SUSITNA-WATANA HYDRO

Clean, reliable energy for the next 100 years.

ALASKA ENERGY AUTHORITY
AEA11-022
13-1402-REP-123114

Appendix A

Probable Maximum Precipitation Study

14-07-REP

by

Applied Weather Associates

SUSITNA-WATANA HYDRO

Clean, reliable energy for the next 100 years.

Report
14-07-REP
v1.0

Susitna-Watana Hydroelectric Project
Probable Maximum Precipitation Study

AEA11-022

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March 2014

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EXECUTIVE SUMMARY

Applied Weather Associates (AWA) has completed a site-specific Probable Maximum Precipitation (SSPMP) study for the Susitna River basin located south of the Alaska Range and north east of Anchorage in Alaska. The purpose of the study was to determine PMP values specific to the watershed, taking into account topography, climate and storm types that affect the region.

The approach used in this study was consistent with those used in the numerous PMP studies that AWA has completed since 1996. This is a storm-based approach similar to the methods and processes employed by the National Weather Service (NWS) in the development of the various Hydrometeorological Reports (HMRs) to the extent the data and current understanding of meteorological processes supports those previous methods. The World Meteorological Organization (WMO) manual for PMP determination (WMO 2009) recommends this storm-based approach when sufficient data are available. This approach identified extreme rainfall events that have occurred over a wide region around southern Alaska from Fairbanks to the Gulf of Alaska west to the Aleutians Island and east to the northern Alaska Panhandle. These storms have meteorological and topographical characteristics similar to extreme rainfall storms that could occur over the Susitna-Watana basin. The largest of these rainfall events were selected for detailed analyses and PMP development.

Nine rainfall events were identified as having similar characteristics to PMP-type events that could potentially occur over the Susitna River basin and could potentially influence the PMP values. Each of these storms were analyzed by AWA for this study using the Storm Precipitation Analysis System (SPAS). Some storms had more than one Depth-Area-Duration (DAD) zone analyzed by SPAS. A total of 13 unique DAD zones were used in the final PMP development for this study.

The general concepts employed to derive the SSPMP values from rainfall maximization, storm transpositioning, and elevation moisture adjustments were consistent with those used in HMR 57 (Hansen et al. 1994) and in the numerous PMP studies completed by AWA (Tomlinson et al. 2006-2013, Kappel et al. 2011-2014). Further, information and processes detailed in Technical Paper 47 (1963), as well as the United States Army Corps of Engineers (USACE) (1975) and Acres (1982) feasibility studies, were used where appropriate. New techniques and databases were used in the study to increase accuracy and reliability, while adhering to the basic approach used in the HMRs and in the WMO Manual. Two updated analysis methodologies were utilized in this study. The first was the use of the Orographic Transposition Factor (OTF), which objectively quantifies the effects of terrain on rainfall enhancement and depletion. This process replaces the NWS K factor/Storm Separation Method (see HMR 57 Section 6 and 8), and allows the unique and highly variable topography at both the in-place storm location and the Susitna River basin to be properly represented in the PMP values and subsequent Probable Maximum Flood (PMF) modeling. The second was the use of the HYSPLIT trajectory model (Draxler and Rolph 2010), which was used to evaluated the general location of the moisture source regions originating over water. These regions were identified using a NWS reanalysis interface.

New storm maximization factors were computed for each storm of the nine most significant storms using an updated sea surface temperature (SST) climatology and a ship report/satellite SST database (Reynolds et al. 2007 and Kent et al. 2007, NCDC DS 540.0). Each historic extreme rainfall event used for PMP development was maximized, transpositioned, and orographically adjusted to a series grid points covering the entire Susitna River basin using methods consistent with HMR 57 and previous AWA PMP studies when possible and modified to work on a gridded basis. The governing equation used for computation of the SSPMP values for the Susitna River basin is shown in Equation ES.1.

$$PMP_{xhr} = P_{xhr} * IPMF * MTF * OTF \qquad \text{ES.1}$$

where:

PMP_{nhr} is the SSPMP value at the x-hour duration for the 5,131-square mile Susitna River basin (target location);

P_{xhr} is the x-hour 5,131-square mile precipitation observed at the historic in-place storm location (source location);

In-Place Maximization Factor (*IPMF)* is the adjustment factor that increases a storm's maximum amount of atmospheric moisture that could have been present to the storm for rainfall production. It is the ratio of the maximum amount to the actual amount of atmospheric moisture that was available to the storm;

Moisture Transposition Factor (MTF) is the adjustment factor which accounts for the difference in available moisture between the location where the storm occurred and the Susitna-Watana basin;

Orographic Transposition Factor (OTF) is obtained from the results of the comparison of the 24-hour precipitation frequency characteristics between the storm target and source locations. The OTF accounts for differences between orographic effects at the historic in-place storm location and the grid point being evaluated within the Susitna-Watana basin.

A total of 4,767 grid cells, at a resolution of .025° decimal degrees x .025° decimal degrees, were analyzed over the Susitna-Watana basin. The resulting values were analyzed hourly for a total of 216-hours and provided by sub-basin average for use in PMF modeling. These data were distributed spatially the precipitation climatology from NOAA Atlas 14 Volume 7 (Perica et al. 2012). The temporal distribution of the hourly rainfall accumulations followed the temporal pattern of three historic storms, each with a distinct accumulation pattern. This procedure is preferred compared to moving each storm to the centroid of the basin because it captures the spatial and temporal variability of PMP rainfall as it would occur over the complex terrain of the Susitna-Watana basin. Values were derived for the all-season period, extending from July 1-August 15, with an additional set of seasonality adjustments for use in defining the PMP rainfall from April 1 through October 31.

The last component of the PMP determination process was the development of the meteorological time series used for snowmelt calculations prior to, coincident with, and after the PMP rainfall period. Hourly values for temperatures, dew points, and wind speeds were derived using historic observed conditions during similar rainfall periods. These values were then maximized to represent the expected conditions during the PMP rainfall. Values were derived representing July 1-August 15, with an additional set of seasonality adjustments for use in defining the meteorological time series from April 1 through October 31.

1. INTRODUCTION

This study provides the Site-Specific Probable Maximum Precipitation (SSPMP) values and development procedures for use in the computation of the Probable Maximum Flood (PMF) for the Susitna River basin in the southern Alaska.

1.1 Background

Definitions of Probable Maximum Precipitation (PMP) are found in most of the Hydrometeorological Reports (HMRs) issued by the National Weather Service (NWS). The definition used in the most recently published HMR is "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year." (HMR 59, pg. 5). Since the mid-1940s, several government agencies have been developing methods to calculate PMP in various regions of the United States. The NWS (formerly the U.S. Weather Bureau) and the Bureau of Reclamation have been the primary agencies involved in this activity. PMP values from their reports are used to calculate the PMF, which, in turn, is often used for the design of significant hydraulic structures.

The generalized PMP studies currently in use in the conterminous United States include: HMR 49 (1977) for the Colorado River and Great Basin drainage; HMRs 51 (1978), 52 (1982) and 53 (1980) for the U.S. east of the 105th meridian; HMR 55A (1988) for the area between the Continental Divide and the 103rd meridian; HMR 57 (1994) for the Pacific Northwest states west of the Continental Divide; and HMR 58 (1998) and 59 (1999) for the state of California (Figure 1.1). The Susitna-Watana basin is located outside the domain of the HMRs and therefore a SSPMP is required to derive quantifiable and reproducible PMP values.

In addition to these HMRs, numerous Technical Papers and Reports deal with specific subjects concerning precipitation (e.g. NOAA Tech. Report NWS 25 1980 and NOAA Tech. Memorandum NWS HYDRO 45 1995). Topics include maximum observed rainfall amounts, return periods for various rainfall amounts, and specific storm studies. Climatological Atlases (e.g. Technical Paper No. 40 1961; Short Duration Rainfall Frequency Relations for the Western United States 1986; NOAA Atlas 2 1973; NOAA Atlas 14 2002-2014) are available for use in determining precipitation return periods. A number of specialized and regional studies (e.g. Technical Paper 47; Tomlinson 1993; Tomlinson et al. 2002-2013, Kappel et al. 2011-2014) augment generalized PMP reports for specific basins and regions included in the large areas addressed by the various HMRs (Tomlinson and Kappel 2009). TP 47 provides PMP values for Alaska for area sizes up to 400 square miles and durations up to 24 hours.

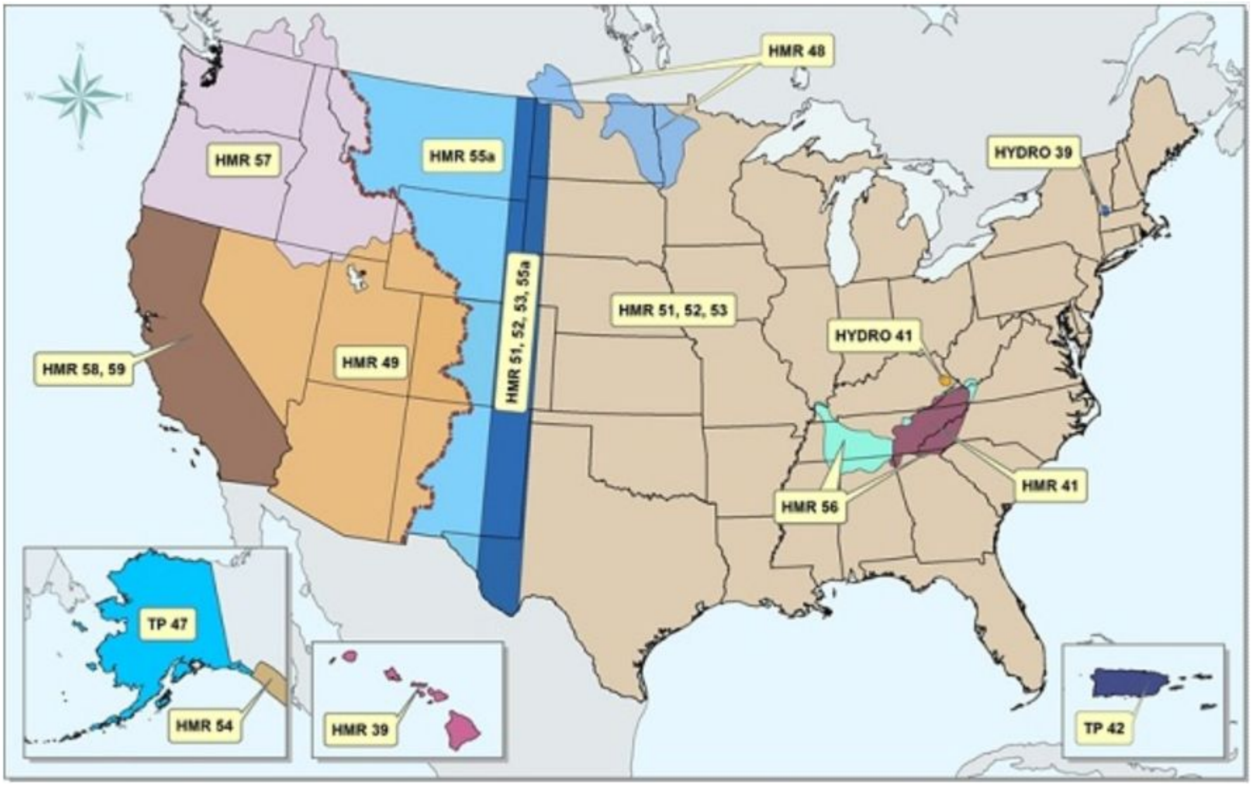

Figure 1.1. Coverage of NWS HMRs as of 2012 (from http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html).

The meteorological and topographical settings within and surrounding the large Susitna River basin create unique effects on precipitation and other meteorological variables that can only be resolved through a detailed analysis specific to the basin. Each of the NWS HMR studies addressing PMP over specific regions also recognized that SSPMP studies could incorporate more site-specific considerations and provide improved PMP estimates. Additionally, by periodically updating storm data and incorporating advances in meteorological concepts, PMP analysts can make improved PMP estimates (HMR 57 Section 14 and Section 15.2 Steps 8-9).

Previous site-specific and regional PMP projects completed by AWA provide examples of PMP studies that explicitly consider the topography of the basins and characteristics of historic extreme rainfall storms over climatologically similar regions surrounding the basins (see Figure 1.2). These site-specific PMP studies have received extensive review and the results have been used in computing the PMF for the watersheds and regions covered. This study follows many of the same procedures used in those studies to determine SSPMP values for the Susitna-Watana basin. These procedures, together with Storm Precipitation Analysis System (SPAS) rainfall analyses[1] are used to compute PMP values using a .025 x .025 decimal degree grid over the Susitna-Watana basin. The grid based approach provides improvements in the spatial evaluation of the historic storm

[1] Appendix D contains a complete description of the SPAS program and its development.

rainfall patterns and how the PMP storm would occur over the highly variable topography unique to the Susitna-Watana basin. In addition, storm specific and generalized temporal distributions can be applied.

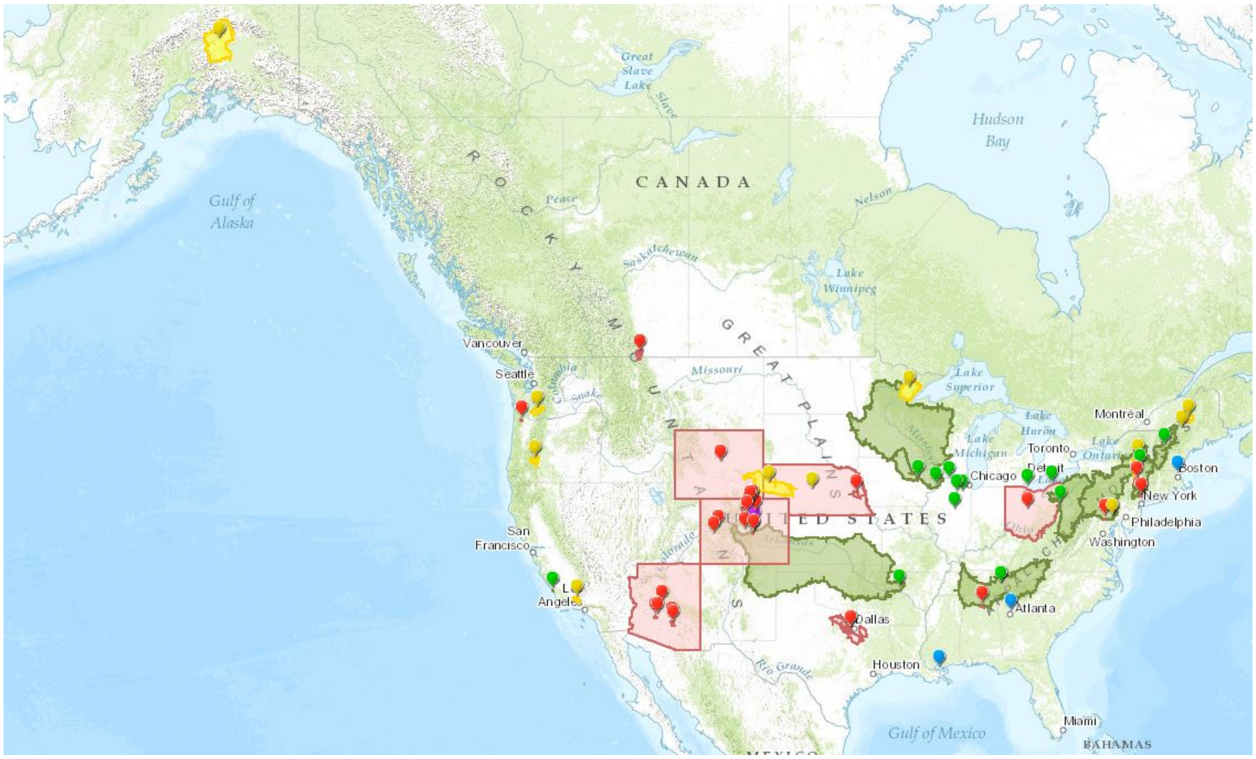

Figure 1.2. Locations of AWA PMP studies as of March 2013.

1.2 Objective

The objective of this study was to perform a site-specific study to determine reliable estimates of PMP values for the Susitna-Watana basin, as well as develop coincident meteorological time series data (temperature, dew point, and wind speed) for use in snow melt calculation. In addition, guidance was provided on the seasonality of both the PMP values and the meteorological time series values because it was critical to provide information on how those values vary beyond the all-season (July-August for PMP) for PMF modeling. This is because it is very likely that the PMF would result at a time when some amount less than the full PMP could accumulate and be augmented by melting snow pack to produce a larger volume of flood runoff versus the time of the year when the full PMP could accumulate but have significantly less snow melt runoff. This all-season PMP would therefore produce a smaller flood volume than the lesser amount of rainfall but higher amount of snow melt. The most reliable methods and data currently available have been used, with new techniques and data used where appropriate.

1.3 Approach

The approach used in this study is consistent with the majority of the procedures that were used in the development of the HMRs, with updated procedures implemented where appropriate. These procedures were applied considering the site-specific characteristics of the Susitna River basin and the unique effects of the topography both in the surrounding region and in the basin. Terrain characteristics are addressed as they specifically affect rainfall patterns, both spatially and in magnitude within the basin. The weather and climate of the region are discussed in Section 2. The process of identifying extreme storms is discussed in Section 3. Procedures used to analyze storms are discussed in Section 4. Adjustments for storm maximization, storm moisture transposition, and orographic transposition are presented in Sections 5, 6, 7 and 8. The meteorological time series and seasonality of PMP development are provided in Section 9. Results are presented in Section 10. Discussions on sensitivities are provided in Section 11 and the recommendations for application are in Section 12.

Procedures used in this study maintained consistency with the general methods used in the HMRs and the previous PMP studies completed by AWA while deviations were incorporated when justified by developments in meteorological analyses and available data. The basic approach identifies major storms that occurred within the region surrounding the Susitna River basin that are PMP storm type (see Section 2.0). This includes the region from central Alaska west to the Bering Strait to the Gulf of Alaska through the Alaska Panhandle (see Section 5.0). The moisture content of each of these storms is increased to a climatological maximum to provide worst case rainfall estimation for each storm at the location where it occurred had all atmospheric process resulting in rainfall production been optimum. The storms are then transpositioned to the Susitna River basin to the extent supportable by similarity of topographic and meteorological conditions. Finally, the largest rainfall amounts from these maximized and transpositioned storms provide the basis for deriving the SSPMP values. Figure 1.3 shows the flow chart of the major steps used in a site-specific storm-based PMP derivation process. Note that the final process used during this study incorporated the use of a grid cell by grid cell delineation and detailed evaluation of orographic effects on rainfall within the basin. The details are included in Equation 1 and Figure 1.4.

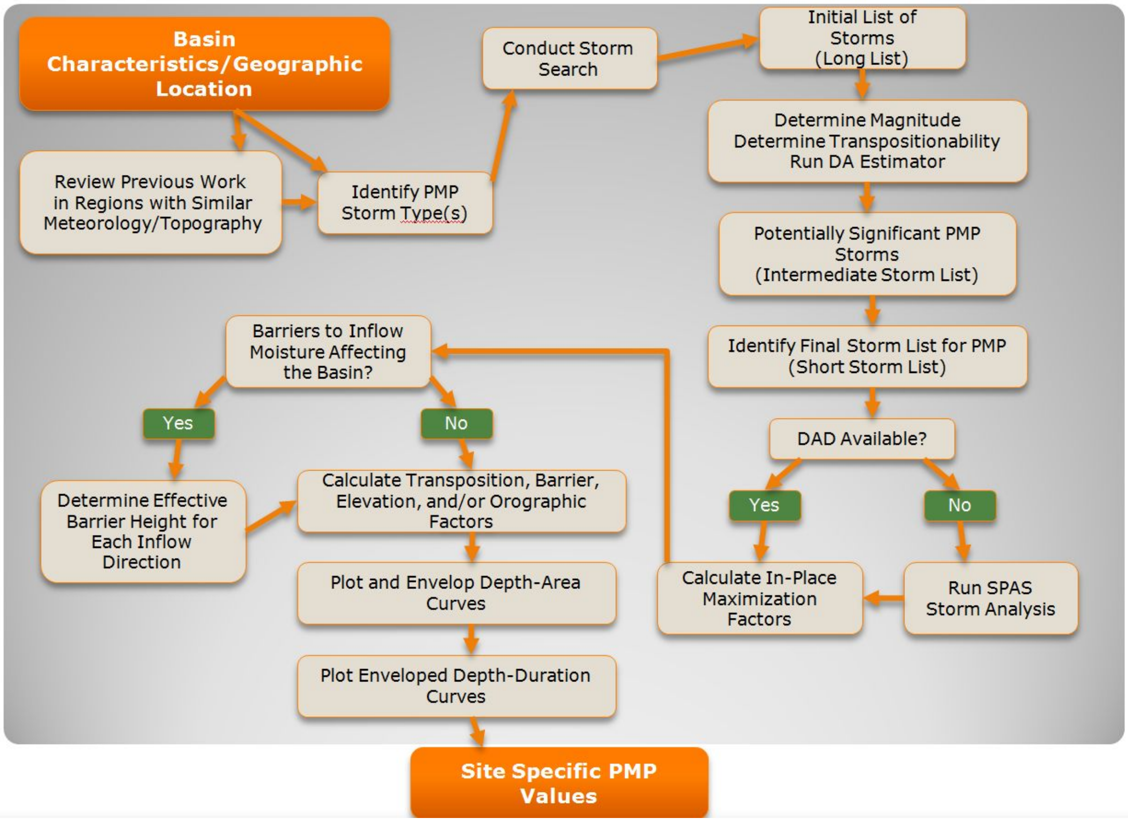

Figure 1.3. Flow chart showing the major steps involved in site-specific PMP development.

For some of the processes used to derive PMP, this study applied standard methods (e.g. WMO 2009 and Hansen et al. 1994), while for others, new techniques were developed. A major advancement utilized during this study was the ability to analyze rainfall and climate data on a gridded basis in a GIS environment. This allowed for in-place maximizations, horizontal moisture transpositioning, and orographic transpositioning using a data grid over the basin. The original SPAS gridded rainfall amounts were analyzed at each storm's in-place location to provide values used for the PMP calculations (see Equation 1.1). The largest of the total adjusted rainfall values at each hour were distributed spatially and temporally over the Susitna-Watana basin. The spatial distribution proved to be very effective in quantifying the unique effects of the highly variable topography on the storm at both the in-place storm location and the Susitna-Watana basin. This process uses the Orographic Transposition Factor (OTF) to quantify the effects of topography on rainfall production and spatial distribution. The OTF is determined by comparing the NOAA Atlas 14 Volume 7 precipitation frequency data (Perica et al. 2012) at the in-place storm location versus the precipitation frequency values at each grid point over the basin. The relationship through a range of precipitation frequency values between the two locations results in a ratio indicating if the in-place storm center location is more or less effective at enhancing rainfall versus the grid point over the basin. The OTF is then combined with the in-place maximization factor and the moisture transposition factor to produce the total adjustment factor for that grid point, for a given storm, for a given duration. This process is then repeated for all grid points in the basin for all duration analyzed. The assumption in the OTF process is that the NOAA Atlas 14 precipitation frequency values adequately represent the expected effects of topography at a given grid point and by upwind and surrounding topography as reflected in the numerous precipitation events that have occurred at that location and within the region used to produce the precipitation frequency estimates.

This process replaces the use of the NWS Storm Separation Method (SSM). A detailed description of the NWS SSM method can be found in HMR 55A Section 7, with updates to the method in HMR 57 Section 6. The OTF is discussed in Section 6.2 with example results and calculations given in Section 7.3.

Figure 1.4 shows a flow chart of the processes that were used during this study to derive the SSPMP values. Note that most of the processes displayed in Figure 1.3 are included, however the flow chart in Figure 1.4 includes the processes that are unique to this SSPMP study.

The governing equation used for computation of the SSPMP values for the Susitna River basin is:

$$PMP_{xhr} = P_{xhr} * IPMF * MTF * OTF \qquad \text{Equation 1.1}$$

where:

PMP_{xhr} is the SSPMP value at the x-hour duration for the 5,131-square mile Susitna River basin (target location);

P_{xhr} is the x-hour 5,131-square mile precipitation observed at the historic in-place storm location (source location);

In-Place Maximization Factor (*IPMF)* is the adjustment factor determined using the maximum amount of atmospheric moisture that could have been present to the storm for rainfall production;

Moisture Transposition Factor (MTF) is the adjustment factor which accounts for the difference in available moisture between the location where the storm occurred and the Susitna-Watana basin;

Orographic Transposition Factor (OTF) is obtained from the results of the calculation which compares the x-hour precipitation frequency characteristics between the basin grind points and the in-place storm location. The OTF accounts for differences between orographic effects at the historic in-place storm location and the Susitna-Watana basin.

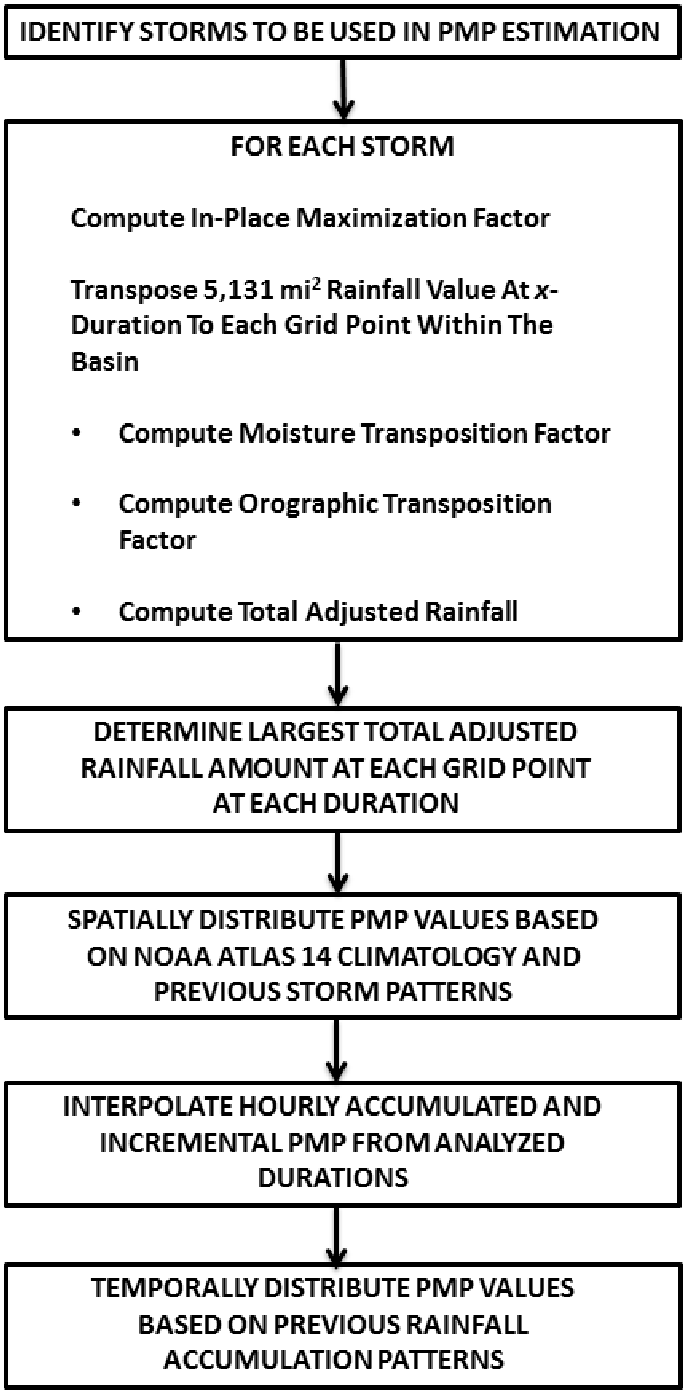

Figure 1.4. Major Components in Computation of Site-Specific PMP for Susitna-Watana Basin.

