Estimating Future Flood Frequency and Magnitude in Basins Affected by Glacier Wastage

FINAL PROJECT REPORT

by

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16. Abstract

Infrastructure, such as bridge crossings, requires informed structural designs in order to be effective and reliable for decades. A typical bridge is intended to operate for 75 years or more, a period of time anticipated to exhibit a warming climate and, consequently, hydrologic changes (IPCC 2007). An understanding of present and future possible hydrologic conditions is necessary to avoid damage to critical infrastructure and costly disruptions to Alaska's transportation network.

Changes in glacier extent in response to climate warming and/or altered precipitation regimes have the potential to substantially alter the magnitude and timing, as well as the spatial variation of watershed-scale hyrologic fluxes. The dominant goal, as highlighted by the ADOT&PF Bridge Section Hydraulic Squad, is to improve estimates of peak flow frequency and magnitude at bridges crossing glacierized basins. This requires an understanding of the coupled hydrologic system (glacier to overall watershed), and therefore, a quantification of the role of glaciers on present watershed-scale runoff before we can estimate how climate warming may affect basin-wide discharge regimes. The project approach will include analysis of a) historic hydrologic data sets and b) complementary field measurements and model simulations to provide refined products that meet ADOT&PF needs.

This project's primary objective is to compare estimates of future flood magnitude and frequency between traditional statistical methods, which sole utilize historic runoff measurements, to physically-based hydrologic model projections.

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Executive Summary

This interim report presents field measurements of meteorology, hydrology and glaciers that were partially supported by PacTrans at two Alaska watersheds with contrasting climates during the hydrologic year 2012-13. Model projections of flood frequency and magnitude estimations will be presented in the final report.

The study basins include Valdez Glacier Stream (342 km^2) and Jarvis Creek (634 km^2), which represents distinctly different climates and glacier coverage. Jarvis Cr. experiences a sub-Arctic continental climate with semi-arid precipitation (~ 140 mm rainfall and ~90 mm SWE at 386 masl), low glacier coverage (~5 %) and discontinuous permafrost. The Valdez Glacier Stream watershed is heavily glacierized (~43%), has isolated permafrost at high elevations and is located in a maritime climate with high rain- and snowfall (~ 1800 mm yr^{-1} at 7 masl).

The two watersheds presented in this study provide useful case studies for assessing the dependence of discharge on glacier cover, precipitation and air temperature. Our data show that the character of the discharge at each watershed requiring unique approaches to planning for and mitigating impacts of climate change on Alaska infrastructure. In Interior Alaska (Jarvis Cr.) the flow is year round (even though it rarely reaches the bridge in winter due to the formation of aufeis) with the highest baseflow during mid/late summer months, which coincides with the warmest temperatures at the glacier (glacier melt). High flows, of similar magnitude, are found both during early season snowmelt (late May) and late season rains in 2013. In maritime Alaska (Valdez Glacier Stream), flow ceases completely in winter. Like Jarvis, high discharge events are correlated both with air temperature and rainfall events, where early season snowmelt produced a significant runoff peak despite lack of observed rainfall near the town of Valdez. During late summer and early autumn, Valdez Glacier Stream peak flow events appear to be more strongly linked to rain storms. Specific total runoff for the two basins are estimated to 200 mm (Jarvis Cr) and 3419 mm (Valdez Glacier Stream), which represents about 87 and 190 % of the annual lowland precipitation in 2012-2013 hydrologic year, respectively.

Chapter 1 Introduction

Infrastructure, such as bridge crossings, requires informed structural designs in order to be effective and reliable for decades. A typical bridge is intended to operate for 75 years or more, a period of time that is anticipated to exhibit a warming climate and consequently, hydrologic changes. An understanding of present and future possible hydrologic conditions is necessary to avoid damage to critical infrastructure and costly disruptions to Alaska's transportation network.

Several major roads in Alaska cross streams that receive runoff from glacierized basins. Projections of glacier wastage under a warming climate show initial increases in glacier runoff (Hock et al. 2005; Radic and Hock, 2011), which can be substantial and exceed all other runoff components in a watershed (Adalgeirsdottir et al. 2006). Accordingly, flood events may become more frequent and more severe. Changes in the proportion of streamflow derived from glacial runoff will affect physical properties of streams such as overflow and stream reorganization (Hood and Berner 2009), which in turn, could have significant impacts on Alaska's infrastructure.

Engineering design criteria continue to rely heavily on the assumption that historical hydrologic conditions will persist. The validity of this claim for Alaska is weak, given the multitude of scientific literature that predicts altered hydroclimatology in coming decades. Efforts in assessing the impacts of climate variability and change on flood frequency and magnitude in Alaska have included statistical techniques confirming the importance of the Pacific Decadal Oscillation (Neal et al. 2002, Hodgkins 2009) and highlighted the constraints of limited runoff records in identifying trends (Tidwell 2010). An application of a physically-based hydrologic model, which is first validated in order to quantify its uncertainty, has the potential to extend statistical analyses into the future and ultimately inform management decisions.

The limited road network of Alaska is not only distributed across an enormous area but also over a multitude of climate regimes. Accordingly we expect a broad range of hydrologic responses to anticipated climate warming, each requiring different solutions in order to adequately manage risk and balance construction, maintenance and flood damage costs. As a first stage of the final report to PACTRANS and Alaska DOT&PF, we here present PACTRANS and Alaska DOT&PF supported hydrological and meteorological field measurements, which form the foundation to the hydrologic projections to be presented in the last report.

Chapter 2 Site description

The study basins included Valdez Glacier Stream (342 km^2) and Jarvis Creek (634 km^2). The watersheds represent distinctly different climates and glacier coverage (Table 1) and therefore, contrasting hydrologic systems. Jarvis Cr. (Delta Junction) experiences a sub-Arctic continental climate with potential evapotranspiration (Patric and Black, 1968) in summer exceeding typical summer rainfall. The Valdez Glacier Stream watershed, which is heavily glacierized and located in a maritime climate with high rain- and snowfall, has a lower potential evapotranspiration than rainfall. Jarvis Cr. has runoff throughout the year that is partly stored as aufeis in winter, while flow in the Valdez Glacier Stream ceases completely.

