Differing contributions of heavily and moderately glaciated basins to water resources of the Eklutna Basin, Alaska

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Abstract

In south-central Alaska, glacier-fed Eklutna Lake contributes freshwater resources for hydroelectric generation and drinking water for Anchorage, the state's largest city. In 2009 and 2010, we measured and compared melt-season stream discharge of the two primary subbasins in the watershed: one with high (46%) glacier cover and one more moderately glaciated (12%). The heavily glaciated subbasin produced twice as much specific runoff ($27.0x10^5 m^3/km^2$) as the larger, but moderately glaciated catchment ($13.3x10^5 m^3/km^2$). Some of the additional discharge in the heavily glaciated basin comes from shrinkage of the upstream Eklutna Glacier. Concurrent measurements of mass balance on the glacier show that net melt contributed 23.7% of that basin's total discharge in 2009 and 3.1% in 2010. We suggest that lower levels of initial abstraction and glacier supported higher orographic precipitation rates also lead to greater specific discharge in the more heavily glaciated basin. Comparison with sparse historic data

suggests that specific yield has increased in the more heavily glaciated basin over recent decades, and demonstrates that both interannual and seasonal discharge variability is higher in the more glaciated basin. Surprisingly, the proportional seasonal delivery of water was similar in the two basins during the two years of our study: we see no evidence of a more dominant spring freshet in the more moderately glaciated basin. In the long-term, ongoing shrinkage of Eklutna Glacier may lead to diminished runoff, forcing power and water utilities to develop alternative supplies with consequently higher costs for users.

1. Introduction

1.1 Significance and Motivation

Climate change will alter the runoff characteristics of high alpine drainage basins substantially [*IPCC*, 2007; *Braun et al.*, 2000; *Bradley*, 2006] and glacier shrinkage is one mechanism for this change. Glaciers play a very important role in global freshwater storage and changes in glacier mass can affect the availability of freshwater supply at seasonal, annual, and decadal timescales. Glaciers are important components in the hydrology of catchments wherever they occur, altering the volume of streamflow and its seasonal distribution [*Hodgkins*, 1997]. At decadal time scales, glaciers store water as snow and ice in cold wet years, and via excess melt, provide additional runoff in water dry years [*Huss et al*,. 2008]. In the 20th century, a majority of the world's glacier underwent a reduction in mass, and the rate of shrinkage has accelerated in recent decades [*Bates*, 2008]. Previous research suggests that a reduction in ice volume will yield a shift in the peak discharge towards early summer and spring combined with a significant increase in annual runoff for several decades, followed by a longer term decrease in runoff [*Braun et al.*, 2000; *Hock et al.,* 2005; *Stahl et al.,* 2006; *Nolin et al.*, 2010]. The societal impacts of such changes may be significant [*Burlando et al.*, 2002; *Hagg et al.*, 2006], especially where water resources are used for operation of hydroelectric facilities and drinking water supplies.

Most existing studies of the effects of glacier change on societal needs have come from arid regions [e.g. *Ribstein et al.,* 1995; *Casassa et al.,* 2002], but glacier shrinkage is most conspicuous in Alaska. About 0.11mm per year of sea level rise during the past 40 years is contributed by glaciers bordering the Gulf of Alaska; a disproportionate amount given that Alaska holds a relatively small proportion of the total ice on Earth [*Arendt et al,. 2002*; *Berthier et al.*, 2010]. While glaciers across the state of Alaska are losing volume, one shrinking glacier in particular has important implications for water users in Anchorage, Alaska's largest population center. The Eklutna Glacier (61°12'N, 148°59'W, Figure 1) is located approximately 72 km north east of the city of Anchorage in the western Chugach Mountains of Alaska. Melt from the Eklutna Glacier and smaller unnamed glaciers in an adjacent basin provide the main input of water to Eklutna Lake, a reservoir that provided 93.3% of the municipal drinking water supply in 2010 for approximately 300,000 people in Anchorage and the surrounding area [*Anchorage Water and Wastewater Utility,* 2011]. In addition, hydropower generated from Eklutna Lake in 2010 provided 126,105 MWh of power [Doug Hall, personal communication, May 22, 2010], enough electricity to sustain 14,000 average households per year for the Municipality of Anchorage (MOA) and the rapidly growing Matanuska-Susitna Borough (Figure 1). Relative to more arid regions, however, Alaska has abundant water resources and, despite accelerating rates of ice loss, retains a large number of relatively accessible glaciers.

In this environment, does ongoing and anticipated future shrinkage of the Eklutna Glacier pose a threat to the water resources that support Anchorage?

The Eklutna watershed includes two adjacent subbasins that differ primarily in glacier cover: one basin is heavily glaciated (46% glacier cover), and the other moderately so (12% glacier cover). The basins are otherwise similar and so offer an opportunity to compare runoff patterns from the more highly glaciated subbasin to runoff from the moderately glaciated one that it may someday resemble. Here, we present streamflow measurements taken during the 2009 and 2010 melt seasons and compare those results with concurrent measurement of mass balance on the Eklutna Glacier and with historic data. We show that the more heavily glaciated basin yields a higher specific discharge and greater seasonal and interannual variability than the modestly glaciated basin, and that these effects were magnified by a warm summer with a more negative glacier mass balance. Using these results, we discuss the potential water-related impact of the recent and predicted future retreat of the Eklutna glacier.

1.2 Study Area

The Eklutna Basin (311 km^2) is characterized by elevations ranging from roughly 260 m at lake level to peaks over 2,500 m with steep valley walls surrounding Eklutna Glacier (Figure 2). Two sub-watersheds account for more than half the drainage basin of Eklutna Lake, feeding the lake through two main inlet streams, East Fork Eklutna River and West Fork Eklutna River, hereafter referred to as East Fork and West Fork. The catchment basin area of the East Fork is 100.8 km^2, with relatively small cirque glacier contributing approximately 12.2% glacier cover. The West Fork subbasin is dominated by a single large glacier, the 29.7 km^2 Eklutna Glacier, which occupies 46.4% of the 64.2 km^2 catchment area. We gaged the outlets of both of these subbasins for this study.

