Susitna-Watana Hydroelectric Project
(FERC No. 14241)

Glacier and Runoff Changes (Study 7.7) and Fluvial Geomorphology (Study 6.5)

Assessment of the Potential for Changes in Sediment Delivery to Watana Reservoir Due to Glacial Surges Technical Memorandum

Prepared for

Alaska Energy Authority

SUSITNA-WATANA HYDRO
Clean, reliable energy for the next 100 years.

Prepared by

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Abbreviation	Definition
AEA	Alaska Energy Authority
cfs	cubic feet per second
FERC	Federal Energy Regulatory Commission
g/l	grams per liter
ILP	Integrated Licensing Process
M	Million
mm	Millimeter
OWFP	open-water flow period
ppm	parts per million
PRM	Project River Mile
RM	River Mile
RSP	Revised Study Plan
sq mi	square mile
SPD	Study Plan Determination
USGS	U.S. Geological Survey
WY	Water Year

1. INTRODUCTION AND BACKGROUND

The Alaska Energy Authority (AEA) is preparing a License Application that will be submitted to the Federal Energy Regulatory Commission (FERC) for the Susitna-Watana Hydroelectric Project using the Integrated Licensing Process. The Project is located on the Susitna River, an approximately 320-mile-long river in the Southcentral region of Alaska. The Project's dam site will be located at Project River Mile (PRM) 187.1. The results of this study will provide information needed to support the FERC's National Environmental Policy Act analysis for the Project license.

On December 14, 2012, AEA filed its Revised Study Plan (RSP) with the FERC for the Susitna-Watana Hydroelectric Project (FERC Project No. 14241), which included 58 individual study plans (AEA 2012). Included with the RSP are the Glacial Runoff Changes Study (RSP Study 7.7) and the Fluvial Geomorphology Study (RSP Study 6.5). Study 7.7 focuses on the potential impacts of glacier wastage and retreat on the flow of water into the proposed reservoir. The goal of Study 6.5 is to characterize the geomorphology of the Susitna River and includes determining the sediment supply.

Harrison (2012), in his submission to FERC, suggested that glacial surges in the upper reaches of the Susitna River Basin could significantly increase sediment loading to the Watana Reservoir. This suggestion was based on observations of sediment production during surge periods of glaciers both within and outside the Susitna basin.

On February 1 2013, FERC staff issued its study plan determination (February 1 SPD) for 44 of the 58 studies, approving 31 studies as filed and 13 with modifications. RSP Section 7.7 was one of the 13 approved with modifications. In the February 1 SPD, FERC recognized the following:

AEA proposes to analyze the potential effects of climate change on glacier wastage and retreat and the corresponding effects on streamflow entering the proposed reservoir, and evaluate the effects of glacial surges on sediment delivery to the reservoir. Specifically, AEA proposes to:

1. *review existing literature relevant to glacier retreat in southcentral Alaska and the upper Susitna watershed and summarize the current understanding of potential future changes in runoff associated with glacier wastage and retreat;*
2. *develop a hydrologic modeling framework that utilizes a glacier melt and runoff model (Hock 1999) and a Water Balance Simulation Model (WaSiM) to predict changes in glacier wastage and retreat on runoff in the Susitna basin;*
3. *simulate the inflow of water to the proposed reservoir and predict changes to available inflow using downscaled climate projections up to the year 2100; and*
4. *analyze the potential changes to sediment delivery from the upper Susitna watershed into the reservoir from glacial surges.*

FERC staff recommended the following in the February 1 SPD.

- *We find that the analysis of the potential changes to sediment delivery from the upper Susitna watershed into the reservoir from glacial surges as proposed by AEA is necessary, and therefore,* *are recommending approval of this portion of AEA's proposed study (item 4 as described above in the applicant's proposed study).*

To address the FERC recommendation, the Geomorphology Study (Study 6.5) included the following effort to provide for the potential analysis of the influence of glacial surge on reservoir sediment accumulation rates in RSP Section 6.5.4.8.2.1 if sediment from glacial surge can actually be delivered to the reservoir:

Potential additional sediment loading resulting from glacial surge will be investigated in the Glacier and Runoff Changes Study ([RSP] *Section 7.7.4.4, Analyze Potential Changes in Sediment Delivery to Watana Reservoir). If this investigation indicates that the increased sediment load can actually be delivered in substantial quantities to Watana Reservoir, more detailed analyses of the increased loading will be performed and a sediment loading scenario accounting for glacial surge will be added to the reservoir trap efficiency and sediment accumulation analysis. This would include an estimate of the reduction in reservoir life that could result from sediment loading associated with periodic glacial surges.*

