7.7 Glacier and Runoff Changes Study

7.7.1 General Description of the Proposed Study

Glaciers have generally retreated during the last century (Kaser et al. 2006; Meier et al. 2007), and glaciers in Alaska are currently subject to some of the highest glacial wastage rates on Earth (Arendt et al. 2002; Hock et al. 2009). Projections indicate that Alaskan glaciers may lose up to 60 percent of their current volume within the next 100 years (Radic and Hock 2011). Figure 7.7-1 provides an example of a glacier within the upper Susitna basin that has recently retreated.

Such changes will alter stream flow both in quantity and timing (Hock and Jansson 2005a). This is because glaciers temporarily store water as snow and ice during varying time scales with the release controlled by both climate and internal drainage (Jansson et al. 2003).

Typical characteristics of discharge from glacier-dominated drainages include pronounced diurnal patterns and mid- to late summer high flows due to the dominance of glacier melt water over precipitation. Annual runoff from a glaciered basin strongly depends on glacier mass balance. During years of positive glacier net, balance water is withdrawn from the annual hydrological cycle into glacier storage, and total stream flow is reduced. During years of negative glacier mass, balance water is released from storage and total stream flow increases.

Glaciers also tend to dampen interannual streamflow variations, where melting variations tend to offset precipitation variations. As little as 10 percent glacierization in a hydrologic basin reduces year-to-year variability in precipitation to a minimum (Huber 2005). As glaciers retreat, total glacier runoff will initially increase but then be followed by a reduction in runoff as the mass of the glacier dwindles (Figure 7.7-2).

With a high fraction of ice cover in the drainage basin, the increases in runoff during glacial mass wasting events can temporarily exceed any other component of the water budget. Nevertheless, glaciers tend to be only crudely represented in hydrological modeling (Hock et al. 2005b). Hence, the watershed runoff response due to glacier retreat is not well understood.

The primary goal of this study is to analyze the potential impacts of glacier wastage and retreat on the Susitna-Watana Hydroelectric Project (Project). Specifically, how will glacier wastage and retreat, along with associated changes to the climate, affect the flow of water into the proposed reservoir and water quality? Currently several glaciers flow down the southern flanks of the Alaska Range near 13,832-foot Mount Hayes to form the three forks of the upper Susitna River (Figure 7.7-3).

Glaciers in this area provide a significant portion of the total runoff within the upper Susitna drainage, and it is well documented that these glaciers are currently retreating (Molnia 2008). Given this trend, changes to the runoff represented by glacial melting may occur in the future, and may affect the Project. Therefore, it is important to understand how changes to the upper basin hydrology due to glacial retreat and climate change can affect Project operations and environmental resources.

Specific objectives of the study are as follows:

1) Review existing literature relevant to glacier retreat in Southcentral Alaska and the upper Susitna watershed. This review will summarize the current understanding of potential future changes in runoff associated with glacier wastage and retreat.
2) Develop a hydrological modeling framework that includes the effects of glacier wastage and retreat on runoff in the Susitna basin, and estimate potential glacier mass changes until the year 2100.
3) Simulate the inflow of water to the proposed Susitna-Watana reservoir and project this runoff from the upper Susitna basin to the year 2100 using downscaled climate projections.
4) Analyze the response of the Susitna River above the proposed Susitna-Watana dam site to changes in climate with respect to annual runoff, seasonality, and peak flows.
5) Summarize the results in a technical report.

Modeling will rely on two existing coupled models. Hydrological processes outside the glacier will be modeled using the Water Balance Simulation Model (WaSiM), and glacier response will be simulated using the glacier melt and runoff model by Hock (1999), which is now included in WaSiM.

7.7.2 Existing Information and Need for Additional Information

Approximately 5 percent of the upper Susitna River basin is covered by glaciers. Permafrost is generally discontinuous, although seasonal freeze and thaw cycles affect the entire basin. Long-term, discontinuous (~ 60 years) stream flow observations from the U.S. Geological Survey (USGS) are available at five locations in the basin: Denali, Cantwell, Gold Creek, Sunshine, and Susitna Station.

7.7.2.1 Existing information on glacial retreat in Alaska

There has been extensive melting of glaciers in Alaska in recent decades (Molnia 2008). Statewide, Alaskan glaciers lost 10.1 mi^3 (41.9 km^3) of water per year, plus or minus 2.1 mi^3 (8.6 km^3) of water per year, between 1962 and 2006 (Berthier et al. 2010). However, like temperature and precipitation, glacier ice loss is not uniform across wide areas; even while most glaciers in Alaska are losing mass, a small number have been advancing (e.g., Hubbard Glacier in Southeast Alaska). Alaska glaciers with the most rapid mass loss are those terminating in sea water or lakes.

7.7.2.2 Documented changes in climate

Scenarios Network for Alaska and Arctic Planning (SNAP) (2011) reported that Alaska has seen a statewide increase in temperatures of 2.69 degrees Fahrenheit (°F) since 1971. This has not been equal across the state. Statewide, Barrow displayed the greatest increase (4.16°F) and Kodiak showed the least (0.87°F). The U.S. Global Change Research Program (2009) reported that Alaska has experienced a 3.4°F rise in average annual temperatures over the past 50 years, with an increase in winter temperatures of 6.4°F. These increases in temperatures have led to other related changes in climate. For example, the average snow-free days have increased across Alaska by 10 days, and the number of frost free days has steadily increased in Fairbanks, Alaska (Figure 7.7-4).

Precipitation rates are generally increasing across the state. On the whole, Alaska saw a 10 percent increase in precipitation from 1949 to 2005, with the greatest increases recorded during winters (U.S. Global Change Research Program 2009). However, this trend is very location-specific across Alaska. Figure 7.7-5 shows that while temperatures have increased in Talkeetna, mean annual precipitation has remained relatively constant (Alaska Climate Research Center 2012).

7.7.2.3 Projections of the future

For any hydropower project it is important to understand the variability of the discharge as it directly affects power generation.