The remaining 145 km^2 of the watershed area that feeds Eklutna Lake is glacier free and comprised of many small streams that drain areas less than 13 km^2 each. Streams in this portion of the watershed are ungaged, but contribute relatively little runoff to the lake because the terrain they drain is relatively low in elevation and sits in the rain shadow of higher elevation portions of the basin that intercept storms originating in the Gulf of Alaska. This ungaged subbasin is also comparatively well vegetated, so of the precipitation that does fall there, more is intercepted prior to runoff by transpiration, infiltration, and evaporation.

Eklutna Lake (14.1 km^2) is 10.5 km long and occupies an elongated, glacially steepened depression dammed at the northwest end by a recessional terminal moraine from the Pleistocene Eklutna Glacier [*Karlstrom*, 1965]. This natural lake was converted to a reservoir with the construction of the first dam in 1927 for the purposes of power generation. The current dam structure, which impounds 100% of Eklutna Lake outflow and has no outlet works, has been in place since 1965. On exceptionally wet years, when the storage capacity of the lake is exceeded, water flows over the dam and no power is harnessed from that outflow. This has occurred only eight times since the newest dam was constructed in 1965, with the last overflow in 1997; no overflow occurred during the period of study.

From a storage point of view, the Eklutna Glacier acts as a second reservoir in the Eklutna basin, storing water seasonally (as accumulated winter snows) and over longer time periods (snow stored as ice during years of positive mass balance can then be subsequently released during wetter/drier years in which the glacier shrinks). Eklutna Glacier has an elevation range of 505 to 1,970 m, with winter snow accumulations of 164-247 cm water equivalent in the accumulation zone of the glacier during the 2008-2010 monitoring years. Mean basin wide ice thickness is 163 m reaching a maximum of

430 m with a total volume of $4.44 \times 10^9 m^3$. The Eklutna Glacier has been studied concurrently by Sass et al. (manuscript in preparation, 2011); smaller glaciers in the East Fork subbasin remain unstudied.

The climate of the Eklutna Basin is sub-arctic, characterized by a short melt-season (late May through October) and large annual temperature variations. During the winter, precipitation falls mainly as snow; in summer, precipitation falls mainly as rain but snow can occur year round at the highest elevations. Two weather stations were maintained in the basin during our study. A SNOTEL station, maintained by the Natural Resources Conservation Service (61°22'.48''N, 148°58'48''W, elevation 640 m) operated year round (http://www.wcc.nrcs.usda.gov/). A higher station, maintained by our research group, near the mid-elevation of the glacier (61°12'39.7''N, 148°57'26.0''W, elevation 1522 m) recorded summer (May-September) conditions only. Average monthly winter (November-April) air temperatures at the SNOTEL station range from -11°C to 1°C with average monthly summer air temperatures from 7°C to 14°C; whereas, average monthly summer temperatures at the glacier station ranged from 0 to 5°C.

Climate at this watershed is affected by weather systems from the Gulf of Alaska and is influenced by orographic effects within the wide elevation range of the basin, with more precipitation distributed at higher altitudes. Precipitation at the SNOTEL site is distributed throughout the year with total winter precipitation of 274 mm in 2009 and

373 mm in 2010; summer precipitation totaled 178 mm and 185 mm in 2009 and 2010 respectively. Winter precipitation at the glacier meteorological station, measured as snow water equivalent, was 1420 mm in 2009 and 2050 mm in 2010. Summer precipitation, measured by a rain gage, totaled 217 mm in 2009 and 306 mm in 2010.

2. Methods

2.1 Streamflow

Stream discharge monitoring stations were established at two locations in the Eklutna Basin in the spring, and removed in the late fall of each year (2009/2010). The East Fork Eklutna River gage was installed in a single, stable, bedrock confined cross section where a bridge crosses the river at mile 10.2 of the Eklutna Lakeside trail (61°17’51.9’’N, 148°58’23.7’’W). The West Fork Eklutna River gaging station was established in a stable reach of unbraided proglacial channel where the stream cuts through a Little Ice Age moraine approximately 2 km below the terminus of the glacier, 150 meters downstream of a bridge crossing (61°17’47.2’’N, 148°58’37.3’’W). These sites were selected because flow is confined to a single dominant and relatively stable channel, because bridges provide stable infrastructure to attach sampling equipment and measure discharge, and because previous studies [*Brabets*, 1992] gaged the streams at approximately the same locations.

Specific equipment and methods utilized at the gaging station evolved over the course of this study, largely in response to the physical challenges of maintaining automated monitoring stations in a variable glacial river which includes considerable in-stream turbulence, high sediment load, and frequently changing channel geometry [*Hock et. al.*, 2005]. For the 2009 field season, both gaging stations were outfitted with Campbell Scientific CS450 submersible vented pressure transducers. In 2010, the West Fork sensor was replaced with an unvented HOBO Barometric Pressure Smart Sensor to eliminate the need for a cabled connection to separate datalogger. Pressure measurements from this sensor were later adjusted to compensate for concurrently measured atmospheric pressure variations [*Freeman* et al., 2004]. All pressure measurements were made at 10 second intervals. Time lapse cameras were set up at the West Fork gaging station as a backup record of stage level during September 2009 and through many periods (17 May-5 June, 12 June-7 July, 24 July-2 August, 1 September-22 September) of the 2010 gaging period.

In both years of this study, stage measurements were conducted during the melt-season only (approximately mid-May to mid-October). Like most glacial streams, winter discharge here is quite low and complete year-long discharge records from the U.S. Geological Survey from the years 1965, 1986, and 1987 suggest that our melt-season measurements include approximately 80% of the total annual discharge (http://waterdata.usgs.gov/ak/nwis).

During each field visit, river discharge was measured using the area-velocity method through wading or bridgeboard field methods using USGS established protocols [*Buchanan*, 1969]. Throughout the 2009 and 2010 sampling seasons, between 6 and 13 discharge measurements were collected on the West Fork and East Fork each year from May-October to capture the variability in streamflow throughout the season. The inherent standard error in the area-velocity method of discharge measurement is 10-15% [*Mutreja*, 1986], and it is assumed those values are applicable in this study. Stage-discharge rating curves were developed using the USGS Graphical Rating and Shift Application Tool (GRSAT) version 2.3 according to standard methods for computation of streamflow described in *Rantz* [1982]. The observed and computed values of streamflow show good correlation, yielding coefficient values ranging from 0.88 (2010) to 0.96 (2009) for the West Fork, and 0.98 (2009) to 0.99 (2010) for the East Fork. The maximum error of the stage-discharge relationship, estimated from the standard error is +/-12%. Figure 3 shows the daily mean hydrographs of the two catchments for 2009 and 2010.

