Springbank Off-Stream Storage Project Preliminary Design Report

Appendix B - Hydrology

September 25, 2020

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Sign-off Sheet

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APPENDIX B.1 – FLOOD OF RECORD

City of Calgary Estimate of June 2013 Inflow Hydrograph into Glenmore Reservoir

Date / Time	Discharge (m^3/s)
6/19/13 0:00	24.45
6/19/13 1:00	25.09
6/19/13 2:00	25.09
6/19/13 3:00	21.09
6/19/13 4:00	25.74
6/19/13 5:00	25.85
6/19/13 6:00	25.86
6/19/13 7:00	21.78
6/19/13 8:00	26.20
6/19/13 9:00	28.50
6/19/13 10:00	26.40
6/19/13 11:00	23.71
6/19/13 12:00	27.88
6/19/13 13:00	27.31
6/19/13 14:00	30.91
6/19/13 15:00	27.28
6/19/13 16:00	27.19
6/19/13 17:00	27.70
6/19/13 18:00	27.52
6/19/13 19:00	31.70
6/19/13 20:00	26.19
6/19/13 21:00	25.78
6/19/13 22:00	33.40
6/19/13 23:00	36.44
6/20/13 0:00	36.22
6/20/13 1:00	34.96
6/20/13 2:00	28.71
6/20/13 3:00	35.92
6/20/13 4:00	36.80
6/20/13 5:00	40.97
6/20/13 6:00	27.37
6/20/13 7:00	28.79
6/20/13 8:00	59.06
6/20/13 9:00	62.54
6/20/13 10:00	84.24
6/20/13 11:00	98.76
6/20/13 12:00	92.83
6/20/13 13:00	116.86
6/20/13 14:00	89.81
6/20/13 15:00	148.37
6/20/13 16:00	146.32
6/20/13 17:00	175.34
6/20/13 18:00	210.76
6/20/13 19:00	292.21
6/20/13 20:00	560.91
6/20/13 21:00	1155.32
6/20/13 22:00	1240.41
6/20/13 23:00	1044.64
6/21/13 0:00	876.94
6/21/13 1:00	829.41
6/21/13 2:00	722.92
6/21/13 3:00	711.05
6/21/13 4:00	699.94

Date / Time	Discharge (m^3/s)
6/21/13 5:00	680.69
6/21/13 6:00	647.25
6/21/13 7:00	707.27
6/21/13 8:00	625.67
6/21/13 9:00	617.52
6/21/13 10:00	635.43
6/21/13 11:00	607.55
6/21/13 12:00	626.89
6/21/13 13:00	609.63
6/21/13 14:00	626.06
6/21/13 15:00	652.99
6/21/13 16:00	664.66
6/21/13 17:00	728.93
6/21/13 18:00	692.29
6/21/13 19:00	677.50
6/21/13 20:00	728.42
6/21/13 21:00	653.50
6/21/13 22:00	661.39
6/21/13 23:00	675.12
6/22/13 0:00	622.24
6/22/13 1:00	698.71
6/22/13 2:00	625.70
6/22/13 3:00	587.61
6/22/13 4:00	623.20
6/22/13 5:00	578.11
6/22/13 6:00	537.99
6/22/13 7:00	515.78
6/22/13 8:00	504.95
6/22/13 9:00	461.53
6/22/13 10:00	451.32
6/22/13 11:00	350.68
6/22/13 12:00	354.69
6/22/13 13:00	379.71
6/22/13 14:00	359.18
6/22/13 15:00	365.16
6/22/13 16:00	169.79
6/22/13 17:00	269.78
6/22/13 18:00	258.81
6/22/13 19:00	246.20
6/22/13 20:00	249.40
6/22/13 21:00	203.46
6/22/13 22:00	225.23
6/22/13 23:00	208.35
6/23/13 0:00	208.56
6/23/13 1:00	198.96
6/23/13 2:00	185.59
6/23/13 3:00	184.57
6/23/13 4:00	176.56
6/23/13 5:00	163.18
6/23/13 6:00	173.95
6/23/13 7:00	177.10
6/23/13 8:00	165.05
6/23/13 9:00	160.61

Date / Time	Discharge (m^3/s)
6/23/13 10:00	148.57
6/23/13 11:00	159.51
6/23/13 12:00	147.83
6/23/13 13:00	153.37
6/23/13 14:00	141.70
6/23/13 15:00	137.61
6/23/13 16:00	143.14
6/23/13 17:00	131.48
6/23/13 18:00	127.39
6/23/13 19:00	131.02
6/23/13 20:00	121.60
6/23/13 21:00	127.30
6/23/13 22:00	127.07
6/23/13 23:00	117.84
6/24/13 0:00	118.48
6/24/13 1:00	103.57
6/24/13 2:00	117.67
6/24/13 3:00	101.95
6/24/13 4:00	92.44
6/24/13 5:00	95.33
6/24/13 6:00	94.74
6/24/13 7:00	95.81
6/24/13 8:00	95.36
6/24/13 9:00	80.77
6/24/13 10:00	83.28
6/24/13 11:00	92.50
6/24/13 12:00	88.94
6/24/13 13:00	77.97
6/24/13 14:00	76.11
6/24/13 15:00	97.02
6/24/13 16:00	83.46
6/24/13 17:00	91.13
6/24/13 18:00	84.82
6/24/13 19:00	85.53
6/24/13 20:00	86.30
6/24/13 21:00	80.30
6/24/13 22:00	78.53
6/24/13 23:00	80.02
6/25/13 0:00	75.02
6/25/13 1:00	89.66
6/25/13 2:00	103.11
6/25/13 3:00	78.24
6/25/13 4:00	79.21
6/25/13 5:00	84.50
6/25/13 6:00	85.26
6/25/13 7:00	79.79
6/25/13 8:00	74.58
6/25/13 9:00	75.59
6/25/13 10:00	82.84
6/25/13 11:00	83.01
6/25/13 12:00	77.36
6/25/13 13:00	83.49
6/25/13 14:00	59.55

Date / Time	Discharge (m^3/s)
6/25/13 15:00	81.28
6/25/13 16:00	81.32
6/25/13 17:00	83.70
6/25/13 18:00	66.66
6/25/13 19:00	78.53
6/25/13 20:00	67.51
6/25/13 21:00	76.44
6/25/13 22:00	76.60
6/25/13 23:00	71.35
6/26/13 0:00	74.24
6/26/13 1:00	74.36
6/26/13 2:00	74.50
6/26/13 3:00	69.07
6/26/13 4:00	74.66
6/26/13 5:00	69.26
6/26/13 6:00	84.27
6/26/13 7:00	73.36
6/26/13 8:00	73.37
6/26/13 9:00	78.84
6/26/13 10:00	73.42
6/26/13 11:00	73.43
6/26/13 12:00	73.45
6/26/13 13:00	68.07
6/26/13 14:00	70.46
6/26/13 15:00	70.45
6/26/13 16:00	75.88
6/26/13 17:00	70.51
6/26/13 18:00	70.51
6/26/13 19:00	65.05
6/26/13 20:00	65.05
6/26/13 21:00	64.97
6/26/13 22:00	64.97
6/26/13 23:00	64.98
6/27/13 0:00	65.06
6/27/13 1:00	54.08
6/27/13 2:00	66.59
6/27/13 3:00	61.14
6/27/13 4:00	61.14
6/27/13 5:00	61.14
6/27/13 6:00	55.70
6/27/13 7:00	67.08
6/27/13 8:00	56.28
6/27/13 9:00	61.75
6/27/13 10:00	61.76
6/27/13 11:00	61.77
6/27/13 12:00	56.27
6/27/13 13:00	61.79
6/27/13 14:00	58.00
6/27/13 15:00	58.00
6/27/13 16:00	57.00
6/27/13 17:00	56.00

APPENDIX B.2 – FLOOD FREQUENCY ANALYSIS REPORT

Springbank Off-Stream Storage Project Hydrology Flood Frequency Analysis

Report on Methods and Results

Prepared for:
Alberta Transportation

Prepared by:
Stantec Consulting Ltd.

Revision 2

March 22, 2017

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

Executive Summary

Flood frequency analyses were performed for the Elbow River in Alberta for use in the design of the Springbank Off-stream Storage (SR1) project for the Province of Alberta. The results of the analyses will be utilized to establish hydraulic and structural design parameters, forecast frequency of project operation and develop operations guidelines.

The analyses were performed through a comprehensive evaluation of relevant recorded streamflow data for the Elbow River near the SR1 Diversion Site. Previous flood frequency studies were reviewed and an independent statistical flood frequency analysis was performed using conventional methods wherein the data was fit to ten probability distributions. Wide variability was observed in past efforts performed by others and the conventional methods performed by Stantec. This is attributed to the year to year variation in hydrometeorological processes (snowmelt, severe summer storms, etc.) that produce floods on the Elbow River. Additionally, the 2013 flood is an extraordinary flood with a peak discharge nearly double any flood in the last 108 years of observations.

Because of the mixed population of annual peak discharges and the presence of the extraordinary 2013 flood, an alternative approach to flood frequency analysis was adopted. The Unbiased Plotting Position Formulae for Historical Floods as described by Guo (1990) was used to calculate the return period for the extraordinary 2013 flood. Mathematic equations were then best fit to the series of flood values and their corresponding return periods.

Based on the presented methods, the 2013 flood event flood peak and volume are estimated to have a return period between 210 and 250 years. For the SR1 Diversion Site, the instantaneous peak discharge, 7-day volume and 56-day volume estimates are provided for floods having a return period between 2 and 500 years. The results are presented in Table E.1 below.

Table E.1 Estimated Flood Frequencies for the Elbow River at the SR1 Diversion Site

Return Period (years)	Instantaneous Peak Discharge (m^3/s)	7-Day Volume (dam^3)	56-Day Volume (dam^3)
500	1,800	174,000	371,000
200	1,110	132,000	322,000
100	765	107,000	290,000
50	530	86,600	260,000
20	330	65,600	226,000
10	200	53,100	203,000
5	140	38,100	172,000
2	70	20,000	105,000

1.0 INTRODUCTION

This report presents flood and volumetric frequency analysis methods and results that have been performed for the Elbow River relevant to the design of the Springbank Off-Stream Storage project (SR1).

Previous flood frequency studies by AMEC (2014) and Golder (2010 and 2014) were reviewed. Stantec then performed an independent flood frequency analysis for a combined record from 1908 to 2013 using conventional methods. Finally, an alternative approach was reviewed to account for a mixed population data set and the presence of an extraordinary event within the data set.

The data, methods and results are presented in the following sections.

2.0 REVIEW OF PREVIOUS STUDIES

Previous studies performed by AMEC (2014) and Golder (2010 and 2014) were reviewed for applicability to the project. A summary of each study follows.

2.1 PRELIMINARY INFLOW DESIGN FLOODS FOR FLOOD CONTROL DAMS ON THE ELBOW AND BOW RIVERS (AMEC, 2014)

AMEC prepared a memo dated May 21, 2014 for the Southern Alberta Flood Recovery Task Force, reporting flood frequency analyses results. Several probability distributions and parameter estimation techniques were presented and tested. The results indicated that the Log Pearson Type III probability distribution with the method of moments for parameter estimation produced the best fit to the data. Flood and volumetric frequency analyses were performed for the Elbow River near Glenmore Reservoir using a combined hydrometric record of 1908 to 2013.

Several large historically observed floods occurred in 1879, 1897, and 1902 on the Bow and Elbow Rivers prior to the beginning of systematic hydrometric monitoring. Estimates of those historical flood peaks are available for the Bow River but not for the Elbow River. AMEC performed flood frequency analysis for the Bow River at Calgary using the 1911 to 2013 recorded data and also using a record length of 1879 to 2013 incorporating the historic data. Based on those analyses, a ratio of flood peaks for a given return period that ranged from 1 to 1.3 was determined. AMEC then performed flood frequency analyses for the Elbow River near Glenmore Reservoir using the combined record for 1908 to 2013. Those results are provided in Table 1 for the mean daily peak discharges and Table 2 for the instantaneous peak discharges. Based on previous flood frequency studies of both the Bow and Elbow Rivers, AMEC applied the ratios described above to the values in Table 1 and Table 2 to indirectly account for historic floods dating back to 1879. Notice that incorporating historic flood records increases the magnitudes of the 100-year to 1000-year flood peaks by 26% to 34%.

Table 1 Mean Daily Discharge Flood Frequency by Others Elbow River near Glenmore Reservoir, in m³/s

Return Period (years)	AMEC 2014 (1908 – 2013)	AMEC 2014 (1879 – 2013)	Golder 2010 (1908 – 2008)	Golder 2014 (1908 – 2013)
1000	812	1013	766	1180
500	686	858	632	885
200	537	665	481	602
100	438	539	385	448
50	350	423	302	331
20	248	289	211	218

Return Period (years)	AMEC 2014 (1908 – 2013)	AMEC 2014 (1879 – 2013)	Golder 2010 (1908 – 2008)	Golder 2014 (1908 – 2013)
10	182	202	154	156
5	124	130	107	108
2	59	53	56	58

Table 2 Instantaneous Peak Flood Frequency by Others Elbow River near Glenmore Reservoir, in m^3/s

Return Period (years)	AMEC 2014 (1908 – 2013)	AMEC 2014 (1879 – 2013)	Golder 2010 (1908 – 2008)	Golder 2014 (1908 – 2013)
1000	1480	1984	1030	2220
500	1230	1625	841	1770
200	933	1197	633	1250
100	737	930	501	954
50	564	695	389	708
20	372	440	267	454
10	252	286	193	307
5	155	168	132	194
2	57	57	67	85

AMEC performed similar Bow River flood frequency analyses for 7-day flood volumes using data from 1908 to 2013 and historic data for pre-1908. AMEC then performed 7-day volumetric analyses for the Elbow River which were modified to account for the historic floods since 1879. The 7-day flood volume frequency results are presented in Table 3.

Table 3 7-Day Volume Flood Frequency by Others Elbow River near Glenmore Reservoir, in dam^3

Return Period (years)	AMEC 2014 (1908 – 2013)	AMEC 2014 (1879 – 2013)
1000	176,256	206,659
500	155,520	183,139
200	130,464	152,203
100	112,320	130,640
50	95,040	109,523
20	74,131	83,049
10	59,270	63,987
5	44,928	46,369
2	26,179	24,104

2.2 HYDROLOGY STUDY, BOW AND ELBOW RIVER UPDATED HYDRAULIC MODEL PROJECT (GOLDER, 2010)

Golder prepared a report dated March 2010 for Alberta Environment (AENV) in cooperation with the City of Calgary, which provided results of flood frequency analyses. Golder used the 3-parameter Log Normal, Log Pearson Type III, and Extreme Value Type II probability distributions. They selected the final results from the Extreme Value Type II probability distribution. The purpose of the study was to provide peak flow estimates for delineation of flood hazards on the Bow River through Calgary. Flood frequency analyses were performed for the Elbow River inflow to Glenmore Reservoir and downstream of the reservoir for which Golder used the period of record 1908 to 2008. Those results are presented in Table 1and Table 2. Golder incorporated historic flood data for the Bow River into those analyses but did not make adjustments to the flood frequency results for the Elbow River for historic flood data.

The Golder 2010 report is of limited value to the SR1 project since it does not include the 2013 flood in the database. However, it is of interest in that it provides an estimate of flood frequency for the Elbow River prior to the occurrence of the 2013 flood.

2.3 BASIN-WIDE HYDROLOGY ASSESSMENT AND 2013 FLOOD DOCUMENTATION (GOLDER, 2014)

Golder prepared a report dated September 2014 for the City of Calgary in partnership with the Alberta Environment and Sustainable Resource Development (ESRD) to update the 2010 to 2012 Bow and Elbow River Hydraulic Model and Flood Inundation Mapping Project. The magnitude of the 2013 flood in the Bow and Elbow Rivers warranted a re-analysis of the flood frequency statistics presented in the Golder 2010 report.

Golder used the Environment Canada Consolidated Frequency Analysis (CFA) procedure. The results for the Elbow River near Glenmore Dam and for the Elbow River at Bragg Creek are presented in Table 2 and Table 4, respectively.

Table 4 Flood Frequency for the Elbow River at Bragg Creek

Return Period (years)	Instantaneous Peak Golder 2014 (m^3/s)
1000	1780
500	1320
200	883
100	643
50	462
20	290
10	198
5	129
2	64

2.4 CONCLUSIONS

The review of past studies identified gaps in available information required for the design of SR1. None of the above referenced studies provided comprehensive analyses for both flood peak and flood volume for the Elbow River at Glenmore and at Bragg Creek as required to estimate flood recurrence intervals and characteristics at the SR1 Diversion Site.

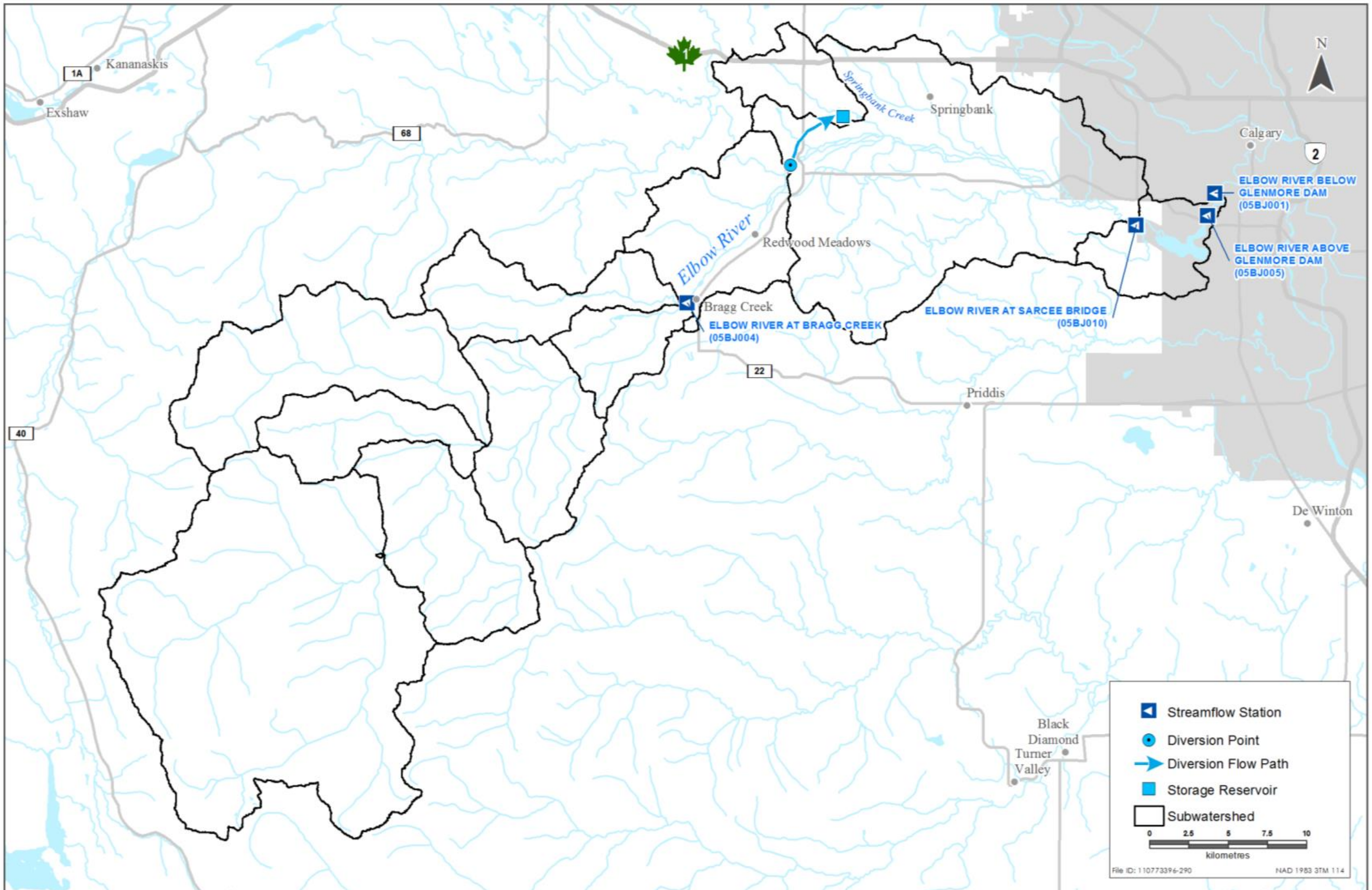
3.0 OBSERVED AND ESTIMATED PEAK FLOW AND VOLUME DATASET

3.1 HYDROMETRIC STATION RECORDS

Stantec identified seven hydrometric stations operated by Water Survey of Canada (WSC) within the Elbow River Basin. Hydrometric stations influenced by dam regulation (Glenmore Reservoir at Calgary (05BJ008)) or those having recorded data of less than 10 years (Little Elbow River above Nihahi (05BJ009)) were omitted from further analysis. The Elbow River station located above Elbow Falls (05BJ006) was also excluded from analysis due to its seasonal operation schedule and lack of relevant flow data (was discontinued in 1995). Therefore, the key gauging stations identified for analysis were Elbow River below Glenmore Dam (05BJ001), Elbow River at Bragg Creek (05BJ004), Elbow River above Glenmore Dam (05BJ005), and Elbow River at Sarcee Bridge (05BJ010). The Bragg Creek Station is located upstream of the proposed SR1 Diversion Site, while the remaining stations are situated downstream of the Diversion Site near the Glenmore Reservoir. See Table 5 and Figure 1 for a summary and figure of the relevant hydrometric stations.

Table 5 Relevant Hydrometric Station Summary

Station ID	Station Name	Drainage Area (km²)	Period of Record		Percent Missing Data	Years of Acceptable Flow Data	Type of Flow	Operation Schedule
			From	To				
05BJ001	Elbow River below Glenmore Dam	1235.7	1908	2011	2%	102	Unregulated (1908 – 1932)/ Regulated	Continuous
05BJ004	Elbow River at Bragg Creek	790.8	1934	2012	25%	59	Natural	Continuous
05BJ005	Elbow River above Glenmore Dam	1220	1933	1977	0%	45	Natural	Continuous
05BJ010	Elbow River at Sarcee Bridge	1189.3	1979	2012	37%	20	Natural	Continuous



Sources: Base Data - Natural Resources Canada. Thematic Data - Water Survey of Canada. Subbasin - Stantec Consulting Ltd. Project Data - Stantec Consulting Ltd.

Disclaimer: This map is for illustrative purposes to support this Stantec project; questions can be directed to the issuing agency.

Figure 1 Hydrometric Station Map

3.1.1 Combined Station

Stations on the Elbow River below Glenmore Dam, above Glenmore Dam, and at Sarcee Bridge have drainage areas of 1236, 1220, and 1189 km^2, respectively. Due to their proximity and similar drainage areas, their data was combined and considered as one station for further analysis (hereafter referred to as the Combined Station). The Combined Station consists of data from 1908 to 1932, 1934 to 1977, and 1979 to 2012, respectively. Only natural, unregulated flow is represented in the data series. Therefore, flow measurements up until the construction of the dam in 1934 were used at the station below Glenmore Dam. No flow data exists in 1933, 1978, and 1991 for any of the stations within the Combined Station grouping.

Annual maximum daily flows were recorded at the Combined Station for years prior to 1979. Peak instantaneous flows were first recorded at the Combined Station in 1979 and are available for most years between 1979 and the present.

Further, estimated annual maximum instantaneous peak flows for 23 additional years prior to 1978 were provided by the Province of Alberta for this location. These instantaneous peak flow estimates were first reported in a study titled Flood Protection – Elbow River Calgary (T. Blench & Associates Ltd, 1965) and have since been used by the Province for subsequent flood frequency estimates including the Calgary Floodplain Study (Alberta Environment 1983) and the Basin-Wide Hydrology Assessment and 2013 Flood Documentation (Golder, 2014).

3.1.2 Bragg Creek Station

Annual maximum daily flows were recorded at Bragg Creek for years prior to 1950. Peak instantaneous flows were first recorded at Bragg Creek in 1950 and are available for most years between 1950 and the present.

3.1.3 Observed Data Gaps

For the period of 1908 to 2013, the Combined Station is missing 2% and 54% of annual maximum daily and peak instantaneous flows, respectively. During the same period the Bragg Creek Station is missing 25% and 41% of annual maximum daily and peak instantaneous flows, respectively. The following sections describe the procedure for infilling missing annual maximum daily and peak instantaneous flows at Bragg Creek and the Combined Station for the flood frequency analyses.

3.2 JUNE, 2013 FLOOD EVENT

Due to damage during the June 2013 flood, official data from the gauging stations Elbow River at Bragg Creek and Elbow River at Sarcee Bridge was unavailable. However, Water Survey Canada (WSC) supplied preliminary 2013 peak instantaneous flows for the Elbow River at Bragg Creek and at Sarcee Bridge as 1150 and 1240 m^3/s, respectively (Lazowski pers. comm. 2015).

In addition, the City of Calgary provided an estimated inflow flood hydrograph into the Glenmore Reservoir for the June 2013 flood based on reservoir level and outflow analysis (see Figure 3). This estimated inflow into the Glenmore Reservoir was used to represent volume of flow at the Combined Station for the 2013 flood.

Real time preliminary water level data for Bragg Creek Station was then downloaded from WSC data server (note: these datasets did not undergo quality assurance and quality control practices by WSC). The WSC also supplied three stage-discharge rating curves (Curves 23, 24 and 25) for the Bragg Creek Station (Lazowski pers. comm. 2015). Curve 23 is applicable to data from January 1, 1998 to June 19, 2005. Curve 24 is fitted for use from June 19, 2005 to January 1, 2006. Curve 25 is related to data from January 1, 2006 and onward.

Stantec used Curves 24 and 25 in conjunction with the preliminary water level data at the Bragg Creek Station to estimate the 2013 flood hydrograph at Bragg Creek. Initially, Curve 25 was used to estimate the full 2013 flood hydrograph, as it was the latest developed curve. However, it appears Curve 25 overestimates the latter part of the falling limb of the 2013 hydrograph (from June 22, 2013 at 15:00 and on, when the stage was less than 3 m and the flow was less than 200 m^3/s). In comparison to the City of Calgary estimated inflow flood hydrograph into the Glenmore Reservoir, the flow at Bragg Creek was considerably greater for the latter part of the falling limb. When comparing Curve 24 to Curve 25, it was found that Curve 24 fit the lower flows better (see Figure 2). Therefore, Curve 25 was used from the beginning of the flood to June 22, 2013 at 15:00 and Curve 24 was used to estimate the remainder of the 2013 hydrograph.

Power equations were developed to fit the rating curve data provided by WSC for Curves 24 and 25. Both curves were fixed such that the maximum peak flow (Q = 1150 m^3/s, provided by WSC) occurred at the maximum level (h = 4.80 m on June 20, 2013 at 10:00, which was obtained from WSC real time stage data). The equations for the curves used to estimate the 2013 flood hydrograph at Bragg Creek are as follows:

$$Curve\ 24: Q = 24.45 \times (h - 0.8)^{2.91}$$

$$Curve\ 25: Q = 37.54 \times (h - 0.8)^{2.47}$$

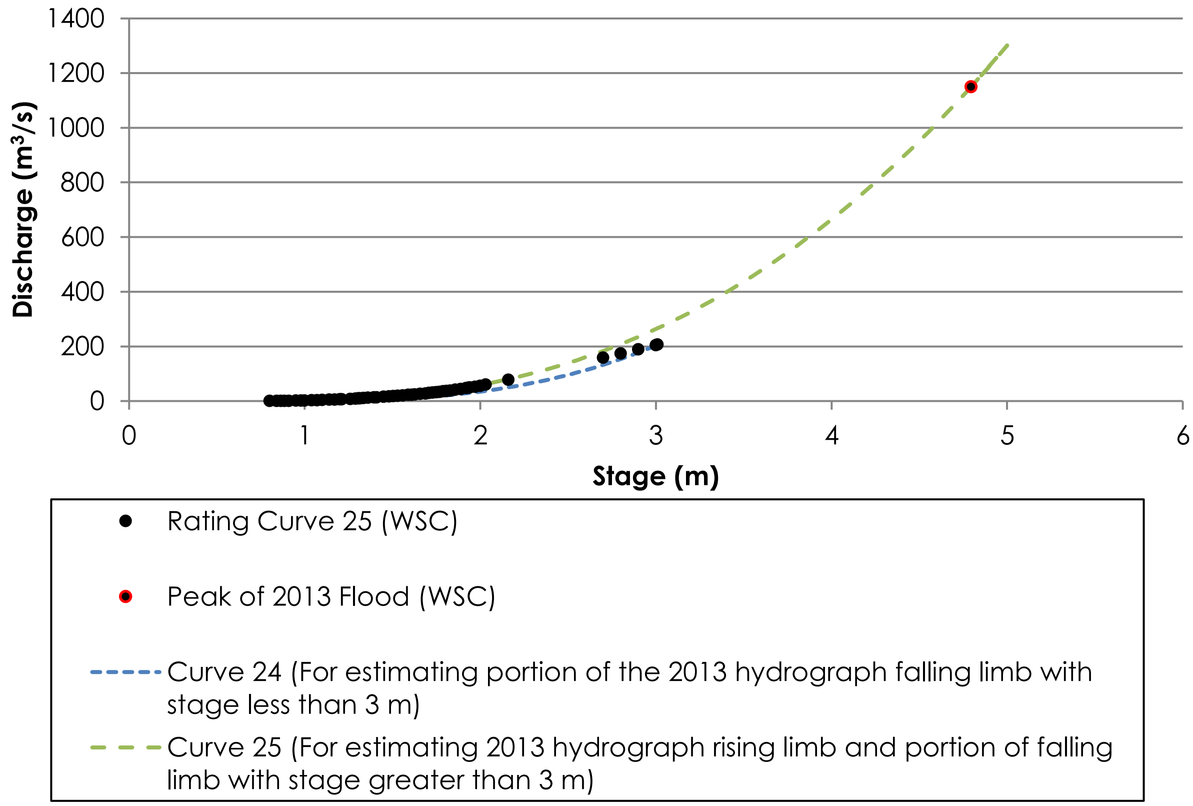


Figure 2 Rating Curves for Bragg Creek Station

Based on these two equations, Stantec generated an estimate of the June 2013 flow hydrograph at Bragg Creek (see Figure 3).

Although the WSC and City of Calgary preliminary values were used for analysis, it is important to note that they are estimates and are still under review by the WSC.

The hydrograph provided by ESRD for the Bragg Creek Station was used only as a comparison to the Stantec estimate and not for analyses. The ESRD and Stantec hydrographs at the Bragg Creek station had similar shapes but differed greatly in peak values. ESRD estimated the instantaneous peak "on the fly" to be 874 m^3/s at 13:14 on June 20, 2013, while WSC estimated the peak flow at approximately 1150 m^3/s at 10:00 on June 20, 2013.

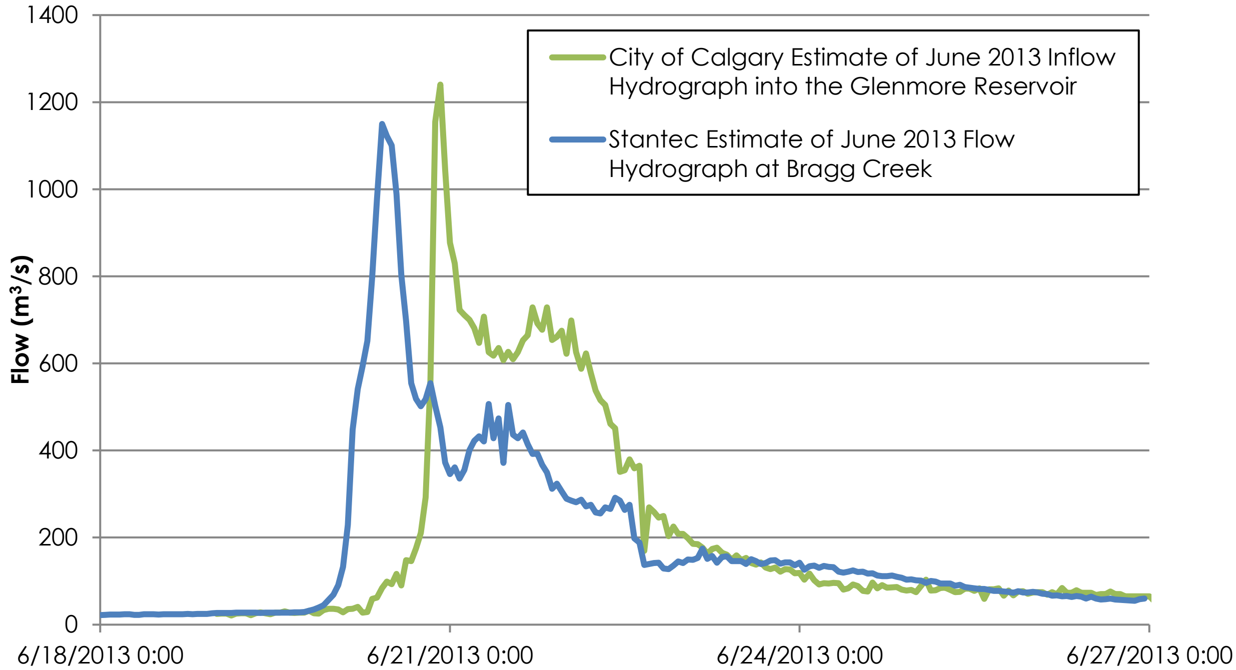


Figure 3 Preliminary 2013 Flood Hydrograph at Glenmore Reservoir and at Bragg Creek Station

The 7-day volume for 2013 the event was estimated based on the City of Calgary calculated inflow hydrograph into the Glenmore Reservoir (see Figure 3) at the Combined Station. This 2013 hydrograph covered a total of seven days, from June 20 to 26. The 2013 Bragg Creek 7-day flood volume also encompassed seven days, from June 20 to 26. It was calculated from the estimated 2013 flood hydrograph at Bragg Creek (see Figure 3).

The 56-day volume dataset did not include 2013 data since only nine days of flow data was available for analysis in 2013.

3.3 CORRELATION OF OBSERVED ANNUAL MAXIMUM DAILY FLOWS TO PEAK INSTANTANEOUS FLOWS

In order to perform comparable streamflow analyses, flow data pertaining to a common time period between the Bragg Creek and Combined Station was desired. Applying a common time period at both locations allowed for comparison of peak flows at the same plotting position. The annual maximum daily and peak instantaneous flow data were first recorded at the Combined Station in 1908 and 1979, respectively. The first record of annual maximum daily and peak instantaneous flow at Bragg Creek was 1935 and 1950, respectively. In order to carryout flow frequency analysis at both the Combined and Bragg Creek Stations using data from 1908 to 2013, an estimate was carried out to infill unrecorded and missing flow data. This was done by developing relationships between maximum daily and peak instantaneous flow at each station. See Table 5 for a description of the data at the WSC stations used for analysis.

3.3.1 Combined Station

A relationship between annual maximum daily and peak instantaneous flow was first developed at the Combined Station. Since peak instantaneous flow data was not recorded at the Elbow River below or above Glenmore Dam Stations, only data from Sarcee Bridge was used to build this relationship.

As stated previously, peak instantaneous flow data was not recorded at the Sarcee Bridge Station until 1979. Furthermore, there is no record of annual maximum daily flows for the years 1978 to 1989, 1991, and 1995 for the Sarcee Bridge Station. However, the complete daily hydrographs for those years, except 1978 and 1991, were available from WSC. Therefore, annual maximum daily flows for these years were taken from daily hydrograph data. In 2003 and 2007, the annual maximum daily flow occurred on a different day than the peak instantaneous flow of that year. For these two cases, annual maximum daily flow values were replaced by daily flow values with the same date as the peak instantaneous flow. Using the data described above, annual maximum daily and peak instantaneous flow data at Sarcee Bridge was analyzed from 1979 to 2013, excluding 1991, to represent the Combined Station (see Figure 4).

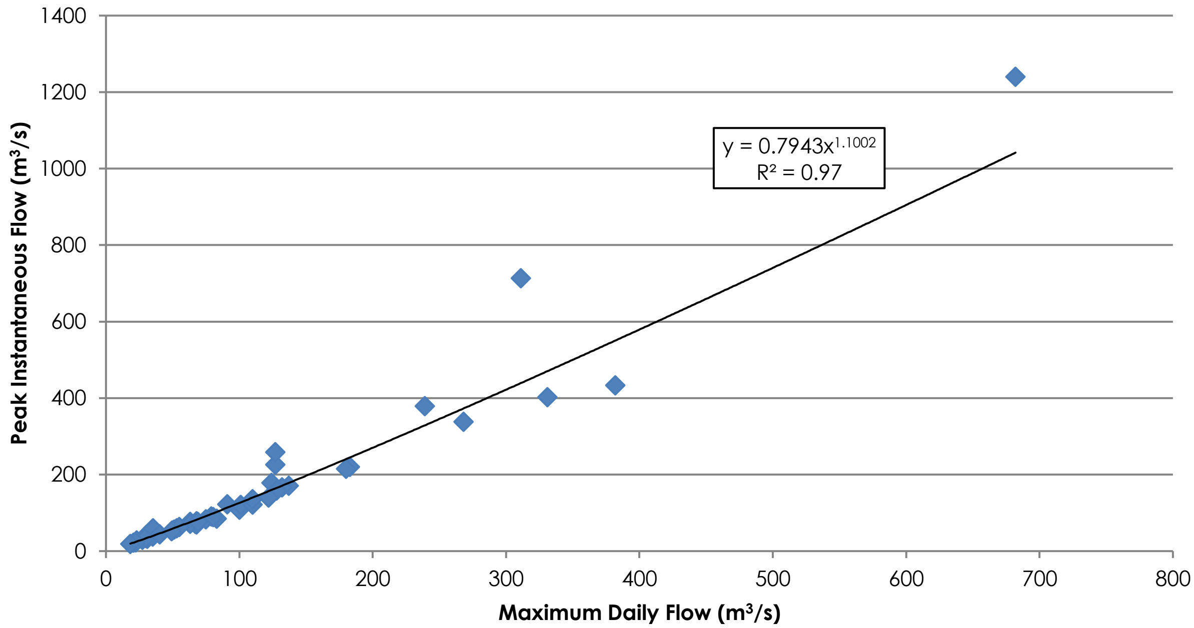


Figure 4 Relationship between Annual Maximum Daily and Peak Instantaneous Flow at the Combined Station.

The relationship in Figure 4 was used to estimate missing peak instantaneous flow records using annual maximum daily flows at the Sarcee Bridge Station. As annual maximum daily values were not recorded in 1978 or 1991 these values were estimated using the relationship between annual maximum daily values at the Bragg Creek and Combined Station (see Section 3.4).

3.3.2 Bragg Creek Station

Similar to the Combined Station, a relationship between annual maximum daily and peak instantaneous flows was developed at the Bragg Creek Station. As stated previously, peak instantaneous flow data was not recorded at the Bragg Creek Station until 1950. Therefore, annual maximum daily and peak instantaneous flow data at Bragg Creek was analyzed from 1950 to 2013.

Similar to the analysis completed at the Combined Station, the data was analyzed to omit flows that originated from different flood events for a particular year. Annual maximum daily flow values were replaced by daily flow values with the same date as the peak instantaneous flow for the years 1952, 1955, 1968, 1973, 1974, 1977, 1982, 1983, 2003, and 2012.

After review, the 1974 data was removed from analysis because of the uncharacteristically large difference between the values. The daily flow recorded on the same day as the peak instantaneous flow was 21 m³/s, while the peak instantaneous flow was 170 m³/s on average the peak instantaneous values were 23% greater than the maximum daily values for maximum daily flow values at Bragg Creek less than 100 m³/s. As a result the relationship at Bragg Creek was developed using data from 1950 to 1973 and 1975 to 2012 for a total of 62 years (see Figure 5).

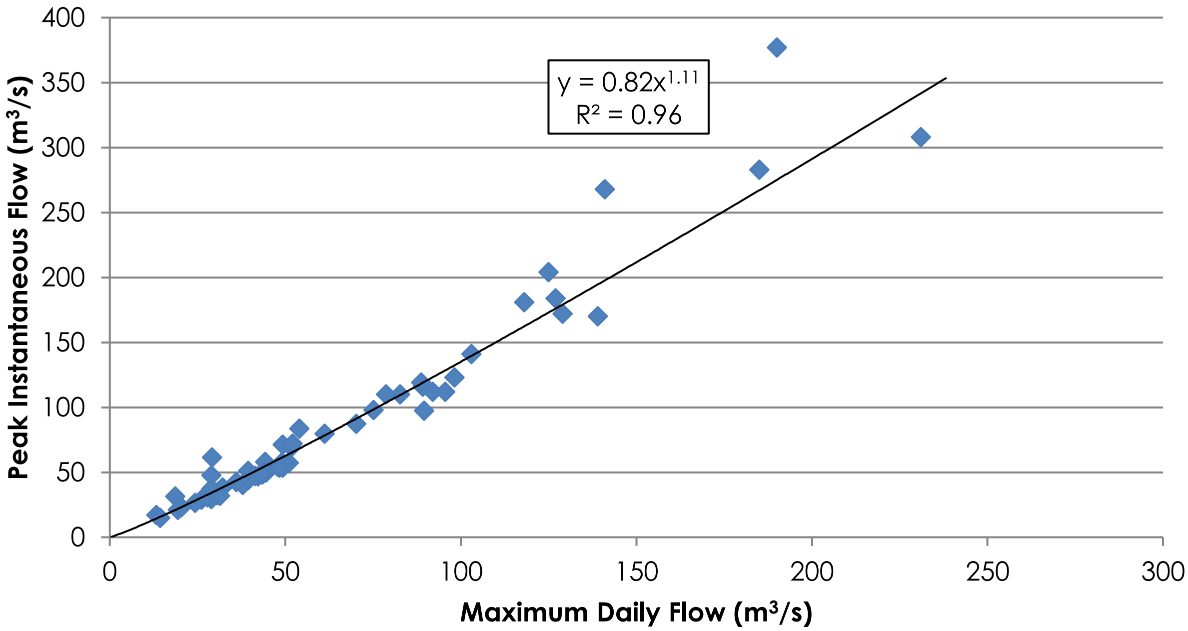


Figure 5 Relationship between Annual Maximum Daily and Peak Instantaneous Flow at the Bragg Creek Station

This relationship was used to estimate peak instantaneous flows for the period from 1908 to 1949 and 1993. As annual maximum daily values were not recorded until 1935, annual maximum daily values from 1908 to 1934 were estimated using the relationship between annual maximum daily values at the Bragg Creek and Combined Stations. The methodology for this relationship is explained in detail in Section 3.4.

3.4 CORRELATION OF OBSERVED FLOOD FLOW AND VOLUMES BETWEEN THE COMBINED AND BRAGG CREEK STATIONS

3.4.1 Annual Maximum Daily Flow Relationship between the Combined and Bragg Creek Stations

The first annual maximum daily record at the Bragg Creek Station was in 1935. To infill the record at Bragg Creek for years prior to 1935, a relationship between the annual maximum daily flows at the Bragg Creek and Combined Station was developed using the corresponding records from 1935 to 2012, excluding 1978 and 1991 as no annual maximum daily flow values were available at the Combined Station. Therefore, the relationship was created using data from 1935 to 1977, 1979 to 1990, and 1992 to 2012; for a total of 76 years. See Figure 6 for this relationship.

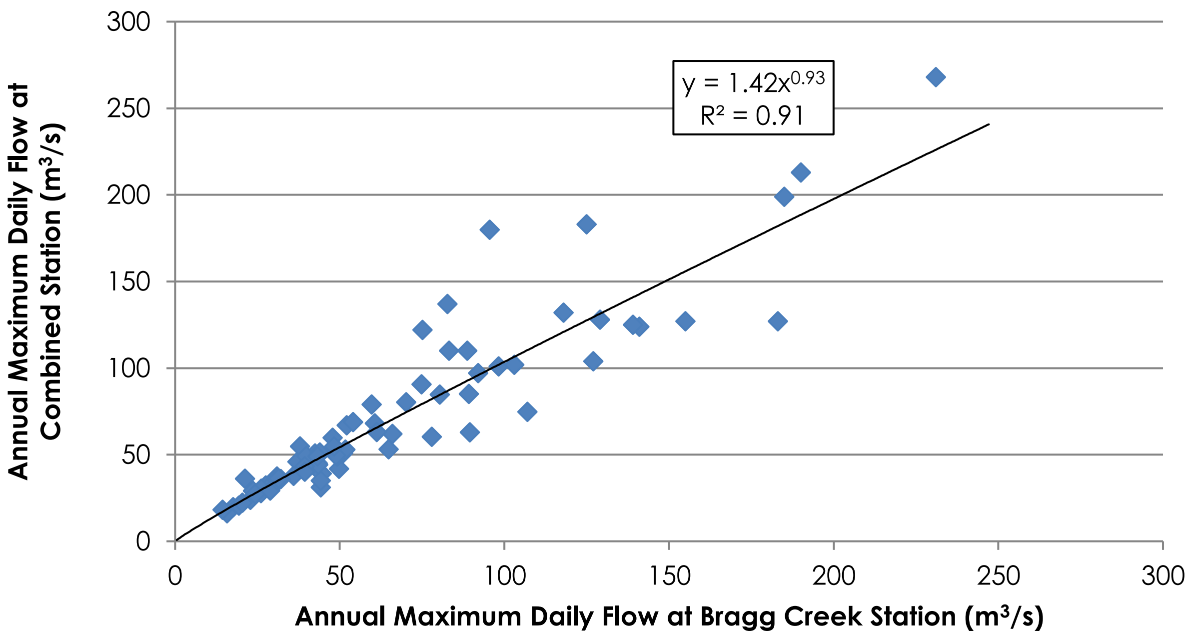


Figure 6 Relationship between Annual Maximum Daily Flow at the Bragg Creek and Combined Stations

3.4.2 Annual Maximum 7-Day and 56-Day Volume Relationship between the Combined and Bragg Creek Stations

Volumetric frequency analysis was carried out for two different time periods of 7- and 56-day duration. In order to calculate the volume of water, moving sums of daily flow were performed for consecutive durations of 7- and 56-day periods at the Combined and Bragg Creek Stations. From this data, the annual maximum 7- and 56-day volumes were identified.

Daily discharge data is available from 1908 to 2012 at the Combined Station. However, the first record of daily flow data at the Bragg Creek Station was in 1934. Therefore, annual maximum 7- and 56-day volumes at the Bragg Creek Station were not available from 1908 to 1933. In order to estimate the 7- and 56-day volumes at Bragg Creek for the period of 1908 to 1933, a relationship was created between the Bragg Creek and Combined Stations based on a time period where data exists for both stations. The 7-day volume relationship was based on data from 1934 to 2013, excluding 1978 and 1991. The 56-day volume relationship was built on data from 1934 to 2012, excluding 1978 and 1991.

The Bragg Creek Station volumes from 1908 to 1933 were then estimated using the relationship between the two stations 7- and 56-day volumes (see Figure 7 and Figure 8). Therefore, 25% of the 7- and 56-day volumes at the Bragg Creek Station were estimated.