Glacial surges in the upper reaches of the Susitna River Basin, where 5 large glaciers and 50-60 small glaciers are located on the southern flank of the Alaska Range (Clarke 1991), could significantly increase suspended sediment loading to the Watana Reservoir. The basis for this concern (Harrison 2012) was the measured behavior of the intensively studied Variegated Glacier located near Yakutat, AK that surged in 1982 and 1983 (Kamb et al. 1985; Harrison and Raymond 1986; Raymond 1987; Raymond et al. 1987). Suspended sediment measurements at the Variegated Glacier outlet streams indicated that there had been on the order of 0.3 m depth of erosion of the underlying bedrock over the 20-year surge cycle ending in 1983. About two-thirds of the erosion occurred during the 2 years of the surge peak and the bulk of this occurred during a two-month period of very high peak discharges from the glacier that occurred as the glacier surge ceased (Humphrey and Raymond 1994). If such extreme bedrock erosion were to occur during a surge of one of the large Susitna Basin surging glaciers (West Fork, Susitna) that greatly exceed the size of the Variegated Glacier (Harrison et al. 1994), Clarke et al. (1986) estimated it would be equivalent to about 30 years of the annual total sediment load estimated at the Gold Creek gage.

This estimate assumes that 100 percent of the sediment evacuated from the glacier over a short time period would be delivered to the proposed Watana Reservoir. Given the extensive presence of braid plains below the glaciers (Raymond and Benedict c. 1990) and the distance (approximately 90 river miles) between the glaciers and the head of the reservoir (Guymon 1974), it may not be reasonable that an appreciable portion of the sediment load associated with a glacial surge would be delivered to the proposed Watana Reservoir. If increased loads do occur, then the reservoir sediment storage and longevity would be affected.

2. STUDY OBJECTIVES

The objectives of this Technical Memorandum are to:

1. Review the literature regarding glacier retreat and glacial surges and pulses in Alaska
2. Review the literature regarding glacial surges within the Susitna River Basin, and

3. Assess the likelihood of a glacial surge in the Susitna River Basin significantly increasing sediment delivery to the proposed Watana Reservoir.

3. STUDY AREA

The study area extends from the headwaters of the Susitna River above PRM 320 and the Maclaren River downstream to the upper extent of the proposed Watana Reservoir at PRM 232 (See Figure 1).

4. REVIEW OF INFORMATION ON GLACIER RETREAT AND GLACIAL SURGES IN ALASKA

Glaciers in Alaska cover an area of about 28,500 square miles (Post and Mayo 1971). For the last 100-200 years there has been a general retreat of the glaciers from their maximum Neoglacial positions (Molnia 2008). In general, the response of Alaskan glaciers to the warming climate has been to retreat (Hall et al. 2005), thin (Adalgeirsdóttir et al. 1998; Arendt et al. 2002; Berthier et al. 2010; Luthcke et al. 2008), and decelerate (Heid & Kääb 2012a). A large number of the retreating glaciers in Alaska have been categorized as surge- and pulse-type glaciers (Post 1960, 1969; Mayo 1978; Ommanney 1980; Clarke et al. 1986; Wilbur 1988; Copland et al. 2003; Turrin 2014). Many have experienced substantial surges and pulses that have resulted in cyclical flow instabilities (Meier and Post 1969; Lawson 1977; Clarke et al. 1986; Kamb et al. 1985; Harrison et al. 1986a; Harrison et al. 1986b; Raymond and Harrison 1988; Kamb 1987; Eschelmeyer et al. 1987; Molnia and Post 1995, 2010; Nolan 2003; Burgess et al. 2012; Tangborn 2013; Turrin 2014). Within the Alaska Range surging glaciers tend to be found in fault-shattered valleys (Post 1969) while the pulsing glaciers tend to be floored by deformable glacial tills (Turrin 2014).

Surging glaciers are distinguished by their periods of brief but anomalously fast flow, known as the active phase, and their often long periods of nearly stagnant flow, known as the quiescent phase (Post 1969). The active phase, or surge, rapidly transports large volumes of ice down-glacier from a reservoir area, often located in the accumulation zone, to the ablation zone and to the terminus, often causing the terminus to thicken by tens of meters and to advance by kilometers (Kamb et al. 1985). Mayo (1978) defined a glacier pulse as periodic, short duration, unstable flow lesser in magnitude than surge-type behavior.

Surges of the glaciers influence their mass balance by transporting large masses of ice to a lower elevation where higher temperatures increase ablation rates and runoff (Eisen et al. 2001; Tangborn 2013). The surges also increase sediment discharge from the glacier (Hance 1937; Humphrey et al. 1986; Eschelmeyer et al. 1987; Humphrey and Raymond 1994; Merrand and Hallet 1996; Harrison et al. 1994; Raymond and Benedict, c.1990). Under non-surging conditions, suspended sediment concentrations from glaciers are generally less than 10g/l (10,000 ppm) (Gaddis 1974; Raymond and Benedict, c.1990) but measured concentrations at the end of surges of both the Variegated and West Fork Glaciers were as high as 30g/l (30,000 ppm) for relatively short periods of time as a result of ice erosion of the underlying bedrock (Humphrey and Raymond 1994: Harrison et al. 1994). Bed load, which can constitute up to 30 percent of the total load directly downstream of the glacier (Ostrem et al. 1973), is generally deposited within a short distance of its source (Guymon 1974; Raymond and Benedict, c.1990). Termination of the surges can also result in one or more large magnitude outburst floods (jokulhaups) as water is released from englacial storage (Kamb et al. 1985; Humphrey and Raymond 1994; Harrison et al. 1994; Lingle and Fatland 2003).