Advanced computer-based technologies, Weather Service Radar WSR-88D NEXt generation RADar (NEXRAD), and HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model trajectories were used for storm rainfall analyses for all storms used in PMP development. New technology and data were incorporated into the study when they improved reliability. This approach provides the most complete scientific application compatible with the engineering requirements of consistency and reliability for credible PMP estimates.

Storm maximization (also called moisture maximization) analyses have historically used monthly maximum observed 12-hour persisting dew points as published in the *Climatic Atlas of the United States* by the Environmental Data Services, Department of Commerce (1969). However, use of surface based dew points (either persisting or average) is only valid for storms where atmospheric moisture can be quantified using land based, surface dew point observations. In this study, sea surface temperature (SST) values were used in-place of dew point temperatures. SSTs were used in HMRs 57 and 59 as well as several site-specific PMP studies completed by AWA where inflow moisture source regions were located over the Atlantic or Pacific Ocean.

As part of this study, an updated maximum SST climatology was developed replacing the Marine Climate Atlas of the World (U.S. Navy 1981) used in HMRs 57 and 59. This updated climatology includes monthly mean and +2-sigma maps for the Pacific Ocean from the coastline of the United States to 180°W and from 15°N to the southern Alaska coast. In conjunction with the +2-sigma climatological maps, daily SST maps based on ship and buoy reports used in deriving the storm representative SST values for each storm event (NOAA 2011, Kent et al. 2007, Reynolds et al. 2007, and Worley et al. 2005).

The ESRI ArcGIS, version 10.2 geographic information system (GIS) software environment was used extensively in the study to analyze storms, evaluate climatology data, complete the OTF analyses, delineate the characteristics of the Susitna-Watana basin, identify unique characteristics and terrain features of the region, and produce basin and regional maps.

SPAS provided gridded storm rainfall analyses. The SPAS analyses produced high-resolution gridded maximum rainfall datasets at hourly intervals over the spatial extent for the entire duration of each storm used in this study.

1.4 Basin Location and Description

The Susitna River basin is located in southern Alaska. The area of the drainage basin is approximately 5,131-square miles. The average elevation within the basin is 3,643 feet and varies from 1,456 feet at the proposed dam site to 13,134 feet in the Alaska Range. Figure 1.5 shows the basin location and surrounding topography. Figure 1.6 shows the topography within the basin and the thirty-four major sub-basins.

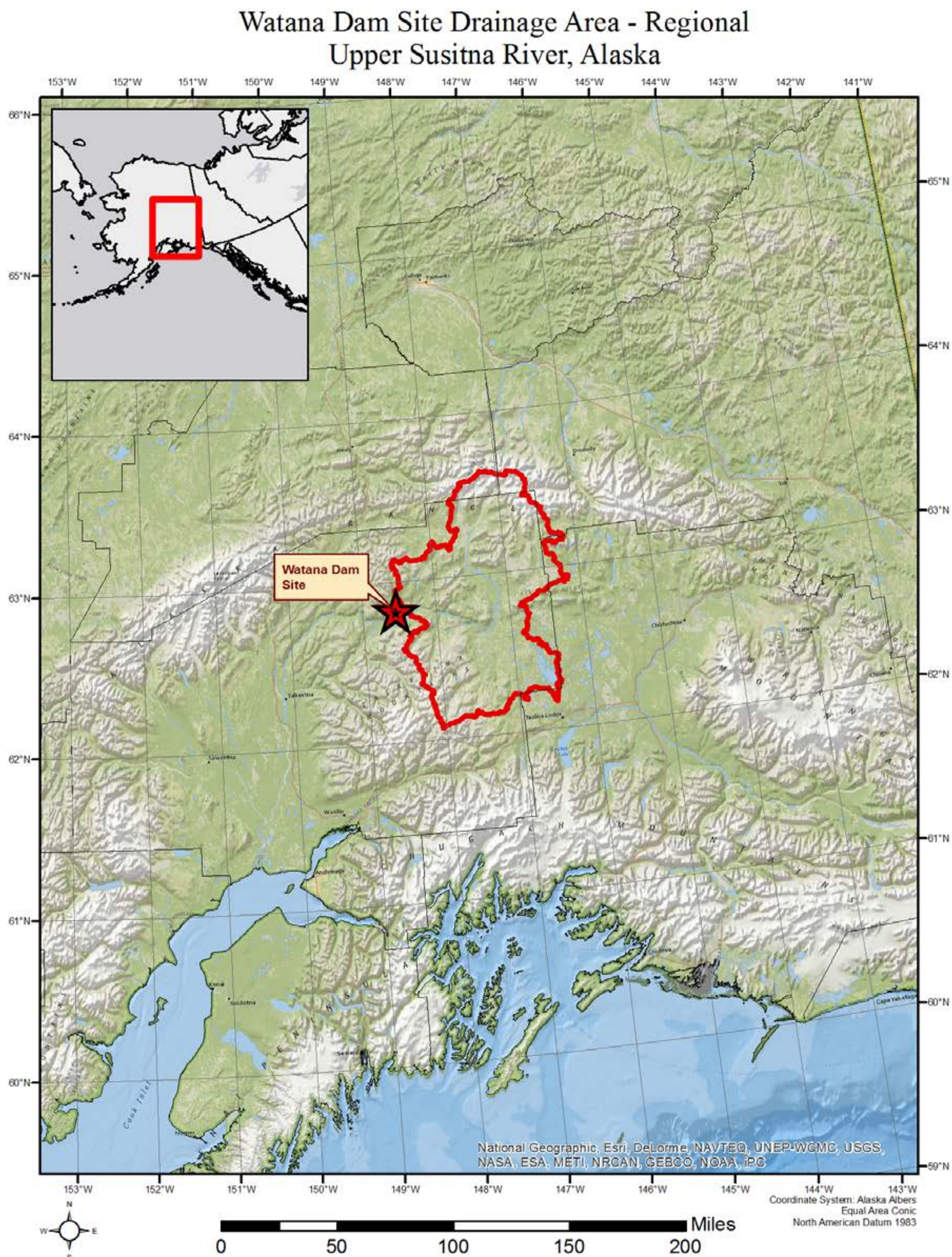

Figure 1.5. Susitna-Watana basin location and surrounding topography.

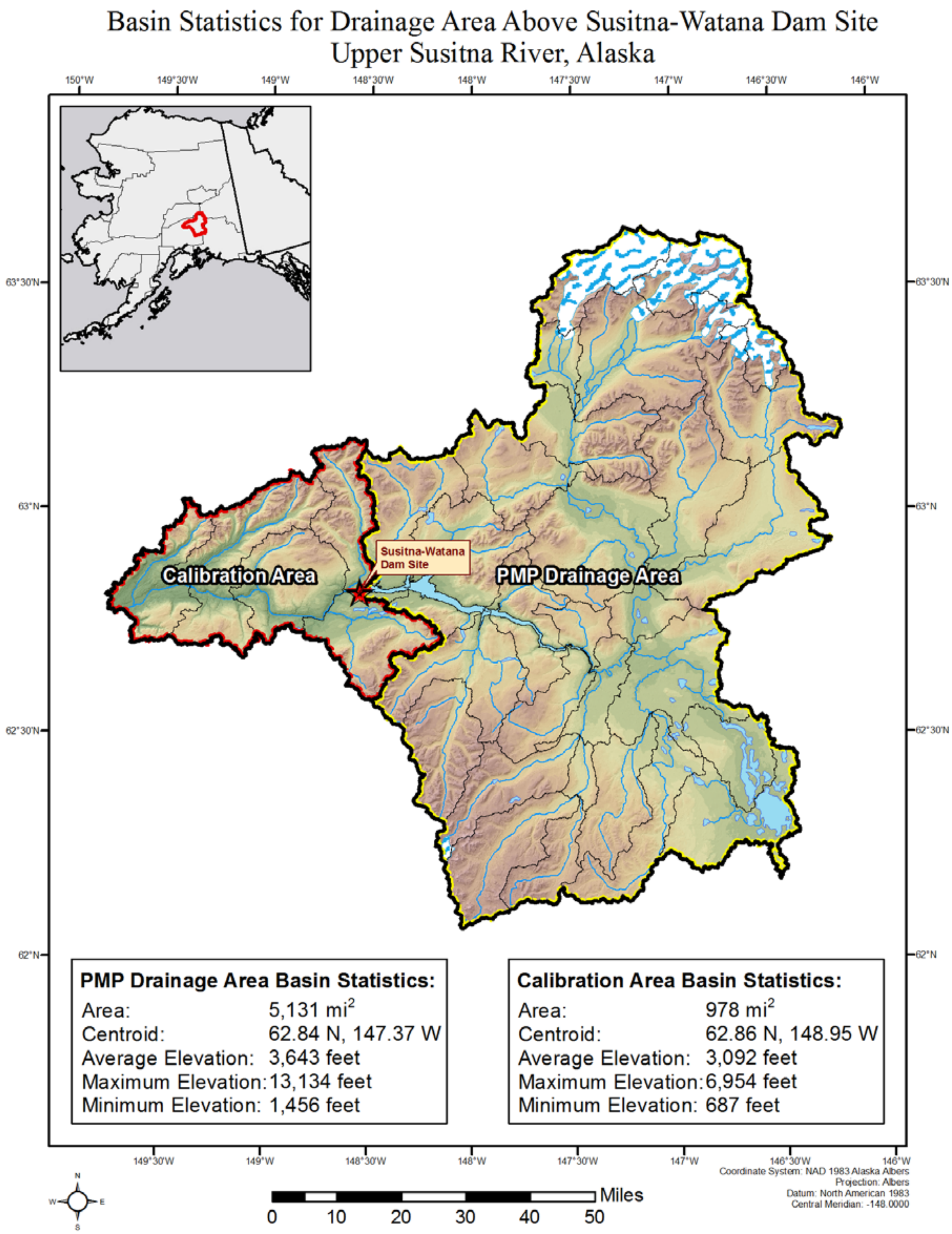

Figure 1.6. Susitna-Watana basin, subbasins, and major hydrologic features.

2. WEATHER AND CLIMATE OF THE SUSITNA-WATANA REGION

2.1 Seasonal Patterns

The weather and climate around the Susitna River basin is known for its extreme seasonality and high variability of weather patterns. Moisture feeding rainfall events in the basin arrives on southerly wind flows, with westerly components sometimes involved. The basin is located between two highly contrasting air mass types. Relatively mild and very moist air masses originated from the Gulf of Alaska and Pacific Ocean contrast with dry and cold Polar air masses from the north. Depending on which air mass is dominating the weather at any given time determines the resulting weather conditions. In addition, the basin is large enough that each of these air masses may be affecting different portions of the basin at the same time. During the months from November through March, temperatures are cold enough that rainfall is rare, and when it occurs it is light enough that flooding is not produced. Starting in April, a rapid transition takes places as warmer temperatures and higher levels of moisture begin to affect the region. Chances for rain increase across the lower elevations closer to the Gulf of Alaska. For most of April and often into May, significant snow pack remains. Over the interior and higher elevations of the basin, significant snow pack often stays well into June. This combination of rain on snow has resulted in some of the largest flood of record for the basin.

The peak season for rainfall occurs from July through early September as the storm track from the Pacific Ocean and Gulf of Alaska intensifies and combines with the highest amount of atmospheric moisture. In rare instances, remnant Tropical Storm moisture becomes entrained in these storms and enhances the rainfall across southern and interior Alaska. An excellent example of this scenario was the Great Fairbanks Flood of August 1967[2]. Rare heavy rainfall events, such as the September 2012 and October 1986, provide examples when the rain season is extended beyond expected time frames.

2.2 Orographic Influences

Rainfall in the region of the Susitna River basin is controlled by the orographic effect associated with the steep rise in elevation from sea level to over 12,000 feet south of the basin along the coastal mountains which intercepts most of the moisture moving in from the Gulf of Alaska. However, a major gap in the mountainous terrain occurs through the Cook Inlet and up the Susitna River valley. This allows significant amounts of low level moisture to move into the lower reaches of the Susitna River basin and into the western portions of the basin. In addition, as this moisture encounters the rising elevations of the Alaska Range around Denali as well as the higher elevation at the edge of the basin, it is forced to rise and precipitation enhancement occurs. In combination, all these upwind and along basin higher elevation serve to limit the amount of low-level moisture

[2] http://en.wikipedia.org/wiki/History_of_Fairbanks,_Alaska

reaching into the basin, especially the middle and eastern interior portions. Therefore, average precipitation amounts fall off very quickly within the basin, especially for elevation below 5,000 ft (the majority of the area within the basin). This effect is known as a rainshadow and it is imperative that the PMP value reflect this phenomena. Because of the unique topographic situations both upstream and within the basin, PMP-type rainfall is rare within the basin, but common at upwind locations. Therefore, extensive evaluations were completed to quantify the effects of topography on rainfall spatially and in magnitude, and to provide information on how storms are transpositioned the basin.

The topography within the basin also creates distinct rainfall patterns with extreme variations within the basin. The heaviest precipitation occurs at the western edge of the basin and along the higher elevation of the northern portion of the basin along the Alaska Range. Mean annual precipitation varies from just over 10 inches in the lower elevations of the southeastern portion of the basin to over 60 inches in the Alaska Range in the northeastern portion of the basin (Figure 2.1). At elevations above 5,000 ft, precipitation can be in the form of snow any time of the year.

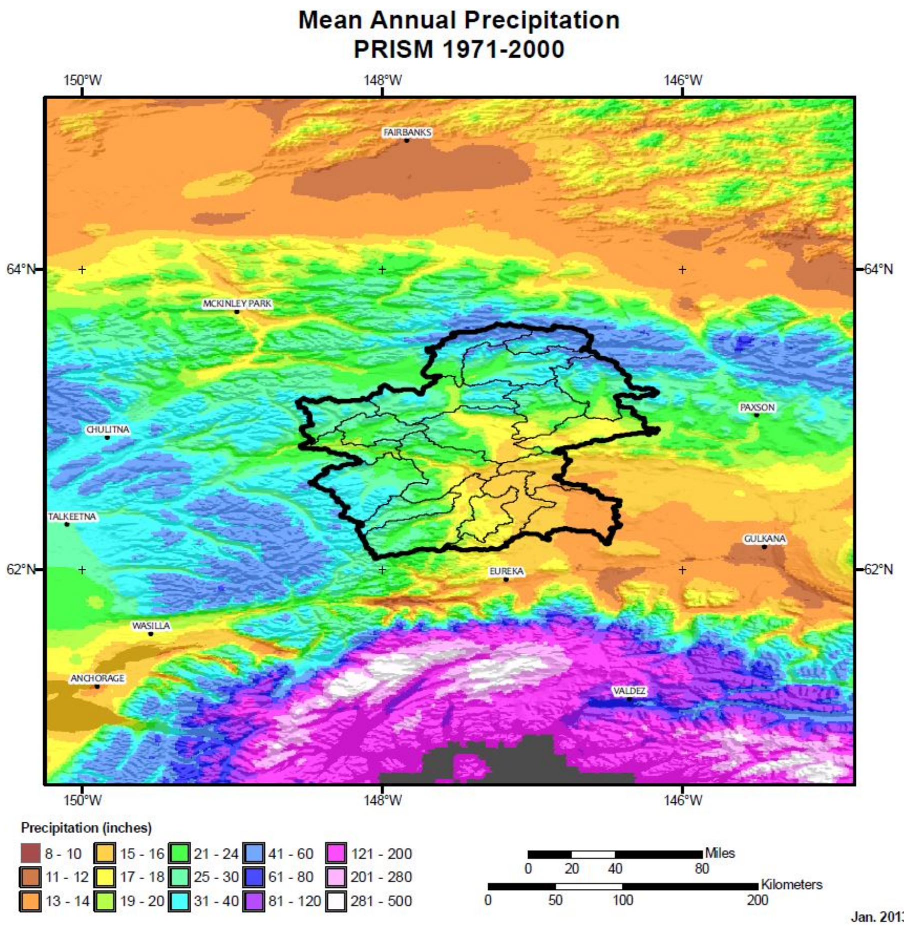

Figure 2.1. Mean annual precipitation based on PRISM 1971-2000 climatology.

2.3 Susitna River Basin PMP Storm Type

The region around the basin is directly influenced by strong areas of low pressure (mid-latitude cyclones) moving in from the Pacific Ocean and Gulf of Alaska. These storms, referred to as synoptic storms, often bring with them very active storm dynamics (lift) and high levels of moisture from locations as far south as the subtropics north of Hawaii and points westward. This combination of enhanced lift and moisture often produces widespread heavy rainfall that may last three or more days. When these storms are able to tap into high levels of moisture supplied by the subtropical regions in and around the central Pacific Ocean, extreme rainfalls can occur. This type of scenario is known as an Atmospheric River. On the upslope regions upwind of the Susitna-Watana basin, the storms are further enhanced by orographic processes associated with the steep terrain encountered as they move onshore and are forced to rise over the slopes of the Coastal Range and Alaska Range. As discussed in the previous section, much of this atmospheric moisture precipitates on the upwind slopes, thereby eliminating much of the low-level atmospheric moisture by the time it reaches the basin. Therefore, extreme rainfall events are rare in the basin and rainfall amounts are generally less than areas to the west and south of the basin. Synoptic storms cover large areas and produce heavy rains over relatively long periods. This storm type is most common from late June through early October.

2.3.1 Atmospheric Rivers and Mid-Latitude Cyclones

An Atmospheric River is an elongated, narrow, water vapor transport band located in the warm sector of a mid-latitude cyclone, often enhanced by convergence of local moisture (Bao et al. 2006). Atmospheric Rivers contain warm temperatures relative to normal in the surrounding air mass, enhanced water vapor and a strong low-level jet approximately 5,000 ft above the surface (Zhu and Newell 1998, Neiman et al. 2001, 2008, 2008, 2011, Ralph et al. 2003, 2004, 2005, 2006, 2011). Ralph (2004) demonstrated that more than 90% of the total meridional water vapor flux in the mid-latitudes is attributed to Atmospheric Rivers.

With this type of storm, flooding can be exacerbated antecedent snowpack, especially in the spring season. This scenario is most common between late May and late June after a cooler than normal spring has allowed higher than normal amounts of snowpack to remain over the basin. High levels of moisture and relatively warm temperatures associated with the Atmospheric River events emanating from the subtropical regions of the central Pacific Ocean result in heavy rainfall on a quickly melting snowpack producing increased runoff. These two factors lead to the largest flood events in the region.

2.4 Storm Types Seasonality

The most likely time for a PMP type storm event to occur in the Susitna River basin is from July through early September. However, extreme storms occur as early as May and as late as October.

Figure 2.2 displays the month of occurrence of the individual storm events from the storm search that were considered for PMP development (see Section 3.0). It should be noted that although the heaviest amounts of rainfall occur in the summer months, the higher amounts of snow pack available to combine with the rainfall runoff are likely to produce the largest volumes of flood runoff. Therefore, it is likely that the PMF would result from a combination of rainfall and snowmelt in May or early June.

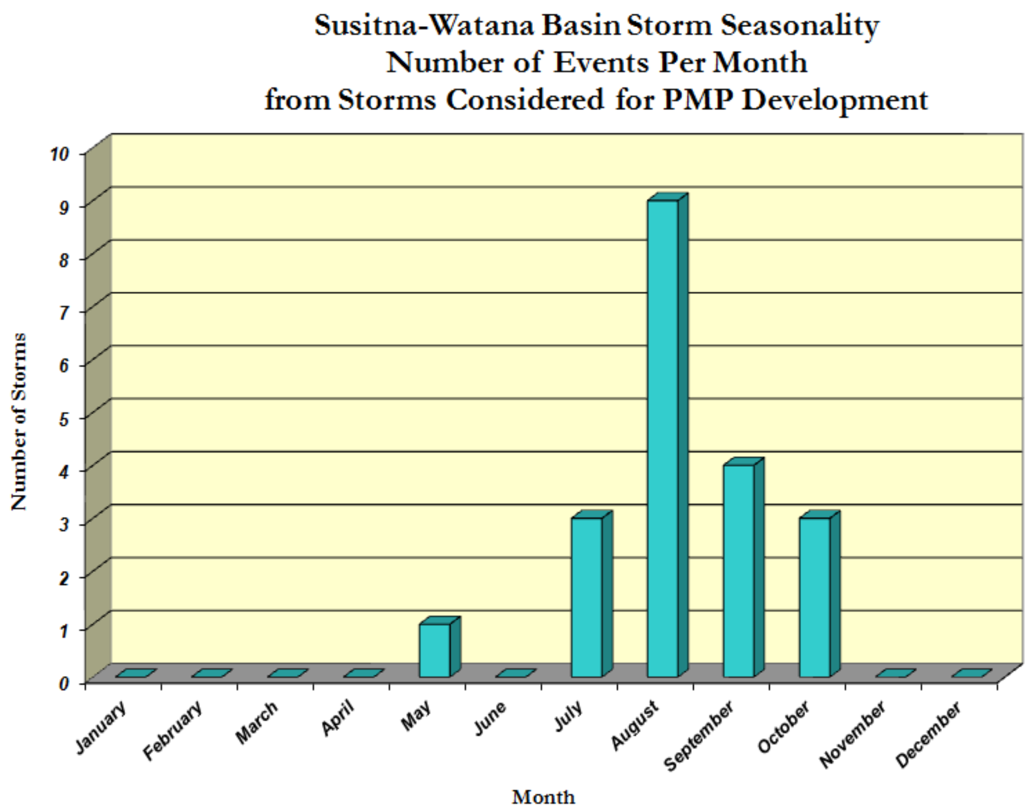

Figure 2.2. Storm seasonality for the Susitna River basin using all storm events from the long storm list.

3. EXTREME STORM IDENTIFICATION

3.1 Storm Search Area

A comprehensive storm search was conducted for this study and included an analysis of all the storms in meteorologically and topographically similar regions to the Susitna-Watana basin. Previous work and documents which discussed and analyzed storm events in the region were also reviewed. These included the reports from the NWS offices in Anchorage and Fairbanks, as well as HMR 57, the Acres (1982) study, and the Harza-Ebasco (1984) PMP work. Nine new storms were identified from the storm search which required full SPAS storm analyses for use in PMP development (Section 4). The primary search area included all geographic locations where extreme rainfall storms similar to those that could occur over the Susitna River basin have been observed. The search area extended from the Alaska Panhandle region (~54°N) to southern interior Alaska (~65°N) and from the Pacific Ocean coastline to northwestern interior Alaska (Figure 3.1). This ensured a large enough area was included in the storm search to capture all significant storms that could potentially influence final PMP values for the basin.

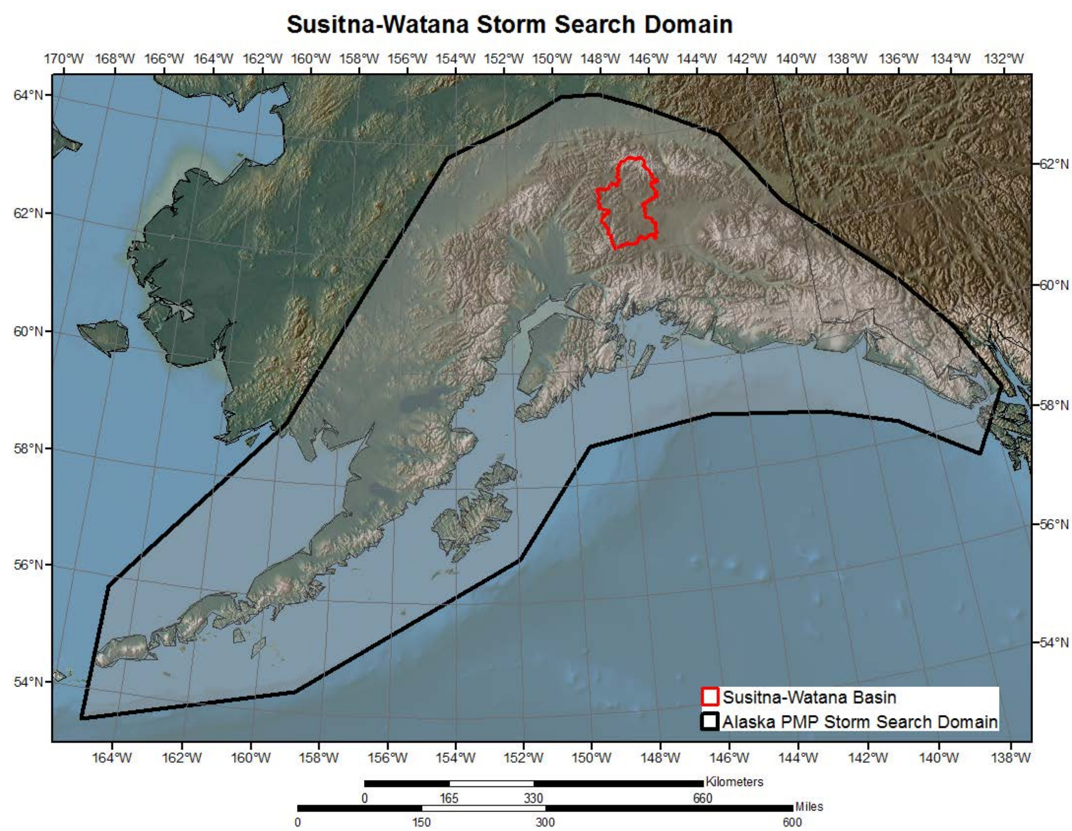

Figure 3.1. Susitna-Watana storm search domain.