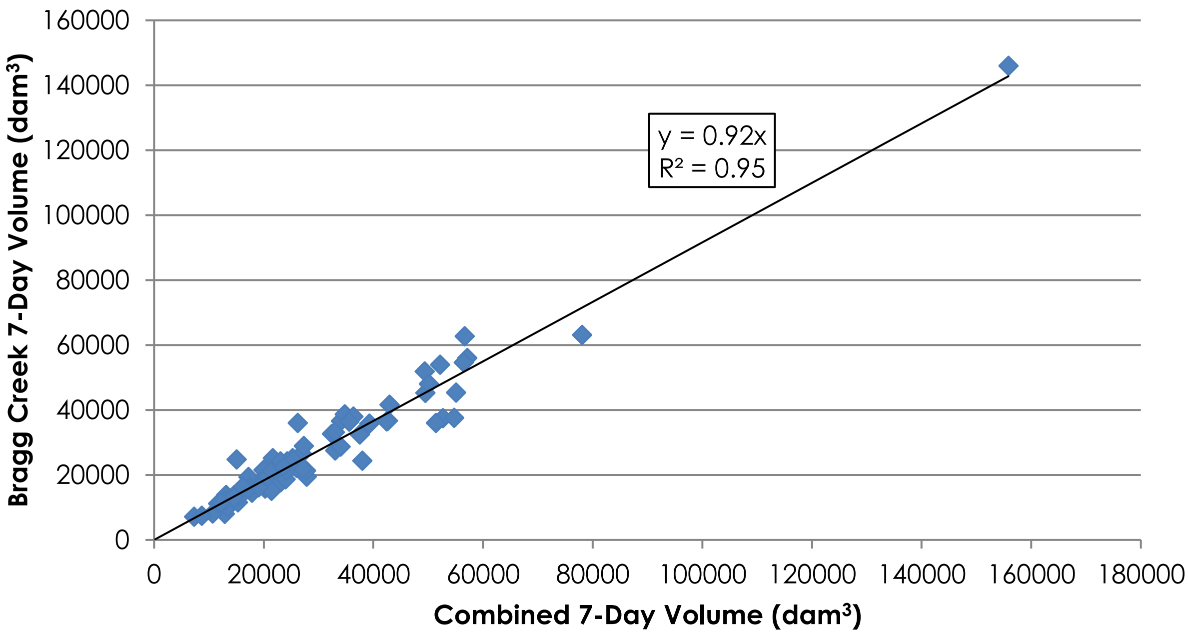


Figure 7 Annual Maximum 7-Day Volume Relationship between the Bragg Creek and Combined Stations (1934 – 2013), in dam^3

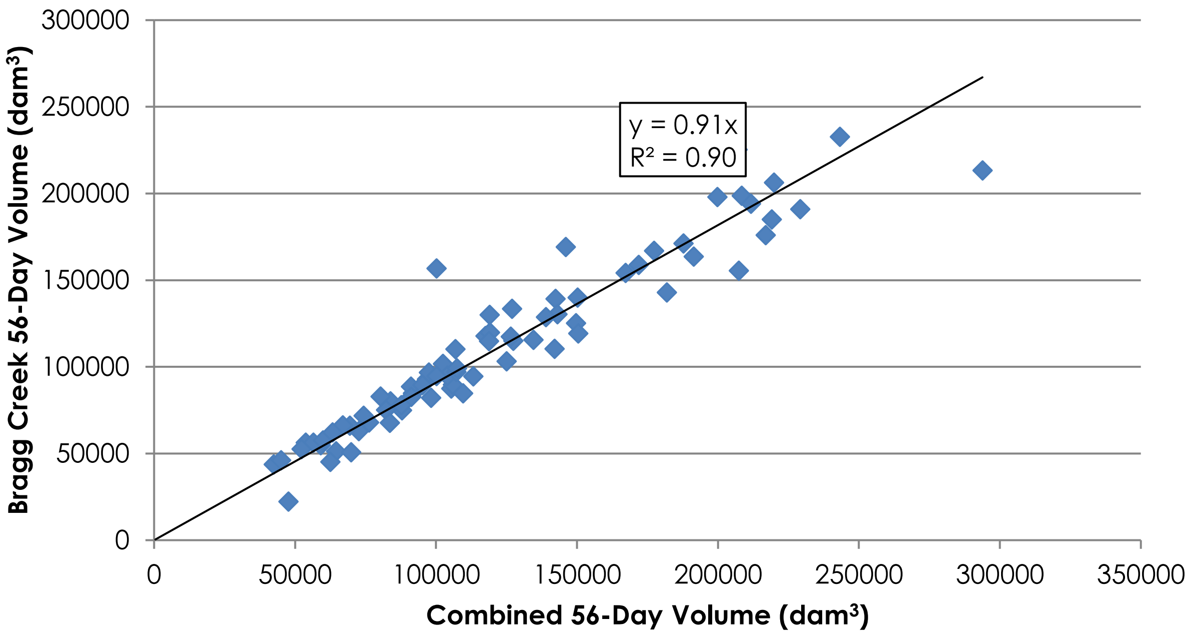


Figure 8 Annual Maximum 56-Day Volume Relationship between the Bragg Creek and Combined Stations (1934 – 2012), in dam3

3.5 CONSTRUCTED DATASETS FOR PEAK FLOW AND VOLUME

Stantec developed a combined record of peak flow and flood volume estimates for the period of 1908 to 2013 using the data and methods described in the previous sections. Tables presenting the observed and estimated values for annual maximum daily, peak instantaneous, 7-day volume and 56-day volume at both the Combined and Bragg Creek Stations are provided in Appendix A. Figures 9 and 10 show the full record of observed and estimated peak instantaneous flows for the Bragg Creek and Combined Stations.

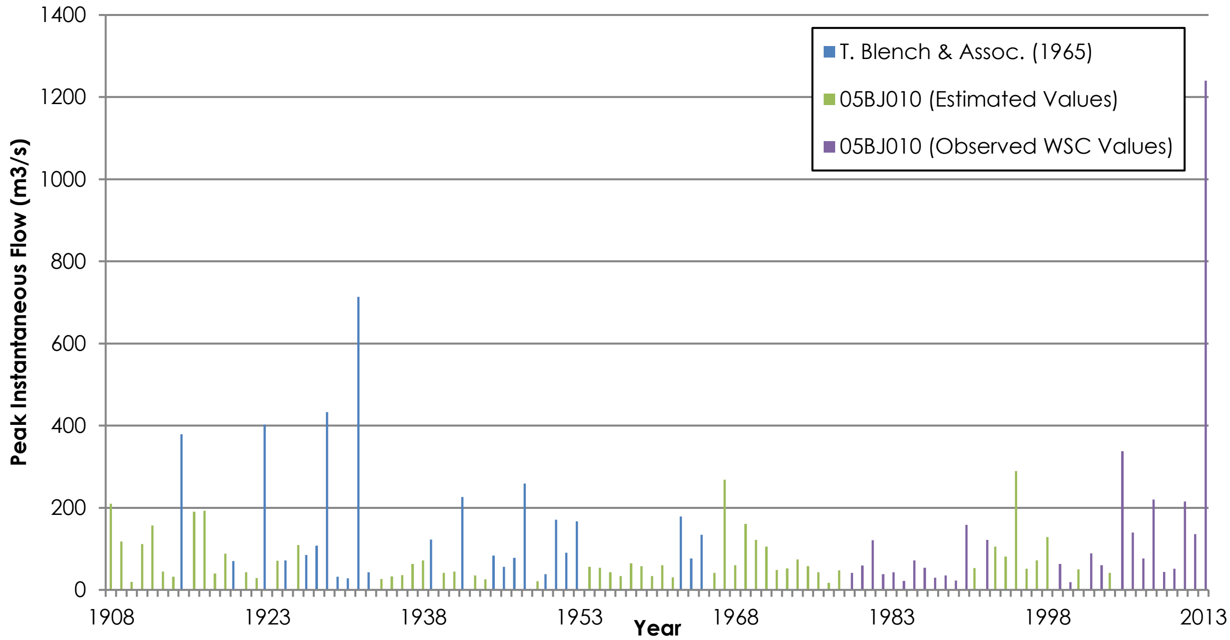


Figure 9 Observed and Estimated Peak Instantaneous Flows of Elbow River at Combined Station (1908 – 2013)

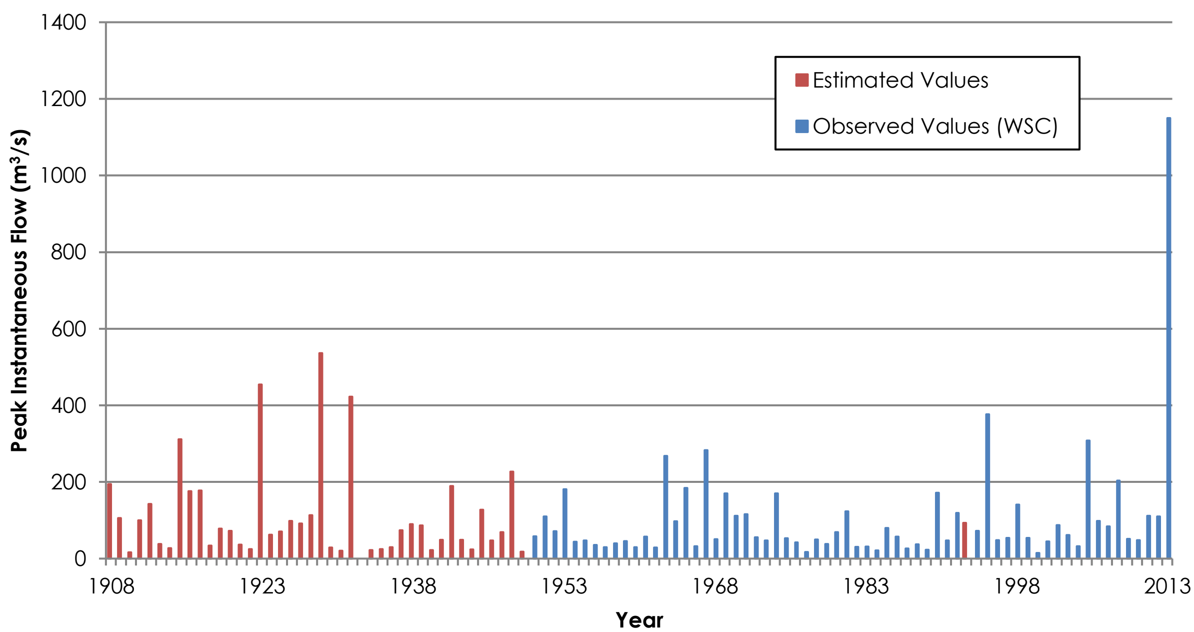


Figure 10 Observed and Estimated Peak Instantaneous Flows of Elbow River at Bragg Creek Station (1908 – 2013)

4.0 FLOOD PEAK AND VOLUMETRIC FREQUENCY ANALYSIS RESULTS

Flood peak and volumetric frequency analyses were conducted on six datasets:

1. Annual peak instantaneous flow at the Combined Station (1908 – 2013),
2. Annual peak instantaneous flow at the Bragg Creek Station (1908 – 2013),
3. Annual maximum 7-day volume at the Combined Station (1908 – 2013),
4. Annual maximum 7-day volume at the Bragg Creek Station (1908 – 2013),
5. Annual maximum 56-day volume at the Combined Station (1908 – 2012), and
6. Annual maximum 56-day volume at the Bragg Creek Station (1908 – 2012).

4.1 FREQUENCY ANALYSIS PROCEDURE

Flood peak and volumetric frequency analyses were carried out at the Combined and Bragg Creek Stations using ten different probability functions. Analysis methods generally followed the Frequency Analysis Procedure for Stormwater Design developed the City of Calgary (City of Calgary 2014). The Hydrologic Frequency Analysis Plus (HYFRAN+) software package was utilized to fit the statistical distributions to the data series. HYFRAN+ is a numerical tool that can be used to compare multiple frequency distributions and parameter estimation methods and perform goodness-of-fit and data series characteristic tests.

The following probability distributions were analyzed with the distribution parameter estimation methods listed in parentheses (MLE = maximum likelihood estimation, MOM = method of moments, and SAM = methodé SAM):

- Normal (MLE)
- Log Normal (MLE)
- Log Normal III (MLE)
- Exponential (MLE)
- Pearson III (MOM)
- Log Pearson III (SAM)
- Gumbel (MLE)
- GEV (MLE)
- Weibull (MLE)
- Gamma (MLE)

Prior to fitting the appropriate curve, a variety of statistical tests were performed to determine the quality of the input data using the City of Calgary's spreadsheet tool (Calgary, 2014). These tests evaluate the dataset for randomness, stationarity, homogeneity, independence and the presence of outliers. A summary of the test results is provided in Table 6. The tests identified potential issues with each of the six constructed datasets to be analyzed.

The results of the ten probability functions analyzed produced wide varying results and did not provide a sufficient representation for the full data set upon visual inspection. As such, a different methodology was selected and is described in the next section.

Table 6 Statistical Characteristics of Flood Peak and Volumetric Frequency Datasets

Statistical Tests		Peak Instantaneous Flow (1908 - 2013)		Maximum 7-Day Volume (1908 - 2013)		Maximum 56-Day Volume (1908 - 2012)	
		Combined Station	Bragg Creek Station	Combined Station	Bragg Creek Station	Combined Station	Bragg Creek Station
Stationarity	Spearman Rank Order Correlation Coefficient (Trend)	no significant trend at a=0.05	no significant trend at a=0.05	no significant trend at a=0.05	no significant trend at a=0.05	no significant trend at a=0.05	no significant trend at a=0.05
	Mann-Whitney Test for Jump	no jump at a=0.05	no jump at a=0.05	no jump at a=0.05	presence of jump possible at a=0.05	no jump at a=0.05	no jump at a=0.05
	Wald-Wofowitz Test (Jump)	presence of jump possible at a=0.05	presence of jump possible at a=0.05	presence of jump possible at a=0.05	presence of jump possible at a=0.05	presence of jump possible at a=0.05	presence of jump possible at a=0.05
Homogeneity	Mann-Whitney U Test	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05
	Terry Test	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05
Independence	Spearman Rank Order Correlation Coefficient	sample is independent at a=0.05	sample is independent at a=0.05	sample is independent at a=0.05	sample is independent at a=0.05	sample is independent at a=0.05	sample is independent at a=0.05
	Wald-Wolfowitz Test for Independence	sample is independent at a=0.05	sample is independent at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05
	Anderson Test	sample is independent at a=0.05	sample is independent at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05
Outliers	Grubbs and Beck Test	high outlier may be present; no low outliers	high outlier may be present; no low outliers	no high outliers; no low outliers	no high outliers; no low outliers	no high outliers; no low outliers	no high outliers: low outlier may be present

4.2 UNBIASED METHOD

As discussed above, traditional flood frequency methods provide a wide range of values for the same exceedance probability. Furthermore, multiple statistical tests were violated for each of the flood peak and volumetric datasets. Limited confidence is warranted for methods that fit the Elbow River hydrometric data to single preordained mathematical probability distributions by statistical methods. This appears related to two factors: first, floods on the Elbow River are from a mixed population of snowmelt, spring rain on snow, and summer rainfall only floods. Therefore, no single probability distribution can be expected to fit the data. Second, the 2013 flood was an exceptional hydrologic event. There is no other recorded flood on the Elbow River that is represented by the 2013 flood in regard to peak discharge, flood volume, or runoff response time (hydrograph shape).

To properly account for the extraordinary 2013 flood, the Unbiased Plotting Position Formulae for Historical Floods as described by Guo (1990) was used. This method accounts for the extraordinary floods by calculating the plotting position for that event as follows:

$$P_e = \left(\frac{m - 0.4}{k + 0.2}\right)\left(\frac{k}{N}\right) \; for \; m = 1, \ldots, k$$

$$P_e = \frac{k}{N} + \left(\frac{N - k}{N}\right)\left(\frac{m - k - 0.4}{N - k + 0.2}\right)\left(\frac{N - k}{N_s - e}\right) \; for \; m = k + 1, \ldots, N_g$$

Where:

- P_e = the probability of exceedance,
- m = the rank of each flood event (from 1 to N_g) in descending magnitude order,
- N = the effective record length,
- N_s = the number of years in the systematic record,
- e = the number of extraordinary floods in the systematic record,
- k = the number of historic plus extraordinary floods, ($h + e$, where h is the number of historic data),and
- N_g = the number of systematic record plus historic data ($N_s + h$, where h is the number of historic data).

For the peak instantaneous flow datasets at the Bragg Creek and Combined Stations the value of N was 106, as the data ranged from 1908 to 2013. A k value of 1 was used because there was one extraordinary flood (the 2013 flood) and no historic floods were considered in this analysis (h = 0).

The instantaneous peak discharges and corresponding probability of exceedance were plotted on log-log paper and best fit lines were mathematically calculated to those data points. A logarithmic equation was found to best fit data with a return period less than the 10 years. For data with return periods greater than 10 years, a power equation was found to best fit the data. The graphical flood peak data analysis for the Combined Station is shown in Figure 11 and for the Bragg Creek Station in Figure 12. From these relationships, Stantec estimated the 5-, 10-, 20-, 50-, 100-, 200-, and 500-year flood peaks as presented in Table 7. The results from this method are used for further analysis and evaluations. Instantaneous peak values are reported to the nearest 5 m^3/s.

Table 7 Flood Peak Frequency Results using Unbiased Method (1908 – 2013)

Return Period (years)	Instantaneous Peak Discharge (m^3/s)	
	Combined	Bragg Creek
500	2,035	1,745
200	1,215	1,085
100	820	755
50	560	525
20	330	330
10	205	200
5	145	140
2	70	70

For the 7-day volumetric analysis, a N value of 106 was used, as the frequency analysis was conducted on data from 1908 to 2013. The value of k was 1 since there was one extraordinary flood (the 2013 flood, e = 1) and no historic floods were considered (h = 0).

The 7-day flood volumes and corresponding probability of exceedance were plotted on log-log paper and best fit lines were mathematically calculated to those data points. A logarithmic equation was found to best fit data with a return period less than the 10-years. For data with return periods greater than 10-years a power equation was found to best fit the data. The graphical 7-day flood volume data analysis for the Combined Station is shown in Figure 13 and for the Bragg Creek Station in Figure 14. From these relationships, Stantec estimated the 5-, 10-, 20-, 50-, 100-, 200-, and 500-year 7-day flood volume as presented in Table 8. The 7-day volumes are rounded to 3 significant figures.

Table 8 7-Day Volumetric Frequency Results using Unbiased Method (1908 – 2013)

Return Period (years)	7-Day Volume (dam^3)	
	Combined	Bragg Creek
500	192,700	170,000
200	146,000	129,000
100	119,000	105,000
50	96,000	85,400
20	73,000	64,900
10	59,700	52,700
5	41,300	37,300
2	21,500	19,700

For the 56-day flow volumes at the Bragg Creek Station and the Combined Station the value of N was 105, as the data ranged from 1908 to 2012. Since there was no 56-day data for the 2013 flood there are no extraordinary floods in the data set. The Unbiased Method formula for a data set with extraordinary flood events (or outliers) follows the Cunnane plotting position formula:

$$P_e = \left(\frac{m - 0.4}{N + 0.2}\right)$$

Where:

– P_e = the probability of exceedance,

– m = the rank of each flood event (from 1 to N) in descending magnitude order, and

– N = the effective record length.

The 56-day flood volumes and corresponding probability of exceedance were plotted on log-log paper and best fit lines were mathematically calculated to those data points. A logarithmic equation was found to best fit data with a return period less than the 10-years. For data with return periods greater than 10-years a power equation was found to best fit the data. That graphical 56-day flood volume analysis for the Combined Station is shown in Figure 15 and for the Bragg Creek Station in Figure 16. From these relationships we were able to estimate the 5-, 10-, 20-, 50-, 100-, 200-, and 500-year 56-day flood volumes as presented in Table 9. The 56-day volumes are rounded to 3 significant figures.

Table 9 56-Day Volumetric Frequency Results using Unbiased Method (1908 – 2012)

Return Period (years)	56-Day Volume (dam^3)	
	Combined	Bragg Creek
500	420,800	358,000
200	360,700	312,000
100	321,000	282,000
50	285,700	254,000
20	245,000	221,000
10	238,000	199,000
5	184,000	169,000
2	112,000	103,000

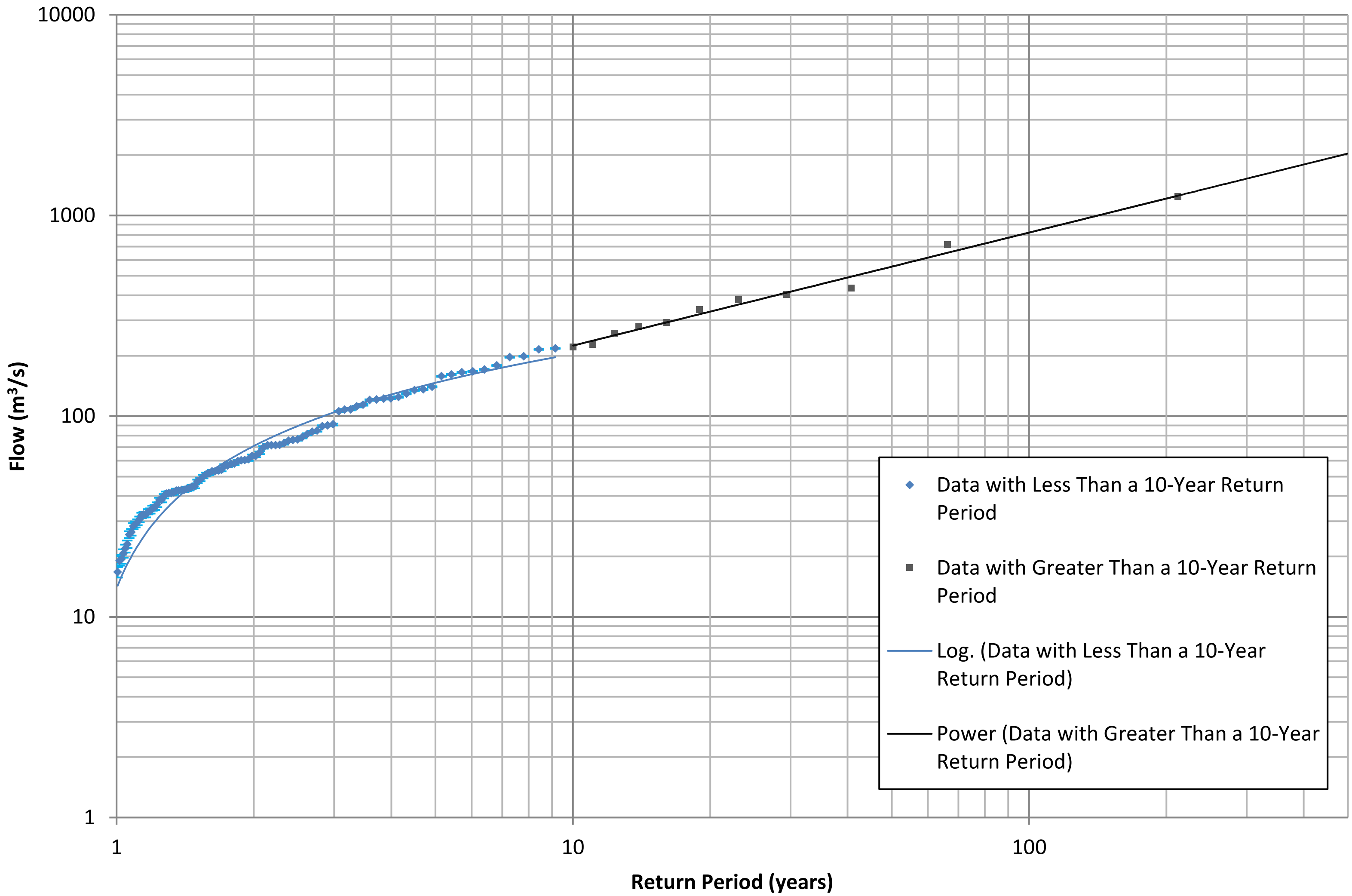


Figure 11 Graph of Elbow River at the Combined Station Flood Peak Frequency Results using Unbiased Method (1908 – 2013)

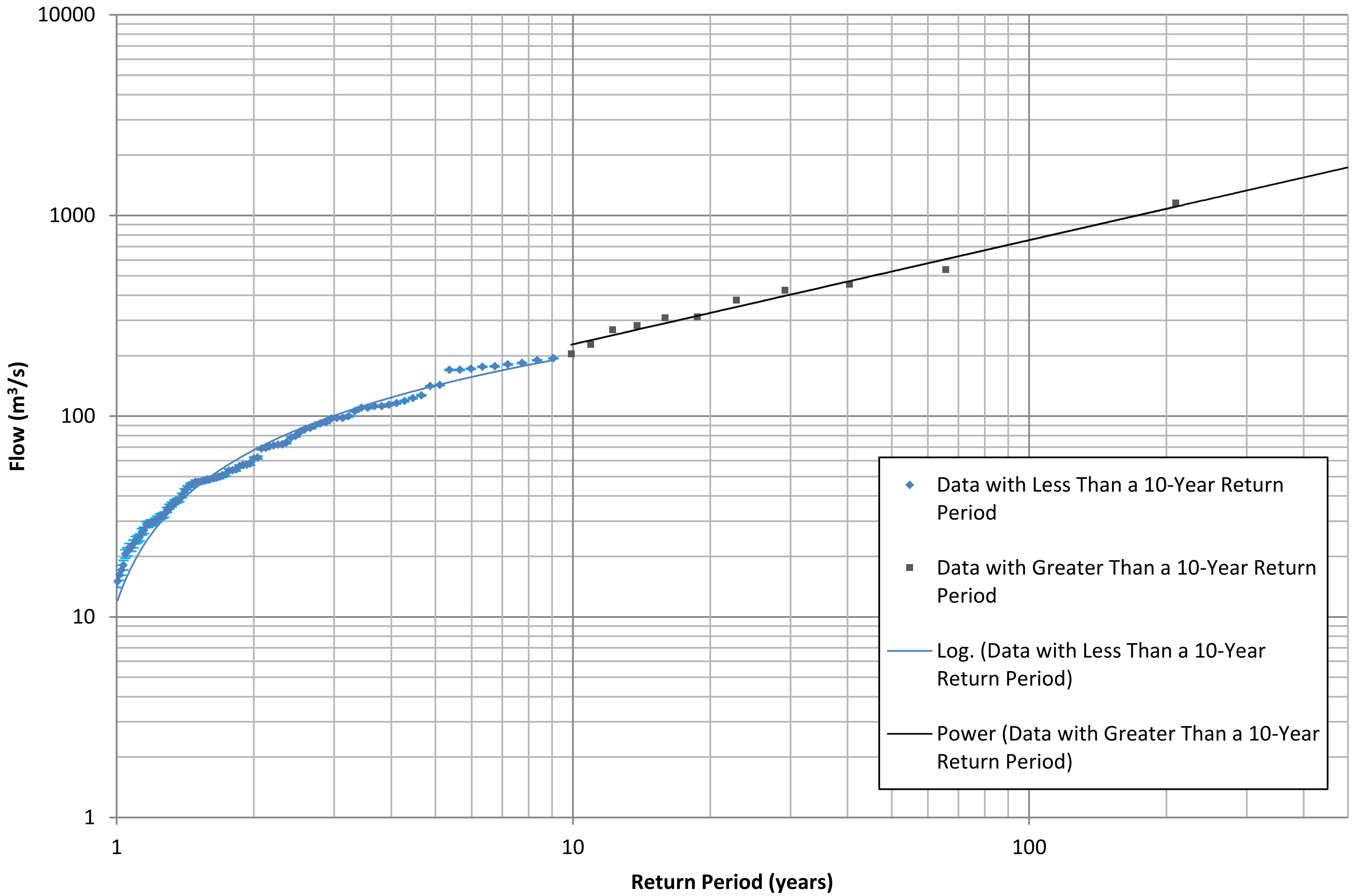


Figure 12 Graph of Elbow River at the Bragg Creek Station Flood Peak Frequency Results using Unbiased Method (1908 – 2013)

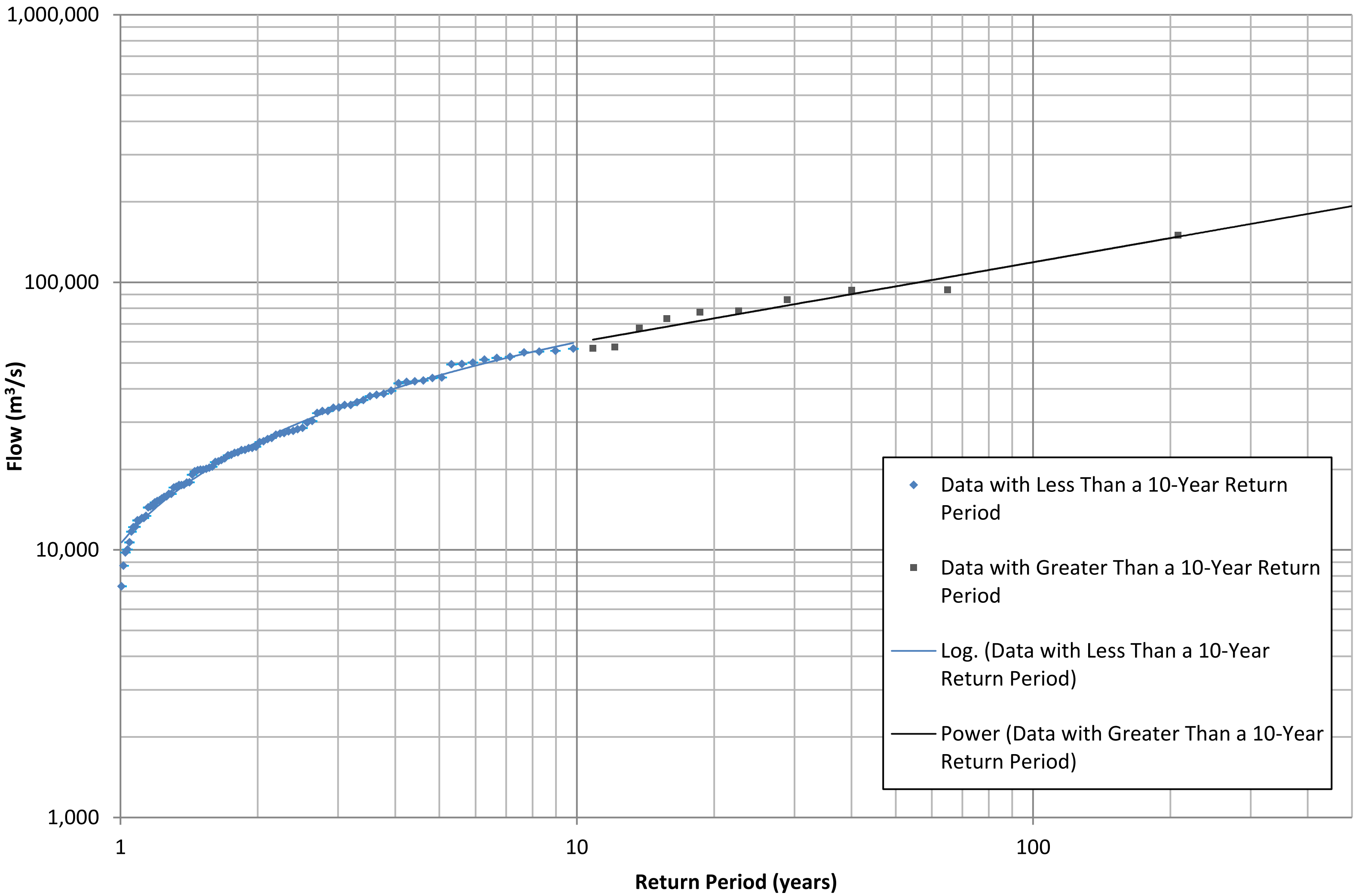


Figure 13 Graph of Elbow River at the Combined Station 7-Day Volumetric Frequency Results using Unbiased Method (1908 – 2013)

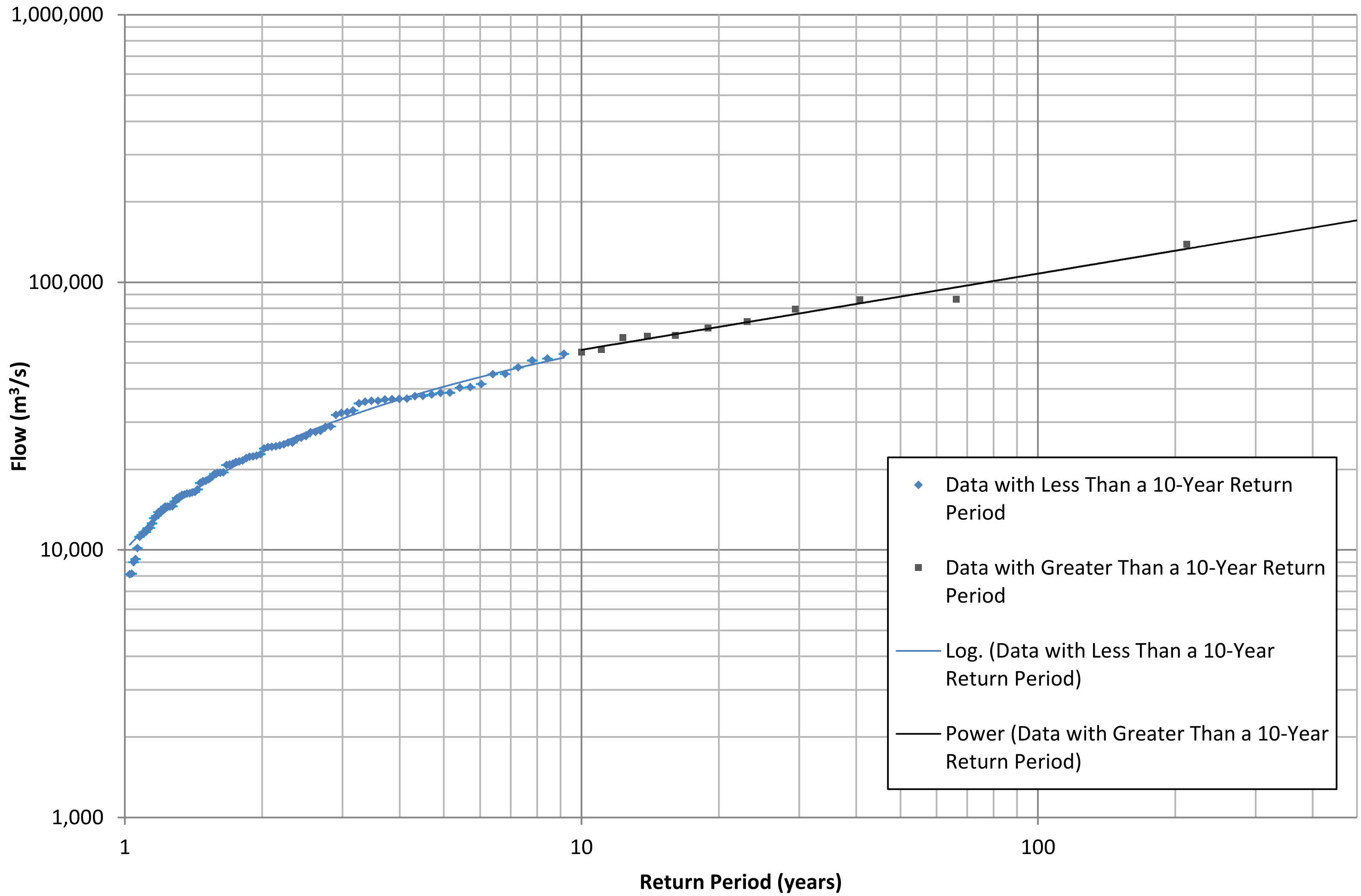


Figure 14 Graph of Elbow River at the Bragg Creek Station 7-Day Volumetric Frequency Results using Unbiased Method (1908 – 2013)

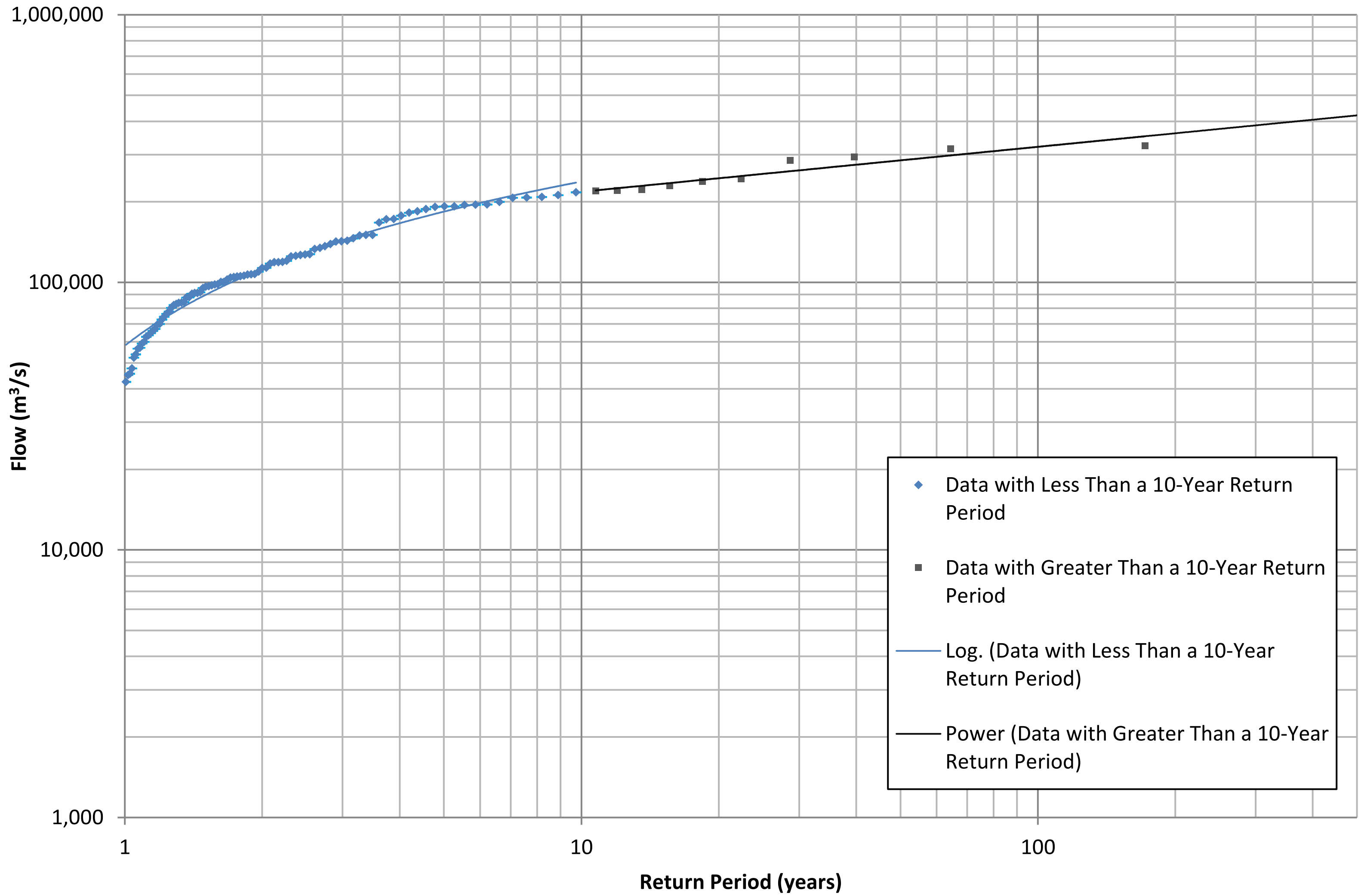


Figure 15 Graph of Elbow River at the Combined Station 56-Day Volumetric Frequency Results using Unbiased Method (1908 – 2012)

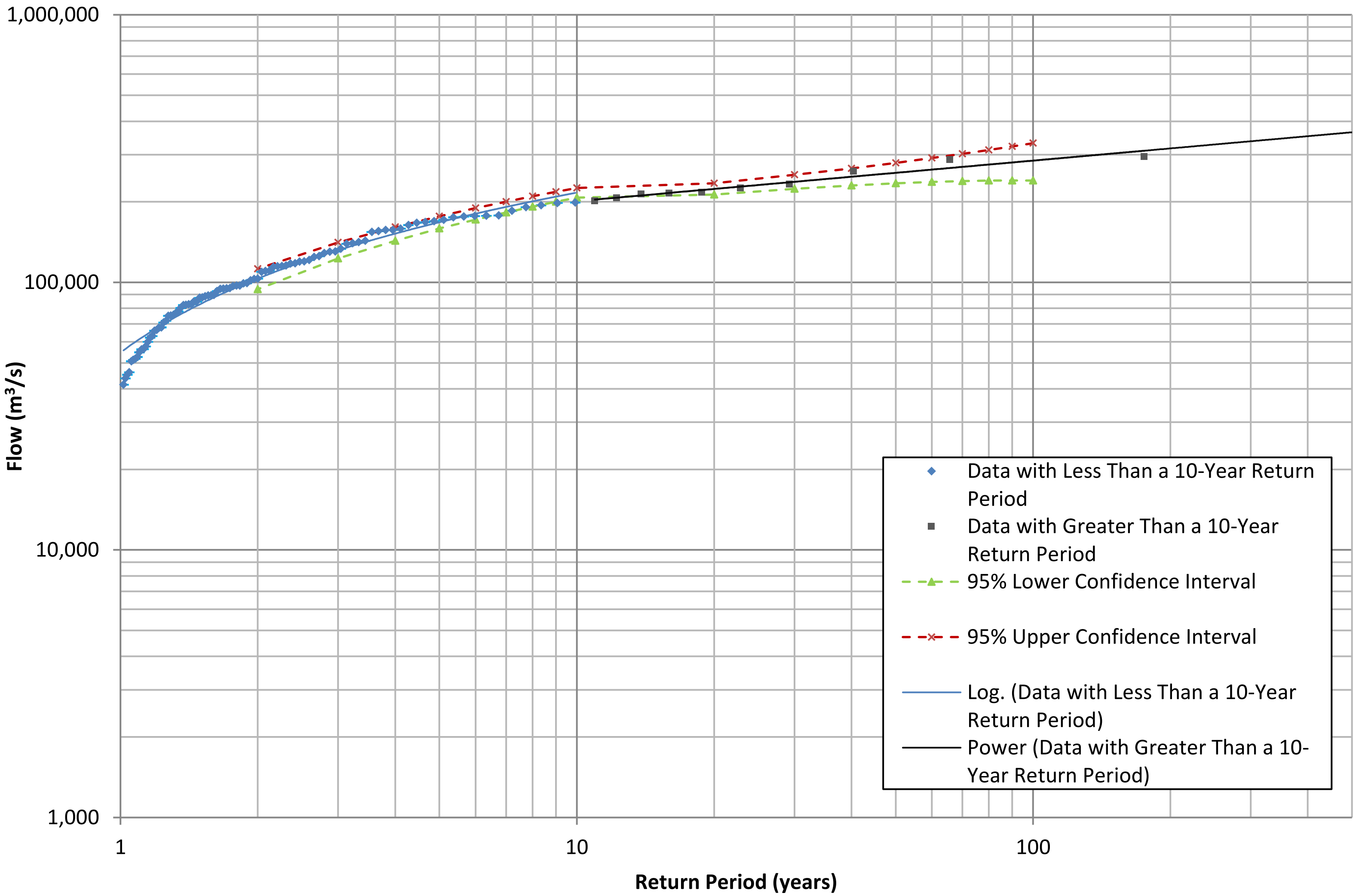


Figure 16 Graph of Elbow River at the Bragg Creek Station 56-Day Volumetric Frequency Results using Unbiased Method (1908 – 2012)

The equations for the best fit lines to the data points in Figure 11 through Figure 16 are provided in Table 10.

Table 10 Equation of the Best Fit Lines for the Combined and Bragg Creek Stations Flood and Volumetric Frequency Results using the Unbiased Method

Location	Instantaneous Peak Flood Frequency				7-Day Volumetric Frequency				56-Day Volumetric Frequency			
	Less than 10-Year Return Period		Equal to or Greater Than 10-Year Return Period		Less than 10-Year Return Period		Equal to or Greater Than 10-Year Return Period		Less than 10-Year Return Period		Equal to or Greater Than 10-Year Return Period	
	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
Combined Station	$Q = 82.55 \ln T + 13.82$	0.98	$Q = 61.37T^{0.57}$	0.99	$V = 21{,}366 \ln T + 10554$	0.99	$V = 29{,}867T^{0.3}$	0.94	$V = 78{,}200 \ln T + 58{,}000$	0.98	$V = 148{,}000T^{0.17}$	0.88
Bragg Creek Station	$Q = 81 \ln T + 11.62$	0.98	$Q = 69.03T^{0.52}$	0.98	$V = 19{,}100 \ln T + 6{,}400$	0.99	$V = 26{,}400T^{0.30}$	0.97	$V = 71{,}900 \ln T + 53{,}300$	0.98	$V = 141{,}100T^{0.15}$	0.94

Where Q = flow (m^3/s), V = volume (dam^3), and T = return period (years)

4.3 SUMMARY OF FLOOD FREQUENCY RESULTS

A summary of Stantec's flood frequency results using the Unbiased Method are presented in Table 11.

Table 11 Summary of Flood Frequency Results by Stantec

Return Period (years)	Instantaneous Peak Discharge (m^3/s)		7-Day Volume (dam^3)		56-Day Volume (dam^3)	
	Combined	Bragg Creek	Combined	Bragg Creek	Combined	Bragg Creek
500	2,035	1,745	192,700	170,000	420,800	358,000
200	1,215	1,085	146,000	129,000	360,700	312,000
100	820	755	119,000	105,000	321,000	282,000
50	560	525	96,000	85,400	285,700	254,000
20	330	330	73,000	64,900	245,000	221,000
10	205	200	59,700	52,700	238,000	199,000
5	145	140	41,300	37,300	184,000	169,000
2	70	70	21,500	19,700	112,000	103,000

Based on Stantec's analysis of available data, the best estimates of the 2013 flood and the corresponding return periods are provided in Table 12.

Table 12 Best Available Estimates of the 2013 Flood for the Elbow River at Combined and Bragg Creek Stations

	Combined Station		Bragg Creek Station	
Drainage Area	1,200 km^2		791 km^2	
Flood Peak	1,240 m^3/s	210-year	1,150 m^3/s	230-year
7-Day Volume	149,600 dam^3	230-year	138,600 dam^3	250-year

4.4 FLOOD FREQUENCY ESTIMATE AT THE SR1 DIVERSION SITE

The drainage area for the SR1 diversion site is 868 km^2, which is 110% of the drainage area at Bragg Creek and 72% of the drainage area at Glenmore Reservoir. Using linear interpolation of values from Table 11 (excluding the entirely observed datasets at Bragg Creek), the estimated flood frequencies for the Elbow River at the SR1 diversion site are provided in Table 13.

Table 13 Estimated Flood Frequencies for the Elbow River at the SR1 Diversion Site

Return Period (years)	Instantaneous Peak Discharge (m^3/s)	7-Day Volume (dam^3)	56-Day Volume (dam^3)
500	1,800	174,000	371,000
200	1,110	132,000	322,000
100	765	107,000	290,000
50	530	86,600	260,000
20	330	65,600	226,000
10	200	53,100	203,000
5	140	38,100	172,000
2	70	20,000	105,000

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APPENDIX A

OBSERVED AND ESTIMATED PEAK FLOW AND VOLUME DATA SET TABLES

Prepared for:
Alberta Transportation

Prepared by:
Stantec Consulting Ltd.