The observed trends in temperature, precipitation, and snowpack are largely consistent with climate model projections for Alaska (Christensen et al. 2007; Karl et al. 2009). The magnitude of projected changes depends on many factors and will vary seasonally. Projected changes in climate will translate into hydrologic changes through alteration of rain and snowfall timing and intensity, evapotranspiration, and groundwater and surface flows. For example, precipitation is predicted to increase in the Susitna basin, but this may be offset by an increase in evapotranspiration from warmer temperatures and a longer growing season. Milder winters could result in reductions in snowpack because a higher percentage of precipitation would occur as rain. But given the elevation of the upper Susitna basin, increases in precipitation may simply result in increased seasonal snow storage, resulting in greater spring runoff.

Both air temperature and precipitation are currently predicted to increase over time in Alaska, including the southcentral region (SNAP 2011). Temperatures in this region are projected to increase over the coming decades at an average rate of about 1^{o}F (~0.6 ^{o}C) per decade (SNAP 2011).

7.7.3 Study Area

The proposed study area is the Susitna River basin upstream of the proposed Watana Dam site.

7.7.4 Study Methods

The studies and study components to be conducted include the following:

- Review existing literature relevant to Southcentral Alaska, the Susitna watershed, and glacier retreat, and document trends in the historic record.
- Develop a hydrological modeling framework.
- Analyze changes in glacial systems, temperature, and precipitation, and their impacts on watershed hydrology, and project future runoff in a set of climate projection scenarios to year 2100.
- Summarize results in a technical report.

7.7.4.1 Review Existing Literature

Existing literature will be reviewed to summarize the current understanding of the rate and trend of glacier retreat and the contribution of glacial mass wasting to the overall flow of the upper Susitna watershed. This will include trend analyses of glacier retreat, temperature, and precipitation.

7.7.4.2 Develop a Modeling Framework

The study will use the fully-distributed temperature index mass balance model by Hock (1999, 2003), that computes snow and ice melt and resulting runoff on hourly to annual time scales based on temperature and precipitation data. The model incorporates the effects of topography on melt by varying the degree-day factor according to potential direct solar radiation, which is computed from topography and solar geometry. The model converts mass changes into glacier geometry changes, and thus it is able to model the effects of a changing geometry on the mass balance.

The model has been used world-wide on many glaciers of different sizes and located in a wide range of climatic settings for a wide range of applications in different disciplines, including basic and applied research, and ranging from providing the mass balance input to ice flow modeling on valley glacier and continental ice sheet scales (Schneeberger et al. 2001), predicting the response of glaciers and glacier discharge to future climate (Schuler et al. 2005; de Woul and Hock. 2005), quantifying the risk for glacier outburst floods (Schuler et al. 2002; Huss et al. 2007), assessing the glacial history of empty cirques (Dühnforth and Anderson 2011), and reconstructing the mass balance history on a century time scale (Huss et al. 2008). Applications have recently been broadened by using global climate data sets including output from global and regional climate models for impact studies (Hock et al. 2007). The model requires a digital elevation model (DEM), temperature, and precipitation data.

Data generated from the glacier mass balance model will be input into the WaSiM to analyze the present and future runoff, soil water storage variations, and permafrost distribution. WaSiM (Schulla 2012) is a well-established tool for modeling the spatial and temporal variability of hydrological processes in complex basins ranging from less than 0.4 mi^2 (1 km^2) (Liljedahl et al. 2009) to more than 193,000 mi^2 (500,000 km^2) (Kleinn et al. 2005). It has been widely used by both research scientists and state agencies for water resources management. In total, WaSiM has been applied to more than 55 watersheds on all continents resulting in more than 120 publications documenting the wide range of applications that have led to constant improvement and refinement of the model.

WaSiM calculates evapotranspiration, snow accumulation, snow and glacier melt, runoff, interception, infiltration, soil water storage, and runoff, such as surface, interflow, and baseflow. Recently, the model has been enhanced to include soil heat transfer and permafrost (Liljedahl et al. 2012). Minimum input data requirements include a digital elevation model, vegetation and soil maps, precipitation, and air temperature. Complementary inputs are wind speed, vapor pressure, and shortwave incoming radiation. Spatial interpolation of the meteorological input data may be applied along with corrections of precipitation and adjustment of radiation due to solar and local geometry. The model can be run with hourly to monthly time steps.

WaSiM currently includes a simple glacier melt model that describes the melt of firn, ice, and snow on glaciers as well as routing of the water through the glacier. The melt model is represented by an extended temperature index method including potential direct radiation (Hock 1999), and the water is routed through the glacier using three linear reservoirs (Hock and Noetzli 1997) to account for the different travel times for firn, snow, and ice storages. WaSiM is considered the ideal model for this project because of the following:

- The model is robust and has been successfully applied to many watersheds as evidenced by the extensive publication record.
- WaSiM is a reasonable compromise between detailed physical basis and minimum data requirements and, therefore, suitable in data sparse regions such as Alaska.
- WaSiM is a very suitable model because it includes a heat transfer model and it couples a soil thermal regime model to the Richards equation, two dimensional (2-D) groundwater module, and the soil moisture evapotranspiration dynamics.
- The model is coded in a modular way allowing easy adjustments and modifications in model formulations, and it can also easily be coupled to existing glacier models.
- The model is user-friendly and includes a very detailed model description and user manual facilitating use of the model code (Schulla 2012).

Although this approach has been shown to be highly efficient in modeling glacier runoff (Hock et al. 2005b), the model does not allow any changes in glacier firn extent, glacier geometry, and area, i.e., the glacier cannot retreat nor advance. Hence, the model will not be able to accurately predict the runoff changes due to expected glacier retreat as the reservoir of ice is depleted. Also, because the firn areas (i.e., the high reaching accumulation areas) are assumed constant in the current version, the model is not able to account for a faster runoff generation when firn areas decline and more bare ice becomes exposed at the surface. The glacier module will be enhanced by allowing for a time-variant firn area and by updating the glacier extent after each mass-balance year. This will be accomplished by volume-area scaling (Bahr et al. 1997; Radic et al. 2008). By accounting for glacier retreat/advance, the model will be able to represent changes in glacier volume and their effects on long-term river runoff.