3.2 Data Sources

The storm search was conducted using a dataset that included rainfall data from several sources. The primary data sources are listed below:

1. Cooperative Summary of the Day / TD3200 through 2013. These data are published by the National Climatic Data Center (NCDC).
2. Hourly Weather Observations published by NCDC, U.S. Environmental Protection Agency, and Forecast Systems Laboratory (now National Severe Storms Laboratory).
3. NCDC Recovery Disk
4. Hydrometeorological Reports
5. Corps of Engineers Storm Studies
6. Other data published by the Alaska State climate office
7. American Meteorological Society journals
8. Personal communications with various members of the Board of Consultants and others involved in this study
9. Watana and Devil Canyon Sites Probable Maximum Flood Report
10. Susitna Hydroelectric Project v4 Appendix A

3.3 Storm Search Method

The primary search began with identifying hourly and daily stations that have reliable rainfall data within the storm search area described previously. These stations were evaluated to identify the largest 1, 3, and 7 observational-day precipitation totals. Other reference sources such as HMRs and USACE storm reports and USGS flood studies (e.g. Smith 1950, USACE 1975, ACRES 1982, Harza-Ebasco 1984, HMR 42 1966) were reviewed to identify other dates with large rainfall amounts within the storm search domain. The criteria for storms to make the initial list of significant storms (referred to as the long storm list) were events that exceeded the 100-year return frequency value for the specified duration at the storm location.

The resulting long storm list was extensively quality controlled to ensure that only the highest storm rainfall values for each event were selected. Each storm was analyzed to verify its precipitation reports and compare it with rainfall amounts associated with other storms.

These storms values were plotted to ensure they occurred over similar meteorological and topographic regions as the Susitna River basin and could, therefore be used in the next steps of the PMP analysis. Table 3.1 is the long storm list and represents an initial assessment of all the storms found during the initial storm search. Quality control checks eliminated storms with duplicate rainfall centers, rainfall amounts which were accumulations, smaller rainfall centers associated with the same storm event, and storms that were deemed not transpositionable to the Susitna-Watana basin, etc.

Table 3.1. Long storm list from the storm search. Rainfall values shown are the highest point values in inches over the total storm duration.

Name	ST	Lat	Lon	Year	Mon	Day	Total Rainfall
COAL HARBOR	AK	55.400	-160.817	1900	4	23	10.00
COAL HARBOR	AK	55.400	-160.817	1909	4	3	8.00
CORDOVA WB A	AK	60.500	-145.500	1912	9	26	19.75
CORDOVA WB A	AK	60.500	-145.500	1917	9	9	9.40
CORDOVA WB A	AK	60.500	-145.500	1925	9	20	15.69
CORDOVA WB A	AK	60.500	-145.500	1925	10	6	24.12
CHIGNIK	AK	56.300	-158.400	1927	8	15	14.99
CHIGNIK	AK	56.300	-158.400	1927	9	19	15.43
CHIGNIK	AK	56.300	-158.400	1929	9	8	16.38
CHIGNIK	AK	56.300	-158.400	1930	5	9	18.93
CHIGNIK	AK	56.300	-158.400	1930	5	25	15.78
DENALI NP	AK	63.038	-150.471	1955	8	22	13.75
CORDOVA	AK	60.646	-145.554	1955	8	22	21.67
CAPE SPENCER	AK	58.200	-136.633	1956	11	24	20.93
MT SPURR	AK	61.346	-152.329	1958	7	25	6.62
LITTLE SUSITNA	AK	61.854	-149.229	1959	8	18	13.05
CAPE HINCHINBROOK	AK	60.233	-146.650	1962	4	13	20.50
CAPE HINCHINBROOK	AK	60.233	-146.650	1962	5	9	29.95
CAPE HINCHINBROOK	AK	60.233	-146.650	1962	5	25	13.75
CAPE SPENCER	AK	58.200	-136.633	1966	11	23	15.80
DENALI NP	AK	62.846	-150.513	1967	8	2	12.45
FAIRBANKS	AK	65.521	-147.329	1967	8	2	12.45
HOMER	AK	59.871	-150.563	1967	8	2	12.45
CHIGNIK	AK	56.300	-158.400	1969	6	4	14.81
CAPE HINCHINBROOK	AK	60.233	-146.650	1969	7	24	22.90
CHIGNIK	AK	56.300	-158.400	1969	10	12	14.68
BLACK RAPIDS	AK	63.471	-145.479	1971	8	5	12.17
SUTTON	AK	61.904	-148.863	1971	8	5	11.39
PORTAGE	AK	61.004	-148.663	1971	8	5	12.17
DENALI NP	AK	62.954	-150.079	1980	7	24	7.33
ANGOON PWR	AK	57.499	-134.586	1982	10	12	15.20
DENALI NP	AK	62.829	-151.138	1986	10	8	11.01
SEWARD	AK	60.113	-149.513	1986	10	8	20.80
OUZINKIE	AK	57.933	-152.500	1991	11	1	10.76
WHITTIER	AK	60.713	-148.779	1995	9	19	26.03
SEWARD	AK	60.117	-149.450	1995	9	20	9.81
BIG RIVER LA	AK	60.817	-152.300	1996	3	22	7.50
ELFIN COVE	AK	58.200	-136.667	1996	9	25	8.61
CANNERY CREEK	AK	60.696	-145.688	2003	9	29	23.69
PELICAN	AK	57.950	-136.233	2005	11	17	26.87
BLACK RAPIDS	AK	63.465	-145.685	2006	8	17	16.12
CANNERY CREEK	AK	60.696	-145.688	2006	10	7	23.63
OLD TYONEK	AK	61.260	-151.860	2012	9	15	15.91
KENAI FJORDS NP	AK	59.610	-150.220	2012	9	15	33.96

3.4 Developing the Intermediate List of Extreme Storms

A multiple step process was followed to develop the list of storms used to define the PMP values. For PMP development, this final list of storms (known as the short storm list) is required to be comprehensive and include all storms which could possibly affect PMP values for the basin. At the same time, there must be a balance to eliminate smaller events that would not be significant for determining PMP values at any area size or duration after all adjustments were applied. Initially, all storms previously analyzed during the ACRES 1982, Harza-Ebasco 1984 or by the USACE were moved to the short storm list. The remaining storms were sorted by maximum rainfall amount. This eliminated events based on different locations reporting rainfall amounts associated with the same event. Further analysis was conducted to verify that each storm was transpositionable to the Susitna-Watana basin. Other checks were performed to see whether conditions within the basin during a storm event would have produced snow instead of rain, whether the storm had enough data available to complete an analysis, and whether the storm was within at least 35% of maximum values from other storms. Table 3.2 displays the results of this iterative analysis, including the reason for elimination or inclusion of each storm. In Table 3.2, the columns highlighted with a green header display the various parameters which were analyzed to determine whether a storm could be moved from the long storm list to the intermediate storm list. Each storm was analyzed going from left to right on the table. Once a storm met or did not meet one of the criteria, no further evaluation using the remaining criteria was completed. A notation was entered into the appropriate column associated with a particular selection criterion (i.e. a “yes” or “no”) with all other selection criteria cells associated with a particular storm left blank. The results of this analysis comprised the short storm list as described in the following section.

Table 3.2. Long storm list storm selection criteria used to derive the intermediate storm list.

Name	ST	Lat	Lon	Year	Mon	Day	Total Rainfall	AWA Storm Analysis	Transpositionable to Basin	Snow in the basin	Larger Storm in Similar Location	No Rain in basin or region	Data to Complete Analysis	More than 35% of Max Storm amount (>12.00")
COAL HARBOR	AK	55.400	-160.817	1900	4	23	10.00							No
COAL HARBOR	AK	55.400	-160.817	1909	4	3	8.00							No
CORDOVA WB A	AK	60.500	-145.500	1912	9	26	19.75						No	
CORDOVA WB A	AK	60.500	-145.500	1917	9	9	9.40							No
CORDOVA WB A	AK	60.500	-145.500	1925	9	20	15.69				Yes			
CORDOVA WB A	AK	60.500	-145.500	1925	10	6	24.12						No	
CHIGNIK	AK	56.300	-158.400	1927	8	15	14.99		No			Yes	No	
CHIGNIK	AK	56.300	-158.400	1927	9	19	15.43		No			Yes		
CHIGNIK	AK	56.300	-158.400	1929	9	8	16.38		No				No	
CHIGNIK	AK	56.300	-158.400	1930	5	9	18.93		No				No	
CHIGNIK	AK	56.300	-158.400	1930	5	25	15.78		No			Yes		
DENALI NP	AK	63.038	-150.471	1955	8	22	13.75	Yes						
CORDOVA	AK	60.646	-145.554	1955	8	22	21.67	Yes						
CAPE SPENCER	AK	58.200	-136.633	1956	11	24	20.93		No					
MT SPURR	AK	61.346	-152.329	1958	7	25	6.62	Yes						
LITTLE SUSITNA	AK	61.854	-149.229	1959	8	18	13.05	Yes						
CAPE HINCHINBROOK	AK	60.233	-146.650	1962	4	13	20.50		No	Yes				
CAPE HINCHINBROOK	AK	60.233	-146.650	1962	5	9	29.95		No					
CAPE HINCHINBROOK	AK	60.233	-146.650	1962	5	25	13.75				Yes			
CAPE SPENCER	AK	58.200	-136.633	1966	11	23	15.80		No					
DENALI NP	AK	62.846	-150.513	1967	8	2	12.45	Yes						
FAIRBANKS	AK	65.521	-147.329	1967	8	2	12.45	Yes						
HOMER	AK	59.871	-150.563	1967	8	2	12.45	Yes						
CHIGNIK	AK	56.300	-158.400	1969	6	4	14.81		No			Yes		
CAPE HINCHINBROOK	AK	60.233	-146.650	1969	7	24	22.90		No					
CHIGNIK	AK	56.300	-158.400	1969	10	12	14.68			Yes		Yes		
BLACK RAPIDS	AK	63.471	-145.479	1971	8	5	12.17	Yes						
SUTTON	AK	61.904	-148.863	1971	8	5	11.39	Yes						
PORTAGE	AK	61.004	-148.663	1971	8	5	12.17	Yes						
DENALI NP	AK	62.954	-150.079	1980	7	24	7.33	Yes						
ANGOON PWR	AK	57.499	-134.586	1982	10	12	15.20		No					
DENALI NP	AK	62.829	-151.138	1986	10	8	11.01	Yes						
SEWARD	AK	60.113	-149.513	1986	10	8	20.80	Yes						
OUZINKIE	AK	57.933	-152.500	1991	11	1	10.76			Yes				
WHITTIER	AK	60.713	-148.779	1995	9	19	26.03		No					
SEWARD	AK	60.117	-149.450	1995	9	20	9.81							No
BIG RIVER LA	AK	60.817	-152.300	1996	3	22	7.50							No
ELFIN COVE	AK	58.200	-136.667	1996	9	25	8.61							No
CANNERY CREEK	AK	60.696	-145.688	2003	9	29	23.69		No					
PELICAN	AK	57.950	-136.233	2005	11	17	26.87		No					
BLACK RAPIDS	AK	63.465	-145.685	2006	8	17	16.12	Yes						
CANNERY CREEK	AK	60.696	-145.688	2006	10	7	23.63		No			Yes		
OLD TYONEK	AK	61.260	-151.860	2012	9	15	15.91	Yes						
KENAI FJORDS NP	AK	59.610	-150.220	2012	9	15	33.96	Yes						

3.5 Short Storm List

Each of the storms on the short storm list were evaluated in detail using the SPAS program. Results of these analysis included the development of storm isohyetals and Depth-Area-Duration tables (DADs). Each of these storms was maximized in-place, transpositioned to each grid point comprising the basin. The storm center locations of the various SPAS DAD analyses are plotted for reference in Figure 3.2. Table 3.3 list the final short list of storms.

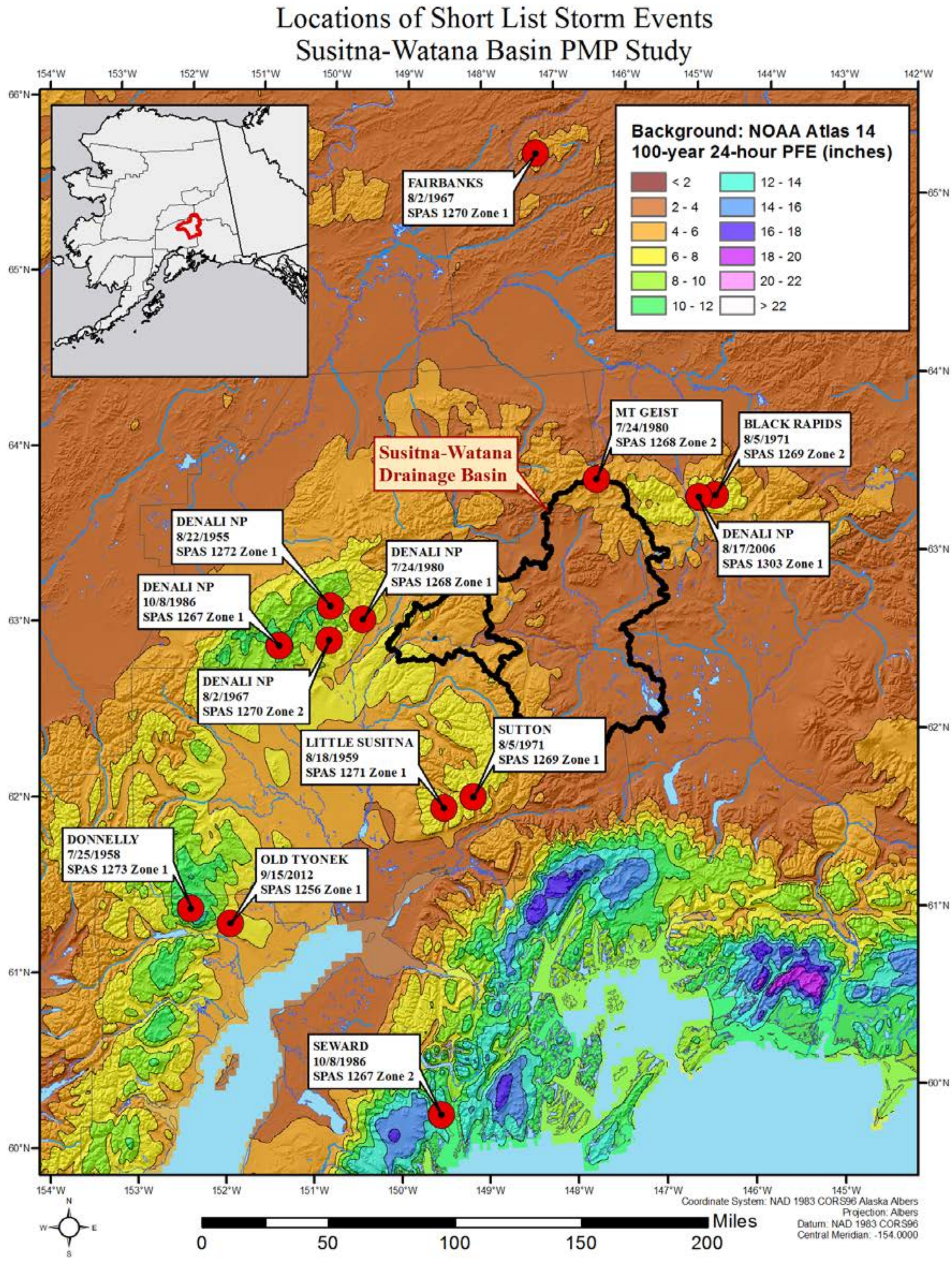

Figure 3.2. Short storm list storm locations.

Table 3.3. Susitna-Watana short storm list used in the SSPMP analysis. Rainfall values are the maximum rainfall totals produced the SPAS storm analyses.

Name	ST	Lat	Lon	Year	Mon	Day	Total Rainfall	Precipitation Source
DENALI NP	AK	63.038	-150.471	1955	8	22	13.75	SPAS 1272 Zone 1
MT SPURR	AK	61.346	-152.329	1958	7	25	6.62	SPAS 1273 Zone 1
LITTLE SUSITNA	AK	61.854	-149.229	1959	8	18	13.05	SPAS 1271 Zone 1
DENALI NP	AK	62.846	-150.513	1967	8	2	12.45	SPAS 1270 Zone 2
FAIRBANKS	AK	65.521	-147.329	1967	8	2	12.45	SPAS 1270 Zone 1
BLACK RAPIDS	AK	63.471	-145.479	1971	8	5	12.17	SPAS 1269 Zone 2
SUTTON	AK	61.904	-148.863	1971	8	5	11.39	SPAS 1269 Zone 1
MT GEIST	AK	63.638	-146.971	1980	7	24	5.26	SPAS 1268 Zone 2
DENALI NP	AK	62.954	-150.079	1980	7	24	7.33	SPAS 1268 Zone 1
DENALI NP	AK	62.829	-151.138	1986	10	8	11.01	SPAS 1267 Zone 1
SEWARD	AK	60.113	-149.513	1986	10	8	20.80	SPAS 1267 Zone 2
BLACK RAPIDS	AK	63.465	-145.685	2006	8	17	16.12	SPAS 1303 Zone 1
OLD TYONEK	AK	61.260	-151.860	2012	9	15	15.91	SPAS 1256 Zone 1

4. STORM DEPTH-AREA-DURATION (DAD) ANALYSES

Gridded rainfall values are required for PMP calculations. Therefore, all storms on the short storm list (see Section 3.5) were required to be analyzed using the SPAS program. This program computed the required rainfall values, along with several other products such as mass curves, isohyetal patterns, analysis statistics, and quality control analyses. Detailed results of each of these analyses are included in Appendix C.

There are two main steps in the SPAS DAD analysis: 1) The creation of high-resolution hourly rainfall grids and 2) the computation of Depth-Area (DA) rainfall amounts for various durations. The reliability of the results from step 2) depends on the accuracy of step 1) (Jones 1969, Gou et al 2001, Duchon and Essenberg 2001). Before this process was automated using SPAS, the storm rainfall analyses were very labor intensive and highly subjective. SPAS utilizes a GIS to create spatially-oriented and highly accurate results in an efficient manner. Furthermore, the availability of NEXRAD data allows SPAS to better account for the spatial and temporal variability of storm precipitation for events occurring since the early 1990s. Prior to NEXRAD, the NWS developed and used a method based on Weather Bureau Technical Paper No. 1 (U.S. Weather Bureau 1946). Because this process has been the standard for many years (all DAD produced by the NWS in all the HMRs used this procedure) and holds merit, the SPAS DAD analysis process used in this study attempts to apply the NWS procedure as much as possible. By adopting this approach, some level of consistency between the newly analyzed storms and the hundreds of storms already analyzed by the NWS is achieved. Comparisons between the NWS DAD results and those computed using the SPAS method for two storms (Westfield, MA 1955 and Ritter, IA 1953) produced very similar results (see Appendix D for complete discussion, comparisons, and results).

4.1 Data Collection

The areal extent of a storm's rainfall was evaluated using existing maps and documents along with plots of total storm rainfall. Based on the storm's spatial domain (longitude-latitude box), hourly and daily rainfall data were extracted from our in-house database for specified areas, dates, and times. Rainfall amounts are either observed and recorded each hour (hourly) or once a day (daily). To account for the temporal variability in observation times at daily reporting stations, the extracted hourly data must capture the entire observational period of all daily station reports. For example, if a station takes daily observations at 8:00 AM local time, then the hourly data need to be complete from 8:00 AM local time the day prior. As long as the hourly data are sufficient to capture all of the daily station observations, the hourly variability in the daily observations can be properly addressed.

The daily rainfall database is comprised of data from National Climatic Data Center (NCDC) TD-3206 (pre 1948) and TD-3200 (generally 1948 through present). The hourly rainfall database is comprised of data from NCDC TD-3240 and NOAAs Meteorological Assimilation Data Ingest System (MADIS). The daily supplemental database is largely comprised of data from “bucket surveys,” local rain gauge networks (e.g. ALERT, USGS, etc.) and daily gauges with accumulated data.

4.2 Mass Curves

The most complete rainfall observational dataset available is compiled for each storm. To obtain temporal resolution to the nearest hour in the DAD results, it is necessary to distribute the daily precipitation observations (at daily stations) into hourly values. This process has traditionally been accomplished by anchoring each of the daily stations to a single hourly timer station. However, this may introduce biases and may not correctly represent hourly precipitation at locations between hourly stations. A preferred approach is to anchor the daily station to some set of the nearest hourly stations. This is accomplished using a spatially based approach that is called the spatially based mass curve (SMC) process.

4.3 Hourly or Sub-hourly Precipitation Maps

At this point, SPAS can either operate in its standard mode or in NEXRAD-mode to create high resolution hourly or sub-hourly (for NEXRAD storms) grids. In practice both modes are run when NEXRAD data are available so that a comparison can be made between the methods. Regardless of the mode, the resulting grids serve as the basis for the DAD computations.

4.3.1 Standard SPAS Mode

The standard SPAS mode requires a full listing of all the observed hourly rainfall values, as well as the newly created estimated hourly values from daily and daily supplemental stations. This is done by creating an hourly file that contains the newly created hourly mass curve precipitation data (from the daily and supplemental stations) and the “true” hourly mass curve precipitation. The option of incorporating basemaps was used in this study. If base maps were not used, the individual hourly precipitation values would simply be plotted and interpolated to a raster with an inverse distance weighting (IDW) interpolation routine or some other mathematical scheme using GIS.

4.3.2 NEXRAD Mode

Radar has been in use by meteorologists since the 1960s to estimate rainfall depth. In general, most current radar-derived rainfall techniques rely on an assumed relationship between radar reflectivity and rainfall rate. This relationship is described by the equation (4.1) below:

$$Z = aR^{b} \qquad \text{Equation 4.1}$$

Where Z is the radar reflectivity, measured in units of dBZ (dBZ stands for decibels of Z), R is the rainfall rate, *a* is the "multiplicative coefficient" and *b* is the "power coefficient". Both *a* and *b* are related to the drop size distribution (DSD) and the drop number distribution (DND) within a cloud (Martner et al. 2005).

The NWS uses this relationship to estimate rainfall through the use of their network of NEXRAD sites located across the United States. A standard default Z-R algorithm of $Z = 300R^{1.4}$ is the primary algorithm used throughout the country and has proven to produce highly variable results. The variability in the results of Z vs. R is a direct result of differing DSD and DND, and differing air mass characteristics across the United States (Dickens 2003). The DSD and DND are determined by a complex interaction of microphysical processes in a cloud. They fluctuate hourly, daily, seasonally, regionally, and even within the same cloud (see Appendix D for a more detailed description).

Although SPAS uses Equation 4.1 to determine rainfall rates, the *a* and *b* coefficients are explicitly determined for each hour of the storm using a calibration technique. Hourly rain gauge data are used with hourly NEXRAD data in the calibration calculations.

4.4 Depth-Area-Duration Program

The DAD extension of SPAS runs from within a Geographic Resource Analysis Support System (GRASS) GIS environment[3] and utilizes many of the built-in functions for calculation of area sizes and average depths. The following is the general outline of the procedure:

1. Given a duration (e.g. x-hours) and cumulative precipitation, sum up the appropriate hourly or sub-hourly precipitation grids to obtain an x-hour total precipitation grid starting with the first x-hour moving window.

2. Determine x-hour precipitation total and its associated areal coverage. Store these values. Repeat for various lower rainfall thresholds. Store the average rainfall depths and area sizes.

3. The result is a table of depth of precipitation and associated area sizes for each x-hour duration. Summarize the results by moving through each of the area sizes and choosing the maximum precipitation amount. A log-linear plot of these values provides the depth-area curve for the x-hour duration.

4. Based on the log-linear plot of the rainfall depth-area curve for the x-hour duration, determine rainfall amounts for the standard area sizes for the final DAD table. Store these values as the

[3] Geographic Resource Analysis Support System, commonly referred to as GRASS, this is free Geographic Information System (GIS) software used for geospatial data management and analysis, image processing, graphics/maps production, spatial modeling, and visualization. GRASS is currently used in academic and commercial settings around the world, as well as by many governmental agencies and environmental consulting companies. GRASS is an official project of the Open Source Geospatial Foundation.

rainfall amounts for the standard sizes for the x-duration period. Determine if the x-hour duration period is the longest duration period being analyzed. If it is not, analyze the next longest duration period and return to step 1.

5. Construct the final DAD table with the stored rainfall values for each standard area for each duration period.

5. STORM MAXIMIZATION

Storm maximization (also called moisture maximization in the HMRs) is the process of increasing rainfall associated with an observed extreme storm. In this process, it is assumed the storms being maximized and the PMP storm would have the same storm efficiency (ability to convert moisture in the atmosphere to precipitation). Therefore, the only variable that would increase or decrease the amount of precipitation produced from a given storm would be the amount of moisture available. During the storm maximization process, a quantification of the amount of additional moisture which could have been available to the storm and would have increased the rainfall production in calculated. This is quantified by comparing the storm representative dew points (or SSTs for all storms used in this study) to some climatological maximum and calculating the enhanced rainfall amounts that could potentially have been produced had the climatological maximum value been present versus what actually occurred (Bolsenga 1965). An additional consideration is usually applied that selects the climatological maximum dew point (or SST for this study) for a date two weeks towards the climatological maximum warm season from the date that the storm actually occurred. This procedure assumes that the storm could have occurred two weeks earlier or later in the year when maximum dew points or SSTs are higher. Calculations for each storm used in this study are shown in Appendix C.

5.1 New Procedures Used in the Storm Maximization Process

The HYSPLIT trajectory model (Draxler and Rolph 2003, 2010) provides detailed analyses of upwind trajectories of atmospheric moisture that was advected into the storm systems. Using these trajectories, the atmospheric moisture source locations are determined. The procedures followed are similar to the approach used in HMRs 57 and 59. However, by utilizing the HYSPLIT model trajectories, much of the subjectivity is eliminated. Further, details of each evaluation can be explicitly provided and the results are reproducible.

Using SSTs for in-place maximization and storm transpositioning (discussed Section 6) followed the same procedure used with land based surface dew points. Use of the HYSPLIT trajectory model provided a significant improvement in determining the inflow wind vectors originating over the ocean compared to older methods of extrapolating coastal wind observations and estimating moisture advection from synoptic features. This more objective procedure is especially useful for situations where a long distance is involved to reach warmer ocean regions. Timing is not as critical for inflow wind vectors extending over the oceans since SSTs change very slowly with time compared to dew point values over land. Changing wind directions are of greater importance, especially for situations where there is curvature in the wind fields. Any changes in wind curvature and variations in timing are inherently captured in the HYSPLIT trajectories.

