INTEGRATED HYDROLOGIC EFFECTS OF CLIMATE CHANGE IN THE CHUITNA WATERSHED, ALASKA

Robert Prucha, Ph.D.[1], Jason Leppi[2], Stephanie McAfee, Ph.D.[2] and Wendy Loya, Ph.D.[2]

[1]Integrated Hydro Systems, LLC, P.O. Box 3375, Boulder, CO 80307
[2]The Wilderness Society, 705 Christensen Dr., Anchorage, AK 99501

TABLE OF CONTENTS

This is summary of the Documentation Report: Development and Application of a Fully Integrated Hydrologic Model to Study the Effects of Climate Change on the Chuitna Watershed, Alaska

CITATION

Prucha, R.H., Leppi, J., McAfee, S., Loya, W., 2011. Integrated Hydrologic Effects of Climate Change in the Chuitna Watershed, Alaska.

DISCLAIMER STATEMENT

This report was prepared under a cooperative agreement with the U.S. Fish and Wildlife Service, an agency of the United States Government. Neither the United States Government nor the USFWS make any warranty, express or implied, or assumes any legal liability or responsibility for use, or the results of such use of any information contained herein. The views and opinions of authors expressed in this document do not necessarily state or reflect those of the United States Government or the USFWS.

ABSTRACT

The main objective of this study was to assess the potential impacts of climate change on the Chuitna watershed hydrologic system. To do so, available geology, soils, climate, surface and groundwater and vegetation data were used to develop a 3-dimensional integrated conceptual flow model of the surface and subsurface flow system within the Chuitna watershed. Based on this conceptualization, a fully integrated hydrologic numerical flow model was then developed for the entire Chuitna watershed using the MikeSHE/Mike11 hydrologic code. We used this model to simulate surface and subsurface hydrologic conditions using spatially distributed air temperature, precipitation and reference evapotranspiration at 3-hour intervals for a historical base case period (1980 to 2000). The model was calibrated against spatially distributed snowpack, streamflow and groundwater depth data over multiple years.

To assess the range of future climate change impacts on system hydrology, we used modeled maximum, minimum and median air temperature and precipitation projections from the International Panel on Climate Change (IPCC) for the A1B emission scenario to develop five seasonally-variable climate scenarios for the Chuitna watershed. Results suggest that for even the minimum projected increases in air temperature and precipitation, significant changes in hydrology are projected to occur in the Chuitna watershed for the 2080 to 2100 time period. Much of the projected changes to the system can be attributed to temperature-driven increases in actual evapotranspiration (AET) and changes in the snowpack. Average annual AET is projected to increase by 10% to 46% in lower watersheds and by 14% to 58% in upper watersheds. Across all climate scenarios, average annual snowpack is projected to decrease by 40% to 95% with an average decrease of 62% across all sub-watersheds in the system. By the end of the century, snowpack is projected to accumulate 1-2 weeks later and to melt out 1 to 3 months earlier. Such changes in the quantity, timing and duration of water inputs to the system result in seasonal impacts to soil moisture, groundwater recharge, and both surface runoff and baseflow to streams. As a result, winter streamflow is projected to increase by 43% to 640% and summer streamflow is projected to decrease by 7% to 73% across the Chuitna watershed for all climate scenarios. Projected changes in spring and fall streamflow are more uncertain yet often show significant changes from historical conditions.

INTRODUCTION

The Chuitna (Chuit River) watershed is located about 45 miles west of Anchorage on the northwestern side of Cook Inlet near the Native Village of Tyonek and the community of Beluga (Figure E-1). It is an important ecosystem that supports five species of Pacific salmon, several species of resident fish and a variety of wildlife such as moose, brown and black bears, wolves, beavers, bald eagles and numerous other species of migratory birds. The watershed consists of a large network of nearly 200 miles of streams that drain about 150 square miles into Cook Inlet. Factors affecting streamflow within this ecosystem are complex and strongly influenced by seasonal changes in climate and dynamic interaction with the groundwater flow system. Groundwater flows are critical to salmon habitat because they cool surface waters in warm months and heat them in cold months. Salmon spawn, rear and overwinter in areas with groundwater upwelling or downwelling which provide oxygenated water at temperatures conducive to development and survival of eggs and juvenile fish (Groot and Margolis, 1991). Because of climate change associated impacts in Alaska, such as wetland drying, rapid glacial retreat, increased bark-beetle infestations and fires, concerns are mounting about similar impacts of climate change on these sensitive hydrologic systems that are fundamental to the integrity of the entire watershed ecosystem.

By the end of 2100, global climate models project that both air temperature and precipitation will increase significantly in southcentral Alaska. The magnitudes of projected changes however depend on many factors and vary seasonally. For example, air temperatures during winter periods are projected to increase between 4^{o}C and 10^{o}C, while precipitation may increase from 6% to greater than 50% over present day conditions based on global climate model results for a "moderate" greenhouse emissions scenario (Christensen et al., 2007). Projected changes in climate will translate into hydrologic changes through alteration of rain and snowfall timing and intensity, evapotranspiration and groundwater and surface flows.

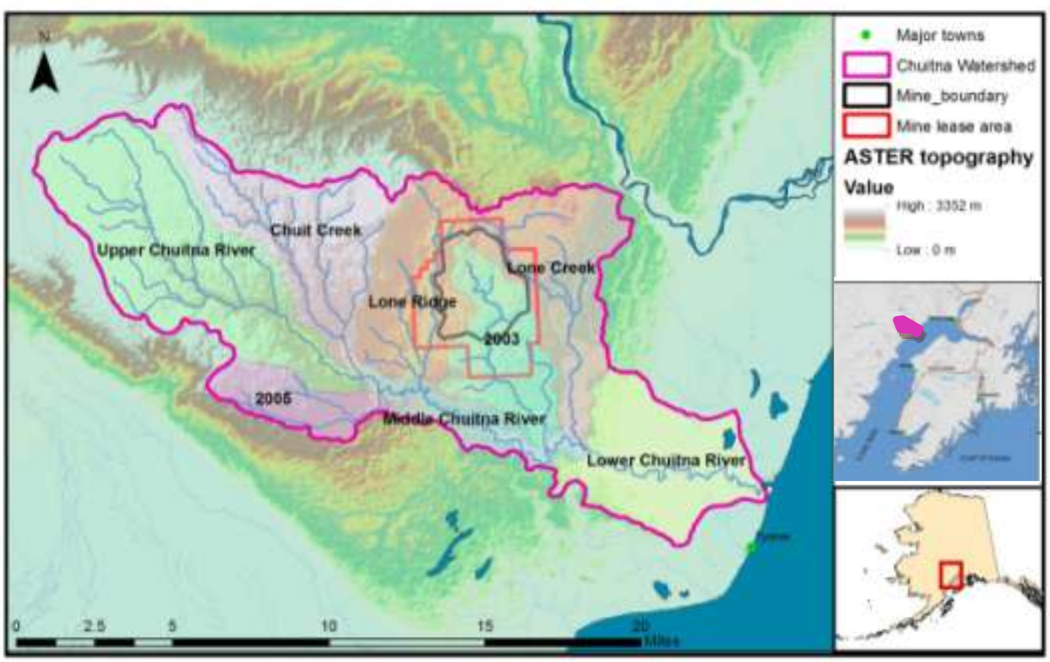


Figure E-1. Chuitna watershed and sub-watersheds in southcentral Alaska

Land-use changes are also expected to change the hydrology of the Chuitna watershed. In the 1960s, oil companies explored the Tyonek Formation of the Kenai Group within the lower watershed area for hydrocarbons. By the mid-1970s coal companies began exploring the extensive coal seams along the middle of the watershed, in the southern part of the Beluga Coal Fields. The PacRim Coal, LLC mining company (PacRim) is currently pursuing a permit to extract approximately 300 million tons of coal from what would be Alaska's largest open-pit coal mine (~5,000 acres). Part of PacRim's proposed plan involves removing about 11 miles of salmon spawning and rearing habitat during a 25-year mining operation. Although the preliminary reclamation plan indicates that the surface of the mined area will be reconfigured similar to pre-mining conditions, concerns have been raised about impacts during mining and post-reclamation on the system hydrology and ecology, especially combined with effects of future climate change. PacRim conducted local baseline characterizations of surface and groundwater hydrology around the proposed mine area, but did not develop an integrated understanding of how the surface and groundwater interact within the watershed. This is important because to fully understand how climate change or mining/mine reclamation impacts the system hydrology, especially downstream of the mine, the integrated hydrologic flow system must be well understood.

The main objective of this study is to assess the potential impacts of climate change on the Chuitna watershed hydrologic system (see Figure E-1) using a physically-based, fully-distributed parameter integrated hydrologic model. This study differs from other climate studies in two ways; it attempts to bracket the range of hydrologic changes given uncertainty in global climate scenarios simulations, and it focuses on detailed changes in hydrologic processes. A secondary objective is to outline a general approach and methodology to investigate climate change in other hydrologic and ecological systems in Alaska. To meet the second objective, a full documentation report was prepared which systematically outlines the steps involved in developing and applying a fully integrated hydrologic model (Prucha et al., 2011).

APPROACH AND METHODS

To simulate future hydrologic conditions in the watershed due to climate change, a mathematical model of the current integrated system (basecase) was constructed. This was done in several steps following industry standard techniques (Refsgaard, 1997, Anderson et al, 1993).