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m^3/s

Combined Station					
Station Number	Year	Maximum Daily Discharge[1,2]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[3]	Date of Peak Instantaneous Discharge
05BJ001	1908	159	2-Jun	*217.5*[4]	*2-Jun*
05BJ001	1909	94	3-Jun	*120.3*[4]	*3-Jun*
05BJ001	1910	18.6	19-Sep	*19.4*[4]	*19-Sep*
05BJ001	1911	89.5	8-Aug	*113.8*[4]	*8-Aug*
05BJ001	1912	122	16-Jun	*161.1*[4]	*16-Jun*
05BJ001	1913	38.8	10-Aug	*44.5*[4]	*10-Aug*
05BJ001	1914	28.9	18-Jun	*32*[4]	*18-Jun*
05BJ001	1915	239	26-Jun	*379.4*	*26-Jun*
05BJ001	1916	146	29-Jun	*196.5*[4]	*29-Jun*
05BJ001	1917	147	3-Jun	*198.8*[4]	*3-Jun*
05BJ001	1918	35.4	10-Jun	*39.9*[4]	*10-Jun*
05BJ001	1919	72.5	6-Aug	*89.8*[4]	*6-Aug*
05BJ001	1920	67.7	13-Jul	*69.9*	*13-Jul*
05BJ001	1921	37.4	25-May	*42.5*[4]	*25-May*
05BJ001	1922	26.5	17-May	*28.9*[4]	*17-May*
05BJ001	1923	331	1-Jun	*402.1*	*1-Jun*
05BJ001	1924	59.5	4-Aug	*71.9*[4]	*4-Aug*
05BJ001	1925	66.5	12-Jun	*71.6*	*12-Jun*
05BJ001	1926	88.1	11-Sep	*111.6*[4]	*11-Sep*
05BJ001	1927	83.3	10-Jun	*84.7*	*10-Jun*
05BJ001	1928	100	19-Jun	*107.9*	*19-Jun*
05BJ001	1929	382	3-Jun	*433.2*	*3-Jun*
05BJ001	1930	30.6	31-May	*32.3*	*31-May*
05BJ001	1931	22.9	8-Apr	*28.3*	*8-Apr*
05BJ001	1932	311	3-Jun	*713.6*	*3-Jun*
05BJ001	1933	30.9	16-Jun	*42.8*	*16-Jun*

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m³/s

Combined Station					
Station Number	Year	Maximum Daily Discharge[1,2]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[3]	Date of Peak Instantaneous Discharge
05BJ005	1934	24.4	10-Jun	*26.4*[4]	*10-Jun*
05BJ005	1935	29.2	18-Jun	*32.3*[4]	*18-Jun*
05BJ005	1936	32.3	2-Jun	*36.2*[4]	*2-Jun*
05BJ005	1937	53.2	14-Jun	*63.4*[4]	*14-Jun*
05BJ005	1938	60.3	3-Jul	*73.1*[4]	*3-Jul*
05BJ005	1939	90.6	17-Jun	*122.3*	*17-Jun*
05BJ005	1940	36.2	6-Sep	*41.1*[4]	*6-Sep*
05BJ005	1941	39.1	2-Jun	*44.7*[4]	*2-Jun*
05BJ005	1942	127	11-May	*226.5*	*11-May*
05BJ005	1943	31.1	4-Apr	*34.8*[4]	*4-Apr*
05BJ005	1944	23.9	13-Jun	*25.7*[4]	*13-Jun*
05BJ005	1945	74.8	1-Jun	*83.5*	*1-Jun*
05BJ005	1946	50.7	7-Jun	*56.6*	*7-Jun*
05BJ005	1947	68.2	11-May	*78.4*	*11-May*
05BJ005	1948	127	23-May	*259.1*	*23-May*
05BJ005	1949	19.7	22-May	*20.7*[4]	*22-May*
05BJ005	1950	35.1	16-Jun	*38.2*	*16-Jun*
05BJ005	1951	137	31-Aug	*170.8*	*31-Aug*
05BJ005	1952	79	23-Jun	*90.9*	*23-Jun*
05BJ005	1953	132	4-Jun	*166.8*	*4-Jun*
05BJ005	1954	48.1	25-Aug	*56.6*[4]	*25-Aug*
05BJ005	1955	45.9	20-May	*53.5*[4]	*20-May*
05BJ005	1956	37.4	4-Jul	*42.5*[4]	*4-Jul*
05BJ005	1957	30.3	9-Jun	*33.7*[4]	*9-Jun*
05BJ005	1958	54.9	14-Jul	*65.7*[4]	*14-Jul*
05BJ005	1959	49.3	27-Jun	*58*[4]	*27-Jun*

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m^3/s

Combined Station					
Station Number	**Year**	**Maximum Daily Discharge[1,2]**	**Date of Maximum Daily Discharge**	**Peak Instantaneous Discharge[3]**	**Date of Peak Instantaneous Discharge**
05BJ005	1960	30	4-Jun	*33.4*[4]	*4-Jun*
05BJ005	1961	51	27-May	*60.3*[4]	*27-May*
05BJ005	1962	27.8	17-Jun	*30.6*[4]	*17-Jun*
05BJ005	1963	124	30-Jun	*178.7*	*30-Jun*
05BJ005	1964	62.9	9-Jun	*76.5*	*9-Jun*
05BJ005	1965	104	18-Jun	*134.5*	*18-Jun*
05BJ005	1966	36.5	3-Jul	*41.6*	*3-Jul*
05BJ005	1967	199	31-May	*279.2*[4]	*31-May*
05BJ005	1968	51.3	8-Jun	*60.9*[4]	*8-Jun*
05BJ005	1969	125	30-Jun	*165.1*[4]	*30-Jun*
05BJ005	1970	97.1	14-Jun	*124.6*[4]	*14-Jun*
05BJ005	1971	85.2	6-Jun	*107.6*[4]	*6-Jun*
05BJ005	1972	41.9	1-Jun	*48.4*[4]	*1-Jun*
05BJ005	1973	45.3	27-May	*53*[4]	*27-May*
05BJ005	1974	62	18-Jun	*75.3*[4]	*18-Jun*
05BJ005	1975	49	21-Jun	*57.8*[4]	*21-Jun*
05BJ005	1976	37.9	6-Aug	*43.3*[4]	*6-Aug*
05BJ005	1977	16.3	15-Aug	*16.7*[4]	*15-Aug*
05BJ005	1978	*41.1*	6-Jun	*47.3*[4]	*6-Jun*
05BJ010	1979	**36**	27-May	41.3	27-May
05BJ010	1980	**52.9**	4-Jun	59.7	4-Jun
05BJ010	1981	**101**	26-May	121	26-May
05BJ010	1982	**32.3**	16-Jun	38.2	15-Jun
05BJ010	1983	**30.4**	25-Apr	42.8	25-Apr
05BJ010	1984	**20.7**	9-Jun	21.9	9-Jun
05BJ010	1985	**63.2**	13-Sep	71.7	13-Sep

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m³/s

Combined Station					
Station Number	Year	Maximum Daily Discharge[1,2]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[3]	Date of Peak Instantaneous Discharge
05BJ010	1986	**49.7**	29-May	54.1	29-May
05BJ010	1987	**27.4**	20-Jul	29.6	19-Jul
05BJ010	1988	**29.4**	8-Jun	35.1	8-Jun
05BJ010	1989	**22.4**	10-Jun	23	10-Jun
05BJ010	1990	128	26-May	158	26-May
05BJ010	1991	45.6	-	*53*[4]	-
05BJ010	1992	110	15-Jun	122	15-Jun
05BJ010	1993	84.8	17-Jun	*105.5*[4]	-
05BJ010	1994	67	7-Jun	*81.2*[4]	-
05BJ010	1995	**213**	17-Jun	*293*[4]	-
05BJ010	1996	44.3	9-Jun	*51.3*[4]	-
05BJ010	1997	59.8	1-Jun	*71.6*[4]	-
05BJ010	1998	102	28-May	*129.4*[4]	-
05BJ010	1999	54.9	15-Jul	63.4	15-Jul
05BJ010	2000	18.3	11-Jun	19	11-Jun
05BJ010	2001	43.3	5-Jun	*50*[4]	-
05BJ010	2002	80.4	17-Jun	89.0	17-Jun
05BJ010	2003	35.2	26-May	60.1	26-Apr
05BJ010	2004	36.4	26-Aug	*41.3*[4]	-
05BJ010	2005	268	18-Jun	338	18-Jun
05BJ010	2006	122	16-Jun	140	16-Jun
05BJ010	2007	68.9	18-Jun	76.1	7-Jun
05BJ010	2008	183	25-May	220	25-May
05BJ010	2009	40.2	14-Jul	43.6	14-Jul
05BJ010	2010	49.1	18-Jun	51.9	18-Jun
05BJ010	2011	180	27-May	215	27-May

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m^3/s

Combined Station					
Station Number	Year	Maximum Daily Discharge[1,2]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[3]	Date of Peak Instantaneous Discharge
05BJ010	2012	110	24-Jun	136	24-Jun
05BJ010	2013	682[5]	21-Jun	1240[6]	21-Jun

[1] **Bolded** maximum daily discharge values were obtained from WSC complete daily hydrographs as WSC did not provide maximum daily discharge values for these years

[2] Underlined maximum daily discharge values were computed using the following relationship derived from observed maximum daily discharge data: $Q_{Combined} = 1.42*Q_{Bragg}^{0.93}$

[3] *Italicized-shaded* annual peak instantaneous discharge, annual maximum daily discharge values and date instantaneous peak dates were taken from '*Alberta Environment 1983. Calgary floodplain study, volume II, Appendix B, Hydrologic Analysis by A. DeBoer*.'

[4] Annual instantaneous peak flows were estimated from annual maximum daily flow based on the following relationship $Q_{instantaneous} = 0.7943*Q_{daily}^{1.1002}$

[5] The 2013 maximum daily discharge was referenced by AMEC (2014) as provided by City of Calgary as a preliminary estimate

[6] The 2013 peak instantaneous discharge is preliminary and was provided by the City of Calgary

Table A.2 Annual Maximum Daily and Peak Instantaneous Flows at Bragg Creek Station (1908-2013), in m³/s

Bragg Creek Station				
Year	Maximum Daily Discharge[1]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[2]	Date of Peak Instantaneous Discharge
1908	158	-	*194*	-
1909	90.1	-	*106*	-
1910	15.8	-	*16.2*	-
1911	85.5	-	*100*	-
1912	119	-	*143*	-
1913	34.9	-	*37.9*	-
1914	25.4	-	*27.0*	-
1915	245	-	*311*	-
1916	145	-	*176*	-
1917	146	-	*177*	-
1918	31.6	-	*34.1*	-
1919	68.2	-	*78.2*	-
1920	63.3	-	*72.3*	-
1921	33.5	-	*36.3*	-
1922	23.1	-	*24.4*	-
1923	348	-	*454*	-
1924	55.2	-	*62.2*	-
1925	62.1	-	*70.8*	-
1926	84.0	-	*98*	-
1927	79.1	-	*92*	-
1928	96.3	-	*114*	-
1929	406	-	*536*	-
1930	27.0	-	*28.8*	-
1931	19.8	-	*20.6*	-
1932	325	-	*422*	-
1933	-	-	-	-
1934	21.2	-	*22.2*	-
1935	23.6	17-Jun	*24.9*	-
1936	27.5	1-Jun	*29.4*	-
1937	64.8	13-Jun	*74.0*	-
1938	77.9	2-Jul	*90*	-

Table A.2 Annual Maximum Daily and Peak Instantaneous Flows at Bragg Creek Station (1908-2013), in m^3/s

Bragg Creek Station				
Year	Maximum Daily Discharge[1]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[2]	Date of Peak Instantaneous Discharge
1939	74.8	22-Jun	*86.4*	-
1940	21.2	25-May	*22.2*	-
1941	44.5	2-Jun	*49.4*	-
1942	155	11-May	*190*	-
1943	44.2	3-Jul	*49.0*	-
1944	22.9	13-Jun	*24.1*	-
1945	107	26-May	*127*	-
1946	42.5	29-May	*47.0*	-
1947	60.6	10-May	*68.9*	-
1948	183	23-May	*227*	-
1949	17.6	22-May	*18.1*	-
1950	44.2	15-Jun	58.0	15-Jun
1951	82.7	30-Aug	110	30-Aug
1952	59.7	23-Jun	71.4	12-Jun
1953	118	13-Jun	181	13-Jun
1954	39.4	25-Aug	43.9	25-Aug
1955	37.1	12-Jun	47.6	19-May
1956	30.9	21-May	35.4	21-May
1957	28.9	8-Jun	30.0	8-Jun
1958	37.9	13-Jul	40.2	13-Jul
1959	39.9	27-Jun	45.9	27-Jun
1960	28.9	3-Jun	29.4	3-Jun
1961	51.0	27-May	57.2	27-May
1962	26.1	16-Jun	28.9	16-Jun
1963	141	30-Jun	268	29-Jun
1964	89.5	8-Jun	97.4	8-Jun
1965	127	18-Jun	184	18-Jun
1966	30.6	5-Jun	32.3	5-Jun
1967	185	31-May	283	31-May
1968	43.9	8-Jun	50.7	10-Jun
1969	139	29-Jun	170	29-Jun

Table A.2 Annual Maximum Daily and Peak Instantaneous Flows at Bragg Creek Station (1908-2013), in m³/s

Bragg Creek Station				
Year	Maximum Daily Discharge[1]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[2]	Date of Peak Instantaneous Discharge
1970	92.0	14-Jun	112	14-Jun
1971	89.2	6-Jun	116	6-Jun
1972	49.8	1-Jun	56.1	1-Jun
1973	43.3	26-May	47.0	7-Jun
1974	66.0	17-Jun	170	29-Jun
1975	49.3	20-Jun	53.5	20-Jun
1976	36.0	6-Aug	42.5	6-Aug
1977	15.8	14-Aug	17.1	13-Aug
1978	44.5	6-Jun	49.8	6-Jun
1979	32.1	27-May	38.4	27-May
1980	51.7	3-Jun	69.3	4-Jun
1981	98.2	26-May	123	26-May
1982	28.9	16-Jun	30.7	14-Jun
1983	26.2	30-May	31.5	25-Apr
1984	19.4	12-Jun	21.1	12-Jun
1985	61.2	13-Sep	79.7	13-Sep
1986	48.9	28-May	57.2	28-May
1987	24.3	19-Jul	26.5	19-Jul
1988	28.9	8-Jun	37.3	8-Jun
1989	20.4	9-Jun	23.1	9-Jun
1990	129	26-May	172	26-May
1991	41.4	21-May	47.2	21-Jun
1992	88.7	15-Jun	119	15-Jun
1993	80.4	16-Jun	93	15-Jun
1994	52.1	7-Jun	72.0	7-Jun
1995	190	7-Jun	377	6-Jun
1996	43.5	8-Jun	48.4	9-Jun
1997	47.8	31-May	54.2	1-Jun
1998	103	28-May	141	28-May
1999	48.3	15-Jul	53.7	15-Jul
2000	14.4	10-Jun	15	10-Jun

Table A.2 Annual Maximum Daily and Peak Instantaneous Flows at Bragg Creek Station (1908-2013), in m^3/s

Bragg Creek Station				
Year	Maximum Daily Discharge[1]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[2]	Date of Peak Instantaneous Discharge
2001	39.4	5-Jun	45.2	4-Jun
2002	70.2	16-Jun	87.3	17-Jun
2003	30.9	25-May	61.5	25-Apr
2004	31.4	26-Aug	31.9	26-Aug
2005	231	7-Jun	308	7-Jun
2006	75.1	16-Jun	97.9	15-Jun
2007	54.0	7-Jun	83.7	6-Jun
2008	125	24-May	204	24-May
2009	39.4	14-Jul	51.2	13-Jul
2010	43.3	18-Jun	48.4	17-Jun
2011	95.5	27-May	112	27-May
2012	83.2	24-Jun	110	6-Jun
2013	756	-	1150[3]	21-Jun

[1] Underlined maximum daily discharge values were computed using the following relationship derived from observed maximum daily discharge data: $Q_{Bragg} = 0.70*Q_{Combined}^{1.075}$

[2] *Italicized-shaded* peak instantaneous discharge values were computed using the following relationship derived from observed discharge data at Bragg Creek Station: $Q_{inst.} = 0.82*Q_{daily}^{1.11}$

[3] The 2013 peak instantaneous discharge is preliminary and was provided by the City of Calgary

Table A.3 Annual Maximum 7-Day and 56-Day Volume at the Combined and Bragg Creek Stations, in dam^3

Year	7-Day Volume at the Combined Station	56-Day Volume at the Combined Station	7-Day Volume at the Bragg Creek Station[1]	56-Day Volume at the Bragg Creek Station[2]
1908	77,250	221,737	71,070	201,781
1909	41,930	194,296	38,576	176,810
1910	10,040	56,945	9,237	51,820
1911	30,283	120,355	27,861	109,523
1912	43,865	192,344	40,356	175,033
1913	17,444	96,396	16,049	87,721
1914	15,777	84,378	14,515	76,784
1915	73,129	285,068	67,279	259,412
1916	67,409	315,567	62,017	287,166
1917	55,477	237,635	51,039	216,247
1918	17,893	77,754	16,462	70,756
1919	22,654	65,856	20,842	59,929
1920	28,547	133,160	26,263	121,175
1921	19,958	98,142	18,362	89,309
1922	13,141	82,985	12,090	75,516
1923	85,925	323,715	79,051	294,581
1924	28,236	125,451	25,977	114,160
1925	29,920	113,054	27,527	102,880
1926	34,741	136,495	31,962	124,210
1927	38,336	172,428	35,269	156,910
1928	44,090	194,797	40,563	177,266
1929	93,407	195,359	85,934	177,777
1930	15,828	90,582	14,562	82,429
1931	9,780	45,543	8,998	41,444
1932	93,563	184,395	86,078	167,799
1933	17,522	104,604	16,120	95,190
1934	13,150	64,554	13,902	51,292
1935	15,284	72,567	11,647	62,954
1936	12,900	47,686	8,111	22,262
1937	25,281	91,825	25,168	84,627
1938	26,205	145,990	36,063	169,171
1939	34,059	118,974	36,685	129,954
1940	13,401	69,886	10,161	50,700

Table A.3 Annual Maximum 7-Day and 56-Day Volume at the Combined and Bragg Creek Stations, in dam^3

Year	7-Day Volume at the Combined Station	56-Day Volume at the Combined Station	7-Day Volume at the Bragg Creek Station[1]	56-Day Volume at the Bragg Creek Station[2]
1941	17,228	53,803	19,440	56,171
1942	42,941	206,963	41,688	225,219
1943	15,042	100,224	24,805	156,851
1944	12,891	62,577	12,053	45,162
1945	34,793	192,067	38,681	215,240
1946	21,997	105,192	19,241	97,133
1947	26,948	142,379	26,594	139,268
1948	49,352	208,423	51,866	198,729
1949	10,670	59,073	8,148	54,754
1950	19,941	96,820	21,574	92,759
1951	52,695	219,862	37,480	206,194
1952	33,013	149,636	27,596	125,159
1953	57,136	243,294	56,022	232,641
1954	23,129	150,440	17,790	119,318
1955	23,976	142,050	18,697	110,367
1956	17,833	105,382	14,532	87,506
1957	15,535	98,289	13,409	82,201
1958	27,864	134,603	19,475	115,551
1959	20,252	105,935	15,803	89,700
1960	14,403	87,937	12,563	74,954
1961	24,296	102,465	24,192	101,628
1962	15,206	83,876	14,265	80,163
1963	36,331	143,104	38,042	130,343
1964	27,328	138,966	28,944	128,632
1965	35,614	181,863	36,478	142,966
1966	19,639	104,043	18,040	94,962
1967	56,670	199,817	62,761	197,994
1968	23,665	107,200	22,360	97,174
1969	56,462	191,454	54,717	163,685
1970	42,664	127,423	36,711	115,085
1971	32,443	117,590	32,702	117,720
1972	21,643	126,999	25,168	133,419
1973	22,559	119,102	22,792	119,794

Table A.3 Annual Maximum 7-Day and 56-Day Volume at the Combined and Bragg Creek Stations, in dam^3

Year	7-Day Volume at the Combined Station	56-Day Volume at the Combined Station	7-Day Volume at the Bragg Creek Station[1]	56-Day Volume at the Bragg Creek Station[2]
1974	32,988	150,198	33,204	139,890
1975	25,955	91,150	22,265	88,594
1976	20,097	69,463	16,831	65,971
1977	7,313	42,451	7,177	43,756
1978	-	-	20,753	99,084
1979	16,183	76,275	14,515	67,891
1980	23,052	106,936	24,270	110,248
1981	49,507	187,739	45,317	171,124
1982	17,470	91,247	16,209	82,679
1983	14,636	82,227	13,850	75,125
1984	11,699	56,526	11,197	56,260
1985	20,468	66,937	19,388	66,322
1986	25,445	107,490	24,572	99,187
1987	14,515	59,918	13,141	57,581
1988	12,200	52,282	11,388	52,608
1989	12,165	63,361	11,647	62,134
1990	50,138	167,201	48,082	154,198
1991	-	-	23,924	141,368
1992	37,532	126,481	32,460	117,435
1993	34,007	171,858	28,771	158,795
1994	21,419	83,680	15,163	67,727
1995	52,177	211,671	54,009	194,063
1996	21,289	118,765	21,004	114,765
1997	27,708	113,262	21,410	94,527
1998	42,422	229,150	36,556	190,901
1999	24,062	97,468	21,324	96,768
2000	8,726	45,064	7,430	46,122
2001	19,863	74,382	18,075	71,835
2002	39,303	177,396	35,821	166,933
2003	17,107	87,716	15,630	77,805
2004	19,094	95,247	16,278	89,484
2005	78,071	293,820	63,193	213,313
2006	38,007	109,564	24,382	84,704

Table A.3 Annual Maximum 7-Day and 56-Day Volume at the Combined and Bragg Creek Stations, in dam³

Year	7-Day Volume at the Combined Station	56-Day Volume at the Combined Station	7-Day Volume at the Bragg Creek Station[1]	56-Day Volume at the Bragg Creek Station[2]
2007	27,207	125,064	22,006	103,239
2008	55,106	219,128	45,403	185,069
2009	16,183	80,309	16,381	82,788
2010	23,596	100,138	22,499	94,643
2011	54,734	216,985	37,610	175,980
2012	51,382	207,420	36,003	155,403
2013	149,609	-	138,552	-

[1] *Italicized*-shaded 7-day volume values were computed using the following relationship derived from observed volume data at Combined and Bragg Creek Stations: $V_{Bragg7\text{-}day} = 0.9 * V_{Combined7\text{-}day} + 382.58$

[2] *Italicized*-shaded 56-day volume values were computed using the following relationship derived from observed volume data at Combined and Bragg Creek Stations: $V_{Bragg56\text{-}day} = 0.86 * V_{Combined56\text{-}day} + 6498.32$

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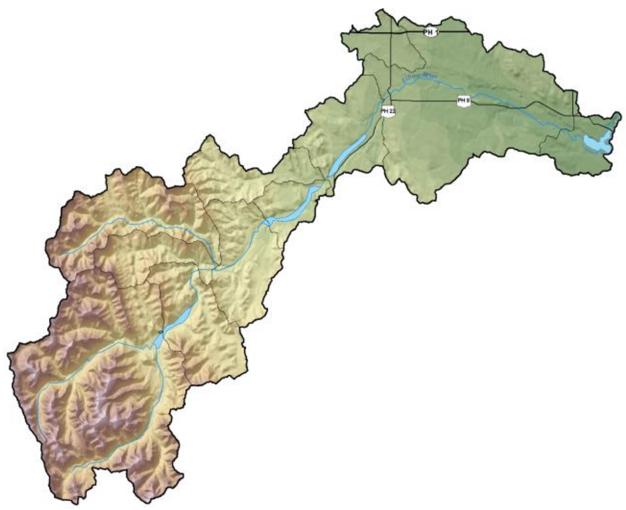
Site-Specific Probable Maximum Precipitation Study for the Elbow River Basin-Springbank Off-Stream Storage Project



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NOTICE

Executive Summary

Applied Weather Associates (AWA) has completed a Site-Specific Probable Maximum Precipitation (PMP) study for the Elbow River Basin-Springbank Off-Stream Storage Project (Springbank) located near Calgary, Alberta. The purpose of the study was to determine Probable Maximum Precipitation (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 numerous PMP studies that AWA has completed since 1996, including several in similar meteorological and topographical settings. Recommendations provided in "Guidelines of Extreme Flood Analysis (Alberta Transportation, 2004) were addressed. AWA employed a storm-based approach similar to the methods and processes employed by the National Weather Service (NWS) and recommended by the Canadian Dam Association to the extent that the data and current understanding of meteorological processes supports those previous methods. The World Meteorological Organization (WMO) manual for PMP determination recommends this storm-based approach when sufficient data are available. This approach identified extreme rainfall events that have occurred over a wide region from the Continental Divide of the Rockies eastward to the High Plains, from northern Alberta through the northern United States. Storms in these regions have meteorological and topographical characteristics similar to extreme rainfall storms that could occur over the basin. The largest of these rainfall events were selected for detailed analyses and PMP development.

Twenty-one storm events were identified as having similar characteristics to PMP-type events that could potentially occur over the basin and could potentially influence the PMP values. Storms were categorized as either general storms (greater than 6-hours and greater than 500-square kilometers) or local storms (6-hours or less and less than 500-square kilometers). PMP values were derived separately according to each storm type. Each storm was 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 22 unique DAD zones were used in the final PMP development for this study.

The general concepts employed to derive the PMP values included rainfall maximization, storm transposition, and topographic adjustments. These PMP development processes were consistent with those used in the numerous PMP studies completed by AWA in regions that were similar to this basin. 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 for PMP. Updated analysis methodologies were utilized in this study. The first analysis method used was the Orographic Transposition Factor (OTF), which objectively quantifies the effects of terrain on rainfall enhancement and depletion. This process replaces the NWS Storm Separation Method as employed in HMR 55A. Use of the OTF allows the unique and highly variable topography at both the in-place storm location and the Springbank basin to be properly represented in the development of PMP values and subsequent Probable Maximum Flood (PMF) modeling. The second analysis method used was the HYSPLIT trajectory model, which evaluates the location of moisture source regions over the Pacific Ocean. These regions were identified using a National Oceanic and Atmospheric Administration (NOAA) model reanalysis

interface. Updated climatological maximum dew point data were developed for the regions of Canada that were analyzed for in-place storm maximization and used in this study.

Storm maximization factors were computed for each storm using an updated dew point climatology, HYSPLIT, and an updated evaluation of the storm representative dew point for each storm event. Each historic extreme rainfall event used for PMP development was maximized, transpositioned, and orographically adjusted to a series of grid cells covering the entire basin. The procedure used methods consistent with HMR 55A and previous AWA PMP studies modified to work on a gridded basis. The governing equation used for computation of the Total Adjusted Rainfall (TAR) is shown in Equation ES.1. The SSPMP becomes the maximum TAR for all analyzed storms at each grid cell at each duration.

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

where:

TAR_{xhr} is the Total Adjusted Rainfall value at the x-hour duration for the specific grid cell at each duration at the target location;

P_{xhr} is the x-hour precipitation observed at the historic in-place storm location (source location) at the basin-area size;

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

Moisture Transposition Factor (MTF) is the adjustment factor accounting for the difference in available moisture between the location where the storm occurred and each grid cell in the basin;

Orographic Transposition Factor (OTF) is the adjustment factor accounting for differences between orographic effects at the historic in-place storm location and the Springbank basin.

A total of 318 grid cells, at a resolution of .025° decimal degrees x .025° decimal degrees (4.92-square kilometers), were analyzed over the basin. The resulting values were analyzed over a total of 48-hours and provided by sub-basin averages for the 11 sub-basins above Glenmore Dam for use in PMF modeling. Use of the 48-hour maximum duration was chosen based on the rainfall accumulation period of the storms used for PMP development, prior use as a standard duration in previous PMP studies in the region, and discussions with the review board regarding requirements for proper Probable Maximum Flood modeling. These data were distributed spatially using both the precipitation climatology developed for this study and historic rainfall events, which occurred over the basin. The temporal distribution of the hourly PMP were accumulated following standard PMP patterns, with general middle and back loaded accumulation patterns. These procedures are preferred because they capture the spatial and temporal variability of PMP rainfall as it would occur over the complex terrain of the basin. Values were derived for the all-season period, extending from the middle of May through the beginning of September.

Table of Contents

List of Figures

List of Tables

List of Appendices

Glossary

Adiabat: Curve of thermodynamic change taking place without addition or subtraction of heat. On an adiabatic chart or pseudo-adiabatic diagram, a line showing pressure and temperature changes undergone by air rising or condensation of its water vapor; a line, thus, of constant potential temperature.

Adiabatic: Referring to the process described by adiabat.

Advection: The process of transfer (of an air mass property) by virtue of motion. In particular cases, advection may be confined to either the horizontal or vertical components of the motion. However, the term is often used to signify horizontal transfer only.

Air mass: Extensive body of air approximating horizontal homogeneity, identified as to source region and subsequent modifications.

Barrier: A mountain range that partially blocks the flow of warm humid air from a source of moisture to the basin under study.

Basin shape: The physical outline of the basin as determined from topographic maps, field survey, or GIS.

Convective rain: Rainfall caused by the vertical motion of an ascending mass of air that is warmer than the environment and typically forms a cumulonimbus cloud. The horizontal dimension of such a mass of air is generally of the order of 12 miles or less. Convective rain is typically of greater intensity than either of the other two main classes of rainfall (cyclonic and orographic) and is often accompanied by thunder. The term is more particularly used for those cases in which the precipitation covers a large area as a result of the agglomeration of cumulonimbus masses.

Convergence: Horizontal shrinking and vertical stretching of a volume of air, accompanied by net inflow horizontally and internal upward motion.

Cooperative station: A weather observation site where an unpaid observer maintains a climatological station for the National Weather Service.

Cyclone: A distribution of atmospheric pressure in which there is a low central pressure relative to the surroundings. On large-scale weather charts, cyclones are characterized by a system of closed constant pressure lines (isobars), generally approximately circular or oval in form, enclosing a central low-pressure area. Cyclonic circulation is counterclockwise in the northern hemisphere and clockwise in the southern. (That is, the sense of rotation about the local vertical is the same as that of the earth's rotation).

Depth-Area curve: Curve showing, for a given duration, the relation of maximum average depth to size of area within a storm or storms.

Depth-Area-Duration: The precipitation values derived from Depth-Area and Depth-Duration curves at each time and area size increment analyzed for a PMP evaluation.

Depth-Area-Duration Curve: A curve showing the relation between an averaged areal rainfall depth and the area over which it occurs, for a specified time interval, during a specific rainfall event.

Depth-Area-Duration values: The combination of depth-area and duration-depth relations. Also called depth-duration-area.

Depth-Duration curve: Curve showing, for a given area size, the relation of maximum average depth of precipitation to duration periods within a storm or storms.

Dew point: The temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content for saturation to occur.

Envelopment: A process for selecting the largest value from any set of data. In estimating PMP, the maximum and transposed rainfall data are plotted on graph paper, and a smooth curve is drawn through the largest values.

Explicit transposition: The movement of the rainfall amounts associated with a storm within boundaries of a region throughout which a storm may be transposed with only relatively minor modifications of the observed storm rainfall amounts. The area within the transposition limits has similar, but not identical, climatic and topographic characteristics throughout.

Front: The interface or transition zone between two air masses of different parameters. The parameters describing the air masses are temperature and dew point.

General storm: A storm event that produces precipitation over areas in excess of 500-square miles, has a duration longer than 6 hours, and is associated with a major synoptic weather feature.

Hydrologic Unit: A hydrologic unit is a drainage area delineated to nest in a multi-level, hierarchical drainage system. Its boundaries are defined by hydrographic and topographic criteria that delineate an area of land upstream from a specific point on a river, stream or similar surface waters. A hydrologic unit can accept surface water directly from upstream drainage areas, and indirectly from associated surface areas such as remnant, non-contributing, and diversions to form a drainage area with single or multiple outlet points. Hydrologic units are only synonymous with classic watersheds when their boundaries include all the source area contributing surface water to a single defined outlet point.

HYSPLIT: Hybrid Single-Particle Lagrangian Integrated Trajectory. A complete system for computing parcel trajectories to complex dispersion and deposition simulations using either puff or particle approaches. Gridded meteorological data, on one of three conformal (Polar, Lambert, or Mercator latitude-longitude grid) map projections, are required at regular time intervals.

Calculations may be performed sequentially or concurrently on multiple meteorological grids, usually specified from fine to coarse resolution.

Isohyets: Lines of equal value of precipitation for a given time interval.

Isohyetal pattern: The pattern formed by the isohyets of an individual storm.

Jet Stream: A strong, narrow current concentrated along a quasi-horizontal axis (with respect to the earth's surface) in the upper troposphere or in the lower stratosphere, characterized by strong vertical and lateral wind shears. Along this axis it features at least one velocity maximum (jet streak). Typical jet streams are thousands of kilometers long, hundreds of kilometers wide, and several kilometers deep. Vertical wind shears are on the order of 10 to 20 mph per kilometer of altitude and lateral winds shears are on the order of 10 mph per 100 kilometer of horizontal distance.

Local storm: A storm event that occurs over a small area in a short time period. Precipitation rarely exceeds 6 hours in duration and the area covered by precipitation is less than 500 square miles. Frequently, local storms will last only 1 or 2 hours and precipitation will occur over areas of up to 200 square miles. Precipitation from local storms will be isolated from general-storm rainfall. Often these storms are thunderstorms.

Low Level Jet stream: A band of strong winds at an atmospheric level well below the high troposphere as contrasted with the jet streams of the upper troposphere.

Mass curve: Curve of cumulative values of precipitation through time.

Mesoscale Convective Complex (MCC): For the purposes of this study, a heavy rain-producing storm with horizontal scales of 10 to 1000 kilometers (6 to 625 miles) which includes significant, heavy convective precipitation over short periods of time (hours) during some part of its lifetime.

Mesoscale Convective System (MCS): A complex of thunderstorms which becomes organized on a scale larger than the individual thunderstorms, and normally persists for several hours or more. MCSs may be round or linear in shape, and include systems such as tropical cyclones, squall lines, and MCCs (among others). MCS often is used to describe a cluster of thunderstorms that does not satisfy the size, shape, or duration criteria of an MCC.

Mid-latitude frontal system: An assemblage of fronts as they appear on a synoptic chart north of the tropics and south of the polar latitudes. This term is used for a continuous front and its characteristics along its entire extent, its variations of intensity, and any frontal cyclones along it.

Moisture maximization: The process of adjusting observed precipitation amounts upward based upon the hypothesis of increased moisture inflow to the storm.

Observational day: The 24-hour time period between daily observation times for two consecutive days at cooperative stations, e.g., 6:00PM to 6:00PM.

One-hundred year rainfall event: The point rainfall amount that has a one-percent probability of occurrence in any year. Also referred to as the rainfall amount that has a 1 percent chance of occurring in any single year.

Orographic Transposition Factor (OTF): A factor representing the comparison of precipitation frequency relationships between two locations which is used to quantify how rainfall is affected by topography. It is assumed the precipitation frequency data are a combination of what rainfall would have accumulated with any topographic affect and what accumulated because of the topography at the location and upwind of the location.

Polar front: A semi-permanent, semi-continuous front that separates tropical air masses from polar air masses.

Precipitable water: The total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels in the atmosphere; commonly expressed in terms of the height to which the liquid water would stand if the vapor were completely condensed and collected in a vessel of the same unit cross-section. The total precipitable water in the atmosphere at a location is that contained in a column or unit cross-section extending from the earth's surface all the way to the "top" of the atmosphere. The 30,000 foot level (approximately 300mb) is considered the top of the atmosphere in this study.

Persisting dew point: The dew point value at a station that has been equaled or exceeded throughout a period. Commonly durations of 12 or 24 hours are used, though other durations may be used at times.

Probable Maximum Flood: The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area.

Probable Maximum Precipitation: Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a certain time of the year.

Pseudo-adiabat: Line on thermodynamic diagram showing the pressure and temperature changes undergone by saturated air rising in the atmosphere, without ice-crystal formation and without exchange of heat with its environment, other than that involved in removal of any liquid water formed by condensation.

Rainshadow: The region, on the lee side of a mountain or mountain range, where the precipitation is noticeably less than on the windward side.

Saturation: Upper limit of water-vapor content in a given space; solely a function of temperature.

Spatial distribution: The geographic distribution of precipitation over a drainage according to an idealized storm pattern of the PMP for the storm area.

Storm transposition: The hypothetical transfer, or relocation of storms, from the location where they occurred to other areas where they could occur. The transfer and the mathematical adjustment of storm rainfall amounts from the storm site to another location is termed "explicit transposition." The areal, durational, and regional smoothing done to obtain comprehensive individual drainage estimates and generalized PMP studies is termed "implicit transposition" (WMO, 1986).

Synoptic: Showing the distribution of meteorological elements over an area, typically with a horizontal scale of the order of 1000's of km, at a given time, e.g., a synoptic chart. Use in this report also means a weather system that is large enough to be a major feature on large-scale maps (e.g., of the continental U.S.).

Temporal distribution: The time order in which incremental PMP amounts are arranged within a PMP storm.

Total storm area and total storm duration: The largest area size and longest duration for which depth-area-duration data are available in the records of a major storm rainfall.

Transposition limits: The outer boundaries of the region surrounding an actual storm location that has similar, but not identical, climatic and topographic characteristics throughout. The storm can be transpositioned within the transposition limits with only relatively minor modifications to the observed storm rainfall amounts.

Acronyms and Abbreviations used in the report

AMS: Annual maximum series

AWA: Applied Weather Associates

DAD: Depth-Area-Duration

dd: decimal degrees

EPRI: *Electric Power Research Institute*

F: *Fahrenheit*

GCS: Geographical coordinate system

GEV: Generalized extreme value

GIS: Geographic Information System

GRASS: Geographic Resource Analysis Support System

HMR: Hydrometeorological Report

HUC: Hydrologic Unit Code

HYSPLIT: Hybrid Single Particle Lagrangian Integrated Trajectory Model

IPMF: In-place Maximization Factor

mb: millibar

MCS: Mesoscale Convective System

MTF: Moisture Transposition Factor

NCAR: National Center for Atmospheric Research

NCDC: National Climatic Data Center

NCEP: National Centers for Environmental Prediction

NEXRAD: Next Generation Radar

NOAA: National Oceanic and Atmospheric Administration

NWS: National Weather Service

NRCS: Natural Resources Conservation Service

OTF: Orographic Transposition Factor

PMF: Probable Maximum Flood

PMP: Probable Maximum Precipitation

POR: Period of Record

PRISM: Parameter-elevation Relationships on Independent Slopes

PW: Precipitable Water

SPAS: Storm Precipitation and Analysis System

TAF: Total Adjustment Factor

USACE: US Army Corps of Engineers

USBR: Bureau of Reclamation

USGS: United States Geological Survey

WBD: Watershed Boundary Database

WMO: World Meteorological Organization

1 Introduction

This study determines the site-specific Probable Maximum Precipitation (PMP) values for use in the computation of the Probable Maximum Flood (PMF) for the Elbow River Basin-Springbank Off-Stream Storage Project (Springbank). The basin drains the southern Rocky Mountain region of Alberta and travels east/southeast ending just west of Calgary at Glenmore Dam. The region extends from the High Plains of western Alberta through the rugged topography of the Rocky Mountains. The terrain plays a key role in the magnitude of rainfall accumulations and their associated spatial distributions. These factors were explicitly accounted for during the PMP development process.

1.1 Background

Definitions of PMP are found in most of the Hydrometeorological Reports (HMRs) issued by the National Weather Service (NWS) and in the World Meteorological Organization Manual for PMP (WMO, 2009). 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, Corrigan, et al., 1999). The Canadian Dam Association (CDA, 2007) defines PMP in a similar manner; "the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends. The PMP is an estimate of an upper physical bound to the precipitation that the atmosphere can produce."

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 or safety evaluation of significant hydraulic structures. Concurrently, government and private consultants have been deriving PMP values for various parts of Canada. There have been several PMP studies conducted in the region of western Alberta which are relevant to this study (e.g. Verschuren and Wojtiw, 1980; Alberta Environment, 1985; Alberta Environment, 1988; Alberta Environment, 1989; Northwest Hydraulic Consultants, 1990; Hopkinson, 1999). In addition, generalized PMP studies in the contiguous 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.

A number of site-specific and regional PMP studies have been completed by Applied Weather Associates across North America since the early 1990's (e.g. Tomlinson 1993; Tomlinson et al., 2003-2013, and Kappel et al., 2012-2015) (Figure 1.1). These studies replace the generalized PMP reports for specific basins and regions included in the large areas addressed by the various HMRs (Tomlinson and Kappel, 2009).

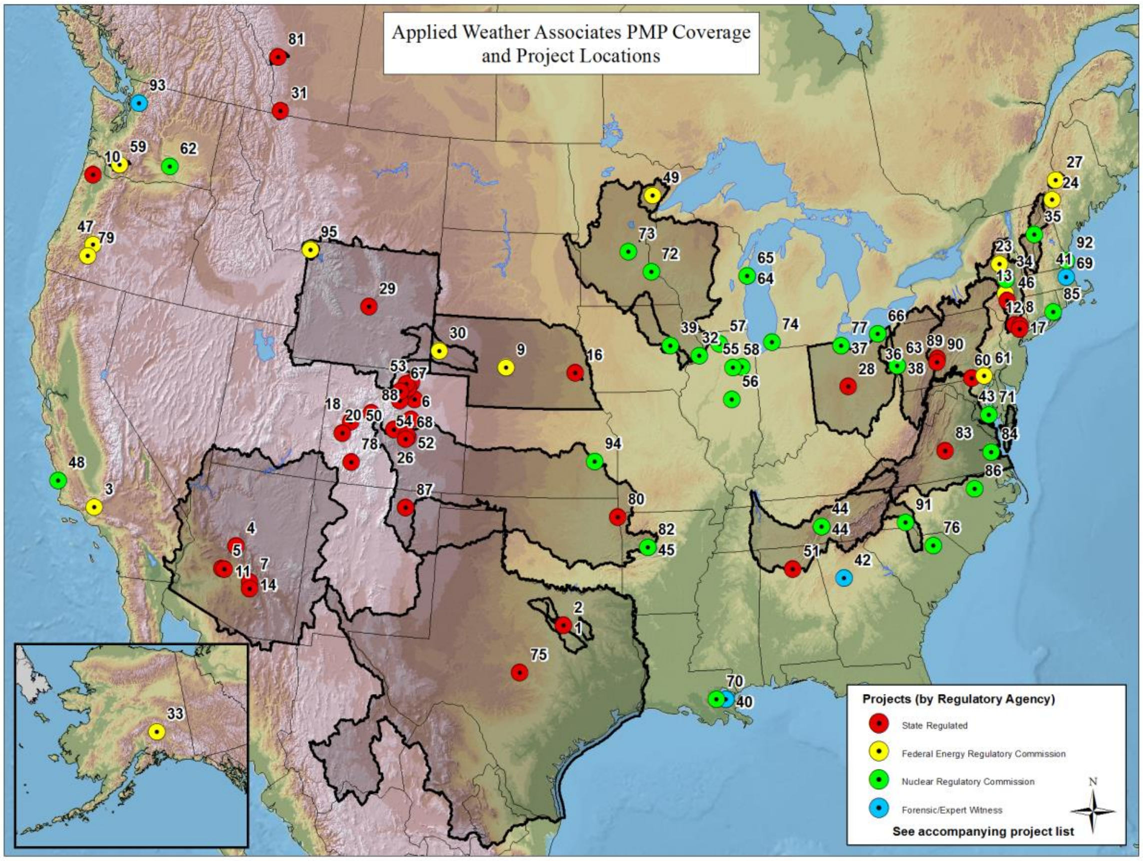

Figure 1.1 Locations of AWA PMP studies as of July 2015

The Springbank basin is located just north of the region covered by HMR 55A. Although it provides generalized estimates of PMP values for a large, climatologically and topographically diverse area, HMR 55A recognizes that studies addressing PMP over specific regions can incorporate more site-specific considerations and provide improved PMP estimates. Additionally, by periodically updating storm data and incorporating advances in meteorological concepts, PMP estimates are improved significantly.

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 (see Figure 1.1). These 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 the same procedures used in those studies to determine PMP values for the Springbank basin. This includes the use of the Orographic Transposition Factor (OTF) procedure to quantify the effect of terrain on the PMP values and investigations of various spatial presentation of the PMP rainfall that reflect the effect of the topography. These procedures, together with Storm Precipitation Analysis System (SPAS) rainfall analyses are used to compute PMP values using a .025°dd x .025°dd grid for both in-place storm rainfall analyses and PMP determination for the basin. The grid based approach provides improvements in the spatial and temporal evaluation of the historic storm rainfall patterns and how the PMP storm would occur over the highly variable topography unique to the basin.

1.2 Approach

The approach used in this study is consistent with many of the procedures that were used in the development of the HMRs and as described in the WMO documents, with updated procedures implemented where appropriate. These procedures were applied considering the site-specific characteristics of the 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, atmospheric moisture depletion and orographic transposition are presented in Sections 7, 8, and 9. The final procedure used to derive the site-specific PMP values from the adjusted rainfall amounts is provided in Section 10. Results are presented in Section 12. Discussions on sensitivities are provided in Section 13 and the recommendations for application are in Section 14.

Procedures used in this study maintained as much consistency as possible with the general methods used in HMRs, WMO Manual for PMP, the Alberta Transportation "Guidelines on Extreme Flood Analysis" (2004), and the previous PMP studies completed by AWA. Updates 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 basin that are of the PMP storm type (see Section 2). This includes the region from the crest of the Rocky Mountains east to the High Plains of Canada and the northern United States above 610 meters in elevation. The northern and southern limits extended from 60°N to 43°N (see Section 6). 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. The storms are then transpositioned to the Springbank basin and each grid cell to the extent supportable by similarity of topographic and meteorological conditions. Finally, the largest rainfall amounts of these maximized and transpositioned storms provide the basis for deriving the SSPMP values. Figure 1.2 shows the flow chart of the major steps used in a generalized 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 1.1 and Figure 1.3.

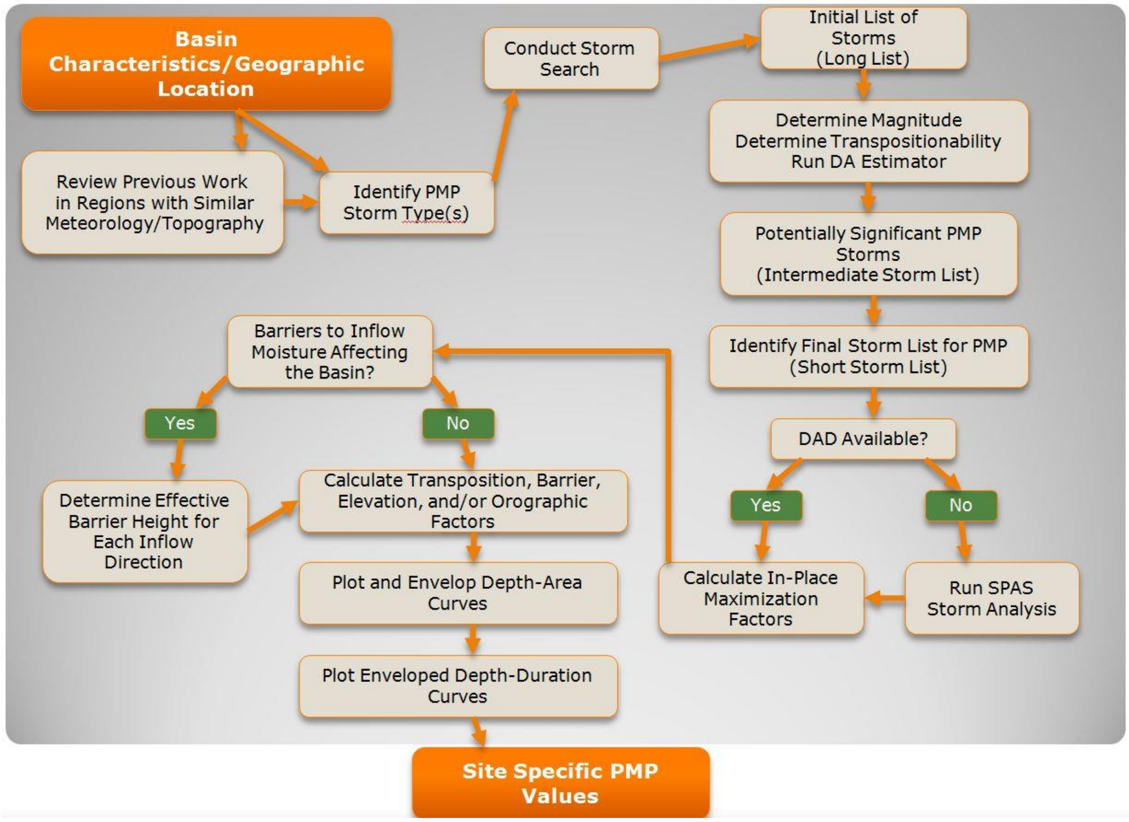

Figure 1.2 Flow chart showing the major steps involved in site-specific PMP development

For some of the processes used to derive PMP, this study applied standard methods (e.g. WMO 1986, 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 each of the storms on the short storm list on a gridded basis at the .025° decimal degrees (dd) x .025°dd resolution in a Geographic Information System (GIS) environment. This allowed for in-place maximization, horizontal moisture transpositioning, and orographic transposition to be completed using gridded data. The largest of the total adjusted values at the basin area size for each duration at each grid cell was distributed spatially and temporally over the basin. This 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 basin. This process replaces the use of the NWS Storm Separation Method (SSM). The OTF is discussed in Sections 9 and 10. Figure 1.3 shows a flow chart of the processes that were used during this study to derive the PMP values. Note that most of the processes displayed in Figure 1.2 are included: however the flow chart in Figure 1.3 includes the processes that are unique to this study.

The governing equation used for computation of the Total Adjusted Rainfall (TAR), for each storm for each grid cell for each duration for the Springbank basin, is given in Equation 1.1. Note, the largest of these values becomes PMP at each grid point, which are then combined as a basin average and redistributed spatially and temporally based on climatological and historic storm patterns:

$$TAR_{xhr} = P_{xhr} * IPMF * MTF * OTF \qquad \text{(Equation 1.1)}$$

where:

TAR_{xhr} is the Total Adjusted Rainfall value at the x-hour (xhr) duration for the specific grid cell at each duration at the target location;

P_{xhr} is the x-hour precipitation observed at the historic in-place storm location (source location) for the basin-area size;

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

Moisture Transposition Factor (MTF) is the adjustment factor accounting for the difference in available moisture between the location where the storm occurred and each grid cell in the basin;

Orographic Transposition Factor (OTF) is the adjustment factor accounting for differences between orographic effects at the historic in-place storm location and the Springbank basin.

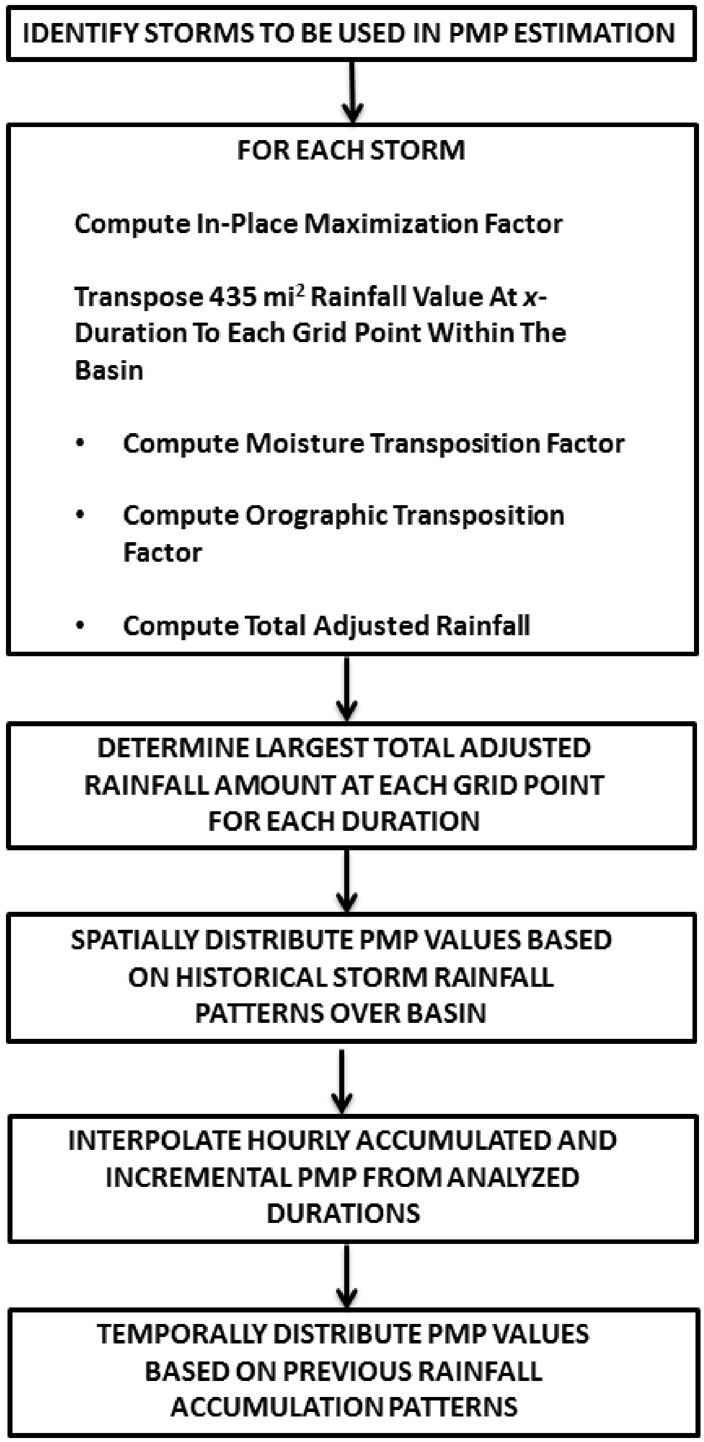

Figure 1.3 Major Components in Computation of Site-Specific PMP for Springbank basin

Advanced computer-based technologies, Weather Service Radar WSR-88D NEXt generation RADar (NEXRAD), and HYSPLIT model trajectories were used for storm analyses along with new meteorological data sources, such as updated storm analyses for storms that have occurred since the publication of HMRs and Environment Canada storm reports (Atmospheric Environment Service, 1985). 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.