5.1.1 HYSPLIT Trajectory Model

The HYSPLIT trajectory model was used during the analysis of each of the rainfall events included on the short storm list when available (1948-present from the National Centers for Environmental Prediction (NCEP) Global Reanalysis fields) (Mesinger et al. 2006). Use of a trajectory model provides increased confidence for determining inflow moisture vectors and storm representative SSTs. The HYSPLIT model trajectories have been used to analyze the moisture inflow vectors in other PMP studies completed by AWA over the past several years. During these analyses, the model trajectory results were verified and the utility explicitly evaluated (e.g. Tomlinson et al. 2006-2011, Kappel et al. 2012-2013).

Instead of subjectively determining the moisture inflow trajectory, the HYSPLIT analysis was used to determine the trajectory of the moisture inflow for various levels in the atmosphere associated with the storm's rainfall production. The HYSPLIT software was run for trajectories at several levels of the lower atmosphere to help determine the moisture source for each storm event. These included 700mb (approximately 10,000 ft), 850mb (approximately 5,000 ft), and storm center location surface elevation[4].

For the majority of the analyses, a combination of all three levels was used to identify the upwind moisture source location. It is important to note that the resulting HYSPLIT model trajectories are only used as a general guide of where to evaluate the moisture source for storms in space and time. The final determination of the storm representative SST and its location is determined following the standard procedures used by AWA in previous PMP studies and as outlined in the HMRs and WMO manuals. Appendix C of this report lists each of the HYSPLIT trajectories used for each storm. As an example, Figures 5.1 show the HYSPLIT trajectories used to determine the inflow moisture vector from the October 1986 rainfall event.

[4] These are standard elevations for atmospheric analysis. Further, the majority of atmospheric moisture available for rainfall production occurs below the 700mb level.

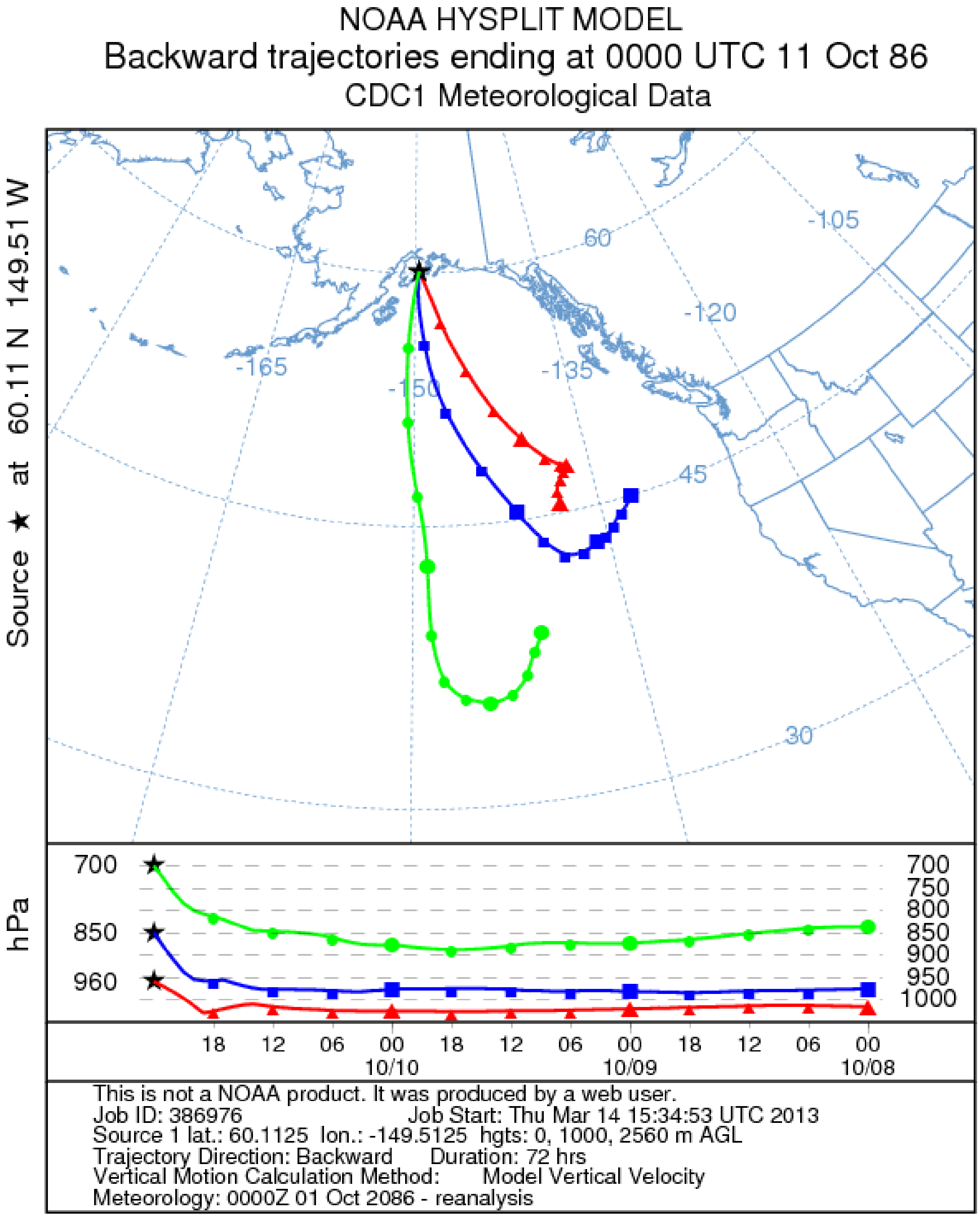

Figure 5.1. Surface (960mb), 850mb, and 700mb HYSPLIT trajectory model results for the October 1986 storm event.

5.1.2 Sea Surface Temperatures (SSTs)

The second data set used in storm analyses contained SSTs derived from the various databases available from NOAA. Daily values were generated from the following sources:

1985 – Present: http://dss.ucar.edu/datasets/ds277.7/
1946 - 1985: http://dss.ucar.edu/datasets/ds195.1/
Prior to 1946: http://dss.ucar.edu/datasets/ds540.0/

Observations were taken from ships, buoys (moored and drifting), automated coastal fixed platforms and drilling rigs, and satellite observations of SSTs (Woodruff et al. 2005). Analyses are archived to the nearest 0.1°F, with a spatial resolution of 1° in both latitude and longitude. For storm analyses, daily SSTs were used to determine the storm representative SST for each storm event on the short storm list. Figure 5.2 is an example daily SST map for the October 1986 storm event.

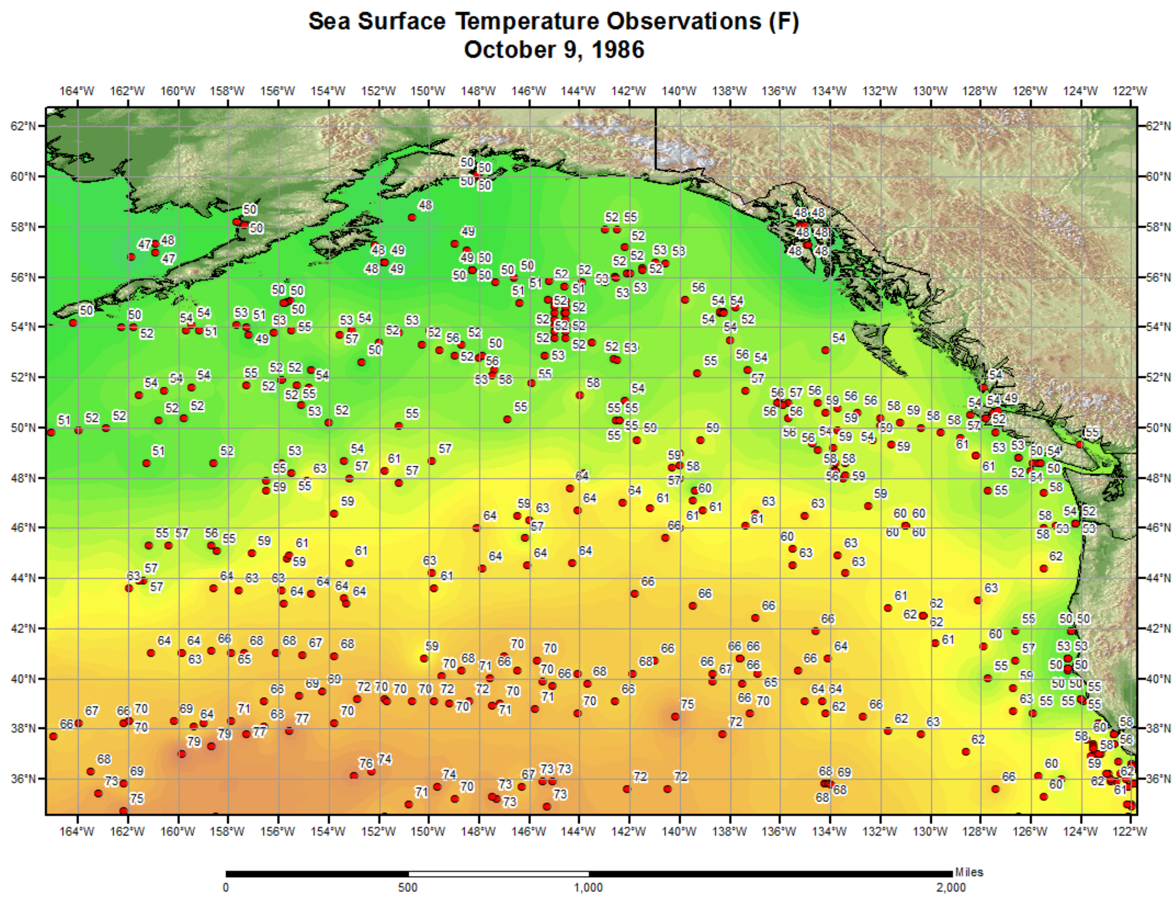

Figure 5.2. Daily sea surface temperatures for October 9, 1986 over the upwind domain used to determine the storm representative sea surface temperature.

For computing the maximization factors, a climatology of SSTs was computed for every 1° latitude and longitude, based on data from 1982 through 2012[5]. The standard deviation for each cell was calculated and plus two standard deviations (+2-sigma) were added to the monthly mean SST values for each cell. Monthly maps were produced to provide spatial analyses of the mean plus 2-sigma (two standard deviations warmer than the mean) SSTs. Use of the mean plus 2-sigma SSTs is consistent with the NWS procedure used in HMRs 57 and 59. Figure 5.3 is an example monthly map for October.

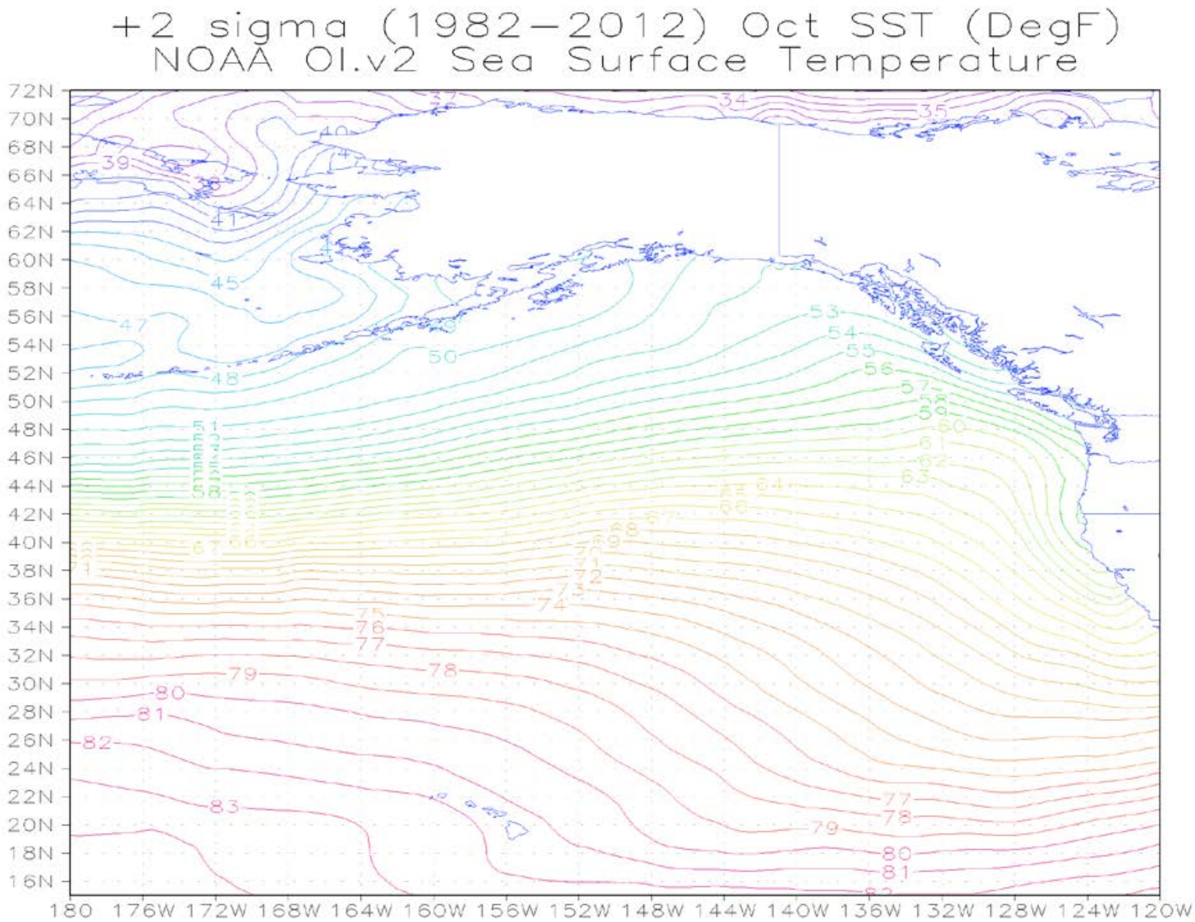

Figure 5.3. +2-sigma sea surface temperature map for October.

Dew point observations are not generally available over ocean regions. When the source region of atmospheric moisture feeding an extreme rainfall event originates over the ocean, a substitute for dew points observations is required. The NWS adopted a procedure for using SSTs as surrogates for dew points over the ocean. The value used as the maximum SST in the PMP calculations is determined using the SSTs plus two standard deviations (+2-sigma) warmer than the mean SST.

[5] From NOAA_OI_SST_V2, http://www.esrl.noaa.gov/psd/

This provides a value for the maximum SST that has a probability of occurrence of about 0.025, i.e. about the 40-year return frequency value (see Section 5.1.2.1 for more detail).

Following the NWS procedure (e.g. HMR 57) and previous AWA PMP work (Tomlinson et al. 2008-2013, Kappel et al. 2011-2014), storm representative SSTs were substituted for dew points. All storms on the short list were reanalyzed to determine the storm representative SST and the +2-sigma SST. These SST values are then treated the same as dew points and the same process is followed for storm maximization as if the SST values were dew point values taken from land based stations.

Where cold currents affect ocean temperatures adjacent to the coast, use of the cold SSTs is inappropriate to represent the storm atmospheric moisture source region. The procedure that selects a storm representative SST in the region that is the primary source of atmospheric moisture available to the storm is then employed. This procedure requires extending the inflow wind vector over the region of colder SSTs along the immediate coastline and selecting a location over the warmer water of the moisture source region. Daily SSTs are then analyzed over this general region, using HYSPLIT as guidance when available, to determine a homogenous region of SSTs in space and time. Generally, this area should show less than a 1°F temperature change in a 1° latitude x 1° longitude box. This value is the storm representative SST.

For storm maximization, the value for the maximum SST is determined using the mean plus 2-sigma SST for that location for a date two weeks before or after the storm date (which ever provides the climatologically warmer 2-sigma SST values). Storm representative SSTs and the mean plus 2-sigma SSTs are used in the same manner as storm representative dew points and maximum dew points in the maximization and transpositioning procedure.

The NWS states in HMR 57 that the two standard deviations warmer values are approximately equal to a 0.02 probability of occurrence. Specifically, HMR 57 Section 4.3, pp 43-44, states that two standard deviations represent about 98 percent of normally distributed values and this "…places the magnitude of this parameter at about the level of other estimates used in this study, e.g. the 100-year frequency values." For the +2-sigma probability, there is 0.05 out of 1.00 that is not included under the normal distribution curve. The 0.05 is divided between the extremes on the upper and lower ends of the normal distribution curve. Since only the high end (i.e. SST plus two standard deviations warmer) is used, only half of the 0.05 is excluded from under the normal distribution curve, i.e. 0.025. Hence 0.975 or 97.5% is included under the normal distribution curve. Figure 5.4 shows the normal distribution curve with the +1-sigma and +2-sigma values.

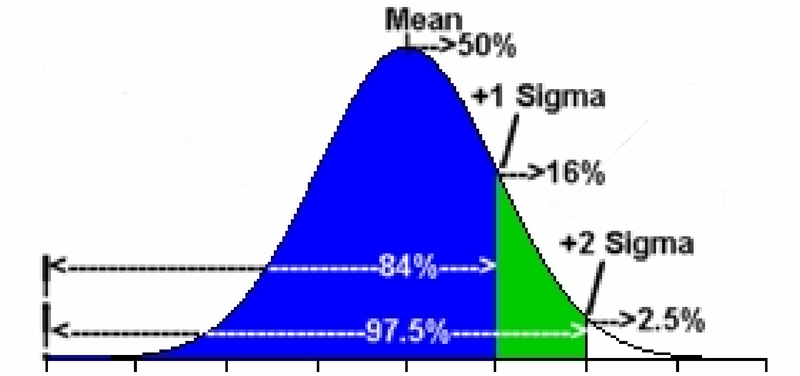

Figure 5.4. Normal distribution curve with +1-sigma and +2-sigma values shown

It appears, for reasons that are not clear in HMR 57, that the NWS increased the value of 0.975 to 0.99 and then concluded that this represents the 100-year frequency value. Therefore, it is important to note that without any adjustments, 0.975 is approximately equal to a 40-year return frequency value.

6. STORM TRANSPOSITIONING

Extreme rain events in meteorologically homogeneous regions surrounding a watershed are an important part of the historical evidence for a basin PMP estimate. Since most basin locations have a limited period of record and number of recording stations for rainfall data collected within the basin boundaries, the number of extreme storms that have been observed over the basin is often limited. This lack of data is especially prevalent for the Susitna River basin because of its remote location. To overcome this, storms that have been observed within similar meteorological and topographic regions are analyzed and adjusted to provide information describing the storm rainfall as if that storm had occurred over the basin being studied. Transfer of a storm from where it occurred to a location that is meteorologically and topographically similar is called storm transpositioning. The underlying assumption is that storms transposed to the basin could occur over the basin under similar meteorological conditions. To properly relocate such storms, it is necessary to address issues of similarity as they relate to meteorological conditions (moisture availability) and topography (difference in elevation and orographic influence) between the in-place storm location and the basin location.

Using ArcGIS, a gridded network was placed over the Susitna-Watana basin. The adopted grid cell resolution for this study is 0.025 x 0.025 decimal degrees in latitude and longitude (90 arc-seconds). The area of the grid cells varies with latitude, averaging approximately 1.4-square miles at the basin location. There are a total of 4,013 grid cells/grid points within the domain. This universal grid provides a consistent template for the grid cell by grid cell analysis. Figure 6.1 shows the grid over the Susitna-Watana basin.

Each of the short list storms were transposed from the storm center location to each of the 4,013 grid points within the Susitna-Watana basin. The transposition process includes a moisture transposition component and an orographic transposition component. The moisture transposition component closely follows the procedures in HMR 57 and previous AWA studies. The orographic transposition process leverages the NOAA Atlas 14 (Perica et al. 2012) 10 to 1,000-year precipitation frequency values to quantify the differences in extreme rainfall between the historic storm centers and the basin, which is primarily a function of elevation and topography. For moisture transpositioning, only the horizontal difference in available moisture between the storm center and the basin grid points is explicitly accounted for. The vertical component, which accounts for the difference in elevation between the two locations, was not calculated as part of the storm (also called moisture) transposition factor. Instead, this component was accounted for in the derivation of the orographic transposition component: the rainfall values used to derive the ratio at the in-place similar area to the Susitna-Watana basin inherently have the elevation component incorporated. The transposition procedures are defined in the following sections.

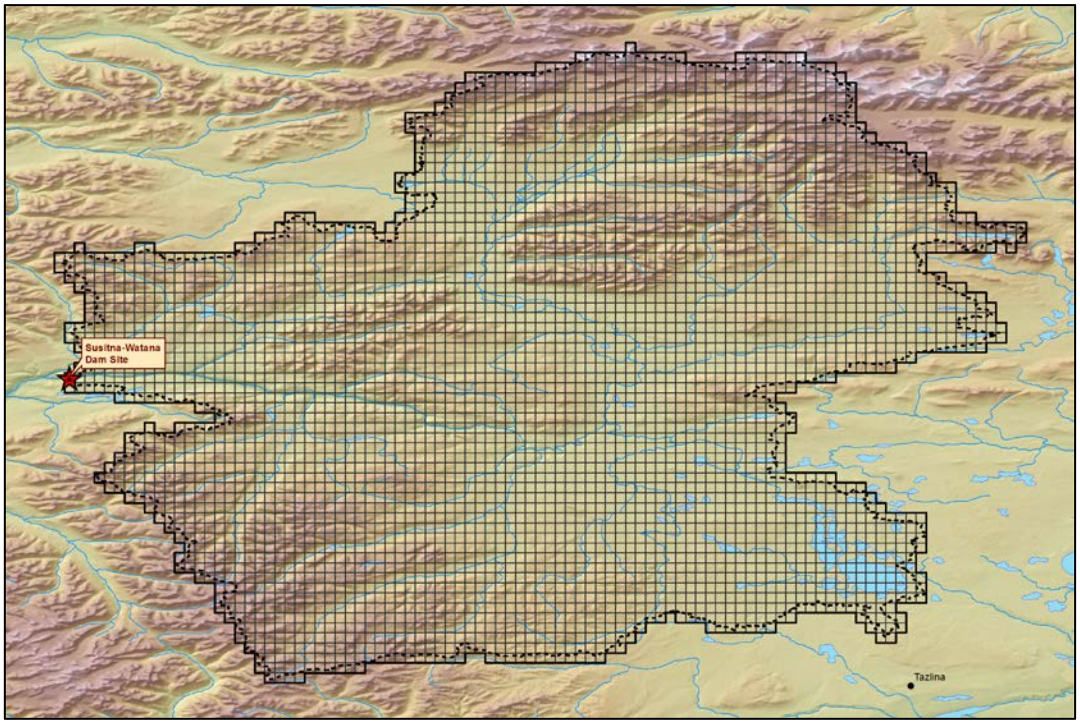

Figure 6.1. The universal 90 arc-second grid network placed over the Susitna-Watana drainage basin.

6.1 Moisture Transposition

The general procedure for storm maximization has been discussed in Section 5. The same data sets used for maximum SSTs are used in the storm transpositioning procedure. The wind inflow vector connecting the storm location with the storm representative SST location was transpositioned to each grid point within the basin. Figure 6.2 shows an example of inflow vector transpositioning for the August 1967, Fairbanks, Alaska storm center. The upwind end of the vector identifies the transposition maximum SST location. The value of the maximum SST at that location provided the transpositioned maximum SST value used to compute the transposition adjustment for relocating the storm to each grid point within the basin. The primary effect of storm transpositioning is to adjust storm rainfall amounts to account for enhanced or reduced atmospheric moisture made available to the storm at the transposed location versus the in-place storm location. The ratio of precipitable water due to available atmospheric moisture (as determined by the SST) at the basin target location to the in-place storm location is expressed as the moisture transposition factor (MTF). Figure 6.2 shows the august +2σ SST as a background grid. The SST grid resolution is 1° x 1° decimal degree; therefore a bilinear interpolation is used to extract the SST value at each grid point with a greater degree of precision.

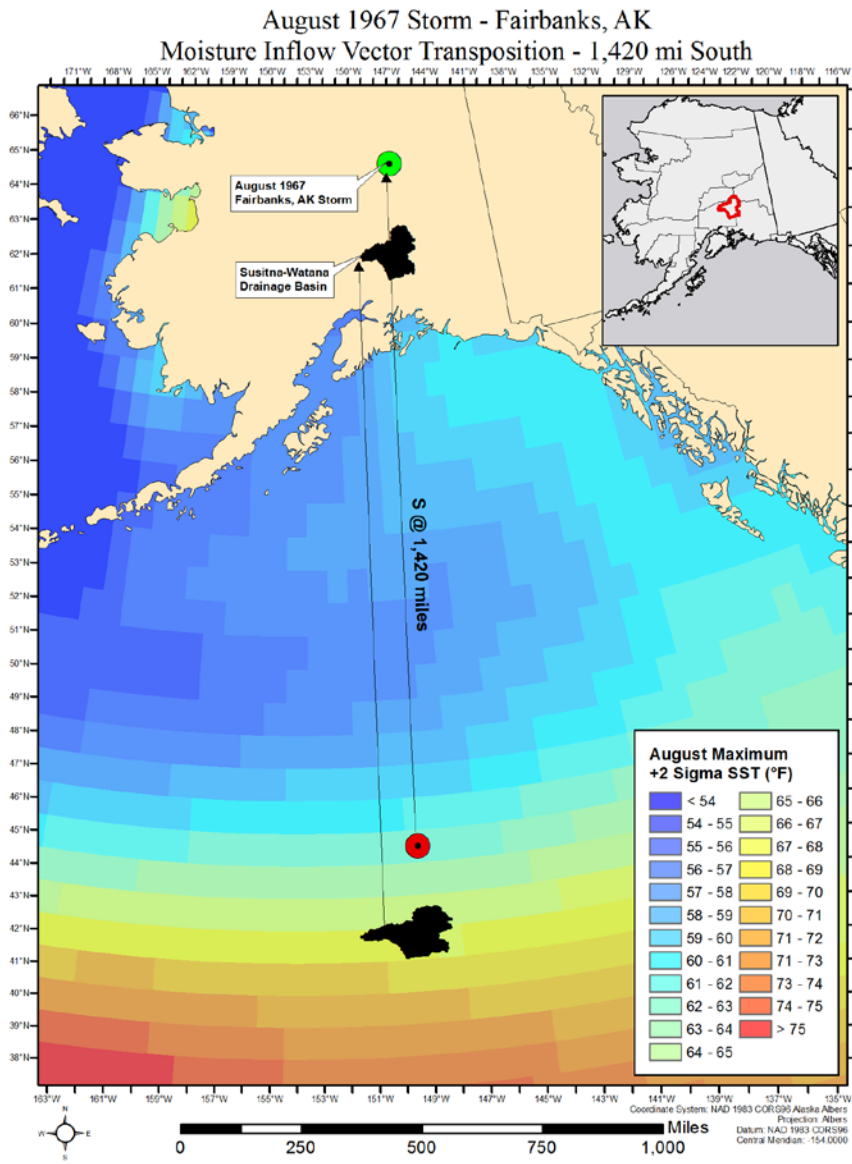

Figure 6.2. An example of inflow wind vector transpositioning for August 1967, Fairbanks storm. The storm representative SST location is ~1,420 miles south of the storm location.