Characterization of the Surface-Subsurface Flow System: Publically available data obtained from various sources were incorporated into a digital database or a Geographical Information System (GIS; ArcGIS 10, ESRI Inc.) to facilitate spatial analysis. Mining consultants have collected extensive physical, chemical and biological data since the early 1980s, but have only made selected data publically available, and generally only in summary tables. Thus, the model developed in this study may differ from modeling results produced by the industry.

Below are some of the key data that were reviewed for this study (Prucha et al.2011) and added to the database/GIS.

- Surface and subsurface hydrologic data
    - detailed stream drainage networks (National Hydrologic Dataset), daily streamflows at a number of gages (Riverside, 2007 and 2009) and snowpack measurements
    - groundwater well construction data and levels (Riverside, 2007 and 2010)
- Climate data including climate station data for the proposed mining area (Riverside, 2009) and a 20-year, 3-hourly time-series of climate variables including precipitation and air temperature from the North American Regional Reanalysis (NARR, Mesinger et al., 2006). NARR data are available from *NOAA/OAR/ESRL PSD in Boulder, Colorado, at* http://www.esrl.noaa.gov/psd/data/narr/*).*

Conceptual flow model: Based on the surface-subsurface geologic and hydrologic characterization, a conceptual flow model of the entire integrated hydrologic flow system was developed that describes flow into, out of and within the watershed (Figure E-2). Specific processes described in the conceptual flow model include snowmelt, overland surface runoff, subsurface flow processes such as infiltration, evapotranspiration, groundwater recharge, groundwater flow and stream flow. This conceptual flow model was then used as the basis for the numerical flow model, which allowed us to determine how climate-induced changes in precipitation and temperature quantitatively alter the hydrology of the Chuitna watershed.

In the present-day system (basecase), precipitation occurs as rainfall during the summer months and snowfall during winter months. The more than 800 meter increase in topographic elevation of the watershed from Cook Inlet (southeast) to Capps Plateau (northwest) results in the doubling of precipitation and a drop in average annual air temperature of more than a 4^{o}C(Figure E-3). As snow melts, it either becomes surface runoff (also known as overland runoff), or infiltrates into the ground. As water infiltrates into the ground, a portion typically flows downward in a partially saturated state through the unsaturated zone as unsaturated flow, until it reaches the groundwater table where it becomes groundwater recharge. In the unsaturated zone, roots extract the remaining soil water as plant transpiration. Water is also lost to the atmosphere from surface soils through soil evaporation. The combined process of soil evaporation and plant

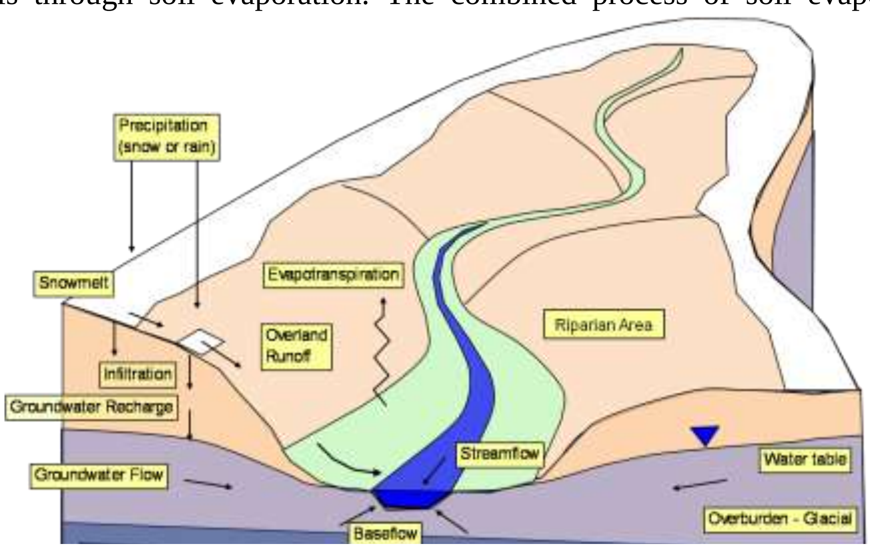


Figure E-2. Conceptual watershed-scale hydrologic flow model showing flow processes and general configuration transpiration is evapotranspiration. In the model, this term also includes the loss of water from open water bodies, snow sublimation and evaporation from the plant canopy. All precipitation in a natural system is lost through either evapotranspiration to the atmosphere, or via streamflow or groundwater discharge out of the watershed.

As groundwater is recharged, groundwater water levels rise and cause the water table gradient to increase towards streams. This increases groundwater discharges into streams and is termed baseflow. The combination of baseflow and overland flow produces streamflow.

The majority of streams deeply incise permeable Quaternary fluvio-glacial deposits that occur throughout the Chuitna watershed, which is typical of a streamflow system dominated by baseflow (Figure E-3). Within the proposed mine area, these deposits overlie a thick bedrock sequence, thousands of meters thick, comprised of alternating, lower permeability, laterally extensive coal seams and alluvial-plain deposits (interburden deposits) that vary from low permeability claystone/siltstone (overbank-floodplains) to more permeable sandstone conglomerate (former braided streams). Groundwater flow within the bedrock hydrostratigraphic units is complicated by substantial vertical (tens to hundreds of meters) and lateral offsets (5 to 26 kilometers) along steep-angle faults that traverse across the watershed; two of these faults extend hundreds of kilometers and are associated with the larger tectonic setting of southcentral Alaska. Groundwater within the bedrock units becomes increasingly confined with depth due to the relatively low permeability of interburden deposits. Although some groundwater drains from the bedrock into streams near the proposed mine, where the overburden has been removed by erosion, the calibrated flow model shows that streamflow is dominated by baseflow discharge from the shallow unconfined aquifer in the Quaternary fluvio-glacial deposits. The faulting and bedrock flow and discharge appear to have limited effects on the current undisturbed coupled shallow groundwater aquifer and streamflow system. However, these features will likely have a much more pronounced effect on the hydrologic system during and after excavation in the proposed mining area.

Overland flow is generated in hydrologic systems in two primary ways. When precipitation intensities exceed the soil infiltration capacity, water ponds at the surface and then flows down the slope as Horton flow, or Infiltration-Excess. Alternatively, when the ground surface saturates from below, typically through rising shallow groundwater, surface runoff can also occur as Dunne flow, or Saturation-Excess, typically near streams (green area on Figure E-2). Over the late-spring/early-summer season, snowmelt provides a constant source of saturation excess near streams. Within the Chuitna watershed, our model simulations show that overland flow to streams occurs through the Saturation-Excess rather than Horton flow because precipitation rates are low relative to calibrated soil hydraulic conductivity values. For example, a 100-year, 1-hour duration maximum storm intensity for the Anchorage area is 0.55 in/hr (USKH, 2006) which translates to 3.9E-06 m/s and is less than the lowest soil hydraulic conductivity value (4.0E-06 m/s). All rainfall events simulated have a much lower intensity than the 100-year storm, which effectively prevents Hortonian flows from being generated, and promotes saturation excess runoff.

The combination of vegetation and soil hydraulic properties within the watershed promotes infiltration rather than surface runoff in non-riparian (upland) areas. Vegetation coverage is high