For some applications such as storm maximization, storm transpositioning, defining PMP by storm type, and combining storms to create a PMP design storm, this study applied standard methods presented in previous publications (e.g. WMO Operational Hydrology Reports 1986, 2009), while for other applications, new procedures were developed. Moisture analyses have historically used monthly maximum 12-hour persisting dew point values (3-hour persisting dew points were also used in HMR 57). For this project, an updated maximum average dew point climatology was developed and merged with the same dew point climatologies developed by AWA across the contiguous United States. This updated dew point climatology provided 100-year recurrence interval values for 6-, 12-, and 24-hour duration periods. These recurrence intervals better represent available atmospheric moisture used to maximize individual storms versus the persisting dew point process employed in the HMRs and previous Canadian PMP studies. The maximum dew point climatologies used the most up-to-date periods of record, adding over 40 years of data to the datasets used in previous climatologies.

The ESRI ArcGIS for Desktop software environment was used extensively in the study for spatial analysis, mapping, and the organization and manipulation of geospatial data. The Storm Precipitation Analysis System (SPAS) provided gridded storm rainfall analyses. SPAS results produced both spatial and temporal analyses for recent storm events as well as being used to re-analyze old storm events.

1.3 Basin Description

The Springbank basin is located in western Alberta. The centroid of the basin is 50.89°N with a longitude of 114.69°W. The area of the drainage basin to Glenmore Dam, the most downstream point of interest in this study, is approximately 1,212 square kilometers. The average elevation within the basin is 1,676 meters and varies from 1,066 meters at Glenmore Reservoir to 3,023 meters at Mount Evan-Thomas. Figure 1.4 shows the basin location and surrounding topography.

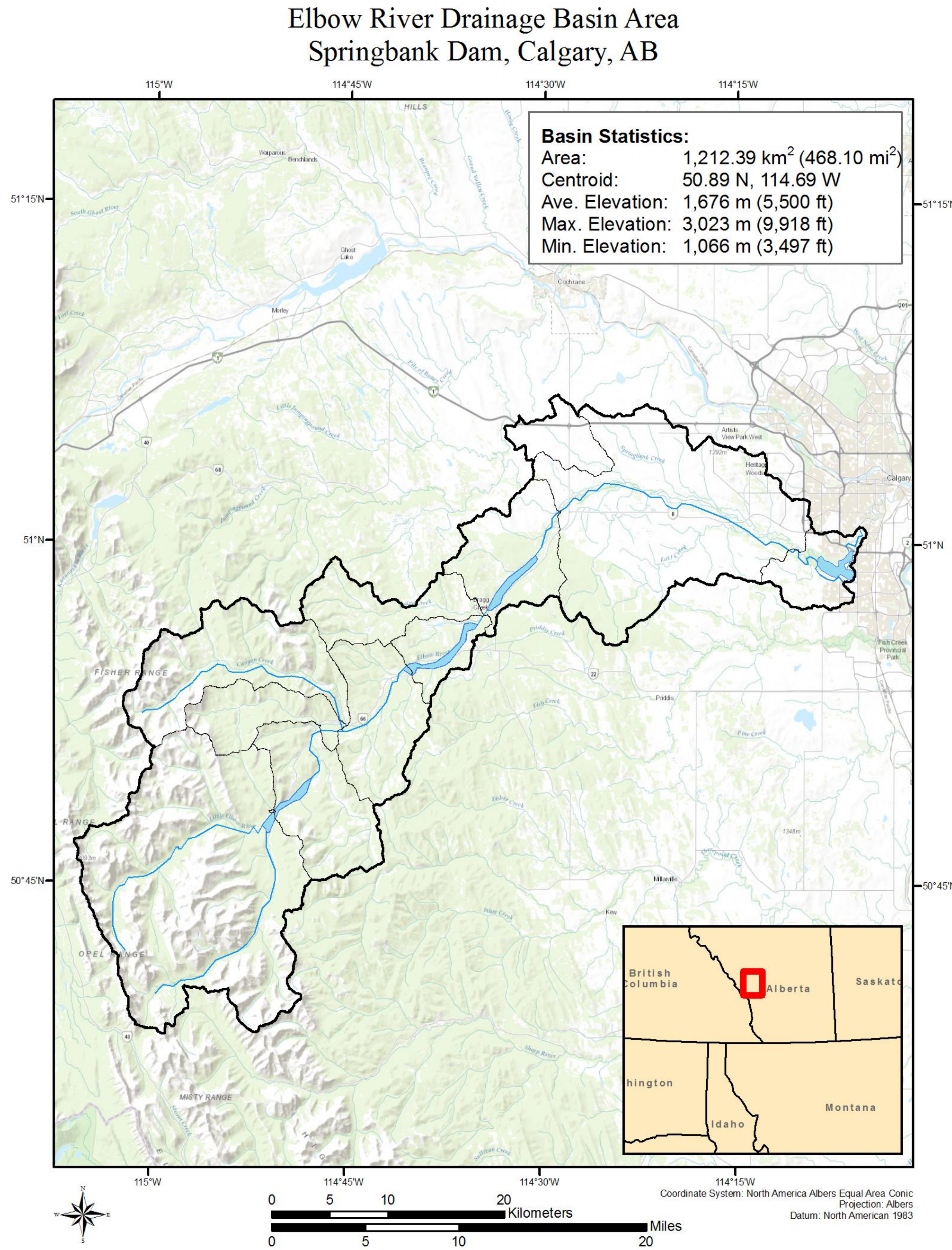

Figure 1.4 Elbow River basin location and regional setting

2 Weather and Climate of the Region

This section describes the general weather patterns and climate of the basin and immediate vicinity and how they relate to the development of PMP for this project. More detailed descriptions of the climate of Alberta and each of the storm types can be found in the following references (e.g. Context of Extreme Floods-Alberta Ministry of Transportation, Large Alberta Storms, available from the Alberta Ministry of Transportation, http://www.transportation.alberta.ca/1831.htm). These references provide additional information and a more detailed analysis.

2.1 Seasonal Patterns

The Elbow River basin is affected by weather systems which enter the region from various source regions, with moisture sources including the Pacific Ocean, the Gulf of Mexico, and local recycled moisture. Mid-latitude storms/synoptic scale systems (called General Storms) which produce rainfall and flooding are most common from late spring/through late summer. This storm type produces general rainfalls which generally last from 24-48 hours and cover area sizes greater than 500-square kilometers. For general storms which produce heavy rainfall and flooding over the basin, the predominant low-level moisture source is the Gulf of Mexico. Occasionally, mid latitude storms affect the mountainous regions with moisture in the middle and upper levels of the atmosphere supplied by the Pacific Ocean. General storms which affect areas are usually associated with areas of low pressure that develop/strengthen along the lee slopes of the Rocky Mountains. Winds turn easterly into the terrain, advecting moisture from the Gulf of Mexico and Great Plains of the United States into the region. The storm dynamics associated with the area of low pressure combine with the orographic effects of the terrain as the moisture is forced upslope to produce widespread rainfall. If these storms are slow moving, with favorable atmospheric instability and large amounts of atmospheric moisture, widespread rain-generated flooding can be produced.

Local storms over the basin are most common from late spring through early fall. Because this storm type relies on extreme instability throughout the atmospheric column (enhanced by warm air near the surface below relatively cooler air above) and the need for sustained warm, moist air inflow, this storm type will not occur with a snowpack on the ground. These storms are most effective at producing heavy rainfall when enhanced by low-level moisture and low-level jets transporting moisture from the Gulf of Mexico. This moisture then interacts with the elevated terrain, which produces extra lift. In addition, the high terrain associated with the Rocky Mountains provides an environment where the surface is heated and the air allowed to rise following the dry adiabatic line. This air parcel continues to rise until reaching the level of free convection. This process occurs more effectively than surrounding lower elevations because of the elevated heat source that the higher terrain provides. This often leads to the initial development of thunderstorms prior to development over the eastern plains. These storms then generally move from west to east along with the natural atmospheric flow. In situations where large amounts of low-level moisture are available, these storms can produce heavy rainfall. When instability and moisture conditions are ideal, these areas of convection can form into Mesoscale Convective Systems (MCSs), moving generally northwest to southeast over the plains of Alberta and Saskatchewan.

2.2 Seasonality of Extreme Storm Events

The seasonality of the local and/or MCS storm types clearly shown in Figure 2.1 occur from late spring through late summer. As described previously, these storms occur when the combination of atmospheric moisture and atmospheric instability are at their greatest. There is less convective storm activity at other times of the year due to stabilizing effects of snow on the ground, decreased solar heating and less moisture in the low levels of the atmosphere to contribute to convective instability.

The seasonality of the general storm type also reflects the strength of the meteorological parameters required for this storm type to produce rainfall (Figure 2.2). These parameters include an active synoptic storm pattern that brings areas of low pressure and associated frontal systems through the region, and temperatures warm enough to produce rainfall at the surface. The high number of heavy rainfall events in June is a result of the ideal combination of moisture, warmer temperatures, and strong storm dynamics that occur frequently during that time of the year. In addition, the jet stream is generally displaced to the north providing extra lift, while high pressure to the east/northeast helps to slow the eastward progression. In addition, this is further supported by the flood record in the region, which reflects June as the month for large flood events on the Elbow River basin (Sabol, 2015). General storms are also common but less frequent during the fall, winter and early spring months, but produce snowfall instead of rain. Therefore they are not included in PMP development.

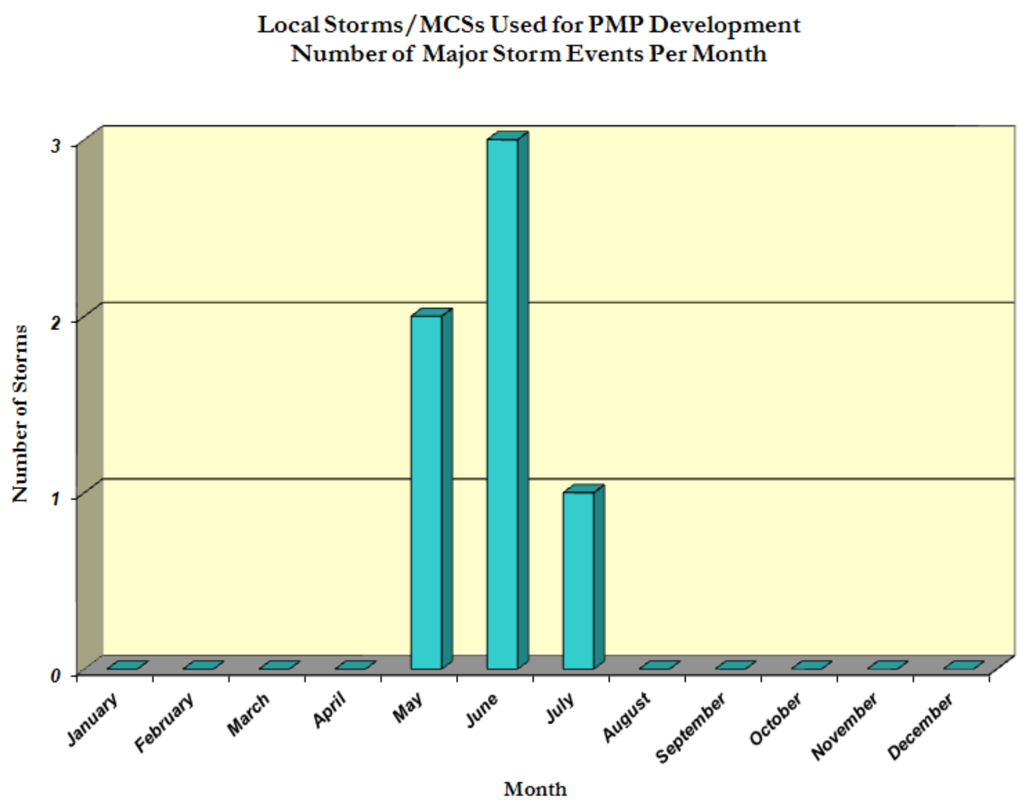

Figure 2.1 Local/MCS storm seasonality of storms used for the PMP study

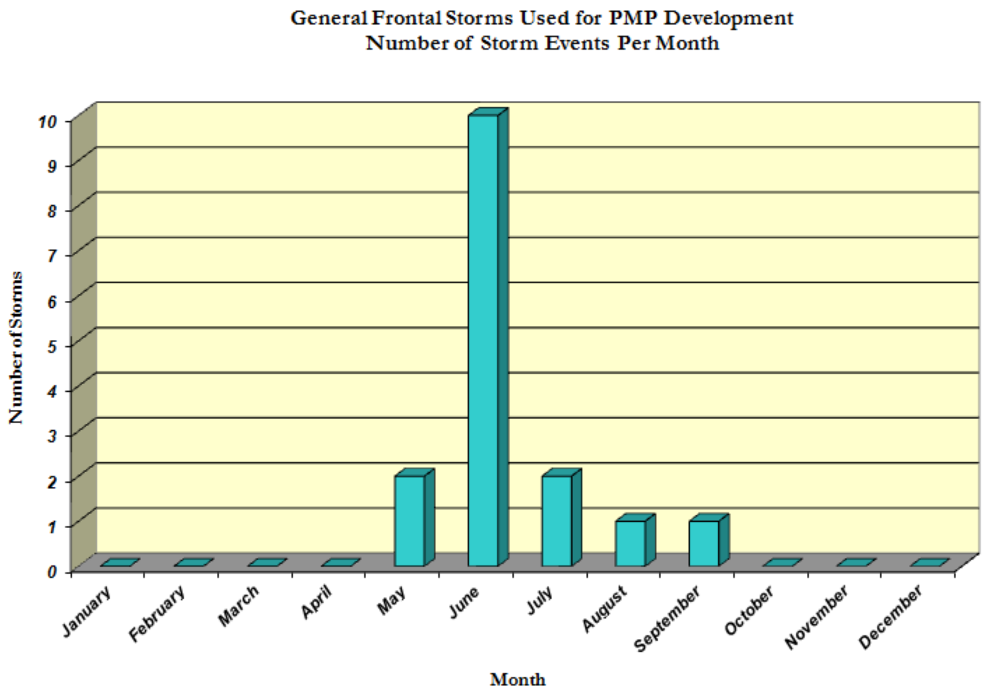

Figure 2.2 General storm seasonality of storms analyzed for the PMP study

3 Topographic Effects on PMP Rainfall

The terrain within the basin varies significantly, often over relatively short distances (Figure 3.1). The average elevation within the basin is 1,676 meters and varies from 1,066 meters at Glenmore Reservoir to 3,023 meters at Mount Evan-Thomas. Elevation increases from east to west across the basin. This increase in elevation helps to enhance lift in the lower atmosphere and thereby increase precipitation production. To account for the enhancements of precipitation by terrain features (called orographic effects), explicit evaluations were performed using precipitation frequency climatologies and investigations into past storm spatial and magnitude accumulation patterns across the basin and surrounding region. The precipitation frequency climatologies were developed as part of this study (see Section 5). These climatologies were also used to derive the Orographic Transposition Factors (OTFs) and the spatial distribution of the PMP. This approach is similar to that used in HMRs 55A, 57 and 59 that used the Storm Separation Method (SSM) to quantify orographic effects in topographically significant regions. In contrast to the SSM methodology, the OTF procedure is significantly more objective and reproducible (see Section 9.2.2). Appendix E provides a detailed example of the subjectivity and issues associated with the SSM. In Appendix E, AWA tried to replicate the SSM process and data using information provided in HMRs 55A, 57, and 59. The results of that analysis explicilty showed that the SSM method is not reproducible and highly subjective.

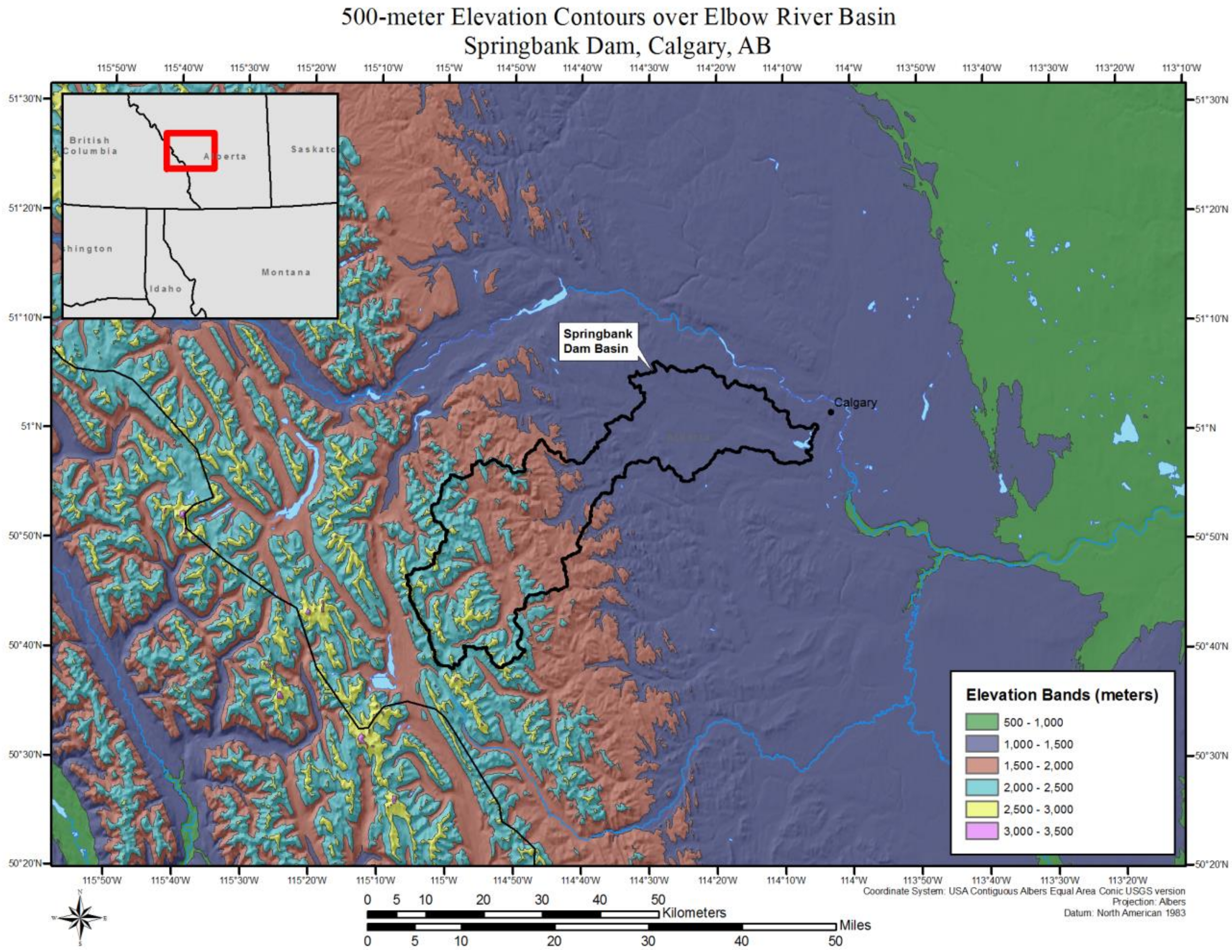

Figure 3.1 Elevation contours at 1,000 foot intervals over Elbow River Basin

3.1 Orographic Effects

Orographic effects on rainfall are explicitly captured in climatological analyses that use precipitation data from historical record. These historical rainfall amounts include precipitation that would have accumulated without topography together with the amount of additional precipitation (or decreased precipitation) that accumulated because of the effects of topography at a surrounding observation site. This relationship between precipitation frequency climatology and terrain is also recognized in the WMO PMP Manual (WMO, 1986 pg. 54 and by the Australian Bureau of Meteorology (Section 3.1.2.3 of Minty et al., 1996). Although the orographic effects at a particular location may vary from storm to storm, the overall effect of the topographic influence is inherently included in the climatology of precipitation that occurred at that location, assuming that the climatology is based on storms of the same type.

For the Elbow River basin, extreme storm events (PMP-type storms) include local storms (both individual thunderstorms and MCSs) and general storms. Thunderstorms/MCSs are the primary controlling storm type of the precipitation frequency climatology at durations of 6 hours or less, while the general storms are responsible for the precipitation frequency climatology values for durations of 24 hours and greater. Hence, climatological analyses of the rainfall data associated with these storm types adequately reflects the differences in topographic influences at different locations when evaluated by storm type and duration.

The procedure used in this study to account for orographic effects determines the differences between the climatological information at the in-place storm location and the individual grid point. This is a departure from the SSM used in HMRs 55A, 57, and 59. The SSM used in the HMRs is highly subjective and is not reproducible. This is because there are unknown variables involved in the computation, specifically what amount of rainfall would have accumulated without the topography (convergence only or free atmospheric forces precipitation, e.g. HMR 55A Section 7.1). A detailed description of the HMR SSM process and an attempt to replicate/validate the process is provided in Appendix E.

The OTF process used in this study (as well as all AWA PMP studies where topography plays a major role in rainfall spatial distribution and magnitude) reduces the amount of subjectivity involved and provides a dataset which is reproducible. By evaluating the rainfall values for a range of recurrence intervals at both locations, a relationship between the two locations was established. For this study, gridded precipitation frequency climatologies developed for this project domain were used to develop relationships and quantify orographic effects.

A major component of the OTF process is the assumption that the relationship between precipitation frequency values in areas of similar meteorology and topography (transpositionable regions) are a reflection of the difference in orographic effect between the two locations being compared. It is also assumed that the influence of terrain is the primary contributing factor to the variability in the relationship between precipitation climatology values at two distinct point locations of interest.

The orographically adjusted rainfall for a storm at a target (grid point) location may be calculated by determining the relationship between the climatological precipitation depth at the source storm location (i.e. the location where the historic storm occurred) and the corresponding depth at the target location. The orographic effect on rainfall is quantified as the OTF and defined as the ratio of the 100-year 24-hour climatological precipitation depth at the storm center location to the target grid point location. A description of the OTF calculation process is given in Section 9.2.2 and an example is provided in Section 10.3.

4 Dew Point Climatology Development

This study incorporated updated procedures and data analysis methods used in other PMP studies completed by AWA. This section describes the development of the updated dew point climatologies used for storm maximizations and PMP development. The maximum average dew point climatology was developed to include portions of Canada where storm moisture source regions occurred for storm events evaluated in this study. This followed the same process as the dew point climatologies developed by AWA over the contiguous United States (e.g. Tomlinson et al., 2008, Kappel et al., 2014) and extended those climatologies through this region.

4.1 6-, 12-, and 24-hour Maximum Average Dew Point Climatology Methodology

These updated dew point climatologies replace those provided in the HMRs and in other PMP studies in the region. The initial task in the development of the updated climatology was a search of the National Climatic Data Center (NCDC stations that record hourly dew point temperature data within a defined search domain surrounding the Elbow River basin (Alberta and Saskatchewan) (Figure 4.1). The dataset searched was DS472 (DL U.S. and Canada Surface Hourly Observations, daily from December 1976 to present). This dataset contains hourly surface observational data for all of Canada.

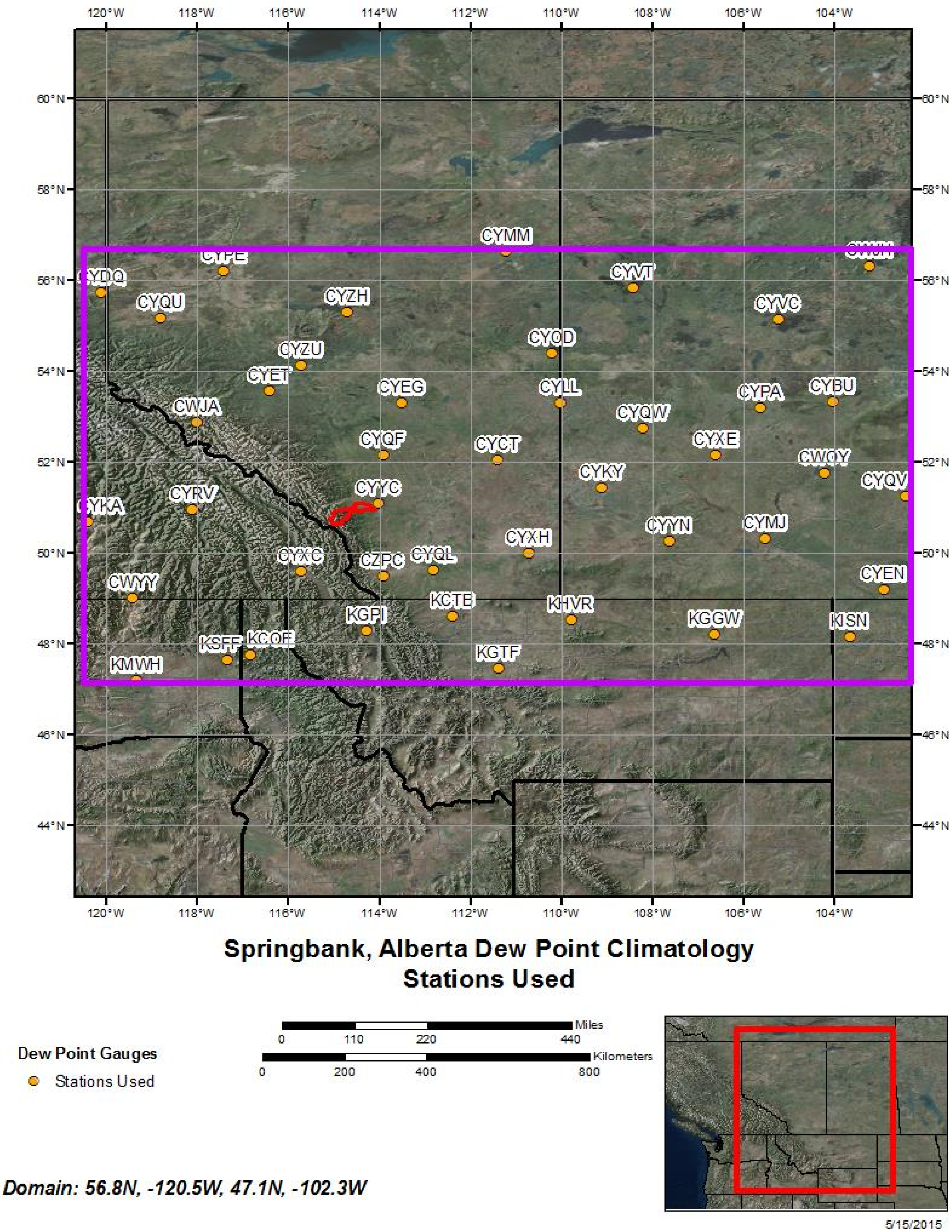

Figure 4.1 Hourly dew point station locations used for the updated maximum dew point climatology development

Once stations were identified, AWA extracted the archived hourly datasets for the maximum average 6-hour, 12-hour, and 24-hour dew point temperatures for each reporting station. A total of 57 hourly stations were within the search domain. Initial quality control (QC) limited stations to 30-years or greater period-of-record. After this initial QC, 37 hourly stations were selected for the dew point temperature analysis (32 stations > 30-years record and 5 stations < 30-years record). These stations are listed in Table 4.1. A script was written to extract each station's monthly maximum dew point temperatures for 6-, 12- and 24-hour durations for each year, providing annual maximum series (AMS) for that station. The AMS for each month for each station served as input to an R-statistical script that calculated L-moment statistics (Hosking, 2015a, and Hosking 2015b). Goodness of fit measures were evaluated for five candidate distributions: generalized logistic (GLO), generalized extreme value (GEV), generalized normal (GNO), Pearson type III (PE3), and generalized Pareto (GPA). An L-Moment Ratio Diagram was also prepared based on L-Skewness and L-Kurtosis pairs for the collection of stations in each homogenous region. The regional weighted-average L-Skewness and L-Kurtosis pairing were found to be very near the GEV distribution. L-moment goodness-of-fit tests were conducted (Hosking and Wallis, 1997), and the GEV distribution was identified as the best-fit three-parameter probability distribution. Using the generalized-extreme-value (GEV) distribution, the 20-year, 50-year, and 100-year return frequency dew point temperature values were calculated for each month for each station. The extracted dew point data were adjusted to the 15th of each month and adjusted to 1000mb dew point values.

The updated dew point climatologies replace the 12-hour maximum persisting dew point climatologies published by the U.S. Department of Commerce Environmental Data Service in the Climatic Atlas of the United States (Environmental Data Service, 1968) and those used in numerous PMP evaluations in the region. The 12-hour maximum persisting dew point climatologies were used to represent the maximum dew points for storm maximization procedures in the HMRs and other PMP studies in the region. The 12-hour maximum persisting dew point climatologies used were outdated but more importantly did not adequately represent the atmospheric moisture available in the PMP storm environment. The 12-hour persisting dew point values often missed or underestimated the atmospheric moisture available and led to overly conservative maximization calculations (see Tomlinson et al., 2008 Section 8.1.1 and Kappel et al., 2014 Section 7.2.2).

The updated climatology more accurately represent the atmospheric moisture fueling storms by using average maximum dew point values observed over durations specific to each storm's rainfall duration. The average maximum dew point values for various durations replace the maximum 12-hour persisting dew point values.

Table 4.1 Stations used to derive the maximum dew point climatology. POR stands for period of record for the given station.

No	Stid	Name	Province	Latitude	Longitude	Elevation (m)	POR
1	CYYC	CALGARY	AB	51.1100	-114.0000	1084	36
2	CYZH	SLAVE LAKE	AB	55.3000	-114.7000	581	36
3	CYET	EDSON	AB	53.5800	-116.4000	925	36
4	CZPC	PINCHER CREEK ARP	AB	49.5100	-113.9000	1190	33
5	CYXH	MEDICINE HAT	AB	50.0100	-110.7000	717	36
6	CYZU	WHITECOURT	AB	54.1500	-115.7000	782	36
7	CYQU	GRANDE PRAIRIE	AB	55.1800	-118.8000	669	36
8	CYPE	PEACE RIVER	AB	56.2300	-117.4000	571	36
9	CYMM	FT MCMURRAY	AB	56.6500	-111.2000	369	36
10	CYQL	LETHBRIDGE	AB	49.6300	-112.8000	929	36
11	CYVM	VALEMOUNT IS.	BC	52.8100	-119.2000	797	34
12	CYXC	CRANBROOK	BC	49.6100	-115.7000	939	36
13	CYCT	CORONATION	AB	52.0600	-111.4000	791	19
14	CYOD	COLD LAKE	AB	54.4100	-110.2000	541	36
15	CWYY	OSOYOOS	BC	49.0300	-119.4000	283	19
16	CYRV	REVELSTOKE	BC	50.9600	-118.1000	443	36
17	CYDQ	DAWSON CREEK	BC	55.7500	-120.1000	655	36
18	CYYN	SWIFT CURRENT	SK	50.2800	-107.6000	818	36
19	CYKY	KINDERSLEY	SK	51.4600	-109.1000	683	36
20	CYVT	BUFFALO NARROWS	SK	55.8500	-108.4000	424	36
21	CYQW	NORTH BATTLEFORD	SK	52.7600	-108.2000	548	36
22	CYXE	SASKATOON	SK	52.1600	-106.6000	504	36
23	CYQF	RED DEER	AB	52.1800	-113.9000	905	36
24	CYLL	LLOYDMINISTER	AB	53.3100	-110.0000	669	28
25	CYKA	KAMLOOPS	BC	50.7000	-120.4000	346	36
26	CWJA	JASPER	AB	52.8800	-118.0000	1061	17
27	CYEG	EDMONTON	AB	53.3100	-113.5000	676	36
28	CWBA	BANFF	AB	51.1800	-115.5000	1397	34
29	CYEN	ESTEVAN	SK	49.2100	-102.9000	572	36
30	CYQV	YORKTON	SK	51.2600	-102.4000	498	36
31	CYPA	PRINCE ALBERT	SK	53.2100	-105.6000	428	36
32	CYMJ	MOOSE JAW	SK	50.3300	-105.5000	577	36
33	CWOY	WYNYARD	SK	51.7600	-104.2000	561	20
34	CWFN	CREE LAKE	SK	57.3500	-107.1000	499	34
35	CWJH	SOUTHEND	SK	56.3300	-103.2000	344	14
36	CYBU	NIPAWIN	SK	53.3300	-104.0000	374	36
37	CYVC	LA RONGE	SK	55.1500	-105.2000	372	36

4.1.1 Procedure for Adjusting to the 15th of the Month

The station data were corrected to the 15th of each month using a linear relationship between the previous month, current month, and the next month. The 15th adjustment was performed using a series of Excel macros. The steps are listed below:

1. Calculate the difference in days between the observed average date of the annual maximum series occurrence of the month being analyzed and the 15th.
2. Depending whether the difference in step 1 is positive or negative (direction of adjustment) calculate the ratio/difference between the non-adjusted dew point temperature (for the months of interest) and the number of days between the dates.
3. Apply the ratio calculated in step 2 to the difference calculated in step 1.
4. Check the adjusted dew point value with the previous and next month values, and the other two durations.
5. Calculate the difference between the original dew point value and the adjusted dew point value.
6. Create station plots of the duration and frequency for additional QC measure.
7. Create a list of the adjusted dew point values for each station in a GIS format.

4.1.2 1000mb Adjustment Procedures

A moist lapse rate (2.7°F/1,000 feet, see http://www.weather.bm/glossary/Glossary.asp for a description of this standard moist lapse rate) was used to adjust the 15th of the month dew point temperature, at the station elevation, to 1000mb (assumed to be at elevation zero, i.e. sea level). A linear relationship between elevation and lapse rate was created and applied to each station. The June 24-hour maximum average dew point data for Calgary, AB are shown in Table 4.2. The table shows the original station data, the data adjusted to the 15th, and the data adjusted to 1000mb.

Table 4.2 Original 24-hour average dew point data, adjusted dew point data (to the 15th), and the 1000mb dew point data for 20-year, 50-year, and 100-year frequencies at Calgary, AB.

Calgary, AB	20-year	50-year	100-year
Station Data	13.9°C	14.2°C	14.3°C
15th Data	13.0°C	13.5°C	13.7°C
1000mb Data	18.3°C	18.8°C	19.1°C

4.1.3 Spatial Interpolation of Data

Inverse distance weighting (IDW) methods are based on the assumption that neighboring points are inversely proportional to the distance separating sample points (Equation 4.1). More weight is applied to closer samples and less weight applied to samples located further away. Station based dew point temperature data were interpolated using IDW, which is the methodology used in previous similar analyses (e.g. Tomlinson et al., 2008; Tomlinson et al., 2013; Kappel et al., 2014):

$$\hat{z}(x_0) = \frac{\sum_{i=1}^{n} \frac{z(x_i)}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \qquad \text{Equation 4.1}$$

where:

$\hat{z}(x_0)$ is the interpolated dew point value,
n is the total number of sample data values,
$z(x_i)$ is the *i*th data value,
d_i denotes the separation distance between interpolated value and data value,
and p denotes the weighting power.

Creation of the final dew point maps used in this project was completed after manual interpretation of the automated IDW algorithms and meteorological analysis by AWA. During this manual analysis, inconsistencies were removed and smoothing was applied where meteorological, climatological, and topographical factors warranted such actions. Further, expertise was used to compensate for the lack of spatial coverage in some sections of the domain and to ensure continuity between months and durations. Example of the 100-year 24-hour dew point for June, July, August, and September are shown in Figures 4.2-4.5.

The Elbow River basin dew point climatology domain was blended together with existing dew point climatologies created using the same procedures but as part of other AWA PMP projects. The blended dew point climatologies created a seamless 6-, 12-, and 24-hour 100-year climatology for the continental United States east of the Cascade and Sierra Nevada mountain ranges. Appendix B contains all the maps used as part of this PMP analysis.

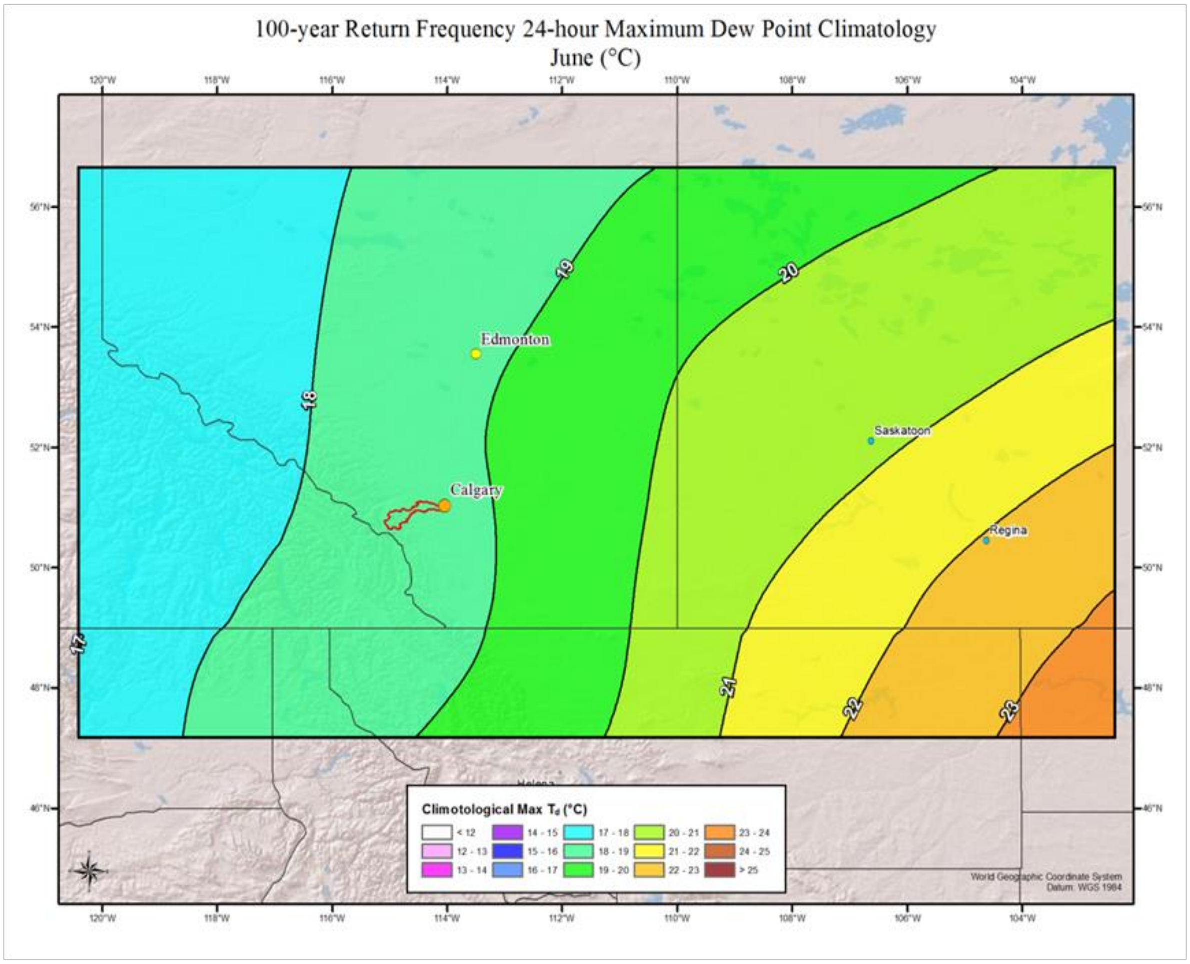

Figure 4.2 June 100-year return frequency maximum average 24-hour 1000mb dew point map

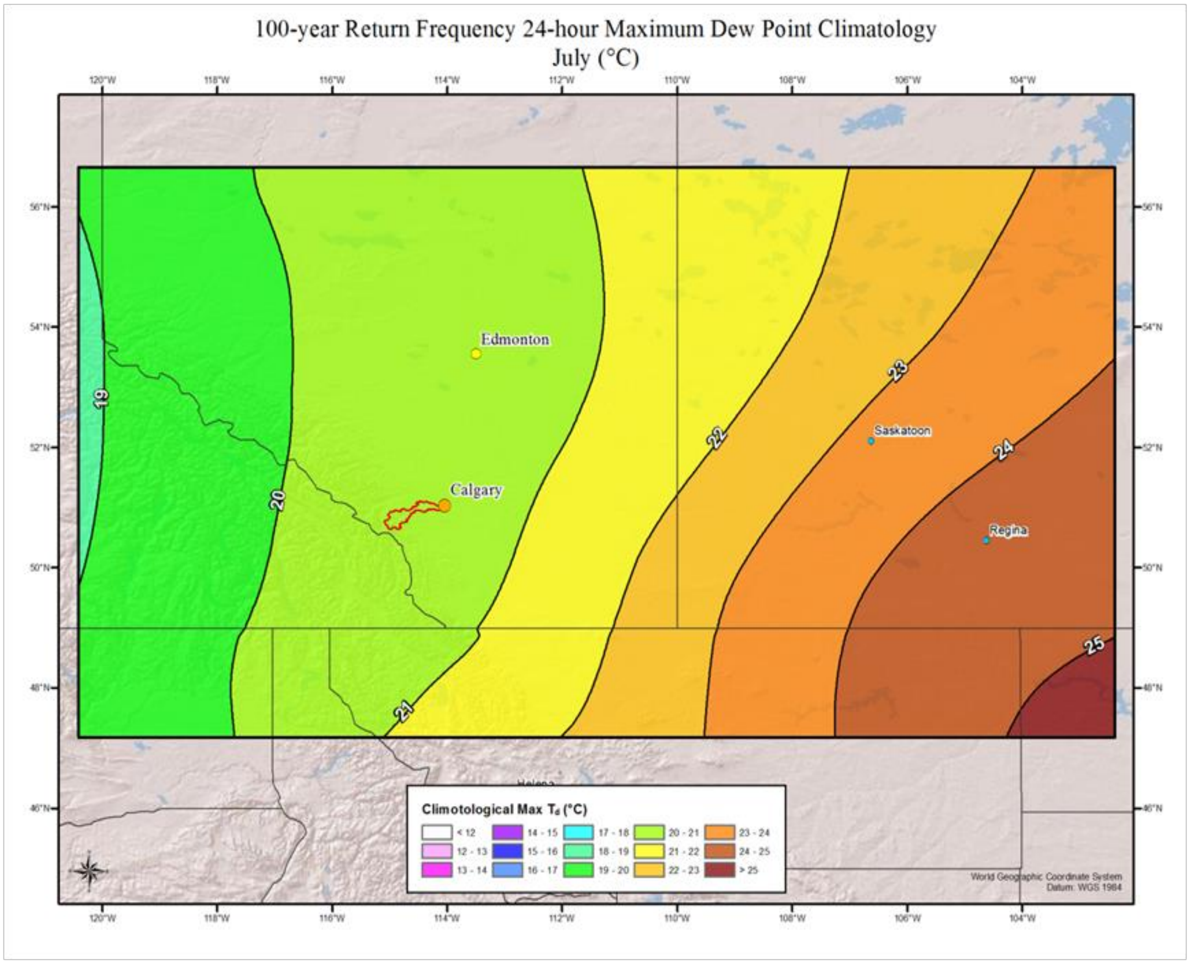

Figure 4.3 July 100-year return frequency maximum average 24-hour 1000mb dew point map

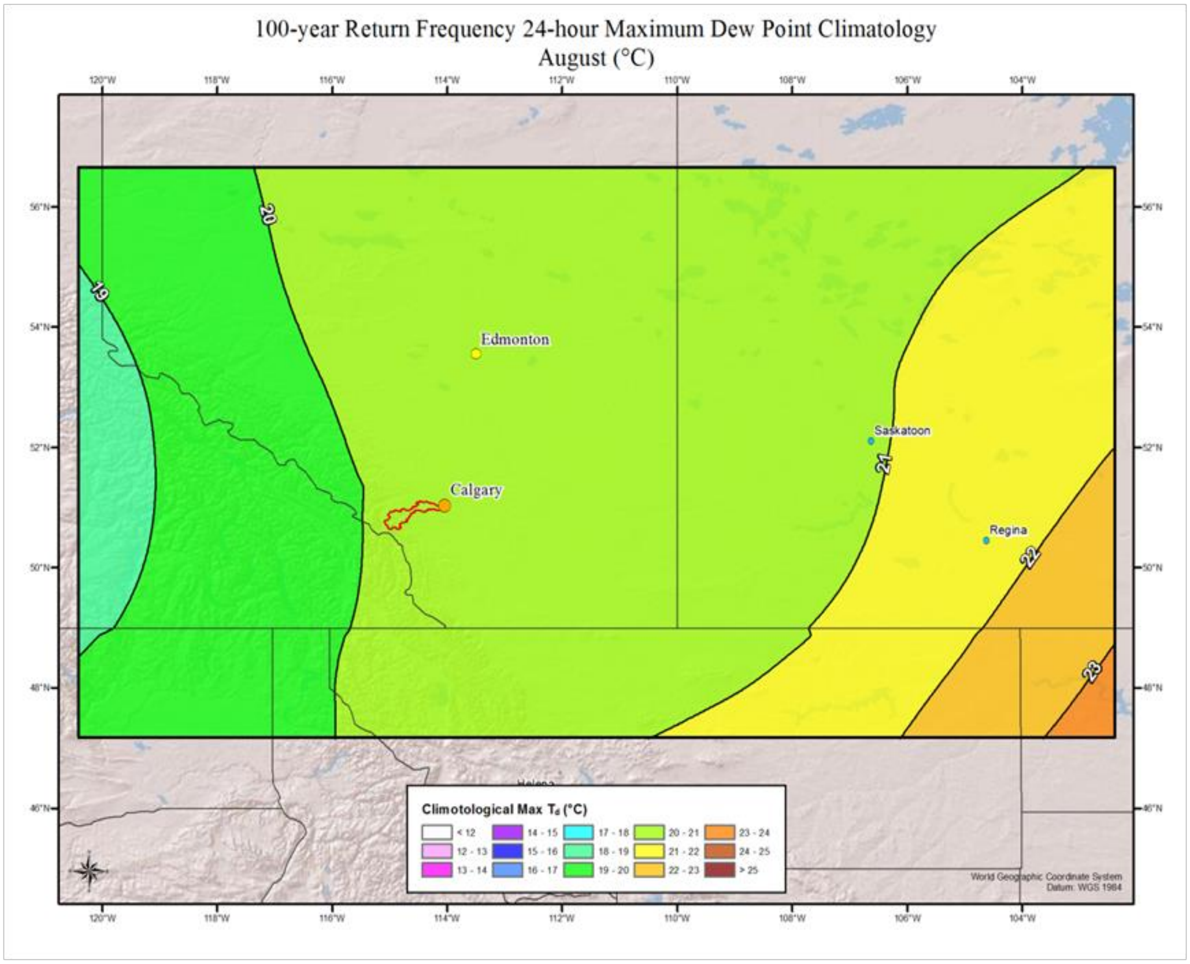

Figure 4.4 August 100-year return frequency maximum average 24-hour 1000mb dew point map

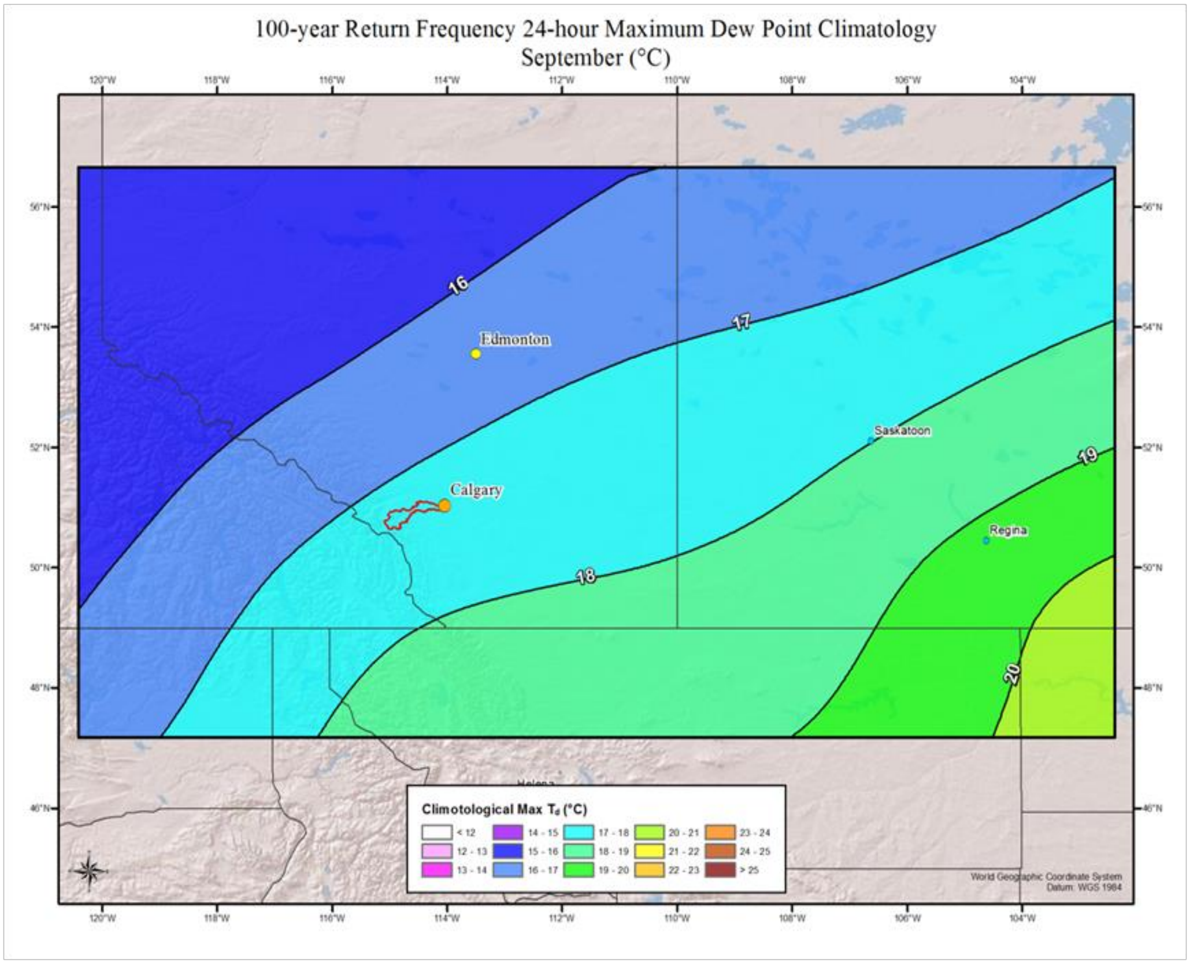

Figure 4.5 September 100-year return frequency maximum average 24-hour 1000mb dew point map

5 100-year Rainfall Development

AWA used procedures to determine the 100-year 24-hour and 6-hour rainfall for the Elbow River basin region. Annual maximum series (AMS) data generated by Environment Canada were provided to AWA (Figliuzzi, 2015) for thirty stations (Table 5.1). In addition to the AMS data, the 100-year 24-hour and 6-hour rainfall values were provided. The return frequencies provided were calculated using L-moments and the Gumbel distribution. Typically, AWA analyzes precipitation-frequency relationships for annual maximum using site specific or regional L-moment frequency analysis methods (Hosking and Wallis, 1997) and R-statistical software packages lmom and lmomRFA developed by Hosking (Hosking, 2015a, and Hosking, 2015b).