6.2 Orographic Transposition

6.2.1 Topographic Effect on Rainfall

The terrain within the Susitna River basin and the surrounding region is complex, often over relatively short distances (Figure 6.3). When a basin has intervening elevated terrain features that deplete some of the atmospheric moisture available to storms before reaching a basin, these must be taken into account during the storm maximization process. Conversely, when a basin includes terrain which enhances the lift in the atmosphere and increases the conversion of moisture to liquid and ice particles, precipitation processes are enhanced. To account for the enhancements and reductions of precipitation by terrain features, called orographic effects, explicit evaluations were performed using the OTF calculation. The OTF evaluation of the orographic effect in this study is significantly more objective and reproducible than the HMR procedure.

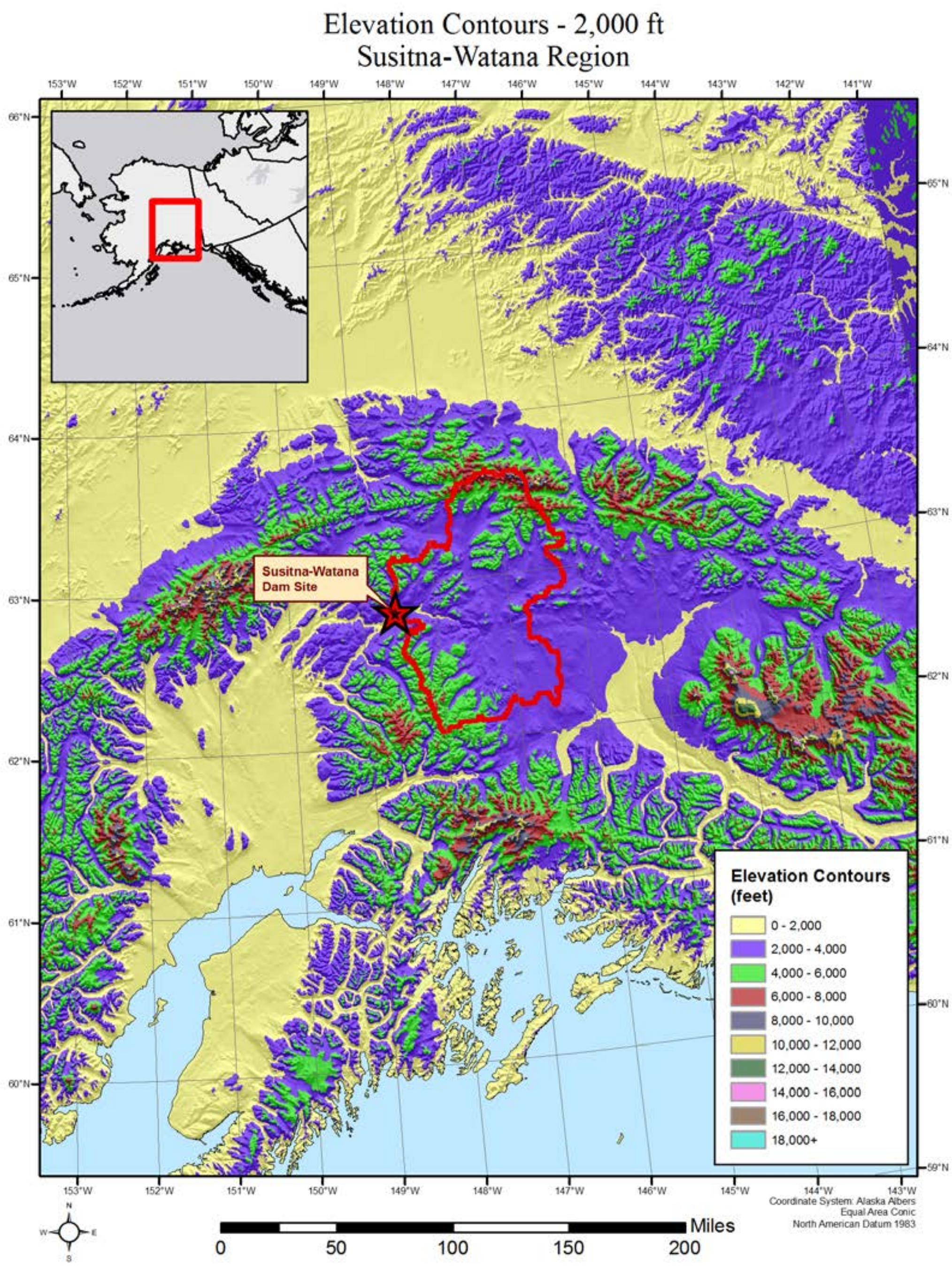

Figure 6.3. 2,000-foot elevation contours over the Susitna-Watana region.

Orographic effects on rainfall are explicitly captured in the NOAA Atlas 14 precipitation frequency climatological analyses. Although the orographic effects at a particular location may vary from storm to storm, the overall effect of the topographic influence is inherent in the climatology of storms that have occurred over various locations, assuming that the climatology is based on storms of the same type being analyzed. The NOAA Atlas 14 analysis should adequately reflect the differences in topographic influences at different locations at durations appropriate to the storm type in similar meteorological and topographical settings.

The procedure used in this study to account for orographic effects assesses the differences between the NOAA Atlas 14 data at the in-place storm location and each grid point within the Susitna-Watana basin. By evaluating the rainfall values for a range of return frequencies at both locations, a relationship between the two locations was established. For this study, precipitation frequency datasets developed as part of NOAA Atlas 14, Volume 7 (Perica et al. 2012) were used to evaluate the orographic effects. Figure 6.4 illustrates the 100-year 24-hour NOAA Atlas 14 precipitation coverage. The spatial distribution clearly exhibits the anchoring of the majority of rainfall to the coastal topography, particularly on the upwind side, while inland regions (such as the Susitna-Watana basin) are under a significant rain shadow effect and experience relatively low rainfall.

The NOAA Atlas 14 precipitation frequency estimates utilize data from the mean annual maximum grids developed using the Oregon State University Climate Group's PRISM system to help spatially distribute the values between data points. PRISM is a peer-reviewed modeling system that combines statistical and geospatial concepts to evaluate gridded rainfall with particular effectiveness in orographic areas (Daly et al. 1994, 1997). NOAA Atlas 14 precipitation frequency estimates implicitly express orographic controls through the adoption of the PRISM system. This study assumes the relationship between precipitation frequency values in areas of similar atmospheric characteristics reveal a quantifiable orographic effect and that terrain influence drives the variability in the relationship between NOAA Atlas 14 values at two distinct point locations.

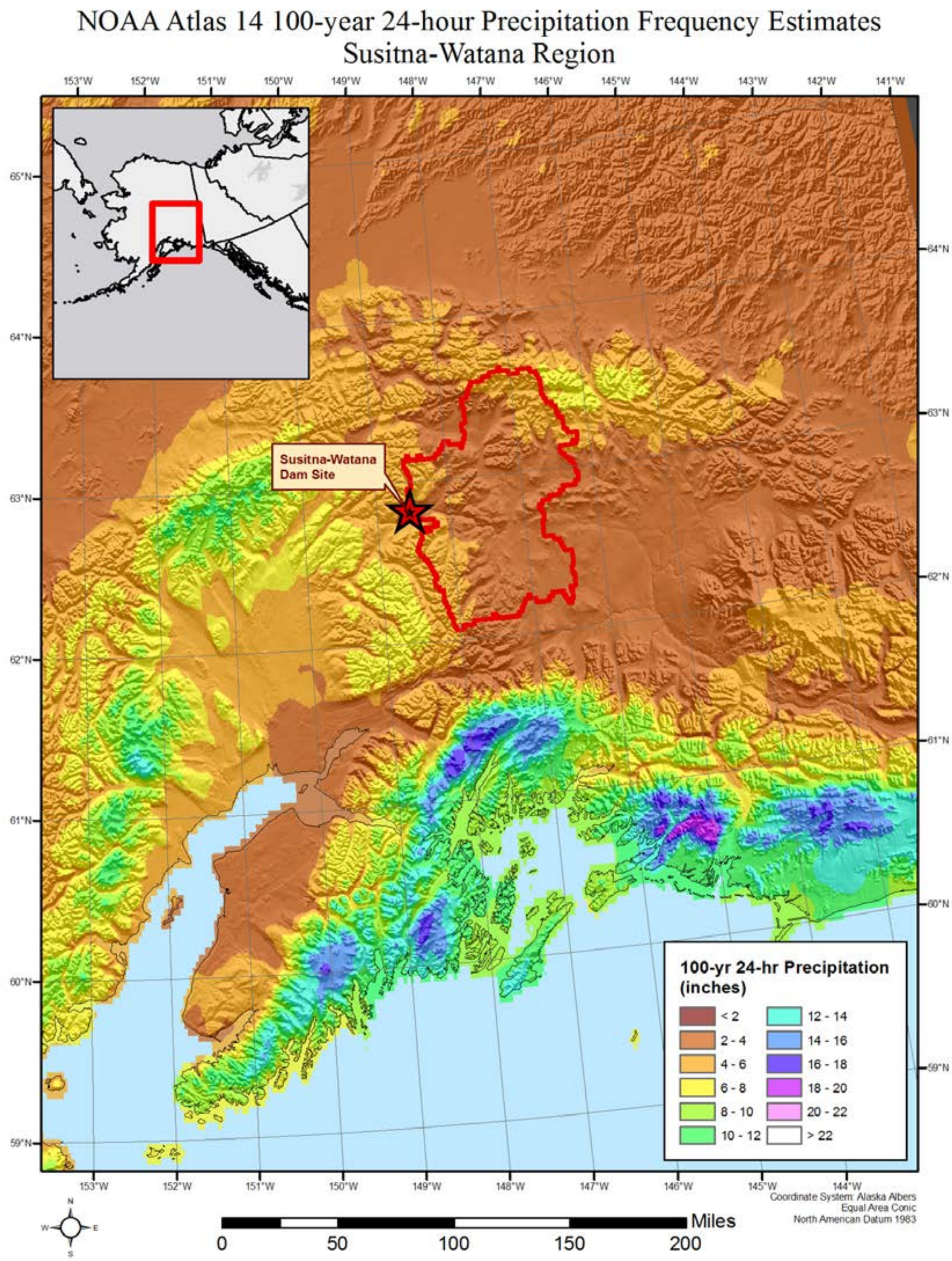

Figure 6.4. 100-year 24-hour NOAA Atlas 14 precipitation over the Susitna-Watana region.

6.2.2 Orographic Transpositioning Procedure

The orographically adjusted rainfall values for a given storm at a target location (grid cell) within the basin are calculated by applying a coefficient of proportionality, determined by the relationship between a NOAA Atlas 14 data series at the source storm location and the corresponding NOAA Atlas 14 values at the target location. For the transposition of a single grid cell at a given duration, the orographic relationship is defined as the linear relationship between the NOAA Atlas 14 values, at that duration, over a range of recurrence intervals. This study evaluates the trend of precipitation frequency estimates through the 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-year average recurrence intervals. The relationship between the target and the source can be expressed as a linear function with P_o as the independent variable and P_i as the dependent variable as shown in Equation 6.1.

$$P_o = mP_i + b \qquad \text{Equation 6.1}$$

where,

P_o	=	orographically adjusted rainfall (target)
P_i	=	in-place rainfall (source)
m	=	proportionality coefficient (slope)
b	=	transposition offset (y-intercept)

Equation 6.1 provides the orographically transpositioned rainfall depth, as a function of the in-place rainfall depth. The in-place rainfall depth used to calculate the orographically transpositioned rainfall use NOAA Atlas 14 values. The 24-hour duration is appropriate for all storms in the short list. To express the orographic effect as a ratio, or OTF, the orographically adjusted rainfall (P_o) is divided by the original source in-place rainfall depth (P_i). It is assumed the orographic effect for a given transposition scenario will remain constant over the durations analyzed. Therefore, the 24-hour OTF is valid for any other duration a storm.

The orographic relationship can be visualized by plotting the average NOAA Atlas 14 depths for the grid point at the source location on the *x*-axis and the NOAA Atlas 14 depths for the grid point at the target location on the *y*-axis, then drawing a best-fit linear trend line among the seven return frequency value points. The trend line describes the general relationship between the NOAA Atlas 14 values at the grid location and the values at the storm location. As an alternative to producing the best-fit linear trendline graphically, linear regression can be used to apply the function mathematically. The mathematical method was applied, in Excel spreadsheets, to efficiently calculate the OTF for each of the basin grid points, for each storm. An example of the determination of the orographic relationship and development of the OTF is given in Section 7.3.

7. PMP CALCULATION PROCEDURES

PMP depths were calculated by comparing the total adjusted rainfall values for all transpositionable storm events for each grid point and taking the largest value, a process comparable to the envelopment of all transpositionable events. In this case, envelopment occurs because the largest PMP depth for a given duration is derived after analyzing all storms for each grid point location for each duration over the Susitna-Watana basin.

The adjusted rainfall at a grid point, for a given storm event, was determined by applying a Total Adjustment Factor (TAF) to the SPAS analyzed rainfall depth value corresponding to the basin area size of 5,131 mi^2, at each analyzed duration. The TAF is the product of the three separate storm adjustment factors, the IPMF, the MTF, and the OTF. In-place maximization and moisture transposition are described in Section 6.1. Orographic transposition is described in Section 6.2. These calculations were completed for all transpositionable storm centers, for each of the 4,013 basin grid cells.

An Excel storm adjustment spreadsheet was produced for each of the transpositionable storm centers. These spreadsheets are designed to perform the initial calculation of each of the three adjustment factors, along with the final TAF. The spreadsheet format allows for the large number of data calculations to be performed correctly and consistently in an efficient template format. Information such as the basin NOAA Atlas 14 data, coordinate pairs, grid point elevation values, equations, and the precipitable water lookup table remain constant from storm to storm and remain static within the spreadsheet template. The spreadsheet contains a final adjusted rainfall tab with the adjustment factors, including the TAF, listed for each grid point. A table holding the TAF for each basin grid point was exported to a GIS feature class for each storm. A Python-language scripted GIS tool receives the storm TAF feature classes and the corresponding DAD tables for each of the 13 SPAS DAD zones as input, along with a basin outline feature layer as a model parameter. The tool then calculates and compares the total adjusted rainfall at each grid point within the basin and determines the PMP depth at each duration up to 216-hours. The tool produces gridded PMP datasets for each duration and a point shapefile holding PMP values for all durations.

The following sections describe the procedure for calculating the IPMF, the MTF, the OTF, and the TAF for the creation of the storm adjustment feature classes. The August 1967, Fairbanks, Alaska event controls PMP at each duration. Examples of calculations using the data from this storm are provided.

7.1 In-Place Maximization Factor

In-place storm maximization is applied to each storm event using the methodology described above. Storm maximization is quantified by applying the IPMF, calculated using Equation 7.2.

$$IPMF = \frac{W_{p,max}}{W_{p,rep}} \qquad \text{Equation 7.2}$$

where,

$W_{(p,max)}$ = precipitable water for the maximum +2σ monthly SST
$W_{(p,rep)}$ = precipitable water for the representative SST

EXAMPLE:

Using the storm representative SST temperature and storm center elevation as input, the precipitable water lookup table returns the depth, in inches, used in Equation 7.2. The storm representative SST is 61.0°F, calculated using the procedures described in Section 5. The storm center elevation is approximated at 7,500 feet at the storm center of 65.52 N, 147.33 W. The storm representative precipitable water value ($W_{p,rep}$) is calculated:

$$W_{p,rep} = W(@60.0°)_{p,30,000'} - W(@60.0°)_{p,7,500'}$$

$$W_{p,rep} = 1.45'' - 0.89''$$

$$\boldsymbol{W_{p,rep} = 0.560''}$$

The temporal transposition date for the August 1967, Fairbanks event is August 15th, therefore the August +2σ SST climatology is appropriate for use to determine the maximum precipitable water. The August climatological maximum +2σ SST at the upwind storm representative location is 62.5°F. The storm location climatological maximum available moisture at the storm in-place elevation of 7,500' ($W_{p,max}$) is calculated:

$$W_{p,max} = W(@62.5°)_{p,30,000'} - W(@62.5°)_{p,7,500'}$$

$$W_{p,max} = 1.56'' - 0.945$$

$$\boldsymbol{W_{p,max} = 0.615''}$$

The ratio of climatological maximum moisture ($W_{p,max}$) to the in-place storm representative moisture ($W_{p,rep}$) yields the in-place maximization factor using Equation 7.2:

$$IPMF = \frac{0.615}{0.560}$$

$$\boldsymbol{IPMF = 1.10}$$

7.2 Moisture Transposition Factor

The change in available atmospheric moisture between the storm center location and the basin target grid point is quantified using the MTF. This MTF represents the change in available atmospheric moisture due to horizontal distance only and is calculated at the storm center elevation. The change in atmospheric moisture due to vertical displacement is quantified in the OTF, described in the next section. The MTF is calculated as the ratio of moisture for the climatological maximum SST at the target grid cell location to the moisture for the climatological maximum SST at the storm center elevation.

$$MTF = \frac{W_{p,trans}}{W_{p,max}} \qquad \text{Equation 7.3}$$

where,

$W_{(p,trans)}$ = maximum precipitable water at the basin grid cell
$W_{(p,max)}$ = maximum precipitable water at the storm center location

EXAMPLE:

The transpositioned climatological maximum available moisture must be determined for each target grid point within the basin domain. There are 4,013 grid cells within the basin domain. Only the first grid cell #1, at 62.075° N, 148.050° W (in the southwest corner of the basin), is discussed in this example. The August climatological maximum SST temperature, at the moisture inflow vector upwind from grid point #1 is 69.0°F. The precipitable water for this SST is adjusted to the in-place storm center elevation of 7,500 ft[6]. The horizontally transpositioned climatological maximum available moisture ($W_{p,trans}$) is calculated.

$$W_{p,trans} = W(@69.0°)_{p,30,000'} - W(@69.0°)_{p,7,500'}$$

$$W_{p,trans} = 2.14'' - 1.21''$$

[6] Note: Although the elevation at grid point #1 is at 6,500 ft, the elevation of the storm center is used to remove the vertical component of the moisture transposition which will be included in the orographic transposition factor.

$$\boldsymbol{W_{p,trans} = 0.930''}$$

The storm location climatological maximum available moisture ($W_{p,\ max}$) was calculated above for the IPMF:

$$\boldsymbol{W_{p,max} = 0.615''}$$

The MTF is calculated as the ratio of moisture for the climatological maximum SST for the grid cell location ($W_{p,\ trans}$) to the moisture for the climatological maximum SST for the storm center location ($W_{p,\ max}$), from Equation 7.3:

$$MTF = \frac{0.930}{0.615}$$

$$\boldsymbol{MTF = 1.51}$$

7.3 Orographic Transposition Factor

Section 6.2 provides detail on the methods used in this study to define the orographic effect on rainfall. The OTF is calculated by taking the ratio of orographically affected rainfall at the storm in-place location to orographically affected rainfall at the basin grid cell location.

$$OTF = \frac{P_o}{P_i} \qquad \text{Equation 7.4}$$

where,

P_o = orographically adjusted rainfall (target)
P_i = SPAS-analyzed in-place rainfall

The orographically adjusted rainfall is determined by applying Equation 7.5 to the SPAS-analyzed rainfall depth. The 24-hour duration was used for P_i to be consistent with the 24-hour duration of the precipitation frequency datasets.

$$P_o = mP_i + b \qquad \text{Equation 7.5 (from Equation 6.1)}$$

where,

P_o = orographically adjusted rainfall (target)
P_i = SPAS-analyzed in-place rainfall
m = proportionality coefficient (slope)
b = proportionality variation offset (y-intercept)

EXAMPLE:

Table 7.1 gives an example using NOAA Atlas 14 24-hour values (in inches) at both the storm center grid cell location (source) and a basin grid cell location (target) used to determine the orographic relationship.

Table 7.1. 24-hour NOAA Atlas 14 Precipitation Frequency values at the storm center (source) and grid cell #1 (target) locations.

	10 year	25 year	50 year	100 year	200 year	500 year	1000 year
SOURCE (X-axis)	3.05	3.73	4.27	4.85	5.46	6.32	7.02
TARGET (Y-axis)	2.99	3.65	4.17	4.71	5.28	6.07	6.70

When the NOAA Atlas 14 values are plotted, a best fit trendline can be constructed to provide a visualization of the relationship between the NOAA Atlas 14 values at the source and target locations (Figure 7.1). In this example, the values for the source grid point nearest the Fairbanks, Alaska (August 1967) storm center are plotted on the *x*-axis while the target values for the first grid point in basin are plotted on the *y*-axis.

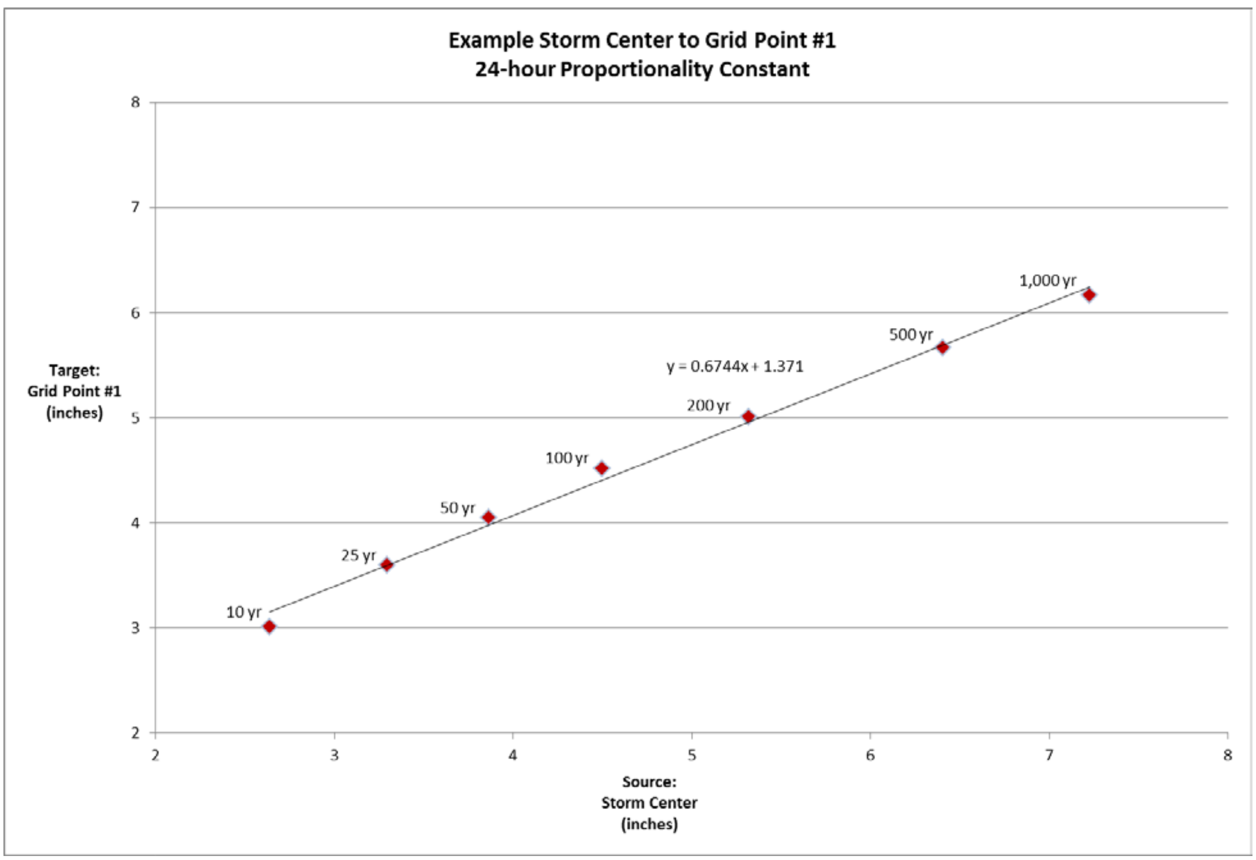

Figure 7.1. Example of NOAA Atlas 14 proportionality between the Fairbanks, 1967 DAD Zone 1 storm center and the Susitna River basin grid cell #1.

The orographically adjusted rainfall at the target location can be determined using the equation of the best fit trendline in slope-intercept form. This linear trendline equation corresponds to equation 7.5.

The slope, *m* is the proportionality coefficient, representing the direct relationship between the source and target cells. The *y*-intercept, *b,* is used to correct for variability in the precipitation frequency estimate recurrence intervals between the source and target locations. The equation for the SPAS 1270_1 24-hour orographically adjusted rainfall transpositioned to grid point #1, based on the linear trendline in Figure 7.5 is:

$$P_o = 0.6744m + 1.371$$

The maximum SPAS analyzed 24-hour point rainfall value of 5.36" is entered as the *Po* value to estimate the target *y*-value, or orographically adjusted rainfall (P_o) of 4.99".

$$P_o = 0.6744(5.36'') + 1.371''$$

$$\boldsymbol{P_o = 4.99''}$$

The ratio of the orographically adjusted rainfall (P_o) to the in-place SPAS analyzed 24-hour rainfall (P_i) yields the orographic transposition factor (OTF).

$$OTF = \frac{4.99''}{5.36''}$$

$$\boldsymbol{OTF = 0.93}$$

The OTF to grid cell #1 of the basin is 0.93, or a 7% rainfall reduction from the storm center location due to terrain effects. The OTF is then considered to be a temporal constant for the spatial transposition between that specific source/target grid point pair, for that storm only, and can then be applied to the other durations for the given storm.

