2,000 Feet

State Plane Coordinate System (NAD 1983, Feet)

Sauk-Suiattle Reservation

Suiattle River

Sauk River

Bryson Road

SR-530

FIGURE 24 – Tree canopy height in the Sauk-Suiattle reach.

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FIGURE 25 – Historical aerial imagery of the Sauk-Suiattle reach.

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Sauk River Historic Sinuosity

Sauk River sinuosity is likely to increase over time either due to renewed channel meandering following historic incision and increased gravel bed growth resulting from higher flows and sediment supply. An increase in sinuosity would correspond to an increase in lateral channel migration.
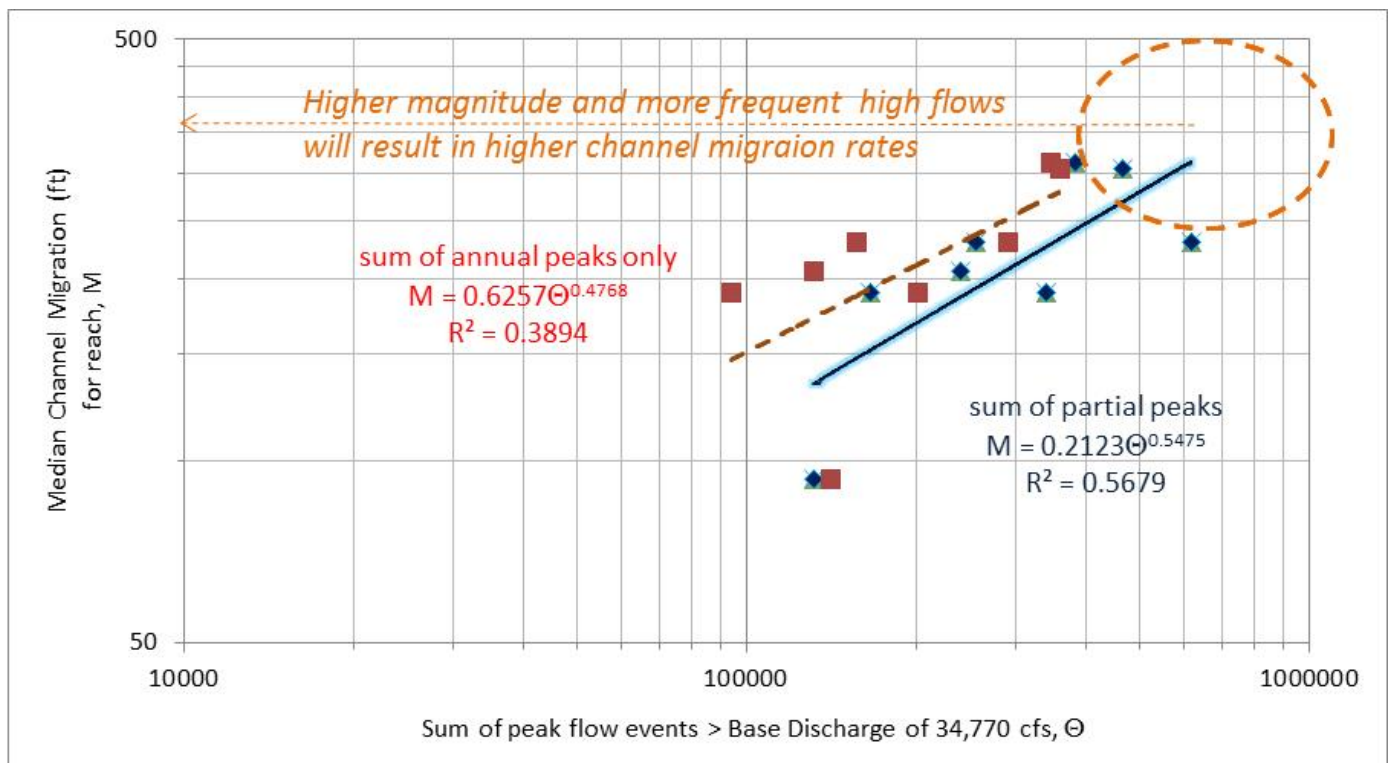
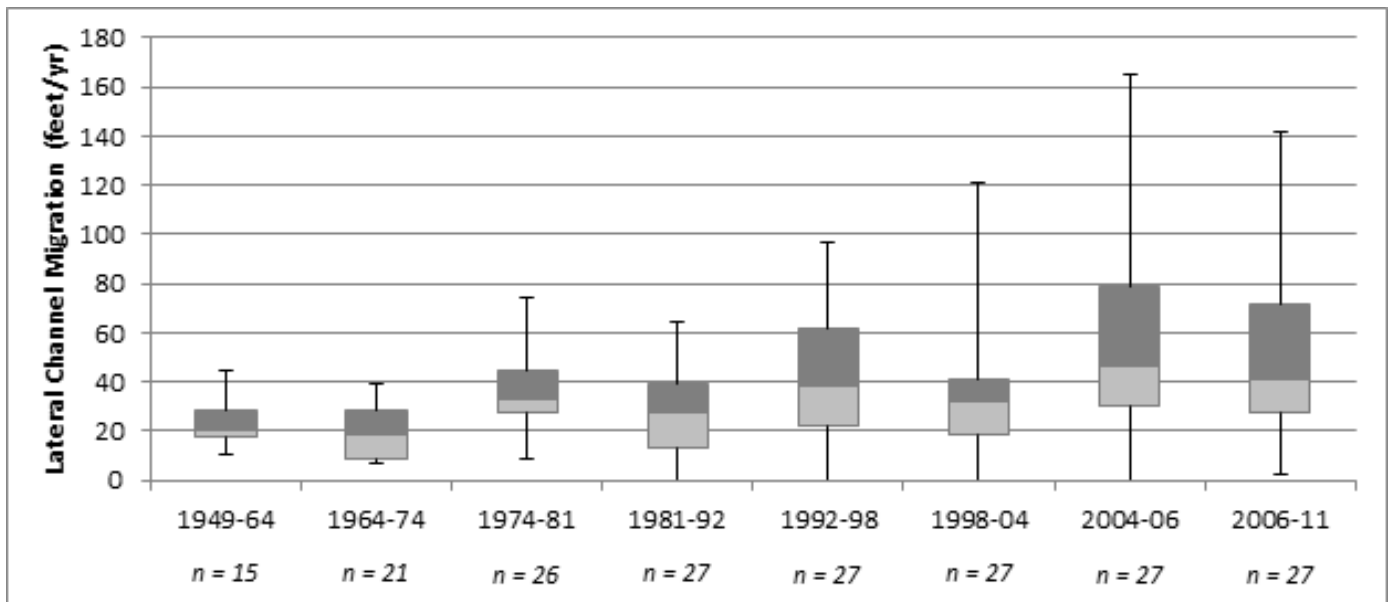FIGURE 26 – Historical changes in channel sinuosity.

