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The Chena River Watershed Hydrology Model

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April 2012



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Final report

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Prepared for U.S. Army Engineer District, Alaska
Anchorage, Alaska

Abstract: Development of a hydrologic model of the Chena River Watershed located in central Alaska is described. The flow in the Chena River is controlled by the Moose Creek Dam project upstream of Fairbanks, AK. The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) hydrologic model is intended to estimate inflows into the Moose Creek Dam Project and determine the Probable Maximum Flood (PMF) hydrograph. The Chena River watershed covers 2115 mi². It is characterized by extensive snowmelt in spring and heavy precipitation events in summer. The Chena River is typically in continuous recession from October through April because of the subfreezing air temperatures. Permafrost areas were estimated using a GIS based binary Logistic Regression model. Monthly values for evapotranspiration and the air temperature lapse rate were estimated using the available data. A temperature index snow model was developed and calibrated with existing snow water equivalent data. The HEC-HMS model was calibrated based on 3 years of continuous simulation between 1 April and 31 August. Both large snowmelt and precipitation events were simulated. The model was verified for an additional three year period. All the HEC-HMS model parameters are listed in the report. The PMF hydrograph was estimated.

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Table of Contents

List of Figures and Tables	v
Preface	vii
Unit Conversion Factors	viii
1 Introduction.....	1
2 The Chena River Watershed.....	2
2.1 The Moose Creek Dam.....	3
2.2 Data	4
2.2.1 Hydro-meteorological data	4
2.2.2 GIS data	6
2.3 Permafrost	6
2.4 Soil types.....	8
2.5 Evapotranspiration	9
2.5.1 Estimation of evapotranspiration using water balance method	9
2.5.2 Estimation of annual evapotranspiration	11
2.5.3 Estimation of monthly evapotranspiration	14
2.6 Air temperature lapse rate	18
3 Hydrologic Model Development.....	21
3.1 Basin model	21
3.1.1 Basin geometry	21
3.1.2 Soil infiltration and loss	23
3.1.3 Land use	24
3.1.4 Baseflow	25
3.1.5 Surface runoff	26
3.1.6 Routing	27
3.1.7 Flood control.....	28
3.2 Meteorological model.....	30
3.2.1 Input data	30
3.2.2 Snow model development	31
3.2.3 Chena River Watershed snow conditions	31
3.2.4 Snow model calibration	34
4 Flow Simulation	36
4.1 Calibration.....	36
4.2 Validation	40
5 Probable Maximum Flood	51
6 Discussion and Summary	53

References.....	54
Appendix A: Snow Model Calibration Periods	57
Report Documentation Page	

List of Figures and Tables

Figures

Figure 1. Chena Watershed site map.....	2
Figure 2. Chena River Watershed, showing locations of meteorological and discharge stations, and subbasins, delineated using Geo-HMS.....	5
Figure 3. Permafrost classification of the Chena Watershed.	7
Figure 4. Daily average air temperatures at the seven stations within the Chena River watershed.	10
Figure 5. The daily average, 10 th and 90 th percentile discharges of the Chena River at Fairbanks.	11
Figure 6. Annual runoff vs. sum of precipitation and snowmelt in the same water year.....	13
Figure 7. Autocorrelation of the annual total discharge for the Chena River showing the low autocorrelation.....	13
Figure 8. Average monthly precipitation, snowmelt and runoff.....	15
Figure 9. Daily average lapse rate for Chena Basin throughout the year.....	19
Figure 10. HMS Chena Basin Model schematic.	23
Figure 11. Soil Moisture Accounting (SMA) model diagram	24
Figure 12. Representative cross-section elevations were obtained from Google Earth	28
Figure 13. Elevation–storage relationship for Moose Creek Dam floodway.	29
Figure 14. Average maximum SWE and elevation observed at each station in the Chena River Watershed.	33
Figure 15 Average annual maximum SWE and average date of the last day of the accumulation period	33
Figure 16. Average snow model error in inches SWE, plotted against number of days after start of simulation.	Error! Bookmark not defined.
Figure 17. Calibration results for 1994.	38
Figure 18. Calibration results for 2008.....	39
Figure 19. Calibration results for 2009.....	40
Figure 20. Validation results for 1994.	41
Figure 21. Validation results for 2008.	42
Figure 22. Validation results for 2009.	43
Figure 23. Validation results for 1992.	44
Figure 24. Validation results for 1995.	45
Figure 25. Validation results for 1967.....	46
Figure 26. PMP inflow hydrograph to Moose Creek Dam.	52

Tables

Table 1. Recorded gate operation events at the Moose Creek Dam (USACE 2008).....	4
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Table 2. Hydro-meteorological stations within the Chena River Watershed.....	6
Table 3. Input variable classes and their statistical coefficients.....	8
Table 4. Modeled soil layers in Chena River Watershed.....	9
Table 5. Annual observed precipitation, snowmelt, runoff and estimated evapotranspiration	14
Table 6. Estimated monthly <i>ET</i> using Hargreaves method and pan observations.....	16
Table 7. Monthly average precipitation, snowmelt, runoff, evapotranspiration, and accumulated storage.	18
Table 8 Average annual ET determined for Chena River watershed and several nearby watersheds.....	18
Table 9. Monthly average lapse rates.....	20
Table 10. Chena River Watershed physical characteristics.	22
Table 11. Percentage land use type in Chena subbasins.	25
Table 12. Baseflow parameters estimated for using streamflow recession.	26
Table 13. Chena River Basin reach properties.....	28
Table 14. Elevation-discharge relationship for floodway sill.....	29
Table 15. Temperature station and elevation band in each subbasin.....	30
Table 16 Average maximum SWE and maximum SWE observed at each station in the Chena River Watershed.	32
Table 17. Snow parameters used in the temperature index snow model.....	34
Table 18. Calibration results	37
Table 19. Validation results.....	46
Table 20. HMS Soil Moisture Accounting Loss model parameters	48
Table 21. HMS Linear reservoir baseflow model parameters.	49
Table 22. HMS Clark unit hydrograph transform model parameters.....	49
Table 23. HMS Muskingum-Cunge routing model parameters.	50

Preface

The work was performed by Carrie M. Vuyovich and Dr. Steven F. Daly (Remote Sensing/GIS & Water Resources Branch, Ice Engineering Group, Timothy Pangburn, Chief), U.S. Army Engineer Research and Development Center–Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Justin Berman was Chief of the Research and Engineering Division. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen and the Director was Dr. Robert Davis.

COL Kevin J. Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters

1 Introduction

The Alaska District of the Corps of Engineers operates and maintains the Moose Creek Dam flood control project on the Chena River upstream of Fairbanks, AK. This structure was designed to control the discharge through Fairbanks by diverting excess discharge to the Tanana River above Fairbanks by way of a 7-mile-long floodway. The project was built in the 1970s following the devastating flood of record in 1967, and several other earlier significant events. Since construction, the dam has provided flood protection during numerous events, with quantifiable benefits to the city.

In 2008, the Moose Creek Dam came under review of the USACE Dam Safety Program. The screening level risk assessment resulted in the dam being assigned a Dam Safety Action Classification of I. This means that risks associated with operation of dam presented an “urgent and compelling” need to address the potential failure modes that drive the unacceptable risks. The District has implemented a number of interim risk reduction measures (USACE 2009), and is currently updating its hydrologic and hydraulic analysis of the watershed to evaluate the system. As part of the Moose Creek Dam evaluation, this study will develop a new hydrologic model for the Chena River watershed based on the USACE Hydrologic Engineering Center’s (HEC) Hydrologic Modeling System (HMS). This model will be used in operational forecasting of inflows to the project, and for computing the Probable Maximum Flood (PMF).

2 Chena River Watershed

The Chena River Watershed extends east from its confluence with the Tanana River in Fairbanks, AK (Figure 1). The watershed has a total area of 2115 mi², and elevations range from 420 ft at the outlet to 5280 ft at the highest point. The basin contains discontinuous permafrost throughout, with the largest percentage of frozen ground located in the higher elevations. Beginning in the fall, the basin largely freezes over and streamflow is primarily receding baseflow. In the spring, snowmelt accounts for a significant portion of the discharge in the Chena River; however, the largest floods have been recorded in the summer as a result of heavy rainfall.

The climate in the Chena Watershed consists of cold, dry winters and warm, moist summers. The average total annual precipitation is about 15 to 20 in. (NRCS 2011). Snowfall makes up approximately 35 to 40% of the total precipitation. The heaviest precipitation falls as rain in July and August. Temperatures range from -5 to 5°F in December and January to 50 to 60°F in July. The following sections describe characteristics of the Chena River Watershed used in developing the hydrologic model of the basin. An overview of the Moose Creek Dam project is provided, as well as a description of the data sources available. Further analyses were necessary to determine the permafrost areas, soil characteristics, evapotranspiration, and temperature lapse rate, which are described in this section.

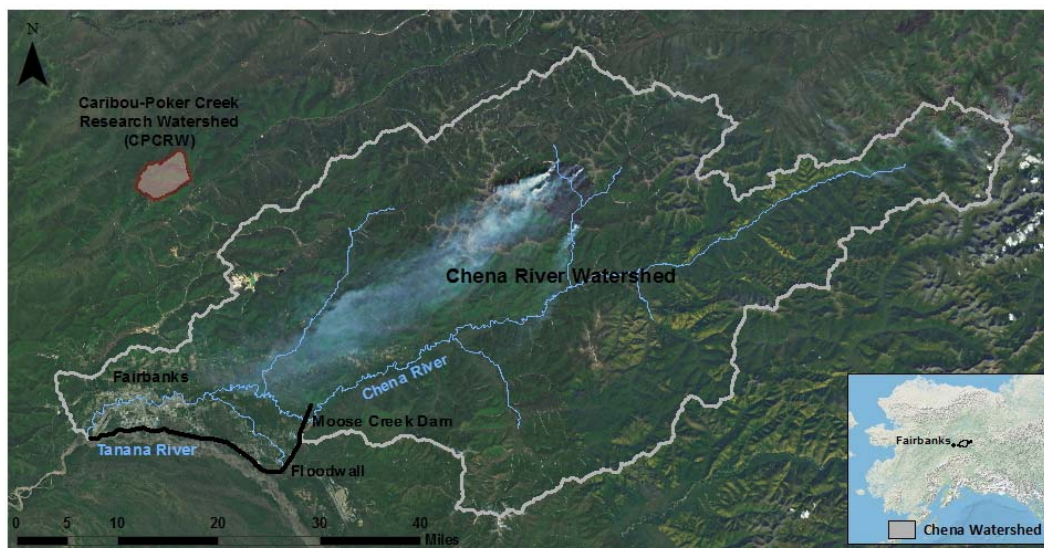


Figure 1. Chena Watershed site map (imagery from ESRI 2011).

2.1 Moose Creek Dam

The flood of record in 1967 was the consequence of 8.9 in. of rain that fell over 3 days in August. Extensive evacuations and damages resulted. The Moose Creek Dam was completed in 1979 as part of the Chena River Lakes Flood Control Project and is located approximately 17 miles east of Fairbanks, and 35 miles upstream from the Chena River discharge gage in Fairbanks (USACE 2008). The Moose Creek Dam is an earthen dam, over 7 miles long. On the upstream side of the dam is the floodway, which varies in width between 1100 and 4200 ft and extends from the control works at the Chena River, south to the Tanana River. Four steel vertical lift gates control the outflow along the Chena River. Typically, the gates are open to allow the Chena River flow to pass downstream. During potential flood events, discharge through the gates is limited to 8300 cfs to restrict the combined discharge of the Chena and Little Chena Rivers in Fairbanks to 12,000 cfs. Excess discharge on the Chena River is diverted through the floodway to the Tanana River. Drainage into the Tanana is controlled by a sill structure that prevents high flows in the Tanana River from entering the floodway.

The Moose Creek Dam has been operated 20 times between 1981 and 2011 to limit discharge through Fairbanks (Table 1). The largest event to pass through the project occurred in 1992 as a result of rainfall and snowmelt. The maximum inflow to the project was over 16,000 cfs, of which only 8200 cfs was allowed to flow through Fairbanks, while the remainder was diverted through the floodway. To forecast flows into the project, the Alaska District uses an operational hydrologic model and real-time data. The Streamflow Synthesis and Reservoir Regulation (SSARR) model (USACE 1987) was developed to simulate discharge in the Chena River and was used until recently. This HMS model will replace the SSARR model for operational forecasting of the Chena River.

Table 1. Recorded gate operation events at the Moose Creek Dam (USACE 2008).

Gate closure period	Peak flow		Cause
	Chena at Fairbanks	Through gate	
13–15 July 1981*	6160	5930	Rain
13–23 June 1984	6800	7100	Rain
20–25 July 1984	8350	8170	Rain
26–29 July 1984	7700	6850	Rain
23 May–3 June 1985	8950	8250	Snowmelt
24–27 June 1986	4750	m	Rain
21–24 July 1986	5900	m	Rain
22–28 August 1986	8300	m	Rain
27–29 June 1989	8600	m	Rain
5–15 May 1991	11350	8300	Snowmelt
10–21 August 1991	7698	7800	Rain
24 May–11 June 1992	10500	8200	Rain/snowmelt
21–30 June 1994	9570	8175	Rain
27–29 June 1995	8640**	8360	Rain
15–17 August 2000	8620**	8300	Rain
2–3 May 2002	4000	(Ice jam in place)	Ice jams
19–21 August 2002	8940	8400	Rain
29–31 July 2003	10400	8700	Rain
4–5 September 2003	9300	8700	Rain
29 July–2 August 2008	9160	8050	Rain

* Test fill

** Daily average flow

2.2 Data

2.2.1 Hydrometeorological data

The Alaska District has helped install and maintain a number of hydrological and meteorological stations throughout the basin. Five discharge gages are located within the Chena Watershed, four along the Chena River and one on the Little Chena River (Figure 2), which are operated by the USGS (accessed 2010). With the exception of the Chena River gage at Fairbanks, the gages are shut down during the winter when the stream is frozen and restarted before the spring melt, typically around 1 May.

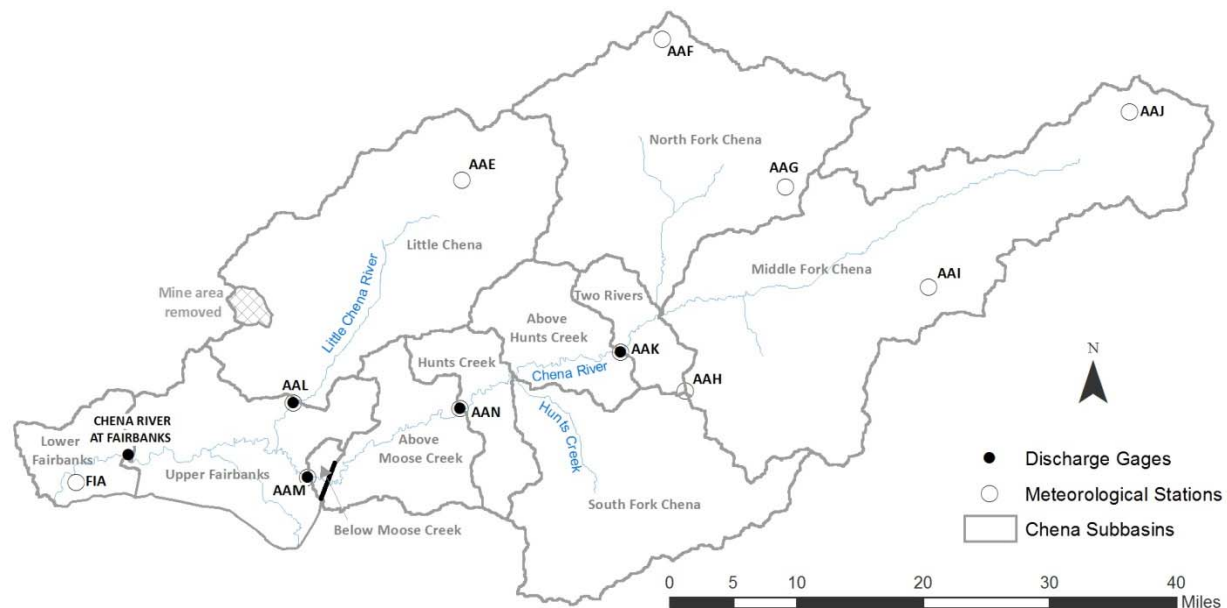


Figure 2. Chena River Watershed, showing locations of meteorological and discharge stations, and subbasins, delineated using Geo-HMS.

Meteorological data are available from 11 stations within the basin: at four of the USGS stream gages and at seven additional meteorological stations (Figure 2 and Table 2). The meteorological station at the Fairbanks International Airport is operated by the National Weather Service (NWS), while the remaining six are operated by the Natural Resources Conservation Service (NRCS) SNOTEL program. These seven stations report Snow Water Equivalent (SWE) data, in addition to temperature and precipitation. The NRCS also conducts snow surveys twice annually, on 1 April and 1 May, at several locations throughout the basin.

All hydrometeorological data are transmitted real-time to the Alaska District office via a Geostationary Operational Environmental Satellite telemetry system GOES. The data are stored in the Hydrologic Engineering Center's Data Storage System (HEC-DSS) database (USACE 2012) for use by the model during operational forecasting. For this study, historical daily and hourly data were collected and quality checked for possible erroneous values and stored in DSS. Table 2 lists the stations, data available, and period of record.