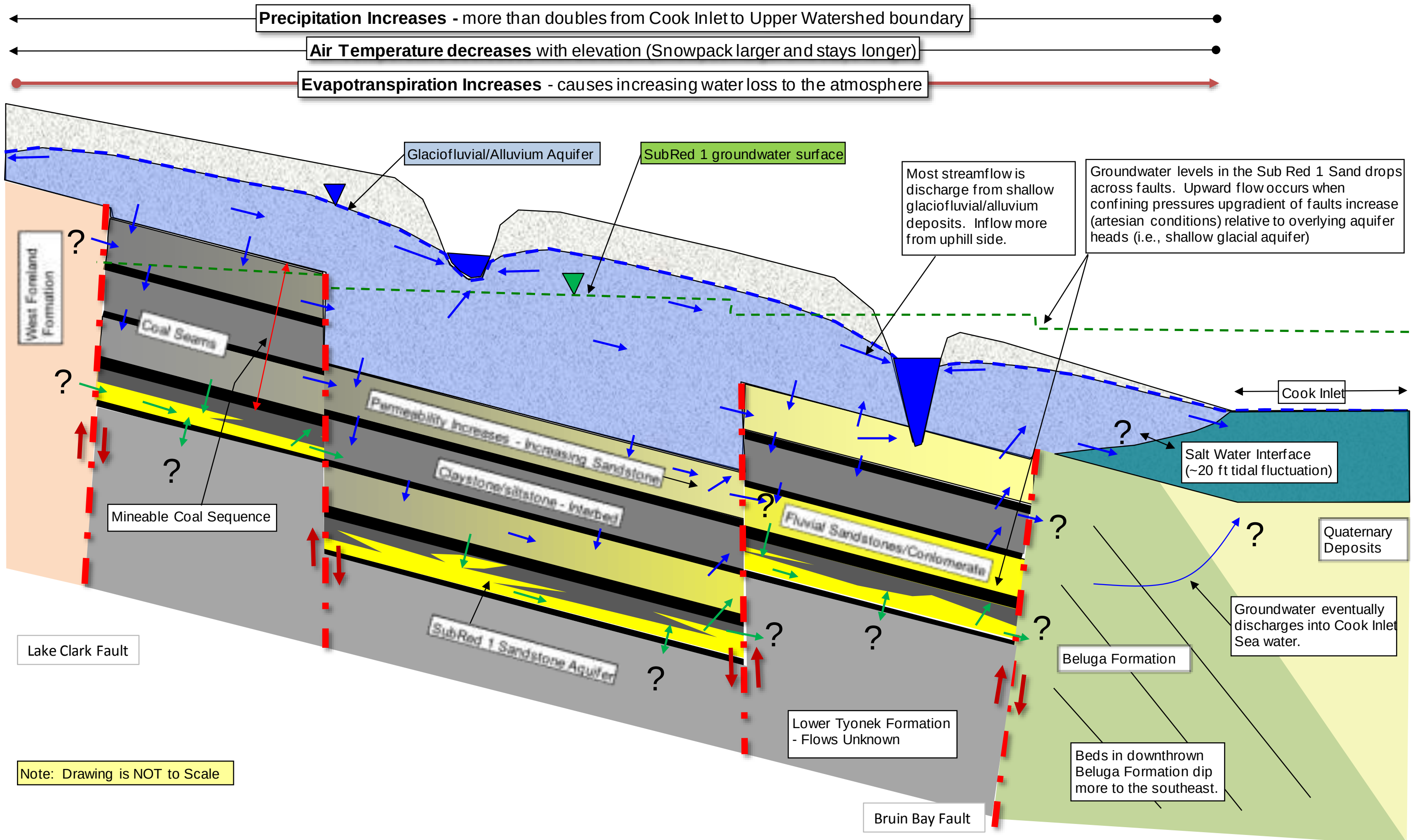


Figure E-3. Conceptual flow model for the Chuitna watershed

throughout the watershed; more than 50% is short shrub/scrub (upper drainages) and nearly 40% is deciduous (lower drainages), and 6% are wetlands. More than 700 ponds and lakes cover about 2% of the entire Chuitna watershed and represent local areas where overland runoff accumulates and possibly interacts with groundwater, though this has not been confirmed by field testing. High amounts of organic matter (i.e., peat) in surface soil also promote infiltration of snowmelt or rainfall due to their high soil water retention characteristics.

Numerical Integrated Flow Model: We used the physically-based, distributed parameter, integrated hydrologic software code MikeSHE/Mike11 (Danish Hydraulic Institute) to develop the hydrologic flow model of the Chuitna watershed. This code is used extensively worldwide in a broad range of water resource applications that range from river basin and wetland management/planning to ecological impacts assessment. It has also been used to study integrated hydrologic systems affected by land use modifications and climate change. It was selected for this study because it simulates all of the key hydrologic processes in the watershed described in the conceptual model, including:

- snowmelt using a modified degree-day snowmelt model,
- 1-dimensional unsaturated zone flow using full Richard's equation (Graham and Butts, 2005),
- actual evapotranspiration (AET) calculated as a function of soil properties, plant community type and rooting depths, and a reference evapotranspiration (RET) calculated based on external climate variables including net short- and long-wave solar radiation, wind speed, vapor pressure, precipitation and air temperatures (Kristensen and Jensen, 1975). The RET is calculated externally using the FAO56 Penman-Monteith method (Allen, 2000).
- fully hydrodynamic streamflow using St. Venant flow equations that allow for wave propagation and backwater effects,
- fully 3-dimensional groundwater flow, and
- two-dimensional diffusive-wave overland flow to streams.

MODEL CALIBRATION

We calibrated this model against several years of available snow depths, streamflow measurements and groundwater levels at a 3-hour time step using NARR derived precipitation, air temperature and reference evapotranspiration (Messinger et al., 2006) that vary spatially with elevation. A detailed description of model calibration results is presented in the Documentation Report. Here we present calibration results only for streamflow.

The model reproduces observed snow depths at different elevations throughout the year, average groundwater levels, and captures key characteristics of streamflow at gauges located within different sub-watersheds, including baseflow, streamflow ascension/recession curves, and peak flows and volumes. Simulated streamflow characteristics at the different gages reproduce those in the observed hydrographs reasonably well (Figure E-4). Although higher correlation coefficients are typically required for watersheds that are well gauged, an average correlation of ~55% was achieved across the Chuitna watershed. The range is 6 to 76% or 45% to 76% excluding gage 180 along Stream 2003. It is unclear why the correlation is poor at gage 180, but simulated flows are lower than observed (peaks and spring runoff). This may be due to errors in streamflow measurements at gage 180, under specifying precipitation, over estimating evapotranspiration, incomplete stream network data or using a surface topography that does not capture localized lateral surface drainage contributions into the mainstem 2003 stream. Despite the lower levels, the model is able to reproduce the two key runoff events (spring snowmelt and fall rains), and is also able to simulate the slow recession curves that appear to be generated by baseflow, rather than surface runoff (weeks to months long). Baseflow is simulated well in all of the gages (see Documentation Report), which is largely dictated by the slope of hillslope topography and lateral saturated hydraulic conductivity in the glacial deposits. Simulated baseflow decreases with elevation, similar to the observed flows.

The model was not calibrated to simulate highly accurate system state variables (e.g. stream depth) at specific points in the Chuitna because this depends on the accuracy of local stream cross-sections, which were unavailable for the watershed.

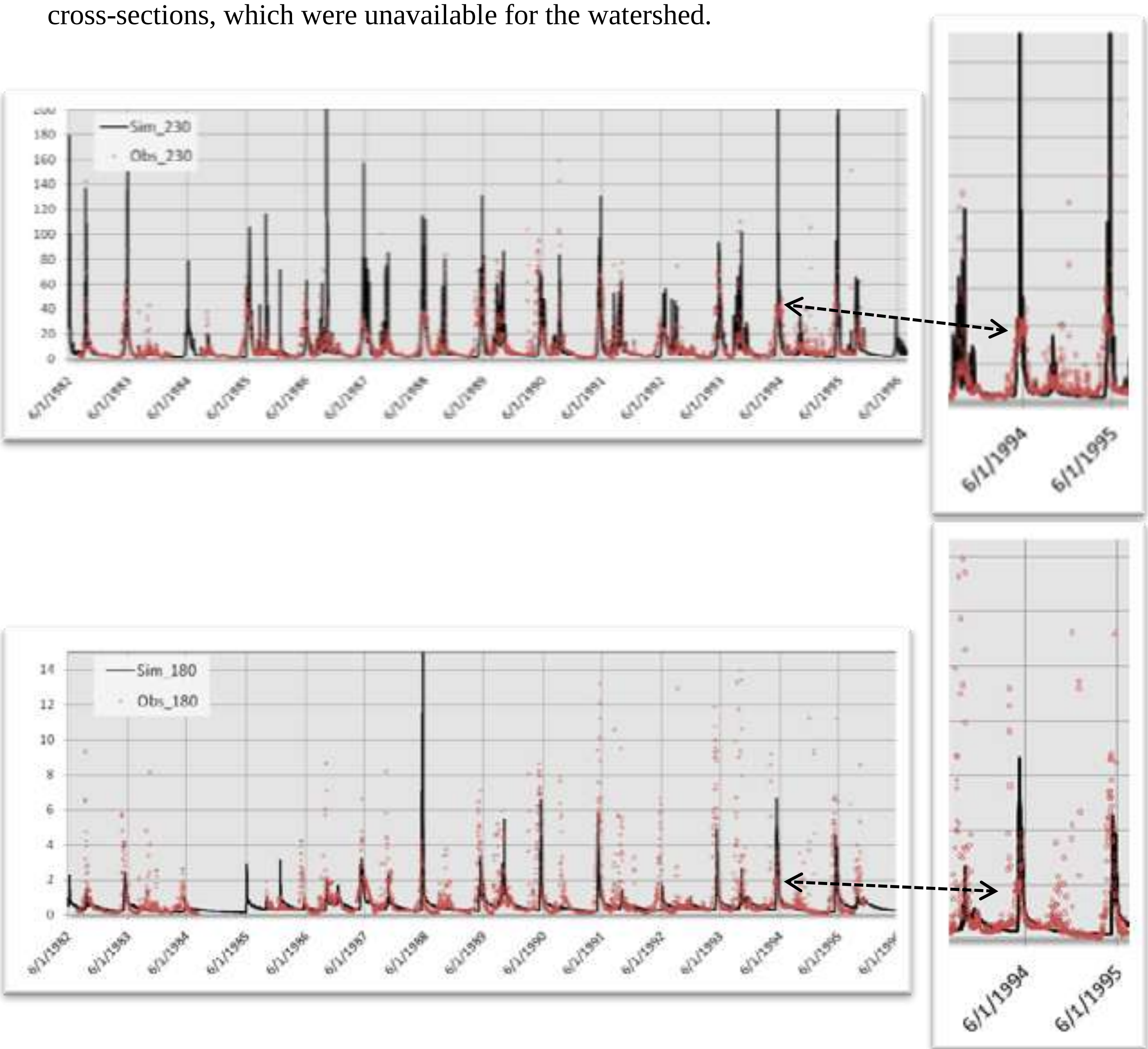


Figure E-4. Daily simulated (black lines) and observed (red dots) streamflow at gage 230 (upper panel) and gage 180 (lower panel) in the Chuitna watershed. Enlargements highlight timing and duration of spring runoff events.