A high flow event on the West Fork Eklutna River on 29 July 2009 destroyed the gaging station. On 28 August, after flows diminished to a level that allowed safe in-stream working conditions, we installed a staff plate at the location of the failed transducer and recorded river stage with a bank-mounted time lapse camera through 29

September, when the water level dropped below the level of the staff plate. We therefore lack direct measurements of stage between 30 July and 28 August, and also during dark night hours from 29 August to 29 September. These missing stage data were reconstructed using a linear regression of West Fork stage against stage data from the East Fork during the period of common record for the months of June and July 2009 (r^2=0.84).

To protect the sensor from sustaining damage during high flow events, in 2010 we attached the new un-cabled sensor to the downstream face of a large in-stream boulder. We were successful in obtaining a complete melt-season record in 2010, but the stage record was complicated by the hydrodynamics of the river in that location. Whereas the hourly hydrograph of 2009 West Fork discharge displays a clear diurnal cycling, this pattern is obscured in the 2010 hydrograph through late July (Figure A1). Careful examination of the stage sensor measurements, along with available concurrent time lapse photos, shows that the boulder caused high frequency fluctuations in the lee side water level recorded by the sensor, on the timescale of seconds to hours. This conclusion is supported by re-emergence of the diurnal pattern in early August on the same day that the time lapse photos show a pile of fine woody debris collected on the boulder; the small logjam reduced turbulence at the location of the sensor.

Amplitudes of these fluctuations were sufficient to obscure diurnal variations, but not the timing or magnitude of seasonal fluctuations. Peaks and lows in the "noisy" stage record between 24 May and 30 July 2010 clearly track changes in water level shown by available time lapse photos. With one exception, this conclusion is also supported by the correlation of calculated West Fork runoff with high temperature (melt) and/or precipitation events recorded at both meteorological stations. One brief spike in the 2010 West Fork hydrograph, lasting from 15:15 hrs on 19 July through 06:30 on 20 July, occurred during a period when the time lapse camera was not operating and is not corroborated by a concurrent spike in East fork stage, or by discernible high temperature or precipitation events. This spike could plausibly be explained as a substantial upstream release of stored subglacial water, but without clear evidence for such an event, we favor the more conservative explanation that this spike was caused by a transient piece of debris that affected stage in a way to provide falsely increased measurements for a period of less than 16 hours. We have therefore removed this spike from our hydrograph by using mean discharge values from the unaffected portions of each day as our daily mean values to connect before and after that event. Figure A 1 shows West Fork 2010 hourly hydrographs with and without the spike.

These sources of uncertainty in our estimates of West Fork streamflow (unmonitored stage intervals in 2009, and noise in the 2010 record) reflect the difficulties inherent in measuring discharge in glacial streams [*Hock et al.,* 2005], but we remain confident that the errors have only a minor impact on the overall results presented in this study. Use of the East Fork record to reconstruct portions of the 2009 West Fork record introduces an unknown error, but the strength of the regression argues that impact of this on our overall daily and seasonal totals is minimal. And we assume that the 2010 turbulence introduced random errors that complicate interpretation of the hourly record but generally cancel out in the daily means we use for all calculation in this study. Later in this paper, we present a more detailed analysis of the sensitivity of our results to these problems.

Streamflow in the East and West Forks of Eklutna River has been intermittently recorded in the past. Daily mean discharge data from the U.S. Geological Survey National Water Information Systems (NWIS) database were available for complete melt season periods during the years 1961 (http://waterdata.usgs.gov/ak/nwis), and 1986-1988 [*Brabets*, 1992] and were used for comparison in this study.

2.2 Glacier

A mass balance program was simultaneously conducted on the Eklutna Glacier for the years 2008-2010 based on bi-annual stake measurements at three locations across the glacier representing the ablation zone, equilibrium line altitude, and accumulation zone. A fifty year history of glacier terminus retreat and thinning is well documented through remote sensing techniques including GPR, ASTER imagery analysis and airborn laser altimetry data. We used Light Detection and Ranging (LiDAR) data, collected in fall of 2010, to assess the hypsometry of the watershed [*Mat-Su Salmon Habitat Partnership,*2010]. For delineation of glaciated area in the East and West Fork basins, a 30m resolution image from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite, acquired on 27 August 2009, was used. Additionally, we used ground penetrating radar (GPR) in May of 2009 to estimate ice thickness and the elevations of bedrock under the Eklutna Glacier. A detailed discussion of the methods and results of the glacier research program is provided in *Sass et al.* (manuscript in preparation, 2011).

2.3 Bathymetry and Lake Volume

To calculate a water budget for the Eklutna watershed, an accurate map of Eklutna Lake bathymetry was needed to create a water level-lake volume rating curve. Eklutna Lake bathymetry was last surveyed in 1986 and reservoirs experience physical changes as a result of sediment deposition, shoreline erosion, and wind processes over time. Therefore, we conducted a new bathymetric survey in October 2010 using a 210 kHz single beam survey grade echosounder. Horizontal position was measured synchronously with a GPS mounted directly above the echo sounder. Depth measurements collected at a frequency of 7 points per second were averaged to a corresponding GPS position. Depth measurements have a manufacturer reported accuracy of +/- 0.01 m or +/- 0.02%, with positional data accuracy of +/-4 m. Data were collected from a moving boat; measured field parameters included water temperature (to determine sound velocity), depth of the transducer below the water surface, and occasional hand tape measurements to verify water depth.

Data were processed using ESRI ArcGIS software version 9.3. The boundary of Eklutna Lake was digitized every 10 m from the USGS Anchorage (B-6) NW Quadrangle Topographic Digital Raster Graphic (DRG) at a scale of 1:25,000 at a lake level elevation of 265 meters. Raw water depths were converted to elevations above sea level by subtracting them from contemporaneous lake level elevations measured by a USGS lake level gage (61◦24’39’’N, 149◦07’20’’W) referenced to the National Geodetic Vertical Datum of 1929 (NGVD29). Survey dates and lake levels are summarized in Table A1.