Table 1. *Mean annual air temperature (MAAT), mean annual precipitation (MAP), mean air temperature (MAT) in January and July and elevation of longer-term (1970-2000) meteorological stations located near the study basins (Shulski and Wendler, 2007).*

	MAAT (°C)	***MAP (mm)***	***Jan. MAT (°C)***	***Jul. MAT (°C)***	***Elevation (masl)***	***Glaciated area (%)***
Delta Junction	-2.9	303	-23.1	21.3	386	~5
Valdez	3.5	1712	-5.9	16.8	7	~50

2.1 Jarvis Creek

Jarvis Cr. serves as a proxy watershed of Interior Alaska basins that drain the north slopes of the Alaska Range (Fig. 1). Like many of the Tanana River sub-basins, Jarvis C. includes a semi-dry climate, high mountains (< 3000 m), glaciers and permafrost. Rivers that drain the north facing slopes of the Alaska Range are perched on top of relatively impermeable till that, in turn, overlay highly permeable outwash gravel. Once the rivers leave the mountains and exit the moraine, the streams loose significant amounts of water to the underlying aquifers. Creek beds of non-glacierized streams are typically dry for a majority of the summer, unlike the glacier fed streams that show continuous summer flow.

Jarvis Cr. watershed represent the only glacier monitoring program that is located on the north side of the Alaska Range. The large orographic effects of the Alaska Range presents a contrasting environment in Jarvis compared to other Alaska Range glacier monitoring programs.

Vegetation in the Jarvis Creek watershed range from bare rock and glaciers to alpine tundra, dense tall shrubs and willows to black spruce and deciduous forest. Discontinuous permafrost is found throughout the basin with active layers as shallow as ~0.5 m. Silt or till cover the top mineral soil horizon apart from the steepest mountain slopes. Small lakes are abundant on the moraine and the lowlands are a mosaic of burns of differing ages.

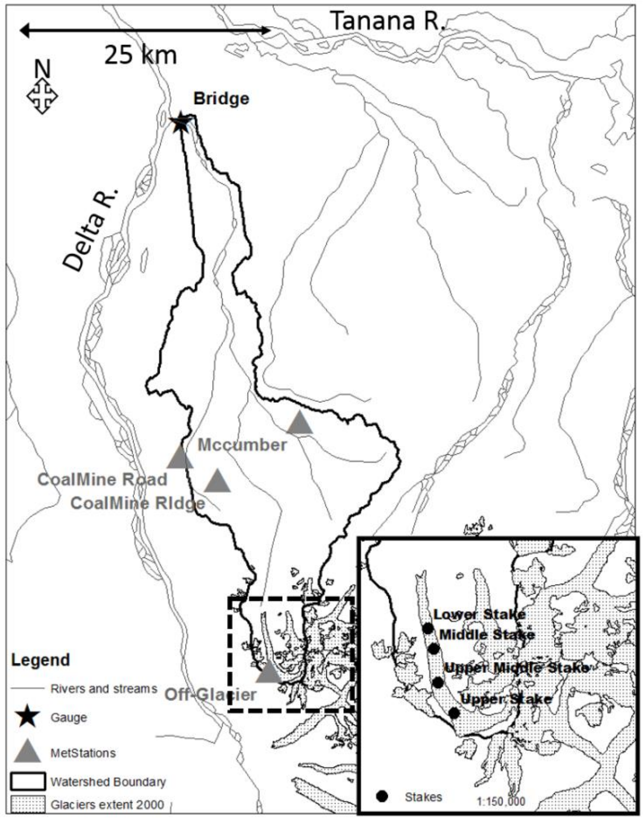


Figure 1. *Jarvis Cr. watershed boundary with the location of the Bridge runoff measurement site (star) and meteorological stations (triangles). The National Weather Service operated meteorological station is located about 5 km southeast of the runoff monitoring site. Glacier extent as of year 2000 and the mass balance stake locations are presented in the insert.*

2.2 Valdez Glacier Stream

The Valdez catchment resides in a coastal maritime climate, with an average annual temperature of 3.5 ^oC, and an average annual precipitation of 1712 mm (NWS station in Valdez). The Valdez Glacier stream drains a 342 km^2 basin of which 43 % is covered by glaciers such as the 138 km^2 Valdez Glacier (Fig. 2). Between year 1950 to 2004 the Valdez Glacier retreated with an average mass balance of -1.37 ± 0.11 m yr^{-1} (Arendt et al., 2006). This retreat caused the formation of a 2 km^2 proglacial, moraine-dammed lake, which captures glacial runoff from Valdez and other glaciers in the catchment, as well as icebergs from calving events at the terminus of Valdez Glacier. The proglacial lake is drained via a braided stream network that flows adjacent to a gravel road, several recreational areas, the Valdez landfill, and lastly under Richardson Highway before entering Prince William Sound. The proglacial area consists primarily of glacial outwash (coarsely sorted sand and gravel with abundant silt. Shrub vegetation covers portions of the proglacial area, while less recently disturbed areas are covered by deciduous forest. Shrubs flank the margins of the glacier up to 750 m, above which is alpine tundra or exposed bedrock. A marginal lake forms each summer on the eastern side of the lower ablation area (east of the Prospector/lower glacier weather station), filled by meltwater from an unnamed glacier. Aerial surveys and satellite data show that the lake drains every season, but the timing of the drainage event is currently unknown.

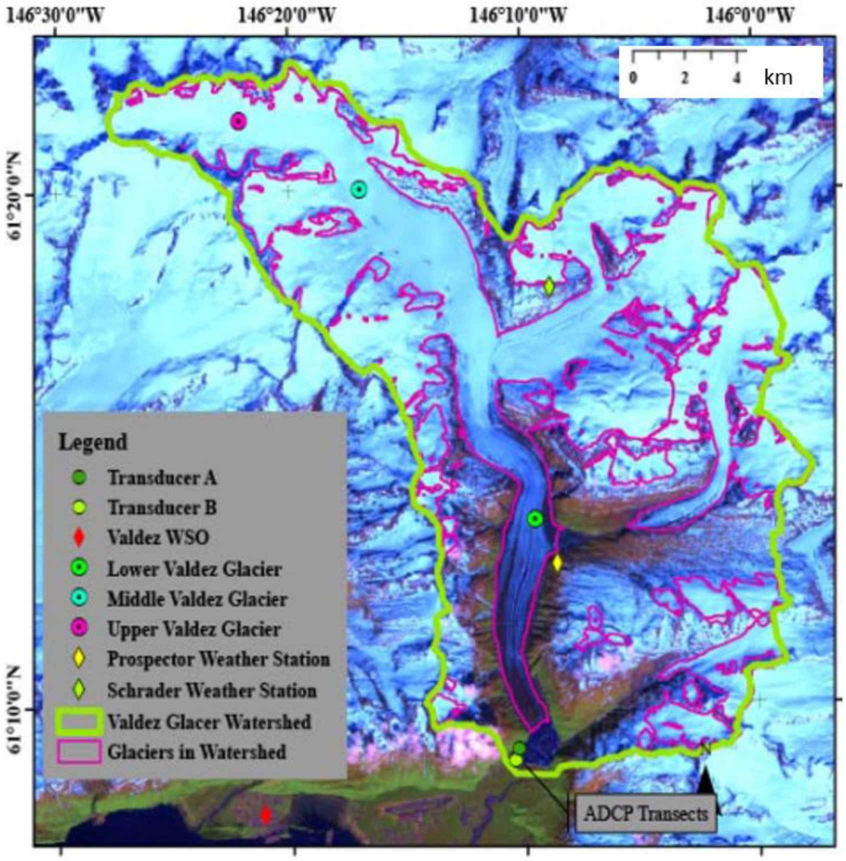


Figure 2. *Valdez Glacier Stream watershed boundary (green line) with the location of the runoff ("ADCP Transects") and water level ("Transducer A and B") measurement sites, meteorological stations including the National Weather Service station in Valdez ("Valdez WSO").*