Input data will include air temperature, precipitation, relative humidity, wind speed, and radiation data. These will be obtained in part from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (OSU 2012). PRISM is a unique knowledge-based system that uses point measurements of precipitation, temperature, and other climatic factors to produce continuous, digital grid estimates of monthly, yearly, and event-based climatic parameters. To obtain daily and sub-daily data, a WGEN (Weather Generator) model will be used that provides daily values for precipitation, maximum temperature, minimum temperature, and solar radiation. The model accounts for the persistence of each variable, the dependence among the variables, and the seasonal characteristics of each variable (Richardson and Wright 1984). For re-analysis and present day assessment, the North America Regional Reanalysis (NARR) will be used, which was computed at NCEP and initially covers the period from 1979 to 2003. The highest resolution output is 20 miles (32 kilometers) every 3 hours. Where available, meteorological data will be used with hourly time resolution from the National Weather Service and from the Alaska-Pacific River Forecast Center, Anchorage.

Field data will be generated from locally installed meteorological stations (MET) stations to aid in downscaling the data from gridded climate products (see Water Quality Study, Section 5.5). The data will allow smaller scale climate variability to be accessed and guide determination of some model parameters (for example, the temperature lapse rate).

Future hydrological simulations will be forced with the Max Planck Institute for Meteorology ECHAM5 model (3-hour time steps) and SNAP (monthly) models. The SNAP dataset includes the years 1980–2099, with data downscaled to 2-kilometer grid cells. Future projections from SNAP are derived from a composition of the 5 best-ranked General Circulation Models (out of

15 used by the Intergovernmental Panel on Climate Change [IPCC]) models for Alaska. Based on how closely the model outputs matched climate station data for temperature, precipitation, and sea level pressure for the recent past, their individual ranking order for overall accuracy in Alaska and the far north was as follows: (1) ECHAM5, (2) GFDL21, (3) MIROC, (4) HAD, and (5) CCCMA. The five-model composite uses mean values from the outputs of these models. Results from three emission scenarios (A2, A1B, and B2) are available from the SNAP website (http://www.snap.uaf.edu/home). Input parameters to the permafrost model within WASIM are spatial datasets of vegetation and soil thermal properties, which are specific for each vegetation and soil class and geographical area. The following datasets will be used:

- **Soils Properties.** Input parameters to the heat transfer model within WaSiM, enabling the modeling of permafrost impacts on the hydrology, are thermal and hydraulic soil characteristics defined by spatial datasets. The parametrization will be based on the U.S. General Soil Map (STATSGO) Data, a digital general soil association map developed by the National Cooperative Soil Survey and distributed by the Natural Resources Conservation Service of the U.S. Department of Agriculture. The soil map units, in Esri digital format, are linked to tabular data stored in an Access Database, containing estimated data on the physical and chemical soil properties, soil interpretations, and static and dynamic metadata. Further data for calibration and validation purposes will be acquired through the Permafrost Laboratory at the Geophysical Institute, University of Alaska, Fairbanks (Jafarov et al. 2012).

Land cover map. Land cover properties will be specified for a land cover map obtained from the National Land Cover Database 2001 (Homer et al. 2007). The dataset, produced through a cooperative project conducted by the Multi-Resolution Land Characteristics (MRLC) Consortium, is derived from 30-m resolution Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper-plus (ETM+) circa 2001 satellite imagery and is available since 2008 (Selkowitz and Stehman, 2011). In their accuracy assessment, Selkowitz and Stehman (2011) evaluated these data to be reasonable for a wide variety of research, analysis, and modeling efforts. The seasonality of different land cover classes will be parameterized according to products available through the Earth Resources Observation System (EROS) Data Center. These include MODIS-based products (ranging from 250 m to 1 km resolution), such as leaf area index (LAI) maps, and are provided through the Land Processes Distributed Active Archive Center (LP DAAC).

The models will be calibrated and validated against existing and new AEA-collected river discharge records and glacier mass balance data. The model will be run over the period from 1960 to present. Future simulations will be forced by a suite of downscaled IPCC AR4 projection scenarios and, if available, the newer AR5 simulations. Assessment of changes in glacier mass and river runoff will be the primary focus, but detailed output from the WaSiM model, such as future permafrost and active layer and soil water storage, will also be analyzed. Change in streamflow will be analyzed on annual, seasonal, and single event time scales. Results will allow quantification of the integrated glacier-hydrology responses to climate change for the upper Susitna basin.

7.7.4.3 Analyze Potential Changes in Sediment Delivery to Susitna-Watana Reservoir

Glaciers in Alaska can exhibit surges (advancement of the ice) with a sudden onset, extremely high (tens of meters/day) maximum flow rate, and a sudden termination, often with a discharge of stored water. Glacial surges have been reported for a number of Alaskan glaciers (Humphrey and Raymond 1994; Clarke et al. 1986), including those that are located in the Alaska Range. Glacial surges have been reported for the Susitna and West Fork glaciers in the upper Susitna basin (Harrison 1994).

Suspended sediment loads as a result of a glacial surge on the Variegated Glacier were reported to increase significantly (Humphrey and Raymond 1994), and it has been suggested that the increased suspended sediment loads resulting from glacial surges might increase sediment delivery to the Susitna-Watana reservoir, thereby accelerating reservoir sedimentation (R&M Consultants and Harrison 1981; Harrison 2012).

This study will analyze potential changes to sediment load resulting from glacial surges. Unpublished sediment data at the West Fork Glacier, Denali Highway Bridge, and Gold Creek following the 1987–1988 surge of the West Fork Glacier (Harrison 2012) will be obtained and reviewed to determine whether the glacial surge produced significantly increased sediment loads at those locations.

It should be noted that the presence of extensive braided streams between the termini of the upper Susitna basin glaciers and the head of the Susitna-Watana Reservoir is likely to buffer the impacts of any surge-related increase in sediment concentration at the reservoir. The braided streams strongly suggest that sediment delivery to the Susitna-Watana Reservoir will not be supply-dependent. Also, there is typically an order of magnitude variability in the suspended sediment loads during times without a glacial surge (Meyer 2012). Because of this sediment delivery, glacial surge may be within normal background variations.