CLIMATE SCENARIOS

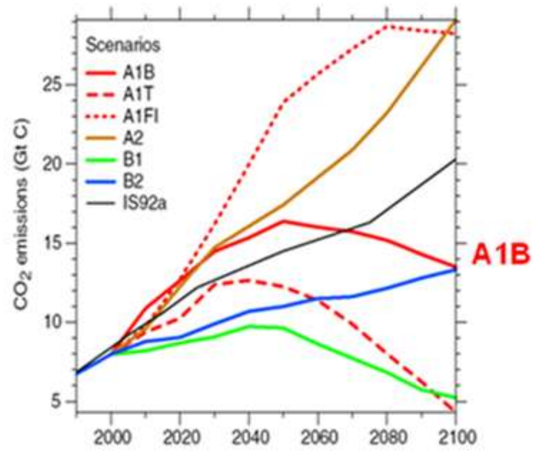


Figure E-5. Climate projections used in this study were based on the A1B emissions scenario. This "moderate" scenario is based on a decrease in emissions mid-century as fewer greenhouse gas emitting technologies are implemented.

We developed five future climate datasets reflecting projected changes in precipitation and air temperature projected for the late 21st century. Climate change projections for Alaska were extracted from a suite of 21 General Circulation Models (GCMs) run using the A1B emissions scenario (Figure E-5) from the Intergovernmental Panel on Climate Change's Fourth Assessment Report (Table 11.1 in Christensen et al, 2007). To evaluate how Chuitna watershed hydrology responds to the broad range of future climate changes predicted by the GCMs, we chose combinations of the maximum and minimum predicted changes in air temperature (Tmax, Tmin) and precipitation (Pmax, Pmin), as well as the median changes in both (T50/P50; Figure E-6).

Though changes in air temperature and precipitation used for each hydrologic model scenario are not simulated by the same GCM model, the extent of hydrologic impacts caused by the range of GCM predictions can be assessed as well as the independent effects of temperature and precipitation changes. Further, the changes projected for the late 21st century in our T50/P50 scenario are the same as those predicted for mid-century under the Tmax/Pmax scenario.

Future climate data series for the Chuitna watershed were prepared by applying seasonally specific changes in temperature and percent changes in precipitation for each of the five scenarios outlined above to the baseline (1980 to 2000) 3-hour time-step NARR data. Often referred to as the "delta method" (Hamlet et al., 2010), this method is simple to implement and preserves the sequence of weather and natural climate variability in the baseline data. The timing and magnitude of extreme climatic events (e.g. intense storms) may change in the future; however, such projections do not currently exist for this region and would be highly uncertain if they did.

Climate change scenarios were seasonally-specific (Figure E-6), with the largest temperature changes occurring in the winter (December through February) and the smallest in the autumn (September through November). Winter is also projected to experience the largest relative changes in precipitation. Evapotranspiration (ET) is another critical external climate variable that strongly influences watershed response to climate change because it is a function of both temperature and precipitation. Increased future air temperature affects hydrology through increased snowmelt resulting from convective air heating (sensible heat), warmer temperatures resulting in rain instead of snow, and increased water loss via ET.

TmaxPmin	Δ T (˚C)	Δ P (%)
Annual	**7**	**3**
Winter (DJF)	10.5	6
Spring (MAM)	7.3	-2
Summer (JJA)	5.4	1
Fall (SON)	4.9	6

TmaxPmax	Δ T (˚C)	Δ P (%)
Annual	**7**	**40**
Winter (DJF)	10.5	53
Spring (MAM)	7.3	36
Summer (JJA)	5.4	29
Fall (SON)	4.9	34

T50P50	Δ T (˚C)	Δ P (%)
Annual	**4**	**20**
Winter (DJF)	6	27
Spring (MAM)	3.3	16
Summer (JJA)	2.3	13
Fall (SON)	4.3	18

TminPmin	Δ T (˚C)	Δ P (%)
Annual	**2.5**	**3**
Winter (DJF)	4.2	6
Spring (MAM)	2.2	-2
Summer (JJA)	1.2	1
Fall (SON)	2.2	6

TminPmax	Δ T (˚C)	Δ P (%)
Annual	**2.5**	**40**
Winter (DJF)	4.2	53
Spring (MAM)	2.2	36
Summer (JJA)	1.2	29
Fall (SON)	2.2	34

Projected Temperature Increase

Projected Precipitation Increase

Figure E-6. Five climate change scenarios for Alaska at the end of the century (2080-2099) derived from 21 GCMs for the moderate A1B emissions scenario (Christensen et al, 2007). Projected changes in Temperature (T) and Precipitation (P) were used to adjust historical baseline climate data (NARR; Messinger et al. 2006) to create future climatologies

RESULTS OF MODEL CLIMATE CHANGE SIMULATIONS

Change in Snowpack

Baseline snowpack in the Chuitna watershed is greatest in the upper reaches and lowest near the coast (Figure E-7). Snow depths increase from mid-October, peak in early April (Lower Chuitna) to mid-May (Upper Chuitna) and melt-out by mid-May (Lower Chuitna) to late June (Upper Chuitna). In the upper Chuitna watershed, the maximum snow water equivalent (SWE) approaches 1000 mm, while in the lower watershed it is less than 200 mm. The spatial variation is primarily due to orographic effects on temperature and precipitation.

In all future scenarios, average annual snowpack decreases and snowmelt increases (Figure E-7), despite minor (Pmin) to significant (Pmax) projected changes in precipitation. For scenarios with the lowest increase in temperature (Tmin), the projected decrease in average annual snowpack for the entire Chuitna watershed is 19% to 46%, relative to the basecase. For the Tmin scenarios, inter-annual variability of winter snowpack increases. In some years the snowpack is projected to exceed historic baseline conditions and, in other years, the snowpack is greatly diminished as it may melt out intermittently throughout the winter (see Documentation Report). Under scenarios with the greatest temperature increase (Tmax), the model projects the virtual elimination (86% to 90%) of the historically continuous winter snowpack (Figure E-7). In the Tmax scenarios, snow accumulates in a series of smaller snowpacks that melt-out every few weeks. The decrease in snowpack relative to the historical baseline is greatest at lower elevations where annual snowfall is lower and air temperatures are higher, indicating that melting thresholds are reached sooner at lower elevations (Figure E-7). The difference in change in snowpack relative to the historical basecase is projected to be least for the Tmin/Pmax scenario (-40% Upper Chuitna; -85% Lower Chuitna) and greatest for the Tmax/Pmin scenario ≥-95%).

Another significant change projected by our model is that the start and end of the snowpack also change due to the climate changes (Figure E-7). For all scenarios, the start of the snowpack is projected to be delayed in most years between 1 to 2 weeks. Break-up, or the melting of the snowpack, begins on average 1 to 3 months earlier than the basecase (Figure E-7), depending on the elevation and scenario. For example, spring snowpack is projected to be reduced by approximately 100 days for Tmax scenarios, approximately 60 days for the T50P50 scenario, and approximately 40 days for Tmin scenarios. Under all scenarios, there are likely to be an increased number of rain-on-snow events as well as intermittent melt-out events during winter.

Change in soil moisture

The soil moisture content at any moment in time at any point within the model is quite variable because it depends on a number of spatially-variable factors such as vegetation, soils, groundwater depths, snowmelt, surface topography and climate. The historical basecase model results show that soil moisture content varies most in surface soils (Figure E-8) because of the direct net effect of precipitation, snowmelt, soil evaporation and plant transpiration. Variation in soil moisture decreases rapidly with depth as the effects of these surface processes diminish. Depending on the location, surface soils saturate during spring snowmelt (June for the Upper Chuitna area "A" and May for the Mine area "B"), de-saturate during the summer (early-August

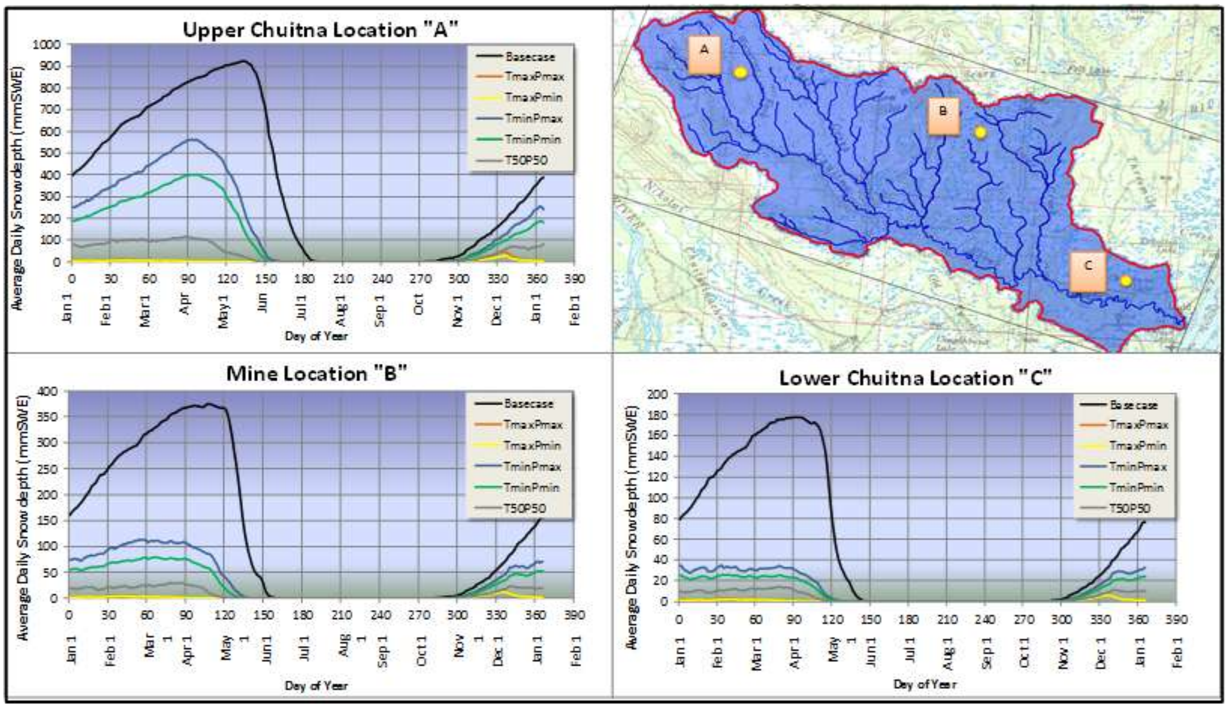


Figure E-7. Simulated average daily snow depth (mm SWE) for three locations in the Chuitna watershed. At each location, future snow depth was modeled under five climate change scenarios. Elevations are A) 512 m, B) 216 m, and C) 15 m.