Table 2. Hydro-meteorological stations within the Chena River Watershed.

Gage	ID	Elev (ft)	Data available	Date start	Date end
Fairbanks International Airport	FIA	453	SWE, P, T	Oct-82	Jun-08
Little Chena Ridge	AAE	2000	SWE, P, T	Oct-81	Current
Mt. Ryan	AAF	2800	SWE, P, T	Oct-81	Current
Monument Creek	AAG	1850	SWE, P, T	Oct-80	Current
Munson Ridge	AAH	3100	SWE, P, T	Oct-80	Current
Tuechet	AAI	1640	SWE, P, T	Oct-81	Current
Upper Chena	AAJ	2850	SWE, P, T	Oct-87	Current
Chena River at Two Rivers (Junction 2)	AAK	720	Q, P, T	Oct-67	Current
Chena River BL Hunts Cr (Junction 4)	AAN	638	Q, P, T	Oct-91	Sep-09
Chena River BL Moose Cr Dam (Junction 5)	AAM	490	Q, P, T	Aug-79	Oct-08
Little Chena River NR Fairbanks (Junction 6)	AAL	460	Q, P, T	Aug-96	Current
Chena River at Fairbanks (Junction 8)		423	Q	Aug-47	Current

2.2.2 GIS data

The geospatial data used in the analysis include a digital elevation model (DEM) of the watershed, high-resolution imagery, and gage locations. The DEM is 2 arc-second (approximately 60 m) resolution data available in GCS NAD83 projection from USGS (2009). The data were re-projected to NAD27 Albers projection. The high-resolution imagery is available through ESRI ArcGIS online service (ESRI 2011), in 1- to 500-m resolution. Shapefiles of the gage locations were provided by the Alaska District.

2.3 Permafrost

The percentage of permafrost area within each basin was used to determine the percolation rates in the Soil Moisture Accounting (SMA) model soil layers. Subbasins with higher percentages of permafrost were given lower percolation rates than what is typical for the mineral soil. This was done to increase the lag time within the bottom soil layer between infiltration and output to baseflow to simulate the impedance of flow by frozen ground. The percentage of permafrost within each basin was estimated by the Alaska District using the Binary Logistic Regression (BLR) model developed by Yoshikawa et al. (2002), which classifies permafrost areas

based on vegetation type and latitude, accounting for aspect and elevation (Table 3). The BLR model has the form of

$$\Pi_i = \frac{1}{1 - e^{-Z_i}} \quad (1)$$

where Z is the propensity towards the event of interest (log-odds) and Π is the probability that the i^{th} case experiences the event of interest. The model assumes that Z is linearly related to the predictors

$$Z_i = b_0 + b_1x_{i1} + b_2x_{i2} + \dots + b_jx_{ij} + \dots + b_px_{ip} \quad (2)$$

Where x_{ij} is the j^{th} predictor for the i^{th} case, b_j is the j^{th} coefficient and p is the number of predictors. In this case six vegetation classes, nine aspect classes, and two elevation classes were used as inputs into the BLR model (Table 3). The value of b_0 was set to -1.05 . A threshold probability of 0.5 was assigned during the regression analysis to classify the output probability at a given location as either “permafrost present” or “permafrost absent.” As expected, subbasins with higher elevations had the greatest percentage of permafrost, greater than 50%, while the subbasins in the valleys, particularly around Fairbanks, had the lowest (Figure 3).

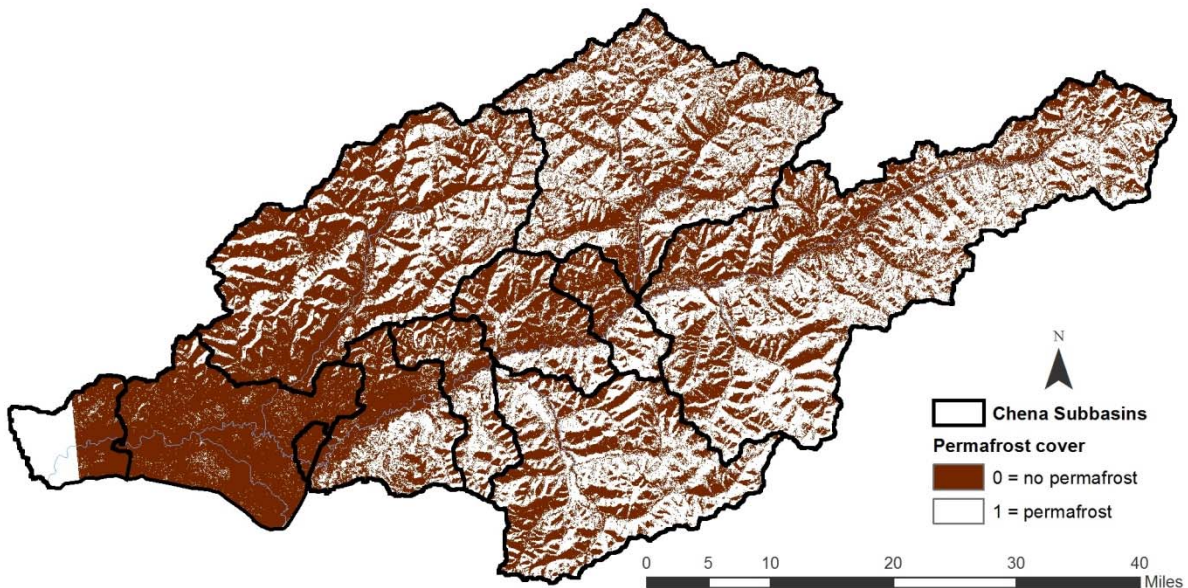


Figure 3. Permafrost classification of the Chena Watershed.

Table 3. Input variable classes and their statistical coefficients (Yoshikawa et al. 2002).

	Class	Description	Coefficient
Vegetation	Aspen	Mostly distinct patches of aspen	-19.62
	Dense tall spruce	Tall (>5 m) and big (diameter>7 cm) spruce trees (both white spruce and black spruce)	1.34
	Scattered short spruce	Mostly black spruce (height<5 m) and (diameter<7 cm), found in low-lying valley and flat areas	21.66
	Deciduous	Mostly deciduous vegetation including primarily birch trees, balsam poplar, dwarf birch, resin birch, alder, aspen	-36.79
	Mixed spruce and deciduous	Mostly mixed spruce (white spruce and black spruce) along with other deciduous vegetation	0.00
	Wetland meadow	Open grass fields in drained lake beds or inactive floodplain	-20.15
Aspect and topography	North	Aspect: 337.51° – 22.50°	19.88
	Northeast	Aspect: 22.51° – 67.50°	0.38
	East	Aspect: 67.51° – 112.50°	0.35
	Southeast	Aspect: 112.51° – 157.50°	-0.32
	South	Aspect: 157.51° – 202.50°	-0.02
	Southwest	Aspect: 202.51° – 247.50°	-20.15
	West	Aspect: 247.51° – 292.50°	7.91
	Northwest	Aspect: 292.51° – 337.50°	17.95
	Low-Lying flat surfaces	Slope<8°	0
Elevation	Lower	<640m	0
	Higher	>640m	1.40

2.4 Soil types

The soil in the Chena River Watershed is composed of two main layers, underlain by bedrock (Table 4) (Kane and Stein 1984; Bolton 2006). An organic soil layer near the surface is an active layer throughout the basin, approximately 10 to 30 in. thick, which thaws immediately after snowmelt and has a high conductivity. A mineral soil layer beneath the organic layer has a lower conductivity and can range in thickness to as much as 100 in. before reaching bedrock. In the upper subbasins, portions of the mineral soil layer are continuously frozen, impeding the flow of water downward.

Table 4. Modeled soil layers in Chena River Watershed.

Soil layers	Hydraulic conductivity	Depth (in.)
Fairbanks Organic Soil	High (0.5– 20 in/hr)	10–30
Mineral Soil	Low (0.001–0.01 in/hr)	100+

During implementation of the SMA loss model in HMS, the top soil layer was modeled as the organic soil in all subbasins with initial infiltration and percolation rates based on expected values for the soil type (Rawls et al. 1982). The upper and lower groundwater layers were modeled as the mineral soil. To account for the effects of permafrost on groundwater flow in the upper subbasins, the percolation rates were significantly reduced based on calibration.

2.5 Evapotranspiration

Evapotranspiration (ET), broadly defined as the “rate of liquid water transformation to vapor from open water, bare soil, or vegetation” (Shuttleworth 1993), is an important component of the water balance of all watersheds, and must be accounted for in the Chena River Watershed Hydrologic Model. The difficulty with ET is that it cannot be observed directly but must be inferred from other observations, estimated as a component of the overall water balance of the watershed, or estimated based on empirical formulas. In this section all three approaches are used to arrive at an estimate of the average monthly ET rate for each month of the year.

2.5.1 Estimating evapotranspiration using water balance method

A generalized water balance for the Chena River watershed can be written as

$$\Delta S = P + S_m - ET - R \quad (3)$$

where

P = precipitation as rainfall over the watershed

S_m = total snowmelt over the watershed

ET = evapotranspiration

R = runoff from the watershed

ΔS = change in storage.

In this report, the water balance will be estimated both annually and monthly. Before applying this equation, it is appropriate to look at some of the specific, unique conditions of the Chena River watershed. One of the dominant conditions is the prolonged period of subfreezing air temperatures each winter, typically beginning in early October and extending through mid-April (Figure 4). The frigid air has a profound impact of the flows in the Chena River, as shown in Figure 5. During the period of subfreezing air temperatures, there is no rainfall or snowmelt, and the discharge in the Chena River results from surface and sub-surface drainage throughout the watershed. During this period, the river discharge is in recession; the discharge slowly decreasing as the amount of available water in the watershed decreases. Starting in mid-April the air temperatures rise to above freezing; snowmelt and rainfall commence, resulting in significantly increased flows through September.

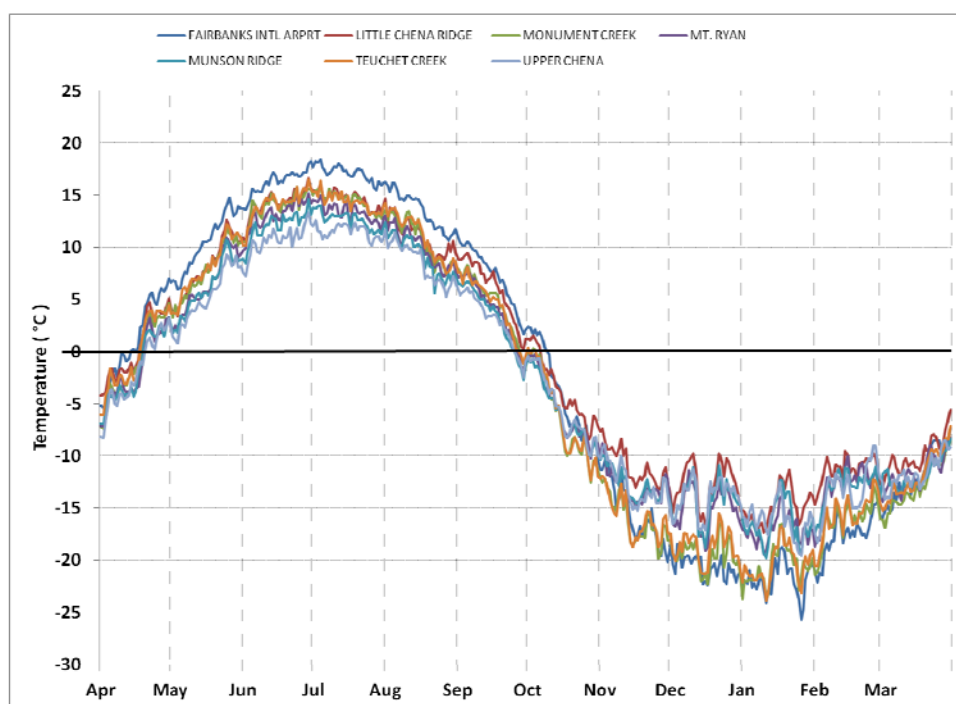


Figure 4. Daily average air temperatures at the seven stations within the Chena River watershed.

Based on this annual cycle, it is convenient to define the water year as beginning on 1 April and extending through the following 31 March for the water balance calculation. The precipitation, snow water equivalent, and runoff are continuously monitored throughout the year and can be estimated using observations. This leaves two components, the evapotranspiration and annual change of storage as unknowns.

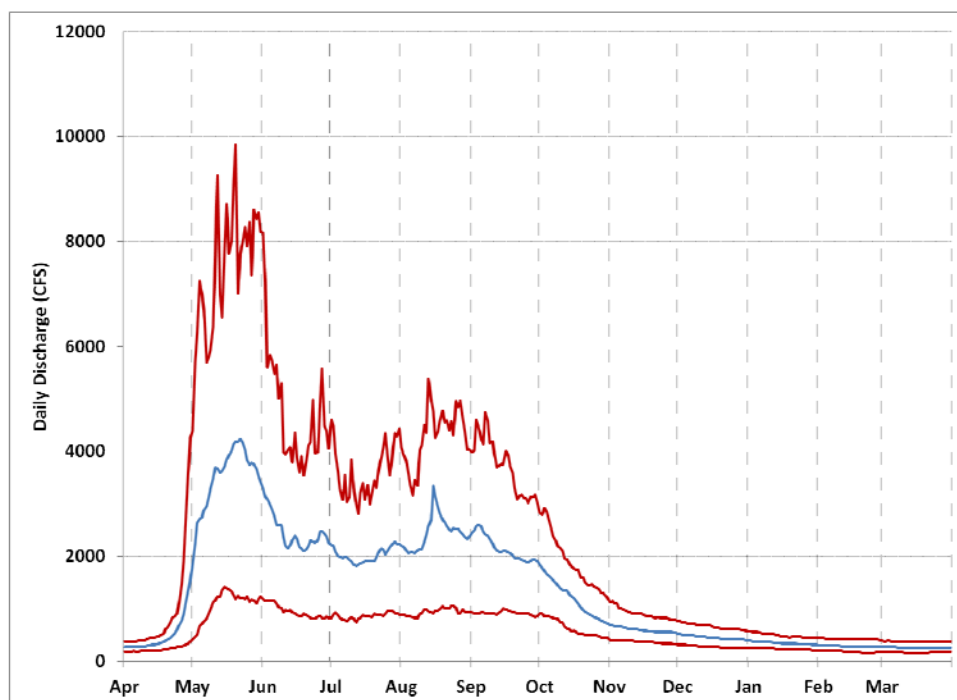


Figure 5. Daily average, 10th and 90th percentile discharges of the Chena River at Fairbanks.

The monthly precipitation at each gage was calculated by accumulating the hourly observations. Precipitation measurements were available starting in late April through October. It is assumed that the precipitation measured during that period was rainfall. The monthly accumulated precipitation over the entire Chena River watershed was then estimated by weighting the gage values using Thiessen polygons. The annual total snowmelt contribution was calculated using the maximum SWE measured at each of the SNOTEL gages. The SWE distribution with elevation was then estimated by fitting a linear function of SWE between pairs of gages. The SWE for each elevation band was then weighted by the area of that band to arrive at a watershed total. Then, the entire snowmelt for each year was applied in May. The monthly watershed runoff was estimated by accumulating the observed flow at the USGS gage “Chena River at Fairbanks” and then converting to a depth by dividing the accumulated flow by the watershed area.

2.5.2 Estimating annual evapotranspiration

The annual rainfall precipitation and runoff can be estimated by summing the values over the water year.

$$P_{annual} = \sum_{j=Apr}^{Oct} P_j \quad (4)$$

$$R_{annual} = \sum_{j=Apr}^{Mar} R_j \quad (5)$$

For the annual water balance calculations, all of the snowmelt was applied during May, though in reality snowmelt can begin in April and extend into June. Before the annual total ET can be estimated, it is necessary to estimate the change in storage over the course of the year. In this case it is assumed that the annual change in storage is effectively zero. This can be stated mathematically as

$$\Delta S_{annual} = \sum_{j=Apr}^{Mar} \Delta S_j = 0 \quad (6)$$

Bolton et al. (2004) noted “that in permafrost basins, year-to-year changes in storage may be significant. In the boreal forest, many of the storage processes, such as interception storage, stream icings (aufeis), and differences in subsurface storage (due to presence or absence of permafrost), are not well quantified.” In the case of the Chena River, the year-to-year changes in storage are probably not significant and eq 6 is justified. There are two sources of data to support this view. First, the total annual runoff, R_{annual} , is very well correlated with the sum of the annual precipitation, P_{annual} , and annual snowmelt, S_m of the same year, with an r^2 value of 0.82 (Figure 6). This suggests that impacts arising from carryover of storage from previous years are not significant. In addition, the autocorrelation of the time series of annual discharges for the period of 1949–2010 shows almost no correlation for any time step from 1 year to 5 years (Figure 7).

Next, the annual total evapotranspiration for each year from 1991 through 2009 was estimated using

$$ET_{annual} = P_{annual} + S_m - R_{annual} \quad (7)$$

The results are listed in Table 5. Equation 7 gives the long term average annual evapotranspiration for the Chena River watershed as 7.53 in.