To interpolate missing values we used kriging, an estimation procedure that computes values for unsampled areas based on the values of the points located around the unsampled area [*Conaway and Moran,* 2004]. Kriging provides measures of the error or uncertainty of the contoured surface using a semivariogram to find an optimal set of weights that are used in the estimation of the surface at an unsampled location [*Davis,* 1973]. We used a spherical-anisotrophic model, because this incorporates the influence of direction dependency based on the enlogated shape and orientation of the lake, and it is well suited to irregularly spaced data. The model parameters for the semivariogram are presented in TableA2 and the final bathymetric map is presented in Figure 4.

A water level-lake volume relationship, or stage curve, was derived from the interpolated bathymetry of the lake (Figure 4). Volume below a surface plane was calculated at 52 lake level elevations ranging from 240.0 meters to 265.0 meters (range of active storage) (Figure 4). A second order polynomial regression was fit to the data to calculate lake volumes recorded by the range of stages experienced during 2008-2010 by the USGS maintained lake level gage:

$$y = 9.513\text{x}10^4 b^2 - 3.674\text{x}10^7 b + 3.552\text{x}10^9 \tag{1}$$

where *y* is lake volume (m^3) and *b* is lake surface elevation (m above MSL).

Evaluating volumetric storage of Eklutna Lake by calculating the volume difference between bathymetry survey data conducted in 1986 and 2010 indicate a reduction in the storage capacity of Eklutna Lake of $0.79\text{x}10^7 m^3$, or approximately 6.5% of the total volume over 25 years. This calculates to an annual sediment input of $0.03\text{x}10^7 m^3$ per year. The original designs for dam construction and water resource usage facilities at Eklutna anticipated a sediment accumulation rate for a 50 year period of 1.2 x$10^7$$m^3$ [*Shira,* 1986], or 0.02x$10^7$$m^3$ annually. Comparing both these sediment accumulation rates over a 50 year period, our measurements indicate 24% more sediment is being delivered to the lake than was originally forecasted.

2.4 Watershed Budget

To compare the contributions of the two studied subbasins to basin-wide water usage, we constructed simple water budgets for each year to examine the inputs and outputs of this watershed system. The basic hydrologic model holds that the total volume of water discharging from this catchment is equal to the volume of water entering the catchment plus a change in storage (ΔS):

$$\Delta S=(R_{EF}+R_{WF}+R_U+GW_D)-(E+DW+HP+GW_R) \tag{2}$$

Inflow, the monthly total streamflow from the upper basin, is calculated by adding the two different routed components of input to Eklutna Lake, runoff from the East Fork (R_{EF}) and West Fork (R_{WF}) rivers with the additional unknown components of runoff from the ungaged lower portion of the basin (R_U) and ground water recharge (GW_D). As discussed previously, the other small streams from the lower portion of the watershed directly surrounding the lake were not measured in this study. Outflow, the monthly total water loss from the lake, is calculated by adding the four different routed components of water leaving the Eklutna Lake: water with drawn for drinking water (*DW*), hydroelectric power generation (*HP*), evaporation (*E*), and groundwater discharge (GW_R). Ancillary data, obtained from Municipal Light and Power and Anchorage Water and Wastewater Utility (Table A3), provided monthly volumes of water diverted from the lake for consumptive use during the period of study; therefore, we did not directly measure water extraction from Eklutna Lake.

Groundwater contribution/loss was not considered in this simple water budget. Because glacial watersheds consist primarily of relatively impermeable bedrock, loss to the groundwater system is not considered significant [*Mark and Seltzer*, 2003]; additionally, previous studies [*Brabets*, 1992] have concluded a groundwater component of zero from the West Fork subbasin, noting that no flow occurred in the West Fork River during the winter, and the river freezes completely to the bed. We therefore treat both GW_D and GW_R as zero.

Evaporation losses were estimated indirectly using a simplified version of the Penman formula for evaporation rate [*Linacre*, 1977]. Evaporation was calculated based on monthly averages of temperature, relative humidity, and lake surface elevation, using a lapse rate of 6.5°C/1,000 m to convert temperatures at the SNOTEL station to temperatures at lake level [*Barry,* 1992]. This provided a monthly point measurement of evaporation which was then applied over the entire surface are of the lake.

3. Results

3.1 Spatiotemporal Comparisons

3.1.1 Discharge, Runoff, and Streamflow Variability in 2009-2010

Hydrographs from the East and West Forks exhibit variable trends over the period of study (Figure 3). West Fork streamflow remains relatively low (~10 m^3/s) through May and early June while the winter snow cover is melting from the lower reaches of the glacier and adjacent mountain slopes and progressively upward in elevation in the basin. Higher flows appear in mid-June, when the seasonal snowpack has melted enough to begin exposing substantial glacier ice. With bare ice and decreased albedo, glacier melt produces high discharges ranging from 15-25 m^3/s, with peaks up to 45 m^3/s, through mid- to late- August. Streamflow decreases rapidly in the fall as temperatures decline and glacial melt ceases; West fork discharge responds sluggishly to late season precipitation events with spikes either absent or less than 5 m^3/s. The East Fork behaves differently, with more response in streamflow in the early season to snowmelt runoff and lower mid-season average discharges ranging from 15-20 m^3/s, with peak mid-season discharges up to 30 m^3/s. The East Fork hydrograph exhibits more prominent spikes in streamflow in response to fall precipitation events in mid- to late-September, with spikes commonly exceeding 5 m^3/s .

Monthly streamflow totals facilitate comparison of the two subbasins in 2009 and 2010 (Figure 5). Runoff volumes are clearly higher for the highly glacierized West Fork than for the East Fork during July, July, and August of both years. In comparison, monthly runoff in spring and fall is similar in both subbasins over both years. Midsummer flows dominate the overall annual water budgets of these rivers: the average July discharge at the West Fork, for example, indicates that this month alone provides 40% of the average melt-season yield from this subbasin. The months of June, August, and September have smaller proportional contributions of 18%, 28%, and 9% respectively. Overall, the West Fork therefore contributes 21-22% more total runoff than the East Fork During both the 2009 and 2010 melt seasons (Figure 6).