for Upper Chuitna area "A" and late June for Mine area "B") and then re-saturate during fall rains by September.

Future climate change is projected to affect surface soil moisture contents primarily through the dramatic shift in snowmelt (Figure E-7). Surface soil moisture contents for all future scenarios are higher than the historical basecase for winter months (from November through about the end of March; Figure E-8) due to increased snowmelt caused by increased winter temperatures. However, from March to mid-summer, moisture contents are projected to decrease compared to the historical basecase. The timing of minimum summer soil moisture content shifts from late-June at the mid-watershed mine location ("B"), to about mid- to early-June (2 to 4 weeks earlier) and from late-July in Upper Chuitna ("A") to late- to early-June (1 to 2 months).
The deviation of soil moisture content from baseline conditions is also greater in the Upper Chuitna area, which suggests upper watershed soils are more sensitive to climate changes. One reason for this may be because lower soil permeability in the upper watersheds causes slower infiltration of precipitation, which increases loss of soil moisture via evapotranspiration. Soil moisture content decreases most for the TmaxPmin case because the increase in precipitation is insufficient to offset the increased "drying" effect due to increased AET caused by increased temperatures. Soil moisture content decreases the least in the TminPmax case because the increase in precipitation is highest relative to the increase in temperature. The changes in shallow soil moisture contents may cause increased stress on vegetation, which may in turn exacerbate current problems like wetland drying, insect outbreaks, or forest fires.

Projected effects of climate change on soil moisture content decreases with depth (see Documentation Report). This is because the effects of plant transpiration and soil evaporation at the ground surface decrease with depth. At one meter depth, simulated soil moisture during summer decreases approximately 10% in the upper Chuitna watershed "A" and increase by approximately 5% in the Mine Area "B" of the Chuitna watershed.

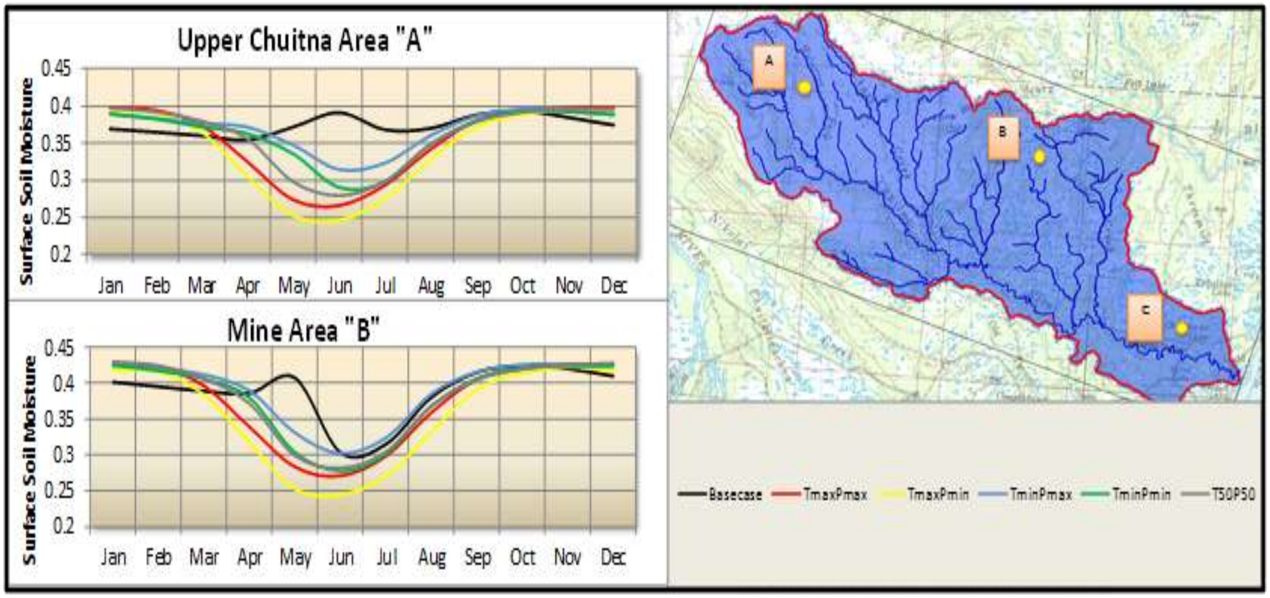
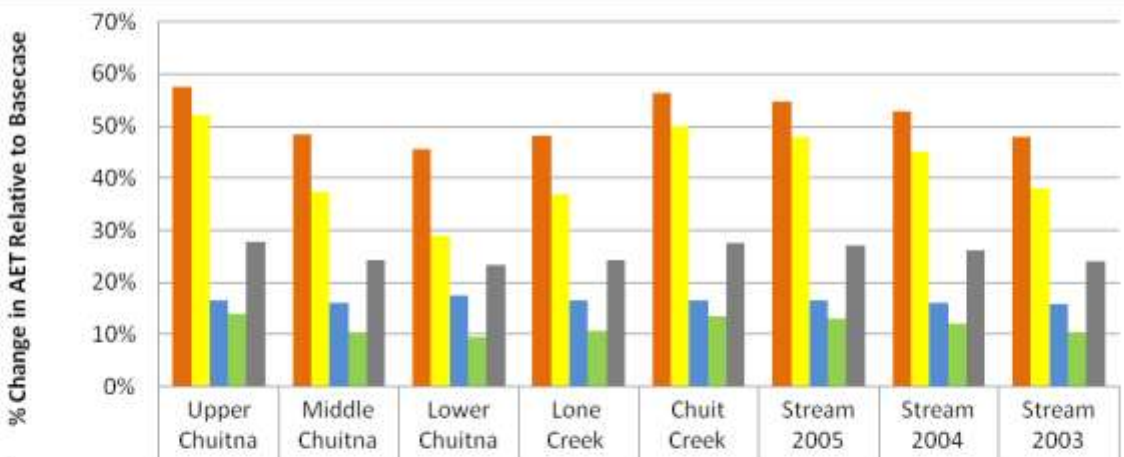


Figure E-8. Simulated average monthly surface soil moisture for two locations in the Chuitna watershed for a historical basecase and five climate change scenarios. Elevations are A) 512 m and B) 216 m.

Change in Actual Evapotranspiration (AET)

Simulated baseline AET in the Chuitna watershed decreases modestly (~10%) from the Lower Chuitna (~25 in yr^{-1}) to the Upper Chuitna (~22 in yr^{-1}; see Documentation report). Seasonal AET patterns are similar to changes in air temperature, with lowest values occurring during the winter (< 1 mm day^{-1}) and highest values during June (>8 mm day^{-1}). Simulations of historical conditions indicate that AET as a percent of annual precipitation decreases with increasing elevation, from 76% in the Lower Chuitna to 31% in the Upper Chuitna (see Documentation report). This is because temperatures are greater and less precipitation falls at lower elevations. The combined plant transpiration and soil evaporation range from 36% to 63% of total AET across the watershed, with only ~35% of this combined amount due to soil evaporation, suggesting plant transpiration is more efficient at removing water from the system than soil evaporation. In addition, sublimation of snow and evaporation of snowmelt water are important components of AET, especially at higher elevations.

Model projections show that AET is driven primarily by temperature, and is therefore likely to increase most for the Tmax scenarios (29% to 58%) and lowest for the Tmin scenarios (10% to 17%; Figure E-9), with highest values in the upper sub-watersheds. This is due to decreased soil infiltration rates and higher precipitation relative to lower areas, which increases evapotranspiration from surface soils. On a seasonal basis, AET is projected to increase by a factor of ~50 during winter (December) compared to negligible change in the spring (TmaxPmax scenario; data not shown). This dramatic increase in AET during former low winter periods is attributed to the significant increase in water available from snowmelt coupled with proportionally warmer winter temperatures.