An initial investigation of the potential loading of sediment from a glacial surge will be developed. The potential for increased sediment loading to the Susitna–Watana Resovoir from a glacial surge will be based on the following:

- The magnitude of previous glacial surges in the upper Susitna River basin glaciers as reported by Harrison (1994) and Humphrey and Raymond (1994).
- The sediment transport capacity of the reaches of the Susitna River upstream of the reservoir.

If this investigation indicates that the increased sediment load can actually be delivered in substantial quantities to Susitna-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 Geomorphology study component of the Geomorphology Study. This would include an estimate of the reduction in reservoir life that could result from sediment loading associated with periodic glacial surges.

7.7.4.4 Assess the Potential Effects on Basin Hydrology

Changes in snowpack, temperature, and precipitation have been previously documented over time in the state (Christensen et al. 2007; Karl et al. 2009). The magnitude of future changes depends on many factors and will vary seasonally. Projected changes in climate will translate into hydrologic changes through alteration of rain and snowfall timing and intensity, evapotranspiration, and groundwater and surface flows.

The study will attempt to qualitatively evaluate the projected changes in precipitation, temperature, and evapotranspiration over the next 100 years in the upper Susitna basin. The assessment will look at a several possible cases to evaluate the sensitivity of glacial retreat and runoff changes to differing climatological inputs. This will include no change from current conditions, continuation of current warming trends, and adherence to various climatological scenarios such as SNAP (2011).

In addition to the temporal and spatial patterns, an estimate the various extreme precipitation indices will be performed. These indices will include consecutive wet days, consecutive dry days, maximum 1-day precipitation (Rx1Day), maximum 5-day precipitation (Rx5Day), total annual precipitation (PRECPTOT), and simple daily intensity index (SDII, annual total precipitation divided by the number of wet days in the year), and will be estimated using open source software. The impact of major extreme precipitation indices on flows will be studied.

7.7.4.5 Summarize Results in a Technical Report

The technical report will include a description of the assumptions made, methods used (including models and projection scenarios), and other background information. Additionally, this report will include an analysis of the impacts of past and projected climate variability on the hydrology of the upper Susitna basin.

7.7.5 Consistency with Generally Accepted Scientific Practice

Modeling will rely on two existing models. Glacier response will be simulated using the glacier melt and runoff model by Hock (1999), which will be fully coupled to WaSiM, a physically-based hydrological model.

7.7.6 Schedule

The study elements will be completed in several stages and based on the following timeline summarized in Table 7.7-1.

Table 7.7-1. Glacial and Runoff Changes Study Schedule.

Activity	2012				2013				2014				2015
	1 Q	2 Q	3 Q	4 Q	1 Q	2 Q	3 Q	4 Q	1 Q	2 Q	3 Q	4 Q	1 Q
Compile data, review glacier wastage & watershed hydrology literature					—								
Process remote sensing imagery					—	—	—						
Spring fieldwork (winter balance measurements and instrument and station deployment)						—				—			
Fall fieldwork (summer balance measurements and data collection)							—				—		
Analyze glacier mass balance and meteorological data							—					—	
Glacier extent variation						—	—	—					
Hydrological & glacier melt model development					—	—							
Hydrological & glacier melt model calibration and validation							—	—	—	—	—	—	
Initial study report issued									Δ				
Updated study report issued													▲

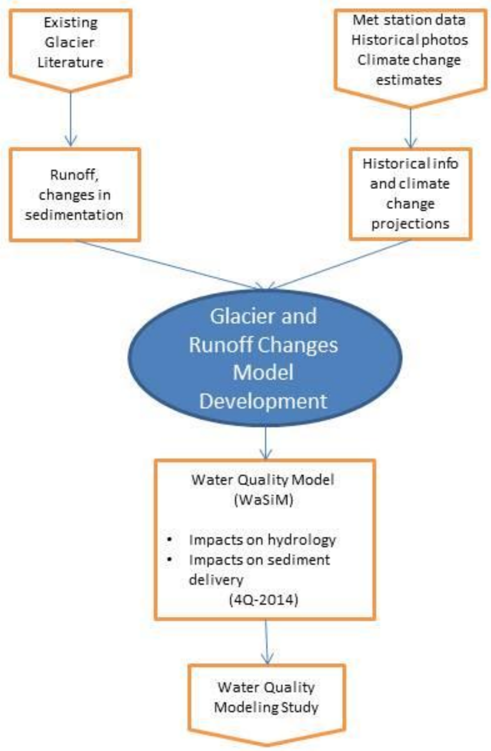
Legend:

—— Planned Activity

Δ Initial Study Report

▲ Updated Study Report

INTERDEPENDENCIES FOR GLACIER AND RUNOFF CHANGES STUDY



7.7.7 Level of Effort and Cost

The total estimated cost is $1,000,000.

7.7.8 Literature Cited

Alaska Climate Research Center. 2012. Climate Time Series, Talkeetna. http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Talkeetna.html

Arendt, A.A., K.A. Echelmeyer, W.D. Harrison, C.S. Lingle, and V.B. Valentine. 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science* 19 Vol. 297 no. 5580 pp. 382-386.

Bahr, D.B., M.F. Meier, and S.D. Peckham. 1997. The physical basis of glacier volume-area scaling. *J. Geophys. Res.*, 102, 20, 355-20, 362.

Berthier, E., E. Schiefer, G. Clarke, B. Menounos, and F. Rémy. 2010. Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. *Nature Geoscience*, Volume 3, Issue 2, pp 92-95.