Chapter 3 Results

3.1 Jarvis Creek

3.1.1 Meteorology

Meteorological measurements were distributed across the Jarvis Cr. watershed to complement the existing National Weather Service station near the town of Delta Junction (Allen Army Airfield) to include McCumber, Coal Mine Road, Coal Mine Ridge and Off-Glacier meteorological stations (Fig. 1, Table 2). Meteorological measurements included air temperature and relative humidity (Hobo U23 with radiation shield, Onset) and rainfall (Hobo RG3, Onset). Precipitation buckets were removed in winter and installed in late March/early April. Rainfall was defined as recorded precipitation when air temperature exceeded −1 °C.

Table 2. *Location of meteorological and hydrological stations, Jarvis Cr.*

Site name	*Variable*	*Vegetation*	*X*	*Y*	*Elev. (masl)*
Delta Junction[1]	Meteorology	n/a	562466	7097125	389
McCumber	Meteorology	Tundra	571534	7066195	890
Coal Mine Road	Meteorology	Coniferous	558145	7063822	840
Coal Mine Ridge	Meteorology	Tundra	561974	7060795	1021
Off-glacier	Meteorology	Rock	565441	7039479	1650
Bridge	Runoff, stream water level	Coniferous/ deciduous	562243	7100272	358

[1] National Weather Service

[2] Tag-line

The largest variation in mean monthly air temperatures was observed at the lowest site (Delta Junction, −22 °C to 16 °C), while the highest-elevated site recorded the least variation (Off-Glacier, −17 °C to 8 °C) (Table 3). June was the overall warmest month at all stations, while the coldest month was represented by either November or December. Mean annual air temperature ranged from −2.8 °C (Coal Mine Road) to −6.2 °C (Off-Glacier) with the Coal Mine sites showing the warmest mean annual air temperatures.

Table 3. *Mean monthly air temperatures during hydrologic year 2012/2013, Jarvis Cr.*

	2012			**2013**									
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	*Mean*
Delta Junction	-6.0	-21.4	-22.1	-17.0	-15.0	-13.3	-9.7	4.5	16.3	15.7	12.0	2.0	*-4.4*
McCumber	-7.8	-17.3	-17.3	-12.4	-10.4	-12.1	-11.4	1.6	13.9	12.6	10.9	3.3	*-4.0*
Coal Mine Road	-6.6	-16.9	-16.3	-12.1	-9.6	-12.1	-9.8	3.2	15.3	13.6	12.0	4.0	*-2.8*
Coal Mine Ridge	-6.6	-16.7	-15.5	-11.1	-9.4	-11.4	-11.0	0.9	13.8	12.3	11.2	2.8	*-3.4*
Off-glacier	-9.1	-15.6	-15.8	-17.0	-15.0	-13.3	-14.3	-2.8	7.7	6.9	6.2	-1.8	*-6.2*

Mean daily air temperature throughout the year was most extreme at the lowland site (Delta Junction), with mean daily air temperatures ranging from – 43 °C to 24 °C (Fig. 3). The lowest range in min/max mean daily air temperature was at the Off-glacier site (– 35 °C to 16 °C). Above freezing air temperatures were recorded several times in mid-winter at the Coal Mine Ridge, while the temperatures remained below freezing at both Delta Junction and up at the glacier.

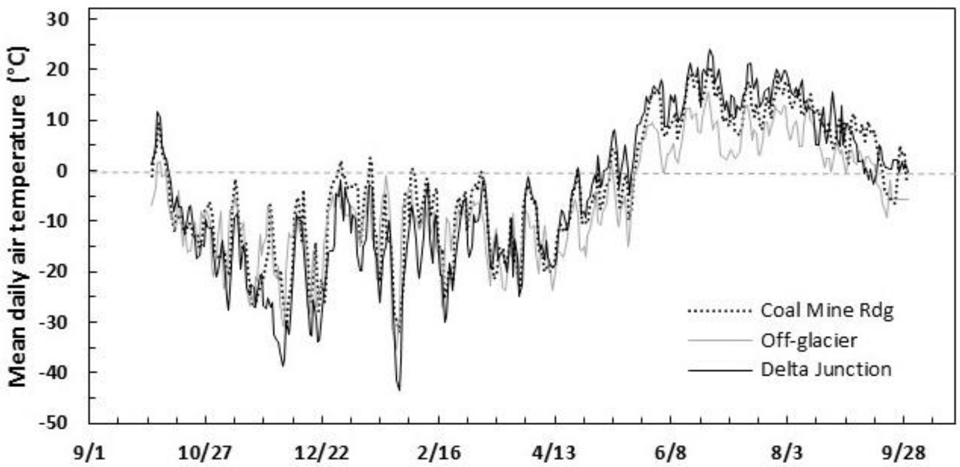


Figure 3. *Mean daily air temperature during the 2012-2013 hydrologic year at the low- (Delta Junction), mid- (Coal Mine Ridge) and high (Off-glacier) elevation sites.*

Distribution of mean summer (JJA) and winter (NDJ) air temperatures with elevation show an opposite relationships with season (Fig. 4). Winters present a strong inversion with all high elevation sites (>840 m) with relatively warm, average winter air temperatures compared to Delta Junction. A cooling trend in air temperatures with increasing elevation is found in summer with the largest rate of change between the two upper sites (840 and 1650 m). Conversely, the largest rate of change in air temperature with elevation in summer is between the two lowermost stations.