Surge frequencies are glacier specific, but reportedly range from about 7 years for the Ruth Glacier (Turrin 2014), to 17-20 years for the Bering Glacier (Molnia and Post 2010; Tangborn 2013) and Variegated Glacier (Humphrey and Raymond 1994), to 50-60 years for the West Fork and Susitna Glaciers (Clarke et al. 1986; Clarke 1991; Harrison et al. 1994). Exactly how surging glaciers will respond to warming climatic trends, either by increasing or decreasing surge frequency and magnitude, is unknown (Turrin 2014). However, within Alaska, general glacier retreat and loss of ice mass is expected to continue in the future (Radic and Hock 2011).

5. REVIEW OF INFORMATION ON GLACIAL SURGES WITHIN THE SUSITNA RIVER BASIN

Glaciers cover about 305 mi^2 (790 km^2) or 5.9 percent of the Susitna Basin area above the proposed Watana Dam site. Because of the significance of the glacierized portion of the basin for both runoff and sediment supply to the Susitna River, a number of investigations were conducted in the 1980s for the Alaska Power Authority (Harrison 1981; Harrison and R&M Consultants, Inc. 1982; R&M Consultants, Inc. and Harrison 1981; Harrison et al. 1983; Clarke et al. 1985, 1986; Clarke 1986). The glacierized portion of the Susitna River Basin produces about 13 percent of the flow at the Gold Creek gage (Clarke et al. 1986), which is approximately 16 percent of the flow to the proposed Watana Dam site. Glacial retreat in the 1949-1980 period was estimated to have produced about 3-4 percent of the flow at the Gold Creek gage (Clarke et al. 1986). Approximately 34 percent of the runoff measured north of the Denali Highway using the Susitna River at Denali and Maclaren River at Denali gages is attributed to the glacierized area (ISR, Study 7.7., Section 4.2.4.2). In addition, it has been suggested that glacial surges could significantly increase the suspended sediment load delivery to the proposed reservoir (Clarke et al. 1986; Harrison 2012).

Five large glaciers, the West Fork, Susitna, East Fork Glaciers on the mainstem Susitna River and the Maclaren and Eureka Glaciers in the Maclaren River Basin, and 50-60 small glaciers form the headwaters of the Susitna River (Clarke 1991) (Figure 1). The West Fork (about 99 mi^2) and Susitna (about 88 mi^2) Glaciers are underlain by faults associated with the Denali Fault System (Post 1969; Clarke et al. 1986; Harrison et al. 1994) and are classified as surge-type glaciers (Post 1960, 1969; Clarke et al. 1986; Wilbur 1988; Eschelmeyer and Harrison 1987; Clarke 1991; Harrison et al. 1994). The East Fork Glacier (about 16 mi^2) is classified as a non-surging-type glacier (Post 1969; Wilbur 1988). Eureka Glacier (about 15 mi^2) has been classified as a surge-type glacier (Post 1969). The Maclaren Glacier (about 23 mi^2) was classified as inconclusive by Post (1969), but Mayo (1978) suggested that it had undergone a strong pulse in 1971. Indicators of surge activity include: a) the presence of looped moraines, b) deformed ice structures, c) heavily crevassed glacier surface in the active phase, d) potholes on the glacier surface during the quiescent phase, e) rapid advance of the glacier terminus when surrounding glaciers are relatively stable in ice-margin position, f) shear margins on the glacier surface, g) surface velocities that are typically an order of magnitude higher than during the quiescent phase, and h) strandlines of ice on surrounding bedrock (Meier and Post 1969; Copland et al. 2003). Wilbur (1988) using the 0-5 scale Canadian Glacier Inventory Code (Ommanney 1980) where Code 0 represents no evidence of surge activity and Code 5 represents the presence of extensive surge features, classified the Eureka Glacier as a Code 2 (few surge features present) and the Maclaren Glacier as Code 3 (moderate presence of surge features). In contrast, the West Fork and Susitna Glaciers were assigned Codes of 4 and 5, respectively which reflect the extensive presence of surge features.

The West Fork Glacier surged between 1935 and 1937 (Clarke 1991) and again about 50 years later in 1987/1988 (Eschelmeyer and Harrison 1989; Harrison 1994; Harrison et al. 1994; Raymond and Benedict, c.1990). The Susitna Glacier last surged either in 1951/1952 (Clarke 1991) or 1952/1953 (Post 1960; Meier and Post 1969; Labelle et al. 1985). Clarke (1991) suggested that the next surge of the Susitna Glacier would occur in the first decade of the 21st century. This estimate was based on the ratio of actual ice flux to balance flux developed from data collected between 1981 and 1983. However, there has been no recent evidence of imminent surge activity, and in fact the surface of the glacier is potholed (Figure 2) which suggests that it is still in a stagnation or quiescent, non-surging phase (Harrison et al. 1994; Copland et al. 2003).