Christensen, J.H., B. Hewitson, A. Busioc, X. Gao Chen, I. Held, R. Jones, R.K. Kolli, W.T. Kwon, R. Laprise, V. Magana Rueda, L. Mearns, C.G. Menendez, J. Raisaned, A. Rinke, A. Sarr, and P. Whetton. 2007. Regional Climate Projection. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S. D., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clarke, T.S., D. Johnson, and W.D. Harrison. 1986. Some aspects of glacier hydrology in the upper Susitna and Maclaren River Basins, Alaska. *Proc. Symp. Cold Regions Hydrology*, Univ. Alaska-Fairbanks. D. Kane (Ed) American Water Resources Association, Bethesda, MD, 329-337.

de Woul, M. and R. Hock. 2005. Static mass balance sensitivity of Arctic glaciers and ice caps using a degree-day approach. *Annals of Glaciology* 42, 217-224.

Dühnforth, M. and R. S. Anderson. 2011. Reconstructing the Glacial History of Green Lakes Valley, North Boulder Creek. *Colorado Front Range Journal Arctic, Antarctic, and Alpine Research*, University of Colorado. ISSN 1523-0430 (Print) 1938-4246 (Online) Issue Volume 43, Number 4 / November 2011 Pages 527-542.

Harrison, W.D. 1994. The 1987-88 surge of West Fork Glacier, Susitna Basin. *Alaska. J. Glaciol.*, 40(135), 241-253.

Harrison, W.D. 2012. Effect of glacier surges on the sediment regime of the Susitna Basin. Submitted to Susitna-Watana Project (P-14241-000).

Hock, R. and C. Noetzli. 1997. Areal mass balance and discharge modeling of Storglaciären, Sweden. *Ann. Glaciol.*, 24, 211-217.

Hock, R. 1999. A distributed temperature index ice and snow melt model including potential direct solar radiation. *Journal of Glaciology* 45(149), 101-111.

Hock, R. 2003. Temperature index melt modeling in mountain regions. *Journal of Hydrology* 282(1-4), 104-115. doi:10.1016/S0022-1694(03)00257-9.

Hock, R. and P. Jansson. 2005a. Modeling glacier hydrology. In: Anderson, M.G. and J. McDonnell (Eds.). *Encyclopedia of Hydrology Science,* John Wiley & Sons, Ltd, Chichester, 4, 2647-2655.

Hock, R., P. Jansson, and L. Braun. 2005b. Modeling the response of mountain glacier discharge to climate warming. In: Huber, U.M., M.A. Reasoner, and H. Bugmann (Eds.): *Global Change and Mountain Regions - A State of Knowledge Overview*. Springer, Dordrecht. pp. 243-252.

Hock, R., V. Radić, and M. de woul. 2007. Climate sensitivity of Storglaciären, Sweden: an intercomparison of mass-balance models using ERA-40 re-analysis and regional climate model data. *Annals of Glaciology*, Volume 46, Number 1, October 2007, pp. 342-348(7).

Hock, R., M. de Woul, V. Radic, and M. Dyurgerov. 2009. Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution. *Geophysics Research Letters*, 36, L07501.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. 2007. Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Huber, U.M., 2005. *Global Change And Mountain Regions: An Overview of Current Knowledge*. Springer Press, 650pp.

Humphrey, N.F. and C.F. Raymond. 1994. Hydrology, erosion and sediment production in a surging glacier: Variegated Glacier, Alaska, 1982-83. *J. Glaciol*., 40(136), 539-552.

Huss, M., A. Bauder, M. Werder, M. Funk, and R. Hock. 2007. Glacier-dammed lake outburst events of Gornersee, Switzerland. *Journal of Glaciology*, Volume 53, Number 181, March 2007, pp. 189-200(12).

Huss, M., A. Bauder, M. Funk, and R. Hock. 2008. Determination of the seasonal mass balance of four Alpine glaciers since 1865. *Journal of Geophysical Research* Vol. 113, 11 pp.

Jafarov, E., S. S. Marchenko, and V. E. Romanovsky. 2012. Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset. *The Cryosphere*, 6, 613–624, 2012.

Jansson, P., R. Hock, and T. Schneider. 2003. The concept of glacier water storage - a review. *J. Hydrol*., 282(1-4), 116-129.

Karl, Thomas R., Jerry M. Melillo, and Thomas C. Peterson, (eds.). 2009. *Global Climate Change Impacts in the United States*. Cambridge University Press.

Kaser, G., J.G. Cogley, M. Dyurgerov, M.F. Meier, and A. Ohmura. 2006. Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004. *Geophys. Res. Lett*., 33, L19501.

Kleinn, J., C. Frei, J. Gurtz, D. Luthi, P.L. Vidale, and C. Schär. 2005. Hydrologic simulations in the Rhine Basin driven by a regional climate model. *J. Geophys. Res*., 110(D0), 4102.

Liljedahl, A.K., J. Schulla, and L.D. Hinzman. 2009. The first application and validation of the hydrologic model WaSiM-ETH at a watershed underlain by permafrost. Abstract C51A-461 American Geophysical Union Fall Meeting, December 14-18, San Francisco, CA, 2009.

Liljedahl, A.K, L.D. Hinzman and J. Schulla. 2012. Ice-wedge polygon type controls low-gradient watershed-scale hydrology. In Tenth International Conference on Permafrost Vol. 1: International Contributions, Hinkel K. M. (Ed.), The Northern Publisher, Salekhard, Russia, pp 231-236.

Meier, M.F., M.B. Dyurgerov, U.K. Rick, S. O'Neel, W.T. Pfeffer, R.S. Anderson, S.P. Anderson, and A.F. Glazovsky. 2007. Glaciers dominate eustatic sea-level rise in the 21st century. *Science*, 317, 1064, doi: 10.1126/science.1143906.

Meyer, D. 2012. Personal Communication. U.S. Geological Survey.

Milliman, J. D., and R.H. Meade. 1983. World-wide delivery of river sediment to the oceans: *Journal of Geology*: v. 91, p. 1-21.

Molnia, B.F. 2008. Glaciers of North America -- Glaciers of Alaska, in Williams, R.S., Jr., and Ferrigno, J.G., eds., Satellite image atlas of glaciers of the world: U.S. Geological Survey Professional Paper 1386-K, 525 p.

Oregon State University (OSU). 2012. Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate mapping system. Developed by Dr. Christopher Daly, PRISM Climate Group, Oregon State University. http://www.prism.oregonstate.edu/.