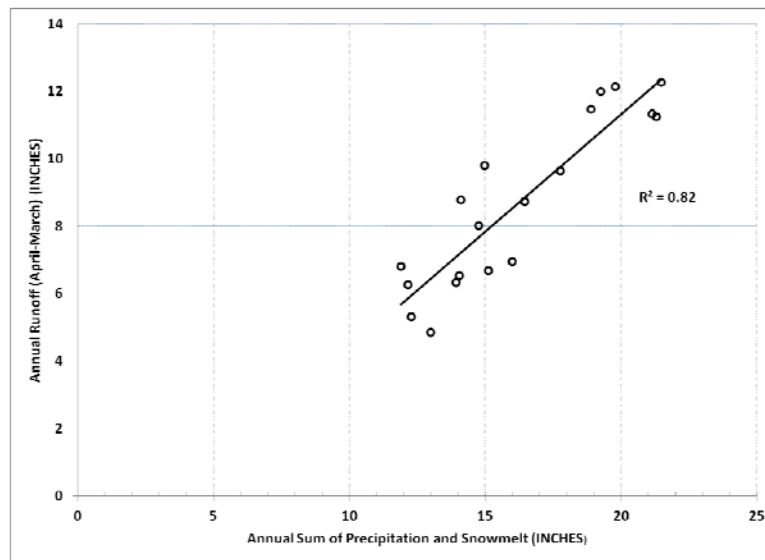


Figure 6. Annual runoff vs. sum of precipitation and snowmelt in the same water year (April through March).

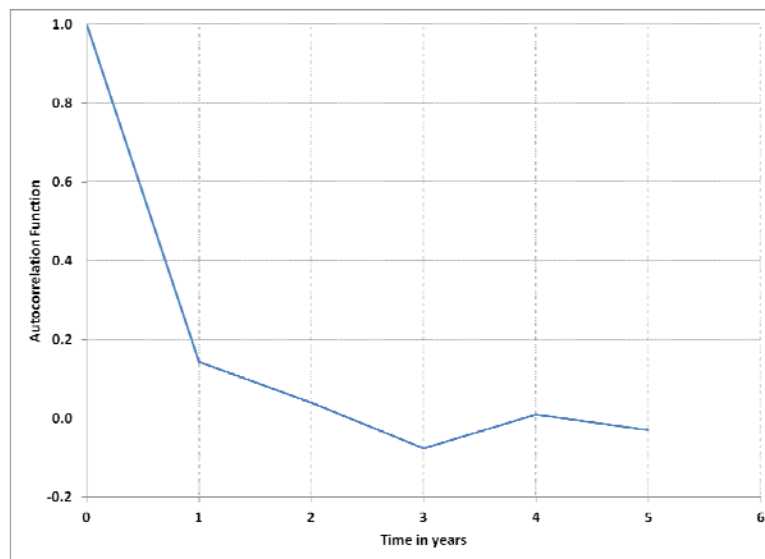


Figure 7. Autocorrelation of the annual total discharge for the Chena River showing the low autocorrelation.

Table 5. Annual observed precipitation, snowmelt, runoff and estimated evapotranspiration (in.).

Year	Total precipitation	Total snowmelt	Total runoff	Calculated evapotranspiration
1991	9.22	10.57	12.15	7.65
1992	7.18	7.79	9.80	5.17
1993	10.17	10.97	11.33	9.80
1994	10.52	5.93	8.73	7.72
1995	13.92	7.39	11.25	10.05
1996	10.26	4.85	6.68	8.44
1997	8.24	4.74	4.85	8.14
1998	10.28	3.78	6.54	7.51
1999	7.74	4.54	5.31	6.97
2000	12.39	6.85	12.00	7.24
2001	10.94	5.05	6.95	9.05
2002	15.60	5.88	12.27	9.22
2003	13.56	5.33	11.48	7.41
2004	6.59	5.56	6.26	5.89
2005	10.92	6.84	9.65	8.12
2006	9.20	5.57	8.02	6.75
2007	9.33	2.56	6.81	5.08
2008	10.14	3.97	8.78	5.33
2009	9.46	4.47	6.33	7.60
Average	10.30	5.93	8.69	7.53

2.5.3 Estimating monthly evapotranspiration

The long term average monthly precipitation, snowmelt, and runoff were estimated based on observations (Figure 8). The procedure described in the previous section cannot be used to estimate the monthly ET because the month-to-month changes in storage are undoubtedly not zero.

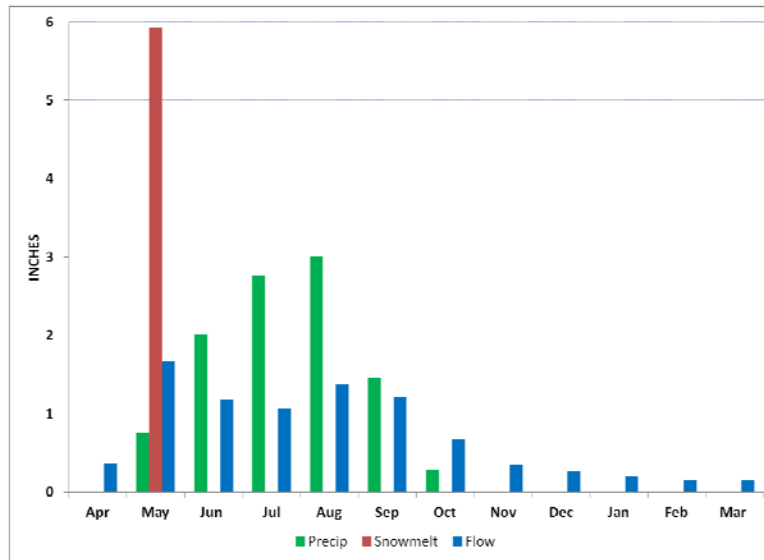


Figure 8. Average monthly precipitation, snowmelt, and runoff.

Alternative methods for estimating evapotranspiration include empirical methods and observations of pan evaporation. A variety of empirical methods have been developed (Shuttleworth 1993). Bolton et al. (2004) estimated evaporation for the Caribou-Poker Creeks Research Watershed based upon the Priestley-Taylor equation (1972). The Priestley-Taylor equation required information on the ground heat flux not available for the Chena River watershed. Instead, daily estimates of evaporation were developed using the Hargreaves method (Shuttleworth 1993; Hargreaves and Allen 2003). The Hargreaves method requires estimates of the integrated short wave solar flux and the air temperature.

$$ET_o = 0.0023S_o(T + 17.8)\sqrt{T_{max} - T_{min}} \quad (8)$$

where

S_o = daily possible solar flux (mm day⁻¹)

T = daily average temperature (°C)

T_{max} = daily maximum air temperature (°C)

T_{min} = daily minimum air temperature (°C)

ET_o = daily evapotranspiration rate (mm).

The Hargreaves method was applied at each air temperature gage in the Chena River Watershed. The potential daily solar radiation was estimated for each hour of the day, based on the location of Chena River watershed using the procedure of Woolf (1968). The solar radiation was set to zero for any hour when precipitation occurred. The hourly solar radiation was

then summed to determine the daily total and converted to an evaporation equivalent. *ET* was assumed to be zero during any day with an average air temperature below 0°C or if snow present, as indicated by a SWE greater than zero. Monthly *ET* at each gage was calculated by accumulating the daily estimates. The monthly accumulated *ET* over the entire Chena River watershed was estimated by weighting the gage values using Thiessen polygons.

Pan evaporation observations in the Chena River watershed are available for the NWS CO-OP station, 509641, College University Experimental Station, AK, for the period 1931 through the present (Western Region Climate Center 2011). The monthly average values based on the Hargreaves method and the unadjusted pan evaporation method are listed in Table 6.

Table 6. Estimated monthly *ET* using Hargreaves method and pan observations.

Month	<i>ET</i> Hargreaves	Pan measurement
April	0.14	0.00
May	2.64	4.25
June	4.99	5.04
July	4.57	4.56
August	2.85	2.82
September	1.08	1.38
October	0.06	0.00
November	0.00	0.00
December	0.00	0.00
January	0.00	0.00
February	0.00	0.00
March	0.00	0.00
Sum	16.33	18.05

Two interesting facts are immediately apparent. The first is that the average annual evapotranspiration values provided by the Hargreaves estimate and the pan observations are very similar: 16.33 in. for the Hargreaves estimate and 18.05 in. based on the unadjusted pan observations. The second is that both of these estimates are very much greater than the average

annual evapotranspiration estimate arrived at through the watershed water balance: 7.53 in. In fact both are greater than the estimated average annual precipitation and snowmelt of the basin, which are 16.23 in. This discrepancy between estimated evapotranspiration based on a watershed water balance and those arrived at using empirical methods or pan evaporation was noted by Dingman (1971) for central Alaska. He noted that the empirical methods provided an estimate that was “certainly too high.”

The pan estimate of evaporation can differ significantly from that from the surrounding countryside. Generally, the evaporation from pans is greater than adjacent areas. Pan evaporation is often adjusted using empirical pan coefficients to account for these differences (Shuttleworth 1993). These coefficients can range from 0.55 to 0.85, depending on the wind, upwind fetch, mean relative humidity, and other factors. The pan coefficient for the observations at NWS CO-OP station, 509641, College University Experimental Station, AK is 0.42, based on the annual evapotranspiration provided by the watershed water balance.

At this point the average annual evapotranspiration provided by the watershed water balance will be accepted as the more representative of the actual *ET* of the Chena River watershed. However, the average monthly *ET* will be estimated by weighting the monthly average Hargreaves estimate of *ET* so that the annual sum of the monthly average Hargreaves estimates will equal the annual sum determined by the watershed water balance method. The average monthly values of the precipitation, snowmelt, runoff, *ET*, and accumulated change in storage are shown for each month of the year in Table 7.

The annual average *ET* for the Chena River watershed can be compared to other estimates of *ET* from nearby watersheds in central Alaska (Table 8). These watersheds include Glenn Creek (Dingman 1971) and the Caribou-Poker Creeks Research Watersheds (CPCRW) sub-watersheds labeled C2, C3, and C4 (Bolton et al. 2004). In Table 8 the watersheds are listed in order of the percentage area of each watershed covered by permafrost—from the largest percentage area to smallest. As the percentage area of each watershed covered by permafrost decreases, the estimated annual *ET* increases. The value determined for the Chena River watershed is similar to the values determined for other watersheds with similar percentage areas covered by permafrost.

Table 7. Monthly average precipitation, snowmelt, runoff, *ET*, and accumulated storage.

Month	Precipitation	Snowmelt	Runoff	ET	Accumulated storage
April	0.00	0.00	0.37	0.06	-0.43
May	0.76	5.93	1.67	1.22	3.37
June	2.01	0.00	1.19	2.30	1.89
July	2.76	0.00	1.07	2.11	1.47
August	3.02	0.00	1.37	1.31	1.79
September	1.46	0.00	1.21	0.50	1.55
October	0.29	0.00	0.68	0.03	1.13
November	0.00	0.00	0.35	0.00	0.78
December	0.00	0.00	0.27	0.00	0.51
January	0.00	0.00	0.20	0.00	0.31
February	0.00	0.00	0.15	0.00	0.15
March	0.00	0.00	0.15	0.00	0.00
Sum	10.30	5.93	8.69	7.53	

Table 8 Average annual *ET* determined for Chena River watershed and several nearby watersheds.

Basin	Average annual <i>ET</i> (in.)	Range annual <i>ET</i> (in.)	POR	Area (mi. ²)	Estimated permafrost area (%)	Elevation range (ft)
Glenn Crk ³	7.65, 3.92	—	1964, 1966	0.70	~55	842–1618
CPCRW C3 ²	7.9	5.2–9.1	1978–2003	2.2	53.2	900–2525
Chena ¹	7.53	5.08–10.05	1991–2009	2053	43.0	400–4800
CPCRW C4 ²	11.7	7.6–13.4	1978–2003	4.40	18.8	740–2250
CPCRW C2 ²	12.3	8.1–14.1	1978–2003	2	3.5	1060–2421

¹Present study

²Bolton et al. (2004)

³Dingman (1971)

2.6 Air temperature lapse rate

The air temperature lapse rate describes the change in temperature with elevation. Normally, the air temperature becomes lower with elevation;

however, under certain conditions, an air temperature inversion can occur. Air temperature inversions are described as “strong and semi-permanent” in central Alaska (Hartman and Wendler 2005). An air temperature inversion is a persistent and common feature over the Chena Watershed each winter. The air temperature lapse rate of the Chena River was estimated using the hourly air temperature observations from the meteorological stations listed in Table 2. The hourly lapse rate was estimated by fitting a straight line through the observed temperatures plotted against the meteorological station elevation. The lapse rate was found to vary from strongly positive values in the winter (air temperature inversion) to strongly negative values in the summer. The lapse rate was also found to have a strong diurnal component as well. The daily average lapse rate for the Chena watershed throughout the year is shown in Figure 9. The monthly average lapse rates are listed in Table 9.

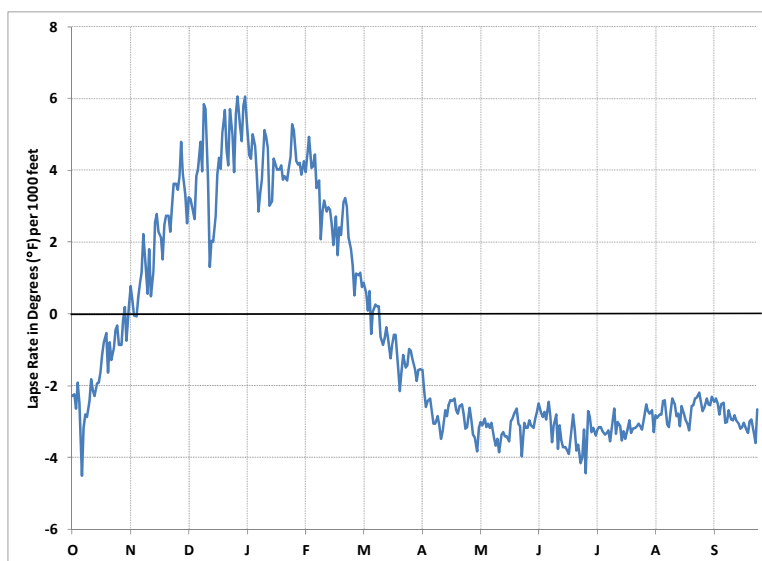


Figure 9. Daily average lapse rate for Chena Basin throughout the year.

Table 9. Monthly average lapse rates.

Month	Monthly average lapse rate (°F per 1000 ft)
October	-1.54
November	2.07
December	4.28
January	4.17
February	2.92
March	-0.42
April	-2.55
May	-3.24
June	-3.23
July	-3.22
August	-2.73
September	-2.63

3 Hydrologic Model Development

The HMS model computes a complete water balance of a basin to estimate discharge, given precipitation input (USACE 2010a). HMS is designed to handle a variety of water resource applications and can be adapted to specific watershed characteristics. Each aspect of the hydrologic process is handled separately, with several modeling options typically available ranging in complexity. Selection of the modeling options requires an understanding of the watershed, the data available, and the goals of the study. Phases of model development include characterizing the basin, developing the meteorological model, selecting a time window and appropriate time step, and linking the input data.

For the Chena River Watershed, an HMS model was developed for continuous simulation of spring snowmelt and summer and fall flows. Geo-HMS is a software extension for the ArcGIS platform, which enables the user to develop the basin hydrologic characteristics within geospatial software (USACE 2010b). This software was used, along with available terrain and land-use geospatial data, to develop the basin geometry for the Chena River Watershed. Results are imported into the HMS framework. The Chena River Watershed has several unique features that were accounted for in the development of the model, including a strong spring snowmelt signal and discontinuous permafrost. HMS includes a temperature index snow model that calculates snow water equivalent (SWE) given temperature and precipitation data. The HMS model was run at an hourly time step during simulation.

3.1 Basin model

3.1.1 Basin geometry

The Chena River Watershed was delineated and the basin's hydrological characteristics were estimated using available geospatial data and GeoHMS within ArcGIS. The outlet of the basin was set to the confluence of the Chena and the Tanana rivers. The watershed was divided into 11 subbasins at the locations of stream gages, major tributaries, and at the Moose Creek Dam (Table 10). A small area in the Little Chena subbasin, upstream of the Ft. Knox Gold Mine, was removed from the delineated ar-

ea because runoff upstream of the tailings dam is completely contained (Johnson 2011). The area around Fairbanks is relatively flat and was incorrectly delineated using the coarse 60-m DEM. Therefore, the watershed was manually delineated using the high resolution imagery, with the flood wall marking the southern boundary.

Table 10. Chena River Watershed physical characteristics.