In both subbasins, 2009 had greater total melt-season runoff than 2010. We attribute this to warm, sunny conditions and the transient effect of volcanic ash in 2009. Average summer temperatures at both stations were approximately 0.5°C warmer in 2009 than 2010. Also, 2010 was generally wetter than 2009. Annual precipitation at the glacier meteorological station, calculated by adding total summer precipitation and measured winter accumulation snow water equivalent at mid-elevation on the glacier, was 2267 mm in 2010 versus 1726 mm in 2009. Total precipitation recorded at the SNOTEL site parallel these findings. Accentuating the effects of a warm, sunny 2009 melt-season, the eruption of Mt. Redoubt in March of 2009 deposited a thin (<1mm) layer of ash across the watershed, substantially lowering the albedo of the snowpack.

This, combined with warm May and June temperatures may be associated with an early pulse of meltwater from the West Fork basin in June of 2009 and probably also affected mid-season flows as well.

To facilitate inter-basin comparisons, we normalized East and West Fork discharge by area to calculate specific discharge (runoff per unit area). Although the East Fork subbasin is larger in area than the West Fork subbasin, the more heavily glacierized West Fork yields much higher flows per unit area than the moderately glacierized East Fork basin (Figure 6). During the 2009 melt-season, West Fork total specific runoff ($27.0x10^5m^3$) was more than twice that of the East Fork ($13.3x10^5m^3$), highlighting the increased generation capacity of the heavily glaciated basin, when other conditions remain similar.

Intraannual discharge variability is also influenced by the degree of glacierization in a catchment. We calculated the cumulative distribution function of daily mean specific discharges, as described in *Fleming* [2005], for each subbasin averaged over the two years of study (“modern average” in Figure 7). These results demonstrate clearly that the range of flows experienced throughout the melt-season is more variable on the West Fork, with a range of 0.01-0.58 m^3s^{-1}/km^2, than on the East Fork, with a smaller range of 0.02 to 0.23 m^3s^{-1}/km^2. The coefficient of variation (CV) of annual runoff, calculated by dividing the standard deviation of the runoff by the mean for all years of data, can also be used as a tool to compare the interannual variability between these two basins. The CV generally increases with mean annual runoff, therefore is no surprise that the CV value of the West Fork River is 0.53 versus a substantially lower CV for the East Fork of 0.11.

The seasonal distribution of discharge is also expected to vary with glacier cover. Figure 8 shows, for any given day of the year in 2009 and 2010, the fraction of cumulative streamflow that has passed by the gage since the start of the melt-season. Over the two years of our study the seasonal timing of flow is almost identical across both basins and years (Figure 8). The East Fork delivers a slightly greater proportion of water earlier in May of both melt seasons, but by 25 July 50% of the total streamflow from each basin has passed by the respective gage sites. Over the longer term, comparison of these results with historic data shows some significant changes; we address historic trends below.

3.1.2 Comparison with Historic Trends

To gain a sense of how water production from each subbasin has changed overtime, total runoff and specific runoff from current (2009/2010) and historic (1961, 1986-88) periods are compared in (Figure 6). In this and all subsequent comparisons of our results with historic data, we acknowledge that the available historic data (1961, 1986-88) limits our ability to confidently infer historic trends. Nonetheless, these historic data provide a useful context for interpreting our results. Both the East and West Fork subbasins produced more water and have higher yields in the last two years than in any other previous years. Historically, the East Fork, draining an area 37% larger than the West Fork, generated greater total runoff volume than the West Fork during measured periods in the 1960s and 1980s, except for 1986 when the two basins produced approximately equal runoff (Figure 6). But the West Fork now yields more water than the East Fork.

East Fork Eklutna River specific discharge has remained relatively constant over time with a mean (*M*) of $11.2 \times 10^5 m^3/km^2$ and small standard deviation (*SD*) of 1.31 (Figure 6). In contrast, specific discharge from the West Fork increased significantly over the observational interval (M=$18.2 \times 10^5 m^3/km^2$, SD=5.3). Averaging the historic and current specific discharge values, specific runoff generation has increased by 43% in the West Fork subbasin and only 17% in East Fork subbasin between the two periods.

Intraannual variability of specific discharge has increased on both forks with respect to the historic data, but more so on the heavily glaciated West Fork (Figure 7). The West fork has seen an increase in both mean discharge and variability around that mean (historic M=$0.12 m^3 s^{-1}/km^2$, SD=0.08; modern M=$0.23 m^3 s^{-1}/km^2$, SD=0.13), while the mean of specific daily discharge on the East Fork has remained stable with only a slight increase in peak flows and overall variability (historic *M*=0.09m^3s^{-1}/km^2, *SD*=0.05; modern *M*=0.11m^3s^{-1}/km^2, *SD*=0.09).

The temporal structure of West Fork streamflow has shifted noticeably over time (Figure 8). Historically, 50% of the volume of total water released from the West Fork basin had passed by the gage location by 1 August; the average date for this event was 25 July during our study: a week earlier. This is a significant shift towards earlier deliver of summer meltwater in the more glacial fork of Eklutna River. We observed no significant change in the distribution of streamflow over the melt-season from the East Fork.

3.2.1 Watershed Budget

3.2.2 Inputs

Since yearly mass balance measurements of net glacial melt are available for the Eklutna Glacier, the total contribution of glacier recession to accumulated runoff during the period of study can be calculated. In the 130 days of measurement between 24 May and 30 September of each year, $17.3 \times 10^7 m^3$ of water was discharged from the West Fork catchment in 2009 and $15.3 \times 10^7 m^3$ in 2010; for comparison, the East Fork produced $13.4 \times 10^7 m^3$ and $12.1 \times 10^7 m^3$ in 2009 and 2010 respectively.

During both those years, the Eklutna Glacier lost more mass during the summer than it gained during the winter. Mass balance measurements [*Sass et al.* (manuscript in preparation, 2011)] indicate net glacial ice melt of $4.1x10^7 m^3$ water equivalent in 2009; in contrast, 2010 net glacial ice melt was substantially less, contributing $0.49x10^7 m^3$ (Figure 9). In the short term, when glaciers experience negative net annual mass balance, the resulting decrease in size results in increased meltwater discharge. Assuming that all ice melt from the glacier became runoff that was measured as discharge at the corresponding gaging station, glacier shrinkage augmented West Fork streamflow by of 23.7% in 2009. In 2010, a much less negative mass balance year, glacier shrinkage contributed 3.1% to total West Fork streamflow.