Radic, V., R. Hock, and J. Oerlemans. 2008. Analysis of scaling methods in deriving future volume evolutions of valley glaciers. *Journal of Glaciology*, 54(187), 601-612, 2008.

Radić, V. and R. Hock. 2011. Regional differentiated contribution of mountain glaciers and ice caps to future sealevel rise. *Nature Geoscience*, 4, 91-94, DOI: 10.1038/NGEO1052.

Richardson, C.W. and D.A. Wright. 1984. WGEN: A model for generating daily weather variables. USDA-ARS Bulletin No ARS-8. Washington, D.C.

R&M Consultants, Inc. and W.D. Harrison. 1981. Alaska Power Authority Susitna hydroelectric project; Task 3 – hydrology; glacier studies. Report for Acres American Inc., Buffalo, NY.

Scenarios Network for Alaska and Arctic Planning (SNAP). 2011. Regional Climate Projections-Southcentral Alaska. Alaska Climate Change Adaptation Series. Available at: www .accap.uaf.edu/documents/4pg_ Climate Projections_ Statewide. pdf and www .accap.uaf.edu/documents/2pg_ ClimateProjections _Regional. pdf.

Schneeberger, C., O. Albrecht, H. Blatter, M. Wild, and R. Hock. 2001. Modeling the response of glaciers to a doubling in atmospheric CO2: a case study on Storglaciären, northern Sweden. *Climate Dynamics* 17, 825-834.

Schuler, T., U. Fischer, R. Sterr, R. Hock, and H. Gudmundson. 2002. Comparison of modeled water input and measured discharge prior to a release event: Unteraar–gletscher, Bernese Alps, Switzerland. *Nordic Hydrology* 33 (1), 27-46.

Schuler, T., R. Hock, M. Jackson, H. Elvehøy, M. Braun, I. Brown, and I.O. Hagen. 2005. Distributed mass balance and climate sensitivity modeling of Engabreen, Norway. *Annals of Glaciology* 42,395-401.

Schulla, J. 2012. Model Description WaSiM (Water balance Simulation Model). Completely revised version 2012, last change May 01, 2012. Available at: http://www.wasim.ch/downloads/doku/wasim/wasim_2012_en.pdf

Selkowitz, D.J., and S.V. Stehman. 2011. Thematic accuracy of the National Land Cover Database (NLCD) 2001 land cover for Alaska. Remote Sensing of Environment, 115 (6), pp. 1401-1407.

U.S. Geological Survey (USGS). 2012. Global Land Cover Characterization Global Land Cover Characteristics Data Base Version 2.0. http://edc2.usgs.gov/glcc/globdoc2_0.php.

U.S. Global Change Research Program. 2009. Global climate change impacts in the United States. Cambridge University Press, New York. http://downloads.globalchange.gov/usimpacts/pdfs/alaska.pdf.

7.7.9 Figures

Figure 7.7-1. September 1999 oblique aerial photograph of the terminus of an unnamed glacier that drains to the East Fork of the Susitna River. The western end of the lake corresponds to the 1955 position of the terminus. The large trimline suggests that the glacier has recently thinned significantly more than 50 meters (164 feet) and retreated more than 2 kilometers (1.2 miles). From Molnia 2008.

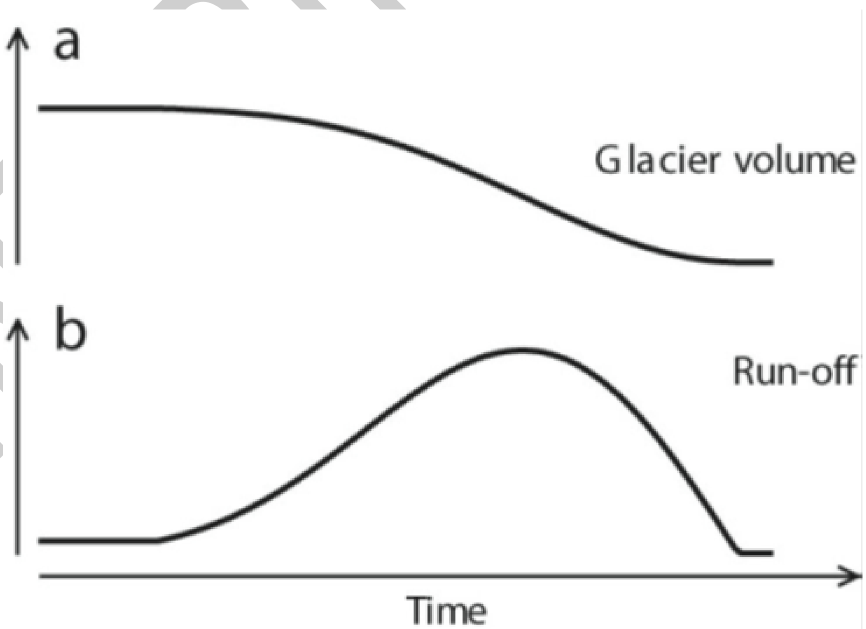


Figure 7.7-2. Schematic representation of the long-term effects of negative glacier mass balances on a) glacier volume and b) glacier runoff. Note that runoff is initially larger during prolonged mass wasting until the glacier is small enough to reduce excess runoff (Jansson et al. 2003).