Before using precipitation frequency estimates provided, three stations (Calgary, Pincher, and Kananaskis) surrounding the Elbow River basin were compared to an independent L-moment frequency analysis by AWA. AWA used goodness of fit measures to evaluate five candidate distributions: generalized logistic (GLO), GEV, generalized normal (GNO), Pearson type III (PE3), and generalized Pareto (GPA). L-Moment Ratio Diagrams were prepared based on L-Skewness and L-Kurtosis (example in Figure 5.1). The regional weighted-average L-Skewness and L-Kurtosis pairing were found to be very near the GEV distribution, which is a mathematical form that incorporates Gumbel's Extreme Value (EV) Type I, II and III distributions for maxima. The parameters of the GEV distribution are the ξ (location), α (scale) and k (shape). The Gumbel EV Type I distribution is obtained when $k = 0$. For $k > 0$, the distribution has a finite upper bound at $\xi + \alpha / k$ and corresponds to the EV Type III distribution for maxima that are bounded above. For $k < 0$, this corresponds to the Gumbel EV Type II distribution.

The results of the comparison demonstrate that the GEV distribution matches satisfactorily with the three stations investigated. Since the Gumbel distribution is imbedded within the GEV distribution the data derived from the Gumbel distribution was determined to be acceptable. AWA calculated return frequency estimates using L-moments and the Gumbel distribution at the three stations for comparison. Figures 5.2 and 5.3 and Tables 5.2 and 5.3 shows good agreement between data provided and the independent AWA L-moment approach using the Gumbel distribution. Based on the comparison, it was determined that the data and return frequencies provided were good estimates and thus, were used for the study.

Table 5.1 Station AMS data and return frequency estimates for data provided to AWA. POR stands for period of record for the given station.

Name	Source	Stid	Longitude	Latitude	Elevation (m)	POR
CAMROSE	IDF	3011240	-112.8167	53.0333	739	11
CORONATION A	IDF	3011880	-111.4500	52.0667	791	17
EDMONTON INT'L A	IDF	3012205	-113.5833	53.3167	723	45
EDMONTON CITY CENTRE A	IDF	3012208	-113.5167	53.5667	670	79
EDMONTON NAMAO A	IDF	3012210	-113.4667	53.6667	687	29
ELLERSLIE	IDF	3012295	-113.5500	53.4167	693	21
ROCKY MTN HOUSE A	IDF	3015522	-114.9167	52.4333	988	29
VEGREVILLE CDA	IDF	3016761	-112.0333	53.4833	635	23
LACOMBE CDA	IDF	3023720	-113.7500	52.4667	847	21
RED DEER A	IDF	3025480	-113.8833	52.1667	904	47
BROOKS AHRC	IDF	3030856	-111.8500	50.5500	758	22
CALGARY INT'L A	IDF	3031093	-114.0167	51.1167	1084	60
LETHBRIDGE A	IDF	3033880	-112.7833	49.6333	928	34
MEDICINE HAT A	IDF	3034480	-110.7167	50.0167	716	35
PINCHER CREEK A	IDF	3035202	-114.0000	49.5167	1189	28
VAUXHALL CDA	IDF	3036681	-112.1333	50.0500	778	31
MANYBERRIES CDA	IDF	3044200	-110.4667	49.1167	934	26
JASPER	IDF	3053520	-118.0667	52.8833	1062	31
KANANASKIS	IDF	3053600	-115.0333	51.0167	1391	16
EDSON A	IDF	3062244	-116.4667	53.5833	927	22
FORT MCMURRAY A	IDF	3062693	-111.2167	56.6500	369	29
SLAVE LAKE A	IDF	3066001	-114.7833	55.3000	580	20
WHITECOURT A	IDF	3067372	-115.7833	54.1333	782	24
BEAVERLODGE CDA	IDF	3070560	-119.4000	55.2000	744	33
FORT CHIPEWYAN A	IDF	3072658	-111.1167	58.7667	232	22
GRANDE PRAIRIE A	IDF	3072920	-118.8833	55.1667	669	25
HIGH LEVEL A	IDF	3073146	-117.1667	58.6167	338	36
PEACE RIVER A	IDF	3075040	-117.4333	56.2167	570	40
WATINO	IDF	3077246	-117.6333	55.7167	393	30
COLD LAKE A	IDF	3081680	-110.2833	54.4167	541	40

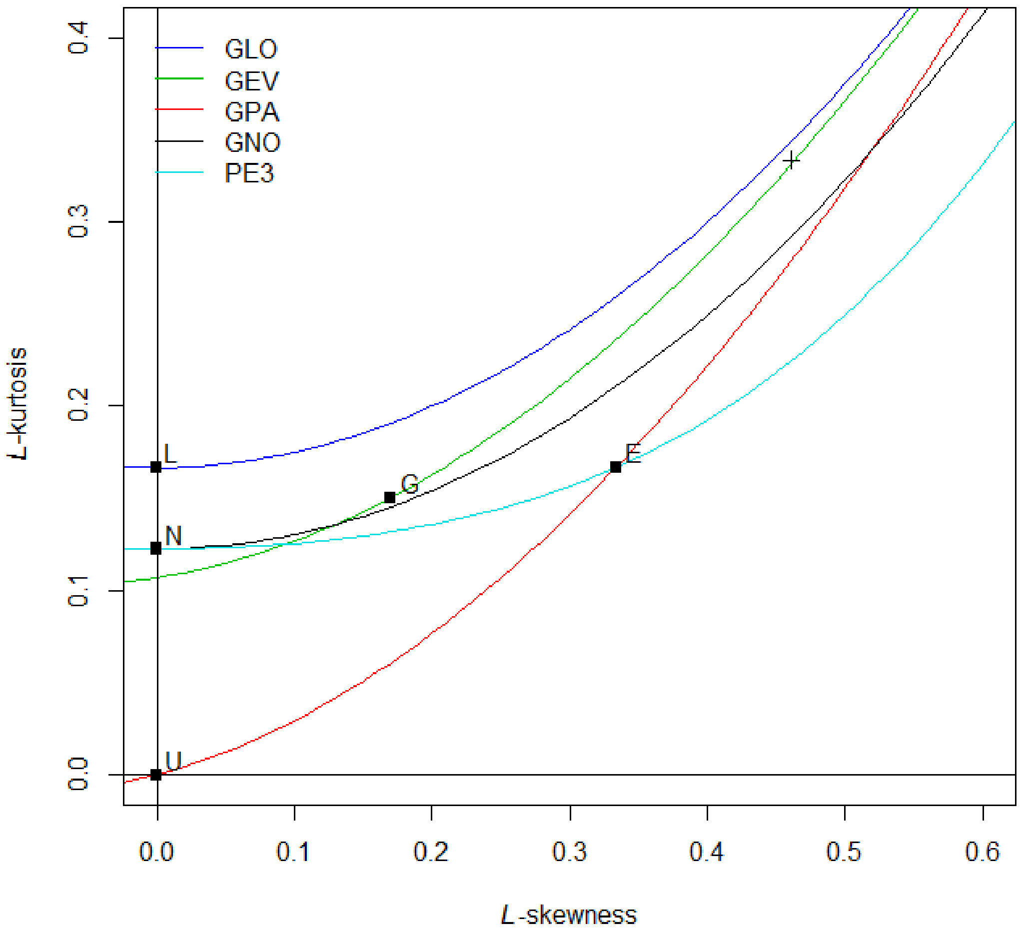

Figure 5.1 Example L-Moment ratio diagram for Kananaskis 6-hour

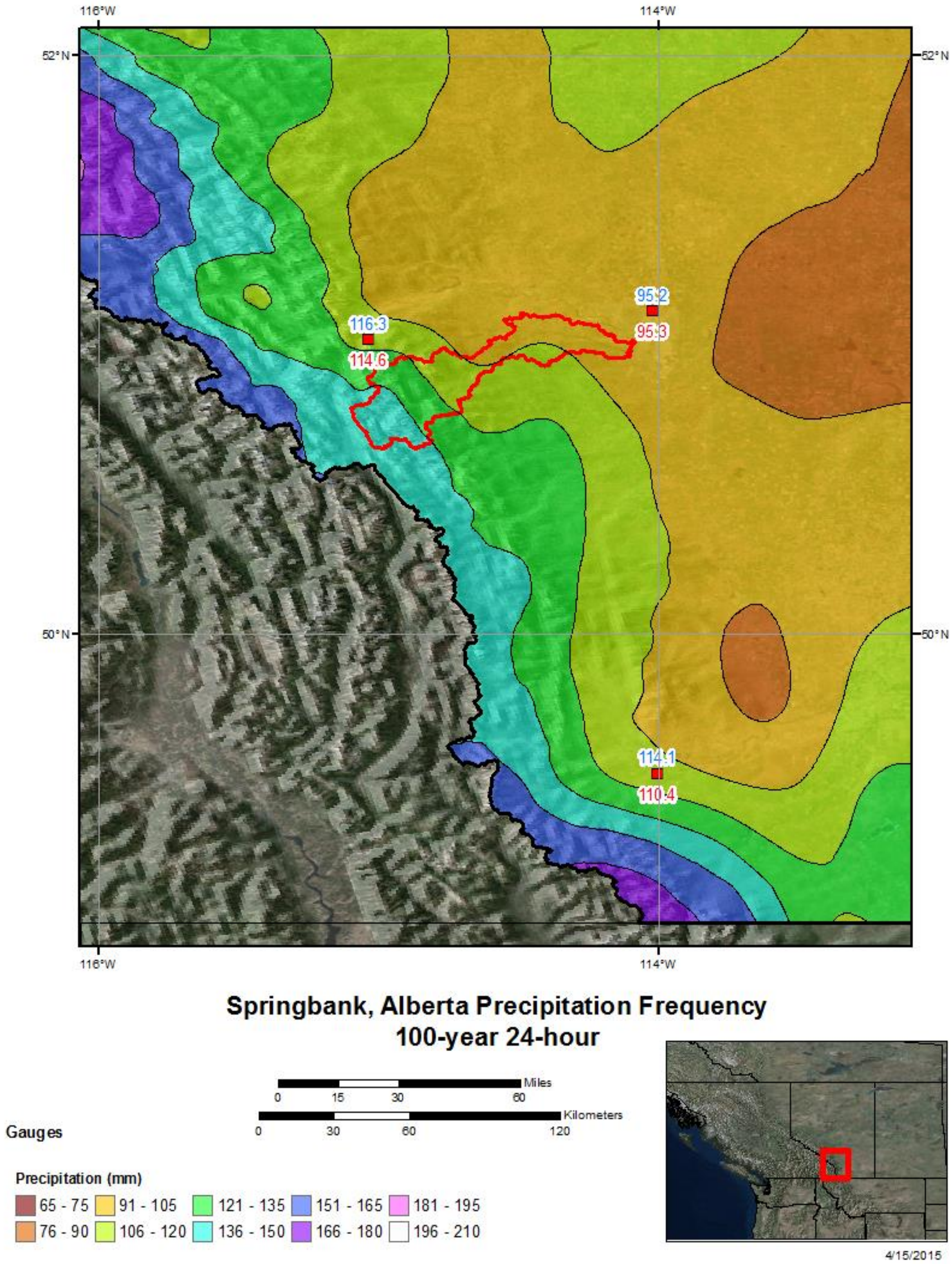

Figure 5.2 100-year 24-hour comparison of provided data (Gumbel) and AWA L-moment estimates using Gumbel distribution.

Table 5.2 100-year 24-hour comparison of Environment Canada estimates (Gumbel) and AWA L-moment estimates using Gumbel distribution.

Station	AWA	Client	Delta
Calgary	95.2	95.3	0.1
Pincher	114.1	110.4	-3.7
Kananaskis	116.3	114.6	-1.7

***100-year 24-hour Gumbel Distribution

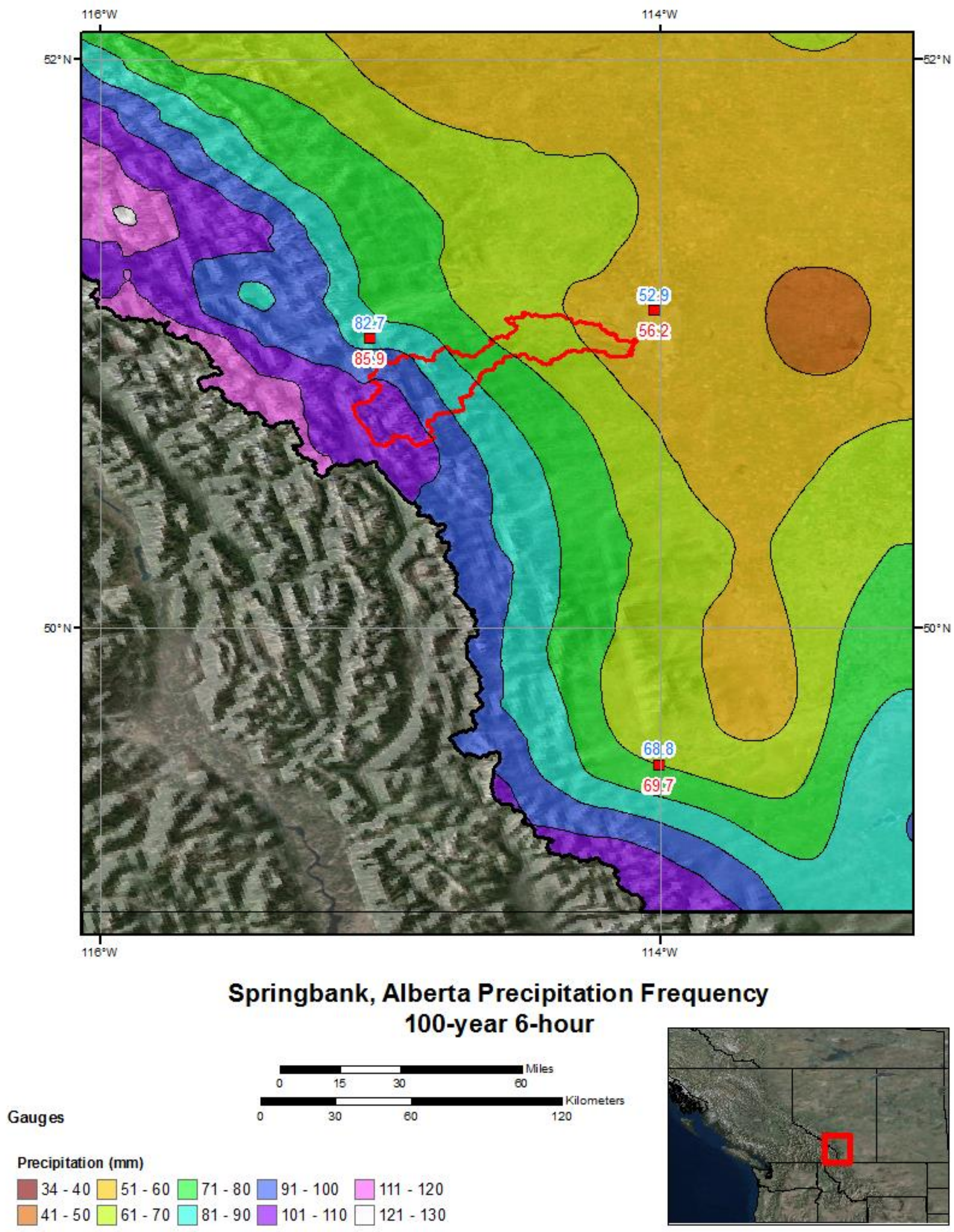

Figure 5.3 100-year 6-hour comparison of provided data (Gumbel) and AWA L-moment estimates using Gumbel distribution.

Table 5.3 100-year 6-hour comparison of Environment Canada estimates (Gumbel) and AWA L-moment estimates using Gumbel distribution.

Station	AWA	Client	Delta
Calgary	52.9	56.2	3.3
Pincher	68.8	69.7	0.9
Kananaskis	82.7	85.9	3.2

***100-year 6-hour Gumbel Distribution

5.1 Creation of Gridded Datasets

Gridded datasets were produced for the 100-year 24-hour and 100-year 6-hour rainfall return frequencies. GRASS GIS was used to interpolate continuous gridded data between each of the station locations for the two durations surrounding the Elbow River basin region. The final gridded datasets were converted to ASCII format (Figure 5.4 and 5.5). All geographic data used in these procedures utilized the WGS 84 spatial reference. The gridded data sets were produced using the following procedure:

1. For each duration, an Excel spreadsheet was composed containing the station data for return frequency estimates (24-hour and 6-hour).
2. Point features were created for each station using the *Make XY Event Layer* tool.
3. Used USDA 1961-1990 Mean Annual Precipitation as a basemap to aid interpolation (same process as SPAS).
4. Calculated the isopercentile (station value / basemap).
5. Applied *IDW* algorithm to isopercentile to create continuous grid.
6. Multiplied isopercentile grid by basemap to obtain final gridded return frequency grid.
7. Clipped gridded data to Alberta boundary.
8. The final grids were converted to ASCII format.

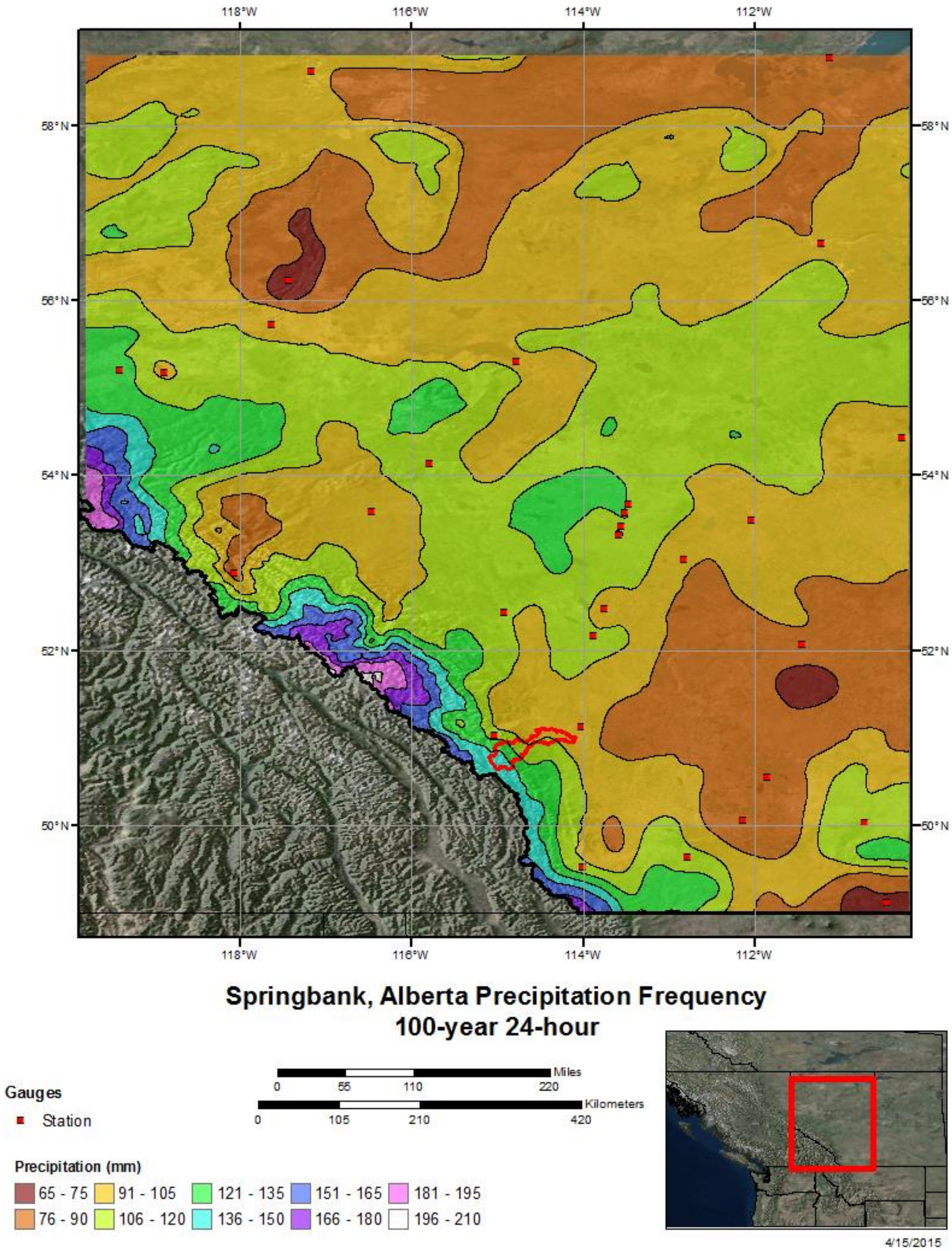

Figure 5.4 Derived 100-year 24-hour Precipitation Return Frequency

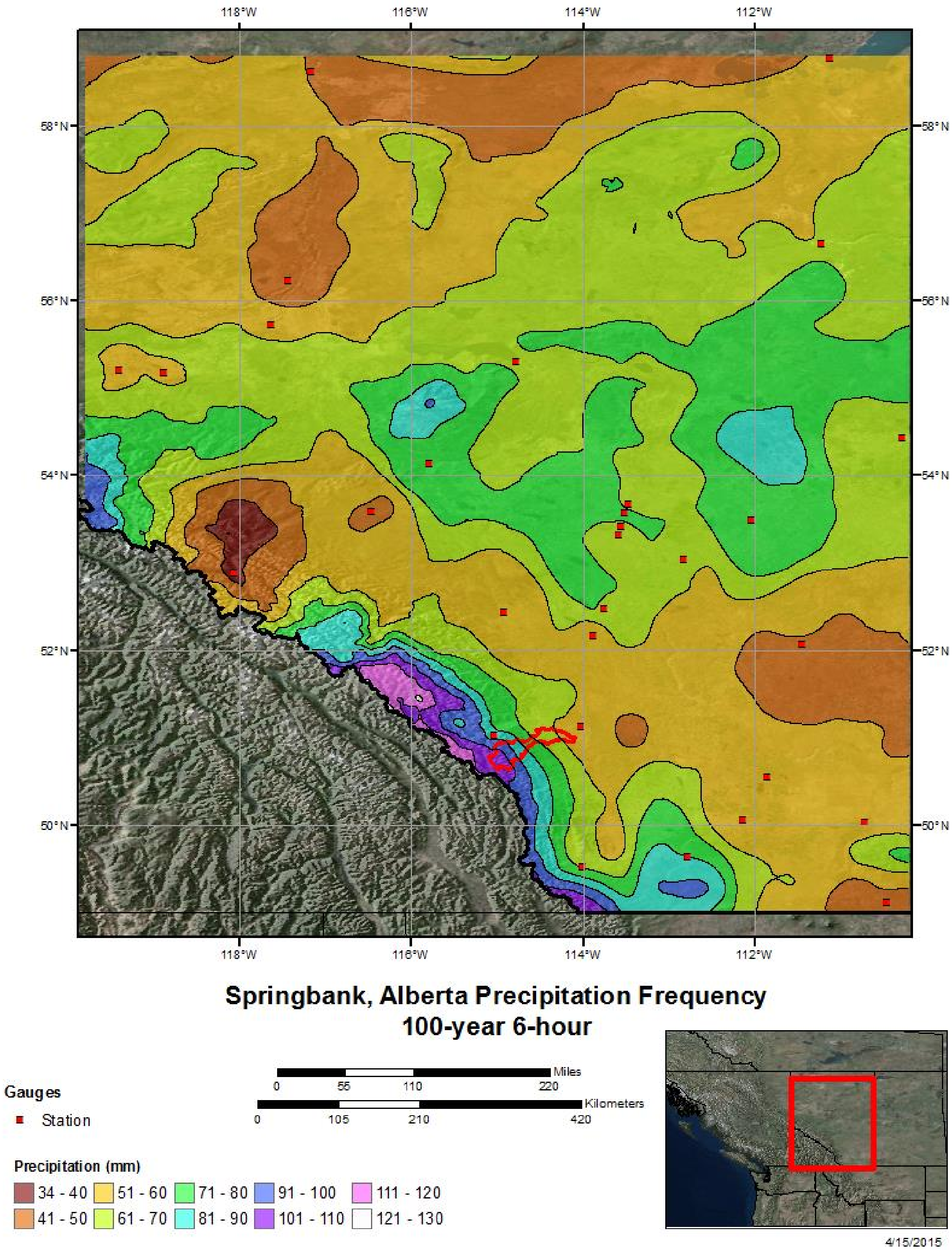

Figure 5.5 Derived 100-year 6-hour Precipitation Return Frequency

6 PMP Storm Identification

6.1 Storm Search Area

A comprehensive storm search was conducted using previous storm search results from several AWA site-specific PMP studies, discussions with members of the review board, and evaluating storm reports and PMP studies in the region for significant events. This included an analysis of all the storms in regions that are meteorologically and topographically similar to the Elbow River basin. Discussion with the review board members and Stantec personnel identified other rainfall events which were important to the basin for both calibration and PMF determination. The primary search area included all geographic locations where extreme rainfall storms similar to those that could occur over the Elbow River basin have been observed. The search area extended from northern Alberta and British Columbia (~50°N) to central Wyoming (~42°N) and from the crest of the Rocky Mountains east to approximately 610 meters in elevation (Figure 6.1). This ensured a large enough area was searched to capture all significant storms that could potentially influence PMP values for the basin.

6.2 Storm Search Data Sources

The storm search was conducted using a database of rainfall information from several sources. The primary data sources are listed below:

1. Cooperative Summary of the Day / TD3200 through 2014. 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. Environment Canada storm studies
4. Previous PMP/PMF reports in the region
5. NCDC Recovery Disk
6. Hydrometeorological Reports
7. Corps of Engineers Storm Studies
8. American Meteorological Society journals
9. Previous storm search conducted by AWA in the region
10. Personal communications with various members involved in this study

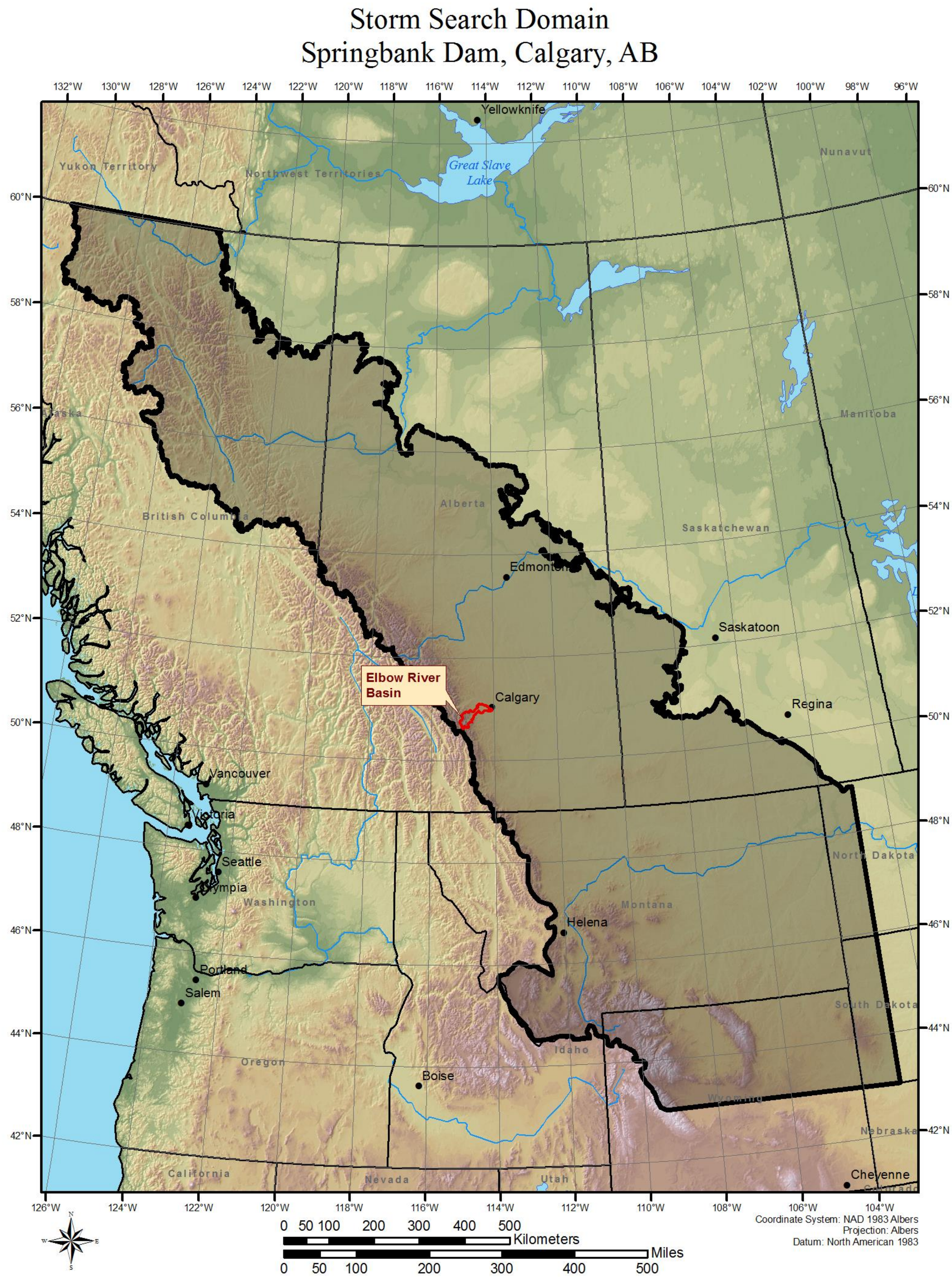

Figure 6.1 Elbow River storm search domain

6.3 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- and 6-hour and 1-, 2-, 3-day precipitation totals. Other reference sources were reviewed to identify other dates with large rainfall amounts for locations within the storm search domain. Discussions with others involved in this study identified other storms that could potentially be important for PMP/PMF development. The initial cut-off 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, or that were important for PMP development in previous studies in the region.

The resulting storm list was extensively quality controlled to ensure that only the highest storm rainfall values for each event were selected. Storms were then grouped by storm type, local or general. These storms were evaluated to ensure they occurred over similar meteorological and topographic regions as the Elbow River basin and could, therefore be used in the next steps of the PMP analysis. Table 6.1 provides the initial list of the storms identified for further evaluation.

Quality control checks and comparisons of rainfall magnitude and flood response were performed for each storm to eliminate storms which, after all maximization, would not be controlling for PMP values for the basin. This analysis resulted in the short storm list (Figure 6.2 and Table 6.2). Each storm on the short storm list was fully analyzed using the SPAS program to produce hourly gridded rainfall and other information required for PMP development and calculations.

Table 6.1 Initial storm list produced from the storm search listed chronologically. Rainfall values shown are the highest point values in mm from the storm search or SPAS storm analysis.

Storm Name	State or Province	Latitude in °	Longitude in °	Year	Month	Day	Maximum Point Rainfall (mm)	Precipitation Source
WARRICK	MT	48.0791	-109.7041	1906	6	6	348	SPAS 1335
SPRINGBROOK	MT	47.3642	-105.7778	1921	6	18	386	SPAS 1336
SAVAGETON	WY	43.8458	-105.8042	1923	9	27	446	SPAS 1325
BUFALLO GAP	SK	49.1146	-105.2896	1961	5	30	267	SPAS 1334
LAFLECHE	SK	49.7062	-106.5745	1962	6	12	229	PR-98
TANTALLON	SK	50.5390	-101.8420	1963	6	8	191	PR-102
GIBSON DAM	MT	48.3542	-113.3708	1964	6	6	487	SPAS 1211
GLEN ULLIN	ND	47.3041	-101.3875	1966	6	24	327	SPAS 1324
PEKISKO	AB	50.2375	-114.2708	1969	6	19	257	ALTA-6-69
GRAVE FLATS	AB	52.8820	-117.1600	1969	8	3	194	ALTA-8-69
PELICAN MOUNTAIN	AB	55.5542	-113.6625	1970	6	28	286	SPAS 1504
RAPID CITY	SD	43.8875	-103.4042	1972	6	9	401	SPAS 1212
NOSE MOUNTAIN	AB	54.5375	-119.5542	1972	6	10	207	SPAS 1503
VETERAN	AB	51.8625	-110.4292	1973	6	15	243	SPAS 1502
WATERTON RED ROCK	AB	49.0875	-114.0458	1975	6	18	367	SPAS 1252
NOSE MOUNTAIN	AB	54.5125	-120.0292	1982	7	15	188	SPAS 1501
PARKMAN	SK	49.7020	-101.8958	1985	8	3	400	SPAS 1337
SIMONETTE LO	AB	54.2375	-118.4042	1987	7	30	318	ALTA-7-87
SPIONKOP CREEK	AB	49.1708	-114.1625	1995	6	5	368	SPAS 1338
VANGAURD	SK	49.9218	-107.2100	2000	7	3	388	SPAS 1177
CALGARY	AB	50.4350	-114.3850	2005	6	1	325	SPAS 1492
CRYSTAL LAKE	MT	45.3150	-107.1750	2011	5	19	232	SPAS 1404
CALGARY	AB	50.6350	-114.8550	2013	6	19	350	SPAS 1320

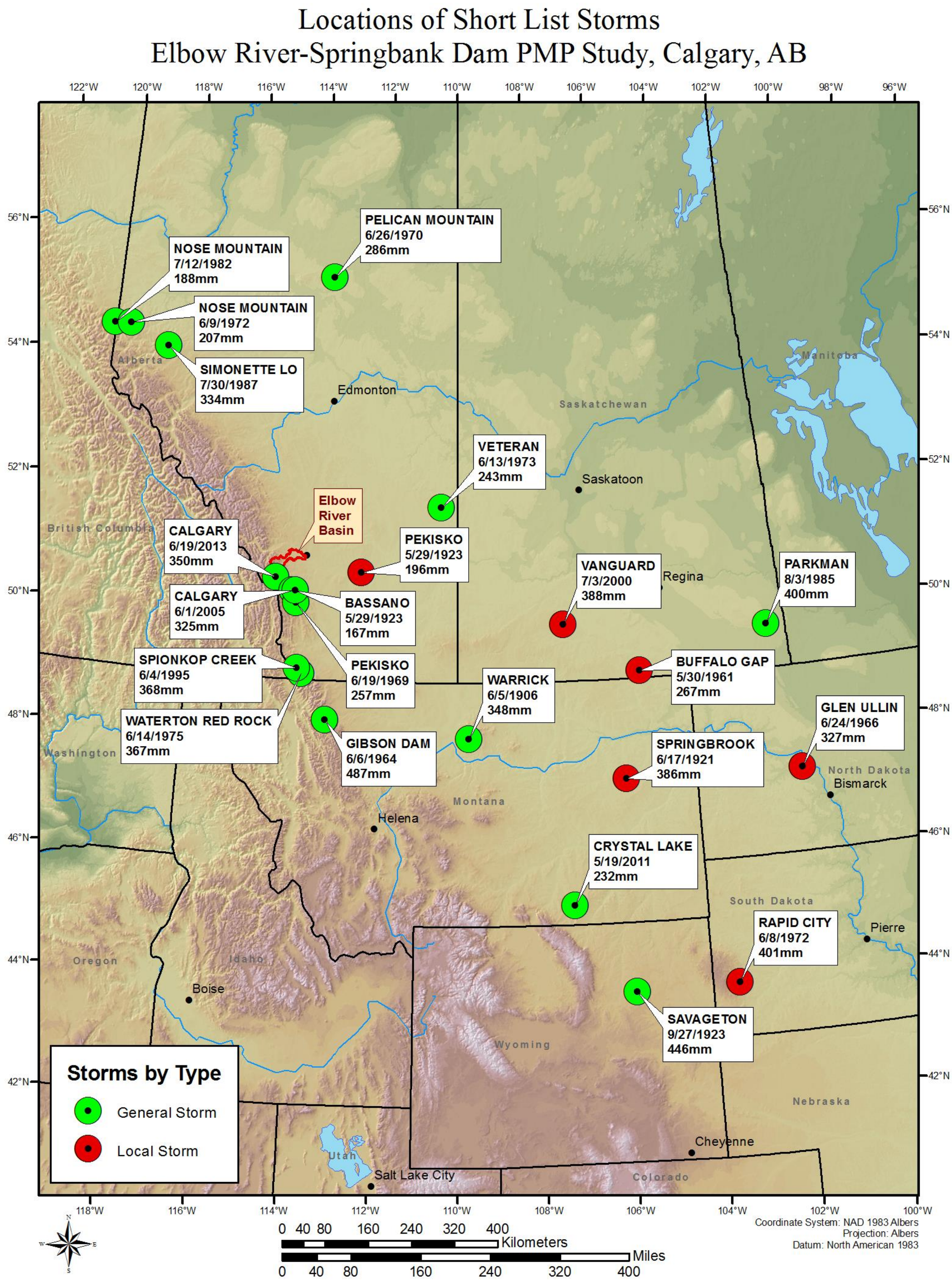

Figure 6.2 Final short storm list storm locations

Table 6.2 Short storm list used in the development of the PMP values, sorted by storm type, chronologically.

Storm Name	State	Latitude in °	Longitude in °	Year	Month	Day	Total Rainfall (mm)	Elevation (meters)	Storm Type
WARRICK	MT	48.0791	-109.7041	1906	6	5	348	1260	General
SAVAGETON	WY	43.8458	-105.8042	1923	9	27	446	1460	General
BASSANO	AB	50.4375	-114.3042	1923	5	29	167	1340	General
GIBSON DAM	MT	48.3542	-113.3708	1964	6	6	487	2440	General
PEKISKO	AB	50.2375	-114.2708	1969	6	19	257	1480	General
PELICAN MOUNTAIN	AB	55.5542	-113.6625	1970	6	26	286	830	General
NOSE MOUNTAIN	AB	54.5375	-119.5542	1972	6	9	207	1490	General
VETERAN	AB	51.8625	-110.4292	1973	6	13	243	670	General
WATERTON RED ROCK	AB	49.0875	-114.0458	1975	6	14	367	2390	General
NOSE MOUNTAIN	AB	54.5125	-120.0292	1982	7	12	188	1370	General
PARKMAN	SK	49.7020	-101.8958	1985	8	3	400	630	General
SIMONETTE LO	AB	54.2375	-118.4042	1987	7	30	334	1280	General
SPIONKOP CREEK	AB	49.1708	-114.1625	1995	6	4	368	1630	General
CALGARY	AB	50.4350	-114.3850	2005	6	1	325	1480	General
CRYSTAL LAKE	MT	45.3150	-107.1750	2011	5	19	232	1520	General
CALGARY	AB	50.6350	-114.8550	2013	6	19	350	2590	General
SPRINGBROOK	MT	47.3642	-105.7778	1921	6	17	386	820	Local
PEKISKO	AB	50.7792	-112.5708	1923	5	29	196	820	Local
BUFFALO GAP	SK	49.1146	-105.2896	1961	5	30	267	790	Local
GLEN ULLIN	ND	47.3041	-101.3875	1966	6	24	327	530	Local
RAPID CITY	SD	43.8875	-103.4042	1972	6	8	401	1440	Local
VANGUARD	SK	49.9218	-107.2100	2000	7	3	388	760	Local

7 Storm Depth-Area-Duration Development

For all short list storm events without published Depth-Area-Duration (DAD) analyses and for previously analyzed storms (either HMRs or Environment Canada) that were used in the development of the final PMP values using the OTF, hourly rainfall grids and DADs needed to be computed. To accomplish this, the SPAS program (Parzybok and Tomlinson, 2006) was used. This program computed the required rainfall analyses, along with several other products such as mass curves, isohyetal patterns, analysis statistics, and quality control analyses, for each storm used in the final SSPMP development. Detailed results of each of these analyses can be found in Appendix F.

There are two main steps in the SPAS DAD analysis: 1) The creation of high-resolution hourly precipitation grids and 2) the computation of Depth-Area (DA) rainfall amounts for various durations. The reliability of the development of the DA data depends on the accuracy of the hourly precipitation inputs and grids (Gou et al., 2001, Duchon and Essenberg, 2001). This process was very labor intensive and more subjective before it's automation by SPAS. SPAS utilizes 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 (WMO, 1986). 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 mimic 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).

7.1 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 the AWA storm database for specified areas, dates, and times. Rainfall amounts are 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 needs 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. AgroClimatic Information Service, ALERT, USGS, etc.) and daily gauges with accumulated data.

7.2 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.

7.3 Hourly or Sub-hourly Precipitation Maps

SPAS can either operate in its standard mode or in NEXRAD-mode to create high resolution hourly or sub-hourly (for NEXRAD storms) grids. Both modes are run when NEXRAD data are available so that a comparison can be made between the results from each mode. The resulting grids serve as the basis for the DAD computations and the analysis of the areal extent of a storm's rainfall.

7.3.1 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. Basemaps are used in the standard SPAS mode to help spatially distribute rainfall between known data points. Basemaps used in this study consisted of PRISM precipitation climatologies or precipitation frequency climatologies.

7.3.2 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 (7.1) below:

$$Z = aR^b \qquad \text{Equation 7.1}$$

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). These are standard parameters measured by NEXRAD radar algorithms. Potential inaccuracies in this process are corrected for using the calibrated ZR relationship derived during the SPAS analysis process by "ground truthing" to rain gauges (see Appendix D for a full description of the SPAS program).

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 7.1 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.

7.4 Depth-Area-Duration (DAD) Program

The DAD extension of SPAS runs from within a Geographic Resource Analysis Support System (GRASS) GIS environment[1] 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 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 valued for each standard area for each durational period.

[1] Geographic Resource Analysis Support System, commonly referred to as GRASS, 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.

8 Storm Maximization

In-place storm maximization is the process of increasing rainfall associated with an observed extreme storm under the potential condition that additional moisture could have been available to the storm for rainfall production. This is accomplished by increasing the dew points to some climatological maximum and calculating the rainfall amounts that could potentially have been produced if those increased amounts of moisture would have been available. The maximum dew point values provided in the maximum average dew point climatologies are for the 1000mb level, so these values are adjusted to the elevation of the storm location. This is done to remove the amount of moisture associated with the 1000mb maximum dew point that would not be available at the storm elevation. Both the storm representative dew point and the maximum average dew point need to represent moisture in the atmospheric column above ground level, i.e. the storm location elevation.

An additional consideration is usually applied that selects the climatological maximum dew point value for a date 15 days towards the warm season (season of higher maximum average dew point climatology values) from the date that the storm actually occurred. This procedure assumes that the storm could have occurred with the same storm characteristics 15 days earlier or later in the year when maximum average dew points are higher and hence, more moisture would be available for rainfall production. This assumption follows HMR guidance and is consistent with procedures used to develop PMP values in all the current HMR documents (e.g. HMR 51 Section 2.3.4) and in the WMO manual (1986), as well as all AWA PMP studies.

8.1 Use of Dew Point Temperatures

The HMR and WMO procedures for storm maximization use a representative storm dew point as the parameter to represent available moisture to a historic storm. Storm precipitation amounts are maximized using the ratio of precipitable water for the maximum average dew point to precipitable water for the observed storm representative dew point.

Maximum dew point climatologies are used to determine the maximum atmospheric moisture that could have been available. Prior to the mid-1980s, maps of maximum dew point values from the *Climatic Atlas of the United States* (EDS, 1968) were the source for maximum dew point values. For the region covered by HMR 49, HMR 50 (Hansen and Schwartz, 1981) provided updated dew point climatologies. HMR 55A contained updated maximum dew point values for a portion of United States from the Continental Divide eastward into the Central Plains. HMR 57 updated the 12-hour persisting dew points values and added a 3-hour persisting dew point climatology. The regional PMP study for Michigan and Wisconsin produced return frequency maps representing the 50-year recurrence interval using the L-moments method. The Review Committee for that study included representatives from NWS, FERC, Bureau of Reclamation, and others. They agreed that the 50-year return frequency values were appropriate for use in PMP calculations. For the Nebraska statewide study, the Review Committee and FERC Board of Consultants agreed that the 100-year return frequency dew point climatology maps were appropriate because their use added a layer of conservatism over the 50-year return period. This has subsequently been employed in all AWA PMP studies across North America. This study used the 100-year return frequency climatologies developed previously and updated during this study (see Section 4).

Observed storm rainfall amounts are maximized using the ratio of precipitable water for the maximum dew point to precipitable water for the storm representative dew point, assuming a vertically saturated atmosphere. The difference between the *maximum* precipitable water and *actual* precipitable water associated with a storm event is converted into a percent, and the storm rainfall totals as they occurred are enhanced (maximized) by this factor, called the in-place maximization factor (IPMF). By definition, maximization factors are always greater than or equal to 1. Following HMR (e.g. HMR 51 Section 3.2.2 and HMR 55A Section 8.4.1.1), WMO (WMO, 2009 Section 2.3.4) and previous AWA PMP in-place storm maximization guidance, the in-place maximization value is capped at 1.50. This 1.50 limitation is based on the consideration that if the moisture is increased beyond 50% (an IPMF of 1.50), the assumption that the moisture can be increased without altering the storm's dynamics is no longer valid (HMR 55A, Section 8.4.1.1). The assumption is that properly analyzed and maximized storms should be some percent larger than the actual storm, but increases beyond certain limits (e.g. 50%) would change the characteristics of the storm. In some cases when the IPMF is greater than 1.50, the storm representative dew point did not adequately represent the true moisture source, either because of a lack of dew point data or misidentification of the moisture source region location. In this study, 8 storms were affected by this 1.50 cap on the IPMF (see Figure 6.2 for location of each of the storms listed):

- June 1906, SPAS 1335
- May 1923, SPAS 1521
- May 1961, SPAS 1334
- June 1969, SPAS 1505
- June 1970, SPAS 1504
- June 1975, SPAS 1252
- June 2005, SPAS 1492
- May 2011, SPAS 1404

The IPMF calculation procedure in this study used the updated maximum dew point climatology described in Section 4. An interesting result of this analysis showed that in several cases, surface dew points and the standard IPMF factor process did not properly identify the primary moisture source associated with rainfall events, resulting in relatively high IPMFs. Several factors combine to produce these general storm rainfall events along the Front Range of the Rockies from Wyoming through Alberta. Although not all of the processes leading to these consistently high IPMFs are understood, some likely causes include the effects of topography (upslope), the interactions of lift by convergence associated with the low pressure system, and frontal dynamics. Examination of the synoptic pattern associated with several of these events (e.g. HMR 55A Section 2.4.1.6) shows that there is an influx of moisture at the mid-levels of the atmosphere (~1,524 to 6,096 meters) from the west (Pacific) that is not reflected at the surface. Because of this, the storm maximization calculation representing the moisture supplying the storms is often not well defined by surface based dew point observations. Several factors affect the standard process of using surface based dew points to represent the moisture source for these storm events. In most cases, the moisture source for the storms is a combination of the Pacific Ocean, which has been disrupted by the interaction of the mountain ranges upstream of the region, and the Gulf of Mexico. In addition, there are generally fewer dew point observation stations in the relatively less populated regions to represent the moisture content of the atmosphere. Finally, the surface flow into these storms transitions from a preferred southeasterly component in southern Front Range to a northeasterly component in northern Front Range (e.g. HMR 55A Figure 3.3). Therefore, the Gulf of Mexico low-level moisture source is more intermittent and not reflected in storm patterns producing extreme rainfall in the northern Front Range.