Assuming that the historical West Fork Glacier surge cycle is maintained, the next surge is likely to occur in about 2,038. However, the effects of climate warming on the frequency and magnitude of glacial surge cycles are unknown (Turrin 2014) and Harrison (personal communication, September 10, 2012) hypothesized that surging may no longer occur at many glaciers, including the West Fork Glacier, because non-surge glacial processes would be able to maintain equilibrium. It is unknown whether the failure of the Susitna Glacier to surge in the first decade of the 21st century supports Harrison’s hypothesis.

6. POTENTIAL FOR INCREASED SEDIMENTATION IN WATANA RESERVOIR DUE TO GLACIAL SURGE

6.1. Glacial Surge Sediment Production

The 1982-1983 surge of the Variegated Glacier produced sediment transported in suspension approximately equivalent to 0.3 m of bed lowering during the 20-year surge cycle (0.015 m/yr). Two-thirds of this lowering occurred over the 2-year surge period (0.1 m/yr), and the bulk of that during a two-month period (Humphrey and Raymond 1994). Clarke et al. (1986) suggested that a similar surge of one of the very large Susitna Basin glaciers (West Fork or Susitna) could produce about 20 x 10^7 tons of suspended sediment, which they indicated was equivalent to about 30 years of the annual total sediment load estimated at the Gold Creek gage (about 6.8 x 10^6 tons/yr). However, downstream storage in extensive braid plains (Figure 1) makes it highly unlikely that the entire estimated sediment production would be transported to the proposed Watana Reservoir (Guymon 1974).

The West Fork Glacier surged in 1987 and 1988 and suspended sediment data were collected at the outlet streams and in the Susitna River upstream of the confluence with the West Fork Susitna River (Figure 3) (Harrison et al. 1994; Raymond and Benedict, c.1990). Suspended sediment concentrations as high as 30 g/l (30,000 ppm) were measured for short periods of time in 1988 (concentrations exceeded 10 g/l for about 16 days) towards the cessation of the surge.

These values greatly exceed the measured concentrations at non-surging glaciers (< 10 g/l; 10,000 ppm) (Gaddis 1974; Raymond and Benedict, c.1990). Measured concentrations in the Susitna River upstream of the confluence with West Fork Susitna River (PRM 301) in 1988 were one to two orders of magnitude less than at the West Fork Glacier outlet (Harrison et al. 1994). For a point of reference, measured suspended sediment concentrations at the USGS Denali gaging station (USGS 15291000) during non-surge conditions in the basin (1958-1986) range from 100 mg/l (100 ppm) to 6,000 mg/l (6,000 ppm) (Figure 4) (Tetra Tech 2014a). Based on the suspended sediment rating curve for the Denali gage (Figure 4), the average annual suspended sediment load is about 3×10^6 tons, of which 57 percent (about 1.7×10^6 tons) is composed of silts and clays and 43 percent (1.3×10^6 tons) is composed of sand (Tetra Tech 2014a). The average annual suspended sediment concentration at the gage is about 1,000 ppm (Guymon 1974; Tetra Tech 2014a).

6.2. Sediment Transport in the Susitna River

6.2.1. Sand Transport

Transport of the sand fraction of the suspended load provided by the upstream glaciers at the Denali gage (PRM 292) is transport capacity dependent and is based on the hydrology and hydraulic conditions at the gage (Figure 4) where there is an almost unlimited supply of sand sized material in the bed (Figure 5). Analysis of a 50-year hydrologic record at the Gold Creek gage (PRM 140) (USGS 15292000), which included two glacier surge periods (Susitna Glacier in 1952/1953 and West Fork Glacier in1987/1988), did not indicate that the surges appreciably affected the mean annual discharge, the average May-September discharge or the maximum daily discharge (Figure 6) which confirms the analysis of Labelle et al. (1985) for the Susitna Glacier surge. The Gold Creek gage was selected because it is the longest operated gage on the Susitna River and neither of the upstream gages (Denali and Cantwell) were in operation during either of the surge periods (1952/1953 and 1987/1988). Ranking of the 50-years of mean annual discharge records indicated that 1952, 1953, 1987 and 1988 years represented the 52nd, 46th, 54th and 76th percentiles, respectively. Ranking of the 50-years of average May-September discharge records indicated that 1952, 1953, 1987 and 1988 years represented the 52nd, 62nd, 58th and 76th percentiles, respectively. Ranking of the 50-years of maximum daily discharge records indicated that 1952, 1953, 1987 and 1988 years represented the 62nd, 40th, 66th and 46th percentiles, respectively (Tetra Tech 2014b). Based on the hydrologic analysis, which indicates these were all fairly typical years hydrologically, it is unlikely that the surges could significantly affect the volume of capacity-limited sand transported at the Denali gage.