Longer term trends in glacier mass loss corroborate these results. Since the Eklutna Glacier was first mapped in 1957, the planimetric area of the glacier has only been reduced by 7.5%; but due to substantial thinning, ice volume has diminished more substantially (22%) over the same period [details and error analysis in *Sass et al.,*(manuscript in preparation, 2011)]. The 50 year net glacial ice melt, as an annual average, is $2.3x10^7 m^3$ as compared to $4.1x10^7 m^3$ in 2009 and $0.49x10^7 m^3$. For comparison purposes, the 50 year annual average ice loss is 15% of the total West fork discharge in 2010.

3.2.2 Outputs

Summer output from Eklutna Lake provide a useful context for evaluating the relative contributions of the East and West Fork subbasins. We defined outputs as the estimated evaporation from the lake, plus the combined volume of water extracted for consumptive uses (drinking water and hydropower; Table1). Supplementary data in Table A3 provides the raw data provided by the water and power utilities and used to calculate outflow numbers. Averaging the outputs over the 2009/2010 melt seasons, evaporation accounted for 5.6% of total outflow, drinking water withdraw consumed 9.1%, and 85.4%was withdrawn for hydropower generation. The total summer consumptive water usage, water extracted from the lake by both the hydropower and drinking water utilities for May through September, totaled $17.7x10^7m^3$ in 2009 and $11.84x10^7m^3$ (Table 1).

Outputs for water and power use, here referred to as consumption, can be usefully compared with net glacier ice melt over the same period to evaluate the proportion of consumption that is supported by “mining” of the Eklutna Glacier. In 2009, 23.2% of summer consumption was derived directly from net glacier melt. This corresponds to 12.3% of annual (not just summer) water resource usage. In 2010, summer water resource consumption was less, but net ice volume loss was much less, consequently net glacial melt contributed only 4.1% to summer water use, and 1.8% to the total yearly water resources usage in the basin.

To more fully constrain this watershed budget, it would be important to collect streamflow data in the ungaged lower portion of the basin where runoff is derived from several small watersheds. Although these small subbasins are not the focus of our study, a well constrained watershed budget should provide us with a good estimate of their contributions. Other than groundwater flux, which we assume to be zero, discharge from the ungaged portion of the watershed is the only unknown variable in our budget (Equation 2). During July, July, and August of 2010, and also during July and August of 2009, our calculations show that the summed discharges of East and West Forks of Eklutna River comprise 100% of the calculated inflows necessary to balance changes in storage and outflows form the lake. Although we assume that the small ungaged streams contribute relatively little water to the lake's overall budget, this suggests, incorrectly, that they make *no* contribution to inflow. The contributions of these streams may be accounted for through other unmeasured process outside the scope of this study such as groundwater flux (assumed, perhaps incorrectly, to be zero) or evaporation (estimated but not measured), or by unrecognized errors in measurements of the other variables.

With the possibility that discharge for the West Fork 2010 melt-season was altered by effects of sensor placement, our calculated West Fork discharge could be over or underestimated. While it is difficult to provide a quantitative estimate of the errors introduced by this complication, we conducted a simple sensitivity analysis to assess if measurement uncertainty in the stage recordings was larger than the magnitude of the trends in runoff production. A synthetic hydrograph was created for the West Fork 2010 for the period of 24 May-30 July. The stage measurements were reconstructed using a linear regression relationship of West Fork stage against East Fork stage based on the period of the 2010 hydrograph from 30 July to 30 September when a clear diurnal signal is present in the West Fork data and the confounding effects of turbulence at the sensor are presumably minimal (r^2=0.94).

Using this reconstructed hydrograph, the melt-season runoff total from the West Fork would be $13.6 \times 10^7 m^3$, 11.7% lower than the results presented here. The magnitude of this change is less than the primary trends identified in this paper. The West Fork, for example, would still yield more than twice the specific discharge of the East Fork in 2010.

4. Discussion

4.1.1 Increase in Specific Yield from Highly Glacierized Subbasin

The West Fork subbasin produces more water, per unit area, than the more modestly glaciated East Fork subbasin (Figure 6). This result is consistent over the period of our study and in historic measurements too, though the effect has apparently grown over time. We attribute this effect to the greater ice cover in the West fork, and base this assertion on three factors that differ between the two watersheds: initial abstraction, hypsometric effects on precipitation, and conversion of glacier ice to river discharge.

4.1.1 Initial abstraction

In deglaciated landscapes, glacier forefields evolve, especially with establishment of vegetation and ongoing soil development [*Anderson et. al.,* 2000]. These developments diminish runoff due to increases in initial abstraction. This term represents all losses of precipitation in a watershed before runoff begins due to interception, infiltration, and surface storage. Initial abstraction losses are negligible in the highly glacierized basin because of the comparative lack of exposed soil and vegetation and because of the glacier itself; the retention and delivery of water is very efficient though it will always be less than precipitation received [*Collins,* 1987]. In unglaciated portions of the West Fork basin, limited vegetation development ensures that losses to interception and evapotranspiration are minimal. On the glacier itself several studies have concluded that evaporation is a minor component in the water balance from snow and ice covered area, even during the melt-season; therefore, generally no attempt is made to estimate evaporation and it is assumed to be zero in glacial watershed balance equations [*Lang,* 1981; *Braun et al.,* 1994; *Bhutiyani*, 1999; *Singh and Bengtsson*, 2004]. Most precipitation that falls on the surface of the Eklutna Glacier runs off directly to streamflow, or turns into ice and is stored for later downstream delivery. Also, loss due to infiltration to groundwater is not considered significant because glacierized watershed consist primarily of relatively impermeable bedrock [*Mark et al.*, 2005].