Sub-basin	Description	Area (mi ²)	Longest flow path (mi)	Elevation at divide (ft)	Elevation at outlet (ft)	Slope (ft/ft)	Percent impervious	Percent permafrost
1	North Fork Chena River	345.9	34.3	4312.5	810.4	0.019	0	53
2	Middle Fork Chena River	539.4	57.3	4807.9	826.8	0.013	0	54
3	Two Rivers Local	49.2	16.2	2574.6	716.4	0.022	0	42
4	Above Hunts Creek Local	89.2	17.2	1906.8	659.5	0.014	0	40
5	South Fork Chena River	249.9	39.6	3096.6	675.9	0.012	0	54
6	Hunts Creek Local	69.4	13.4	2442.3	610.2	0.026	0	45
7	Above Moose Creek Dam Local	104.4	25.5	2094.1	481.7	0.012	1	34
8	Below Moose Creek Dam Local	7.4	2.1	521.7	475.7	0.004	0	3
9	Little Chena (w/out area above mine)	364.6	40.2	2905.8	495.4	0.011	0	39
10	Upper Fairbanks Local	168.1	38.2	1312.2	446.2	0.004	20	5
11	Lower Fairbanks Local	58.0	14.3	1355.0	400.3	0.013	35	4

GeoHMS was used to delineate the stream paths in the upper portions of the basin where there is considerable elevation change. The reach from the confluence upstream to Hunts Creek was manually delineated using high-resolution imagery to capture the entire length of the meandering river in the flatter areas. Several basin physical characteristics were estimated, including area, stream length, elevation, and slope (Table 10). A background map file and all physical characteristics were exported from GeoHMS and imported to the HMS model (Figure 10).

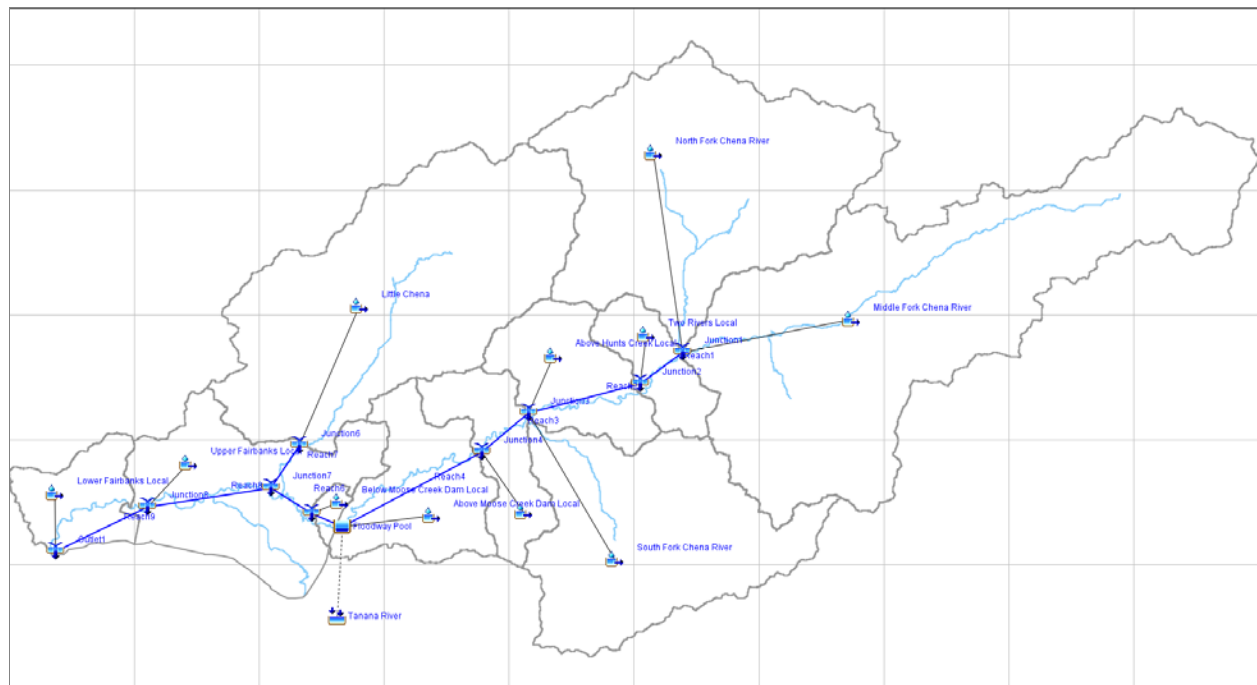


Figure 10. HMS Chena Basin Model schematic.

3.1.2 Soil infiltration and loss

The Soil Moisture Accounting (SMA) loss model was used to simulate infiltration in HMS. The SMA model continuously accounts for soil moisture, using ET , percolation to deeper layers, and lateral flow to dry out the soil layers between events. Three soil layers were used in the HMS model of the Chena Basin. Lateral flow from the bottom two layers contributed to baseflow through the Linear Reservoir method (described in the next section). No losses to deep percolation from the bottom layer were allowed to maintain a complete water balance. An evaluation of subbasin land use, permafrost coverage, and soil components was necessary to estimate parameters for the SMA loss model. Figure 11 shows how the SMA model is implemented in HMS.

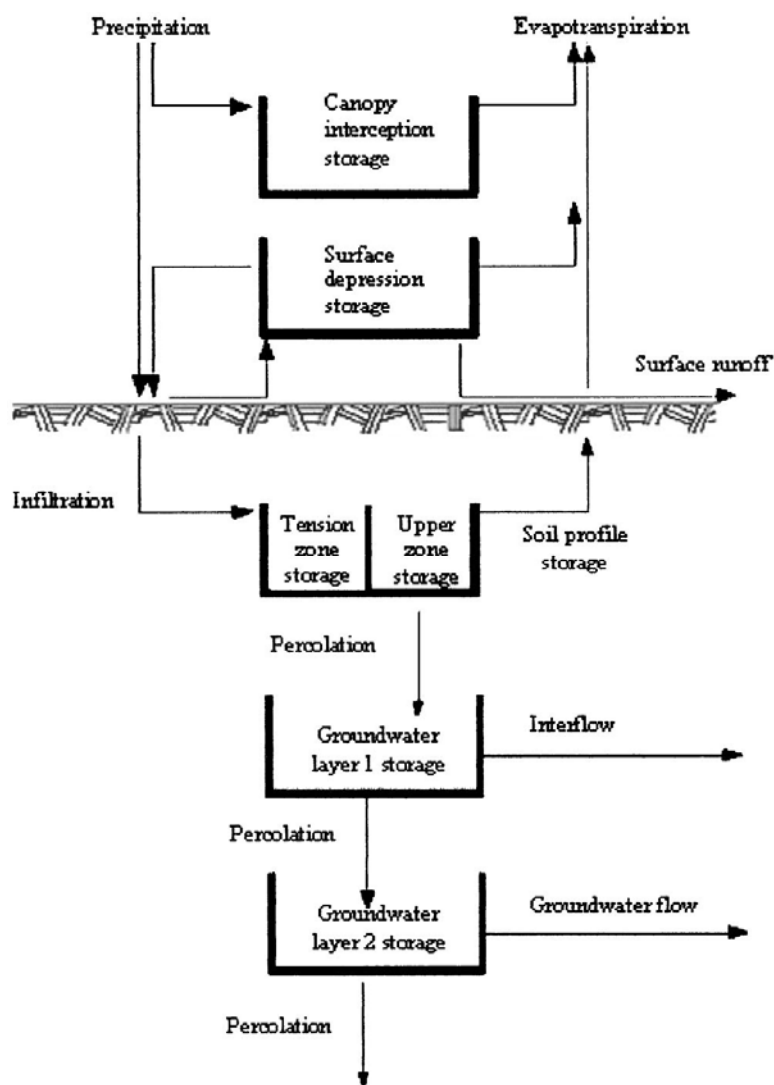


Figure 11. Soil Moisture Accounting (SMA) model diagram (from Bennett 1998).

3.1.3 Land use

The National Land Cover Database (Homer et al. 2007) for Alaska was used to estimate the land use types for each subbasin (Table 11). The majority of the watershed is forested, approximately 53% evergreen forest and 21% deciduous forest. Approximately 3% of the total watershed is developed, with almost all of the developed land located in the Upper and Lower Fairbanks subbasins (Table 10).

Table 11. Land use type in Chena subbasins (%).

Land use	1	2	3	4	5	6	7	8	9	10	11
Barren Land	1	1	0	0	0	0	0	0	1	1	1
Cultivated Crops	0	0	0	0	0	0	0	0	0	1	1
Developed	0	0	0	0	0	0	0	2	0	19	37
Deciduous Forest	13	15	42	37	21	22	31	53	25	28	25
Evergreen Forest	50	54	36	38	61	57	36	21	45	25	17
Mixed Forest	3	3	6	11	5	10	11	9	14	4	3
Open Water	0	0	1	1	0	1	1	2	0	2	3
Shrub/Scrub	29	26	11	5	7	0	3	2	7	1	1
Woody Wetlands	2	1	4	9	4	10	15	11	6	18	10
Other	1	1	0	0	0	0	0	0	0	0	1

3.1.4 Baseflow

The baseflow was modeled using the Linear Reservoir method within HMS. This method is used with the SMA loss model to continuously simulate subsurface flow. Lateral flow from the bottom two groundwater layers in the SMA model enter the same two layers within the baseflow and can be used to represent baseflow hydrographs from layers with varying conductivity. Within each baseflow layer, there are two parameters that determine the rate of baseflow: storage coefficient and maximum storage. These parameters were estimated using the method outlined in Fleming (2002). This method reduces the total number of parameters by accounting for the timing completely within the SMA model and routing the baseflow through the Linear Reservoir method in one timestep.

The storage coefficient and maximum storage for each layer can be found by analyzing available discharge data and calculating the recession constant following events. The baseflow recession constant, K , is found by

$$Q_t = Q_o K^t \quad (9)$$

Where Q_t is the baseflow at time, t , and Q_o is the initial baseflow. The Linear Reservoir parameters are related to the recession constant by

$$\text{Storage Coefficient (hr)} = -\frac{1}{\ln(K)} \quad (10)$$

$$\text{Storage (ft}^3\text{)} = -\frac{q_t}{\ln(K)} \quad (11)$$

Historical discharge data on the Chena River at the Two Rivers and the Fairbanks stations were used in estimating the parameters. Baseflow recharge immediately following an event is assumed to come from the upper groundwater layer, while the longer baseflow recession evident in the fall and winter months comes from the slower-moving lower groundwater layer. The flow immediately following six events between 2003 and 2009 was used to estimate the parameters for the upper groundwater layer. Discharge data between September and November for the period of record were used to estimate parameters for the lower groundwater layer (Table 12).

Table 12. Baseflow parameters estimated for using streamflow recession.

Parameters	Upper groundwater	Lower groundwater
Storage Coefficient (hr)	80–135	1100
Maximum Storage (in.)	0.9–0.22	2

3.1.5 Surface runoff

Excess precipitation that does not infiltrate the soil but travels on the surface to the basin outlet was modeled using the Clark Unit Hydrograph method. In this method, two parameters are needed to transform precipitation to outflow at the basin outlet: time of concentration, t_c , in hours and storage coefficient, R , in hours. The time of concentration was estimated using the Williams formula (Maidment 1993)

$$t_c = 0.355LA^{-0.1}S^{-0.2} \quad (12)$$

where

L = longest flow path (mi)

A = basin area (mi²)

S = average channel slope.

In most cases, the estimated value using the Williams equation was doubled to match results during calibration. The ratio of the storage coefficient to the time of concentration is typically constant over a region. A ratio of 1.5, determined by calibration, gave the best results.

3.1.6 Routing

The Muskingum-Cunge method was used to route the flow downstream through each reach. This method requires a representative 8-point cross-section for each reach, which extends into the overbanks. The Chena River regularly goes out of banks at high flows in the reaches upstream of the Moose Creek Dam. The densely forested land causes an attenuation of the discharge hydrograph. Google Earth was used to determine the overbank elevations and channel locations and top widths (Figure 12). Google Earth also uses the 60-m National Elevation Dataset to estimate elevations and additionally provides a profile graph of the delineated line. Channel depth, y , was then estimated using Manning's equation, assuming a trapezoid channel with 2:1 side slope:

$$\frac{Qn}{1.49\sqrt{s}} = AR^{2/3} = (Wy - 2y^2) \left(\frac{Wy - 2y^2}{W + 0.472y} \right)^{2/3} \quad (13)$$

where

- A = channel area (ft²)
- R = wetted perimeter (ft)
- Q = bankfull flow (cfs)
- n = Manning channel roughness coefficient
- s = average reach slope
- W = top width (ft).

Manning's roughness coefficients of 0.031 to 0.05 were used for the main channel and 0.1 to 0.15 in the overbanks. Bankfull flow was estimated based on conversations with the Alaska District. Table 13 gives the reach properties used in HMS.

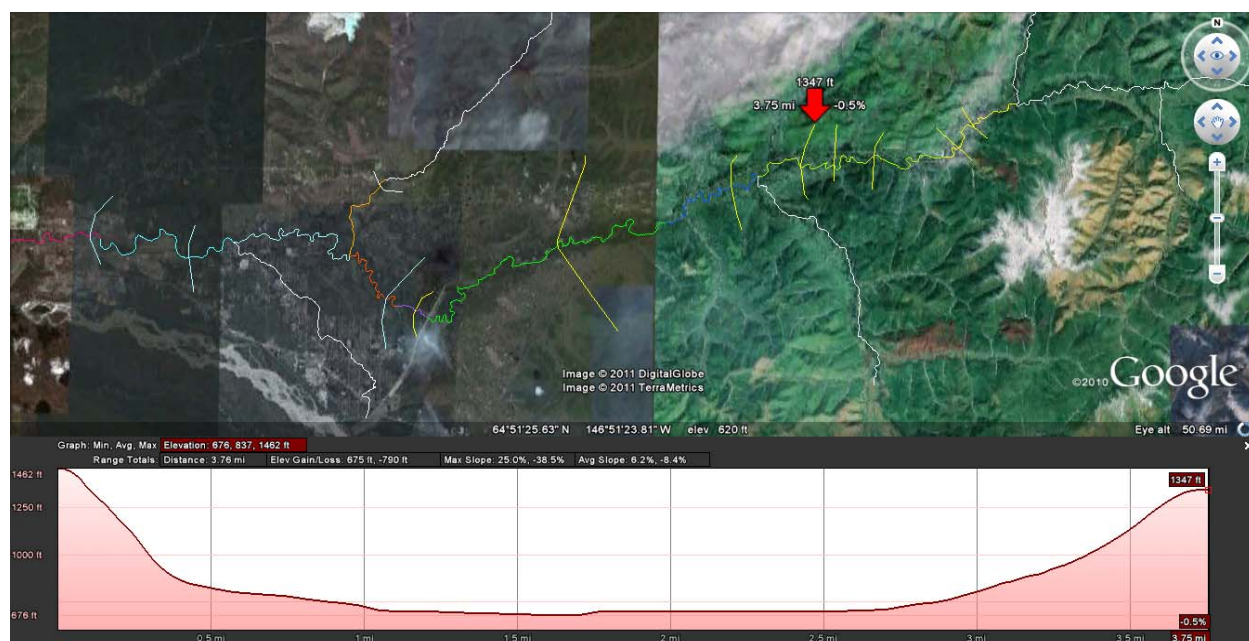


Figure 12. Representative cross-section elevations were obtained from Google Earth (© 2011 Google).

Table 13. Chena River Basin reach properties.

Reach	Description	Length (mi)	Slope	Top width (ft)	Bankfull flow (cfs)
1	Confluence of North and Middle Fork to gage at Two Rivers, AK	6.7	0.00265	148.5	6000
2	Gage at Two Rivers, AK to confluence with Hunts Creek	14.4	0.00075	150.7	6000
3	Confluence with Hunts Creek to gage below Hunts Creek	9.0	0.00104	153.2	7000
4	Gage below Hunts Creek to Moose Creek Dam	24.4	0.00102	147.5	7000
5	Moose Creek Dam to gage below Moose Creek Dam	3.5	0.00019	142.3	8000
6	Gage below Moose Creek Dam to confluence with Little Chena River	17.8	0.00038	149.7	8000
7	Gage on Little Chena River to confluence with Chena River	17.2	0.00061	75.0	3000
8	Confluence of Chena and Little Chena to gage at Fairbanks	14.3	0.00013	165.9	10000
9	Gage at Fairbanks to confluence with Tanana	11.3	0.00049	177.2	10000

3.1.7 Flood control

The Moose Creek Dam project is modeled as a reservoir with two outflow structures. Typically, flow passes through the Moose Creek Dam and down

the Chena River. A rule curve maintains flow along the Chena River until discharge reaches 8300 cfs. Additional flow above this amount is routed through the floodway to the Tanana River. An elevation–storage function determines the water volume within the floodway (Fig. 13), and an elevation–discharge relationship for the spillway determines the discharge into the Tanana River (Johnson 2011) (Table 14).