8.1.1 In-Place Maximization of the Gibson Dam, June 1964 Storm

For the Gibson Dam, MT, June 1964 (SPAS 1211) storm there was insufficient data to accurately determine the storm representative dew point. Further, because this storm was one of the storms most important for determining the level of PMP values, a more accurate representation of the IMPF was required. During evaluation of this storm as part of the Wyoming statewide PMP study (see Section 7.1, Kappel et al., 2014), discussions with the Review Board and others involved in that project determined that it was more appropriate to look at the average IPMF for all storms of the same type in the same region and utilize those data to justify a more appropriate IPMF. This analysis produced an average IPMF of 1.30 for general storms east of the Continental Divide. Therefore, the IPMF for the Gibson Dam, MT, June 1964 (SPAS 1211) event was at 1.30. The rationale for this decision was based on the extraordinary magnitude of the storm, which is highly unlikely to have maximization factors greater than the overall average of many storms, all of which are much smaller in magnitude.

8.2 Storm Representative Dew Point Determination Process

Storm maximization and average dew point values for the duration most consistent with the actual rainfall accumulation period for an individual storm (i.e. 6-, 12-, or 24-hour) were used to determine the storm representative dew point. To determine which time frame was most appropriate, the total rainfall amount was analyzed. The duration closest to when approximately 90% of the rainfall had accumulated was used to determine the duration used, i.e., 6-, 12-, or 24-hour.

The storm representative dew point was investigated for each of the storm events analyzed during this study. Once the general upwind location was determined, the hourly surface observations were analyzed for all available stations within the vicinity of the inflow vector. From these data, the appropriate durational dew point value was averaged for each station (6-, 12-, or 24-hour depending on storm's rainfall accumulation). These values were then normalized to 1000mb (approximately sea level) and the appropriate storm representative dew point and location were derived. The line connecting this point with the storm center location (point of maximum rainfall accumulation) is termed the moisture inflow vector. The information used and values derived for each storm’s moisture inflow vector are included in Appendix F.

The HYSPLIT trajectory model developed by the NOAA Air Resources Laboratory (Draxler and Rolph, 2012) was used during the analysis of each of the rainfall events included on the short storm list when available (1948-present). Use of a trajectory model provides increased confidence in determining moisture inflow vectors and storm representative dew points. 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., 2006-2013, Kappel et al., 2012-2015).

In determining the moisture inflow trajectory, the HYSPLIT model was used to compute the trajectory of the atmospheric moisture inflow associated with the storm's rainfall production, both location and altitude, for various levels in the atmosphere. The HYSPLIT model was run for trajectories at several levels of the lower atmosphere to capture the moisture source for each storm event. These included 700mb (approximately 3,000 meters), 850mb (approximately 1,500 meters), and the storm center location surface elevation. For the majority of the analyses, a combination of all three levels was determined to be most appropriate for use in evaluation of the upwind moisture source location. It is important to note that the resulting HYSPLIT model trajectories are only used as a general guide to evaluate the moisture source for storms in both space and time. The final determination of the storm representative dew point 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.

The process involves deriving the average dew point values at all stations with dew point data in a large region along the HYSPLIT inflow vectors. Values representing the average 6-, 12-, and 24-hour dew points are analyzed in Excel spreadsheets, and with the appropriate duration representing the storm being analyzed, plotted for evaluation of the storm representative dew point. This evaluation includes an analysis of the timing of the observed dew point values to ensure they occurred in a source region where they would be advected into the storm environment at the time of the rainfall period. Several stations are investigated to find values that are of generally similar magnitude (within a degree or two Celsius). Once these representative locations are identified, an average of the values to the nearest half degree is determined and a location in the center of the stations is identified. This becomes the storm representative dew point value and the location provides the inflow vector (direction and distance) connecting that location to the storm center location. This follows the approach used in HMR 51 Section 2, HMR 55A Section 5, and HMR 57 Section 4 with improvements provided by the use of HYSPLIT and updated maximum dew point climatologies. Appendix F of this report contains each of the HYSPLIT trajectories analyzed as part of this study for each storm (when used).

8.3 Storm Representative Dew Point Determination Process

As an example, Figure 8.1 shows the HYSPLIT trajectory model results used to analyze the inflow vector for the Glen Ullin, ND June 1966 (SPAS 1324) storm. Note, in this HYSPLIT analysis, both the 700mb and 850mb inflow vectors (green and blue lines) are very similar in direction and distance, while the surface inflow vector (red line) is similar initially, then changes direction after the first 12 hours. In this case, surface dew point values were analyzed for a region starting at the storm center and extending south and east into Great Plains and along the Front Range. All of the HYSPLIT inflow vectors showed a south to southeast inflow direction (the most common inflow direction for storms in this region). The air mass source region supplying the atmospheric moisture for this storm was located over western Nebraska 48-72 hours prior to the rainfall occurring, showing the influence of the Low-Level Jet over the Great Plains and moisture feed initially from the Gulf of Mexico. This is very similar to several other analysis of moisture sources for the region around the Elbow River basin (e.g. Hunter et al., 2002; Flesch and Reuter, 2011; Szeto et al., 2011; Milrad et al., 2015). Surface dew points were analyzed over this source region, ensuring that the dew point observations were located outside of the area of rainfall to avoid contamination of the dew points by evaporating rainfall. Figure 8.2 displays the stations analyzed and their representative 6-hour average dew point values. The region encircled in red is considered the moisture source region for this storm.

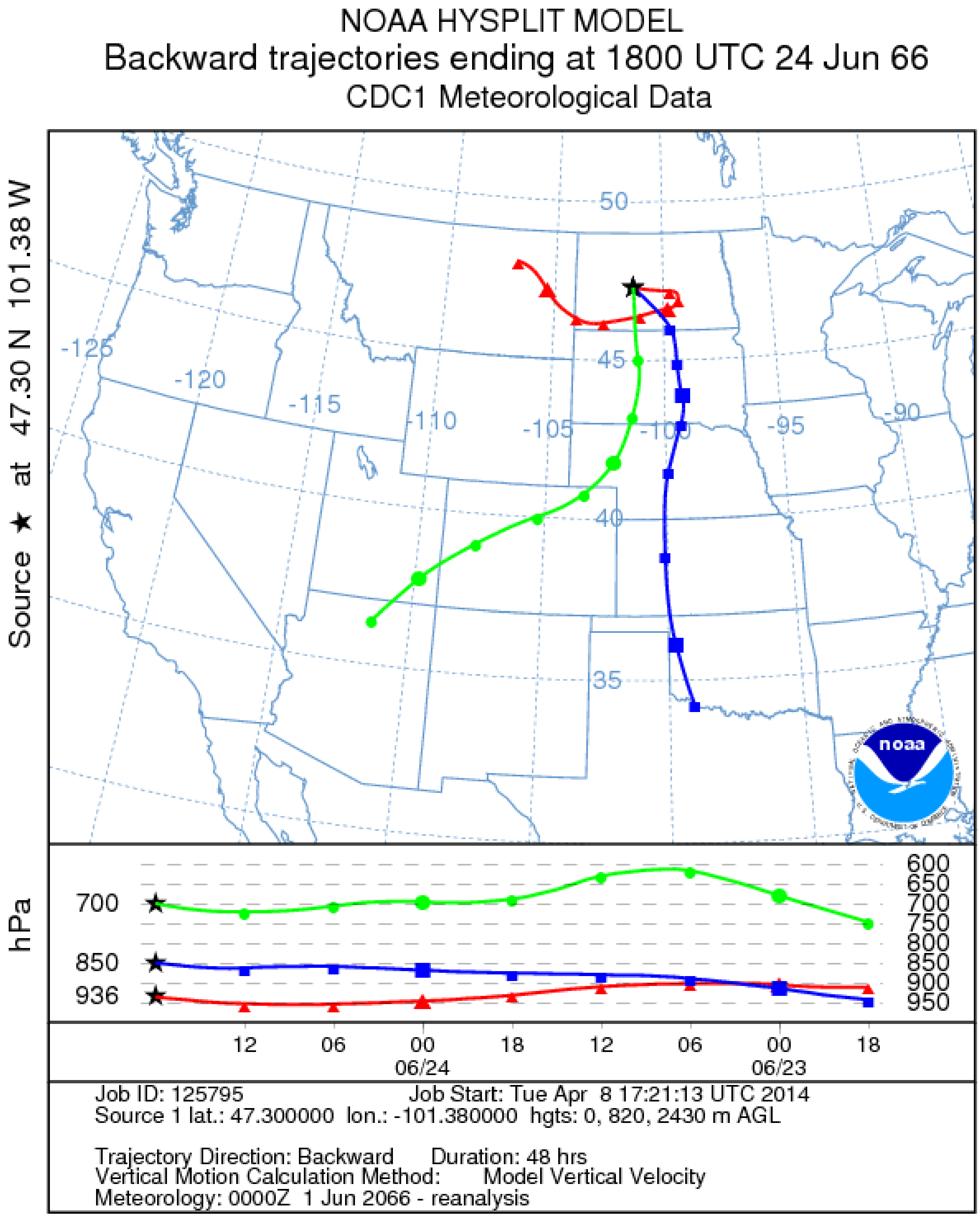

Figure 8.1 HYSPLIT trajectory model results for the Glen Ullin, ND June 1966 storm

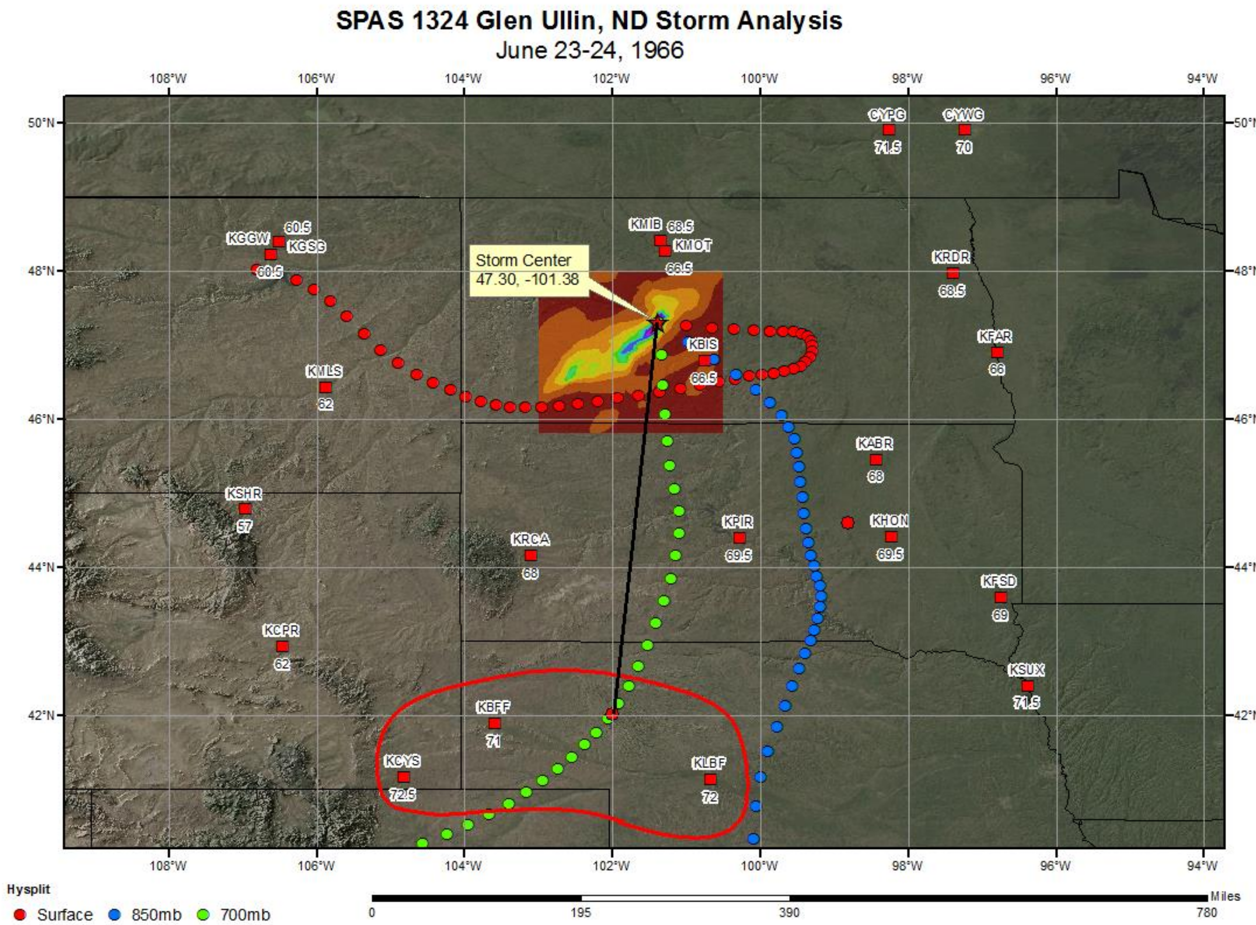

Figure 8.2 Surface stations, 6-hour average dew points, and moisture source region, along with HYSPLIT trajectory model results for the Glen Ullin, ND June 1966 storm

9 Storm Transpositioning

Extreme rain events in meteorologically similar regions surrounding a watershed are a very 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. 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 that could have occurred if that storm had been located 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 grid was placed over the Elbow River 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 and average approximately 5-square kilometers at the basin location. There are a total of 318 grid cells/ grid points in the grid network above the Glenmore Dam. There are 226 grid points when considering only the area upstream of the SR1 diversion, and 19 grid points upstream of the SR1 dam. This universal grid provides a consistent template for the grid cell by grid cell analysis. Figure 9.1 shows the grid over the Elbow River basin.

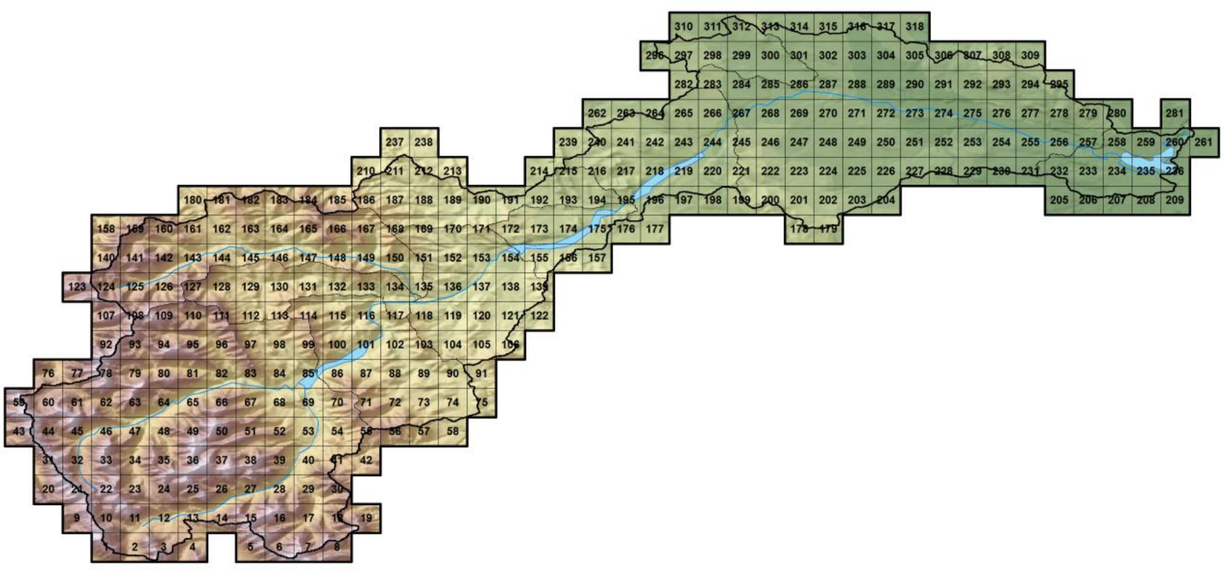

Figure 9.1 The universal 90 arc-second grid network placed over the Elbow River basin

Each of the 22 short list storm centers were transposed from the storm center location to each of the grid points within the target drainage basin area. The transposition process includes a moisture transposition factor (MTF) component and the OTF component. The moisture transposition component closely follows the procedures in HMR 55A, WMO (2009), and previous AWA studies. The orographic transposition process uses 100-year precipitation frequency values to quantify the differences in extreme rainfall between the 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 was 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 OTF: the rainfall values used to derive the ratio at the in-place storm center location to the basin inherently have the elevation component incorporated. All else being equal, the total adjustment factor would change by approximately 1% per 30 meters difference in elevation. In other words, about 1% less moisture would be available to a given storm if one were to transpostion the storm to a new location that was 30 meters higher than its original location, and conversely, about 1% more moisture would be available in one were to transpostion a storm to a new location that was 30 meters lower than the original location. The transposition procedures are defined in the following sections.

9.1 Moisture Transposition

The same monthly climatological maximum +2 sigma SST data sets used for storm maximization 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 9.2 shows an example of inflow vector transpositioning for the Simonette Lo, Alberta, July 1987 storm center. The upwind end of the vector identifies the location for the transposition maximum dew point. The value of the climatological maximum dew point at that location provided the transpositioned maximum dew point value used to compute the moisture 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 temporal transposition date for the storm transposition shown in Figure 9.2 is July 15th. For this storm, the 100-year, 24-hour July dew point data are extracted to obtain the transpositioned dew point at each basin grid point. Figure 9.2 shows the July 100-year 24-hour dew point climatological data as a background grid.

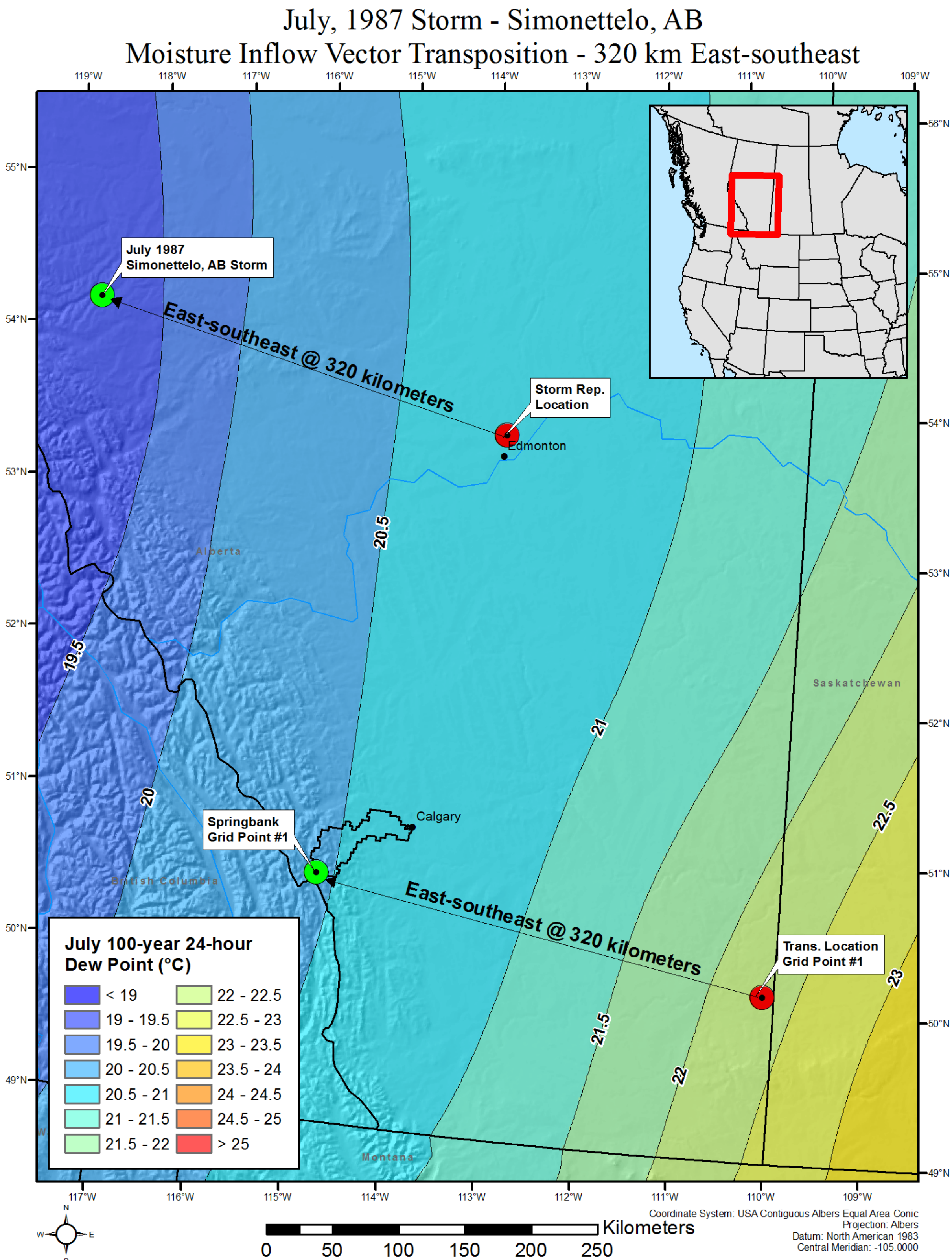

Figure 9.2 An example of inflow wind vector transpositioning for the July 1987 storm. The storm representative dew point location is ~320 kilometers east-southeast of the storm location.

9.2 Orographic Transposition

9.2.1 Topographic Effect on Rainfall

The terrain within the Elbow River basin and the surrounding region is complex, varying significantly over relatively short distances (Figure 9.3). 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. This was completed using the precipitation frequency datasets to derive the OTF. This approach is similar to what was used in recent HMRs (e.g. HMR 59, Corrigan, 1999) for evaluating barrier heights and orographic effects in topographically significant regions. However, the OTF procedure is significantly more objective and reproducible than the HMR procedure.

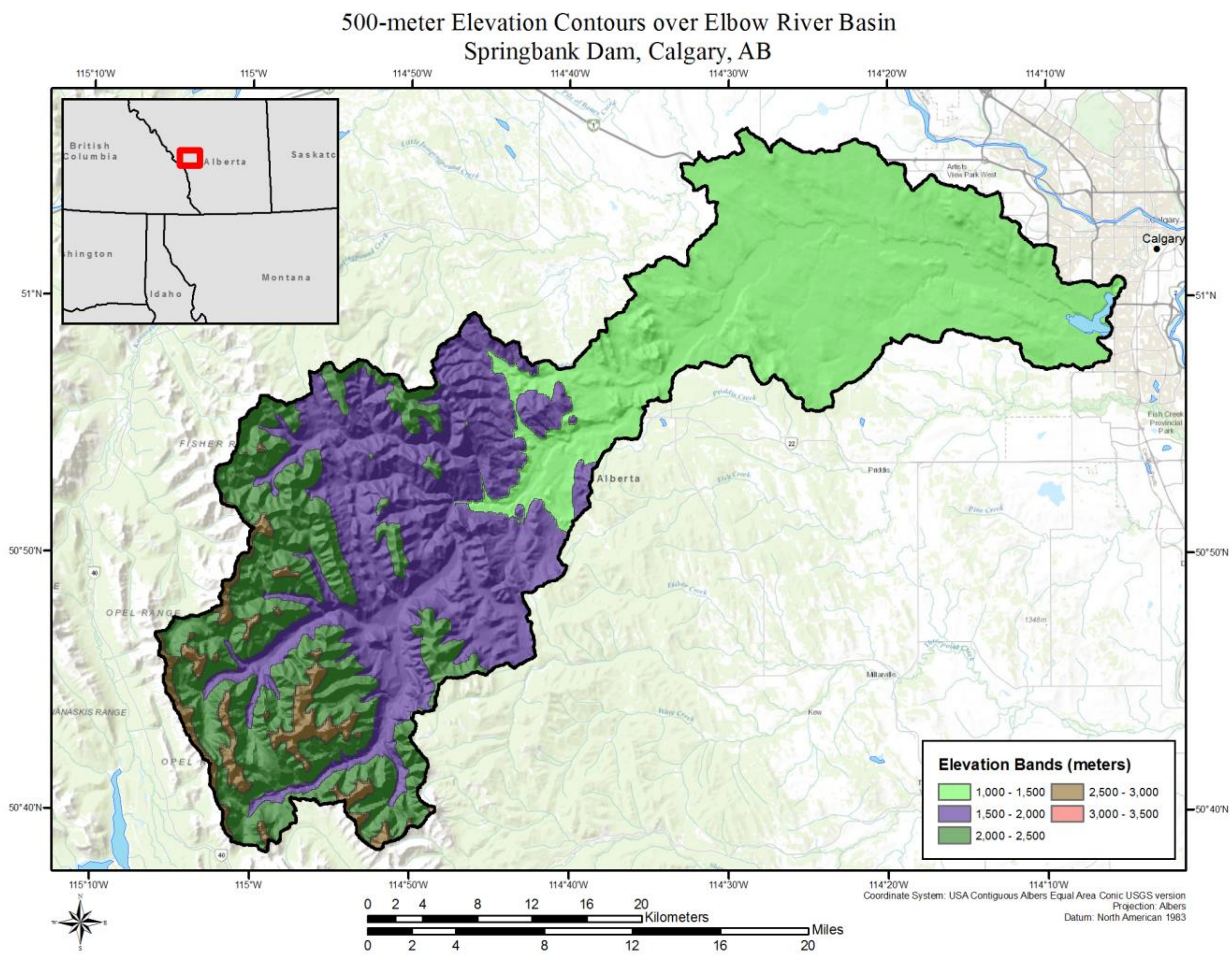

Figure 9.3 500-meter elevations contours over the Elbow River basin and surrounding region

Orographic effects on rainfall are explicitly captured in the 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. The precipitation frequency 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 determines the differences between the precipitation frequency data at the in-place storm location and each grid point within the Elbow River basin. By evaluating the climatological precipitation values at both locations, a relationship between the two locations was established. Figure 9.4 illustrates the 100-year 24-hour precipitation coverage over the region. The spatial distribution clearly exhibits the anchoring of the majority of rainfall to the topography associated with the Rocky Mountains and immediate foothills.

9.2.2 Orographic Transpositioning Procedure

The orographically adjusted rainfall for a given storm at a target (grid cell) location is calculated by applying a ratio, OTF, determined by the relationship between the climatological precipitation depth at the source storm location and the corresponding precipitation at the target location. This study evaluates the relationship of precipitation frequency estimates at the 100-year average recurrence interval. The relationship between the target and the source can be expressed as the ratio shown in Equation 9.1.

$$OTF = \frac{P_t}{P_s} \qquad \text{Equation 9.1}$$

where:

P_t = 100-year precipitation at the target location

P_s = 100-year precipitation at the source location

An example of the determination of the orographic relationship and development of the OTF is given in Section 10.3.

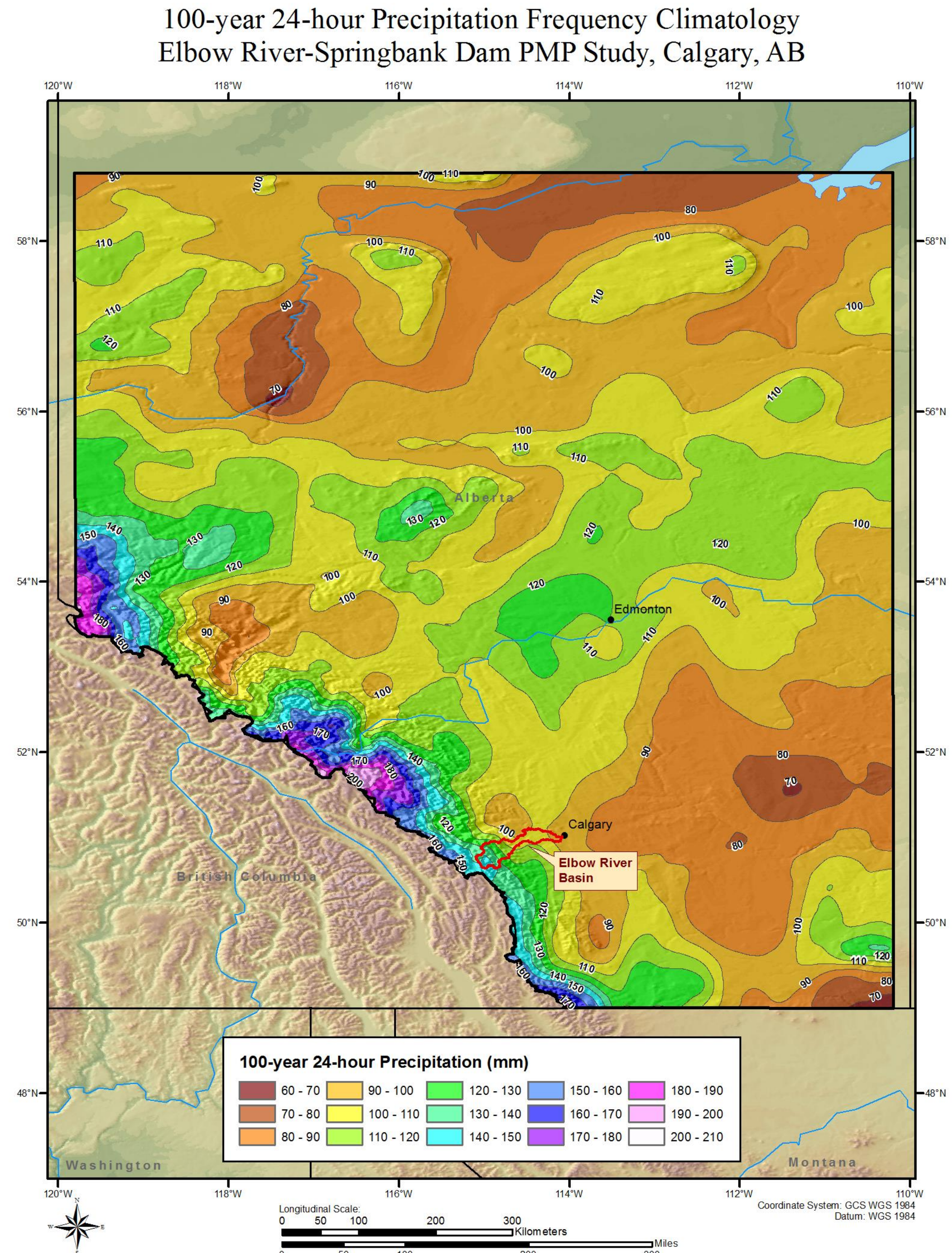

Figure 9.4 100-year 24-hour precipitation over the Elbow River basin and surrounding region

10 PMP Calculation Procedures

PMP depths were calculated by comparing the total adjusted rainfall values for all transpositionable storm events for each grid cell and taking the largest value. This process is similar to the envelopment process described in the WMO Manual for PMP (2009). In this case, envelopment occurs because the largest PMP depth for a given duration is derived after analyzing all storms for each grid cell at each location, and for each duration, over the Elbow River basin.

The adjusted rainfall at a grid cell, 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, at each analyzed duration. The TAF is the product of the three separate storm adjustment factors, the IPMF, the MTF, and the OTF (see Equation 1.1). In-place maximization and moisture transposition are described in Sections 8 and 9. Orographic transposition is described in Section 9.2. These calculations were completed for all transpositionable storm centers for each of the 318 analyzed basin grid cells.

An Excel storm adjustment spreadsheet was produced for each of the transpositionable storm centers. These spreadsheets are designed to perform the calculation of each of the three adjustment factors, along with the final TAF, for each grid cell. 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 precipitation frequency 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 22 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. The tool produces gridded PMP datasets for each duration and a point shapefile holding PMP values for all durations. The PMP durations calculated for this project are 1-, 6-, 12-, 24-, and 48-hours for general storm types and 1-, 2-, 3-, 4-, 5-, and 6-hours for local storm types.

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. Examples of calculations using the data from the maximized and transpositioned Calgary, Alberta, June 2013 storm are provided.

10.1 In-Place Maximization Factor

In-place storm maximization is applied to each storm event using the methodology described in Section 8. Storm maximization is quantified by the calculation of the IPMF using Equation 10.1.

$$IPMF = \frac{W_{p,max}}{W_{p,rep}} \qquad \text{Equation 10.1}$$

where:

$W_{(p,max)}$ = precipitable water for the maximum dew point

$W_{(p,rep)}$ = precipitable water for the representative dew point

Example:

Using the storm representative dew point and storm center elevation as input, the precipitable water lookup table returns the depth, in millimeters, to be used in Equation 10.1. The storm representative dew point is 18.6 °C, calculated using the procedures described in Section 8. The storm center elevation is approximated at 2,600 meters at the storm center of 50.635°N, 114.855°W. The storm representative available moisture (*Wp, rep*) is calculated:

$$W_{p,rep} = W(@18.6°)_{p,91,000m} - W(@18.6°)_{p,2,600m}$$

or,

$$W_{p,rep} = 46mm \text{ - } 29\text{mm}$$

$$\boldsymbol{W_{p,rep} = 17mm}$$

The temporal transposition date for the Calgary, Alberta, June 2013 event is July 10th, therefore a combination of the June and July 100-year 24-hour climatological maximum dew point is the appropriate dataset to use as a moisture source for this storm. The combined June-July maximum dew point at the upwind storm representative location is 21°C at the in-place elevation of 2,600 meters. The storm location climatological maximum available moisture ($W_{p,\ max}$) is calculated:

$$W_{p,max} = W(@21°)_{p,91,000m} - W(@21°)_{p,2,600m}$$

$$W_{p,max} = 56mm \text{ - } 34\text{mm}$$

$$\boldsymbol{W_{p,max} = 22mm}$$

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, from Equation 10.1:

$$IPMF = \frac{22mm}{17mm}$$

$$\boldsymbol{IPMF = 1.29}$$

10.2 Moisture Transposition Factor

The change in available atmospheric moisture between the storm center location and the basin target grid cell is quantified as the MTF. This MTF represents the change due to horizontal distance only and is calculated at the storm center elevation. The change 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 dew point at the upwind end of the moisture inflow vector for the target grid cell location, to the moisture for the climatological maximum dew point at the upwind end of the moisture inflow vector for the storm center location.

$$MTF = \frac{W_{p,trans}}{W_{p,max}} \qquad \text{Equation 10.2}$$

where:

$W_{(p,trans)}$ = precipitable water at the target location

$W_{(p,max)}$ = precipitable water at the storm center location

Example:

The transpositioned climatological maximum available moisture must be determined for each target grid cell within the basin domain. There are 318 grid cells within the basin domain, however, only the first grid cell #1, at 50.650° N, 115.025° W (at the southwestern corner of the basin), is discussed in this example. The July 10th climatological maximum dew point temperature at the upwind end of the moisture inflow vector from grid point 1 is 21°C. The moisture transposition factor is computed using the precipitable water in the atmosphere above the storm center elevation, 2,600 meters. The horizontally transpositioned climatological maximum available moisture ($W_{p,\,trans}$) is calculated:

$$W_{p,trans} = W(@21°)_{p,91,000m} - W(@21°)_{p,2,600m}$$

$$W_{p,trans} = 56mm - 34\text{mm}$$

$$W_{p,trans} = 22mm$$

The in-place storm climatological maximum atmospheric moisture ($W_{p,\,max}$) was calculated above for the IPMF:

$$W_{p,max} = 22mm"$$

The MTF is calculated as the ratio of atmospheric moisture for the climatological maximum dew point for the upwind end of the moisture inflow vector for the target grid cell location ($W_{p,\,trans}$), to the moisture for the climatological maximum dew point for the upwind end of the moisture inflow vector for the storm center location ($W_{p,\,max}$), from Section 10.1:

$$MTF = \frac{22mm}{22mm}$$

$$MTF = 1.00$$

In this example, the Calgary, Alberta, June 2013 storm center is very close to grid point 1, so there is no significant difference between the climatological maximum dew point temperature at the storm representative location and the grid point 1 transposition location, resulting in a transposition factor of 1.00.

10.3 Orographic Transposition Factor

Section 9.2 provides details on the methods used in this study to define the orographic effect on rainfall for grids within the basin. The OTF is calculated by computing the ratio of the 100-year 24-hour precipitation at the target grid point location to the source, or storm center location.

$$OTF = \frac{P_t}{P_s} \qquad \text{Equation 10.3}$$

where:

P_t = 100-year precipitation at the target location

P_s = 100-year precipitation at the source location

Example:

Table 10.1 gives an example of 100-year 24-hour precipitation frequency values (in millimeters) at both a storm center location (source) grid cell and a basin (target) grid cell to be used to determine the orographic relationship.

Table 10.1 100-year 24-hour precipitation depths at the storm center (source) and grid cell #1 (target) locations

	100-yr 24-hr Precipitation Depths
SOURCE (X-axis)	140 mm
TARGET (Y-axis)	142 mm
Ratio/Slope (OTF)	1.009

The OTF can be represented graphically as the slope of a line between the target/source depths and the origin when plotted on an x/y axis (Figure 10.1). A slope greater than one indicates a positive orographic effect on rainfall while a slope less than one indicates a negative effect. In this example, the values for the source grid point nearest the storm center are plotted on the *x*-axis while the corresponding target values for the first grid cell in basin are plotted on the *y*-axis.

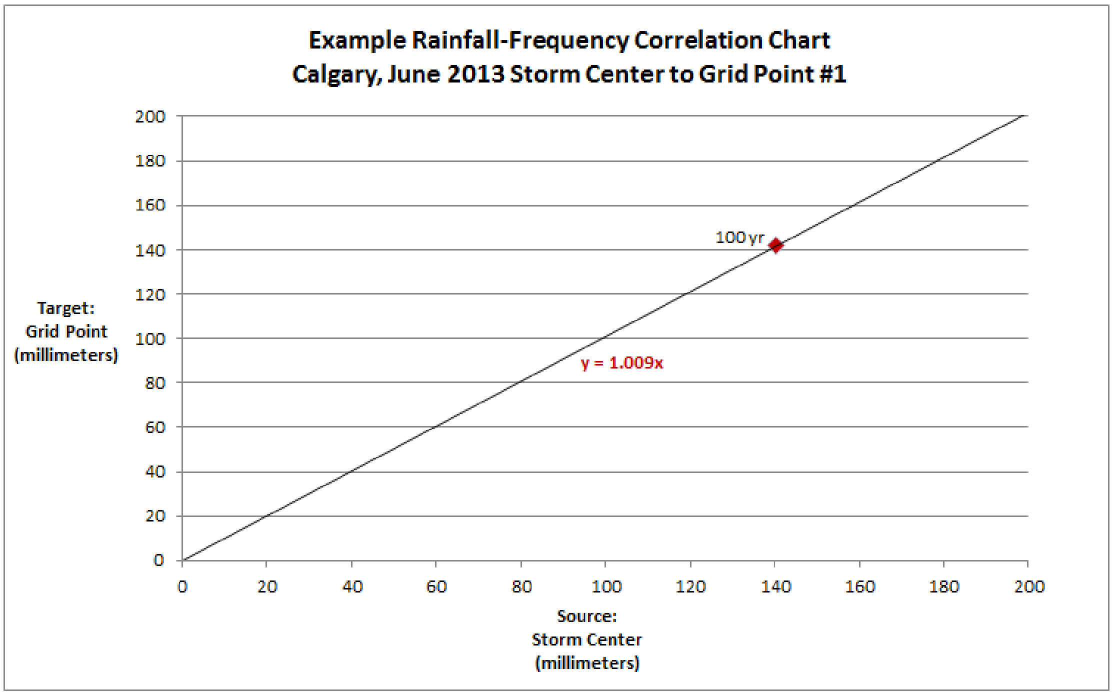

Figure 10.1 Example of orographic proportionality between the Calgary, 2013 storm center and the Elbow River basin grid point 1

The ratio of the target location precipitation (P_t) to the source location precipitation (P_s) yields the OTF.

$$OTF = \frac{142\ mm}{140\ mm}$$

$$\boldsymbol{OTF = 1.01}$$

The OTF to grid cell 1 of the basin is 1.01, or a 1% rainfall increase from the storm center location due to terrain effects. The OTF is then considered to be a temporal constant for the spatial transposition between the specific source/target grid point pair, for that storm only, and can then be applied to the other durations for the storm.

10.4 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.

$$TAF = IPMF * MTF * OTF \qquad \text{Equation 10.4}$$

Example:

For grid point 1, the TAF is calculated as shown in Equation 10.4 using the IPMF from Equation 10.1, the MTF from Equation 10.2, and the OTF from Equation 10.3:

$$TAF = 1.29 * 1.00 * 1.01$$

$$TAF = 1.30$$

To calculate the total adjusted rainfall, the TAF is applied to the SPAS analyzed rainfall depth at the basin area size (1,212 km^2). For the Calgary, Alberta, June 2013 event, the 48-hour SPAS analyzed rainfall depth at the basin size is 264 millimeters. Therefore, the total adjusted rainfall for this storm at grid cell 1 is:

$$Total\ Adj.Rainfall_{48-hr} = TAF * Rainfall_{48-hr}$$

$$Total\ Adj.Rainfall_{48-hr} = 1.30 * 264\ mm$$

$$Total\ Adj.Rainfall_{48-hr} = 344\ mm$$

10.5 Gridded PMP Calculation

The total adjusted rainfall values are computed for each of the 318 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 2-day period. For this study, the index durations are 1-, 6-, 12-, 24-, 48-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 for storms on the short list. Then the total adjusted rainfall values for all storms at a given grid cell are compared and the largest at each grid cell at each duration becomes the PMP value. The PMP at each grid cell will be derived from whichever storm, after maximization and transposition, produces the largest rainfall.

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

11 Development of PMP Values for the Basin

General storm gridded PMP values were developed for the entire drainage basin above Glenmore Dam (1,212 square kilometers) and for the area upstream of the SR1 diversion (863 square kilometers). Local storm gridded PMP values were also developed for the area upstream of the SR1 diversion and the sub-basin upstream of the SR1 dam (31 square kilometers). The three distinct drainage basin scenarios are as follows:

- Scenario 1: Glenmore Dam (1,212-km^2 – includes Scenarios 2 and 3)
- Scenario 2: Above SR1 Diversion (863-km^2)
- Scenario 3: Above SR1 Dam (31-km^2)

General storm PMP depths were produced for scenarios 1 and 2 for the 1-, 6-, 12-, 24-, and 48-hour durations by evaluating the maximized and transpositioned rainfall depths for each general storm at the drainage basin area-size.

Local storm PMP depths were calculated for scenario 2 at the 1-, 2-, 3-, 4-, 5-, and 6-hour durations by evaluating the maximized and transpositioned rainfall depths for each local storm at the 1 square kilometer area-size. The 1 square kilometer area-size is considered to be point rainfall for the purpose of this evaluation as the SPAS-analyzed gridded rainfall spatial resolution is roughly equivalent to 1 square kilometer. The maximum 1 square kilometer gridded PMP value was redistributed over the drainage area as described in Section 8.1. For scenario 3, the gridded local storm PMP was calculated at the sub-basin area-size of 31 square kilometers as no further spatial distribution was necessary.

11.1 Spatial Distribution of PMP

The spatial distribution of the PMP is controlled by 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 100-year 24-hour precipitation frequency spatial distribution over the basin. The spatial distribution is also affected to a lesser extent by variation in moisture, which is controlled by the gradient of the monthly dew point climatology at the source of the moisture inflow vector for the controlling storm event.

The variation in available moisture has a smooth gradient and varies minimally over the relatively small extent of the basin area. For example, the MTF calculated for the June 2013 event is 1.01 over most of the basin with a change to 1.04 over the far eastern portion. A map of the MTF over the basin (Figure 11.1) illustrates the distribution due to moisture.

As discussed in Section 9.2.1, the topography of the basin and surrounding region varies significantly over short distances. Therefore, it is expected that the effect of mountainous terrain would be the defining factor in the spatial distribution of PMP rainfall. 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 precipitation frequency relationship between each grid cell in the basin and a constant location at the storm center. A map of the OTF over the basin for the June 2013 event (Figure 11.2) illustrates the spatial distribution due to terrain.

The spatial distribution patterns, due to the variation in terrain and moisture are apparent in the gridded basin PMP maps. Figure 11.3 shows the basin 48-hour PMP, before storm-specific spatial distribution patterns were applied. The 48-hour PMP was controlled by the Gibson Dam, MT June 1964 and Veteran, AB June 1973 events.