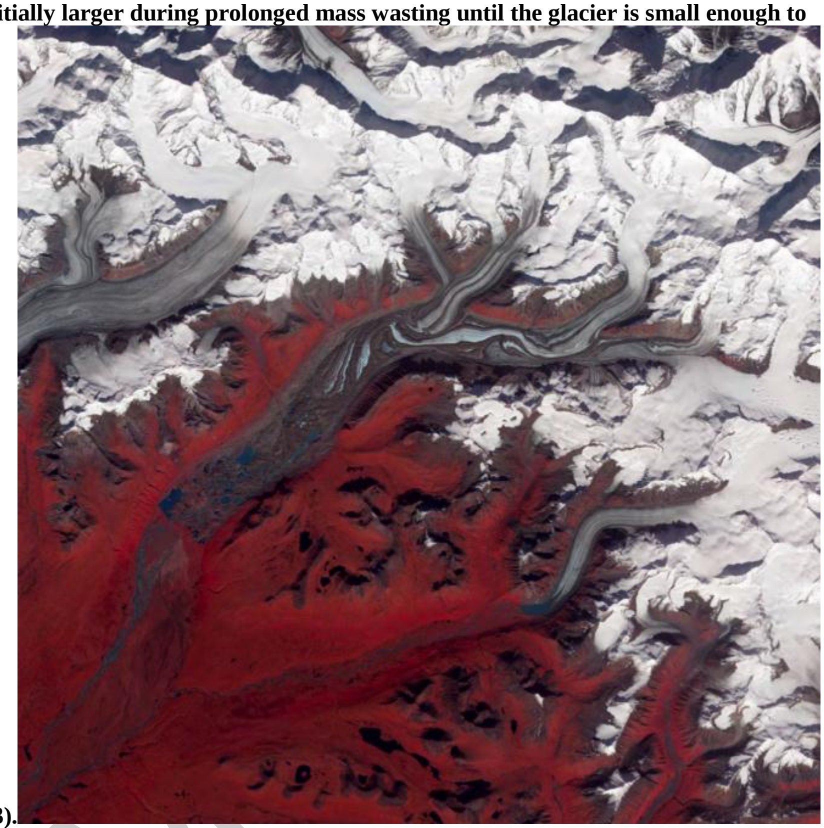


Figure 7.7-3. Susitna Glacier and other unnamed glaciers contributing to upper Susitna River drainage.

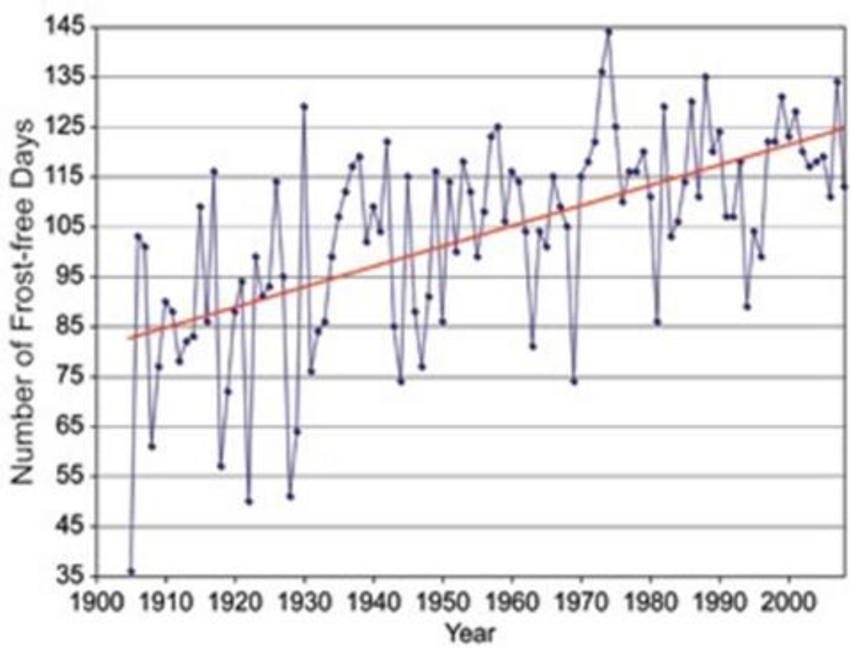


Figure 7.7-4. Fairbanks Frost-Free Season, 1904 to 2008. Over the past 100 years, the length of the frost-free season in Fairbanks, Alaska, has increased by 50 percent. U.S. Global Change Research Program (2009).