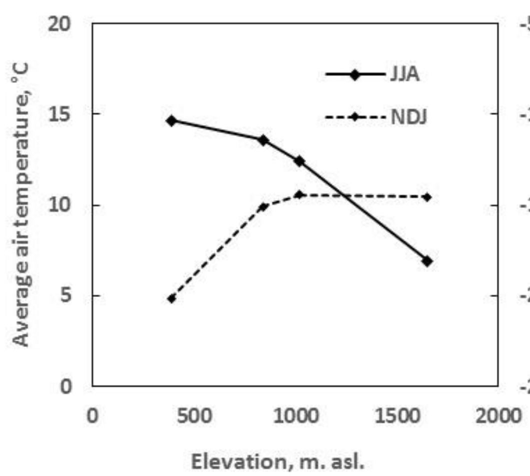


Figure 4. *Mean monthly winter (NDJ) and summer (JJA) air temperatures amongst four of the stations (Delta Junction, Coal Mine Road, Coal Mine Ridge and Off-Glacier), which are here organized by elevation. Average Nov-Jan. air temperature is similar at the upper three sites (840 to 1650 masl) and lower in Delta due to inversion, while the lapse rate is low between Delta (389 m) and Coal Mine Road (840 m) in summer (but high between the upper three sites).*

Measured rainfall amounts in 2013 increase with elevation (Fig. 5). The total seasonal rainfall amount at McCumber (277 mm) was twice that of Delta Junction (138 mm), while less differences were observed between individual mid-elevation stations (McCumber, Coal Mine

Road and Coal Mine Ridge). An individual rain event often occurred throughout all sites, but there were also several instances where rain was recorded at Delta Junction but not the high-elevation sites (>800 m) and vice versa.

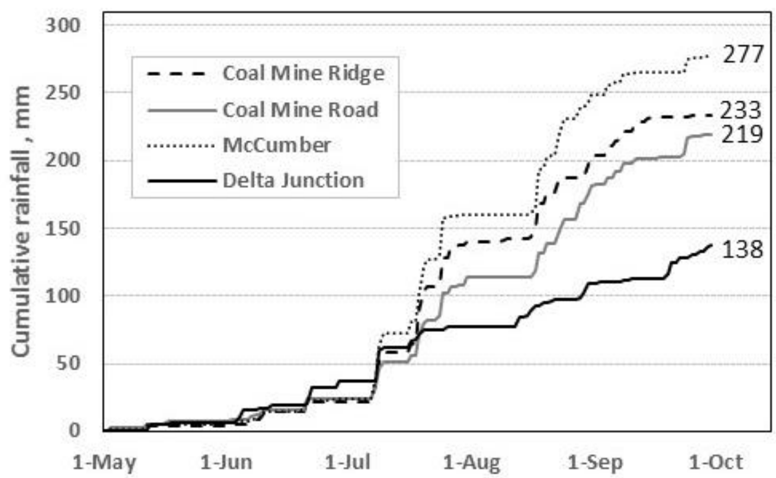


Figure 5. *Cumulative rainfall during the 2013 summer season, Jarvis Cr. Seasonal totals are shown as individual numbers for respective site. The data is not corrected for under-catch.*

3.1.2 Snow accumulation

End-of-winter snow surveys (late March-early April) via snow machine allowed for an estimation of the accumulated snow water equivalent prior the snowmelt. The snow surveys were according to the protocol described by *Rovansek et al.* (1996) where each survey included 50 depth measurements and five density samples.

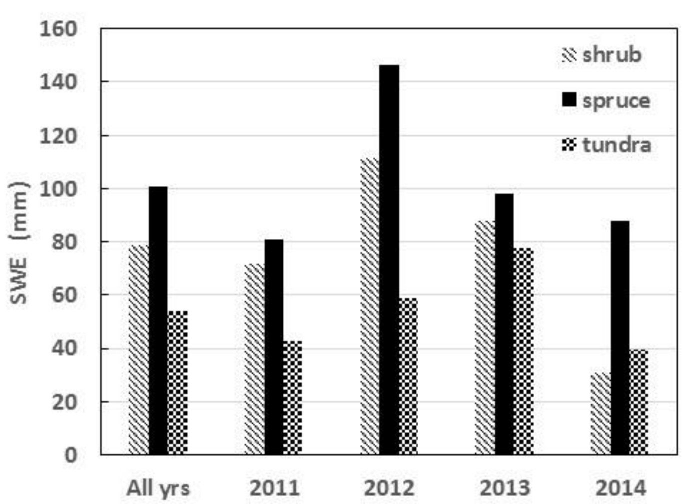
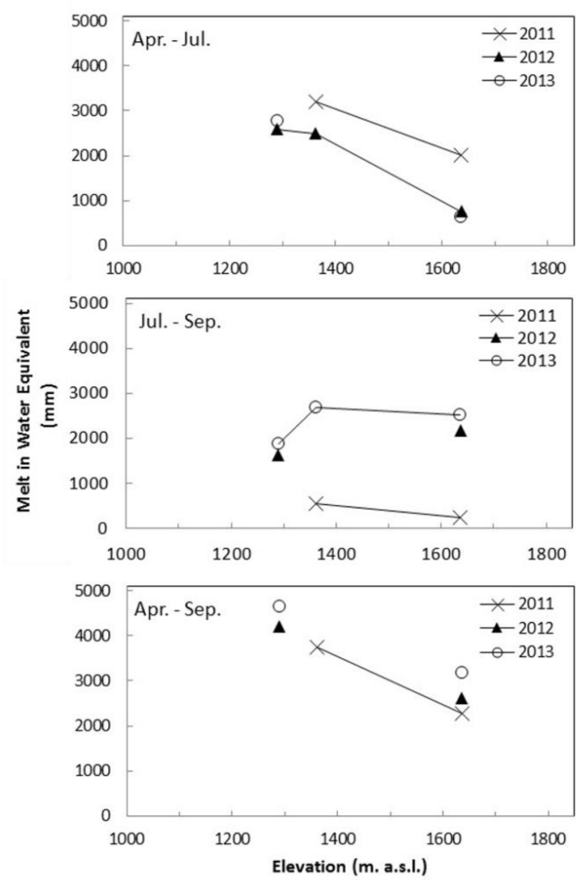


Figure 6. *Average end-of-winter snow accumulation presented as units of Snow Water Equivalent, SWE, of the three major vegetation types (alpine tundra, shrub and spruce forest). Measurements were made in late March-early April.*

End-of-winter snow accumulation in the tundra (alpine), shrub and forest (spruce) ecotypes was largest in the forest vegetation cover throughout year 2011-2014 (Fig. 6). In three of the four years, the second largest accumulation was measured in the shrub ecotype. The outlier of 2014 (alpine tundra SWE was larger than shrub) had a major snowmelt event in late January that resulted in runoff at the bridge. Overall, the SWE averaged 101 (spruce forest), 79 (shrub) and 54 mm (alpine tundra).