Though the above analysis shows the surge years were all very typical in terms of the recorded flows on the Susitna at Gold Creek, it is possible that these may have been low flow years in general. This would have then masked the effect of the glacier surge at Gold Creek. To investigate this, the Gold Creek and Talkeetna USGS gage records were also compared to assess whether the surge years for the Susitna basin produced higher than expected flows. The long-term average runoff volume measured at Gold Creek is 2.41 times the runoff volume at Talkeetna. For just the open-water flow season the average ratio is 2.43. These values are based on 44 years when the gage observations are concurrent. This period includes the 1987-1988 surge for the West Fork Glacier but not the 1952-1953 surge of the Susitna Glacier. Table 1 shows the variability of this ratio for open-water periods and the values for 1987 and 1988 (flows for 1952 and 1953 are not available for the Talkeetna gage). The first year of the surge is nearly equal to the long-term average and the second year is at the midpoint of the upper quartile. Because there are four non-surge years that have ratios greater than 1987, there is no evidence that Gold Creek flows in 1987 were unusual within the period of record. The year following the cessation of the surge (1989) also shows no unusual difference when compared to the Talkeetna gage and is slightly below average. Therefore, this is further indication that the occurrence of surges in the Susitna glaciers does not appear to have an appreciable hydrologic effect on flow volumes further downstream in the basin and thus sand delivery to the proposed Watana Reservoir.

Table 1. Comparison of Gold Creek to Talkeetna Flow Volumes.

Quartile or Year observed	**Ratio of Open-Water Flow volumes (Gold Creek/Talkeetna)**
Minimum	1.92
1st Quartile	2.21
Median	2.42
3rd Quartile	2.58
Maximum	2.98
1987	2.46 (Rank is 24 of 44)
1988	2.78 (Rank is 40 of 44)
1989	2.34 (Rank is 16 of 44)

6.2.2. Silt-clay Transport

The volume of silt and clay transported is dependent on the supply from upstream. The total glaciated area upstream of the Denali gage is on the order of 250 mi^2 (Clarke et al. 1986) and the contributing drainage area at the gage is 950 mi^2, which provides a ratio of glaciated area to total area of 0.26. The glaciated area produces approximately 34 percent of the flow for this drainage area (ISR, Study 7.7, Section 4.2.4.2). If the average annual suspended sediment concentration (silt/clay and sand) at the Denali gage (1,000 ppm) is divided by these ratios to reflect the downstream dilution (Guymon 1974), the average annual sediment concentration at the glaciers under non-surge conditions should be on the order of 3,800 ppm based on area to 2,900 ppm based on flow, which is within the range of measured values (Gaddis 1974; Harrison et al. 1994; Raymond and Benedict c1990). Therefore, the maximum measured suspended sediment concentrations (30,000 ppm) at the West Fork Glacier during the surge are close to a factor of 10 higher than under non-surge conditions.

Based on this information, if there is a glacial surge every 50 years within the basin based on the historical record, and it is assumed that the higher concentration would be representative of the entire 6-month open-water flow period (OWFP) of that year rather than for a short period of time (weeks), this would very conservatively provide about 55 years of total load within a 50-year period since the silt-clay fraction represents about 50 percent of the total suspended load. Based on an estimated reservoir life of 850 years (Tetra Tech 2014c) this could represent a reduction in reservoir longevity by about 10 percent to 770 years. If, on the other hand, the elevated suspended concentration (30,000 ppm) was applied for only the measured duration (approximately 2 weeks above 10,000 ppm of a single 6-month OWFP), this would provide approximately 50.5 years of total load in a 50-year period. This would represent about a one percent reduction in reservoir longevity (from 850 to 840 years).

Although it is highly unlikely that sediment concentrations at the glacier would be at the upper limit for an entire OWFP, the period could also be more than 2 weeks given the greater size of the West Fork and Susitna Glaciers compared to the Variegated Glacier. The assumption that silt/clay and sand concentrations are approximately equal is based on downstream measurements. Because sand is deposited in the extensive braid plains below the glaciers, the proportion of sand is probably much higher at the glacier. This assumption makes either calculation conservative resulting in greater reductions in estimated reservoir longevity. Therefore, the results are probably conservative, though likely closer to the lower one percent estimate of increased long-term sediment deliver to the reservoir.