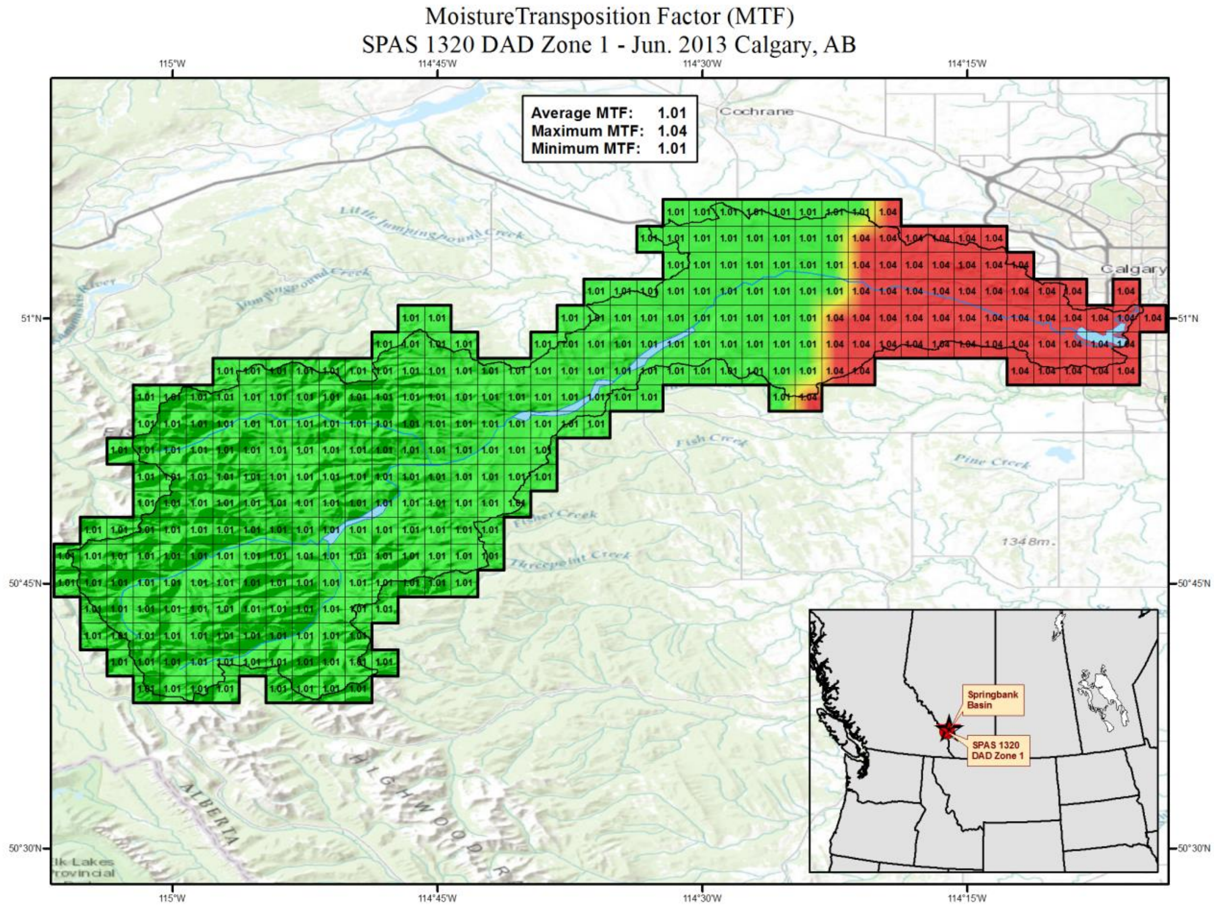

Figure 11.1 Moisture Transposition Factors over the basin

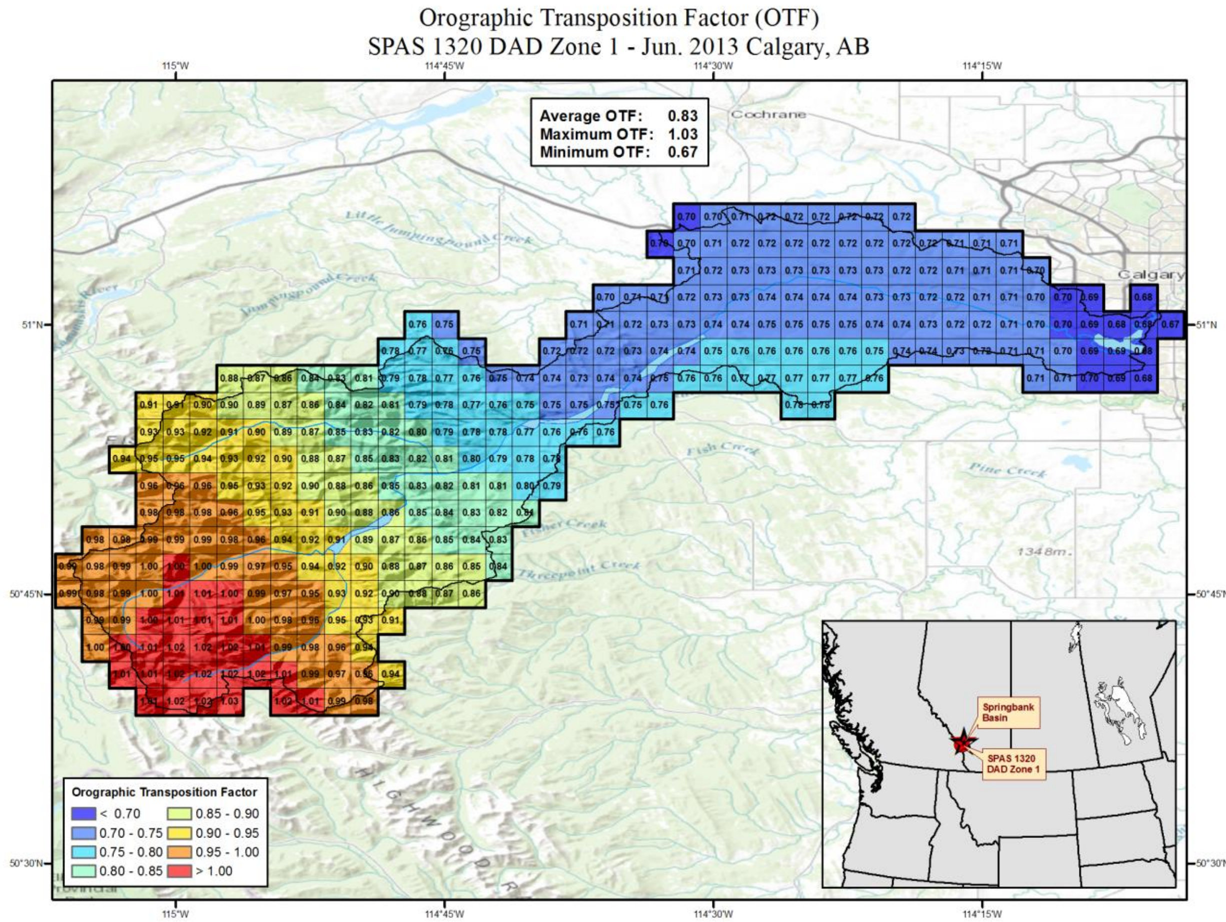

Figure 11.2 Orographic Transposition Factors over the basin

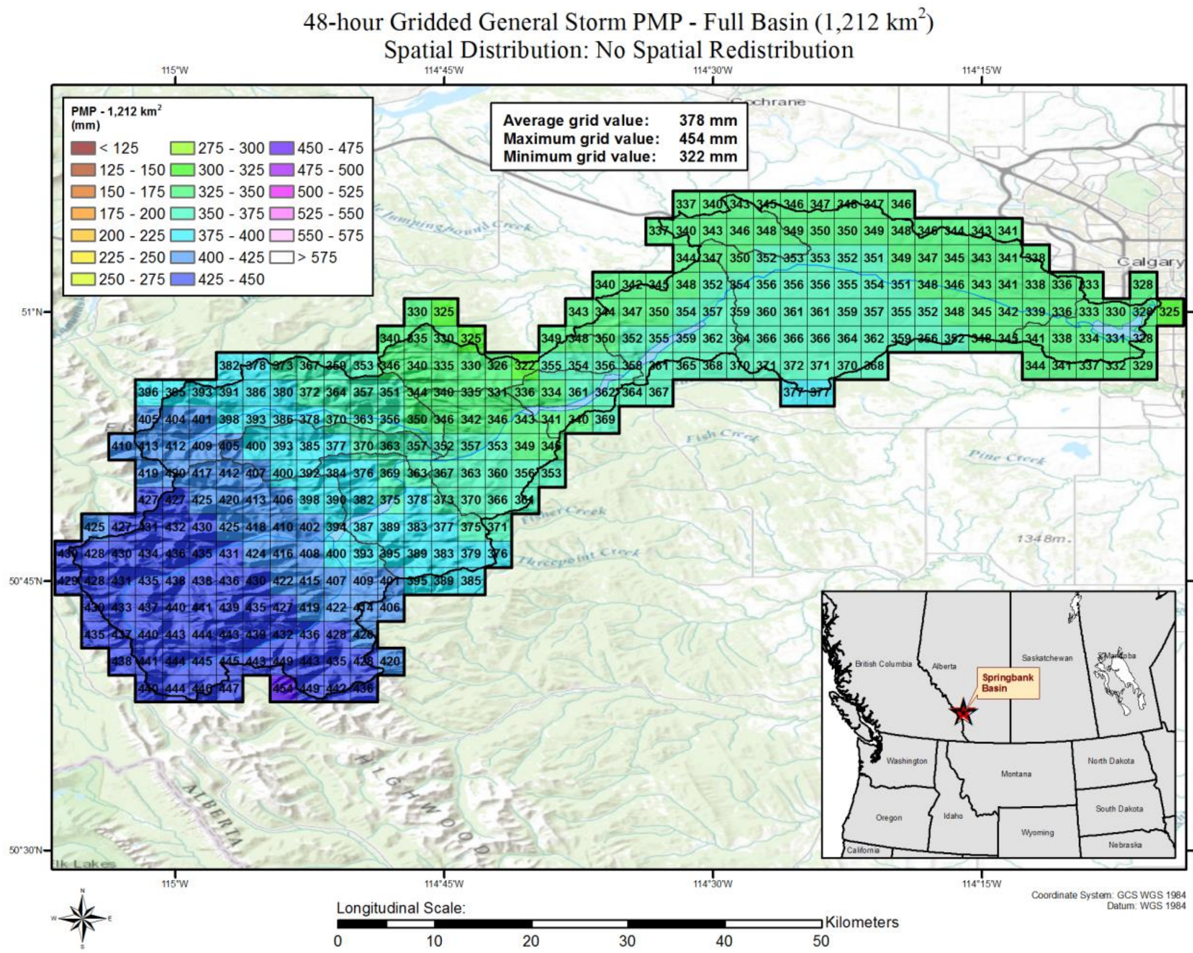

Figure 11.3 Elbow River basin 48-hour gridded PMP

The spatial distribution defined by moisture variation and precipitation frequency variation accurately describes general spatial distribution based on these physical controls as they apply to the driving storms. However, the spatial distribution of general storm PMP depths over the basin were evaluated using actual extreme rainfall events of similar type that have been recorded and analyzed over the basin itself. Two storms; Calgary, Alberta, June 2005 (SPAS 1492), and Calgary, Alberta June 2013 (SPAS 1320) both provided significant rainfall centered over the Elbow River basin and provided appropriate patterns to be considered for the spatial distribution of general PMP.

The spatial distribution of general storm PMP, as illustrated in Figure 11.3, was redistributed over the basin using the patterns of the two SPAS-analyzed historical events which produced significant rainfall over the basin, along with the 100-year 24-hour precipitation climatology pattern.

The various storm distribution patterns are applied by calculating a spatial distribution factor to calculated PMP depth at each grid cell. The spatial distribution factors for each grid cell are determined for a given storm by first extracting the total storm rainfall to each grid cell. An example of the total storm rainfall extracted to each grid cell for the Calgary, Alberta June 2013 event is shown in Figure 11.4a. A ratio, the spatial distribution factor, is then calculated at each grid cell by dividing the grid cell total storm value by the basin average total storm value. An example of the spatial distribution factor at each grid cell for the June 2013 event is shown in Figure 11.4b. An example of the 48-hour basin PMP redistributed to the June 2013 event is shown in Figure 11.5.

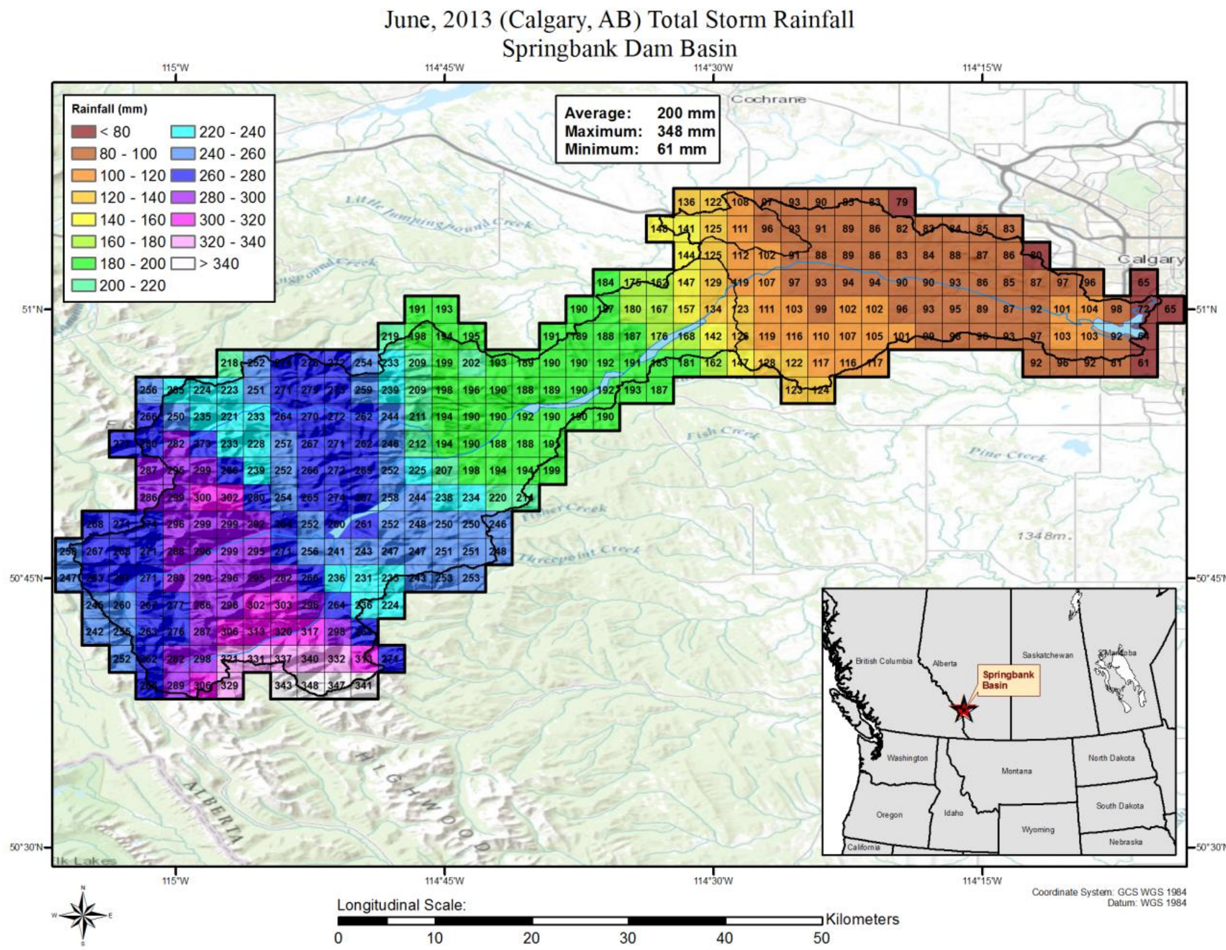

Figure 11.4 a) June 2013 total storm rainfall extracted to each grid point, (b) Spatial distribution factors for the June 2013 event

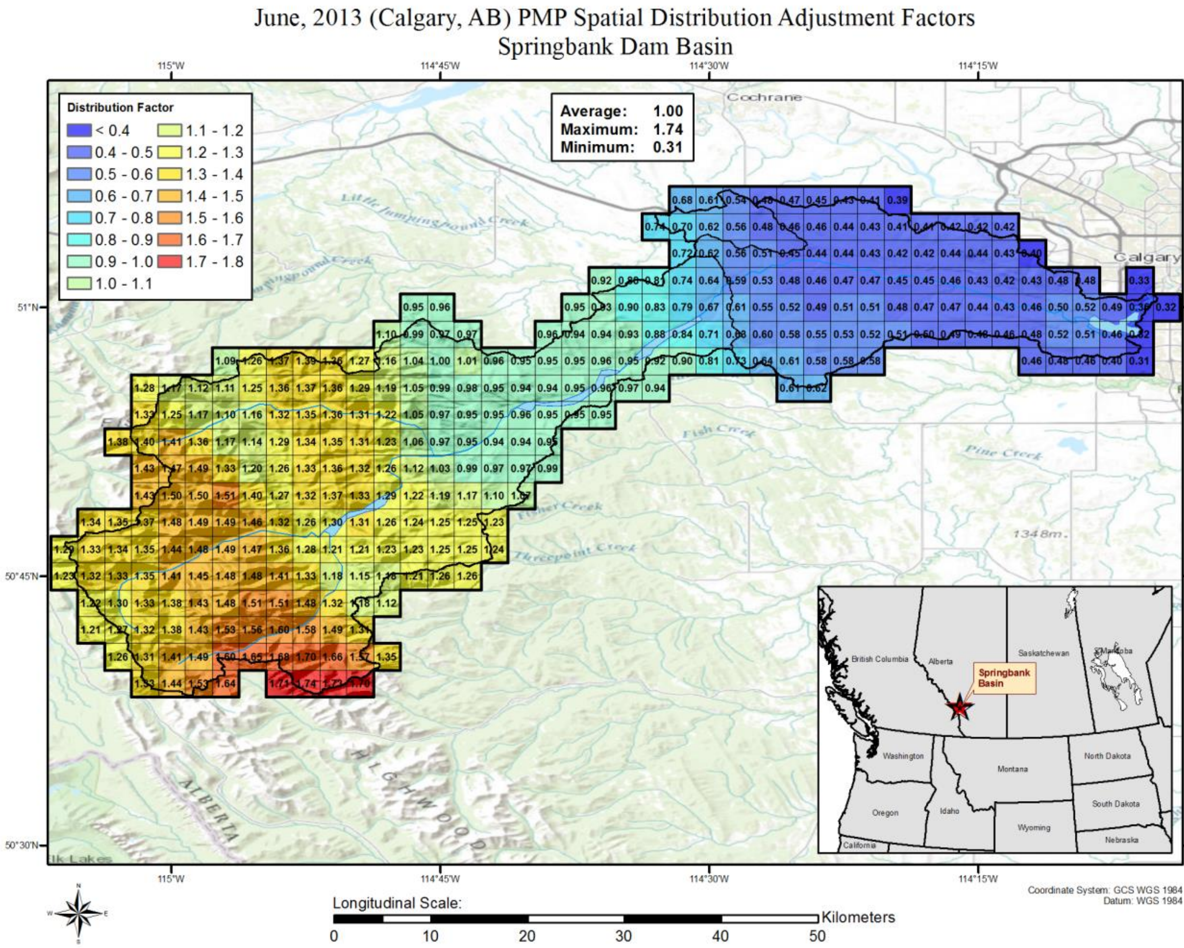

Figure 11.5 a) June 2013 total storm rainfall extracted to each grid point, (b) Spatial distribution factors for the June 2013 event

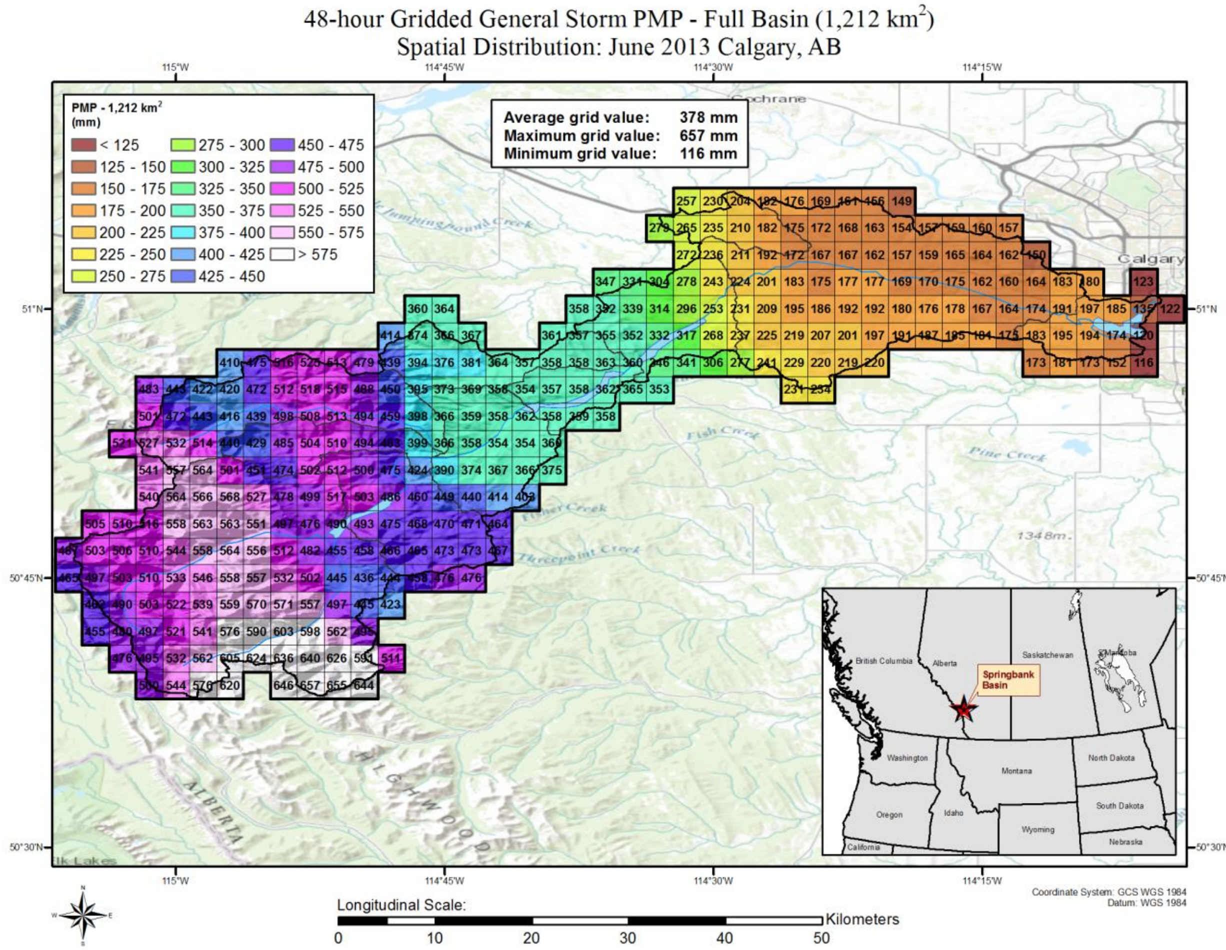

Figure 11.6 Calgary, Alberta, June 2013 spatial distribution applied to the 48-hour gridded PMP

The three different general storm PMP distribution scenarios are shown in Figure 11.6a (Calgary, June 2005), Figure 11.6b (Calgary, June 2013), and Figure 11.6c (100-year 24-hour precipitation.

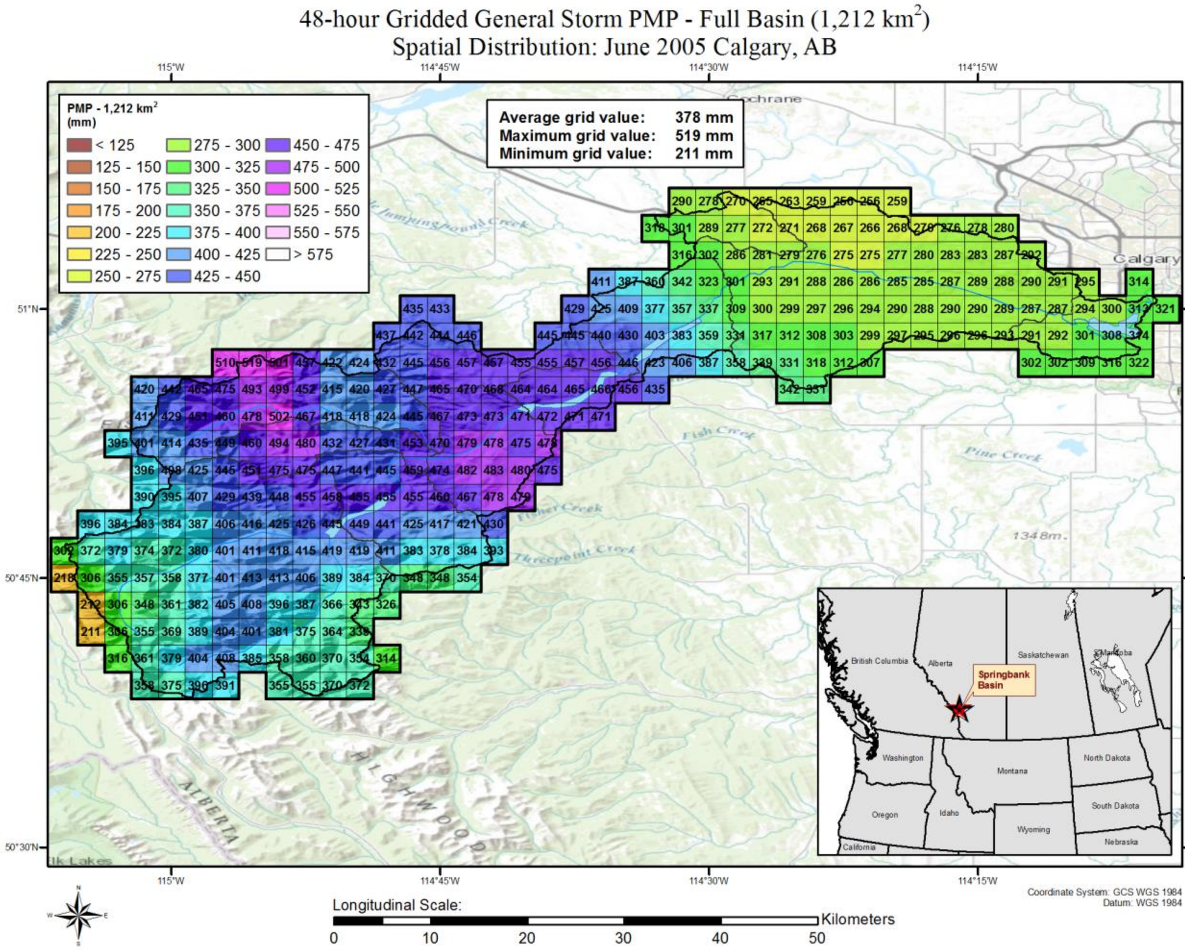

Figure 11.7 48-hour basin PMP from the a) Calgary, Alberta, June 2005 spatial distribution, b) Calgary, Alberta, June 2013 spatial distribution, c) Alternate 100-year 24-hour precipitation climatology spatial distribution

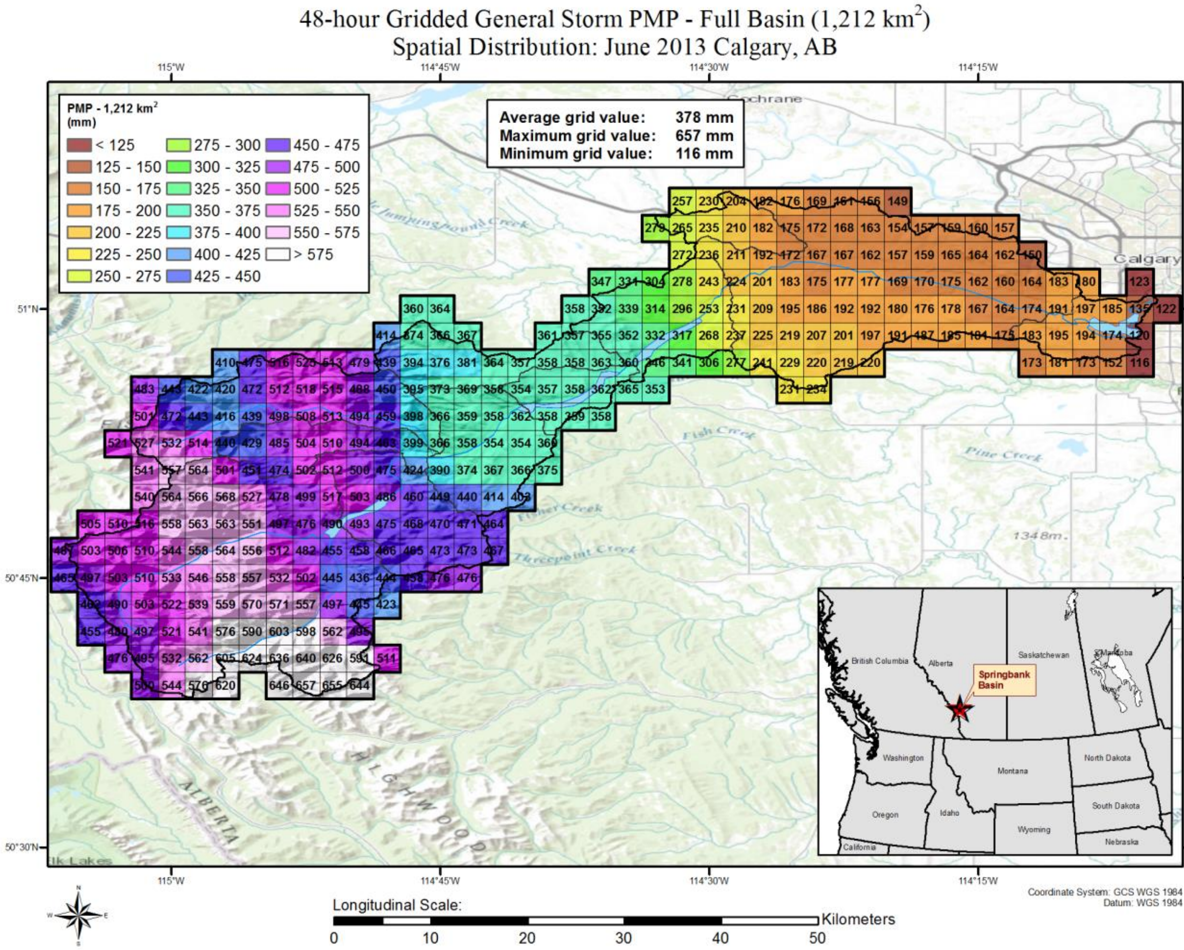

Figure 11.8 48-hour basin PMP from the a) Calgary, Alberta, June 2005 spatial distribution, b) Calgary, Alberta, June 2013 spatial distribution, c) Alternate 100-year 24-hour precipitation climatology spatial distribution

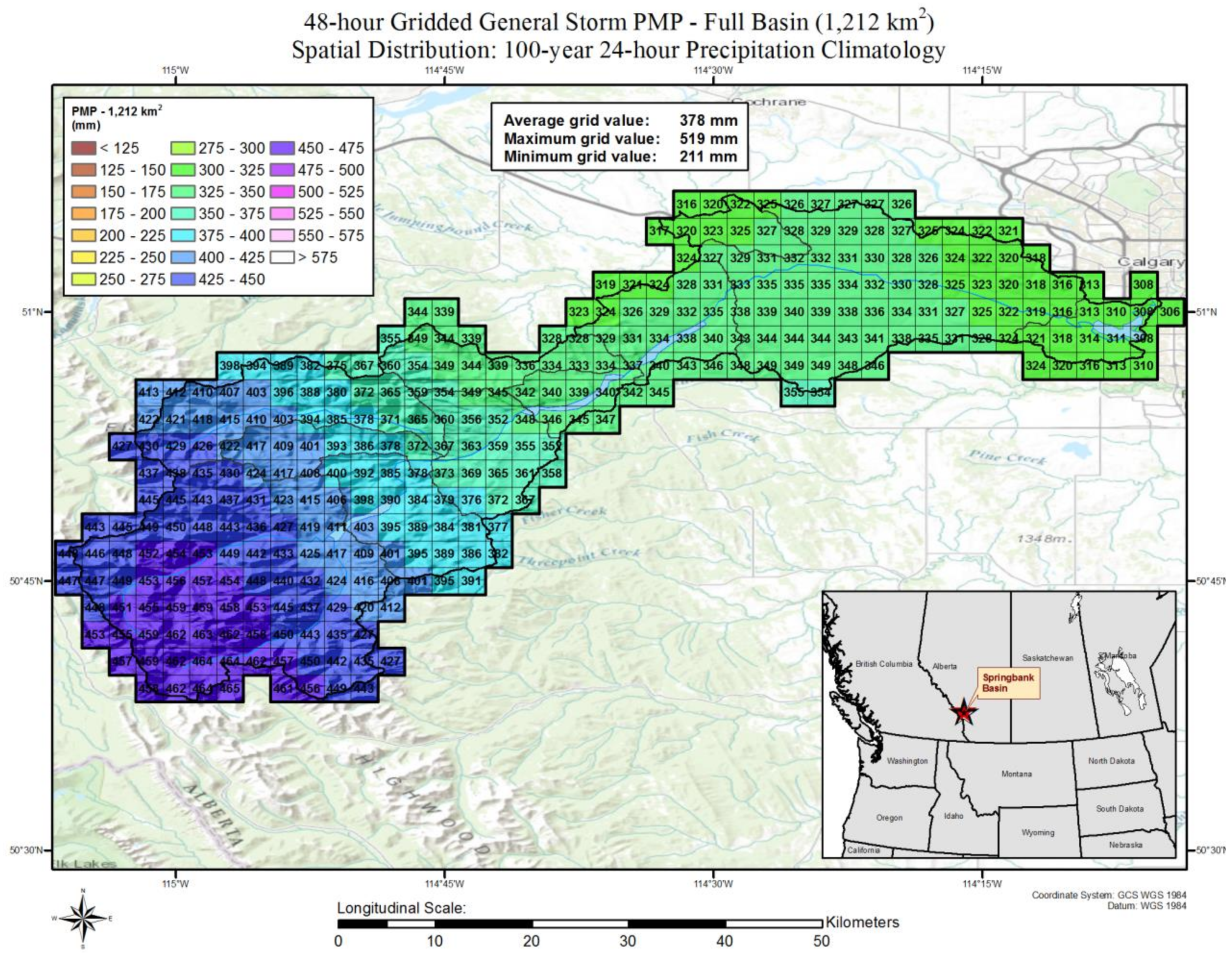

Figure 11.9 48-hour basin PMP from the a) Calgary, Alberta, June 2005 spatial distribution, b) Calgary, Alberta, June 2013 spatial distribution, c) Alternate 100-year 24-hour precipitation climatology spatial distribution

Additional investigation of the local storm spatial distribution was required for the portion of the basin above the SR1 diversion (863km^2). Instead of distributing the 863 square kilometer PMP values over the drainage basin using the local storm 863 square kilometers total adjusted values at each grid point, the maximum 1 square kilometer PMP value was distributed over the basin using a historical storm pattern transposed and centered over the basin. This was done to best replicate the expected accumulation pattern associated with a local storm over the large area size. It was considered inappropriate to assume the local storm would produce full-PMP rainfall at all grid points covering the 863 square kilometer area size for each hour. This is because by definition, a local storm is a short duration (6-hours or less), small area size event (less than 500-square kilometers). Instead, this storm type is expected to produce heavy rainfall over a small area with significantly decreasing rainfall accumulations away from the localized storm center. Therefore, to accurately represent this pattern, yet still achieve the appropriate level of conservatism, the rainfall accumulation patterns of the local storms used in this study were investigated. Each was critically centered over the basin to determine how the actual rainfall accumulation patterns would look had the storm occurred over the basin instead of its original location. After investigating each pattern and through discussions with the review board and hydrologists, it was determined that the Glen Ullin, ND, June 1966 storm event provided a rainfall accumulation pattern that best represented this process. Therefore, the Glen Ullin, ND, June 1966 event was positioned over the basin and rotated so that the maximum amount of rainfall fell inside the drainage boundaries. Spatial distribution factors were calculated for each grid point by taking the ratio of the greatest 1-hour rainfall at each grid point to the maximum 1-hour rainfall depth over the basin. The local storm spatial distribution factors are shown in Figure 11.7. The spatial distribution factors were applied to the maximum calculated 1-hour gridded rainfall PMP depth for the basin. The resulting 1-hour gridded local storm PMP is shown in Figure 11.8.

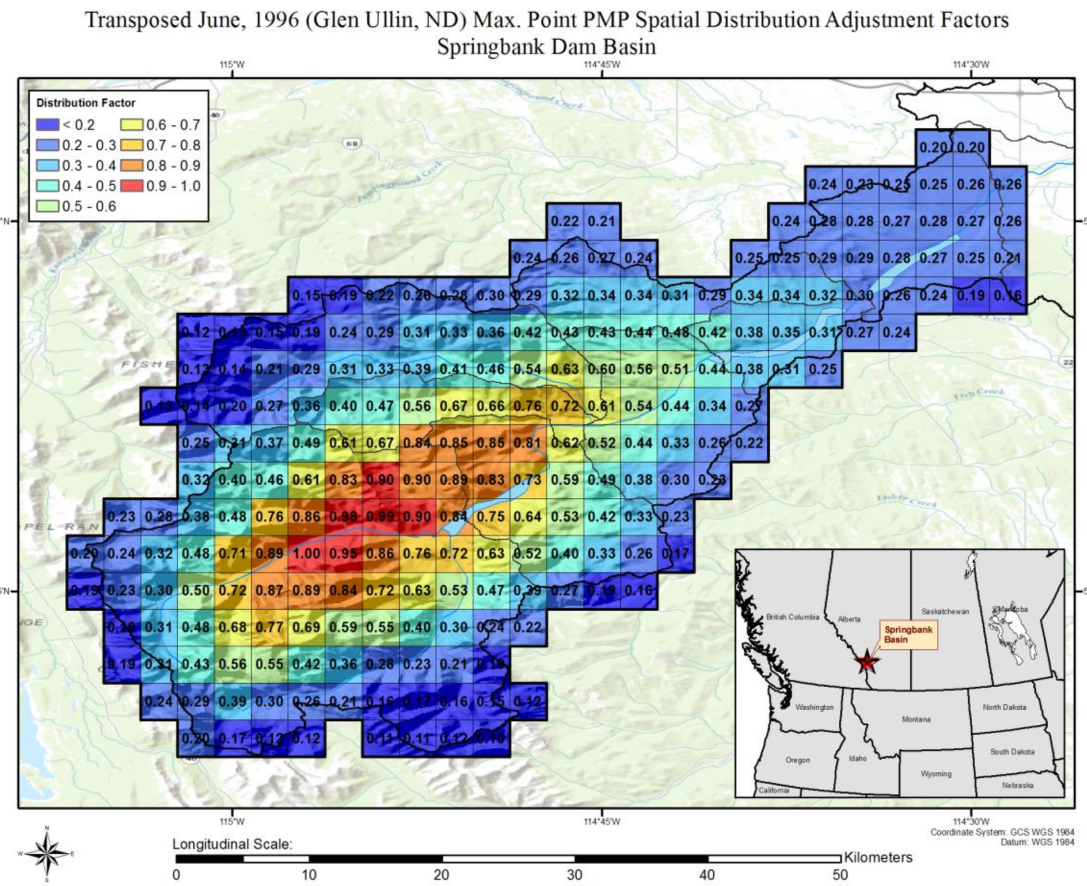

Figure 11.10 Spatial distribution factors for the local storm PMP based on the centered Glen Ullin, ND, June 1966 1-hour Rainfall.

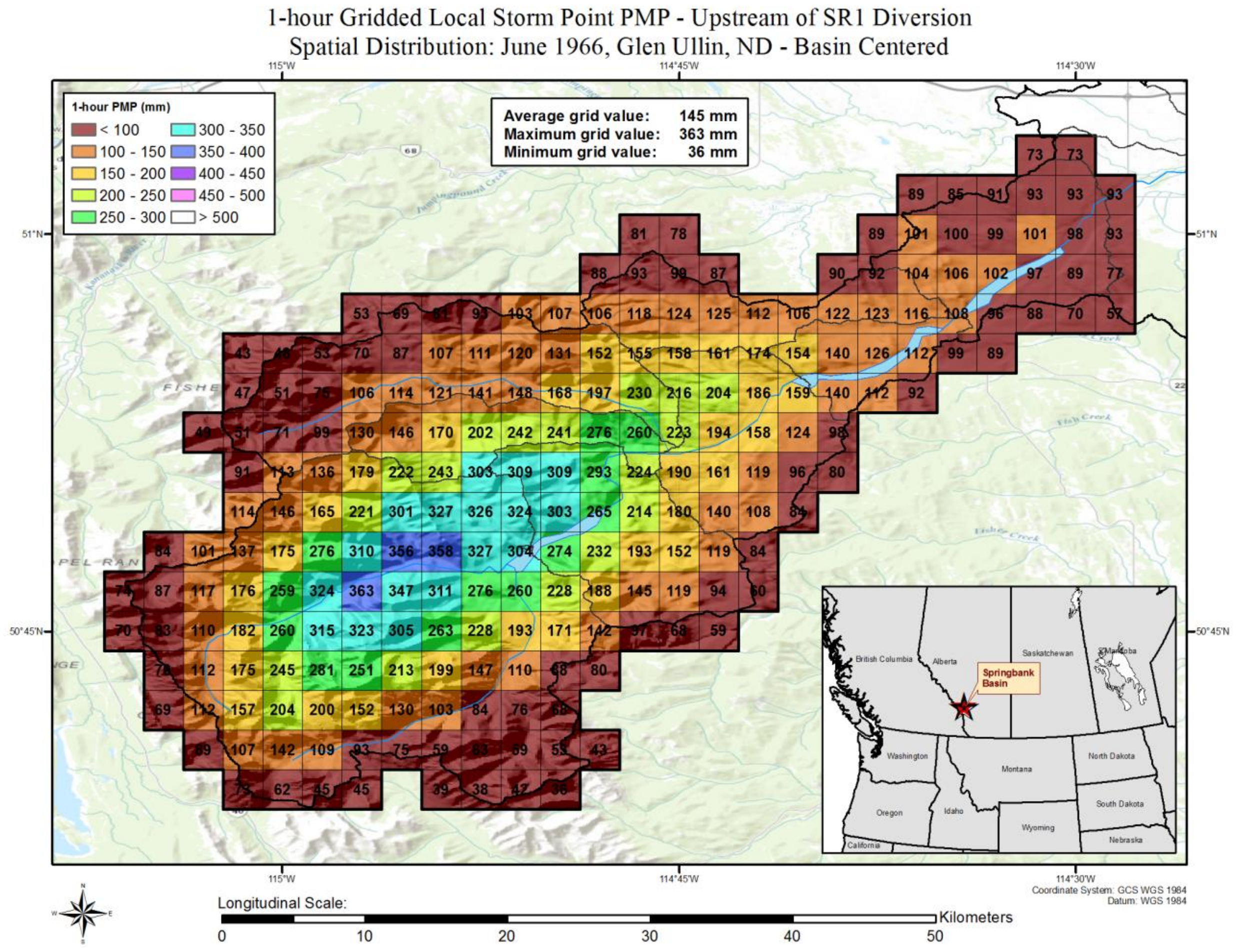

Figure 11.11 Local storm spatially adjusted 1-hour gridded PMP based on the centered Glen Ullin, ND, June 1966 storm pattern.

11.2 Sub-basin Average PMP

For each spatial distribution scenario, the gridded average PMP was determined for each sub-basin within the drainage area. Although grid cells intersecting the basin outline were included within the original analysis, only those with their centroids within the drainage area were included in the sub-basin averages. Sub-basin averages were calculated for general storm PMP for the 11 sub-basins above the Glenmore Dam (1,212 square km), for general and local storm PMP for the 8 sub-basins upstream of the SR1 diversion (863 square km), and the single sub-basin upstream of the SR1 dam (31 square km).

12 Results

Gridded PMP values were calculated for the drainage area of each dam scenario: 1) general storm PMP for the area upstream of Glenmore Dam (1,212 km^2); 2) general and local storm PMP for the area upstream of the SR1 diversion (863 km^2); and 3) local storm PMP for the area upstream of the SR1 dam (31 km^2) (Table 12.1). The gridded PMP was spatially redistributed following the procedures described in Section 11.1 for dam scenarios 1 and 2. For each of these scenarios, PMP was summarized by the gridded average over the sub-basins that comprise the drainage area.

Table 12.1 Drainage basin PMP scenarios. PF in this table refers to Precipitation Frequency.

Scenario	Drainage Basin	Basin Area	Sub-basin Count	PMP Type	Spatial Redistribution
1	Upstream of Glenmere Dam	1212 km²	11	General Storm	Jun. 2005, Jun. 2013, PF Climatology
2	Upstream of SR1 Diversion	863 km²	8	General & Local Storm	Jun. 2005, Jun. 2013, PF Climatology
3	Upstream of SR1 Dam	31 km²	1	Local Storm	None

The following tables summarize the sub-basin average PMP values for each dam scenario. Scenario 1 (Table 12.2) includes general storm PMP for the 11 sub-basins upstream of the Glenmore Dam (shown in Figure 12.1).

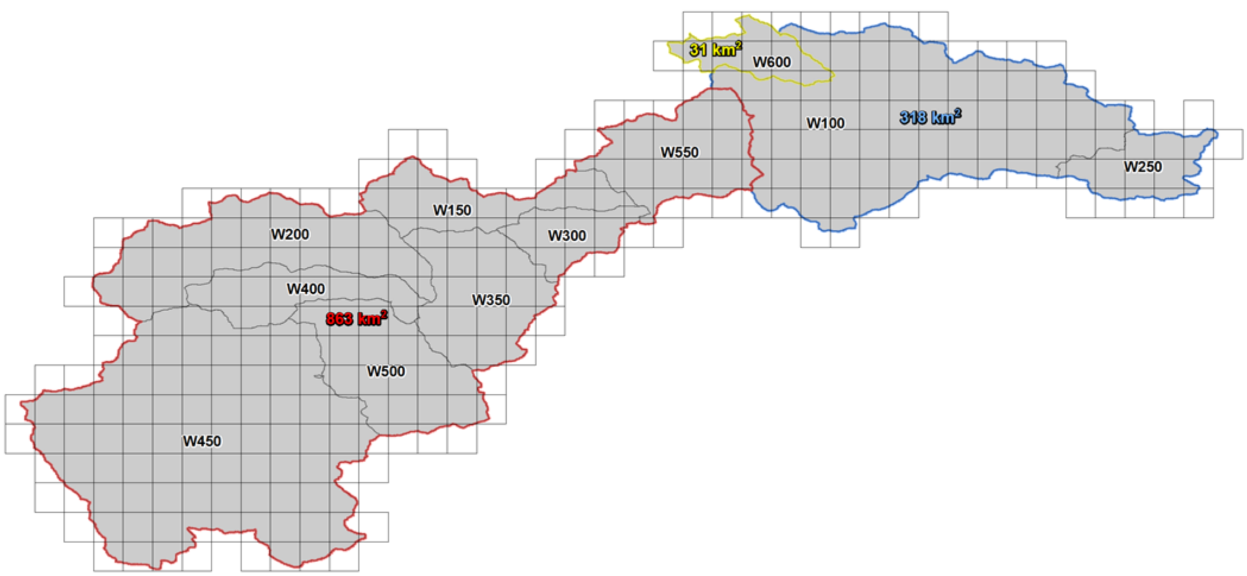

Figure 12.1 The 11 sub-basins included in the PMP analysis for Scenario 1 – upstream of Glenmore Dam (1,212 km^2)

Table 12.2 Sub-basin average 1,212 km² general storm PMP

Sub-basin Name	Sub-basin ID	Sub-basin Area	1-hr PMP (mm)	6-hr PMP (mm)	12-hr PMP (mm)	24-hr PMP (mm)	48-hr PMP (mm)
W100	45	278 km²	47	170	235	312	353
W150	46	58 km²	38	130	212	301	341
W200	47	121 km²	37	126	229	336	382
W250	82	40 km²	45	161	222	294	333
W300	49	34 km²	39	136	217	306	347
W350	52	81 km²	34	116	212	311	353
W400	53	50 km²	38	126	229	337	382
W450	55	353 km²	42	141	256	376	427
W500	56	89 km²	37	126	229	336	381
W550	73	77 km²	48	171	236	313	354
W600	78	31 km²	46	166	229	304	344

Scenario 2 includes the 8 sub-basins upstream of the SR1 Diversion (shown in Figure 12.2). Table 12.3 provides the general storm PMP values for the drainage above the SR1 diversion. Table 12.4 provides the local storm PMP using the 1-hour Glen Ullin, ND, June 1966 spatial redistribution. Table 12.5 provides the local storm PMP for the 31 square kilometer drainage upstream from the SR1 dam.

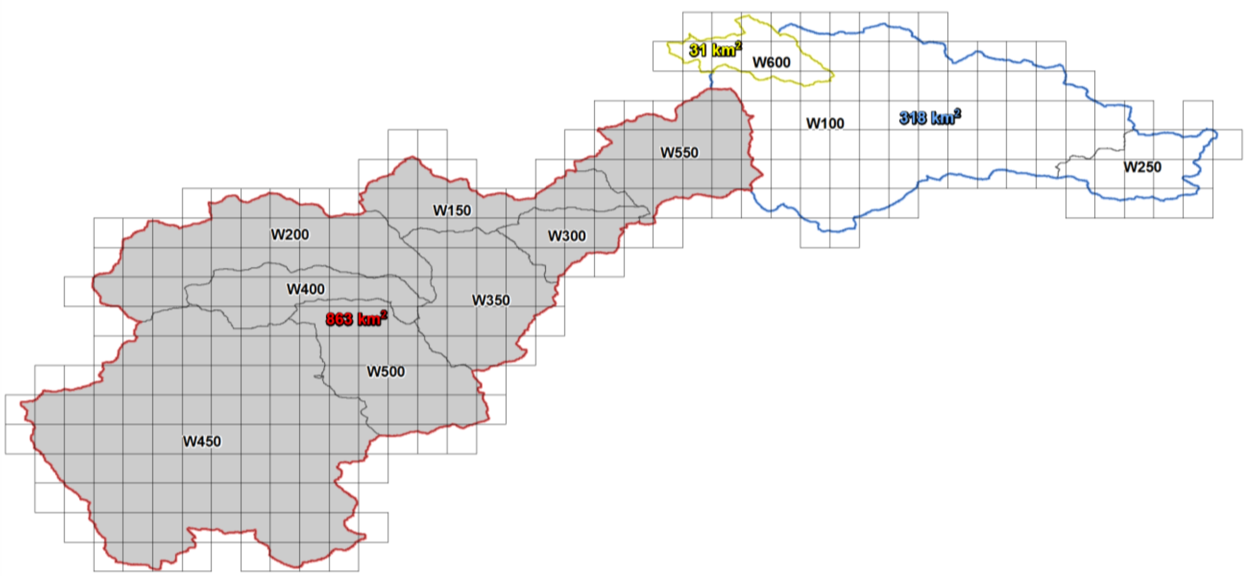

Figure 12.2 The 8 sub-basins included in the PMP analysis for Scenario 2 – upstream of SR1 Diversion (863 km^2)

Table 12.3 Sub-basin average 863 km² general storm PMP for the drainage above the SR1 diversion

Sub-basin Name	Sub-basin ID	Sub-basin Area	1-hr PMP (mm)	6-hr PMP (mm)	12-hr PMP (mm)	24-hr PMP (mm)	48-hr PMP (mm)
W150	46	58 km²	36	125	213	307	347
W200	47	121 km²	42	145	247	356	402
W300	49	34 km²	36	124	211	305	345
W350	52	81 km²	38	131	224	323	365
W400	53	50 km²	42	145	247	356	403
W450	55	353 km²	47	161	275	397	448
W500	56	89 km²	41	142	243	350	396
W550	73	77 km²	35	121	206	298	337

Table 12.4 Sub-basin average local storm PMP using the Glen Ullin, ND June 1966 1-hour rainfall pattern

Sub-basin Name	Sub-basin ID	Sub-basin Area	1-hr PMP (mm)	2-hr PMP (mm)	3-hr PMP (mm)	4-hr PMP (mm)	5-hr PMP (mm)	6-hr PMP (mm)
W150	46	58 km²	116	122	128	141	150	160
W200	47	121 km²	112	118	124	136	145	155
W300	49	34 km²	134	141	148	163	173	186
W350	52	81 km²	153	161	169	186	198	212
W400	53	50 km²	222	233	244	269	286	307
W450	55	353 km²	191	201	211	232	247	264
W500	56	89 km²	214	225	236	259	276	296
W550	73	77 km²	97	102	107	118	126	135

Scenario 3 is the 31 km² sub-basin average local storm PMP (Table 12.5) upstream of the SR1 Dam (shown in Figure 12.3)

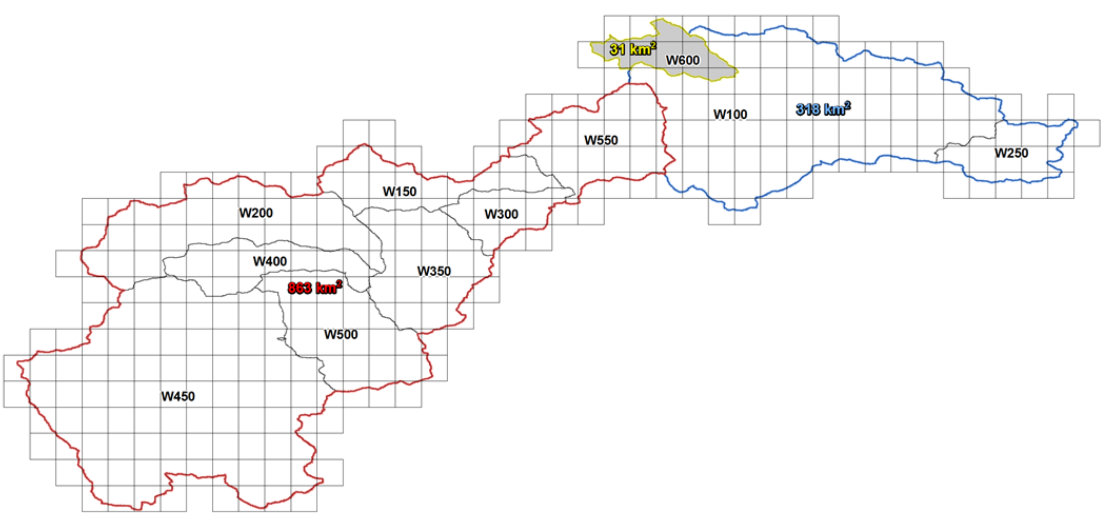

Figure 12.3 The sub-basin included in the PMP analysis for Scenario 3 – upstream of SR1 dam (31 km²)

Table 12.5 Sub-basin average 31 km² local storm PMP upstream of SR1 dam

Sub-basin Name	Sub-basin ID	Sub-basin Area	1-hr PMP (mm)	2-hr PMP (mm)	3-hr PMP (mm)	4-hr PMP (mm)	5-hr PMP (mm)	6-hr PMP (mm)
W600	78	31 km²	157	195	228	245	264	286

12.1 Comparison of the PMP Values with the 24-hour 100-Year Precipitation Frequency

Hourly PMP values were compared with 100-year 24-hour rainfall values as a general check for reasonableness. The ratio of the 10-square mile 24-hour 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 this study we are able to compare values at the individual grid cell size and at the total basin area size of 1,212 square kilometers. 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*" (Corrigan, 1999). Therefore, it would be reasonable to expect the ratios for the Elbow River basin to be in the middle to low end of the range. Comparison of the highest grid cell 24-hour site-specific PMP value to the 100-year 24-hour precipitation frequency value and the 24-hour total basin average rainfall to the 24-hour 100-year return frequency value at the same area size are shown in Table 12.6.