On the more vegetated East Fork basin landscape, water is intercepted in many ways before it becomes runoff including absorption by soil and infiltration to groundwater, water taken up by vegetation and transpired, evaporation, and water retained in any surface depression. The amount of initial abstraction greatly depends on what type and how much vegetation covers the landscape, soil type, how saturated the soil is, etc., but studies have measured initial abstraction losses ranging from 4.3 to 59.6% of the total precipitation that fell during any given rain event [*Baltas et al*., 2007]. *McNamara et al.* [1998] measured initial abstraction losses ranging from 0 to 36.1% of total precipitation during multiple rainfall events in Alaska’s Kuparuk River Basin. Though we cannot estimate initial abstraction in the two basins with available data, the potential clearly exists for significantly more initial abstraction in the East Fork subbasin compared with the more heavily glaciated West Fork catchment, with a concomitant reduction in specific runoff.

4.1.2 Hypsometric Effects on Precipitation

Hypsometric differences between the two subbasins in this study likely lead to greater precipitation in the highly glacierized catchment. While hydrological processes depend on many basin properties, the hypsometric (area-elevation) curve provides a useful framework for assessing precipitation rates in the two subbasins, and also for how that may change as the glacier continues to thin. Studies have suggested that topography plays a significant role in determining a basin's hydrological response to precipitation [*Howard*, 1990] and that there is interplay between runoff and a basin's geomorphic shape. Regardless of any differences in the bedrock elevations of the two subbasins, the greater glacier thickness in the West Fork subbasin (up to 400 m) increases that basins mean elevation and hence its received orographic precipitation. Thinning of the Eklutna Glacier, causing a decrease in mean surface elevation, also creates a feedback mechanism where a less glaciated basin will receive less precipitation due to the overall changes elevation distribution of land within the basin.

Hypsometric curves were obtained for the West Fork and East Fork basins from the 2010 LiDAR dataset. Since ice thickness for the glacier area was known, we subtracted ice thickness from the current basin surface elevations to generate a third curve representing the West Fork basin with the glacier completely removed (Figure 10).

Taking the present glacier masses into account, the median elevation of the present West Fork subbasin is higher (1410 m) than the East Fork subbasin (1203 m), and the West Fork therefore presumably receives more orographic precipitation. Importantly, some of this difference is due to the presence of a substantial glacier in the West Fork. Without the glacier, the median elevation would drop to 1362 m. We do not know the hypsometry of an ice free East Fork, but the glacier there are much smaller and it is clear that the thicker ice in the West Fork subbasin yields a higher level of orographic precipitation than does the ice in the East fork.

To estimate the magnitude of this effect using available data, we used 3 years (2008-2010) of winter precipitation measurements on the Eklutna Glacier at low, medium, and high elevations [*Sass et al.* (manuscript in preparation, 2011)], to calculate a winter precipitation (snowfall) gradient. Using the hypsometry of the West Fork with and without glacier presence, we calculated the total winter precipitation that falls in the basin under both scenarios. Though this simplistic calculation omits the role of summer precipitation (for which we lack a well-constrained precipitation gradient), the difference between our two scenarios suggests an 8.9% increase in winter precipitation in the West Fork basin due merely to the presence of the modern glacier. Despite the limitations of this analysis, it is clear that the glacier’s effect on basin hypsometry can provide a substantial increase in precipitation relative to the moderately glaciated East Fork-an effect that will diminish over time as the glacier shrinks.

4.1.3 Conversion of Glacier Ice to River Discharge

Analysis of changes in ice volume over the period of historical data available (1957-2011) indicates that the Eklutna Glacier is in a phase of pronounced negative mass balance. *Collins* [2008] describes the component of flow in excess of that related to contemporary precipitation as a "deglaciation discharge dividend" that is added to basin runoff from depletion of the amount of water stored as ice. Reduction of the mass of Eklutna Glacier augmented melt season river flow by 24% in 2009 and 3% in 2010, and this extra component of river flow will increase if melt rates rise in a warming climate. In fact, the historic trend of increasing specific runoff in the West Fork (Figure 6) may reflect a trend of increasing rates of glacier shrinkage on the Eklutna over that same period, a speculation that is corroborated by increasing rates of glacier melt statewide [*Bates*, 2008; *Arendt et al.,* 2002*; Sass et al.,* (manuscript in preparation, 2011)].

It is important to note that such an increase in discharge con only be transient [*Moore and Demuth,* 2001]. While increased temperature leads to rapid glacier melt, and therefore increased streamflow, the consequences of glacier recession overtime will overcome this effect, ultimately leading to substantial declines in streamflow. As the area of the glacier is reduced, runoff from the glacierized portion of a basin will decline, because water yield is effectively determined by the product of the amount of melt per unit area and the surface area of the glacier over which melting takes place [*Collins*, 2006]. Prolonged, long-term mass loss will reduce the surface area and volume of the Eklutna Glacier to a critical diminished size and it will produce reduced water yields, even if a negative mass balance persists over time. A glacier discharge simulation study by *Nolin et. al.* [2010] suggests that, there is an average decrease of 0.9% in total glacier runoff for each 1% reduction in glacier area.

While glaciers in the East Fork have retreated substantially in area since 1988 (8%), total streamflow volume has remained relatively stable in comparison to the larger deglaciation dividend prominent in West Fork streamflow volume trends. This suggests, though we have no data to confirm this, that these small glaciers have already passed their initial phase of significantly increased runoff and are now shrinking more by area loss than by thinning [*Schiefer et al.*, 2007; *Bolch et al.*, 2008].

4.2 Streamflow Variability and Seasonal Distribution

4.2.1 Interannual Variability

The coefficient of variation is a commonly used metric to describe the interannual runoff variability of streamflow and can vary greatly with the percentage of the catchment that is glacierized. Several studies have determined that variability is at a minimum for catchments that are ~40% glacierized and goes up as glacier cover increases or decrease from that value [*Willis,* 2005]. In other words, increases in glacier cover may decrease year-to-year runoff variability only until a critical value of ice cover is reached. Beyond this value, which appears to differ among study areas, variability increases and ultimately reaches levels comparable to a non-glacierized catchment [*Fountain and Tangborn,* 1985; *Braithwaite and Olesen,* 1988; *Chen and Ohmura,* 1990; *Moore*, 1992; *Fleming and Clark,* 2005].