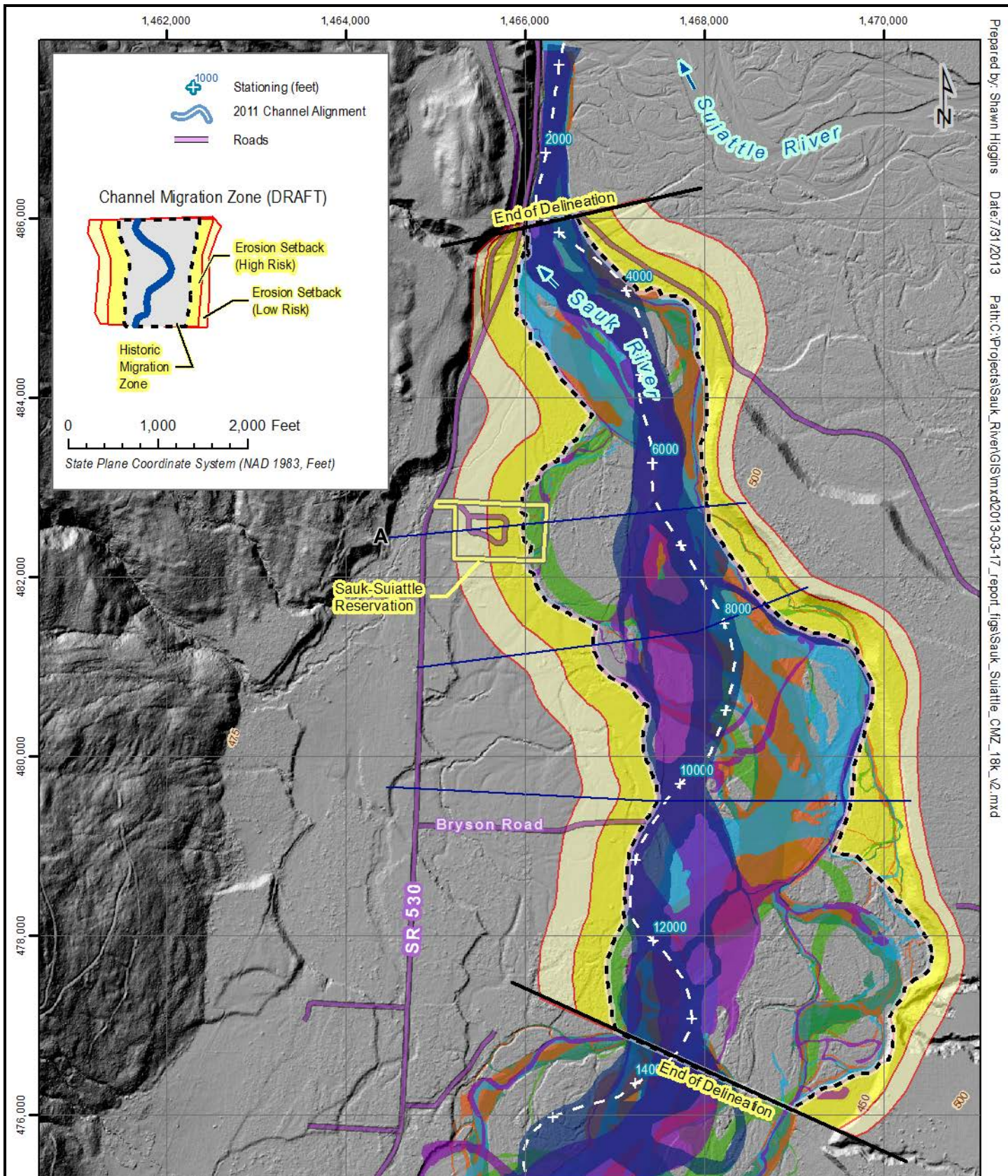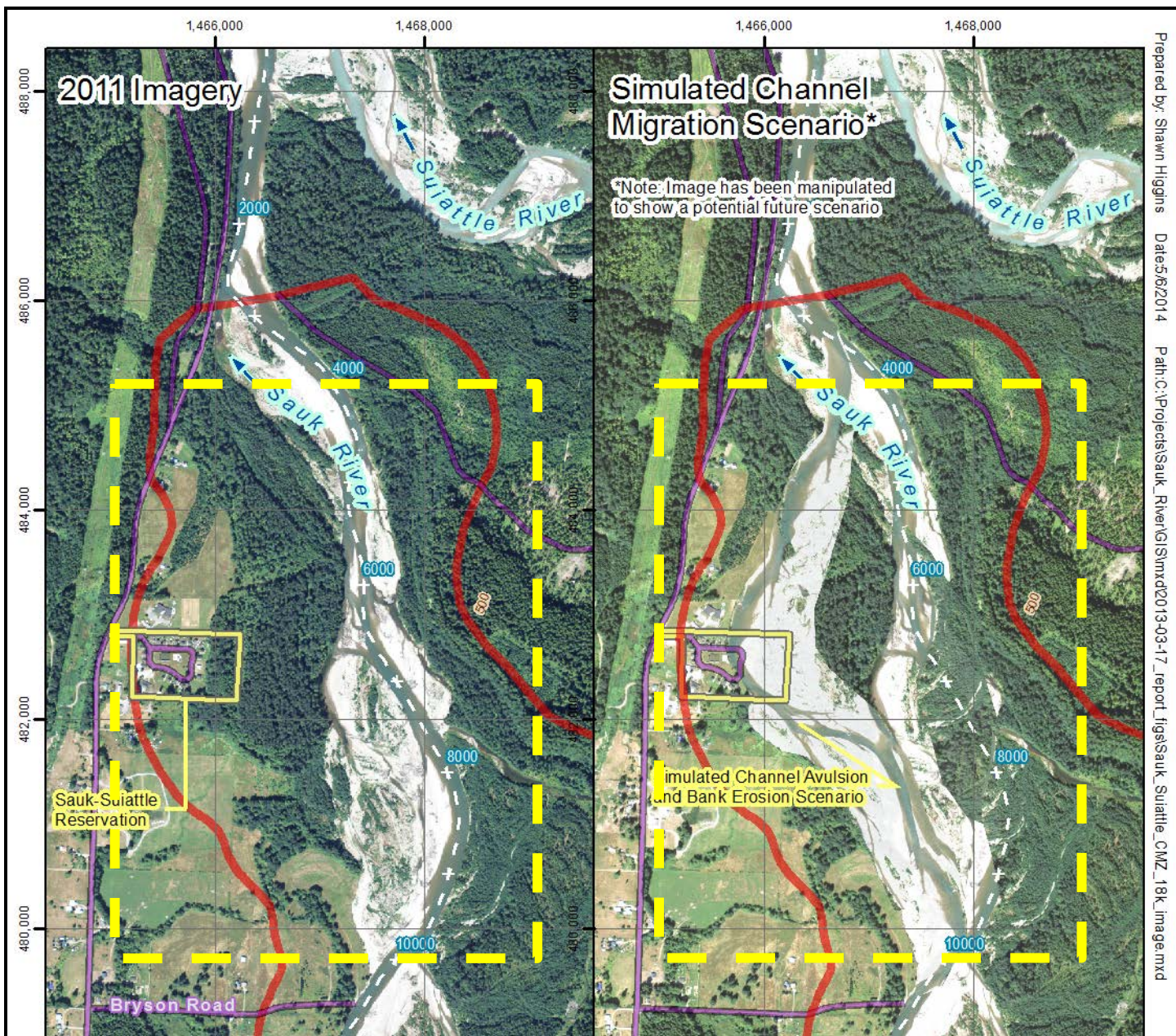FIGURE 27 – Channel migration rates.

FIGURE 28 – Preliminary channel migration zone delineation, based on historic erosion rates. Incorporating future increases in peak flow magnitude and frequency due to climate change, high risk setback would extend through low-risk zone depicted above.

Flood and Erosion Hazard Assessment
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FIGURE 29 – CMZ and simulated channel migration scenario within next 50 years. (within dashed box)

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