3.1.3 Glacier melt

Glacier melt was measured via ablation stakes, which were drilled into the glacier ice. The stakes were installed in spring (prior the onset of snowmelt) and included end-of-winter snow accumulation measurements on the glacier (snow depth and density). The glacier ice/snow surface in relation to the fixed stake was measured during visits in July and September. Stakes were re-installed as they melted out of the ice.



Total seasonal (Apr. – Sep.) melt of snow and ice increased as the elevation decreased (Fig 7). Total melt at the upper stake (1636 masl) ranged from 2.26 (2011) to 3.17 m (2013) of water equivalent, while the low elevation stake ranged from 4.21 (2012) to 4.65 m (2013). Overall seasonal melt was the largest in 2013 at all stakes and the lowest in 2011. The melt was not continuously higher at the lower compared to the upper sites throughout the melt season. Early season melt (Apr.-Jul.) was larger at the lower two sites in all years, while late season melt (Jul.-Sep.) was lowest at the lower most stake in 2012 and 2013. The phenomena can also be described as change in daily melt rate with elevation decrease/increase (mm day^{-1} m^{-1}). Late season melt rate between the upper and mid stakes was 0.12 mm day^{-1} m^{-1} in 2012, while the melt rate between the low and mid stakes was dramatically lower (0.03 mm day^{-1} m^{-1}). The low elevation stake was located in an area covered by debris, which suppressed the melt and also reduced the interannual variability in melt.

Figure 7. *Measured melt of snow and ice on the glacier during different time periods (Apr-Jul, Jul-Sep and Apr-Sep) in 2011, 2012 and 2013. The uppermost mass balance stake was located at 1636 masl.*

3.1.4 Stream water levels

Water levels were measured continuously where the Richardson Hwy Bridge crosses Jarvis Cr. (Fig 8). Diurnal fluctuations were observed throughout the season, with the highest water levels corresponded to rain storms in late summer. The early season (mid/late May) stream water levels (snowmelt) were similar to peak magnitudes in late summer/early fall. Lowland snowmelt was late in 2013 (mid- to late-May).

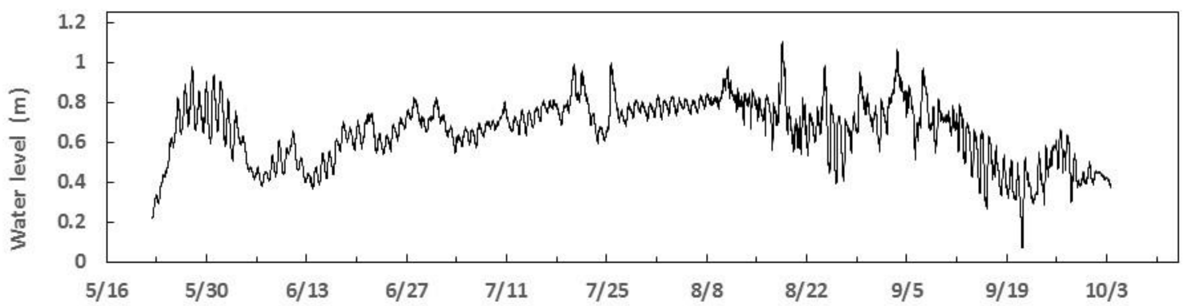


Figure 8. *Jarvis Cr. 2013 stream water levels (hourly) near the Bridge with the typical diurnal variations.*

3.1.5 Runoff

Runoff at Jarvis Cr. was measured just upstream of Jarvis Cr. confluence with the Delta River (Richardson Hwy Bridge) in summer and further upstream in winter. A handheld electromagnetic flowmeter (Marsh-McBirney) was used when the waters were safe to cross by foot, which was typically only during late-May/early-June and prior freeze-up (mid-Sep and onwards) in Jarvis Cr. At other time, the discharge was measured with an Acoustic Doppler Current Profiler, ADCP, (StreamPro, Teledyne) mounted to a smaller boat, which was ferried across the channel using a pulley-rope system spanning the entire river cross section.

The time lag between a rainfall event (Coal Mine Ridge) to peak runoff (Bridge) was calculated from four larger rain events (ranging from 7 to 25 mm) in July 2013. Lag-times, defined as the time between the centroid of the rain event to the peak runoff, averaged about 10 h (9 to 13.5 h).

Table 4. *Discharge measured with FloMate (*) and ADCP in 2013 at the Richardson Hwy Bridge, Jarvis Cr. Italicized observations are questionable due to poor estimation of channel depth with no sonic depth sounder mounted to the StreamPro (was added in late 2014).*

Date	Discharge (cms)
6/12/13 14:30	7.2*
7/2/13 16:50	12.2
7/3/13 1:24	11.9
7/3/13 5:31	12.6
7/10/13 18:11	*17.8*
7/11/13 9:50	12.4
7/11/13 18:12	10.6
7/17/13 18:20	13.6
8/8/13 14:32	13.1
8/15/13 12:00	12.8

8/19/13 10:40	*16.1*
8/19/13 16:00	*16.6*
8/19/13 21:00	*16.6*
8/20/13 8:00	*14.3*
8/21/13 11:00	*15.1*
8/21/13 13:15	13.8
(10/1/13 9:32	3.1)
10/3/13 14:01	3.5*
10/10/13 13:11	2.4*

Winter runoff measurements (located between N63° 47.669' and N63° 45.859') decreased from 2.2, 2.1 to 1.5 cms as the season progressed (18 Nov., 22 Jan., 6 Mar., respectively), although an atypical melt event in late January (~Jan. 27th) resulted observations of significant flows downstream at the bridge.

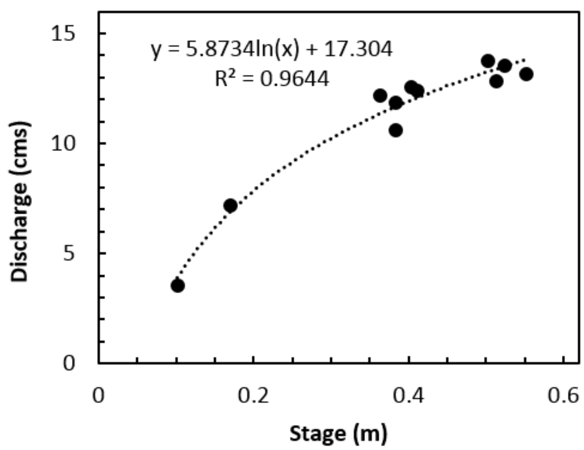


Figure 9. *Measured discharge (< 14 cms) and coinciding water level during the 2013 season, resulting in a logarithmic stage-discharge relationship.*

A stage-discharge curve was established using data considered reliable in 2013 (Fig. 9). Evaluations of the StreamPro measurements in 2014 concluded that the measurements were not reliable at discharges >14 cms without a separate sonic depth sounder due to the large sediment load in the water column. Therefore, the stage-discharge relationship was established based upon measurements <14 cms. Estimated runoff present diurnal variations throughout late May until late Sep. in 2013 (Fig. 10). Baseflow appears at its highest in late July/early August, with the largest runoff reaching above 15 cms in late May/early June, probably due to the unusually late snowmelt in 2013, and again during individual larger rain events in mid- to late summer, with the last high flows in early Sep. The cooling of air temperatures at the glacier, but also in the lowlands (Fig. 3), and the lack of rainfall in mid-/late Sep. resulted in a dramatic decline in flow from ~10 cms to < 5 cms within a 2-week time period. Overall, the estimated specific runoff totaled 200 mm during May 22 - Oct. 3rd.