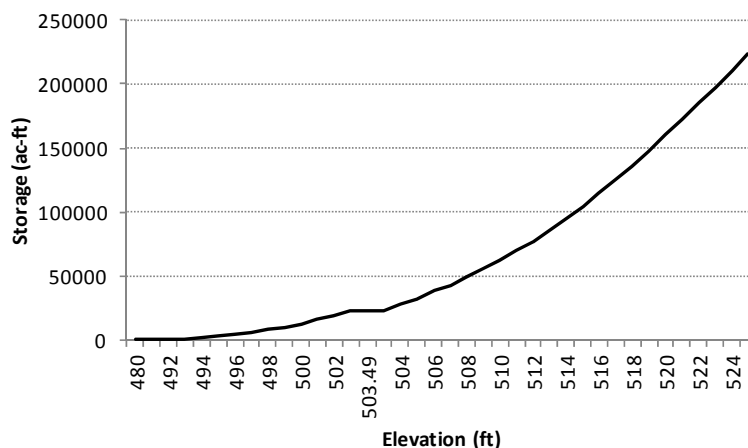


Figure 13. Elevation–storage relationship for Moose Creek Dam floodway.

Table 14. Elevation-discharge relationship for floodway sill.

Elevation (ft)	Discharge (cfs)
480.00	0
506.65	0
506.75	200
507.16	2000
507.73	5000
508.62	10000
510.21	20000
512.74	40000
515.96	74000
521.88	160000

3.2 Meteorological model

3.2.1 Input data

Hourly precipitation data from 11 meteorological stations were used in the HMS model. Data from gages within 60 miles of the subbasin centroid were interpolated using the Inverse Distance Weighted method to estimate the subbasin precipitation with available data.

Temperature data from the meteorological stations were used in the temperature index snow model. Each subbasin is assigned a single gage and a lapse rate, which is used to estimate the hourly temperature in each of the elevation bands. The selected gage was determined by which gage was located within the basin, most representative of the subbasin elevation, and was not missing data during the simulation Table 15 gives the percent of area per elevation band in each subbasin, and temperature stations assigned to each. The air temperature lapse rate was set to a value of $-3.0^{\circ}\text{F}/1000\text{ ft}$ based on the average lapse rate for April and May as described above.

Table 15. Temperature station and elevation band in each subbasin.

Elevation band				BAND 1	BAND 2	BAND 3	BAND 4	BAND 5
Elevation range (ft)				400–1000	1000–2000	2000–3000	3000–4000	4000–5220
Average elevation (ft)				700	1500	2500	3500	4500
Subbasin	Temp station	Elev (ft)	Lapse rate ($^{\circ}\text{F}/1000\text{ft}$)	Percent area of each subbasin				
North Fork Chena River	AAF	2800	-3.0	2	34	55	9	0
Middle Fork Chena River	AAF	2800	-3.0	3	39	42	14	2
Two Rivers Local	AAG	1850	-3.0	18	60	20	2	0
Above Hunts Creek Local	AAG	1850	-3.0	31	59	10	0	0
South Fork Chena River	AAG	1850	-3.0	11	69	19	1	0
Hunts Creek Local	AAG	1850	-3.0	43	55	2	0	0
Above Moose Creek Dam Local	FIA	453	-3.0	77	23	0	0	0
Below Moose Creek Dam Local	FIA	453	-3.0	100	0	0	0	0
Little Chena River	AAE	2000	-3.0	19	58	21	2	0
Upper Fairbanks Local	FIA	453	-3.0	95	5	0	0	0
Lower Fairbanks Local	FIA	453	-3.0	95	5	0	0	0

3.2.2 Snow model development

In the HMS temperature index snow model, snow accumulates and melts snow based on the input precipitation and air temperature data. Precipitation falls as snow when the air temperature is below the rain/snow discriminating temperature, T_{PX} . The temperature of a snowpack varies over time because of energy transfer between the snowpack and the surrounding air. During periods of lower air temperatures, the snow is cooled as heat from the snowpack is transferred to the air. This causes the *cold content* of the snowpack to increase. When the air temperature is greater than the snow temperature, heat is transferred into the snowpack, decreasing the cold content, which must be zero when the snowpack reaches its maximum base temperature, T_{BASE} , usually set to 0°C.

When the air temperature rises above freezing, two conditions must be met before snowmelt liquid water can reach the base of the snowpack. The cold content of the snowpack must be depleted and the liquid water deficiency must be filled. The cold content, cc , is defined as the amount of heat required to raise the temperature of the snowpack to 0°C. Cold content can be conveniently described in terms of the equivalent inches of ice. When the snowpack is at an isothermal 0°C throughout its depth, the cold content is zero. Before runoff can occur, the storage capacity of the snowpack, known as the liquid water capacity, LW_{cap} , must also be filled. This value is given as a percentage of the snowpack, typically 2–5%.

Snow can melt at two interfaces: at the snow–ground interface driven by heat from the earth; and at the snow–air interface, driven by heat transfer from the atmosphere. In the Chena River watershed, ground melt is not considered. At the air interface, different melt rate coefficients are used for dry conditions versus rain conditions. The dry melt rate coefficient is a function of a degree-day index, which allows the rate to change during the season as the albedo and density of the snow change. During rainy conditions, snow melts at a faster rate because heat from the liquid precipitation warms the snowpack.

3.2.3 Chena River Watershed snow conditions

The snowpack of the Chena River Watershed begins accumulating in early October and continues to accumulate until April or May. In general, the air

temperature remains below freezing during this time and episodes of mid-winter snowmelt are relatively rare. The average maximum SWE observed at each station along with the maximum recorded SWE at each station are listed in Table 16. The average maximum SWE is strongly influenced by the elevation of the station as shown in Figure 14. The maximum SWE is reached at the end of the accumulation period and then the snowmelt period begins. The date of the beginning of the snowmelt period is quite variable from year to year and also varies with elevation as shown in Figure 15. The snowmelt period corresponds to the time when the air temperatures rise above freezing, shown in Figure 4 to happen in mid-2840 April to late April. Prior to the onset of snowmelt, the Chena River is in recession as seen in Figure 5.

Table 16 Average maximum SWE and maximum SWE observed at each station in the Chena River Watershed.

Gage	ID	Elev. (ft)	Average max. SWE (in.)	Max SWE (in)
Fairbanks F.O.		450	4.5	11.2
Little Chena Ridge	AAE	2000	5.7	11.1
Mt. Ryan	AAF	2800	6.5	12.5
Monument Creek	AAG	1850	5.5	9.8
Munson Ridge	AAH	3100	8.7	18.4
Tuechet	AAI	1640	4.6	9.4
Upper Chena	AAJ	2850	7.0	13.3

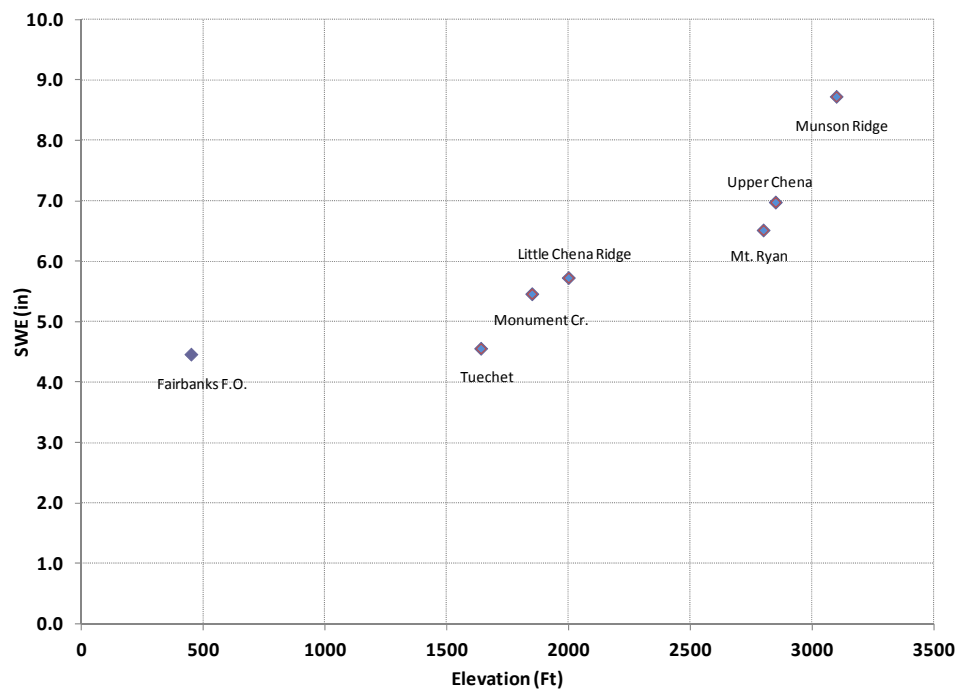


Figure14. Average maximum SWE and elevation observed at each station in the Chena River Watershed.

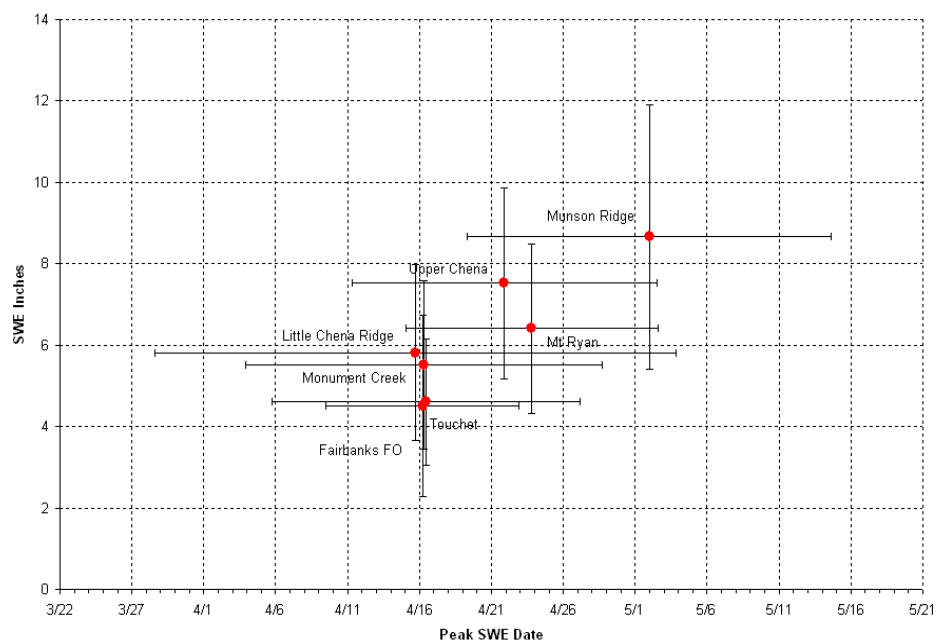


Figure 15. Average annual maximum SWE and average date of the last day of the accumulation period ($\pm$ one standard deviation).

3.2.4 Snow model calibration

The snow model melt rate values were calibrated by adjusting the melt rate factor until the sum of squares difference between the observed and modeled SWE were minimized. Only the melt period was modeled. All the stations and all the years were calibrated simultaneously. The calibration period was chosen to be to extend from the date of maximum SWE until the date of zero SWE. The dates of the calibration period for each gage are listed in Appendix A. It was assumed that the cold content and the initial liquid water content of the snow were both zero at the start of each calibration period. All parameter values used in the snow model are given in Table 17. Snow model calibration results for each station were calculated (Fig. 16), including the average model error (black line), maximum and minimum error (red lines), and standard deviation (bars) for each day of the simulation period.

Table 17. Snow parameters used in the temperature index snow model

Snow model parameter		Value
Snow/rain discriminating temperature	T_{PX}	34°F
Snow melt temperature	T_{BASE}	32°F
Wet meltrate	R_{MR}	0.25 in./°F-day
Rain rate limit	L_{rain}	1.0 in./day
Antecedent temperature index-meltrate coefficient	K	0.98
Cold Limit	L_{snow}	5 in./day
Antecedent temperature index-coldrate coefficient	$C_{AT/CC}$	0.4
Liquid water capacity	LW_{cap}	5%
Groundmelt rate	R_{GM}	0.0 mm/day
Antecedent Temperature Index, ATI (°F-day)	Meltrate, C_{MR-dry} (in./°F-day)	Coldrate, C_{CR} (in/°F-day)
0	0.39	0.005
1000	0.39	0.005

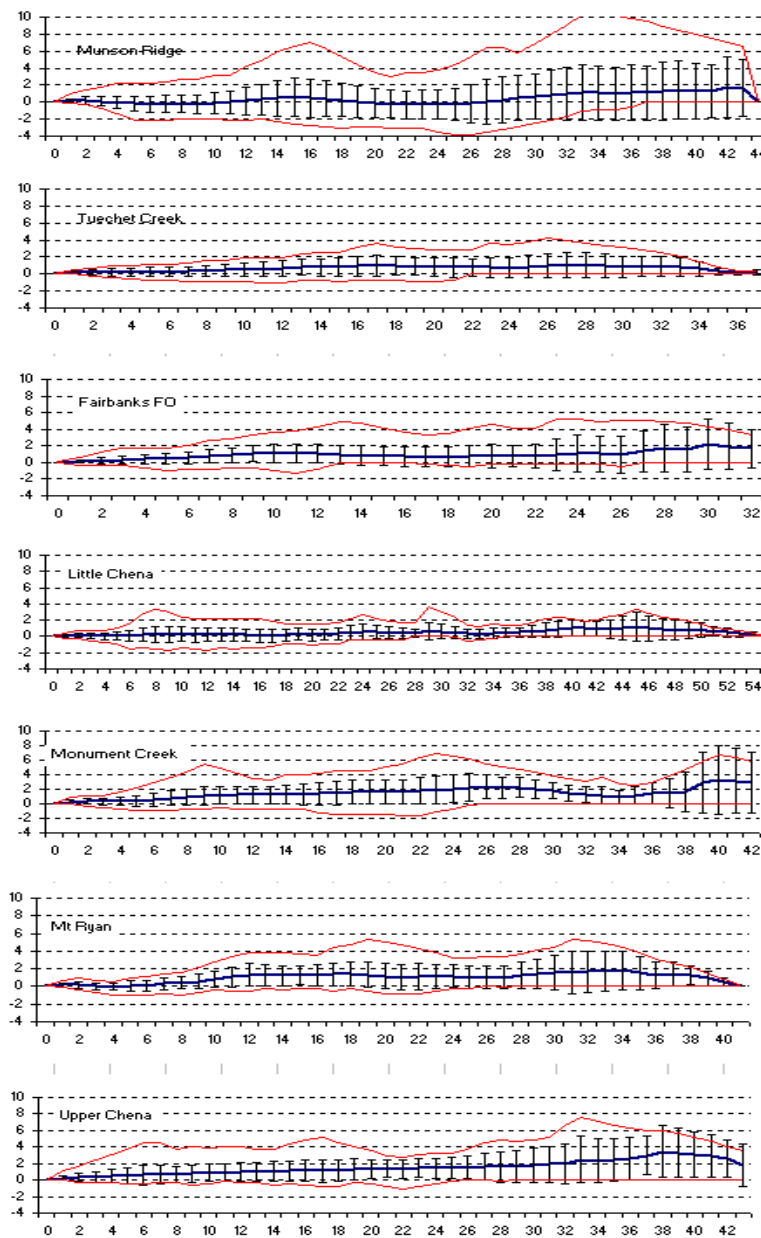


Figure 13. Average snow model error in inches SWE, plotted against number of days after start of simulation.

4 Flow Simulation

4.1 Calibration

The HMS model was calibrated to 3 years: 1994, 2008 and 2009. For each year the simulation period began on 1 April and ran continuously through 31 August to capture the entire snowmelt and summer period. Calibration focused on matching the peak flows during large events and the discharge recession during low flows. All 3 calibration years had high flow events mid-summer; in 2009 a large snowmelt event occurred at the beginning of the season. Each of the 3 years was calibrated separately, and then the results were used to develop one set of parameters that gave the best results for all 3 years.

To test the overall performance of the model, the modeled and observed values were compared for overall average discharge, peak discharge, timing of peak discharge, and the Nash-Sutcliffe efficiency was computed (Table 18). The Nash-Sutcliffe efficiency, E , is defined as

$$E = 1 - \frac{\sum_{i=1}^n (O_i - M_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (14)$$

where O_i is the observed value and M_i is the model value at time i (Nash and Sutcliffe 1970). E can range from 1 to $-\infty$, with an efficiency close to 1 signifying a strong fit between the modeled and observed values and a negative value indicating that the average observed value would lead to better results than the model. The model's capability in matching the peak discharge and the timing of the peak was measured by the error between the observed and modeled results. Figure 14–19 show the observed and modeled calibration results at three locations: Chena River at Two Rivers, Little Chena River near Fairbanks, and Chena River at Fairbanks.

Table 18. Calibration results.