7. CONCLUSIONS

1. Two large surging-type glaciers with a surge cycle of about 50 years are located within the Upper Susitna River Basin. The West Fork Glacier surged in 1935/1937 and again in 1987/1988. The Susitna Glacier surged in 1952/1953 and was expected to surge again in the first decade of the 21st century. The fact that it has not surged again could be taken as evidence that surging is not required to maintain glacial equilibrium under the warming climatic regime (W.D. Harrison, personal communication, 2012). However, the effects of climate warming on the frequency and magnitude of glacial surge cycles are as yet unknown (Turrin 2014).
2. Glacial surges result in increased ablation losses and increased runoff from the glacier. Analysis of the hydrologic record at the USGS Gold Creek gage indicated that the 1952/1953 and 1987/1988 surges had no apparent effect on either the mean annual discharge, the average May-September discharge or the maximum daily discharge and thus would have had no significant influence on the volume of sand transported to the Watana Reservoir.
3. Glacial surges also increase the suspended sediment discharge from the glacier for relatively short periods of time by an order of magnitude. Measurements at the outlet to the West Fork Glacier during the 1987/1988 surge indicated suspended sediment concentrations of up to 30,000 ppm which is an order of magnitude higher than under non-surge conditions (3-4,000 ppm) and 30 times higher than the average measured annual suspended sediment concentration (1,000 ppm) at the USGS Denali gage under non-surge conditions.
4. If a glacial surge was to occur within the Upper Susitna Basin that is very conservatively estimated as producing 30,000 ppm concentrations for an entire OWFP during the year, then the elevated silt-clay fraction of the annual suspended sediment load could result in 55 years of sediment delivery to the proposed Watana Reservoir within a 50 year period. This could reduce the longevity of the reservoir by approximately 10 percent from 850 to 770 years. If the elevated concentrations are applied to the measured duration of approximately 2 weeks, the surge could reduce reservoir longevity by about 1 percent (850 to 840 years).
5. Based on this review and evaluation, no further geomorphic investigations are warranted for flow or sediment production from glacial surges. This includes a recommendation to not

include a glacial surge sediment loading scenario in the reservoir sediment trap efficiency and sediment accumulation modeling.