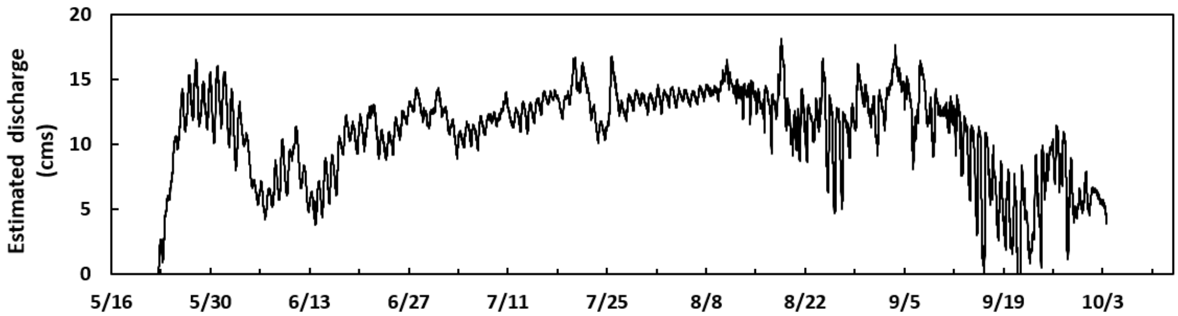


Figure 10. *Estimated continuous (hourly) runoff, Jarvis Cr., near the Richardson Hwy in 2013. Note that estimated discharge >14 cms is solely speculative as the measured runoff above > 14 cms was unreliable without a separate depth sounder.*

3.2 Valdez Glacier Stream

3.2.1 Meteorology

Three HOBO Pro v2 U23-001 air temperature and relative humidity (T/RH) sensors were installed on the glacier on April 19, 2012, using a floating temperature stand to maintain the height of the sensor (2 m) above the glacier surface throughout the melt season (Fig. 2). Two off-glacier weather stations were constructed on ridge tops adjacent to the glacier, at elevations of 486 m (labelled "Prospector") and 1465 m (labelled "Schrader"). The Prospector station was located in shrub tundra on the southern flank of the east branch of the glacier, and the Schrader station was on exposed bedrock on a ridge above the accumulation area. Each off-glacier weather station was equipped with a Campbell Scientific 107-L temperature sensor, a 41303-5A 6-gill radiation shield, and a Campbell Scientific TE525WS-L tipping bucket rain gauge. Data from all stations were downloaded between October 8 and 12, 2012. Equipment failures and wildlife disturbance resulted in several data gaps at the two off-glacier weather stations.

A comparison of temperature on- and off the Valdez glacier shows that the Prospector station (486 m asl) experienced higher mean daily air temperatures than the lowest on-ice temperature sensor (380 m asl) (Fig. 9). This shows that temperatures are lower on the glacier compared to temperatures recorded outside the glacier surface at similar elevations. Accordingly, bias-correction of off-glacier air temperature records are important for melt modelling. The mean daily air temperatures observed at the Schrader station (1465 m asl) were comparable to those temperatures observed at the upper on-glacier sensor (1495 m asl), and even indicate lower mean daily temperatures than those observed at the upper on-glacier sensor.

Rainfall data collected at each ridge top weather station is plotted in Fig. 12, along with rainfall from the NOAA WSO. The WSO recorded precipitation amounts that were greater than those recorded at the Prospector and Schrader sites. This was likely due to undercatch by the unshielded tipping bucket gages used at the Prospector and Schrader sites, and the fact that both stations were on high elevation ridges that likely experienced high winds, reducing precipitation catch. We therefore only use the Prospector and Schrader data to identify the timing, rather than the magnitude, of precipitation events.

Table 5. *Location of meteorological and hydrological stations, Valdez Glacier Stream watershed.*

Site name	*Variable*	*Vegetation*	*X*	*Y*	*Elev. (masl)*
Transducer A	Lake water level	Deciduous	544572	6780041	68
Transducer B	Air pressure	Deciduous	544445	6779630	71
ADCP Transects	Runoff	Deciduous	544825	6779466	70
Valdez WSO	Meteorology	Deciduous	534823	6777612	11
Lower Glacier	Meteorology	Glacier	545163	6788323	381
Middle Glacier	Meteorology	Glacier	542816	6795136	821
Upper Glacier	Meteorology	Glacier	533753	6802648	1326
Prospector	Meteorology	Shrub	546030	6786717	486
Schrader	Meteorology	Bedrock	545715	6796714	1465

Table 6. *Mean monthly air temperatures (^oC), Valdez Glacier Stream watershed.*

	2012			**2013**									
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	*Mean*
Valdez Town	2.8	-3.8	-5.9	-3.2	-1.4	-2.1	-0.3	5.9	14.0	14.9	12.9	9.8	*3.1*