The CV for the West Fork, 0.53, is very high: outside the range of any published values for glacierized basins. This may be based on the short period of record (6 years). CV values from basins having less than about 30 years of record may be subject to considerable uncertainty [*Moore,* 1992], though we note that the CV for individual year of streamflow data on the West Fork are fairly consistent (*SD*=0.04), lending some confidence to our overall result. Nonetheless, we conservatively focus here only on the comparative variability of the two basins: streamflow from the highly glaciated (46%) West fork subbasin is substantially more variable than streamflow from the East Fork basin (12% glaciated, CV=0.11). This contrast between the two basins is insensitive to the potential errors in the 2010 West fork hydrograph; the West Fork CV would be reduced only to 0.51 with the synthetic hydrograph described earlier.

This result supports the argument that modest glacier cover smooths interannual variations, but a high degree of glacier cover exaggerates variability.

4.2.2 Intraannual Variability

Previous research suggests that, in contrast to snow-covered basins subject to spring meltwater peaks, seasonal glacier meltwater runoff is generally delayed due to the postponement of the onset of melt from the glacier ice surface [*Hock et al.,* 2005] and the temporary storage of water as ice [*Fountain and Tangborn,* 1985]. In contrast with this expectation, our results (Figure 8) show little difference in the seasonal timing of runoff from a moderately and heavily glaciated basin. Both rivers delivered 50% of their total melt season volumes by 25 July in both 2009 and 2010.

Intriguingly, though, the timing of meltwater delivery has changed over time on the West fork only: the date on which half the summer flow volume has been delivered has advanced by up to 7 days. This shift towards earlier delivery of runoff is concurrent with documented glacier mass reduction, as predicted by theory.

There is no discernible change in runoff timing from the East Fork subbasin (Figure 8). This is an unexpected result because *Fountain and Tangborn* [1985] determined that in basins with initially small glacier cover, the shift towards earlier streamflow with diminishing ice cover is even more prominent than in basins with high initial glacier cover. Although the East Fork is considered only the moderately glaciated (12%) basin in this study, it would be considered perhaps highly glaciated by many standards in other studies of glacierized basins. A large proportion of the literature reviewed in research for this study consider the effects of basins with less than 20% glacier cover as highly glacierized and utilize hydrographs from those basins as the main basis for detecting glacial influences on river discharge.

4.3 Implications for Further Change

Even in a wet, heavily glaciated region like Alaska, our results suggest that glacier change will have consequences for drinking water and hydropower supplies. Over time, expected shrinkage of the Eklutna Glacier will diminish total annual discharge on the West Fork River. In the short term, net ice loss in the West Fork is yielding a “deglaciation discharge dividend,” which will diminish over time. Meanwhile, thinning of the glacier will yield less orographic precipitation in that subbasin. And reduction of glacier surface area will expose more watershed area to soil development and vegetation establishment, increasing initial abstraction. If Eklutna Glacier continues to shrink, these processes will diminish specific yields from the basin, independent of any changes in regional climate.

The populations of Anchorage and the Matanuska-Susitna Borough are growing rapidly, and diminished discharge will have economic costs. In the last decade, Anchorage has had a growth rate of 10%, and an even greater Matanuska-Susitna Borough growth rate of 51% (http://labor.alaska.gov/research/census). Decrease in future specific discharges from the Eklutna watershed do not threaten their water supplies in the literal sense in the way that glacier loss may impact users in some other, more arid, regions; Alaskans are not going to run out of water. But there may be a substantial financial cost if future yields are lower than what engineers and regional planners forecasted when developing infrastructure for municipal services. Especially in the face of a growing population, costs to construct facilities in additional watersheds to provide power and drinking water supplies may be substantial and unanticipated. This is especially true for electricity: hydropower from the Eklutna Power Plant is currently the least expensive power in the area, and the most immediate practical alternative is natural gas, which already produces roughly 70% of electricity for the state of Alaska (www.angda.state.ak.us) and is expected to increase in price with diminishing gas reserves in Cook Inlet [*Stokes et al.,* 2010].

The unpredictability of interannual and seasonal timing of discharge may also have a substantial impact on near term water resources management. The goal of water managers in this basin is to go into the dry season, which is winter, when little water is flowing in to the lake, with the most water in storage in the lake as possible. Late in the melt-season, when the lake is at its highest level, is when streamflow variability most effects water resource planning. While glaciers can smooth inter-annual fluctuations [*Hock,* 2005], our results suggest that this is not the case in the Eklutna watershed, at least for the more heavily glaciated West Fork. Water managers can somewhat reliably predict the timing and magnitude of discharge from East Fork, but the higher variability of the West Fork increases the probability of late season flows either failing to meet projections and leaving the reservoir low as managers enter the “dry season” (winter), or worse, exceeding projects and leading to an unavoidable overtopping of the dam. Since there are no hydroelectric outlet works in the spillway at the lake’s surface, potential generation capacity and revenue is lost.

5. Conclusions

Melt season discharge measurements from 2009 and 2010 show a clear distinction between the heavily and moderately glacierized subbasins of the Eklutna watershed. The West Fork catchment produced twice as much water runoff per unit area than the larger but moderately glaciated East Fork subbasin. The Eklutna Glacier currently enhances runoff to Eklutna Lake and to water users by limiting initial abstraction, increasing orographic precipitation, and yielding a deglaciation discharge dividend through ongoing mass loss. Through continued shrinkage, these enhancements will diminish, including the deglaciation discharge dividend from a reduced-area glacier. Hydrographs from both rivers demonstrate streamflow from the highly glacierized subbasin has higher inter- and intra-annual variation than the moderately glacierized basin, despite being comprised of almost equal ice-free and ice-covered portions.

If Eklutna Glacier's volume continues to diminish, there will be significantly less water available for the water supply and power systems dependent on them. In the last two years alone, net glacier melt augmented West Fork streamflow by 3 to 24% and contributed 4 to 23% of the total water used for hydroelectric power generation and water consumption during the period of study. As the glacier continues to melt, this deglaciation dividend will be lost, and there will be less water available to meet the demands of the utlilities that operate in this basin. The cost of developing alternative supplies should be factored into future planning, and development of new hydropower projects in the state should recognize explicitly the likely effects of ongoing glacier mass loss on future yields.

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