1994	Chena River at Two Rivers		Little Chena River		Chena River at Fairbanks	
Statistics	Model	Observed	Model	Observed	Model	Observed
Average discharge (cfs)	1839.3	1414.6	298.7	394.5	2943.3	2529.1
Peak discharge (cfs)	17894.0	18300.0	2495.1	2490.0	10870.0	9630.0
Error timing of peak (hr)	1		12		108	
Nash-Sutcliffe	0.85		0.85		0.81	
2008	Chena River at Two Rivers		Little Chena River		Chena River at Fairbanks	
Statistics	Model	Observed	Model	Observed	Model	Observed
Average discharge (cfs)	1029.3	1295.5	514.8	404.6	2596.0	2501.4
Peak discharge (cfs)	7625.4	8490.0	2060.8	1740.0	10751.0	9120.0
Error timing of peak (hr)	8		15		10	
Nash-Sutcliffe	0.72		0.46		0.84	
2009	Chena River at Two Rivers		Little Chena River		Chena River at Fairbanks	
Statistics	Model	Observed	Model	Observed	Model	Observed
Average discharge (cfs)	1513.1	1614.7	513.0	378.2	2420.0	2457.2
Peak discharge (cfs)	10631.0	10300.0	2786.1	2140.0	11122.0	9620.0
Error, timing of peak (hr)	4		21		29	
Nash-Sutcliffe	0.87		0.24		0.88	

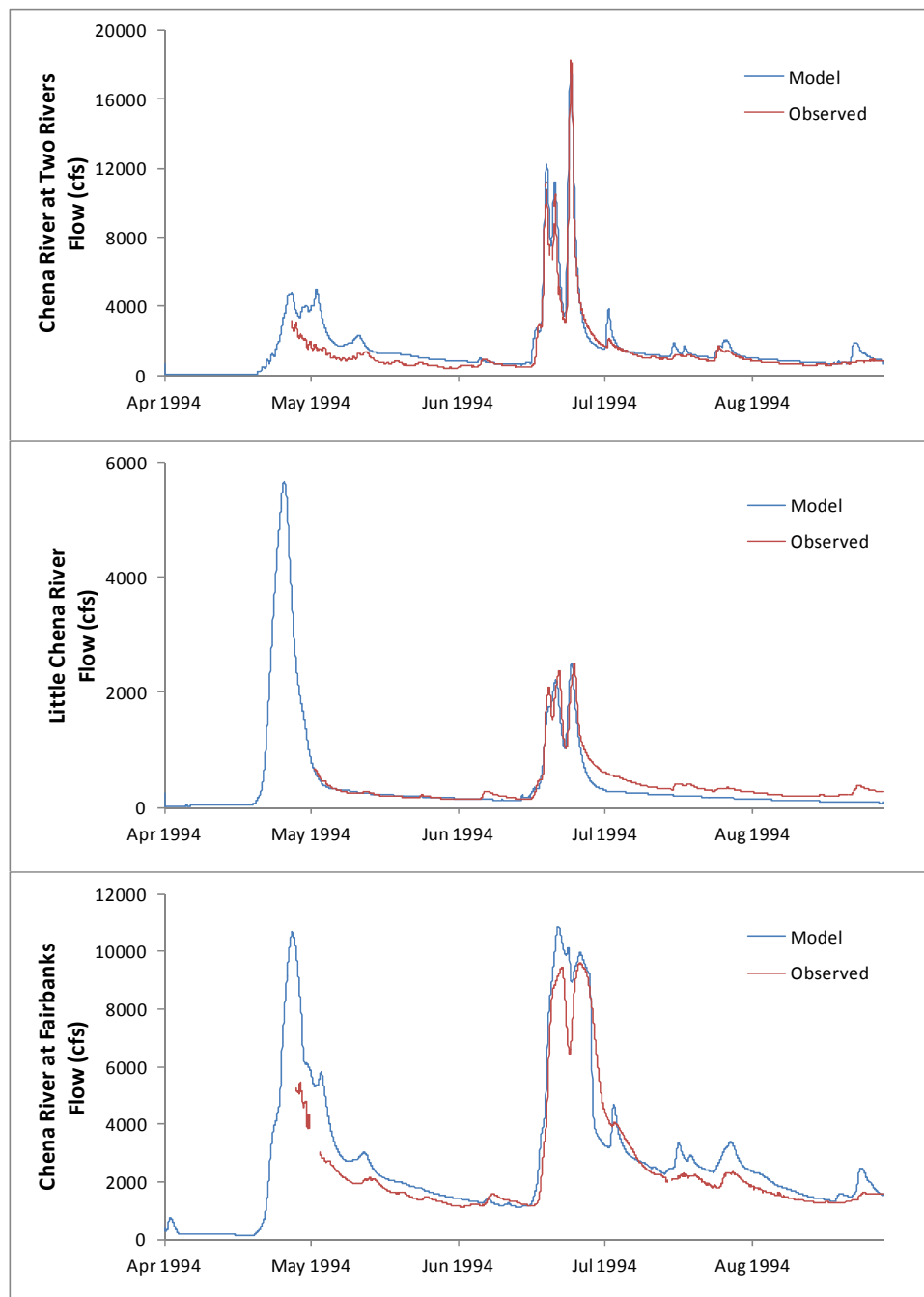


Figure 14. Calibration results for 1994.

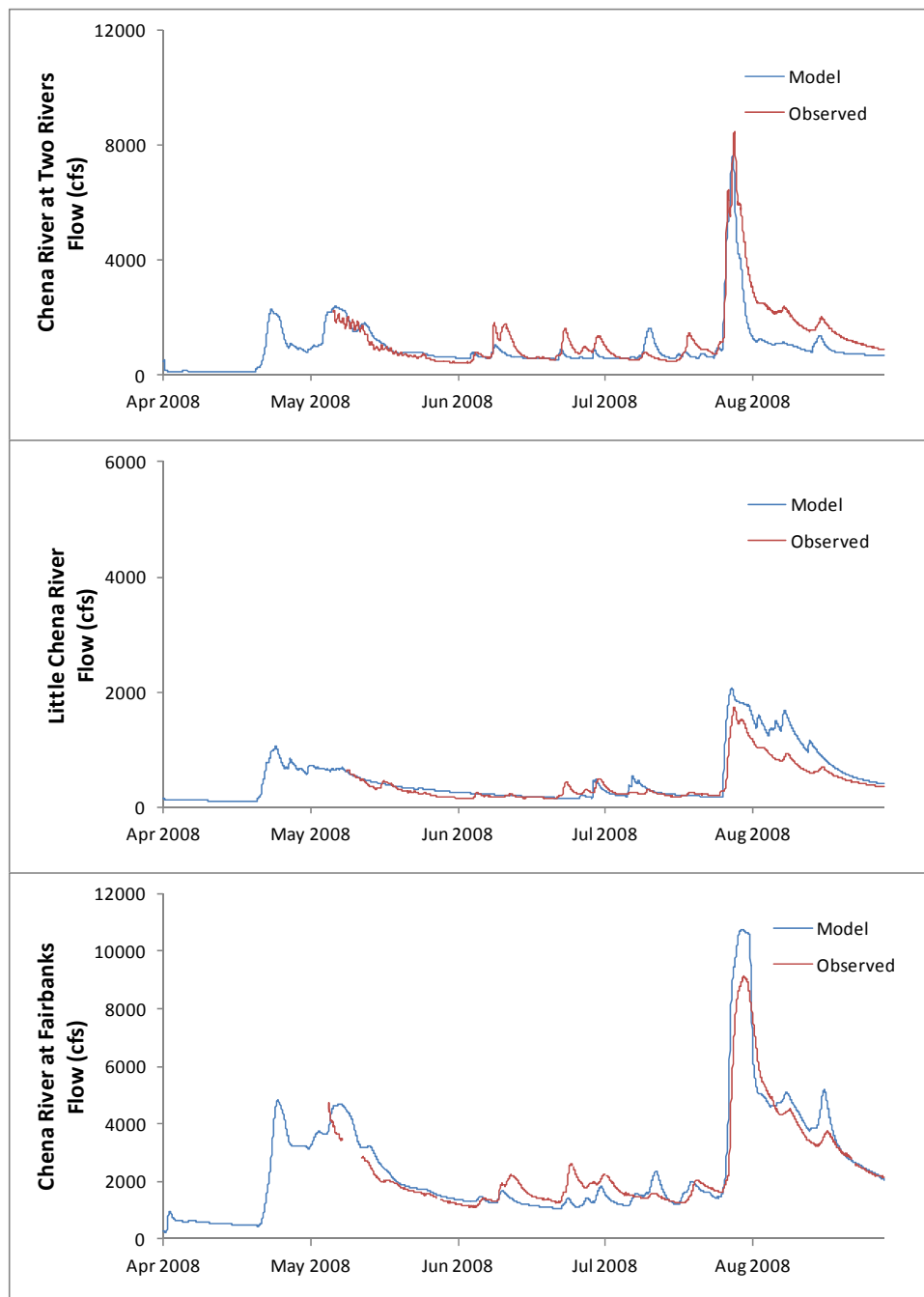


Figure 15. Calibration results for 2008.

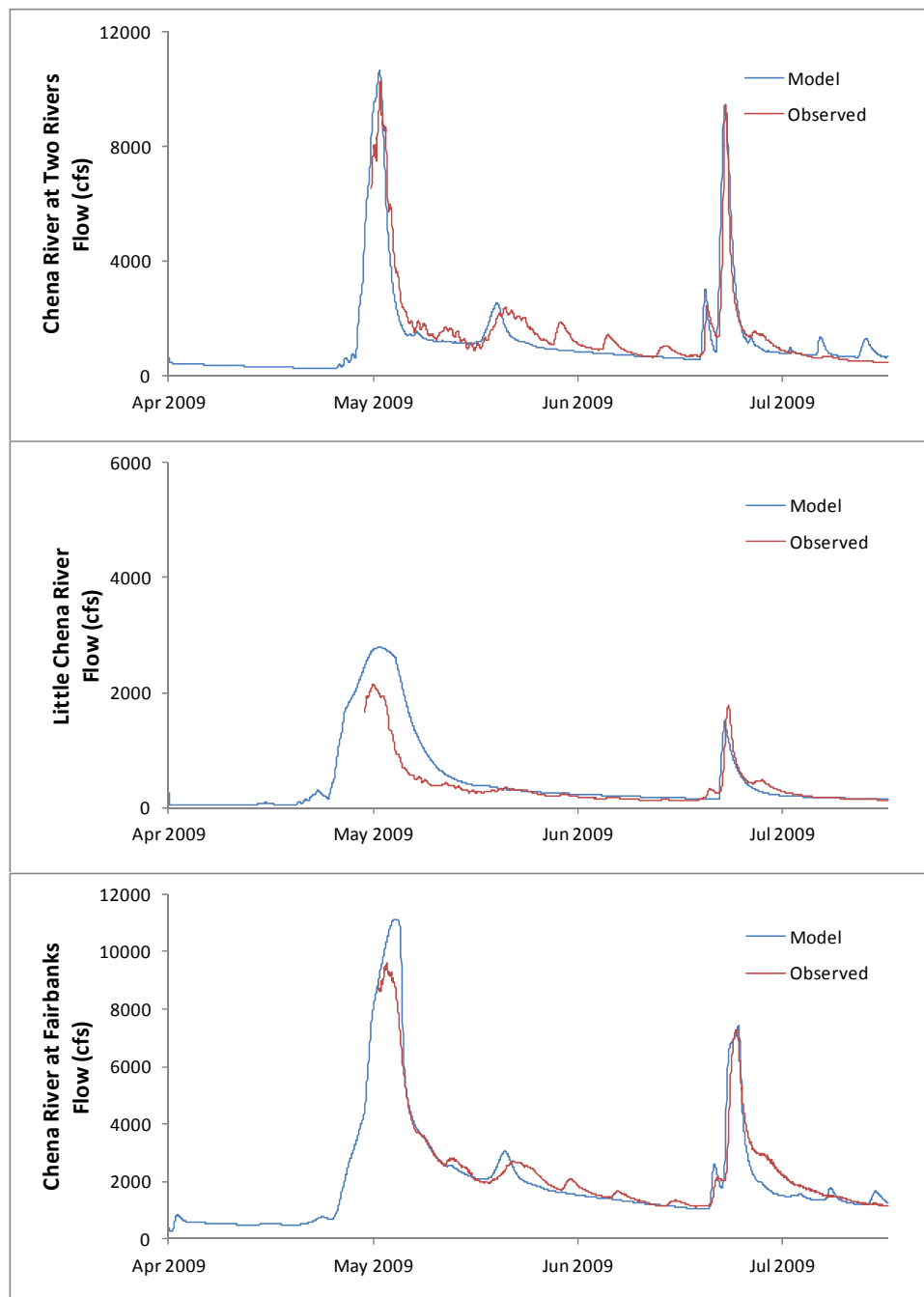


Figure 16. Calibration results for 2009.

4.2 Validation

The model parameters developed during calibration were combined into a final set of parameters that gave the best results during each of the 3 calibration years (Figure 17–22). The model was then validated against 3 years: 1992 and 1995, and the 1967 flood of record in Fairbanks (Figure

20–25). The final validated parameters developed for the HMS basin model of the Chena River Watershed are given in Table 21–23.

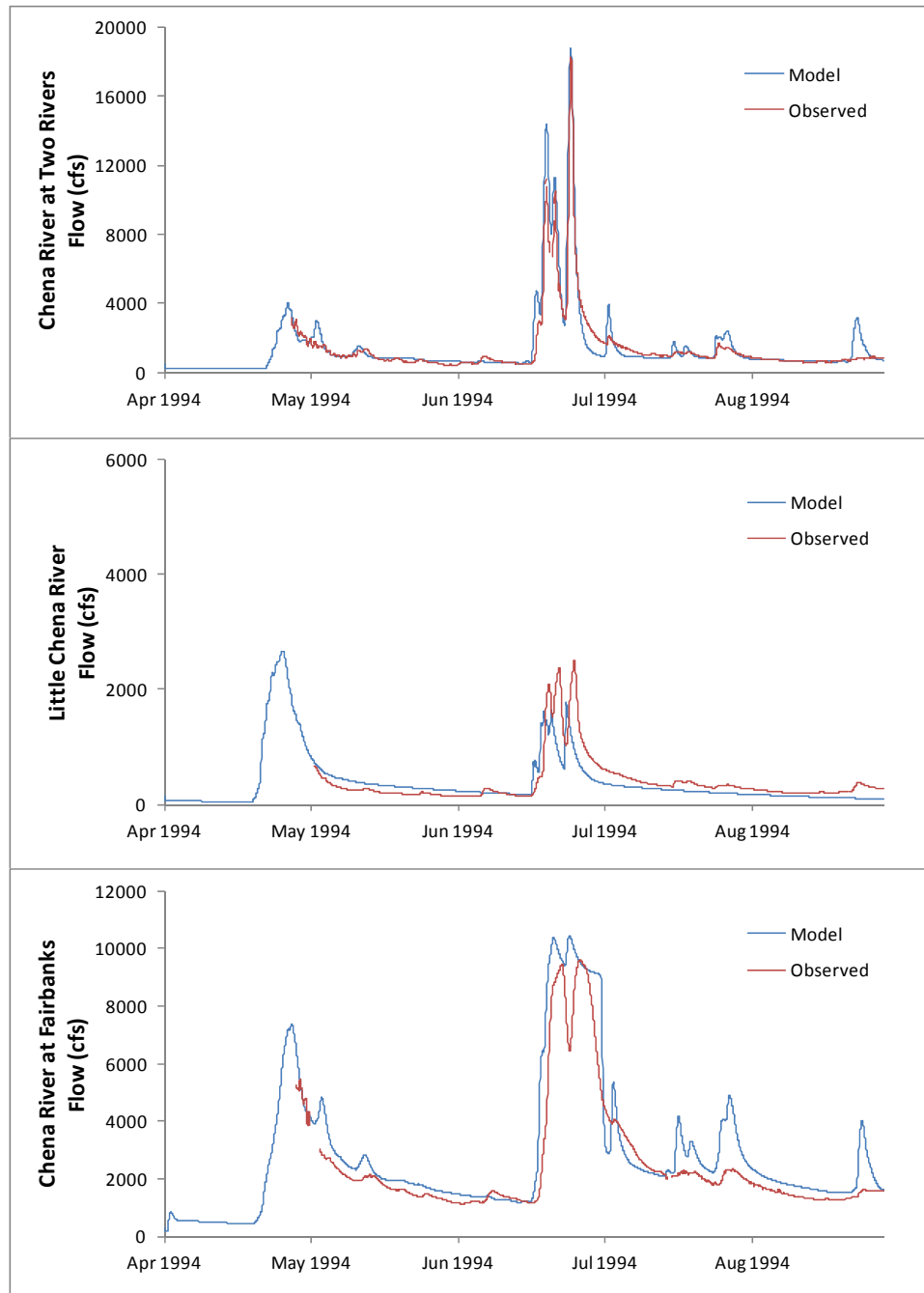


Figure 17. Validation results for 1994.