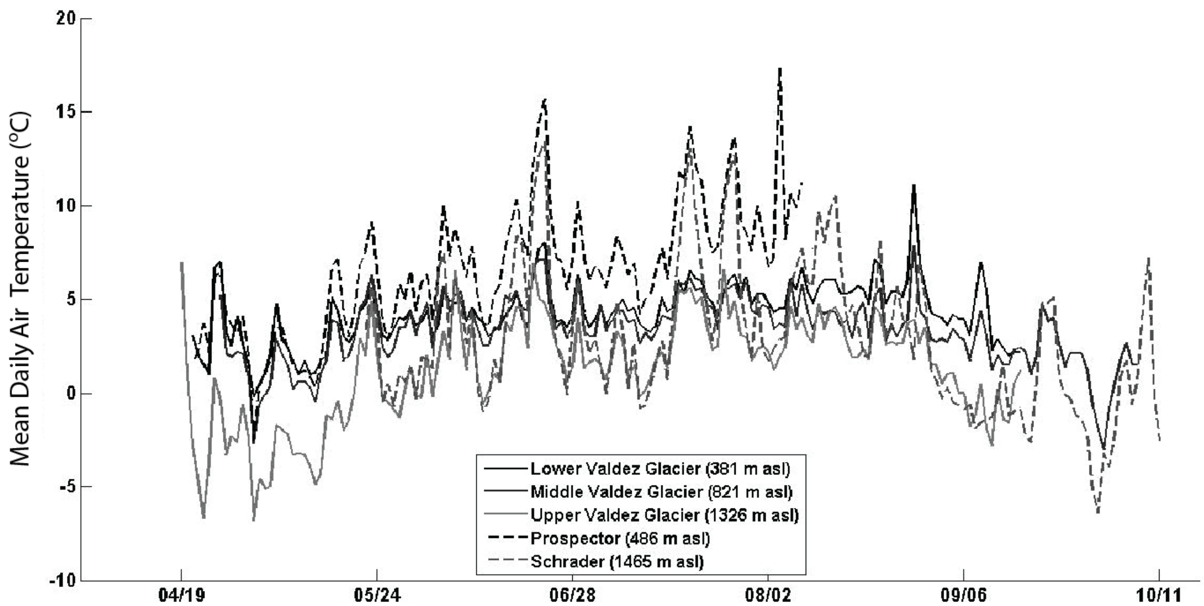


Figure 11. *Mean daily air temperature at three station on the Valdez Glacier (lower, middle and upper) and two ridge top stations (Prospector and Schrader) during the summer of 2013.*

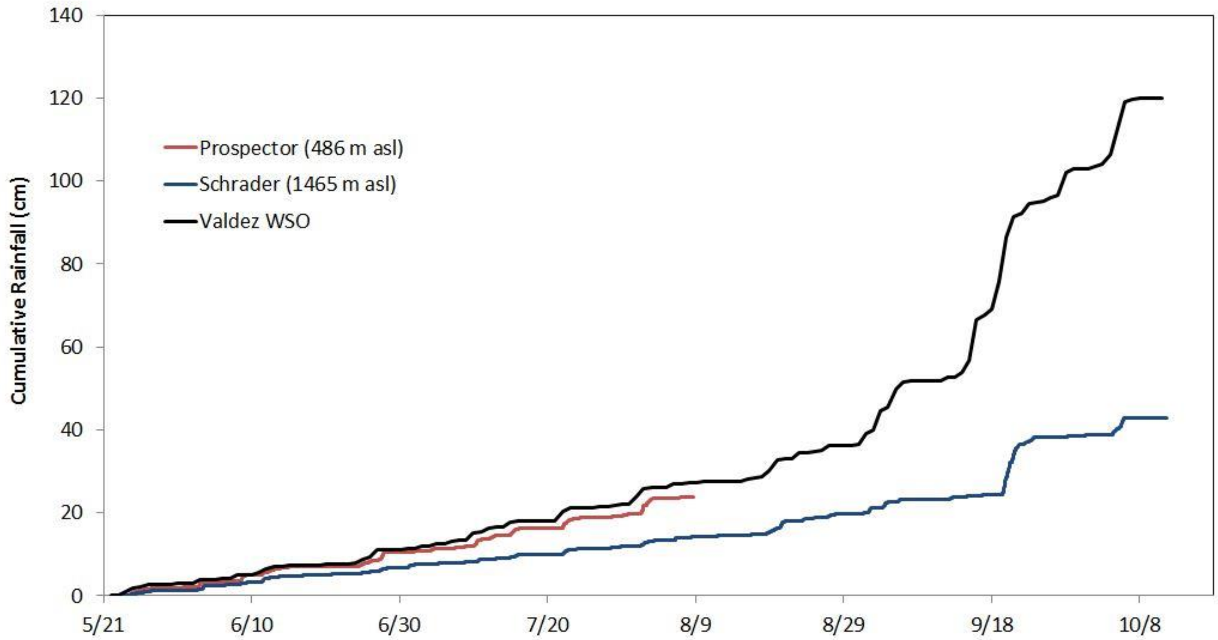


Figure 12. *Measured cumulative rainfall during summer 2013 two ridge-top stations (Prospector and Schrader) near Valdez Glacier and the NWS station at the town of Valdez.*

3.2.2 Lake water levels

Lake water level (Fig. 11) was measured using a HOBO U20-001-01 sensor installed in a steel pipe the along the northwestern shore of Valdez Glacier Lake (Transducer A, Fig. 3). A second transducer of the same type was deployed in the air to correct for barometric air pressure (Transducer B). Both sensors sampled at 15-minute intervals.

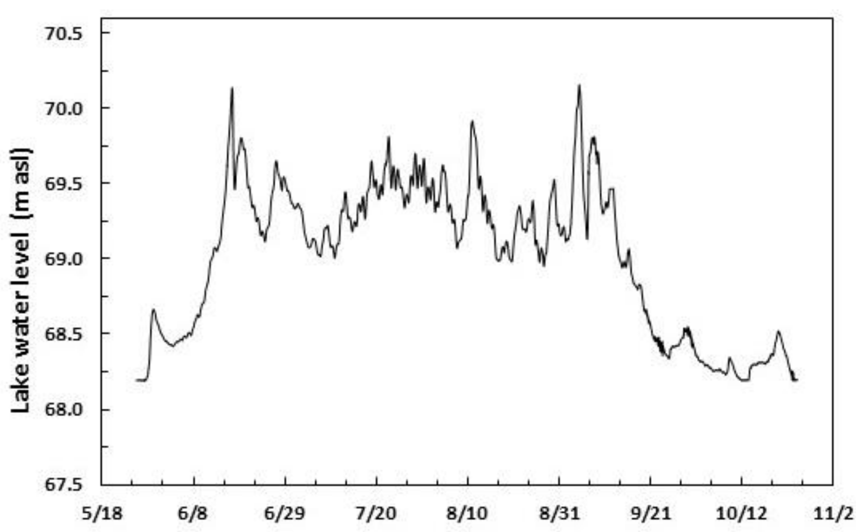


Figure 13. *Water level variations at Valdez Glacier Lake throughout the 2013 season.*

3.2.3 Runoff

Runoff from the Valdez Glacier watershed was determined by calculating the relationship between lake water level and discharge. Lake (rather than river) stage observations were carried out due to difficulties encountered in measuring flow at a downstream location during the 2012 field season, and due to erosion of the river bed at the 2012 measurement site. Our method follows similar lake stage observations employed to assess glacial watersheds within which runoff is intercepted by a proglacial lake (e.g. Neal and Host, 1999). An analysis of the energetics of the Valdez Lake outlet stream relative to its bed composition suggests that the bed is suitably stable for establishing a rating curve at this location.