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9. FIGURES

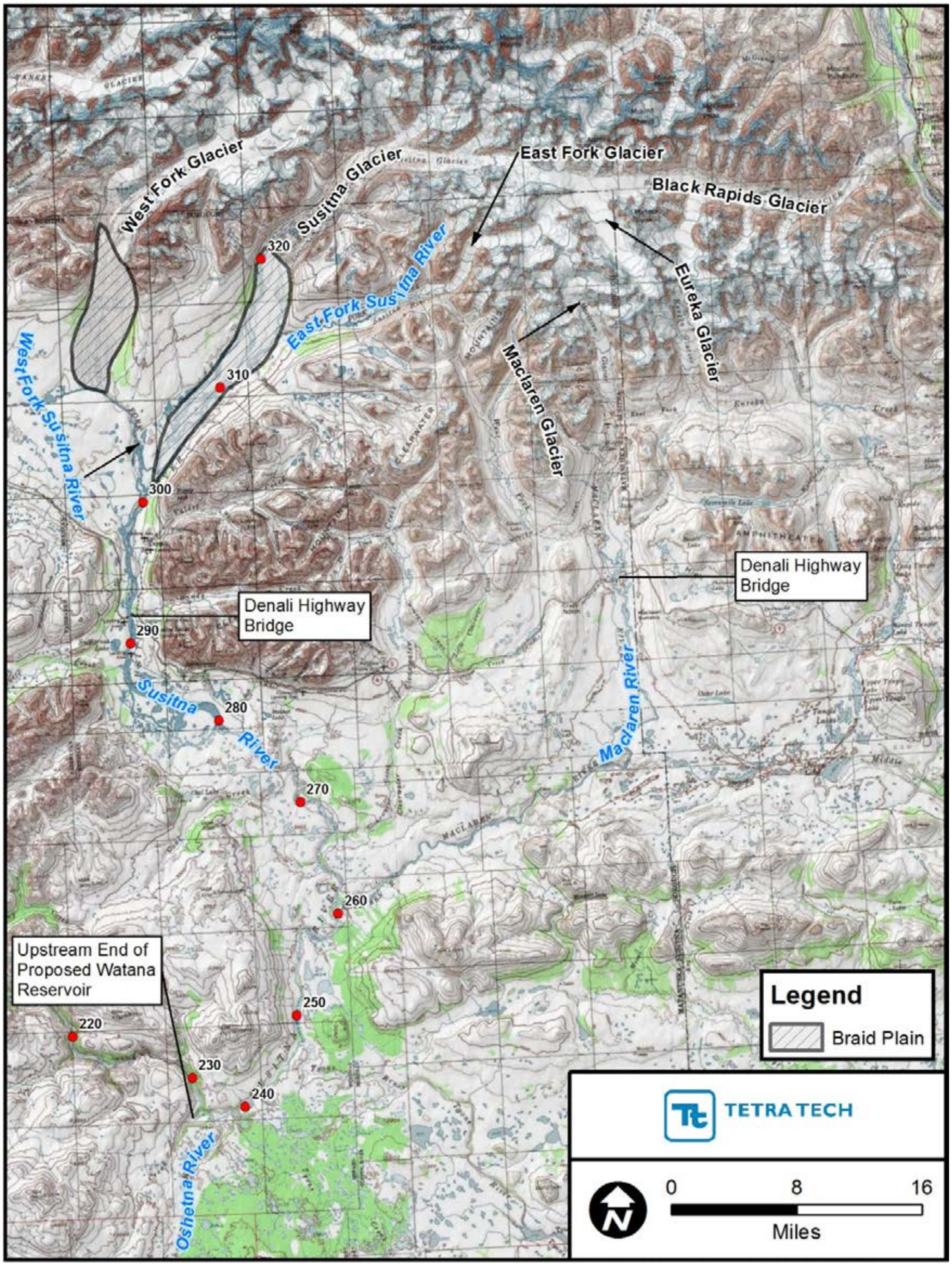

Figure 1. Map showing the upper Susitna River Basin including the locations of the West Fork, Susitna, East Fork, Maclaren and Eureka Glaciers. Project River Miles (PRM) are also shown from the upstream end of the Watana Reservoir pool (PRM 230) to the terminus of the Susitna Glacier (PRM 320).

Figure 2. Photograph of the lower reach of the Susitna Glacier showing potholes that are considered to be indicative of glacier stagnation. The photograph was taken on September 19, 2013.

Figure 3. Upstream view of the confluence of the West Fork Susitna River with the Susitna River at PRM 301. The photograph was taken on September 19, 2013.

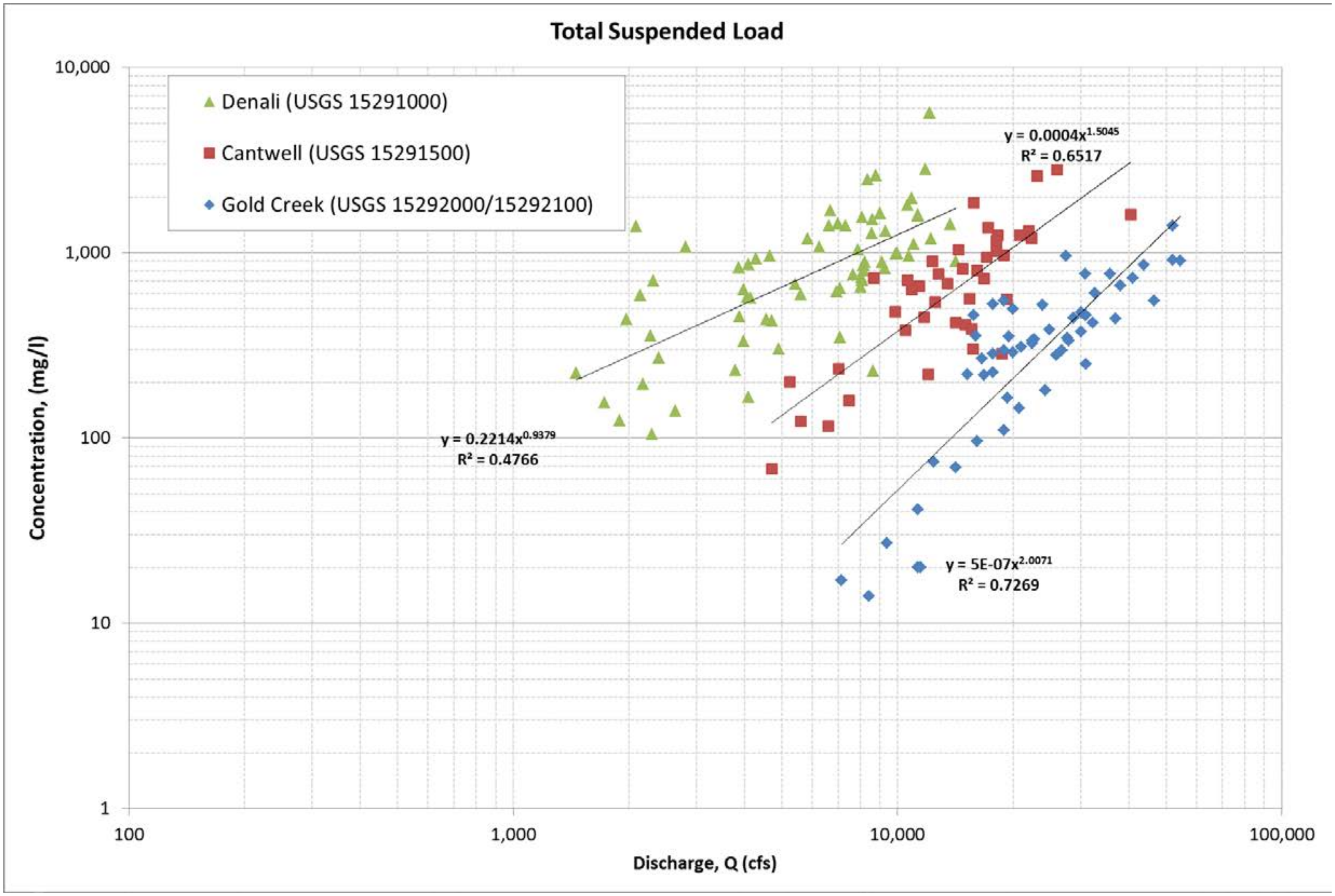

Figure 4. Total suspended sediment rating curves for the Denali (PRM 292), Cantwell (PRM 225) and Gold Creek (PRM 140) USGS gages on the Susitna River.