	Upper Chuitna	Middle Chuitna	Lower Chuitna	Lone Creek	Chuit Creek	Stream 2005	Stream 2004	Stream 2003
TmaxPmax	58%	48%	46%	48%	56%	55%	53%	48%
TmaxPmin	52%	37%	29%	37%	50%	48%	45%	38%
TminPmax	16%	16%	17%	16%	16%	16%	16%	16%
TminPmin	14%	10%	10%	11%	13%	13%	12%	10%
T50P50	28%	24%	23%	24%	28%	27%	26%	24%

Figure E-9. Projected percent change in mean annual actual evapotranspiration (AET) for five climate change scenarios relative to the historical baseline by sub-watershed.

Groundwater Recharge and Baseflow to Streams

The hydrologic model calculates either positive or negative groundwater recharge; positive values indicate a net gain in groundwater storage, while negative values indicate a net loss in storage. Simulated basecase average monthly groundwater recharge rates in the Upper Chuitna are positive during May to June and August to September (black outline in upper plot; Figure E-10) in response to infiltration of snowmelt and fall rains, respectively. Simulated recharge is highest in May (more than 550 mm/month), indicating that the historical snowmelt pattern produces a significant spike in recharge to the groundwater system. In all other months, simulated groundwater recharge rates are negative, indicating a decrease in groundwater storage.

In contrast, most scenario climate changes increase the average monthly groundwater recharge (lower plot; Figure E-10). The early seasonal loss of snowpack (Figure E-7) and decrease in soil moisture (Figure E-8) cause a reduction in average monthly recharge during the months of May and June for all scenarios (lower plot; Figure E-10), though recharge in only the Tmin cases remains positive (May). All scenarios in December and January show increased net recharge and positive values, compared to former negative values, which reflected the lack of infiltration during the historical continuous winter snowpack. Nearly all scenarios show an increase in recharge in August through October, indicating that even with increased air temperatures during this period, groundwater recharge increases due to the increased precipitation during this period. Part of this can be explained by the non-linear behavior of soil hydraulic conductivity and soil moisture. Even small increases in soil moisture can cause significant increases in unsaturated zone infiltration and groundwater recharge.

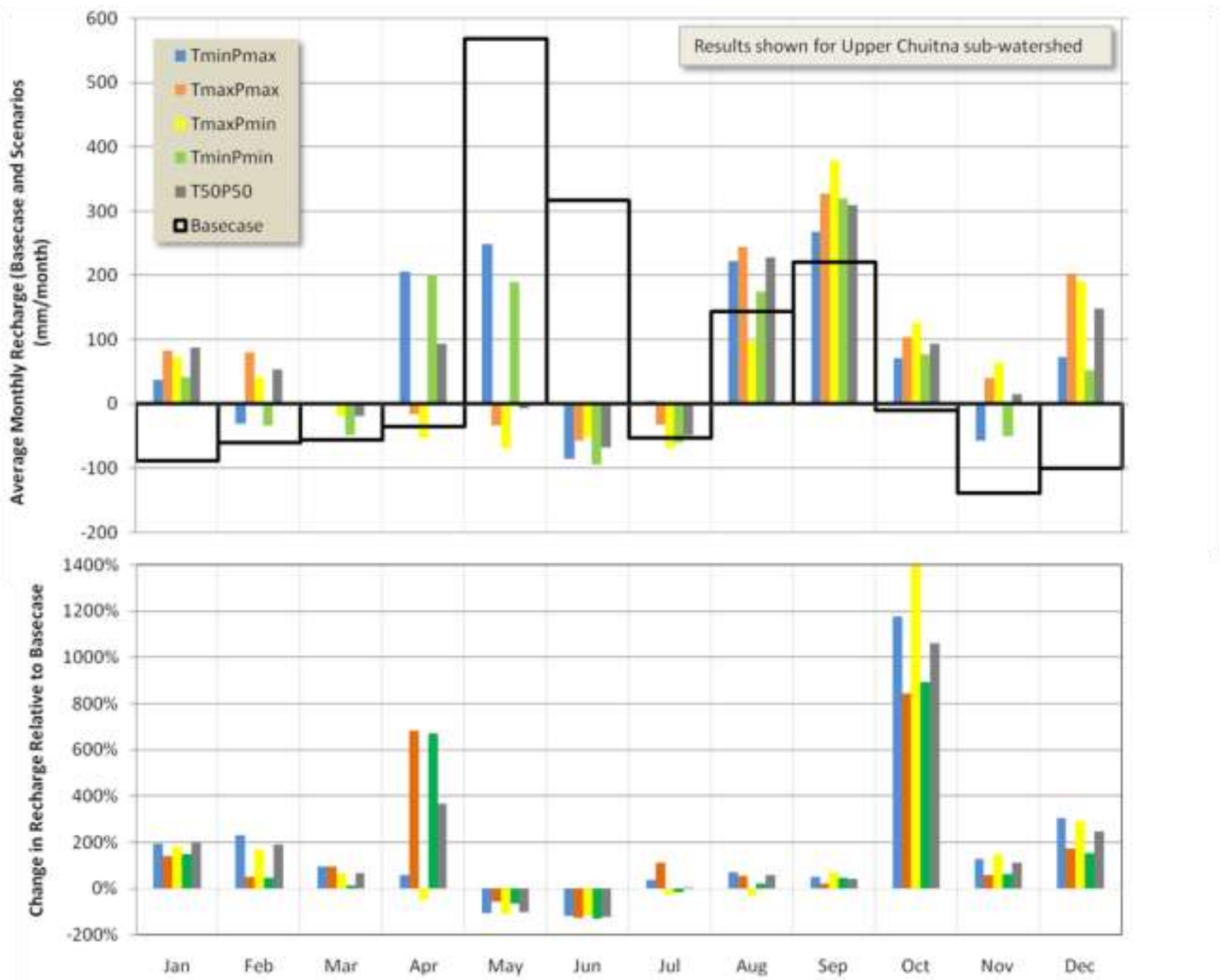
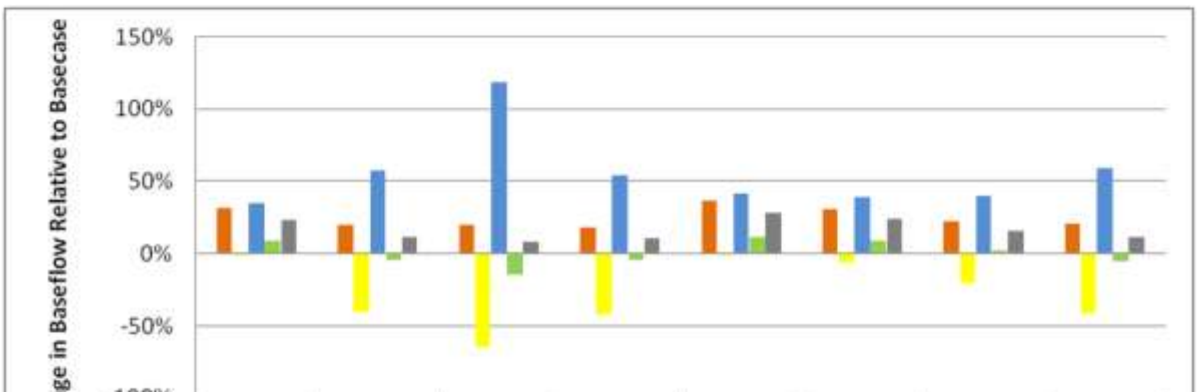


Figure E-10. **Simulated average monthly basecase and scenario recharge (mm/month) for the upper Chuitna sub-watershed (upper plot) and net change in average monthly recharge relative to the basecase (lower plot).**

Basecase simulations indicate baseflow contributes from 50% to over 90% of streamflow (see Documentation report), with higher percentages in lower sub-watersheds. In upper watershed areas, increased topographic gradients lead to higher percent overland flow contributions to streamflow than from baseflows. The model also suggests that baseflow is higher on uphill sides of watersheds because these areas have higher groundwater gradients towards the stream.

On an annual basis, projected changes in groundwater baseflow into streams are similar to the changes in groundwater recharge (Figure E-11). Once infiltrating water enters the groundwater system, little water is actually lost via evapotranspiration to the atmosphere because depths are generally less than the ~ 1 meter root depth. As a result, effects of climate change on baseflow are similar to those on recharge. On an annual basis, projected baseflows increase in all sub-watersheds for the Pmax and T50P50 scenarios (8% to 119%). For Pmin cases, baseflows decrease in lower watersheds (to -65%) and increase in upper watersheds (to 12%). This is because recharge and baseflow are more sensitive to AET in lower watersheds. For example, in the basecase 76% of annual precipitation is lost to AET in the Lower Chuitna watershed compared to only 31% in Upper Chuitna.