Date	*Discharge (cms)*
9/11/2013 9:00	156.5
9/12/2013 12:00	148.9
9/13/2013 10:30	94.8
9/14/2013 11:20	74.8
9/15/2013 17:00	85.4
10/23/2013 11:45	13.2

Table 7*. Discharge measured with the ADCP at Valdez Glacier Stream.*

Total discharge was measured using either a StreamPro Acoustic Doppler Current Profiler (ADCP) or a River Ray ADCP. Discharge was measured on a periodic basis to capture the flow during a range of lake stages indicated by the pressure transducer in Valdez Glacier Lake (Table 7). A rating curve was established based on a linear fit of discharge to lake stage (Fig. 12). Continuous runoff was estimated by solving for discharge as a function of lake stage (Fig. 13), based on the 2013 rating curve.

The total estimated specific runoff was 3914 mm over the 2013 measurement period (May 26 – Oct. 24). Large fluctuations in flow occurred in relative short time period (up to 82 cms occurring within a 24 hour time span, June to mid-Sept.) .there were several. These diurnal flow variation reduced in late Sept. and Oct., with the exception of heavy rainfall events that occurred near the end of the measurement period.

Five large peak flow events occurred in 2013 (June 16, July 22, Aug. 11, Sept. 4, and Sept. 7) (Fig. 13). Air temperatures throughout the measurement period remained above freezing, indicating a steady generation of glacial melt. Based on climate data, it appears that the June 16 event is most likely a result of rapid increases in air temperature (e.g. snowmelt) resulting in a peak daily discharge of 214.5 cms. The runoff peak on July 22 coincides with a spike in air temperature, as well as a rainfall event that occurred on July 20. The Aug. 11 peak flow event was preceded by a rainfall event that spanned from Aug. 9 – 11, with the maximum rainfall of 50 mm (Valdes weather station) occurring on Aug. 10. The two peak flow events in early September occurred in the midst of a longer period of rain (Aug. 31 - Sept. 18), of which the two largest rainfalls occurred immediately prior the high-flow events. The Sept. 4 peak flow event is the largest observed in the hydrograph, and is estimated to 228 cms (note that the largest measured runoff was 156.5 cms).

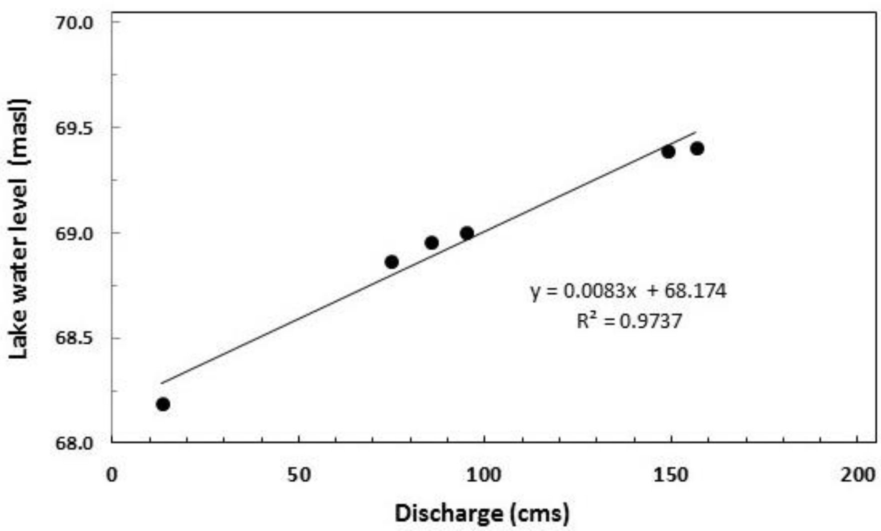


***Figure 14**. Stage-discharge relationship at Valdez Glacier Stream representing the 2012 and 2013 field measurements.*

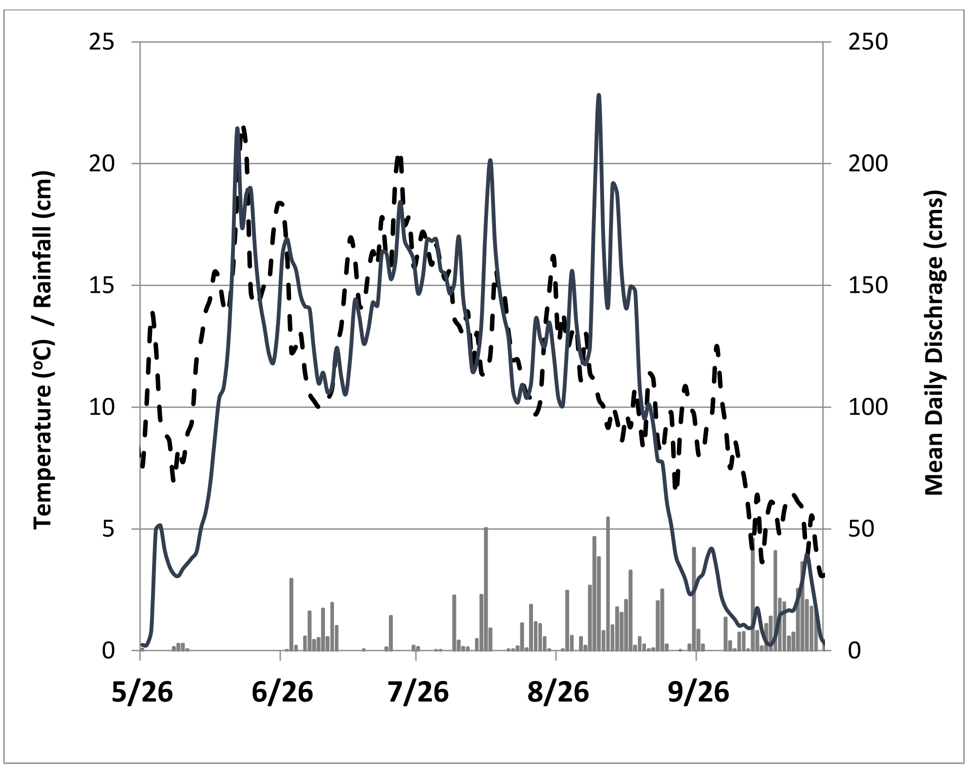


***Figure 15**. Estimated mean daily discharge at the Valdez Glacier Stream during the 2013 melt season (solid line, right axis) and air temperature measured at Valdez WSO (dotted line, left axis). Bar chart shows daily total rainfall events at Valdez WSO (left axis).*

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