7.4 Total Adjusted Rainfall

The TAF is a product of the linear multiplication of the IPMF, MTF, and OTF. The TAF is a combination of the total moisture and terrain influences on the SPAS analyzed rainfall when maximized and transpositioned to the target grid cell.

$$TAF = IPMF * MTF * OTF \qquad \text{Equation 7.7}$$

EXAMPLE:

For grid point #1, the TAF is calculated as shown in Equation 7.7 using the IPMF from Section 7.1, the MTF from Section 7.2, and the OTF from Section 7.3:

$$TAF = 1.10 * 1.51 * 0.93$$

$$TAF = 1.54$$

To calculate the total adjusted rainfall, the TAF is applied to the SPAS analyzed rainfall depth at the basin area size (5,131 mi^2). For the Fairbanks, Alaska event, the 216-hour SPAS analyzed rainfall depth at the basin size is 8.52”. Therefore, the total adjusted rainfall for this storm at grid point #1 is:

$$Total\ Adj.Rainfall_{216-hr} = TAF * Rainfall_{216-hr}$$

$$Total\ Adj.Rainfall_{216-hr} = 1.54 * 8.52''$$

$$Total\ Adj.Rainfall_{216-hr} = 13.12''$$

7.5 Gridded PMP Calculation and Envelopment

The total adjusted rainfall values are computed for each of the 4,013 grid cells in the basin. These calculations are made for a series of index durations sufficient to provide a framework for the temporal distribution of PMP over the basin through a 9-day period. For this study, the index durations are 1-, 6-, 12-, 24-, 48-, 72-, 96-, 120-, 144-, 168-, 192-, and 216-hour durations.

Once the total adjusted rainfall values have been calculated for each of the basin grid cells, the process is repeated for each SPAS DAD zone on the short list. Then the total adjusted rainfall values for all storms at a given grid point are compared and the largest becomes the PMP. When this comparison is made at a grid by grid basis for all storms, the result is an envelopment of adjusted rainfall values. The PMP at each grid point will be derived from whichever storm, after maximization and transposition, produces the largest rainfall. After the total adjusted rainfall had been calculated for all grid points in the basin, for all storms, the Fairbanks, Alaska event of August 1967 produced the largest depths, at all durations.

The resulting gridded PMP values for each index duration are contained within GIS files in both raster and vector (point) datasets. Due to the large amounts of calculations needed to create the PMP grids, a scripted ArcGIS tool was created using the Python language. The tool performs the following tasks:

1) Calculates the basin size
2) Looks up the SPAS analyzed rainfall depths at the basin size
3) Applies the rainfall depths to the total adjusted rainfall factor for each storm
4) Compares the adjusted rainfall values for all storms to get PMP
5) Outputs the PMP to GIS files
6) Repeats the process for each duration

8. SPATIAL AND TEMPORAL DISTRIBUTION OF PMP

8.1 Spatial Distribution

The spatial distribution of the Susitna-Watana PMP is dependent on a combination of the variation of the gridded OTF and MTF values over the basin. Therefore, the spatial distribution is largely dependent on variation in terrain, which is represented by the 10- through 1,000-year 24-hour NOAA Atlas 14 precipitation frequency spatial distribution over the basin, and to a lesser extent, variation in moisture which is controlled by the gradient of sea surface temperatures at the source location for the controlling storm event.

The variation in available moisture is a smooth gradient with larger values at the southern end of the basin transitioning to smaller values at the northern end. A map of the MTF over the basin (Figure 8.1) illustrates the distribution due to moisture.

As discussed in Section 6.2.1, the topography of the basin and surrounding region is dynamic and varies greatly over the surface of the basin. Therefore, it is expected that the effect of mountainous terrain would be the defining factor in the spatial distribution. The variation of rainfall due to orography, as a result of slope, elevation, and rain shadow effect is inherently represented in the OTF due to it being a function of the NOAA Atlas 14 precipitation frequency relationship between each grid point in the basin and a constant location at the storm center. A map of the OTF over the basin (Figure 8.2) illustrates the spatial distribution due to terrain.

The spatial distribution pattern, due to the variation in terrain and moisture is apparent in the gridded basin PMP maps. Figures 8.3a, 8.3b, and 8.3c show the basin 24-hour, 72-hour, and 216-hour PMP, respectively.

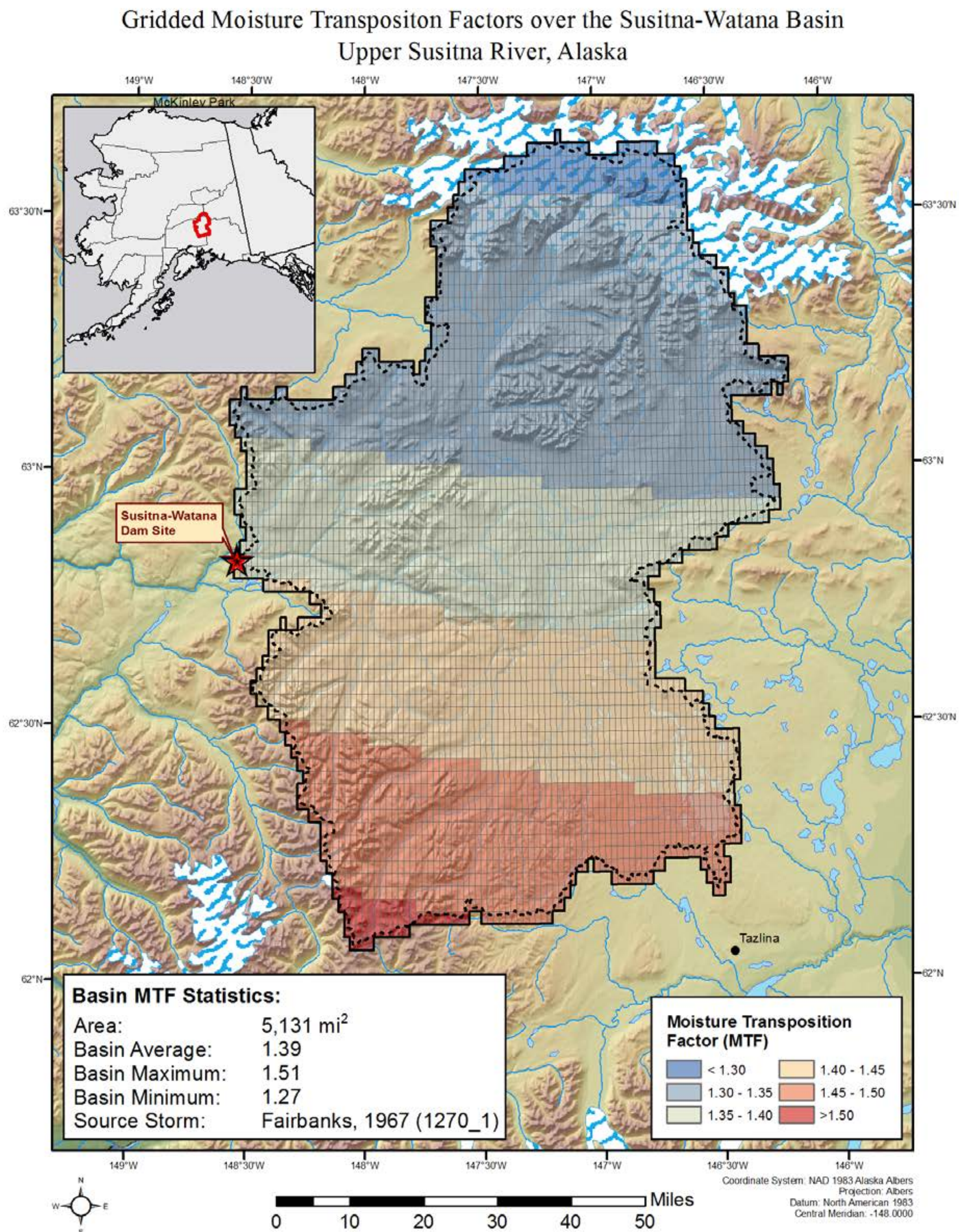

Figure 8.1. Moisture Transposition Factors over the basin.

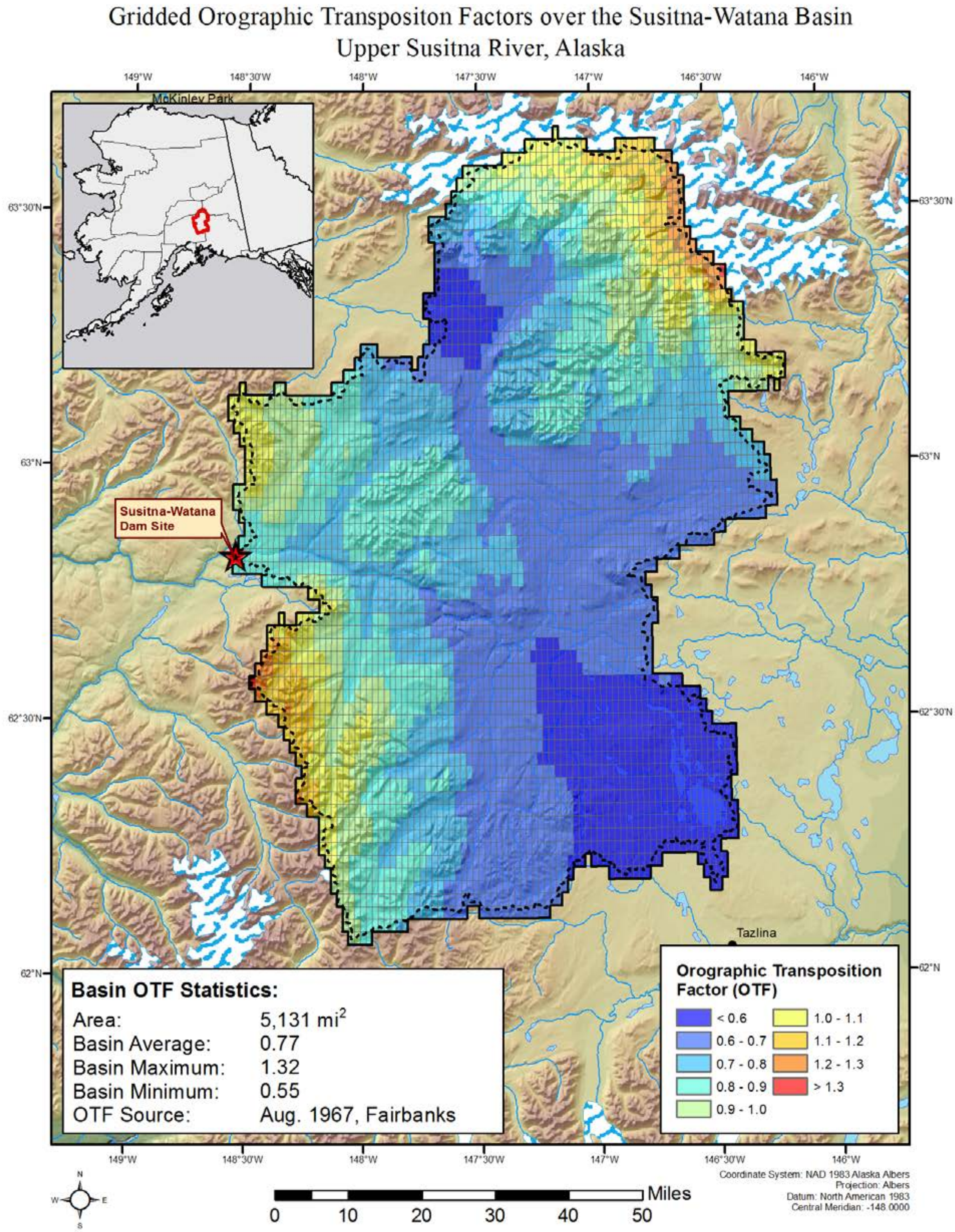

Figure 8.2. Orographic Transposition Factors over the basin.

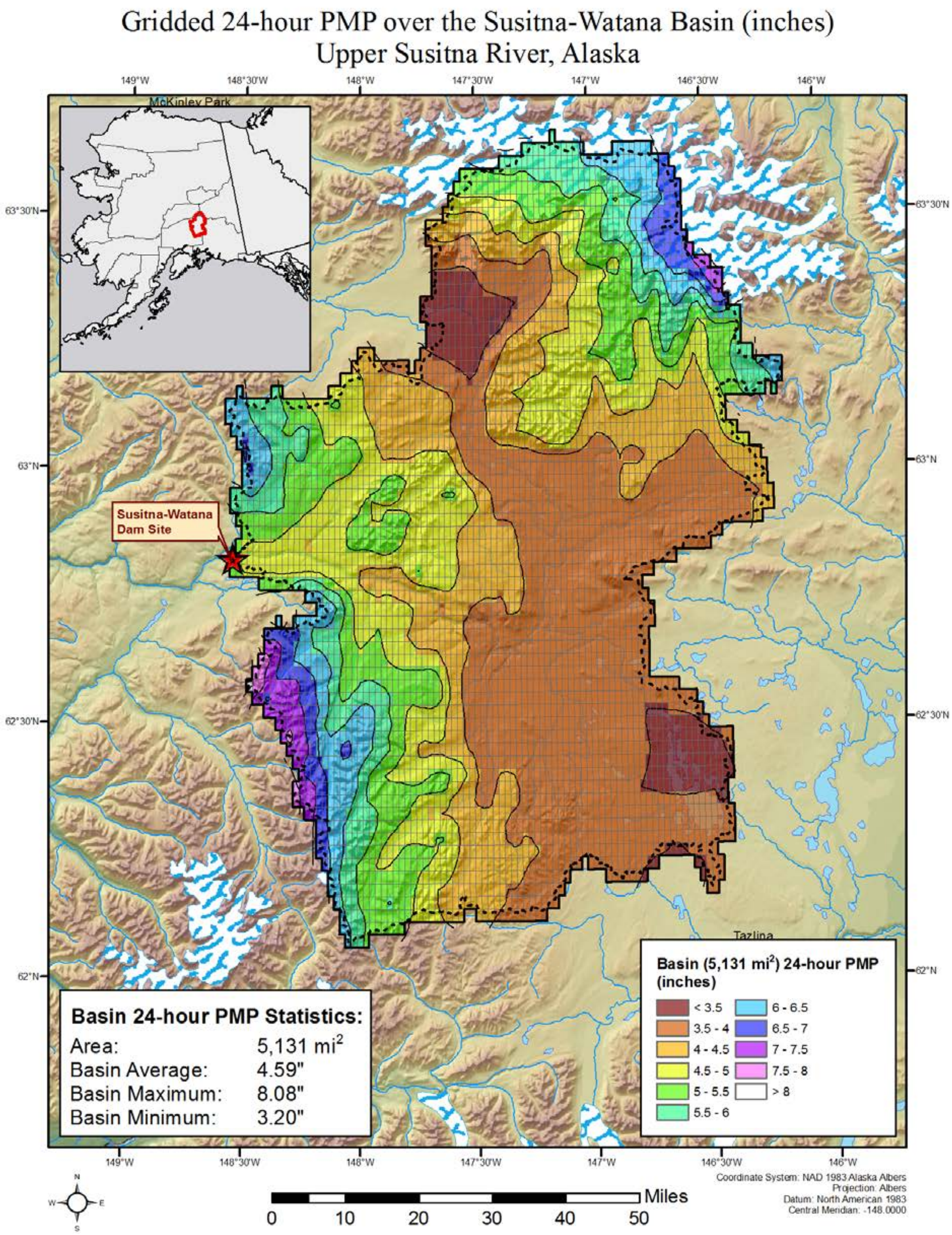

Figure 8.3a. Susitna River basin 24-hour gridded PMP.

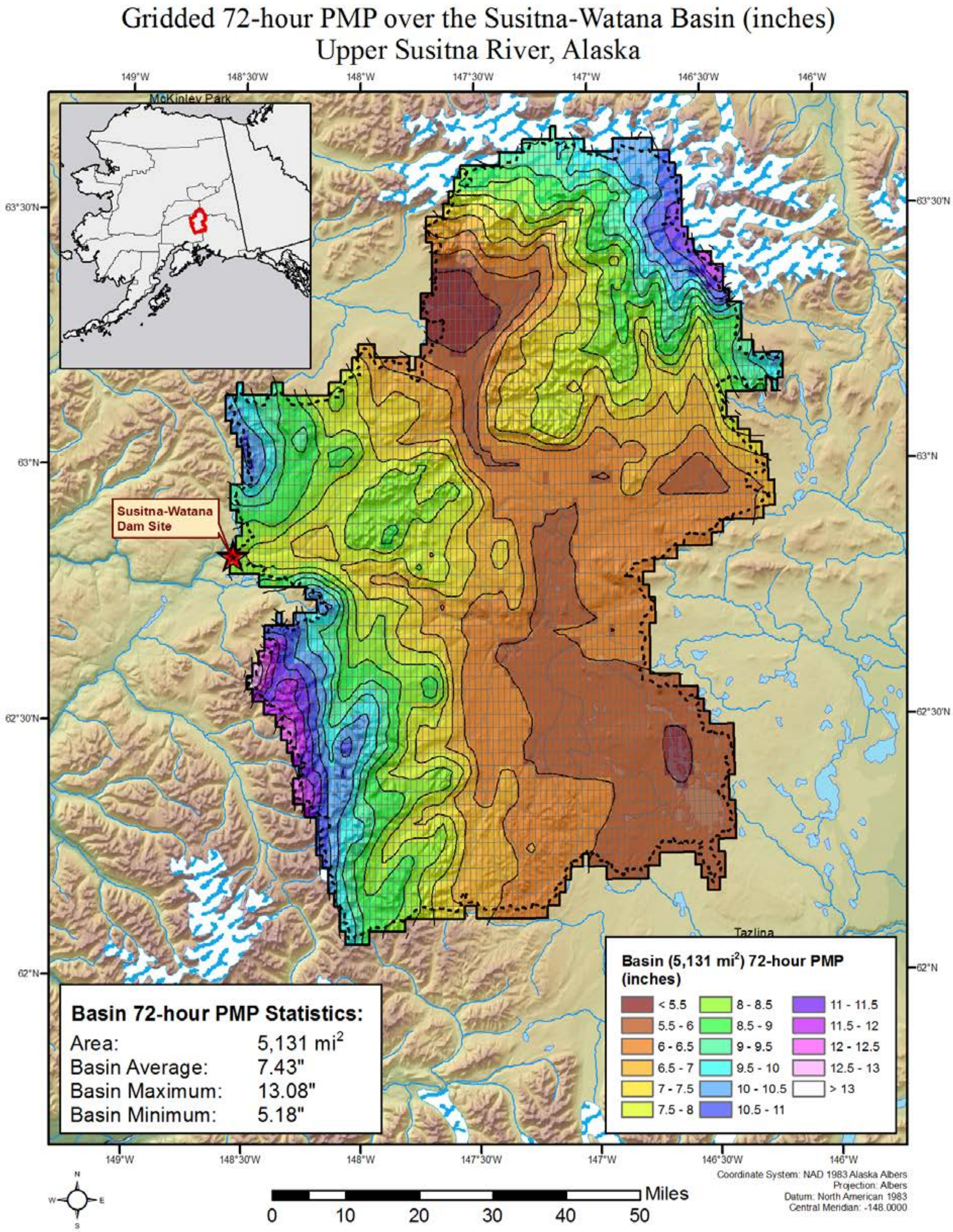

Figure 8.3b. Susitna River basin 72-hour gridded PMP.

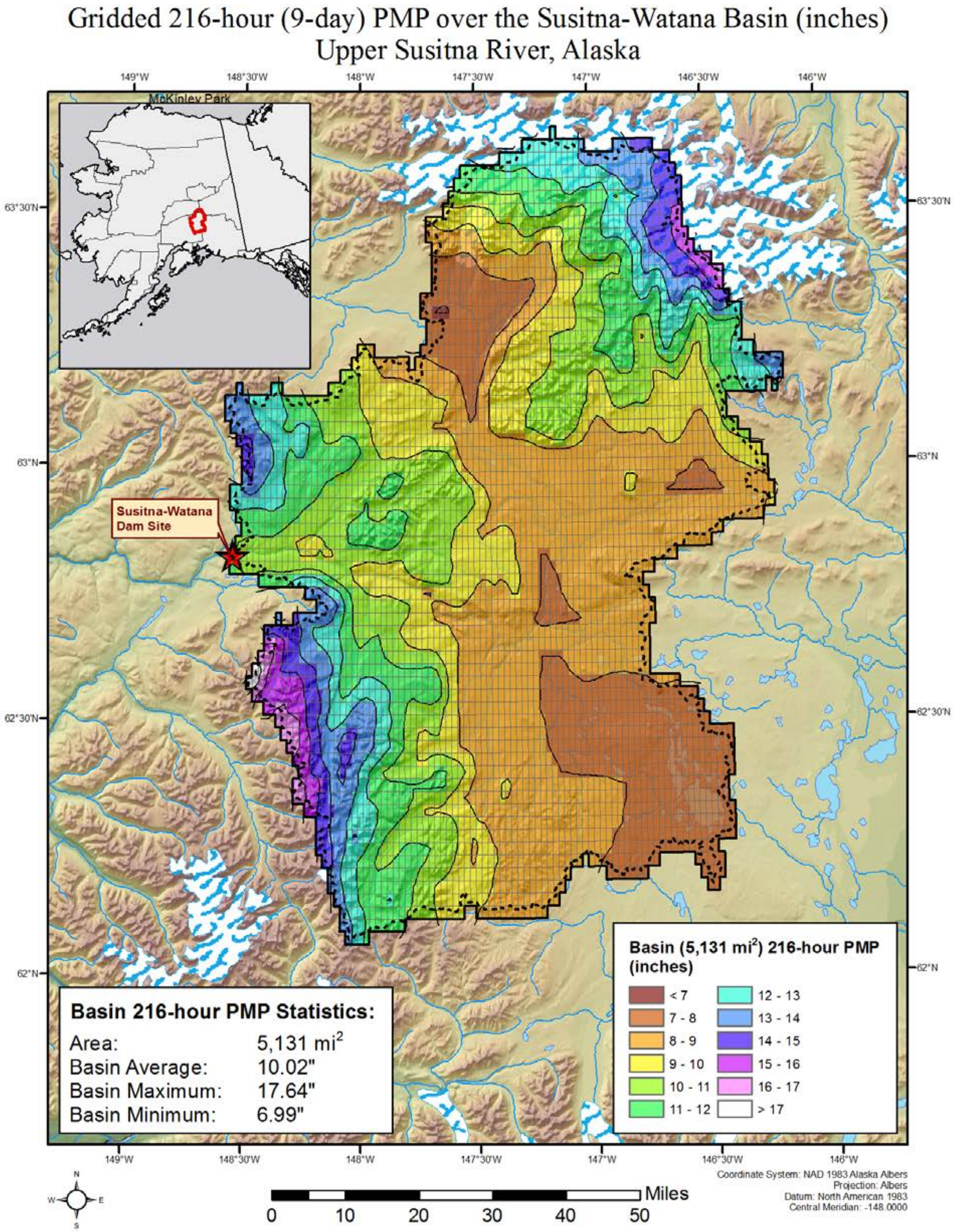

Figure 8.3c. Susitna River basin 216-hour gridded PMP.

8.2 Temporal Distribution

Hourly accumulated PMP depths for each grid point were determined by plotting the basin average PMP values, for each index duration, on a graph. A smooth curve was drawn through each index duration, 1-hour through 216-hour. Using this curve, the PMP accumulations at each hourly interval were estimated. The hourly incremental PMP values could then be calculated from the accumulated PMP values. This process follows the general procedure outlined in HMR 57, however, here it has been scaled up to 1-hour (instead of 6-hour intervals), and extends to a total duration of 216-hour (instead of 72-hours).

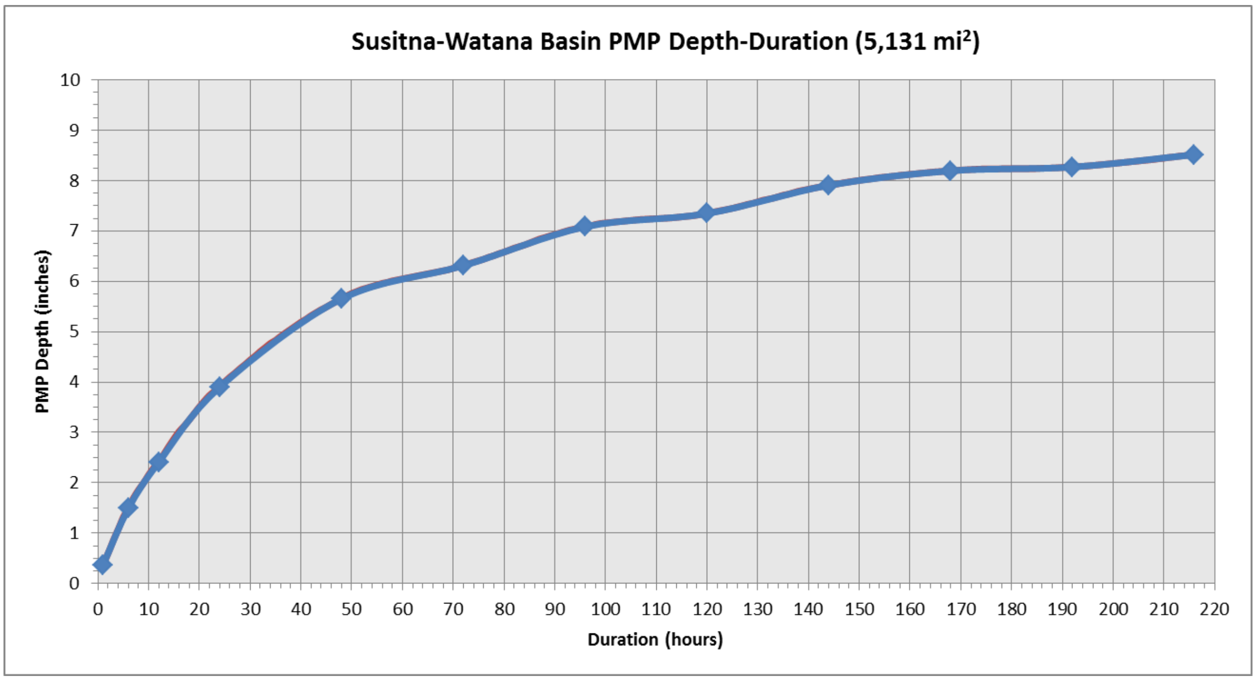

Figure 8.4. Depth-Duration PMP curve used to interpolate accumulated PMP at hourly intervals.

To temporally distribute the gridded PMP values, the incremental depths are re-ordered to mirror the mass curve of three separate storm events: August 1955, Denali N.P. (SPAS 1272) DAD zone 1; August 1967, Fairbanks (SPAS 1270) DAD zone 1; and August 2012, Old Tyonek (SPAS 1256) DAD zone 1.

The temporal distribution pattern for August 1955, Denali N.P. (SPAS 1272) DAD zone 1 applied to the total basin average PMP is shown in Figure 8.5.