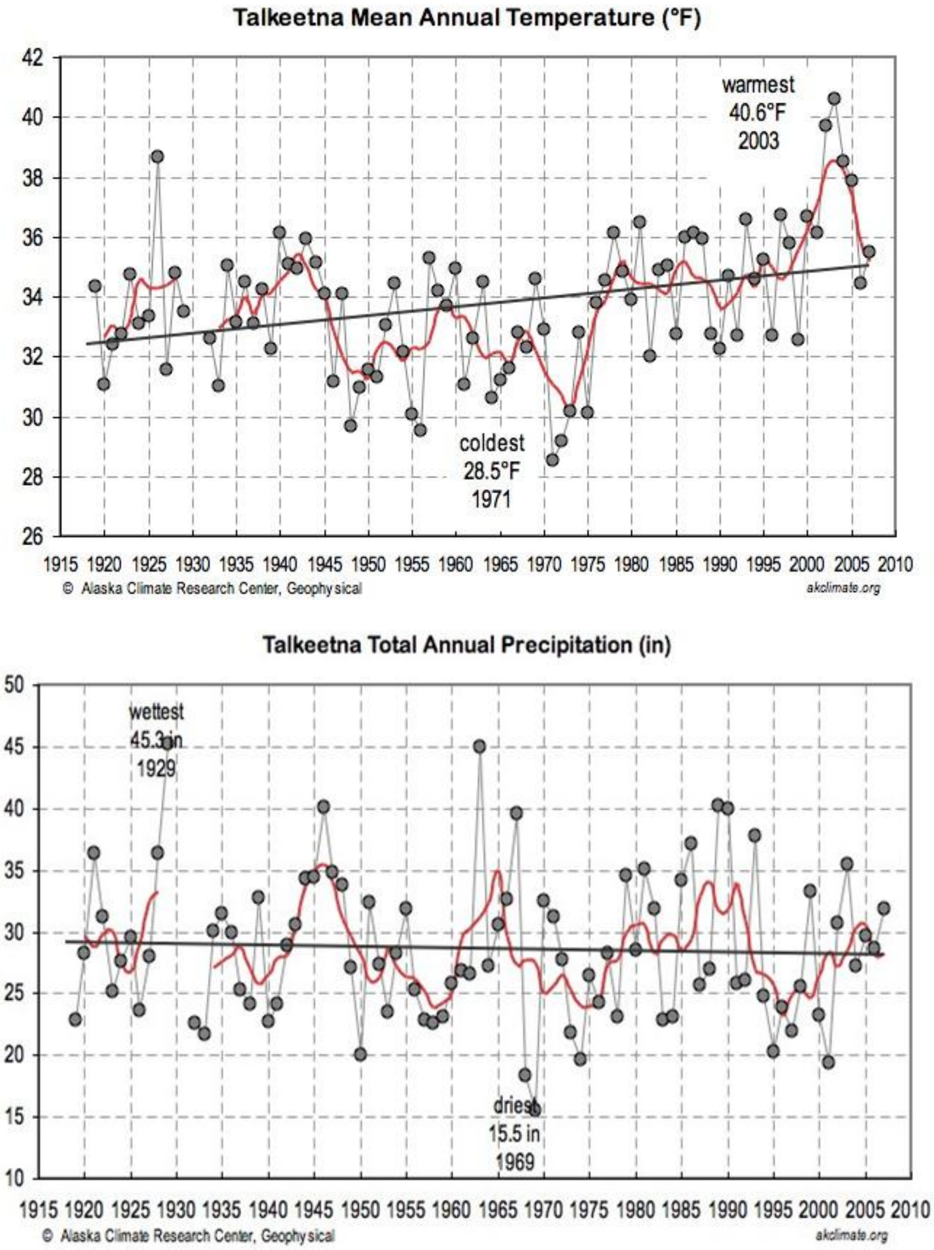


Figure 7.7-5. Mean annual and total annual precipitation at Talkeetna, Alaska 1915-2010 showing the trend line. From Alaska Climate Research Center, http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Talkeetna.html

Glossary of Terms and Acronyms

Glacier and Runoff Changes Study

AEA:	Alaska Energy Authority.
Baseflow:	Baseflow is the portion of streamflow that comes from the sum of deep subsurface flow and delayed shallow subsurface flow. It should not be confused with groundwater flow.
Braided streams	Stream consisting of multiple small, shallow channels that divide and recombine numerous times. Associated with glaciers, the braiding is caused by excess sediment load.
CCCMA:	Canadian Centre for Climate Modeling and Analysis.
Cirques:	A bowl-shaped depression on the side of a mountain at the head of a glacier.
Consecutive wet days:	Number of days in a row with precipitation. Soil can hold precipitation, but as more consecutive days of precipitation occur, runoff increases.
Consecutive dry days:	Number of days in a row without precipitation.
DEM:	Digital elevation model.
Direct solar radiation:	Sunlight not blocked by clouds.
Diurnal:	Any pattern that reoccurs daily.
ECHAM5:	A global climate model developed by the Max Planck Institute for Meteorology.
Evapotranspiration:	The sum of evaporation and plant transpiration to the atmosphere.
EROS:	Earth Resources Observation System.
Firn:	Granular, partially consolidated snow that has passed through one summer melt season but is not yet glacial ice.
Glacier geometry changes:	Changes in the size or shape of a glacier over time.
Glacier mass balance:	The difference between accumulation and ablation of a glacier. Changes in mass balance control a glacier's long term behavior, and cause either advance or retreat.
Glacial mass wasting:	When large amounts of glacial ice rapidly disintegrate and melt.

Glacier outburst:	A sudden release of water from a glacier.
Glaciers retreat:	The upslope migration of the terminus of a glacier.
Glacial surge:	Relatively rapid movement of a glacier downgradient. Frequently accompanied by increase flow of melt water and additional sediment production. These events typically have a sudden onset, extremely high (tens of meters/day) maximum flow rate, and a sudden termination, often with a discharge of stored water.
Heat transfer model:	A model for migration of heat from a warm body to cold.
Interannual streamflow variations:	Changes in stream flow on a year to year basis.
Interflow:	The lateral movement of water in the upper part of the unsaturated zone, or vadose zone, which directly enters a stream channel or other body of water. It is above the regions where baseflow takes place. Interflow is slower than throughflow but faster than groundwater flow.
IPCC:	Intergovernmental Panel on Climate Change.
LAI:	Leaf area index. LAI is the one sided green leaf area per unit ground area in broadleaf canopies, or as the projected needle leaf area per unit ground area in needle canopies.
LP DAAC:	Land Processes Distributed Active Archive Center.
MET:	Meteorological stations.
MIROC:	Model for Interdisciplinary Research on Climate.
MRLC:	Multi-Resolution Land Characteristics.
NARR:	North America Regional Reanalysis.
Permafrost:	Permanently frozen soil.
PRECPTOT:	Total precipitation for a year.
PRISM:	Parameter-elevation Regressions on Independent Slopes Model. PRISM uses point measurements of precipitation, temperature, and other climatic factors to produce continuous, digital grid estimates of monthly, yearly, and event-based climatic parameters.
Simple daily intensity index:	Known also as SDII, it is the annual total precipitation divided by the number of wet days in the year.

SNAP:	Scenarios Network for Alaska and Arctic Planning.
Soil heat transfer:	Heat flow between the soil surface and the deeper layers. Heat transfer varies with soil type, moisture, horizon, etc. The flow of heat is directed from warmer layers to cooler layers. Heat transfer in soil is substantially influenced by the snow cover, vegetation, and terrain.
Soil water storage variations:	Seasonal changes in where and how water is stored in a hydraulic system.
Solar geometry:	Angle of the sun's rays to the surface.
STATSGO:	U.S. General Soil Map Data, a digital general soil association map developed by the National Cooperative Soil Survey and distributed by the Natural Resources Conservation Service of the U.S. Department of Agriculture.
Terminus:	The downgradient end of a glacier.
TM:	Thematic Mapper. One of the Earth observing sensors introduced in the Landsat program.
Trimline:	Soil stripped of vegetation by a glacier.
WaSiM:	Water Balance Simulation Model.
WGEN:	Weather generator model that can be used to generate daily values for precipitation, maximum temperature, minimum temperature, and solar radiation. The model accounts for the persistence of each variable, the dependence among the variables, and the seasonal characteristics of each variable