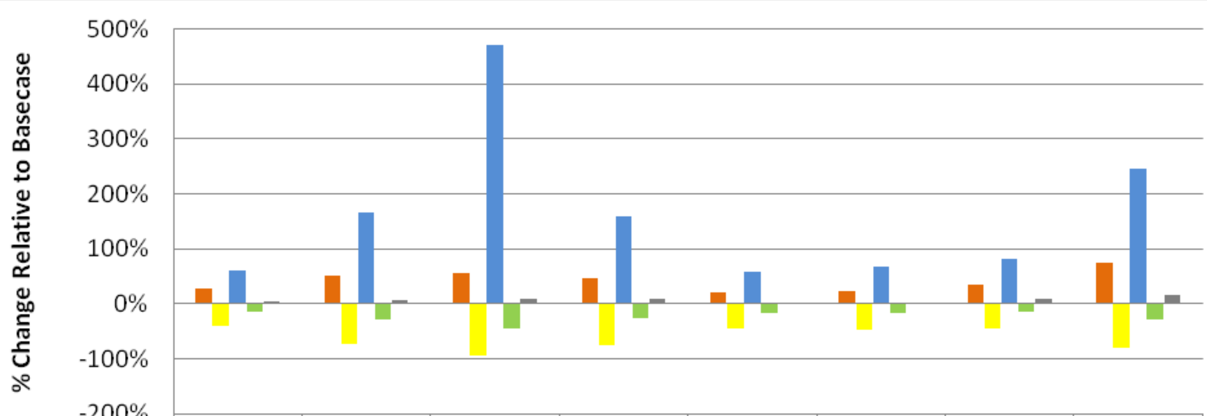


	Upper Chuitna	Middle Chuitna	Lower Chuitna	Lone Creek	Chuit Creek	Stream 2005	Stream 2004	Stream 2003
TmaxPmax	32%	20%	20%	18%	37%	31%	22%	21%
TmaxPmin	-1%	-40%	-65%	-42%	0%	-6%	-20%	-42%
TminPmax	35%	57%	119%	54%	42%	39%	40%	59%
TminPmin	9%	-4%	-15%	-4%	12%	9%	2%	-5%
T50P50	23%	11%	8%	10%	28%	24%	16%	11%

Figure E-11. Average annual change in baseflow into streams relative to the basecase by sub-watershed.

Change in Overland Flow

In the basecase model simulations, overland flow to streams is generated from cells adjacent to the streams. On a monthly basis, flow has historically been highest during spring melt and fall runoff and lower during other periods (see Documentation Report). Results also show that 10 to 100 times the amount of overland flow is generated in the upper sub-watersheds like the Upper Chuitna and Chuit Creek sub-watersheds than in lower sub-watersheds such as the Lower Chuitna or Stream 2003 (see Documentation Report). This is due to a combination of lower permeability of soils in the upper half of the Chuitna watershed, increased precipitation and steeper topography. Accordingly, the percent of annual precipitation as overland flow to streams ranges from an estimated 1% (lower elevations) to 31% (upper elevations). Simulated average annual overland flow to streams as a percent of total streamflow ranges from 6% (Stream 2003) to 50% (Chuit Creek). In reality, the simulated overland flow percentage in Stream 2003 is likely higher due to a bias in calibrated streamflow attributed to limited accuracy of the topography which prevented explicitly simulating smaller surface water drainages apparent in higher resolution hard-copy topography in mining reports. Increasing grid resolution to less than 200m may also increase the overland flow percentages somewhat as near stream overland areas are better simulated. Despite this, results from the hydrologic model suggest the majority of streamflow are derived from baseflow (groundwater) rather than overland flow (precipitation runoff).



	Upper Chuitna	Middle Chuitna	Lower Chuitna	Lone Creek	Chuit Creek	Stream 2005	Stream 2004	Stream 2003
TmaxPmax	27%	52%	57%	46%	20%	24%	34%	74%
TmaxPmin	-39%	-72%	-94%	-75%	-44%	-48%	-46%	-80%
TminPmax	61%	167%	471%	158%	57%	67%	81%	244%
TminPmin	-14%	-29%	-44%	-26%	-17%	-17%	-14%	-29%
T50P50	5%	8%	9%	10%	1%	2%	10%	17%

Figure E-12. Projected percent change in overland flow to streams relative to historical basecase for five climate change scenarios by sub-watershed.

Climate induced changes in overland flow are more sensitive to the changes in precipitation than temperature because they happen relatively quickly compared to subsurface flow processes. Overland flow is projected to increase for Pmax scenarios in all sub-watersheds, and decreases for Pmin scenarios (Figure E-12). The greatest projected increase is for the TminPmax scenario (471%). This indicates that when enough precipitation is added to the system (i.e., Pmax), both overland flow and baseflow increase, and when too little is added (Pmin), even the smaller increases in temperature cause decreases in both of these. The T50P50 scenario projects overland flow most similar to current conditions.

The relative change in overland flow is amplified in lower sub-watersheds because flows are low and therefore more sensitive to changes in AET compared to flows in upper areas (Figure E-12). As a result, even small changes in climate can lead to larger relative impacts on overland flow compared to higher elevations. On a monthly basis, overland flows are projected to increase during fall and winter months (November through April), but decline from May through July due to the earlier melt-out (see Documentation report).

Changes in Streamflow

Current seasonal streamflow characteristics of the Chuitna watershed are similar to other non-glacial Alaska watersheds. Generally, flows peak during late-spring/early-summer snowmelt and late-summer/early-fall rains, and slowly recede (several weeks to months) leading up to these periods. The rise in streamflow is relatively quick relative to its decline, which increasingly becomes dominated by groundwater baseflow. Despite the sub-freezing air temperatures and continuous snowpack during winter months that virtually eliminate surface runoff, warmer groundwater continuously discharges to streams.

On an annual basis, significant changes in average streamflow are predicted for the five climate change scenarios (Figure E-13). When precipitation increases significantly (Pmax), annual streamflow averages are predicted to be greater than the historical basecase. When increases in precipitation are minimal or moderate (Pmin or P50), streamflow is projected to remain similar to or decrease relative to the basecase. These projected responses are similar to the responses in baseflow (Figure E-11) and overland flow (Figure E-12).

Seasonally, the model projects that winter streamflow may increase between 100% to 300% and summer streamflow may decrease by 5% to 60% for all climate change scenarios (Figure E-14). This dramatic increase in winter streamflow is caused by greater winter precipitation and the shift towards earlier and greater snowmelt during winter (Figure E-7). Summer decreases are primarily a result of increased AET due to the increase in air temperatures (Figure E-9). However in fall, streamflow is projected to increase relative to the basecase when precipitation is sufficient (Pmax) to offset temperature induced increases in AET, and may remain similar to historical conditions or decrease when insufficient (P50 and Pmin) to overcome increased AET. Spring streamflow decreases for all but the TminPmax scenario, suggesting that only with significant increases in precipitation will sufficient water be available to offset the decrease in spring runoff due to warmer winter temperatures.

In addition to annual and seasonal variation in the magnitude and direction of changes for the five climate scenarios, there are also differences in responses at the sub-watershed level (Figure E-15). For example, simulated winter flows generally increase significantly in the upper sub-watersheds (i.e., Chuit Creek and Upper Chuitna), and decrease for Stream 2003 and the Lone Creek sub-watersheds. Summer streamflow is projected to decrease for all sub-watersheds and scenarios except one (Lone Creek shows a slight increase for the TminPmax scenario). Spring dynamics at the sub-watershed level are highly variable, reflecting the balance between timing and magnitude of winter melt and spring precipitation inputs. In fall, variability appears to be related to the balance of precipitation inputs with higher temperature driven rates of AET.

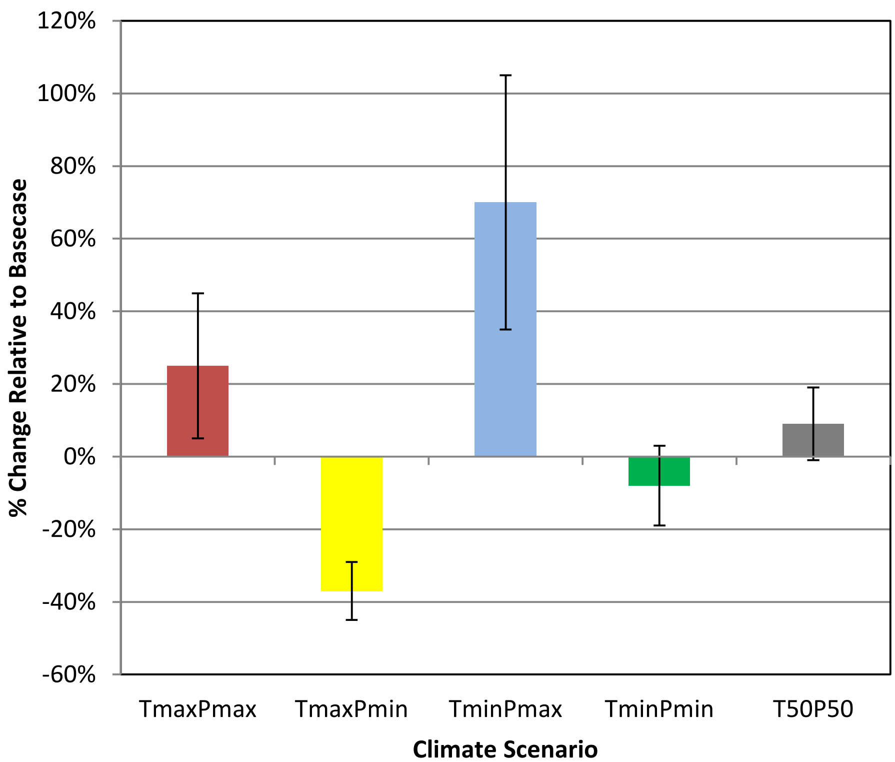


Figure E-13. Projected annual changes in streamflow for five climate change scenarios relative to historical basecase. Values are annual means with standard error bars for nine flow gauges within the Chuitna watershed.