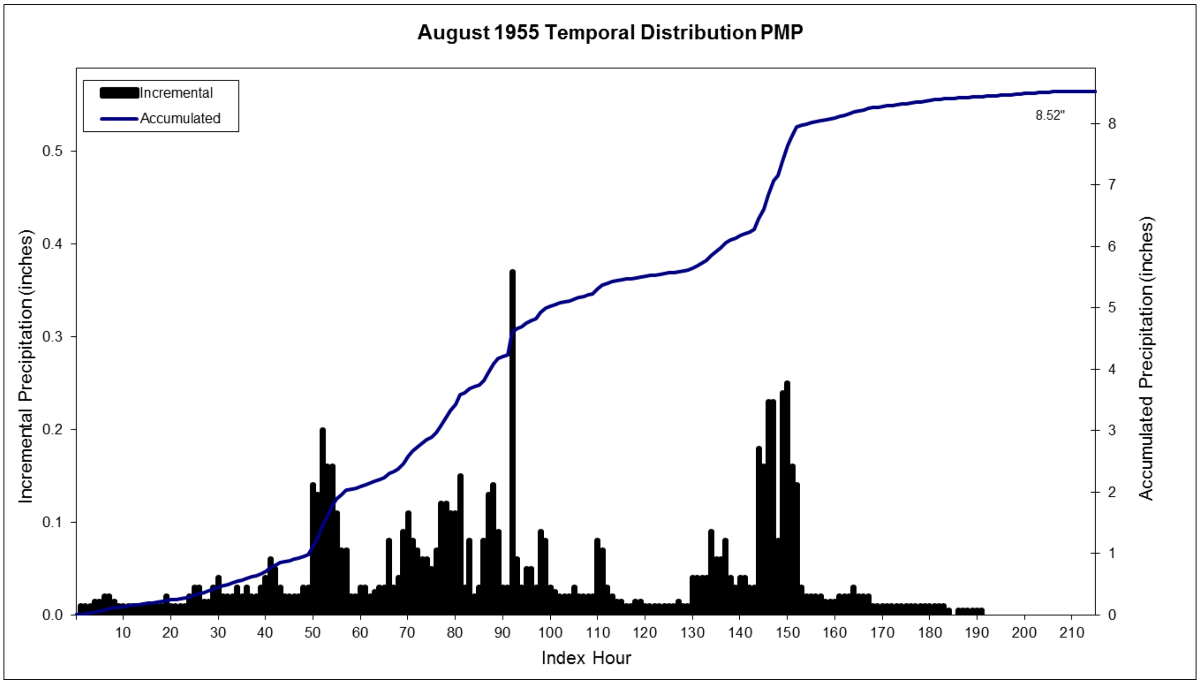

Figure 8.5. August 1955, Denali NP mass curve pattern used for the temporal distribution of the Susitna-Watana PMP.

The temporal distribution pattern for August 1967, Fairbanks (SPAS 1270) DAD zone 1 as applied to the total basin average PMP is shown in Figure 8.6.

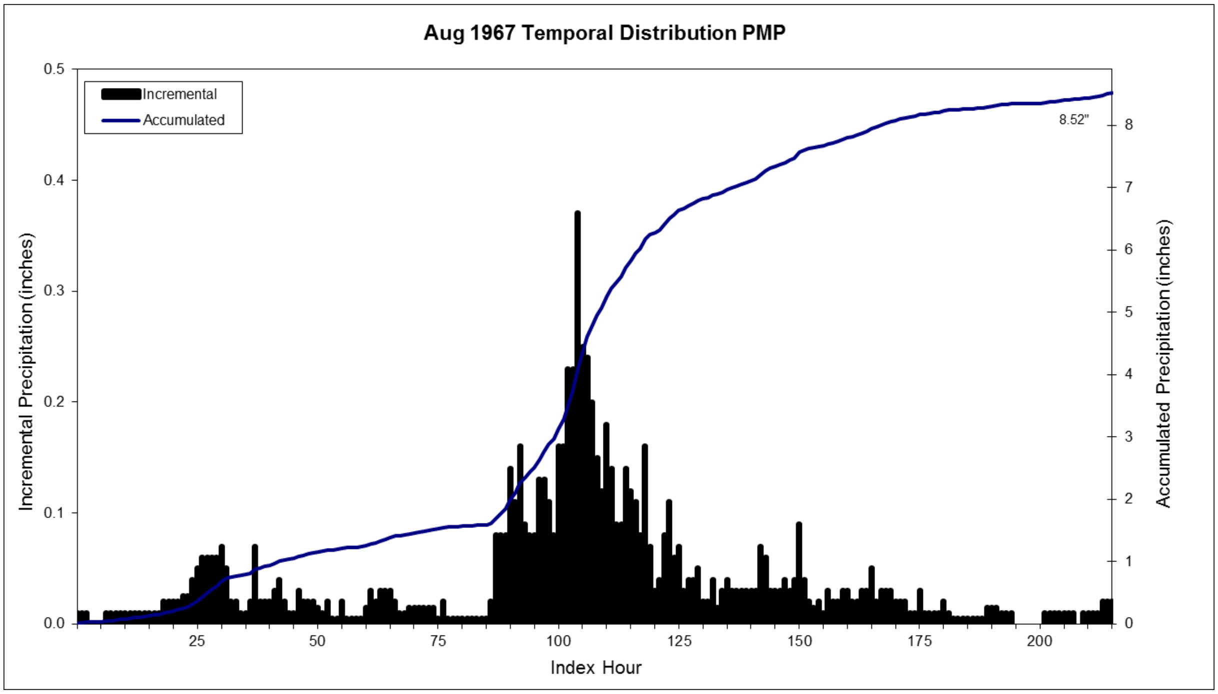

Figure 8.6. August 1967, Fairbanks storm zone 1 mass curve pattern used for the temporal distribution of the Susitna-Watana PMP.

The temporal distribution pattern for August 2012, Old Tyonek (SPAS 1256) DAD zone 1 as applied to the total basin average PMP is shown in Figure 8.7.

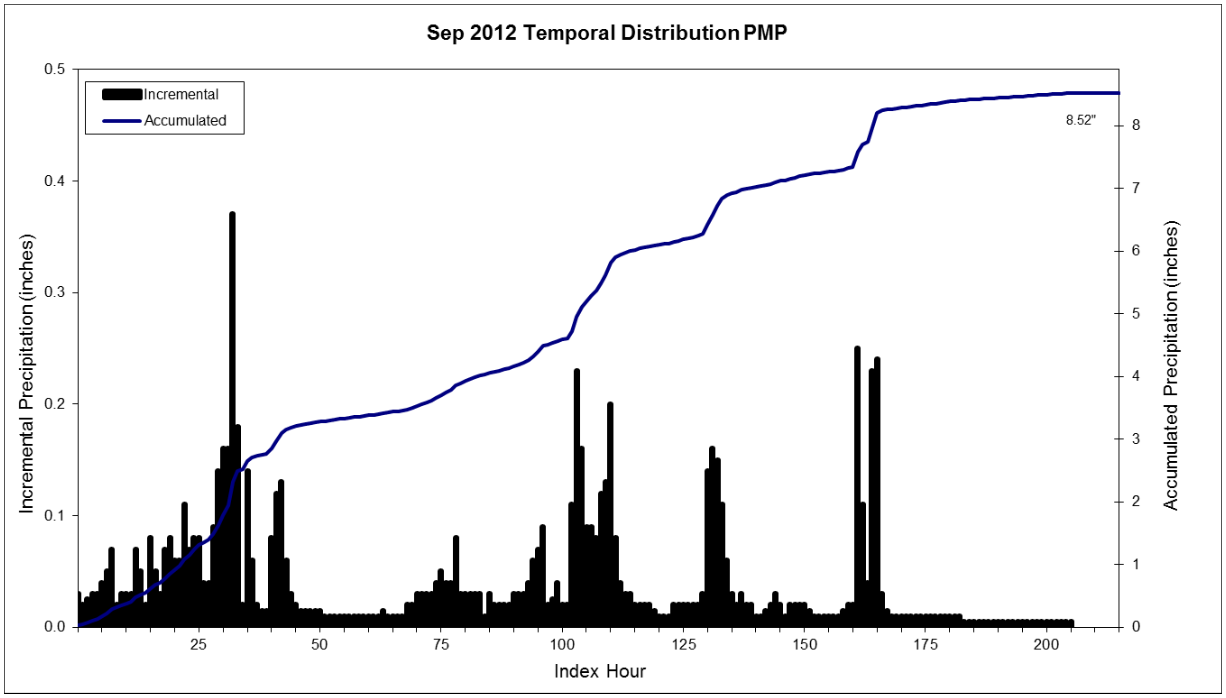

Figure 8.7. August 2012, Old Tyonek storm mass curve pattern used for the temporal distribution of the Susitna-Watana PMP.

9. PMP METEOROLOGICAL TIME SERIES DEVELOPMENT

Hourly meteorological time series were developed for the six calibration events (see Table 12.2.1) over the Susitna River basin in order to aid the hydrologic modeling to best represent expected conditions that would be associated with the PMP rainfall. Meteorological time series parameters have been derived for temperature, dew point temperature and wind speed over the Susitna-Watana basin. The hydrologic model requirements are a single temperature and dew point temperature time series at a given base elevation and wind speed at 1,000-foot increments from 0-feet to 15,000-feet. Temperature lapse rates were estimated using observed surface temperature data for stations in and around the Susitna-Watana basin and Fairbanks radiosonde data.

Vertical wind speed profiles at 1,000-foot increments were derived base on wind speed data from the Fairbanks radiosonde and observed surface wind speed data for stations in and around the Susitna-Watana basin. The radiosonde wind speeds represents free atmospheric winds (unobstructed flow). This free-air data were adjusted to surface wind speeds based on comparisons of anemometer level wind speeds with concurrent free-air wind speeds. The wind speed derivation methodology was based on methods described in HMR 42 (Weather Bureau 1966). HMR 42 measured winds at Gulkana glacier (4,800 ft) and compared to free-air winds at Fairbanks, the study found that average winds on the glacier was 0.60 that of the free-air. In this updated analysis, comparisons were made using both Anchorage and Fairbanks radiosonde data. This analysis showed the Anchorage radiosonde data were not as representative of the surface wind speeds over the basin based on comparisons made to the September 2012 storm event. Instead, the Fairbanks data better represented the timing and magnitude of the observed surface wind speeds.

All six storms were normalized to have a similar index period of 312-hours (see Figure 9.1). For each storm, the index time of the maximum 216-hour accumulated precipitation was determined; this represents the PMP rainfall accumulation window. Then, the 216-hour mid-point was determined by shifting the maximum 216-hour accumulated precipitation index hour 108-hours earlier. Finally, the 108-hour mid-point was used to determine the start and end times of the 216-hour PMP analysis window. The 312-hour window was completed with 24-hours added at the beginning and 72-hours added at the end of the 216-hour PMP window. Hourly temperatures, dew point temperatures, and vertical wind speeds were derived for each of these events for the 312-hour time frame. Figure 9.2 shows the indexed temperature and dew point temperature for the six storm events (base elevation of 2,500 ft).

Once the proper 312-hour window was identified for each of the six storm events, the 312-hour time series data were grouped by month (i.e. all June events grouped together, all August events grouped, and all September events grouped together). For each monthly grouping, an average time series was created based on averaging the individual hourly station meteorological data. Since the all-season PMP event is more conducive to the rainfall associated with the September and August storm events, an average time series was created based on averaging the September and August storm events time series values. The monthly averaged temperature and dew point temperature profiles for June, August, September and average August/September events are shown in Figure 9.3. The final temperature, dew point temperature and wind speed information were based on the average profiles for August/September (Figure 9.4 and 9.5).

The averaged September and August meteorological time series was selected because it best represents the expected conditions that would be associated with the PMP rainfall. The final PMP temperature and dew point temperature have a base elevation of 2,500-ft, the lapse rate used to adjust PMP temperature and dew point temperature to other elevations was -2.63°F per 1,000 ft. The -2.63°F lapse rate was based on the average of all August (1967 and 1971) and September (2012) storm event lapse rates (-2.87°F, -2.85°F, -2.70°F = 2.63°F).

The final vertical wind speed values were based on the average of all August (1967 and 1971) and September (2012) storm events anemometer height wind speeds.

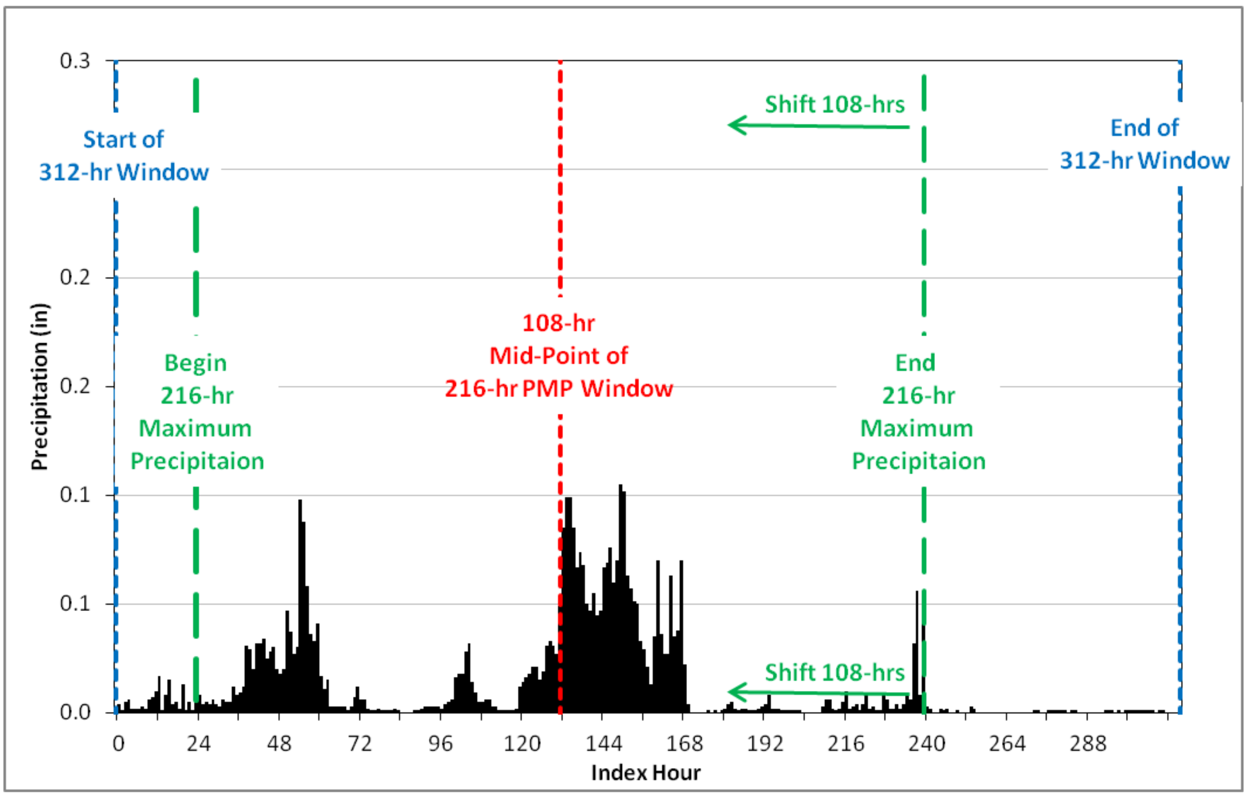

Figure 9.1. Methodology used to create the normalized 312-hour meteorological time series. Maximum 216-hour accumulated precipitation (green line). Mid-point of the 216-hour window basin on the 108-hour shift from the maximum 216-hour accumulation (red line). Start and end point of the 312-hour duration used in this example analysis (blue lines).

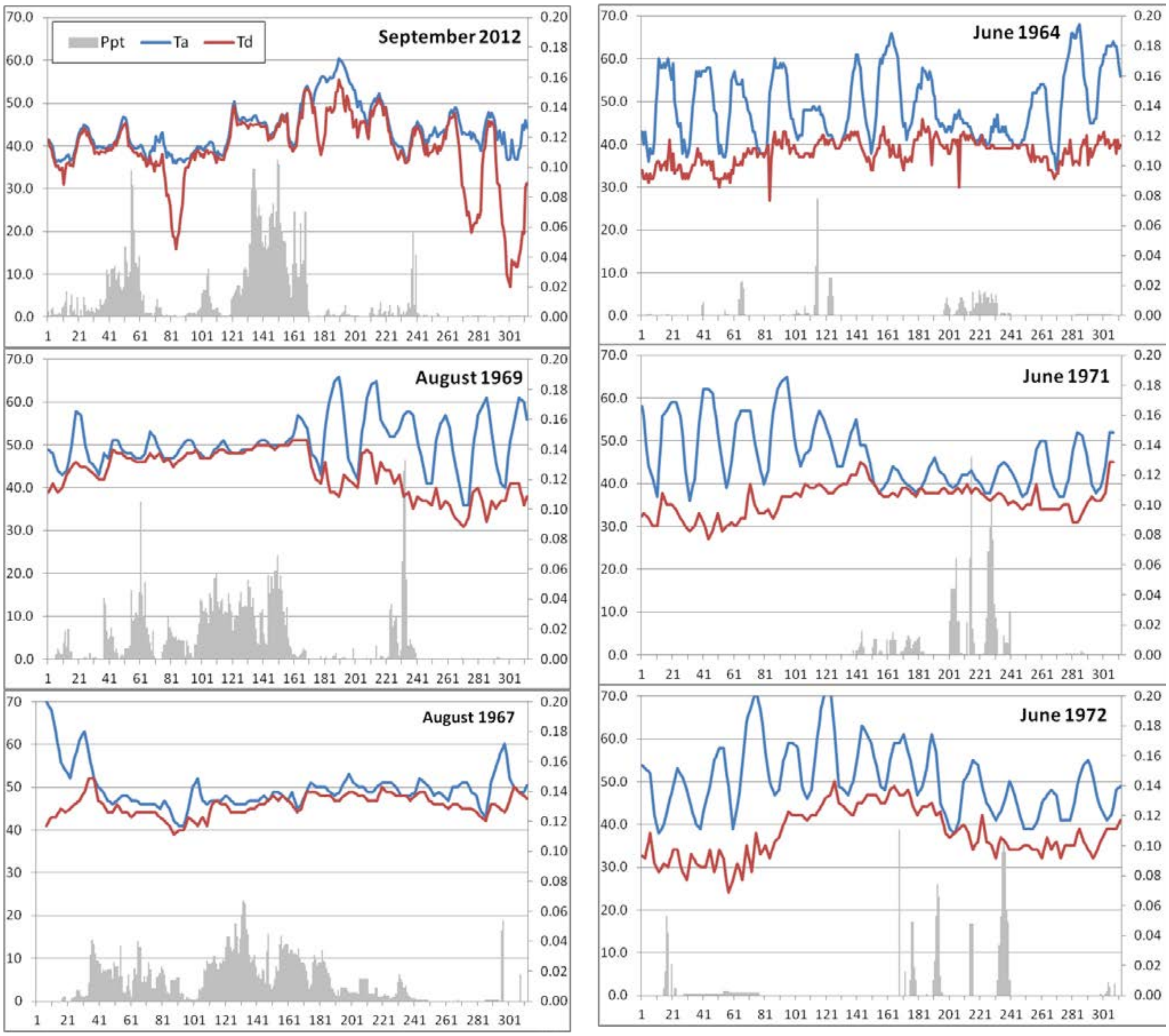

Figure 9.2. Indexed temperature and dew point temperature for the six storm events for a base elevation of 2,500 feet.

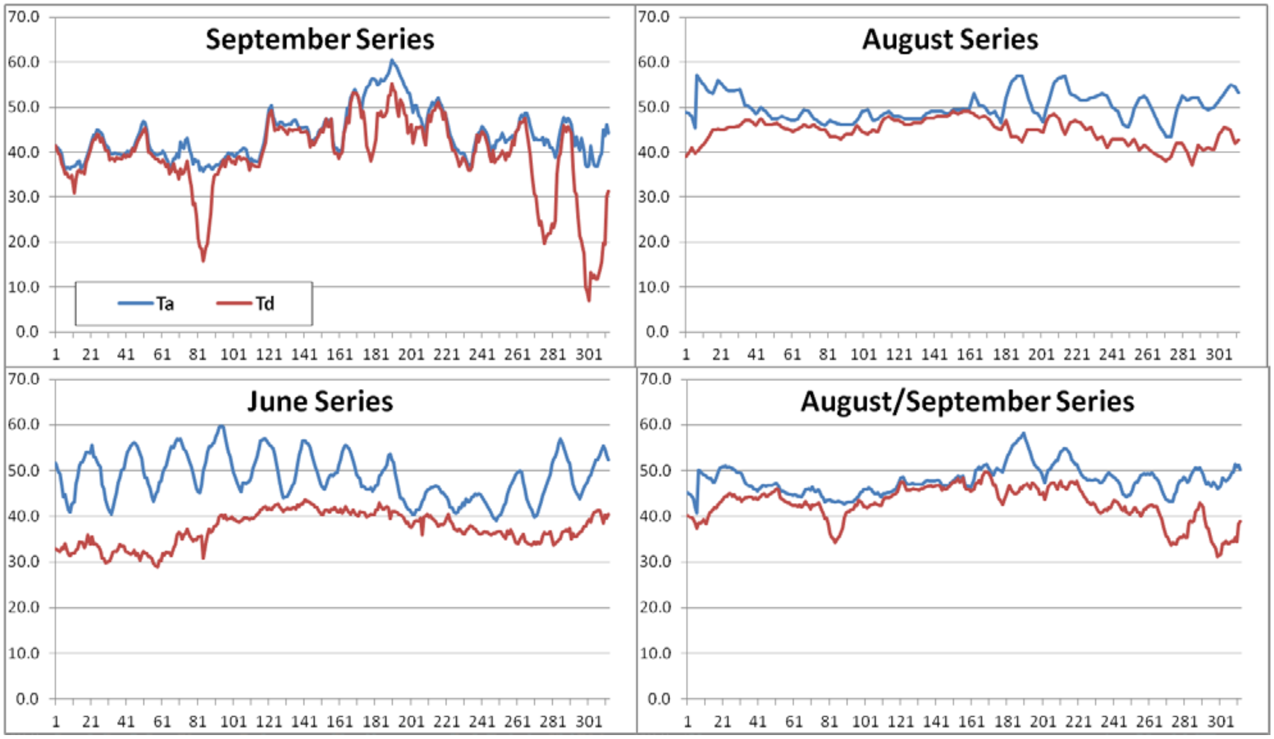

Figure 9.3. Indexed monthly averaged profiles for June, August, September and average August/September for a base elevation of 2,500 feet.

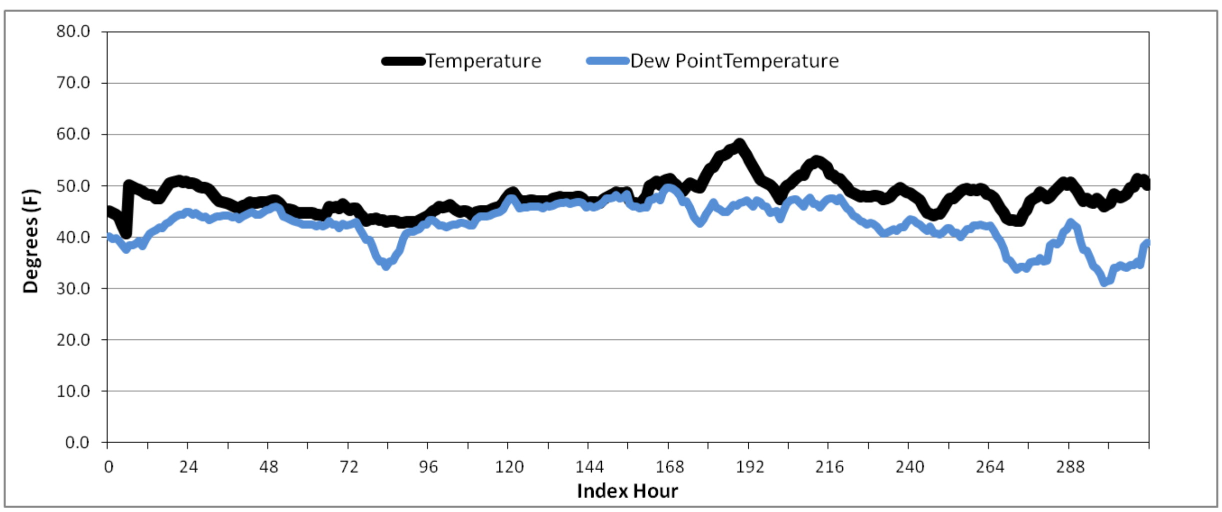

Figure 9.4. PMP non-maximized temperature and dew point temperature data based on the average profiles for August/September for a base elevation of 2,500 feet and lapse rate of -2.63°F per 1,000 feet.

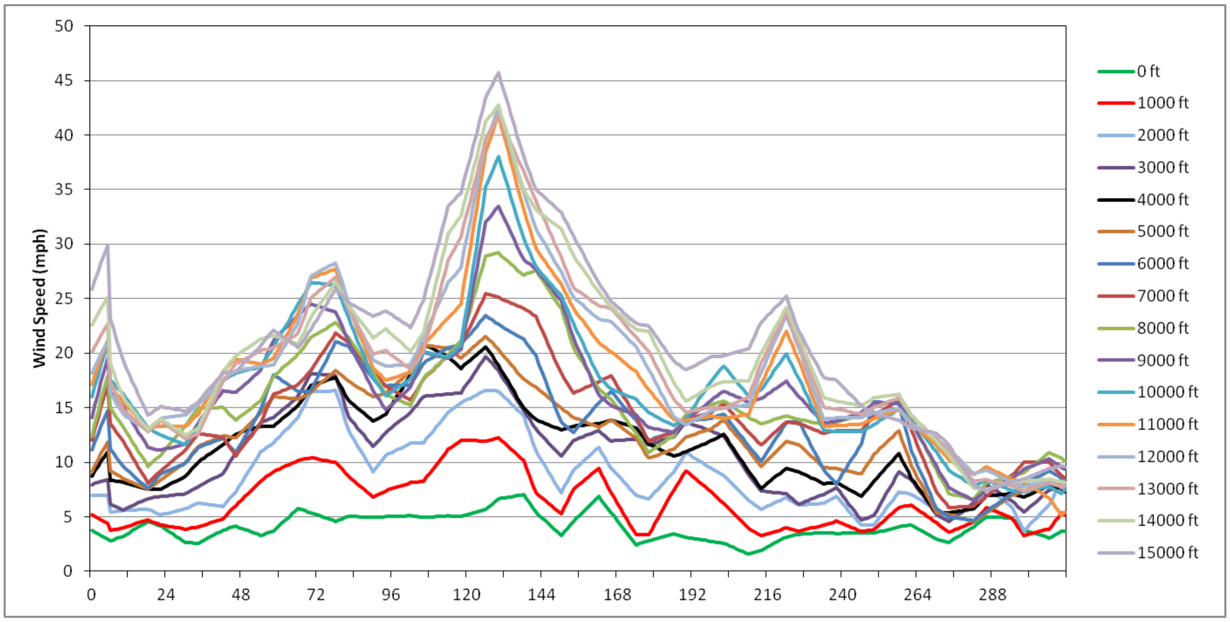

Figure 9.5. Final PMP wind speed values based on the average profiles for August/September for a base elevation of 2,500 feet.