Figure 5. Upstream view of the Denali Highway crossing the Susitna River at PRM 292. The USGS Denali gage was located at the bridge between 1958 and 1986. The braid bars in the river are composed of sand. The photograph was taken on September 19, 2013.

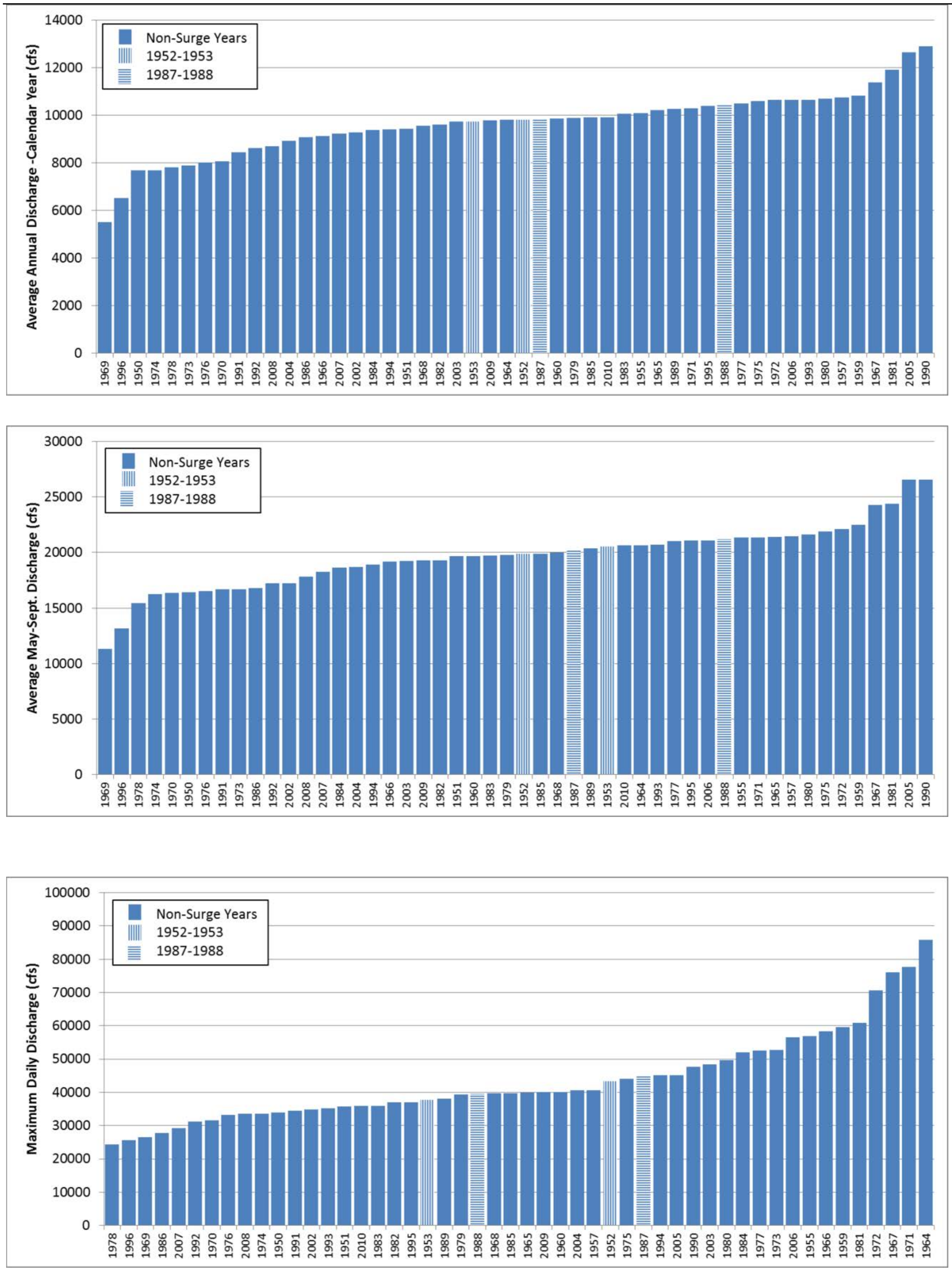

Figure 6. Ranked mean annual discharge, average May-September discharge and maximum daily discharge for 50 years of flow record at the Gold Creek gage (Tetra Tech ISR Study 6.6., Appendix E).