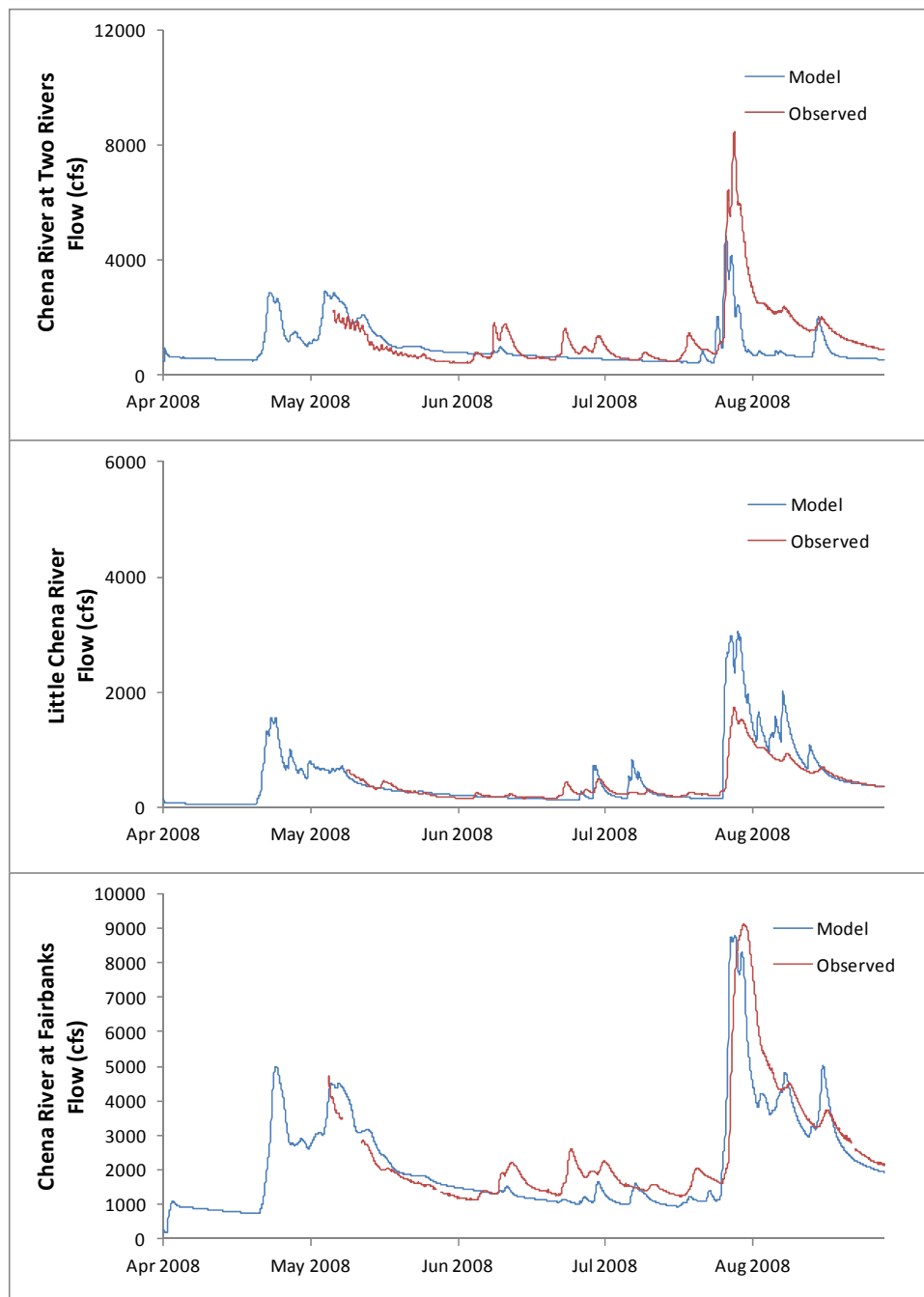


Figure 18. Validation results for 2008.

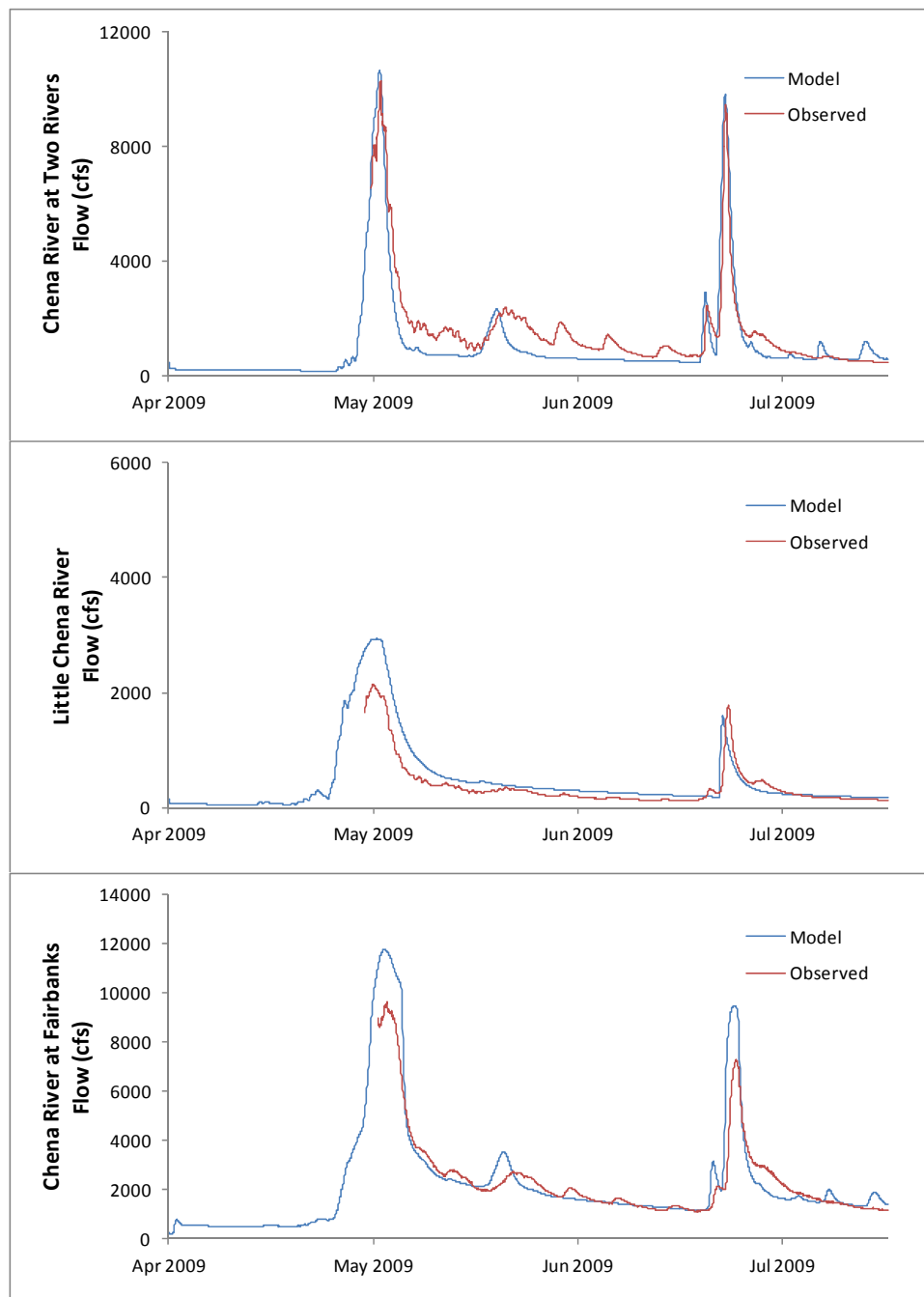


Figure 19. Validation results for 2009.

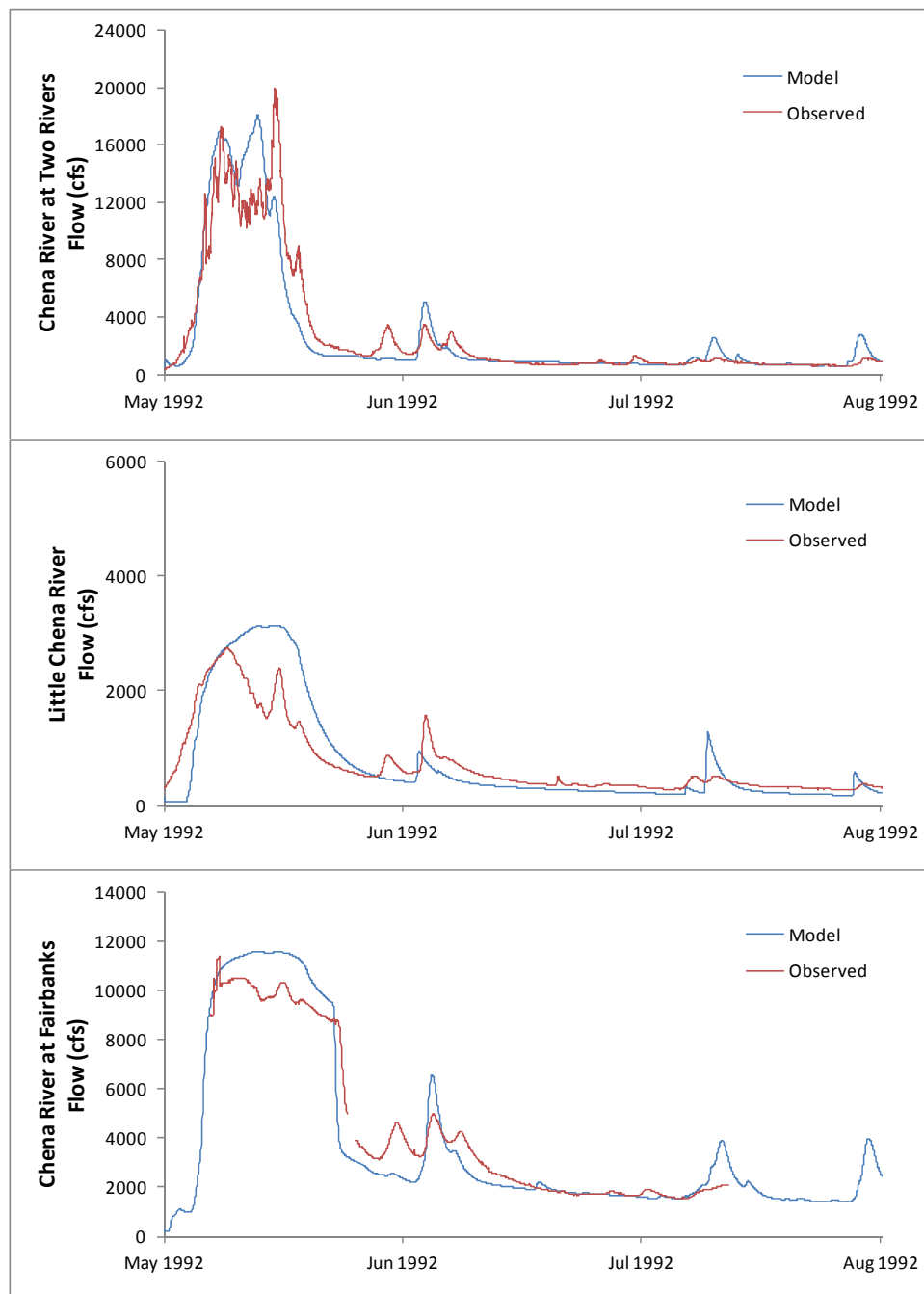


Figure 20. Validation results for 1992.

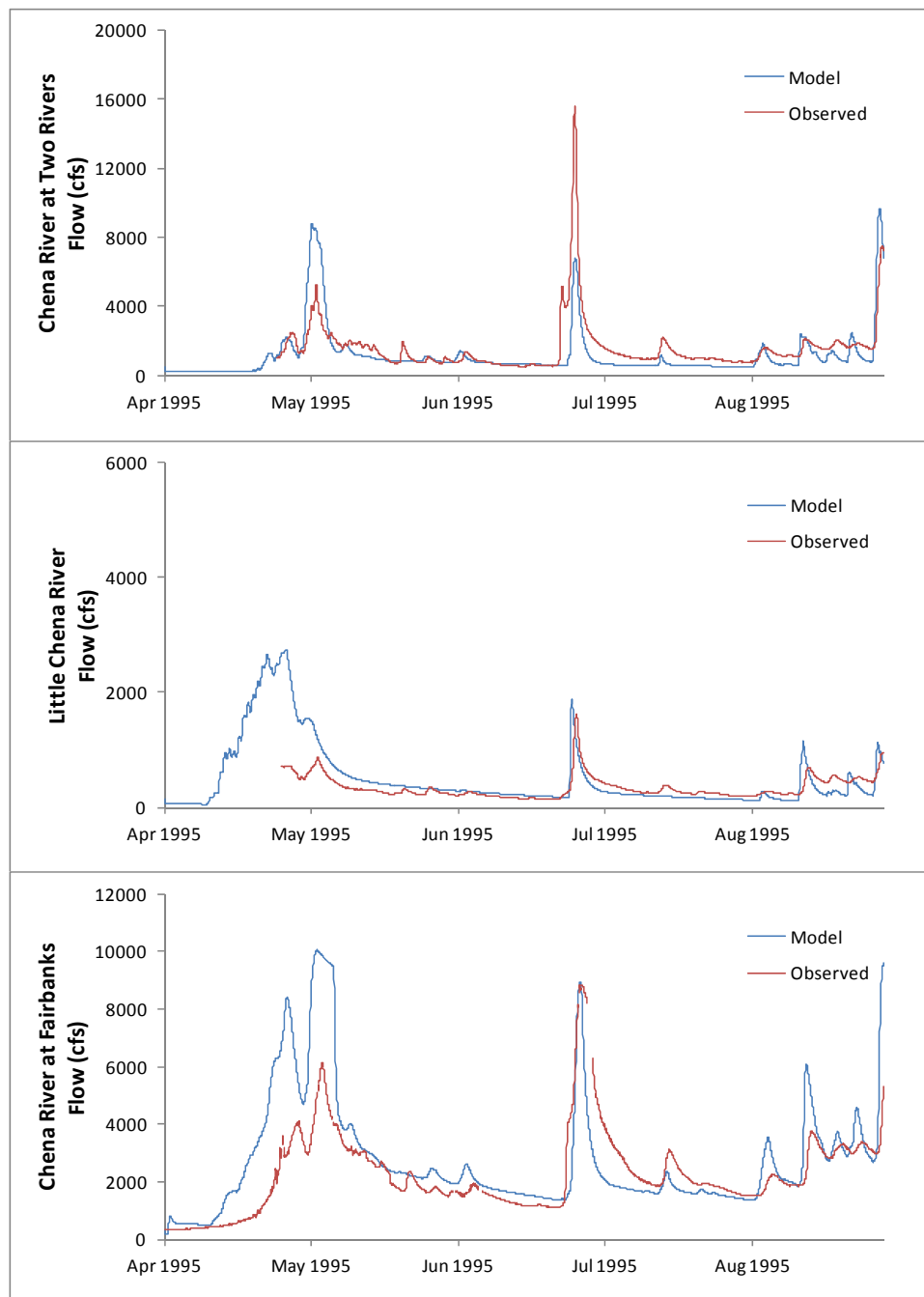


Figure 21. Validation results for 1995.

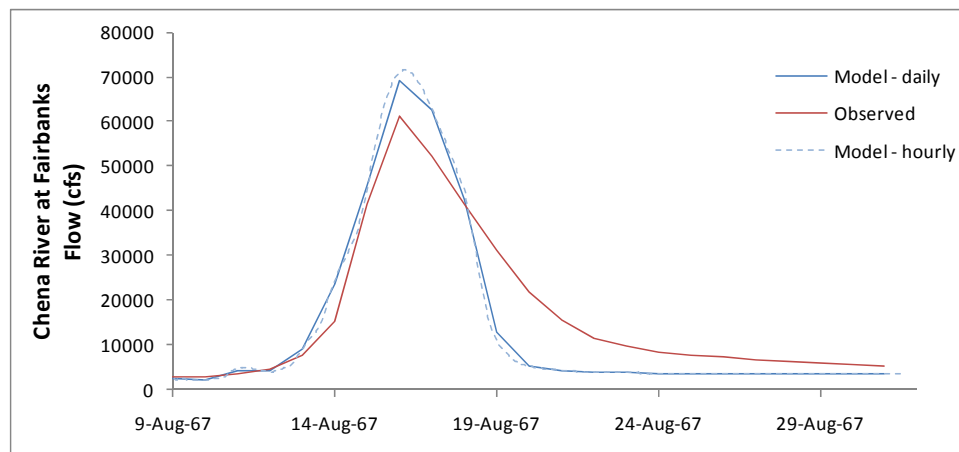


Figure 22. Validation results for 1967.

Table 19. Validation results.

1994	Chena River at Two Rivers		Little Chena River		Chena River at Fairbanks	
Statistics	Model	Observed	Model	Observed	Model	Observed
Average discharge (cfs)	1556.9	1414.6	321.3	394.5	3065.8	2529.1
Peak discharge (cfs)	18821.0	18300.0	1772.4	2490.0	10426.0	9630.0
Error timing of peak (hr)	2		41		51	
Nash-Sutcliffe	0.85		0.55		0.75	
2008	Chena River at Two Rivers		Little Chena River		Chena River at Fairbanks	
Statistics	Model	Observed	Model	Observed	Model	Observed
Average discharge (cfs)	914.2	1295.5	495.6	404.6	2262.7	2501.4
Peak discharge (cfs)	4851.4	8490.0	3041.4	1740.0	8802.9	9120.0
Error timing of peak (hr)	42		19		44	
Nash-Sutcliffe	0.24		-0.18		0.73	

Table 20 (cont'd). Validation results.