9.1 PMP Temperature Time Series Maximization

The storm representative SST temperature and climatological maximum SST temperature associated with each of the short list storms were analyzed to derive the average difference between the two values in degrees Fahrenheit. The values associated with the storms which control the PMP values were averaged and the resulting value was then applied to each hourly temperature and dew point temperature value. The value derived from this process was 3.0°F. This was the value applied in the maximization process of the temperature and dew point temperature time series used for the snow melt calculations. This was done for all hourly data (in 216-hour window) in order to provide a consistent maximization of the temperature and dew point temperature time series that would be expected to occur during a cool-season PMP rainfall event.

An example of the maximized PMP temperature and dew point temperature data for a PMP event is shown below and the temperature and dew point temperature results displayed in Figure 9.6.

Storm rep SST for = 54.0°F
August 15[7] 2-sigma SST at the storm rep location = 57.0°F
September 15 2-sigma SST at the storm rep location = 56.5°F
Maximization Value = 57.0°F – 54.0°F = 3.0°F

[7] A combination of August and September +2-sigma SST values was used following the procedure of moving a storm two week towards the warmer season for maximization purposes. Because the example event occurred on September 15, the storm is moved to September 1 for storm analysis purposes.

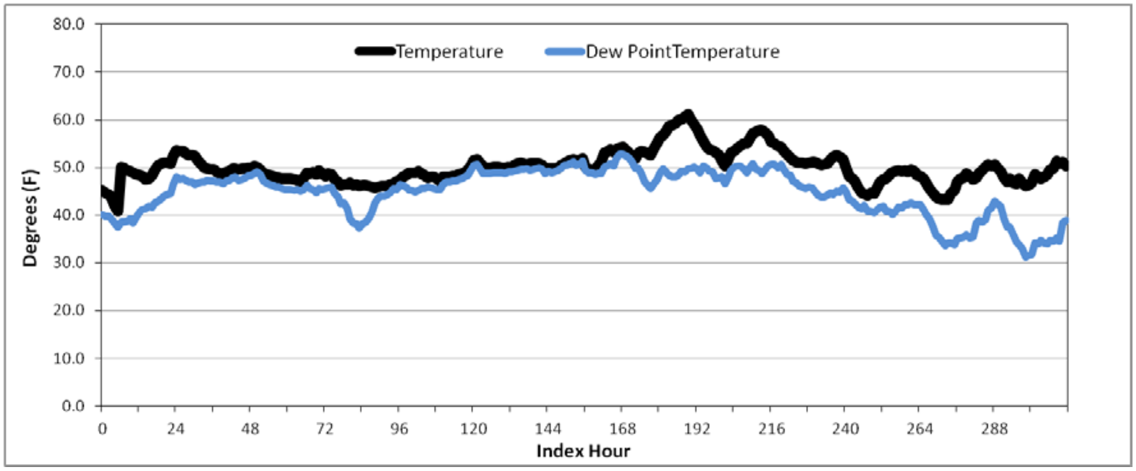

Figure 9.6. Final maximized PMP temperature and dew point temperature data based on the average profiles for August/September for a base elevation of 2,500 feet and lapse rate of -2.63°F per 1,000 feet.

9.2 Seasonality Adjustments for Moving to Other Months

Investigations of the seasonal variation in the Susitna-Watana PMP/PMF required that the maximized PMP temperature, dew point temperature, and wind speed time series values be moved, with appropriate adjustments to the other months when a lesser amount of these values could combine with a great snow melt runoff to produce a larger PMF. Three adjustment factors were determined: i) moving the maximized temperature and dew point temperature time series to other months, ii) moving the wind speed time series to other months, and iii) moving the all-season PMP to other months.

9.2.1 Temperature Seasonality Adjustments

Daily surface climate normal data (1981-2010) were acquired for ten stations (Table 9.1) for a period of April 1 to October 31. For each day, the average temperature was calculated from the ten stations. The average daily temperature for the Susitna-Watana basin, based on ten stations 30-year climate normal is shown in Figure 9.7. The maximum daily average temperature was computed to be 56.6°F. The maximum daily average temperature was used to scale the daily average temperature on a scale of 0.0 to 1.0, with 1.0 equal to 56.6°F. The 1st and 15th of each month scaled daily average temperature were extracted from April to November. The temperatures for July and August were set to 1.00, based on the small changes in temperature and this period represents the all season PMP months. The final seasonality adjustment factors to apply to the all-season PMP temperature and dew point temperature time series are shown in Table 9.2. The adjustment factors should be applied to move the all-season temperature and dew point temperature time series to other months. For example, moving the all-season temperature and dew point temperature from July 15 to May 15 would reduce the time series data by 0.80 (see example below).

July 15 all-season PMP at index hour 1 has a T_a of 45.1°F and T_d of 40.2°F
July 15 to May 15 adjustment = 0.80
May 15 PMP at index hour 1 T_a is 36.1°F and T_d is 32.2°F

Table 9.1 Stations used for temperature and dew point temperature seasonality adjustments.

Station	Elevation (ft)
Anchorage	130
Fairbanks	433
Talkeetna	350
Gulkana	1560
Chulitna River	1355
Paxson	2700
Lake Susitna	2375
Cantwell 2E	2130
Tahneta Pass	2620
Sutton 1W	550

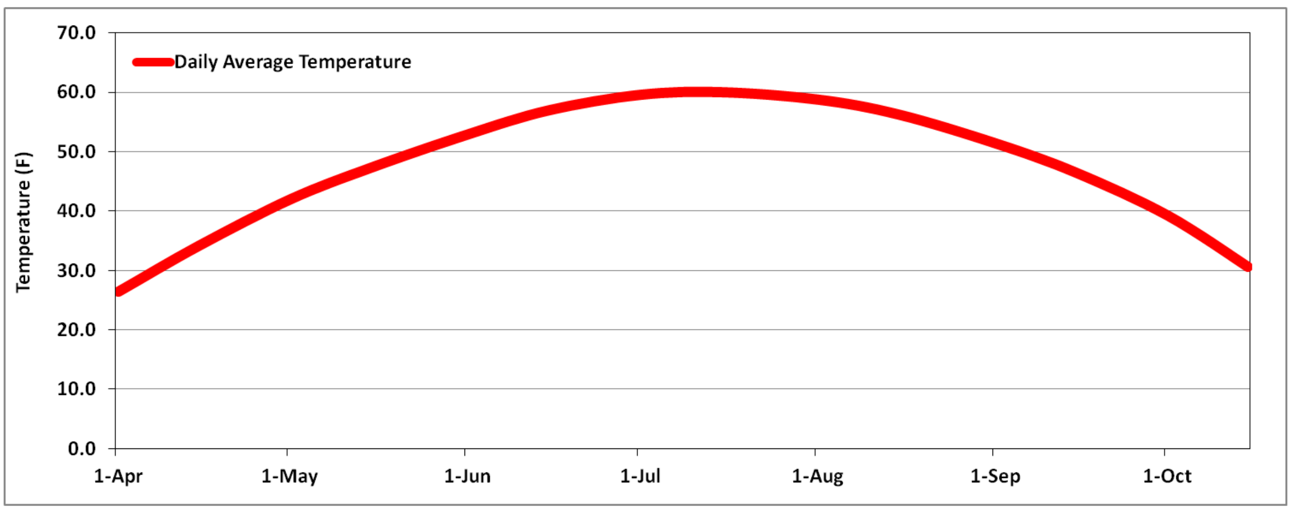

Figure 9.7. Daily average temperature based on ten stations 30-year climate normal around the Susitna-Watana basin.

Table 9.2. Seasonality adjustments to all season PMP temperature and dew point temperature time series.

Ta Td Time Series Seasonality	
Date	Ratio
1-Apr	0.39
15-Apr	0.55
1-May	0.69
15-May	0.80
1-Jun	0.90
15-Jun	0.95
1-Jul	1.00
15-Jul	1.00
1-Aug	1.00
15-Aug	1.00
1-Sep	0.94
15-Sep	0.86
1-Oct	0.77
15-Oct	0.64
1-Nov	0.51

9.2.2 Wind Speed Seasonality Adjustments

Daily average wind speed data was acquired from the Global Historical Climatology Network (GHCN) daily database at four stations (Table 9.3) surrounding the Susitna-Watana basin. The entire period of record for each station was extracted and analyzed. The average daily wind speed for each station was grouped by month; the monthly values were used to identify the monthly average maximum wind speed and average wind speed.

Table 9.3. Stations used for wind speed seasonality adjustments.

Station	Elevation (ft)
Gulkana	1560
Talkeetna	350
Anchorage	433
Fairbanks	500

A final average monthly maximum and average wind speed was calculated based on each of the four stations monthly values. For example, the August average monthly wind speed of 17.2 mph was calculated with the four stations maximum daily wind speed as:

Station		August Wind Speed
Talkeetna	=	14.8
Gulkana	=	23.7
Fairbanks	=	17.0
Anchorage	=	13.2
Average	*=*	*17.2*

The August average wind speed was computed to be 17.2 mph. The August average wind speed was used to scale the monthly maximum wind speed on a scale of 0.0 to 1.0, with 1.0 equal to 17.2 mph. The final seasonality adjustment factors to apply to the all-season PMP wind speed time series are shown in Table 9.4. The adjustment factors should be applied to the move the all-season wind speed time series to other months. For example, moving the all-season wind speed from August 15 to May 15 would increase the time series data by 1.06 (see example below).

August 15 all-season PMP at index hour 1 and 5000 ft has a Ws of 9.1 mph
August 15 to May 15 adjustment = 1.06
May 15 PMP at index hour 1 and 5000 ft Ws is 9.7 mph

Table 9.4. Seasonality adjustments to all season PMP wind speed time series.

Ws PMP Seasonality	
Month	**Ratio**
15-Jan	-
15-Feb	-
15-Mar	1.45
15-Apr	1.25
15-May	1.06
15-Jun	0.87
15-Jul	0.92
15-Aug	1.00
15-Sep	1.15
15-Oct	1.25
15-Nov	1.28
15-Dec	-

9.2.3 PMP Seasonality Adjustments

Monthly maximum 1-day precipitation data was acquired from the Alaska Climate Research Center for four stations (Table 9.2.5) surrounding the Susitna-Watana basin. Each stations maximum 1-day precipitation was used to scale each stations monthly 1-day maximum precipitation from 0.0 to 1.0. For example, Fairbanks monthly 1-day maximum precipitation was 3.42 inches and occurred in August, the scaled maximum precipitation data at Fairbanks is 1.0 for the month of August. The average of each four stations monthly scaled maximum precipitation was used to initially identify the PMP seasonality adjustment. The all-season PMP is for the months of July and August, these months had a seasonality adjustment of 1.0. All other months had a reduction based on the average scaled maximum 1-day precipitation. The final PMP seasonality adjustment are shown in Table 9.6.

Table 9.5. Stations used for PMP seasonality adjustments.

Station	Elevation (ft)
Gulkana	1560
Talkeetna	350
Anchorage	433
Fairbanks	500

The adjustment factors should be applied to the move the all-season PMP to other months. For example, moving the all-season PMP from August 15 to May 15 would reduce the PMP magnitude by 0.83 (see example below).

August 15 sub-basin 1 average all-season PMP at 72-hours is 9.95 inches
August 15 to May 15 adjustment = 0.83
May 15 PMP sub-basin 1 72-hour PMP would be 8.26 inches

Table 9.6. Seasonality adjustments to all season PMP.

PMP Seasonality	
Month	**Ratio**
15-Jan	-
15-Feb	-
15-Mar	0.30
15-Apr	0.60
15-May	0.83
15-Jun	0.94
15-Jul	1.00
15-Aug	1.00
15-Sep	0.92
15-Oct	0.80
15-Nov	0.65
15-Dec	-

10. RESULTS

10.1 Site-Specific PMP Values

This study produced site-specific PMP values for use in computing the PMF for the Susitna-Watana basin. Values for durations from 1- through 216-hours have been computed for each grid cell within the basin. After all adjustments were applied to all the storms on the short storm list, the Fairbanks August, 1967 storm event resulted in the largest values at all area sizes and all durations. The spatial and temporal patterns associated with the three storms from the storm list with different temporal patterns were then used to distribute the PMP rainfall. Finally, the gridded hourly PMP values were averaged by sub-basin.

Results of this analysis are displayed in Tables 10.1a-c, one for each of the temporal distributions applied. These include the all-season PMP values for each sub-basin as a sub-basin average amount at the x-duration. The total basin (5,131 mi^2) is also included and used for comparisons to previous work in the region.

Table 10.1a. Site-specific PMP values for Susitna-Watana basin using the August, 1967 storm temporal distribution.

Sub-basin	Drainage Area (sq.mi.)	All Season 1-hr PMP (inches)	All Season 6-hr PMP (inches)	All Season 24-hr PMP (inches)	All Season 72-hr PMP (inches)	All Season 216-hr PMP (inches)
1	52.6	0.60	2.47	6.09	9.95	13.83
2	226.4	0.50	2.04	5.02	8.21	11.41
3	295.4	0.37	1.53	3.77	6.16	8.56
4	149.3	0.56	2.31	5.69	9.31	12.93
5	354.0	0.44	1.79	4.43	7.24	10.06
6	153.4	0.48	1.97	4.86	7.94	11.03
7	67.5	0.32	1.31	3.23	5.29	7.35
8	189.9	0.39	1.60	3.94	6.44	8.95
9	187.7	0.41	1.69	4.18	6.83	9.50
10	326.8	0.39	1.61	3.98	6.51	9.04
11	273.5	0.41	1.67	4.12	6.73	9.35
12	74.7	0.36	1.46	3.61	5.90	8.21
13	222.5	0.34	1.39	3.44	5.62	7.81
14	135.1	0.33	1.36	3.35	5.48	7.62
15	185.1	0.36	1.50	3.69	6.03	8.38
16	164.3	0.37	1.51	3.73	6.10	8.48
17	253.2	0.35	1.45	3.57	5.84	8.12
18	100.0	0.43	1.78	4.39	7.18	9.98
19	202.2	0.50	2.04	5.04	8.24	11.45
20	36.3	0.37	1.53	3.77	6.16	8.56
21	162.7	0.50	2.06	5.07	8.29	11.52
22	92.0	0.36	1.47	3.63	5.93	8.25
23	174.2	0.41	1.70	4.19	6.86	9.53
24	157.4	0.43	1.78	4.38	7.17	9.96
25	184.0	0.61	2.52	6.23	10.18	14.15
26	222.9	0.54	2.23	5.50	8.99	12.49
27	269.6	0.47	1.94	4.78	7.81	10.85
28	218.5	0.52	2.13	5.26	8.60	11.96
29	36.8	0.43	1.75	4.31	7.05	9.80
Total/Avg.	5168.2	0.43	1.78	4.40	7.19	10.00

Table 10.1b. Site-specific PMP values for Susitna-Watana basin using the August, 1955 storm temporal distribution.

Sub-basin	Drainage Area (sq.mi.)	All Season 1-hr PMP (inches)	All Season 6-hr PMP (inches)	All Season 24-hr PMP (inches)	All Season 72-hr PMP (inches)	All Season 216-hr PMP (inches)
1	52.6	0.60	1.93	3.83	7.64	13.83
2	226.4	0.50	1.59	3.16	6.31	11.41
3	295.4	0.37	1.20	2.37	4.73	8.56
4	149.3	0.56	1.81	3.58	7.15	12.93
5	354.0	0.44	1.40	2.79	5.56	10.06
6	153.4	0.48	1.54	3.06	6.10	11.03
7	67.5	0.32	1.03	2.04	4.06	7.35
8	189.9	0.39	1.25	2.48	4.95	8.95
9	187.7	0.41	1.33	2.63	5.25	9.50
10	326.8	0.39	1.26	2.51	5.00	9.04
11	273.5	0.41	1.31	2.59	5.17	9.35
12	74.7	0.36	1.15	2.27	4.54	8.21
13	222.5	0.34	1.09	2.16	4.32	7.81
14	135.1	0.33	1.06	2.11	4.21	7.62
15	185.1	0.36	1.17	2.32	4.63	8.38
16	164.3	0.37	1.18	2.35	4.69	8.48
17	253.2	0.35	1.13	2.25	4.49	8.12
18	100.0	0.43	1.39	2.77	5.52	9.98
19	202.2	0.50	1.60	3.17	6.33	11.45
20	36.3	0.37	1.20	2.37	4.73	8.56
21	162.7	0.50	1.61	3.19	6.37	11.52
22	92.0	0.36	1.15	2.28	4.56	8.25
23	174.2	0.41	1.33	2.64	5.27	9.53
24	157.4	0.43	1.39	2.76	5.51	9.96
25	184.0	0.61	1.98	3.92	7.82	14.15
26	222.9	0.54	1.74	3.46	6.91	12.49
27	269.6	0.47	1.52	3.01	6.00	10.85
28	218.5	0.52	1.67	3.31	6.61	11.96
29	36.8	0.43	1.37	2.72	5.42	9.80
Total/Avg.	5168.2	0.43	1.40	2.77	5.53	10.00

Table 10.1c. Site-specific PMP values for Susitna-Watana basin using the September, 2012 storm temporal distribution.

Sub-basin	Drainage Area (sq.mi.)	All Season 1-hr PMP (inches)	All Season 6-hr PMP (inches)	All Season 24-hr PMP (inches)	All Season 72-hr PMP (inches)	All Season 216-hr PMP (inches)
1	52.6	0.60	1.79	3.77	6.40	13.83
2	226.4	0.50	1.47	3.11	5.28	11.41
3	295.4	0.37	1.11	2.33	3.96	8.56
4	149.3	0.56	1.67	3.52	5.99	12.93
5	354.0	0.44	1.30	2.74	4.66	10.06
6	153.4	0.48	1.42	3.00	5.11	11.03
7	67.5	0.32	0.95	2.00	3.40	7.35
8	189.9	0.39	1.16	2.44	4.15	8.95
9	187.7	0.41	1.23	2.59	4.40	9.50
10	326.8	0.39	1.17	2.46	4.19	9.04
11	273.5	0.41	1.21	2.55	4.33	9.35
12	74.7	0.36	1.06	2.23	3.80	8.21
13	222.5	0.34	1.01	2.13	3.62	7.81
14	135.1	0.33	0.98	2.07	3.53	7.62
15	185.1	0.36	1.08	2.28	3.88	8.38
16	164.3	0.37	1.09	2.31	3.93	8.48
17	253.2	0.35	1.05	2.21	3.76	8.12
18	100.0	0.43	1.29	2.72	4.62	9.98
19	202.2	0.50	1.48	3.12	5.30	11.45
20	36.3	0.37	1.11	2.33	3.96	8.56
21	162.7	0.50	1.49	3.14	5.34	11.52
22	92.0	0.36	1.06	2.25	3.82	8.25
23	174.2	0.41	1.23	2.59	4.41	9.53
24	157.4	0.43	1.29	2.71	4.61	9.96
25	184.0	0.61	1.83	3.85	6.55	14.15
26	222.9	0.54	1.61	3.40	5.78	12.49
27	269.6	0.47	1.40	2.96	5.03	10.85
28	218.5	0.52	1.54	3.26	5.54	11.96
29	36.8	0.43	1.27	2.67	4.54	9.80
Total/Avg.	5168.2	0.43	1.29	2.72	4.63	10.00

10.2 PMP Comparison with Previous Studies

There have been previous studies investigating PMP over the Upper Susitna drainage basin: the Susitna Hydroelectric Project Feasibility Report (Acres 1982) and the Harza-Ebasco Susitna Joint Venture (1984). The PMP calculation procedures and tools employed in this study have significantly evolved since the publication of these PMP studies. However, the generalized approach of storm maximization and transposition is similar. Furthermore, despite the occurrence and analysis of recent precipitation events that have occurred since these studies, the August 1967 (the Great Fairbanks Flood) event remains the controlling storm for PMP.

The Harza-Ebasco study reported an all-season basin average 72-hour PMP of 6.85” for 5,180 mi^2. A seasonality factor of 0.93 was applied to June 15th and a factor of 0.73 was applied to May 15th. The 72-hour PMP from the Harza-Ebasco study is summarized in Table 10.2.

Table 10.2. Harza-Ebasco 1984 Susitna 72-hour Basin PMP and spring season adjustments.

Season	72-hour PMP: Harza-Ebasco	
	Factor	PMP
All-season	1.00	6.85
15-Jun	0.93	6.37
15-May	0.73	5.00

The Acres study reported an all-season basin average 72-hour PMP of 5.90” for 5,180 mi^2. A seasonality factor of 0.70 was applied to June 15th. The Acres study did not seasonally adjust PMP to May. At the 216-hour duration, a basin average PMP of 12.54” was reported. The 72-hour PMP from the Acres study is summarized in Table 10.3 and the 216-hour PMP is summarized in Table 10.4.

Table 10.3. Acres 1982 Susitna 72-hour Basin PMP and spring season adjustments.

Season	72-hour PMP: Acres	
	Factor	PMP
All-season	1.00	5.90
15-Jun	0.70	4.13
15-May	N/A	N/A

Table 10.4. Acres 1982 Susitna 216-hour Basin PMP and spring season adjustments.

Season	216-hour PMP: Acres	
	Factor	PMP
All-season	1.00	12.54
15-Jun	0.70	8.90
15-May	N/A	N/A

The gridded basin average 72-hour PMP provided by AWA in this study is 7.43” for 5,132 mi^2, before the application of the various storm-based temporal distribution patterns. A seasonality factor of 0.94 was applied to June 15th and a seasonality factor of 0.83 was applied to May 15th. At the 216-hour duration, a basin average PMP of 12.54” was calculated. The 72-hour PMP from this study is summarized in Table 10.5 and the 216-hour PMP is summarized in Table 10.6

Table 10.5. AWA Susitna-Watana 72-hour Basin PMP and spring season adjustments

Season	72-hour PMP: AWA	
	Factor	PMP
All-season	1.00	7.43
15-Jun	0.94	6.98
15-May	0.83	6.17

Table 10.6. AWA Susitna-Watana 216-hour Basin PMP and spring season adjustments

Season	216-hour PMP: AWA	
	Factor	PMP
All-season	1.00	10.02
15-Jun	0.94	9.42
15-May	0.83	8.32

The ratio of AWA PMP to the Acres (72-hour and 216-hour) and Harza-Ebasco (216-hour) is shown in Table 10.7.

Table 10.7. Ratios of AWA PMP to the Acres and Harza-Ebasco studies.

Season	Ratio of AWA PMP to:		
	Acres (72hr)	Acres (216hr)	Harza-Eb.
All-season	1.26	0.80	1.08
15-Jun	1.69	1.06	1.10
15-May	N/A	N/A	1.23

Generally, the AWA PMP magnitudes are somewhat larger than previous estimates, particularly for the Acres study at 72-hours. There are numerous factors contributing to the differences stemming from both the source data and methods applied. There are several methodologies and data sets employed by the AWA PMP study that differ from previous studies and may contribute to differences in PMP. These include; high spatial and temporal resolution SPAS analyses for each storm and the resulting DAD tables and mass curves, updated storm maximization using SST data, improved geospatial technologies that allow for improved analysis of source moisture and storm maximization, gridded analysis of moisture and orographic transposition over the basin, availability of NOAA Atlas 14 values, and improved temperature-time series and seasonality relations. It is also likely that there are differences in the basin boundary delineation.

10.3 Comparison of PMP with NOAA Atlas 14

NOAA Atlas 14 Volume 7 provides gridded partial duration and annual maximum precipitation data over Alaska. In addition to return frequency analysis, these data can provide an accurate representation of the relationship between historical rainfall and terrain. PMP values were compared with 100-year rainfall values as a general check for reasonableness. The ratio of the PMP to the 24-hour 100-year return period rainfall amounts is generally expected to range between two and four, with values as low as 1.7 and as high as 5.5 found in HMRs 57 and 59 (Hansen et al. 1994, Corrigan et al. 1999). In HMR 59 it is stated "…*the comparison indicates that larger ratios are in lower elevations where short-duration, convective precipitation dominates, and smaller ratios in higher elevations where general storm, long duration precipitation is prevalent*". Therefore, it would be reasonable to expect the ratios for the Susitna River basin to be in the low end of the range.

A gridded basin comparison was made between the 24-hour AWA PMP values and the 24-hour NOAA Atlas 14 precipitation frequency datasets. The NOAA Atlas 14 precipitation depths are considered point values and have no areal reduction applied. For this reason, the 24-hour basin PMP was calculated with the minimum SPAS resolution (0.20 mi^2) to approximate point values, instead of the basin size of 5,131 mi^2. The ratio of 24-hour PMP to NOAA Atlas 14 precipitation was calculated for the 100-year return period. Table 10.8 shows the basin average NOAA Atlas 14 precipitation for 10-year through 1,000-year events. The 100-year basin average is 3.65” over 24-hours. The basin average 0.20 mi^2 PMP is 6.34” for a 24-hour period (Table 10.8). This indicates a factor of 1.74 times the 100-year NOAA Atlas 14 depth (Table 10.9). The largest ratio for all of the 4,013 grid points was 1.86 and the smallest ratio was 1.58, indicating a fairly low amount of variation over the basin.

Table 10.8. Gridded basin average 24-hour NOAA Atlas 14 precipitation for the 10-1,000 year return periods. Gridded basin average 24-hour point PMP.

	10-year	25-year	50-year	**100-year**	200-year	500-year	1,000-year
24-hr Precip. Frequency (NOAA Atlas 14)	2.37	2.85	3.24	**3.65**	4.11	4.73	5.19
Gridded Basin Average 24-hour PMP (0.2sqmi)				6.34			

Table 10.9. Ratio of 24-hour PMP to 100-year NOAA Atlas 14 precipitation.

Average Basin Ratio (24hr PMP:NOAA Atlas 14 100-yr)	**1.74**
Max. Basin Ratio (24hr PMP:NOAA Atlas 14 100-yr)	1.86
Min. Basin Ratio (24hr PMP:NOAA Atlas 14 100-yr)	1.58

It should also be noted that the 24-hour basin average 1,000-year rainfall is 5.19”, putting the basin average PMP of 6.34” well above the 1,000 return frequency.