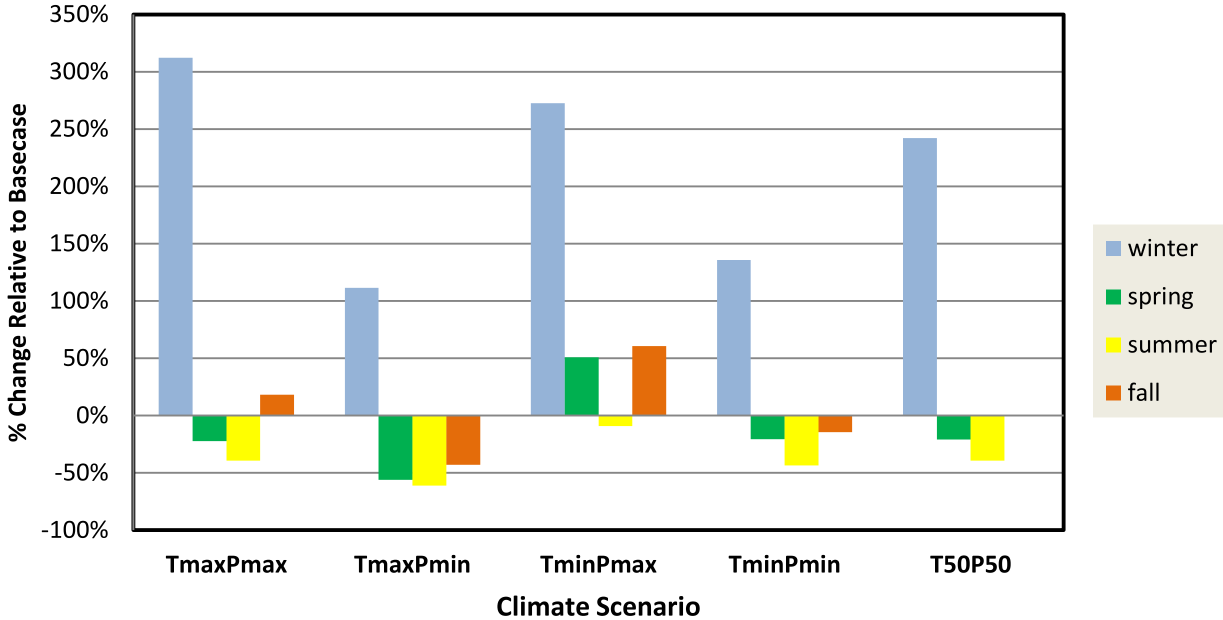


Figure E-14. Projected seasonal changes in streamflow for five climate change scenarios relative to historical basecase. Values are seasonal means for nine flow gauges within the Chuitna watershed.

Chuit Creek	winter	spring	summer	fall	Middle Chuitn	winter	spring	summer	fall
TmaxPmax	638%	-38%	-51%	43%	TmaxPmax	478%	-23%	-53%	38%
TmaxPmin	365%	-60%	-73%	-16%	TmaxPmin	242%	-52%	-73%	-19%
TminPmin	312%	-23%	-58%	5%	TminPmin	216%	-10%	-58%	1%
TminPmax	493%	23%	-28%	54%	TminPmax	381%	45%	-30%	53%
T50P50	522%	-36%	-53%	22%	T50P50	378%	-20%	-54%	18%
Upper Chuitna					**2003**				
TmaxPmax	629%	-11%	-58%	44%	TmaxPmax	173%	6%	-28%	3%
TmaxPmin	370%	-42%	-77%	-8%	TmaxPmin	-19%	-55%	-59%	-60%
TminPmin	275%	13%	-62%	7%	TminPmin	43%	-21%	-40%	-30%
TminPmax	436%	76%	-37%	50%	TminPmax	228%	59%	-7%	64%
T50P50	495%	-5%	-60%	24%	T50P50	122%	1%	-28%	-12%
2005					**Lone Creek**				
TmaxPmax	477%	-42%	-45%	35%	TmaxPmax	170%	-9%	-23%	7%
TmaxPmin	248%	-63%	-67%	-28%	TmaxPmin	-7%	-60%	-57%	-58%
TminPmin	241%	-31%	-51%	-2%	TminPmin	65%	-18%	-28%	-20%
TminPmax	395%	10%	-16%	55%	TminPmax	226%	45%	4%	61%
T50P50	390%	-40%	-46%	15%	T50P50	125%	-9%	-22%	-7%
Lone Ridge					**Lower Chuitna**				
TmaxPmax	363%	-37%	-43%	26%	TmaxPmax	417%	-21%	-50%	35%
TmaxPmin	146%	-61%	-64%	-40%	TmaxPmin	194%	-53%	-72%	-23%
TminPmin	178%	-29%	-46%	-10%	TminPmin	186%	-11%	-56%	-1%
TminPmax	324%	14%	-13%	56%	TminPmax	353%	47%	-27%	54%
T50P50	284%	-36%	-44%	4%	T50P50	327%	-19%	-52%	16%

Figure E-15. Simulated average seasonal change in streamflow relative to the basecase by sub-watershed for five climate change scenarios. Green shades indicate an increase in streamflow, while red shades indicate a decrease.

MODEL LIMITATIONS AND FUTURE APPLICATIONS

Although a reasonable calibration of the integrated hydrologic model to available data was accomplished in this study, uncertainties in climate data, model structure (i.e., geologic framework, aquifers etc.), parameter values and conceptualization of flows across the entire Chuitna watershed are significant and affect the accuracy of the calibration and future predictions. Detailed geologic and hydrologic information collected for the company seeking mining permits was unavailable for public use or only available in summarized form, limiting the development of the numerical flow model. We also found some climatic, geologic and hydrologic data essential to understanding the hydrologic system of the watershed have not been collected. Finally, the long run-times and complexity of the fully integrated model did not permit performing a detailed uncertainty analysis. Nevertheless, results are believed to be reasonable for purpose of estimating approximate flow conditions within the historical system and future changes in flows within the system for the range of specified climate changes.

The integrated surface and groundwater model used in this study has helped elucidate the linkages between climate and hydrology in the Chuitna watershed. The hydrologic system responded to even the minimum climate change scenario with significant changes in many key variables, including streamflow. These results should be indicative of how other non-glacial watersheds with similar hydrology in the region would respond to climate change, although the magnitude of change is likely to vary. Future work will include understanding climate change impacts on stream temperature and linking temperature and changes in flow with impacts to salmon habitat.

ACKNOWLEDGEMENTS

This work was funded by the US Fish and Wildlife Service and The Wilderness Society. Phil Brna, Ann Rappoport and Frances Mann of the US Fish and Wildlife Service identified the questions addressed in this research and provided scientific guidance and review. Sue Mauger of Cook Inletkeeper also provided scientific guidance and review. Ron Burnett guided a field visit during the model conceptualization.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop Evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome, 300 p.

Anderson, M.P., Ward, D.S., Lappala, E.G., Prickett, T.A., 1993. Computer models for subsurface water. Chapter 22 in Handbook of Hydrology, Maidment, D.R. Editor in Chief. McGraw-Hill, Inc.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: Regional Climate Projections. 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. 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.

Graham, D.N. and M. B. Butts (2005) Flexible, integrated watershed modelling with MIKE SHE. In Watershed Models, Eds. V.P. Singh & D.K. Frevert Pages 245-272, CRC Press. ISBN: 0849336090.

Hay, L.E. and G.J. McCabe (2010) Hydrologic effects of climate change in the Yukon River Basin. Climatic Change, 100, pp. 509-523

Groot, C. and Margolis, L. 1991. Pacific salmon life histories. UBC Press, Vancouver, B.C.

Hamlet, A.F., P. Carrasco, J. Deems, M.M. Elsner, T. Kamstra, C. Lee, S-Y Lee, G. Mauger, E. P. Salathe, I. Tohver, L. Whitely Binder, 2010, Final Project Report for the Columbia Basin Climate Change Scenarios Project, http://www.hydro.washington.edu/2860/report/

Kristensen, K. J. and S.E. Jensen, 1975. A model for estimating actual evapotranspiration from potential evapotranspiration. Royal Veterinary and Agricultural University, Nordic Hydrology 6, pp. 170-188

Mesinger, F,,. G. DiMego, E. Kalnay, K. Mitchell, PCP.C. Shafran, W. Ebisuzaki, D Jovic. Jović, J. Woollen, E. Rogers, EHE.H. Berbery, MBM.B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, W. Shi, (2006.) North American Regional Reanalysis. Bulletin of the American Meteorological Society, 87, pp. 343-360

Prucha, R.H., Leppi, J., McAfee, S., Loya, W.. 2011. Development And Application Of A Fully Integrated Hydrologic Model To Study The Effects Of Climate Change On The Chuitna Watershed, Alaska. Documentation Report.

Refsgaard, J.C. 1997. Parameterisation, calibration and validation of distributed hydrological models. Journal of Hydrology, 198 (1997) 69-97 p.

Riverside Technology, inc. (Riverside) 2007. Chuitna Coal Project Hydrology Component Baseline Report: Historical Data Summary. Revised March 2007.

Riverside Technology, inc. (Riverside) 2009. Chuitna Coal Project Surface Water Component Baseline Report – Final Draft: 1982 through September 2008. Revised June 2009.

Riverside Technology, inc. (Riverside) 2010. Chuitna Coal Project Groundwater Baseline Report –Draft: 1982 through January 2010. April 2010.