2009	Chena River at Two Rivers		Little Chena River		Chena River at Fairbanks	
Statistics	Model	Observed	Model	Observed	Model	Observed
Average discharge (cfs)	1293.6	1614.7	504.7	378.2	2613.7	2457.2
Peak discharge (cfs)	10660.0	10300.0	2935.7	2140.0	11751.0	9620.0
Error, timing of peak (hr)	4		21		29	
Nash-Sutcliffe	0.81		0.57		0.74	
1992	Chena River at Two Rivers		Little Chena River		Chena River at Fairbanks	
Statistics	Model	Observed	Model	Observed	Model	Observed
Average discharge (cfs)	2737.7	2792.1	762.8	734.5	4448.0	4368.7
Peak discharge (cfs)	18081.0	20000.0	3131.7	2750.0	11588.0	11400.0
Error timing of peak (hr)	55		148		120	
Nash-Sutcliffe	0.85		0.47		0.90	
1995	Chena River at Two Rivers		Little Chena River		Chena River at Fairbanks	
Statistics	Model	Observed	Model	Observed	Model	Observed
Average discharge (cfs)	1301.6	1592.5	415.5	347.7	2755.3	2238.9
Peak discharge (cfs)	6785.0	15600.0	1892.2	1610.0	8932.0	8840.0
Error timing of peak (hr)	1		23		7	
Nash-Sutcliffe	0.32		-2.3		-0.25	
9-31 August 1967	Chena River at Fairbanks					
Statistics	Model	Observed				
Average discharge (cfs)	14105	16377				
Peak discharge (cfs)	69285.0	61246.0				
Error, timing of peak (days)	0					
Nash-Sutcliffe	0.82					

Table 21. HMS Soil Moisture Accounting Loss model parameters

Subbasin	Soil (%)	GW1 (%)	GW2 (%)	Max infiltration (in./hr)	Impervious (%)	Soil Stor. (in.)	Tension Stor. (in.)	Soil perc. (in./hr)	GW1 stor. (in.)	GW1 perc. (in./hr)	GW1 coeff. (hr)	GW2 stor. (in.)	GW2 perc. (in./hr)	GW2 coeff. (hr)
Above Hunts Creek Local	10	10	20	1	0	3	2	0.3	0.5	0.3	200	3	0	1100
Above Moose Creek Dam Local	10	10	20	1	0	3	2	0.3	0.5	0.3	200	3	0	1100
Below Moose Creek Dam Local	10	10	20	1	0	3	2	0.3	0.5	0.3	200	3	0	1100
Hunts Creek Local	10	10	20	1	0	3	2	0.3	0.5	0.3	200	3	0	1100
Little Chena	0	0	10	0.8	0	3	1	0.3	1.5	0.04	100	3	0	1100
Lower Fairbanks Local	10	10	20	1	15	2.5	0.4	0.2	0.25	0.2	100	2	0	1100
Middle Fork Chena River	0	0	10	0.8	0	2.5	2.42	0.1	0.2	0.04	200	4	0	2000
North Fork Chena River	0	0	10	0.8	0	2.5	2.42	0.1	0.2	0.04	200	4	0	2000
South Fork Chena River	10	10	20	1	0	3	2	0.3	0.5	0.3	200	3	0	1100
Two Rivers Local	10	10	20	0.8	0	2.5	2.42	0.3	0.25	0.04	200	3	0	1100
Upper Fairbanks Local	10	10	20	1	10	2.5	0.4	0.2	0.25	0.2	100	2	0	1100

Parameters:

Soil (%), Initial moisture conditions in percent saturation of the top soil layer at the start of the simulation.

GW1 (%), Initial moisture conditions in percent saturation of the upper groundwater layer at the start of the simulation.

GW2 (%), Initial moisture conditions in percent saturation of the lower groundwater layer at the start of the simulation.

Maximum Infiltration (in./hr), maximum rate at which water can infiltrate the surface soil layer.

Impervious (%), percent of the basin which is impervious.

Soil Storage (in.), total storage available in the top soil layer.

Tension storage (in.), amount of water that remains in the soil layer and does not percolate due to gravity, but can be lost by evapotranspiration.

Soil percolation (in./hr), rate at which water flows from the top soil layer to the upper groundwater layer

GW 1 storage (in.), total storage available in the upper groundwater layer.

GW 1 percolation (in./hr), rate at which water flows from the upper groundwater layer to the lower groundwater layer.

GW 1 coefficient (hr), time lag to transform the water stored in the upper groundwater layer to lateral outflow (available to become baseflow)

GW 2 storage (in.), total storage available in the lower groundwater layer.

GW 2 percolation (in./hr), rate at which water flows from the lower groundwater layer to the deep storage (lost from model).

GW 2 coefficient (hr), time lag to transform the water stored in the lower groundwater layer to lateral outflow (available to become baseflow)

Table 22. HMS Linear reservoir baseflow model parameters.

Subbasin	GW1 Initial (cfs/mi ²)	GW1 Coeff. (hr)	GW1 Reservoirs	GW2 Initial (cfs/mi ²)	GW2 Coeff. (hr)	GW2 Reservoirs
Above Hunts Creek Local	0.5	1	1	0.2	1	1
Above Moose Creek Dam Local	0.5	1	1	0.2	1	1
Below Moose Creek Dam Local	0.5	1	1	0.2	1	1
Hunts Creek Local	0.5	1	1	0.2	1	1
Little Chena	0.3	1	1	0.1	1	1
Lower Fairbanks Local	0.5	1	1	0.2	1	1
Middle Fork Chena River	0.3	1	1	0.2	1	1
North Fork Chena River	0.3	1	1	0.2	1	1
South Fork Chena River	0.5	1	1	0.2	1	1
Two Rivers Local	0.3	1	1	0.2	1	1
Upper Fairbanks Local	0.5	1	1	0.2	1	1

Table 23. HMS Clark unit hydrograph transform model parameters.

Subbasin	Time of concentration (hr)	Storage coefficient (hr)
Above Hunts Creek Local	12.57	11.31
Above Moose Creek Dam Local	18.89	17
Below Moose Creek Dam Local	2.54	2.28
Hunts Creek Local	8.85	7.96
Little Chena	40.0	35.0
Lower Fairbanks Local	11.14	10.02
Middle Fork Chena River	35.34	26.5
North Fork Chena River	20.48	15.36
South Fork Chena River	27.08	24.37
Two Rivers Local	11.45	10.3
Upper Fairbanks Local	33.14	29.82

Table 24. HMS Muskingum-Cunge routing model parameters.

Reach	Manning's n	Invert (ft)	Left bank Manning's n	Right bank Manning's n
1	0.04	774	0.15	0.15
2	0.04	690	0.15	0.15
3	0.05	638.25	0.15	0.15
4	0.05	573	0.15	0.15
5	0.031	470.14	0.1	0.1
6	0.031	472.48	0.1	0.1
7	0.031	480	0.1	0.1
8	0.031	419.5	0.1	0.1
9	0.031	421.37	0.1	0.1

5 Probable Maximum Flood

The HMS model was used to simulate the probable maximum flood (PMF) inflow to the Moose Creek Dam project. The PMF is the largest flood that can be expected in the basin, based on the most severe meteorological and hydrological conditions projected (USACE 1994). The most recent PMF computed for the Moose Creek Dam was completed in 1974 (USACE 1985). The recent Dam Safety evaluation of the project recommended that this be reviewed and updated.

The probable maximum precipitation (PMP), which represents the worst meteorological conditions expected, was reevaluated for the Chena Watershed (USACE 2011). The resulting isohyetal shapefile for the Chena Basin PMP was used to estimate subbasin precipitation as input to HMS. To do this, first the average total PMP precipitation was determined for each subbasin. The PMP hyetograph was normalized to 1 in. of precipitation, and multiplied by each of the subbasin PMP estimates to develop specific hyetographs for each subbasin. A Standard Project Storm (SPS) equal to half the PMP was included 5 days prior to the PMP to saturate the ground within the model, representing the worst hydrologic conditions expected.

The initial storm and PMP precipitation last approximately 8 days. The model was allowed to run an additional 23 days to capture the entire run-off event. Initial soil moisture conditions were set at 80% saturated to represent typical summer conditions based on earlier model runs. The subbasin times of concentration were adjusted by 25%, as is recommended (USACE 1991), to account for unit hydrographs being typically developed from smaller events.

The estimated PMF inflow to the Moose Creek Dam based on this analysis is 171,481 cfs. Figure 23 shows the inflow hydrograph to the Moose Creek Dam.

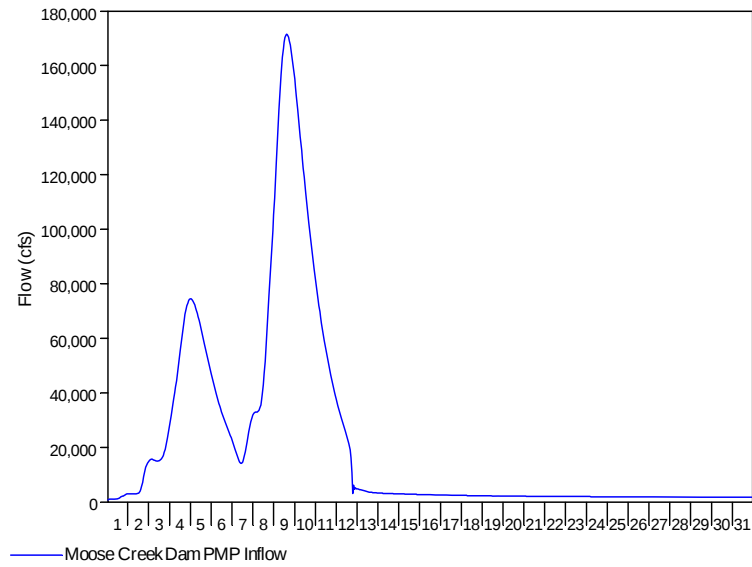


Figure 23. PMP inflow hydrograph to Moose Creek Dam.

6 Discussion and Summary

A hydrological model was developed for the Chena River Watershed that will continuously simulate the river discharge throughout spring, summer, and fall when streamflow data are available. The HMS model includes a temperature index snow model to simulate snowmelt runoff, which contributes the largest portion of discharge in the spring. The model was calibrated to three historical events: 1994, 2008, and 2009. A combined set of best parameters were developed from the three calibration years and validated to three additional years when significant events occurred: 1967, 1992, and 1995. The model was used to estimate of the PMF to the project, based on a recently developed PMP.

The model was able to reasonably simulate Chena River flows from 1 April to 30 August for each of the calibration and validation years. To further improve model results, it is recommended that representative cross-sections used in the routing model be surveyed in the field. In addition, analysis of the soil types and percolation rates in both permafrost and unfrozen areas may reduce some uncertainty in the soil moisture accounting model.

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Appendix A: Snow Model Calibration Periods

Fairbanks F.O.

Max date	Max SWE (in.)	End date of SWE
13Apr83	5.20	24Apr83
18Apr84	3.70	30Apr84
25Apr85	6.90	15May85
16Apr86	2.40	27Apr86
12Apr87	2.50	25Apr87
12Apr88	2.60	21Apr88
15Apr89	4.60	25Apr89
10Apr90	5.20	27Apr90
25Apr91	11.20	09May91
20Apr92	6.50	13May92
14Apr93	9.50	02May93
20Apr94	4.20	27Apr94
01Apr95	6.70	28Apr95
22Apr96	3.50	01May96
24Apr97	3.50	29Apr97
05Apr98	2.80	14Apr98
08Apr99	2.10	18Apr99
21Apr01	3.60	05May01
25Apr02	3.80	03May02
11Apr03	3.40	24Apr03
11Apr04	4.10	23Apr04
20Apr05	5.50	29Apr05
22Apr06	3.60	03May06
09Apr07	2.30	19Apr07
20Apr08	3.30	02May08

Upper Chena

Max date	Max SWE (in.)	End date of SWE
01May91	10.30	24May91
20May92	9.00	04JUN92
14Apr93	13.30	17May93
14Apr94	7.40	09May94
11Apr95	7.40	07May95
08Apr96	6.50	12May96
10Apr97	7.00	08May97
13Apr98	4.70	17May98
12May01	6.40	24May01
29Apr02	8.10	26May02
16Apr03	7.10	14May03
23Apr04	6.80	13May04
21Apr05	10.50	08May05
30Apr06	7.80	19May06
26Apr09	8.60	19May09
20Apr10	3.40	03May10

Little Chena Ridge

Max date	Max SWE (in.)	End date of SWE
24Apr91	9.10	16May91
21May92	7.60	31May92
14Apr93	11.10	13May93
05Apr94	6.40	29Apr94
08Apr95	7.80	02May95
12Apr96	6.00	12May96
06Apr97	5.10	01May97
06Apr98	4.00	25Apr98
15Apr99	4.60	13May99
03Apr00	8.30	19May00
09Apr01	5.60	19May01
29Apr02	6.80	19May02
19Apr03	6.50	02May03
10Apr04	6.20	04May04
20Apr05	6.40	29Apr05
29Apr06	5.40	11May06
05FEB07	1.90	18Apr07
20Apr08	3.10	04May08
26Apr09	3.90	02May09
20Mar10	2.20	23Apr10

Monument Creek

Max date	Max SWE (in.)	End date of SWE
23Apr91	8.00	09May91
20May92	9.20	30May92
10Apr93	9.80	13May93
29Mar94	5.30	27Apr94
07Apr95	7.60	02May95
14Apr96	6.00	09May96
07Apr97	4.70	01May97
05Apr98	4.40	21Apr98
15Apr99	4.10	11May99
23Apr00	9.20	17May00
19Apr01	5.30	14May01
28Apr02	6.50	16May02
16Apr03	6.30	01May03
05Apr04	5.90	30Apr04
19Mar05	6.70	28Apr05
27Apr06	6.10	11May06
24Mar07	3.30	19Apr07
21Apr08	3.20	03May08
26Apr09	7.10	04May09
16Apr10	2.50	24Apr10

Mt Ryan

Max date	Max SWE (in.)	End date of SWE
27Apr91	8.70	15May91
19May92	8.40	31May92
14Apr93	10.50	15May93
15Apr95	7.50	05May95
19Apr96	5.40	21May96
09Apr97	4.50	02May97
15Apr98	3.50	09May98
17Apr99	4.20	14May99
27Apr00	9.40	29May00
11May01	5.10	23May01
21Apr03	4.80	04May03
15Apr04	6.60	07May04
20Apr05	8.60	06May05
01May06	7.40	19May06
18Apr07	3.30	02May07
20Apr08	4.30	07May08
26Apr09	7.40	08May09

Munson Ridge

Max date	Max SWE (in.)	End date of SWE
15Apr91	18.40	19May91
22May92	12.90	09Jun92
28Apr93	15.10	26May93
26Apr94	10.20	22May94
28Apr95	9.40	14May95
05May96	6.10	26May96
22Apr97	6.70	20May97
14Apr98	5.50	21May98
17Apr99	5.20	22May99
24May00	13.90	10Jun00
15May01	7.20	31May01
29Apr02	8.30	25May02
23Apr03	7.50	25May03
01May04	7.20	18May04
28Apr05	10.60	14May05
09May06	9.00	24May06
19Apr07	4.20	23May07
04May08	7.60	17May08
27Apr09	9.80	26May09
19Apr10	6.10	21May10

Teuchet Creek

Max date	Max SWE (in.)	End date of SWE
20Apr91	6.00	07May91
04May92	5.30	25May92
09Apr93	9.40	05May93
09Apr94	3.50	28Apr94
04Apr95	5.80	02May95
17Apr96	3.20	05May96
09Apr97	4.30	01May97
09Apr98	3.60	24Apr98
16Apr99	2.70	28Apr99
20Apr00	6.40	07May00
18Apr01	4.40	11May01
27Apr02	4.80	13May02
19Apr03	4.40	30Apr03
15Apr04	4.70	30Apr04
12Apr05	5.50	29Apr05
23Apr06	5.40	10May06
08Apr07	2.60	22Apr07
21Apr08	3.60	04May08
09Mar10	3.30	02May10

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) April 2012		2. REPORT TYPE		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE The Chena River Watershed Hydrology Model				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Carrie M. Vuyovich and Steven F. Daly				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Cold Regions Research and Engineering Laboratory U.S. Army Engineer Research and Development Center 72 Lyme Road Hanover, NH 03755				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CRREL TR-12-1	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Engineer District, Alaska Anchorage, Alaska				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Development of a hydrologic model of the Chena River Watershed located in central Alaska is described. The flow in the Chena River is controlled by the Moose Creek Dam project upstream of Fairbanks, AK. The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) hydrologic model is intended to estimate inflows into the Moose Creek Dam Project and determine the Probable Maximum Flood (PMF) hydrograph. The Chena River watershed covers 2115 mi ² . It is characterized by extensive snowmelt in spring and heavy precipitation events in summer. The Chena River is typically in continuous recession from October through April because of the subfreezing air temperatures. Permafrost areas were estimated using a GIS based binary Logistic Regression model. Monthly values for evapotranspiration and the air temperature lapse rate were estimated using the available data. A temperature index snow model was developed and calibrated with existing snow water equivalent data. The HEC-HMS model was calibrated based on 3 years of continuous simulation between 1 April and 31 August. Both large snowmelt and precipitation events were simulated. The model was verified for an additional 3-year period. All the HEC-HMS model parameters are listed in the report. The PMF hydrograph was estimated.					
15. SUBJECT TERMS Alaska Chena River		Fairbanks HEC-HMS model Hydrologic model		Moose Creek Dam	
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
U	U	U	None	71	