Table 12.6 Comparison of Site-Specific PMP with 24-hour 100-year rainfall frequency data

24-hour Depth at Largest PMP Grid Point*	
24-hour PMP	497 mm
100-year 24-hour Precipitation	143 mm
Ratio of PMP to 100yr 24hr Precipitation	3.48

*Grid point #5 (50.65°,-114.90°)

24-hour Basin Average Depth	
24-hour PMP	396 mm
100-year 24-hour Precipitation	117 mm
Ratio of PMP to 100yr 24hr Precipitation	3.38

13 Assumption and Sensitivity Discussions

In the process of deriving PMP values, various assumptions were made and specific procedures were used which could be derived from a range of possible alternatives. Therefore, it is important to understand how the assumptions made could potentially affect certain aspects of the PMP calculations. Assumptions related to a saturated atmospheric column from the surface through to the 300mb level during the storm maximization and transposition process and that the storms analyzed are at maximum storm efficiency are discussed.

13.1 Assumptions

Several assumptions are critical to the derivation of PMP values in the storm-based methodology. It is important to understand each of these and how they may affect the resulting PMP values.

13.1.1 Saturated Storm Atmosphere

The atmospheric air masses that provide moisture to both the historic storms and the PMP storm are assumed to be saturated through the entire depth of the atmosphere and to contain the maximum moisture possible based on the surface dew point. This assumes moist pseudo-adiabatic temperature profiles for both the historic storms and the PMP storm. Limited evaluation of this assumption in the EPRI Michigan/Wisconsin PMP study (Tomlinson, 1993) and the Blenheim Gilboa study (Tomlinson et al., 2008) indicated that historic storm atmospheric profiles are generally not entirely saturated and contain somewhat less precipitable water than is assumed in the PMP procedure. It follows that the PMP storm (if it were to occur) would also have somewhat less precipitable water available than the assumed saturated PMP atmosphere would contain. What is used in the PMP procedure is the *ratio* of precipitable water associated with each storm. If the precipitable water values for each storm are both slightly overestimated, the ratio of these values will be essentially unchanged. This is a standard assumption in the PMP calculation process (e.g. Section 2.2 of WMO, 2009).

13.1.2 Maximum Storm Efficiency

The assumption is made that if a sufficient period of record is available for rainfall observations, at least a few storms would have been observed that attained or came close to attaining the maximum efficiency possible in nature for converting atmospheric moisture to rainfall for regions with similar climates and topography. Further assumption is made that if additional atmospheric moisture had been available, the storm would have maintained the same efficiency for converting atmospheric moisture to rainfall. The ratio of the maximized rainfall amounts to the actual rainfall amounts would be the same as the ratio of the precipitable water in the atmosphere associated with each storm. Because only the amount of moisture is increasing compared to the amount observed, the ratio derived for PMP calculation in this process provides the most conservative estimation possible.

There are two issues to be considered. First is the assumption that a storm has occurred that has a rainfall efficiency close to the maximum possible. Unfortunately, state-of-the-science in meteorology does not support a theoretical evaluation of storm efficiency. However, if the period of record is considered (generally over 100 years), along with the extended geographic region with transpositionable storms, it is accepted that there should have been at least one storm with dynamics that approach the maximum efficiency for rainfall production.

The other issue is the assumption that storm efficiency does not change if additional atmospheric moisture is available. Storm dynamics could potentially become more efficient or possibly less efficient depending on the interaction of cloud microphysical processes with the storm dynamics. Offsetting effects could indeed lead to the storm efficiency remaining essentially unchanged. For the present, the assumption of no change in storm efficiency is accepted.

13.2 Sensitivity of Parameters

The maximization factor depends on the determination of storm representative dew points, along with maximum historical dew point values. The magnitude of the maximization factor varies depending on the values used for the storm representative dew point and the maximum dew point. Holding all other variables constant, the maximization factor is smaller for higher storm representative dew points as well as for lower maximum dew point values. Likewise, larger maximization factors result from the use of lower storm representative dew points and/or higher maximum dew points. The magnitude of the change in the maximization factor varies depending on the dew point values. For the range of dew point values used in most PMP studies, the maximization factor for a particular storm will change about 5% for every 0.5ºC difference between the storm representative and maximum dew point values. The same sensitivity applies to the transposition factor, with about a 5% change for every 0.5ºC change in either the in-place maximum dew point or the transposition maximum dew point.

13.2.1 Elevation Effects on Atmospheric Moisture Availability

Elevated topographic features remove atmospheric moisture from an air mass as it moves over the terrain. When storms are transpositioned, the elevation of the original storm (at either the storm center location or the grid cell location) is used to compute the amount of atmospheric moisture depleted from or added to the storm atmosphere. The absolute amount of moisture depletion or addition is somewhat dependent on the dew point values, but is primarily dependent on the elevation at the original storm location and the elevation of the study basin and any intervening barriers before reaching the grid cell location. The elevational differences between the original storm location and the grid cell, as well as any intervening barriers, are reflected in the precipitation climatology patterns used to calculate the OTF. The elevation adjustment is slightly less than 1% for every 30 meters of elevation change between the original storm location elevation and the study basin elevation. This is related to the amount of moisture the atmospheric column can contain given a starting dew point value and assuming a saturated atmospheric column through the top of the atmosphere. If some amount of the total atmospheric column is removed (added) because the new location is higher (lower) than the original location, the amount of moisture associated with the starting dew point value would no longer be available in the atmosphere below that elevation (or more would be available if more atmosphere was available). This follows the same process as employed in the WMO Manual for PMP (2009).

14 Recommendation for Application

14.1 Site-Specific PMP Applications

Site-specific PMP values have been calculated that provide rainfall amounts for use in computing the Probable Maximum Flood (PMF). This study addressed several issues that could potentially affect the magnitude of the PMP storm over any drainage basin within the project area. It is important to remember that the methods used to derive PMP and subsequently, the methods used to derive the PMF from those data, adhere to the caveat of being "physically possible" as described in the definition of PMP (see Section 1.1). In other words, various levels of conservatism and/or extreme aspects of storms that would not occur/co-occur in a PMP storm environment should not be compounded together to generate unrealistic results in either the PMP values or the hydrologic applications of those values to derive the PMF.

The storm search process and selection of storms analyzed in this study only considered events that occurred over areas that are both meteorologically and topographically similar to locations within the Elbow River basin. Each storm type (local/MCS and general) that occurs in the overall project domain was analyzed. Therefore, results of this study should not be used for watersheds where meteorological and/or topographical parameters are different from those found within the project domain without further evaluation.

14.2 Calibration Storm Events

AWA utilized SPAS to analyze rainfall over the Elbow River basin. Two storm events were selected for calibration of the PMF hydrologic model (Table 14.1). AWA analyzed a sufficiently large storm domain that included numerous hourly rain gauge observations and calibrated the NEXRAD data. Quality controlled NEXRAD data were acquired from Weather Decisions Technologies, Inc. The rainfall analysis results were provided on a 1-km^2 grid with a temporal frequency of 60-minutes.

Table 14.1 Two storm events selected for hydrologic model calibration

Hydrologic Calibration Events Selected

SPAS #	Date	Radar
1492	6/01-09/2005	Yes
1320	6/19-22/2013	Yes

14.2.1 June 1-9, 2005 Precipitation

The focus of this analysis was the Elbow River basin, with a slightly larger domain (53.3°N/116.8°W to 46.0°N/110.0°W) analyzed to ensure a reliable sample size as well as providing an ample buffer area. The hourly precipitation grids derived from the June 2005, SPAS 1492 analysis were used as the basis for Elbow River basin calibration. The hourly grids were provided in a Geographic-Longitude/Latitude projection based on the WGS84 Datum at a spatial resolution of 36 seconds (1-km^2). The grid cell units are floating point inches. Each grid represents the total 1-hour rainfall ending at the specified date/time of the file. For instance, P_allsites_spas1492_001_20050601_0800_UTC.asc.gz contains the total 1-hour precipitation for the period 06/01/2005 0705 UTC through 06/01/2005 0800 UTC; 2005 is the year, 06 is the month, 01 is the day, and 0800 is the ending hour. There are 192-hourly grids and 1 total storm grid. A total storm image, summation of the 192-hourly grids is shown in Figure 14.1.

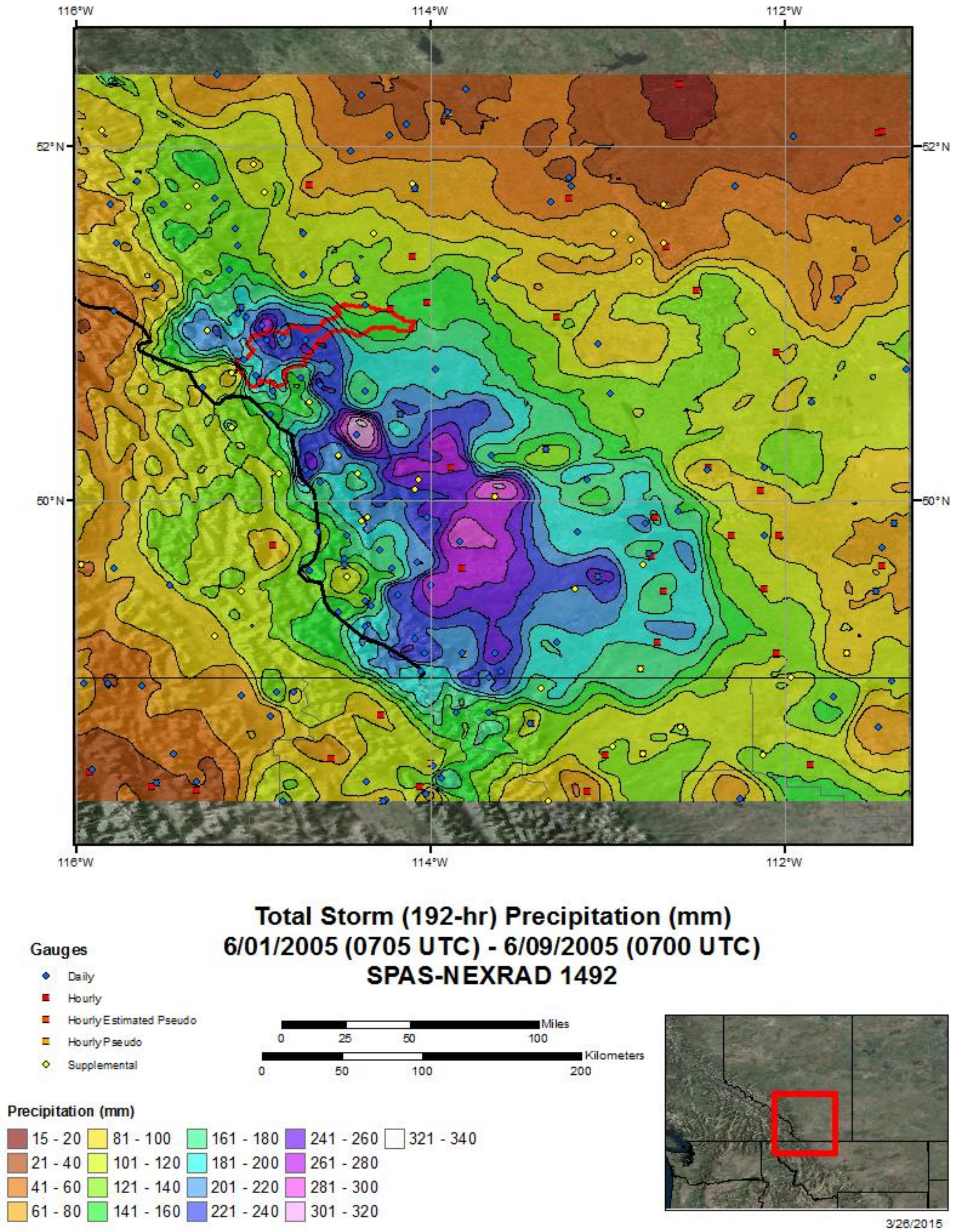

Figure 14.1 Total storm rainfall for SPAS 1492 from June 1-9, 2005

14.2.3 June 13-28, 2013 Precipitation

Again, the focus of this analysis was the Elbow River basin, with a slightly larger domain (53.3°N/118.0°W to 48.8°N/113.2°W) analyzed to ensure a reliable sample size as well as providing an ample buffer area. The hourly precipitation grids derived from the June 2013, SPAS 1320 analysis were used as the basis for Elbow River basin calibration. The hourly grids were provided in a Geographic-Longitude/Latitude projection based on the WGS84 Datum at a spatial resolution of 36 seconds (1-km^2). The grid cell units are floating point inches. Each grid represents the total 1-hour rainfall ending at the specified date/time of the file. For instance, P_allsites_spas1320_001_20130619_0800_UTC.asc.gz contains the total 1-hour precipitation for the period 06/19/2013 0705 UTC through 06/19/2013 0800 UTC; 2013 is the year, 06 is the month, 19 is the day, and 0800 is the ending hour. There are 72-hourly grids and 1 total storm grid. A total storm image, summation of the 72-hourly grids is shown in Figure 14.2.

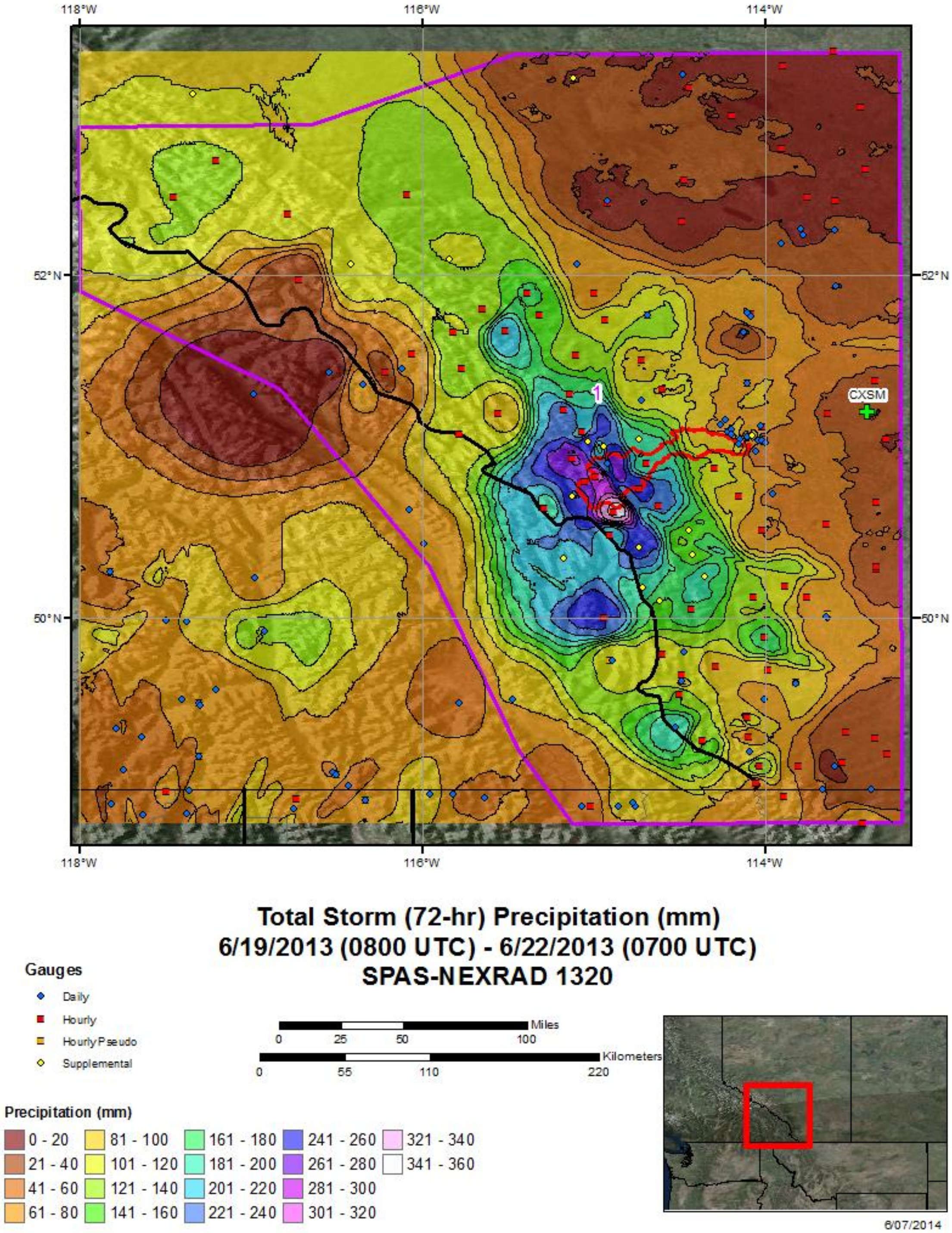

Figure 14.2 Total storm rainfall for SPAS 1320 June 19-22, 2013

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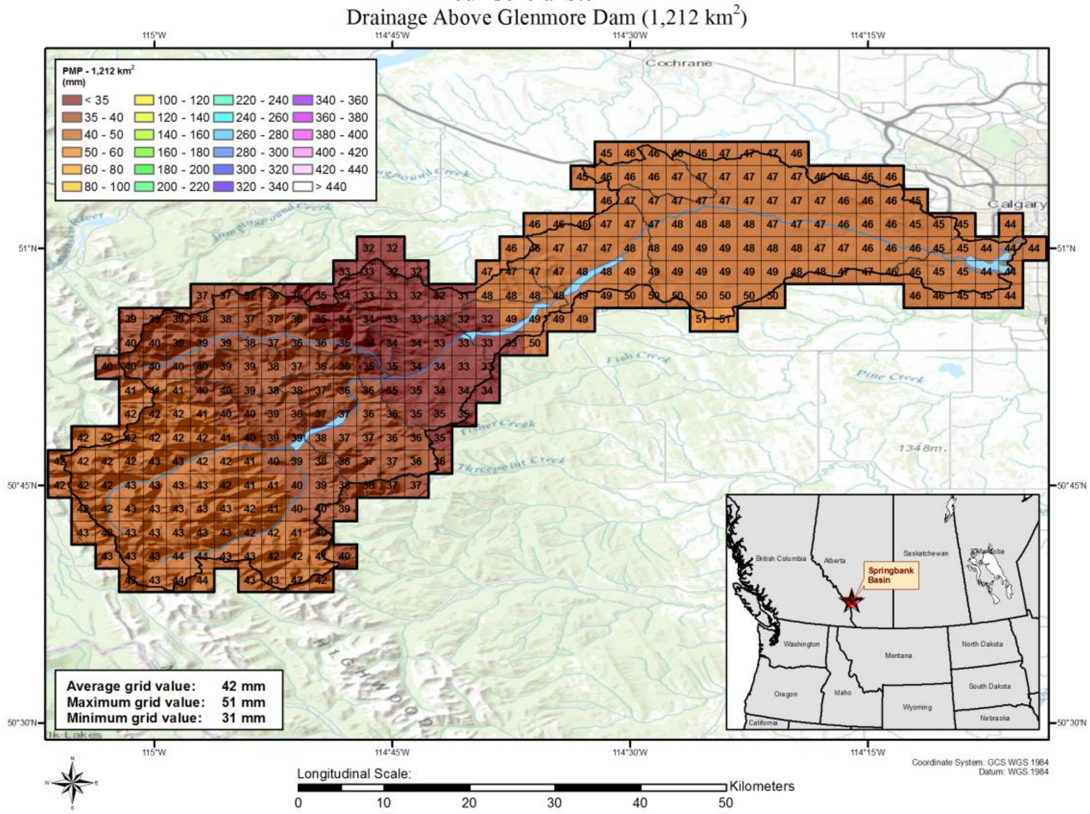
Appendix A

Gridded PMP Maps for General and Local Storms

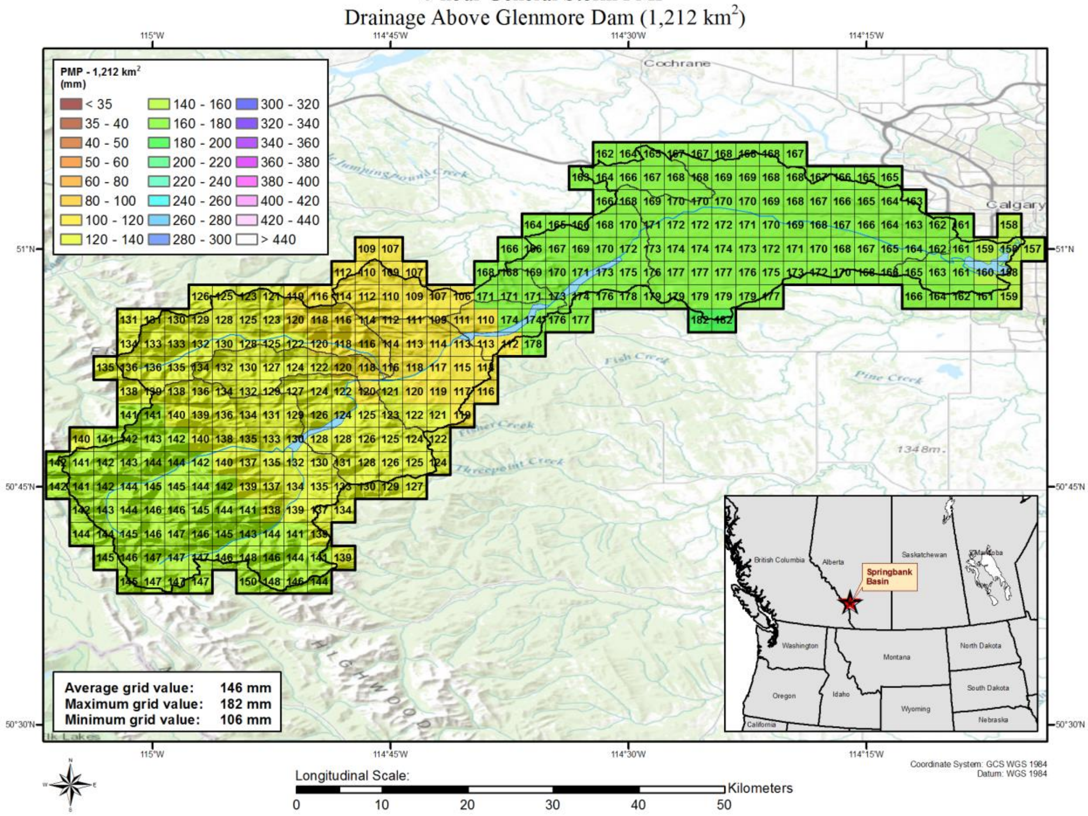
General Storm PMP

Drainage above Glenmore Dam (1,212 km^2)

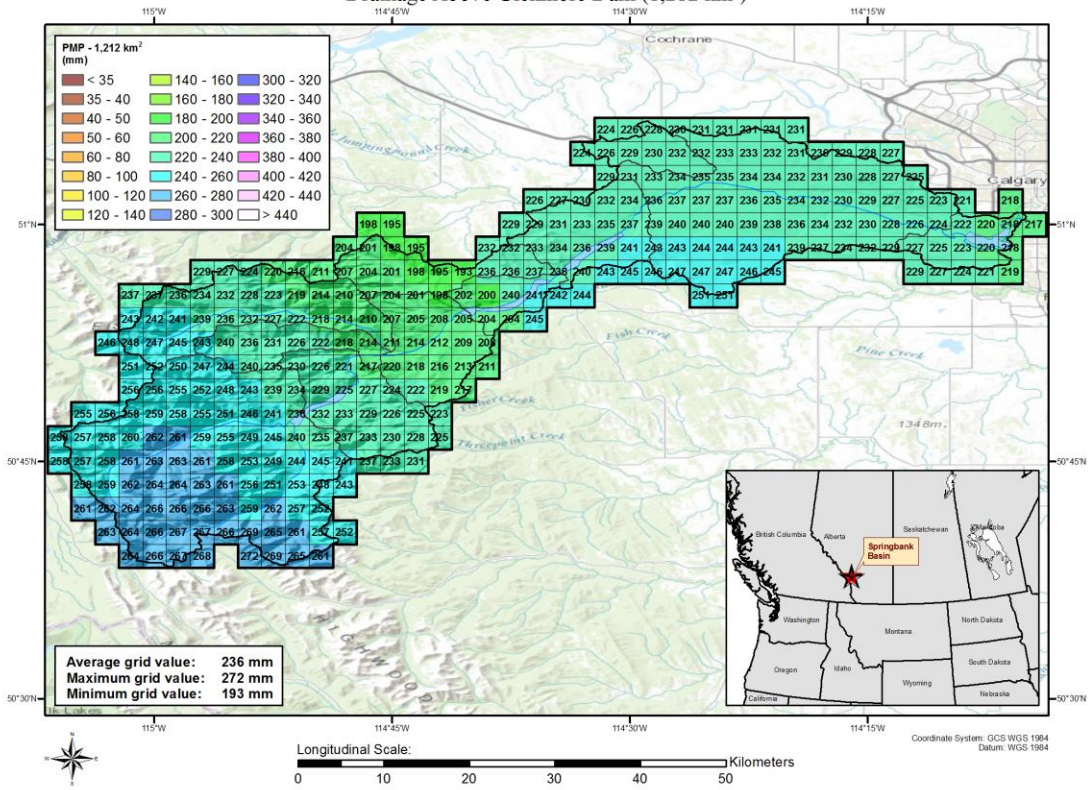
1-hour General Storm PMP
Drainage Above Glenmore Dam (1,212 km^2)



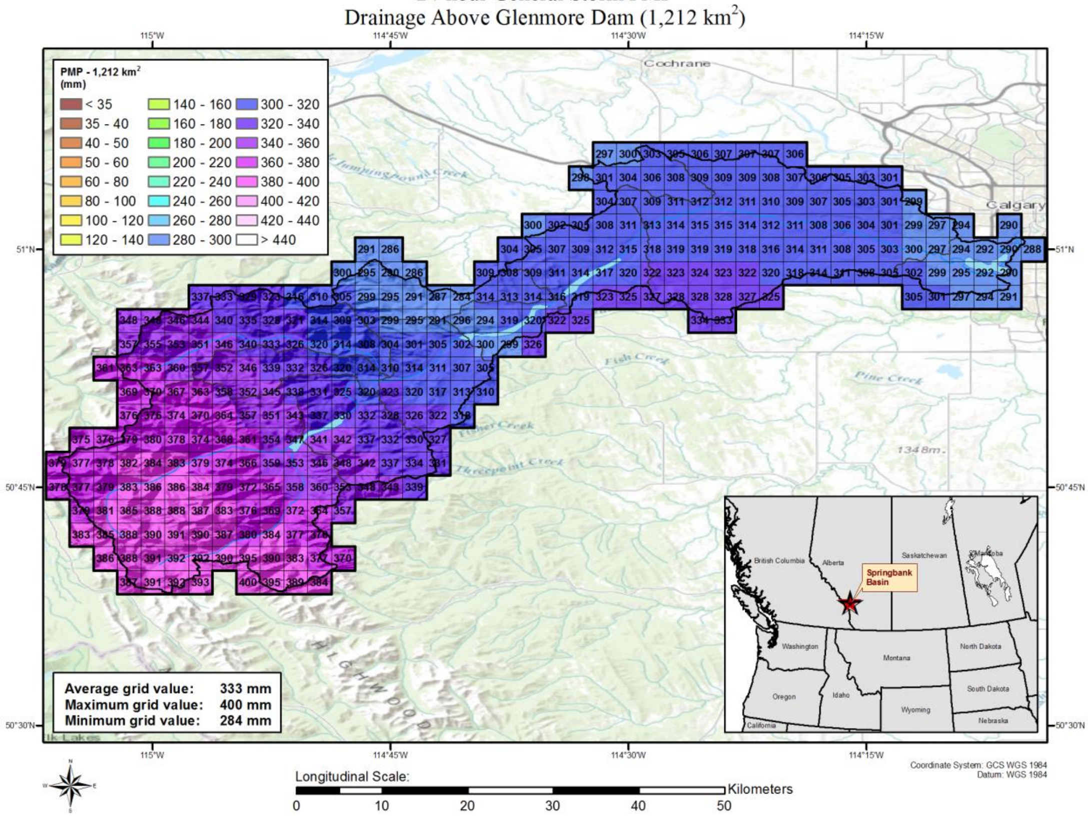
6-hour General Storm PMP
Drainage Above Glenmore Dam (1,212 km^2)



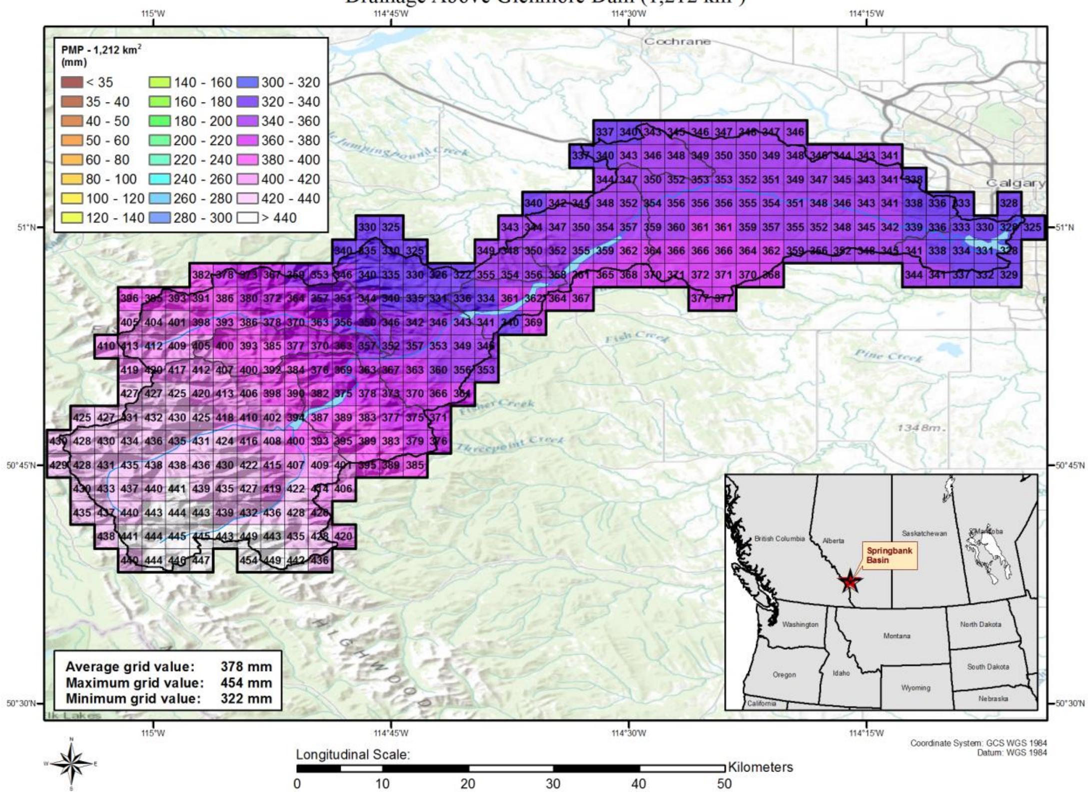
12-hour General Storm PMP
Drainage Above Glenmore Dam (1,212 km^2)



24-hour General Storm PMP
Drainage Above Glenmore Dam (1,212 km^2)



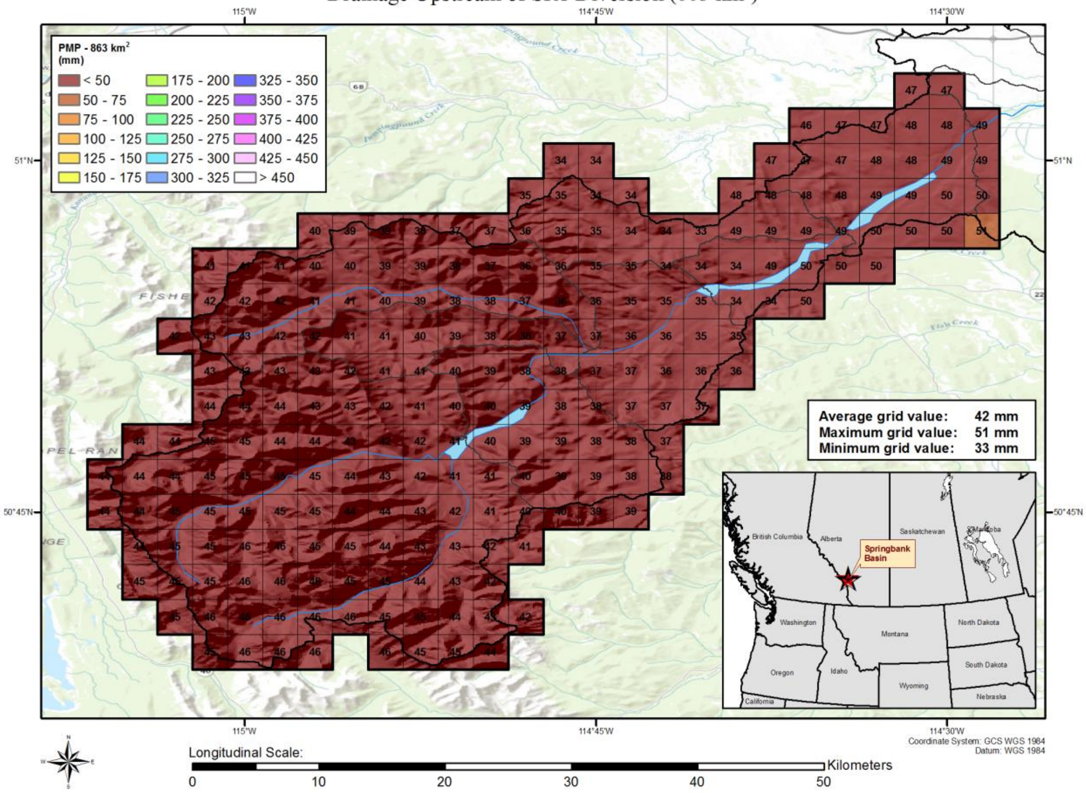
48-hour General Storm PMP
Drainage Above Glenmore Dam (1,212 km^2)



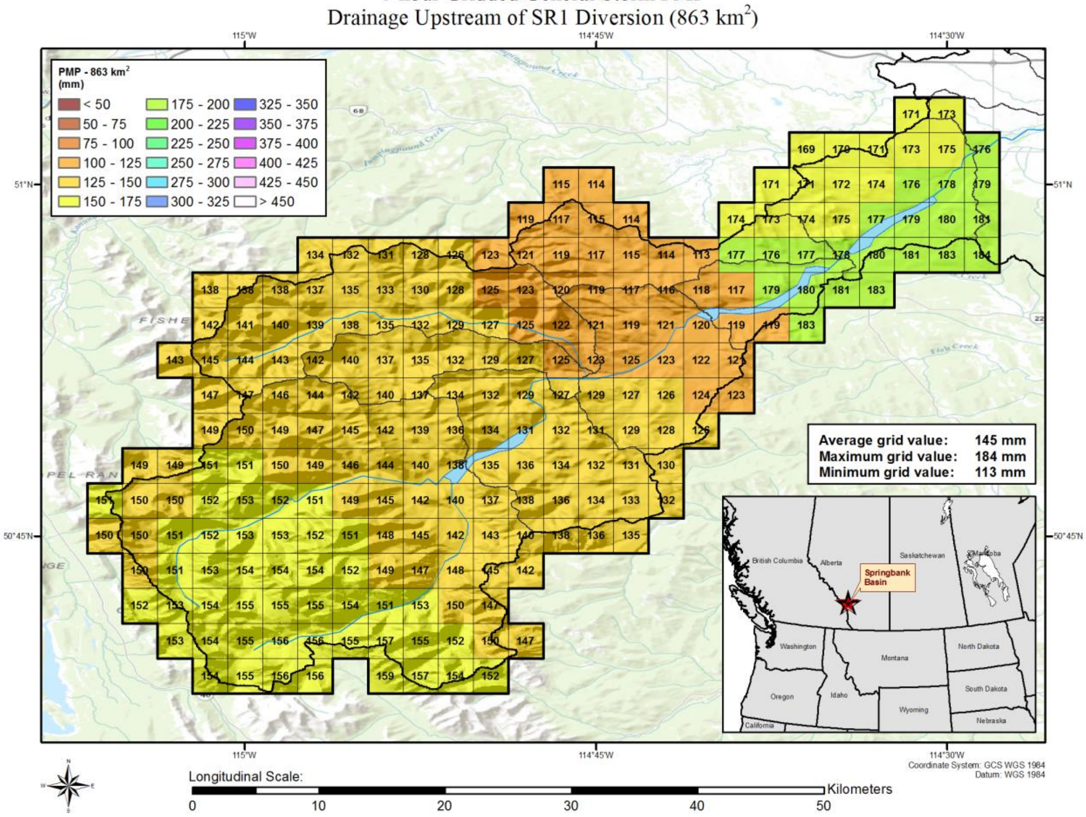
General Storm PMP

Drainage above SR1 Diversion (863 km^2)

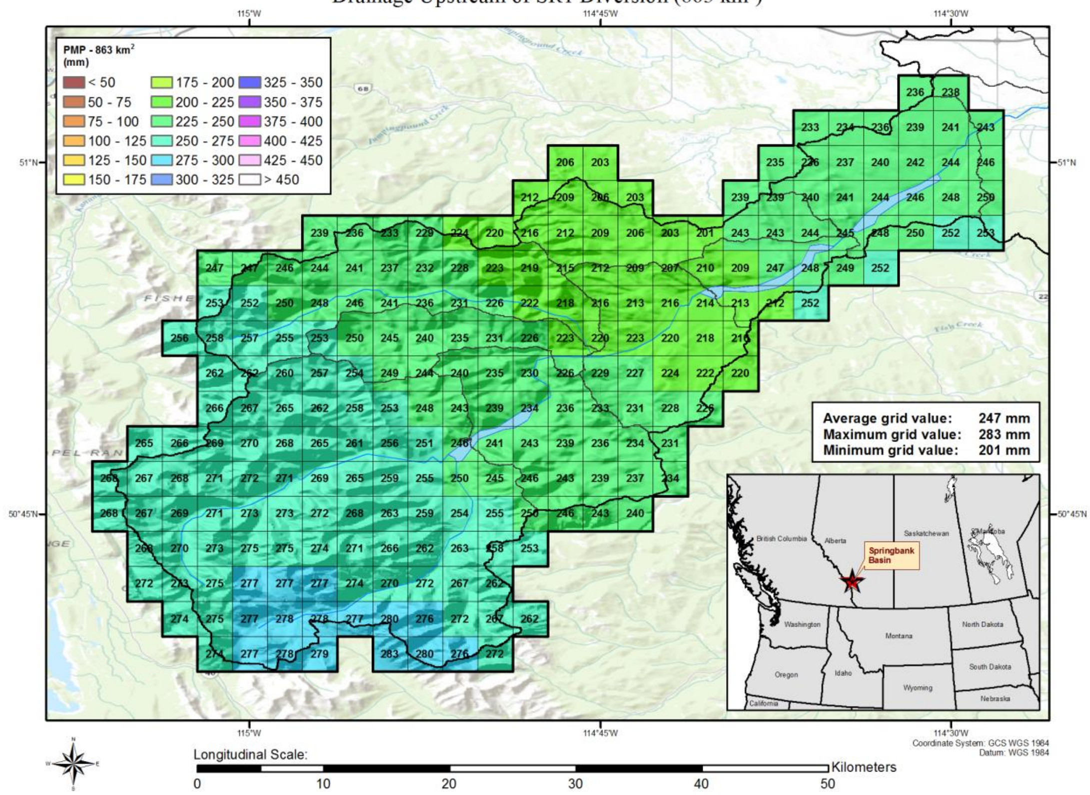
1-hour Gridded General Storm PMP
Drainage Upstream of SR1 Diversion (863 km^2)



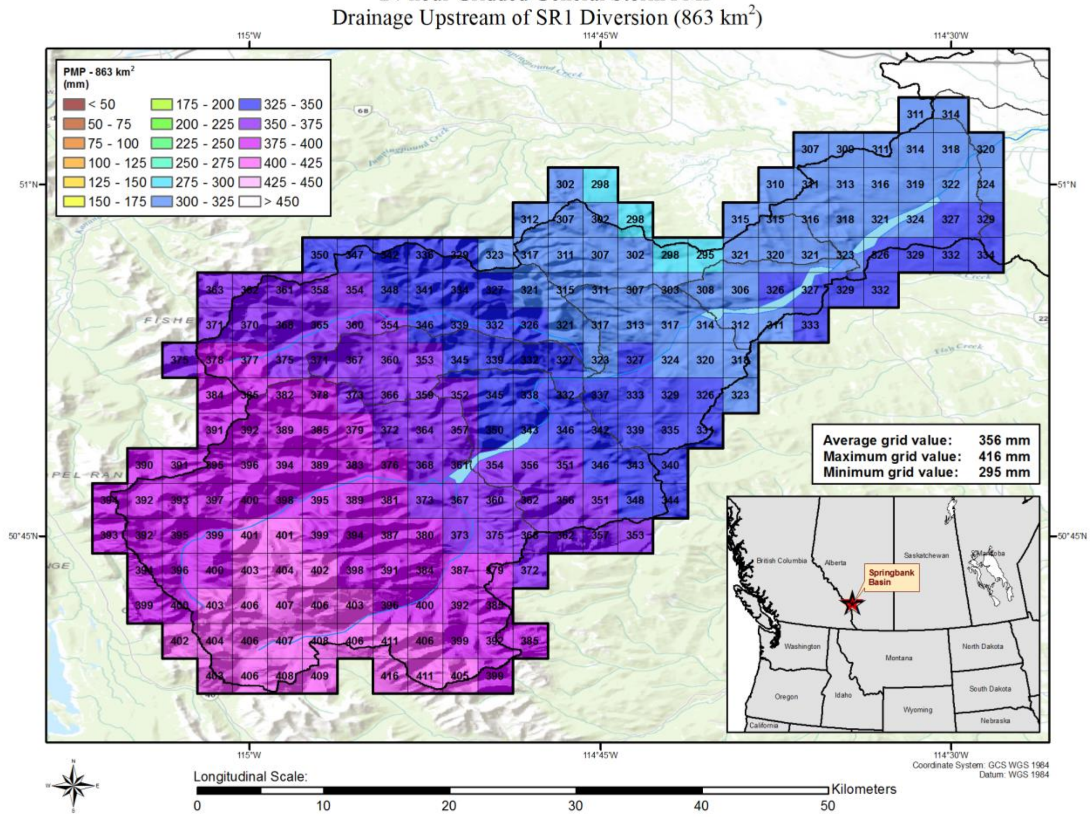
6-hour Gridded General Storm PMP
Drainage Upstream of SR1 Diversion (863 km^2)



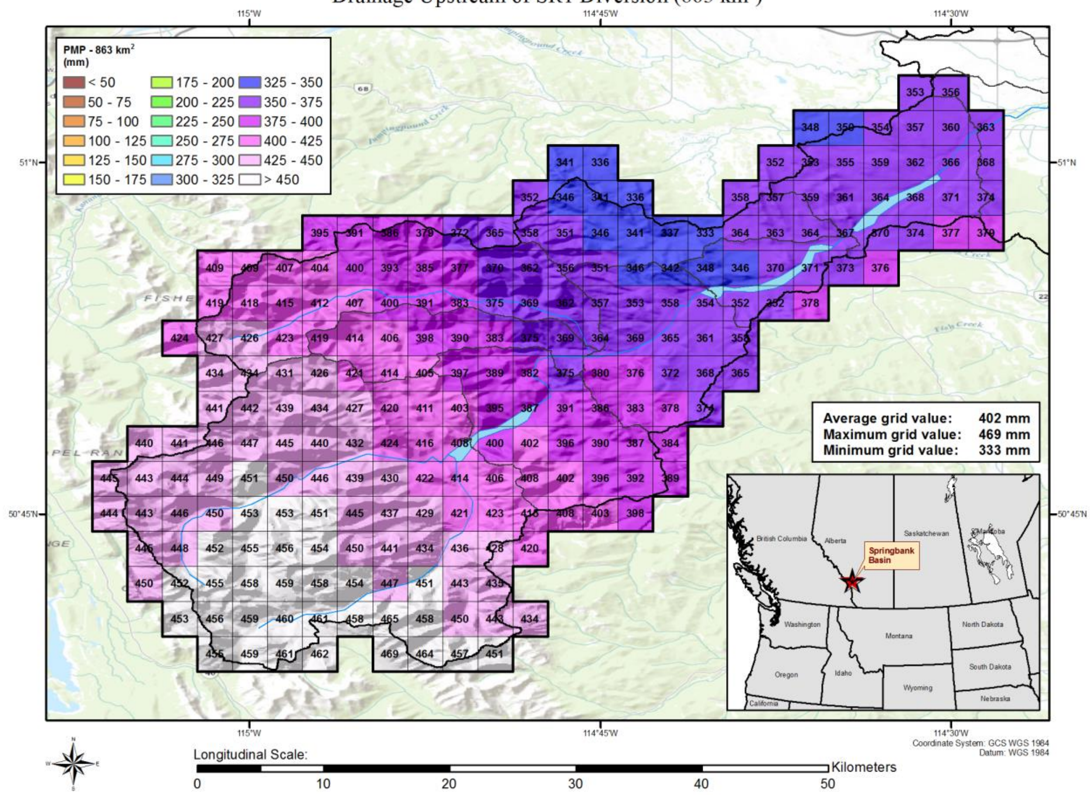
12-hour Gridded General Storm PMP
Drainage Upstream of SR1 Diversion (863 km^2)



24-hour Gridded General Storm PMP
Drainage Upstream of SR1 Diversion (863 km^2)



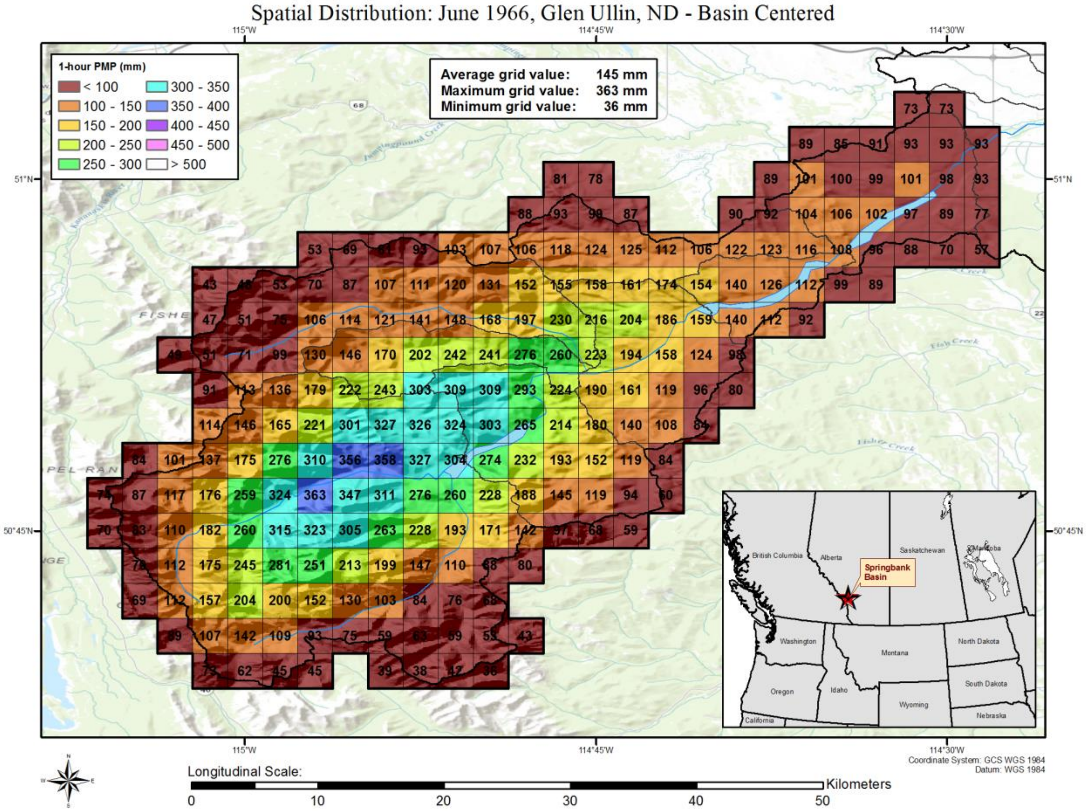
48-hour Gridded General Storm PMP
Drainage Upstream of SR1 Diversion (863 km^2)



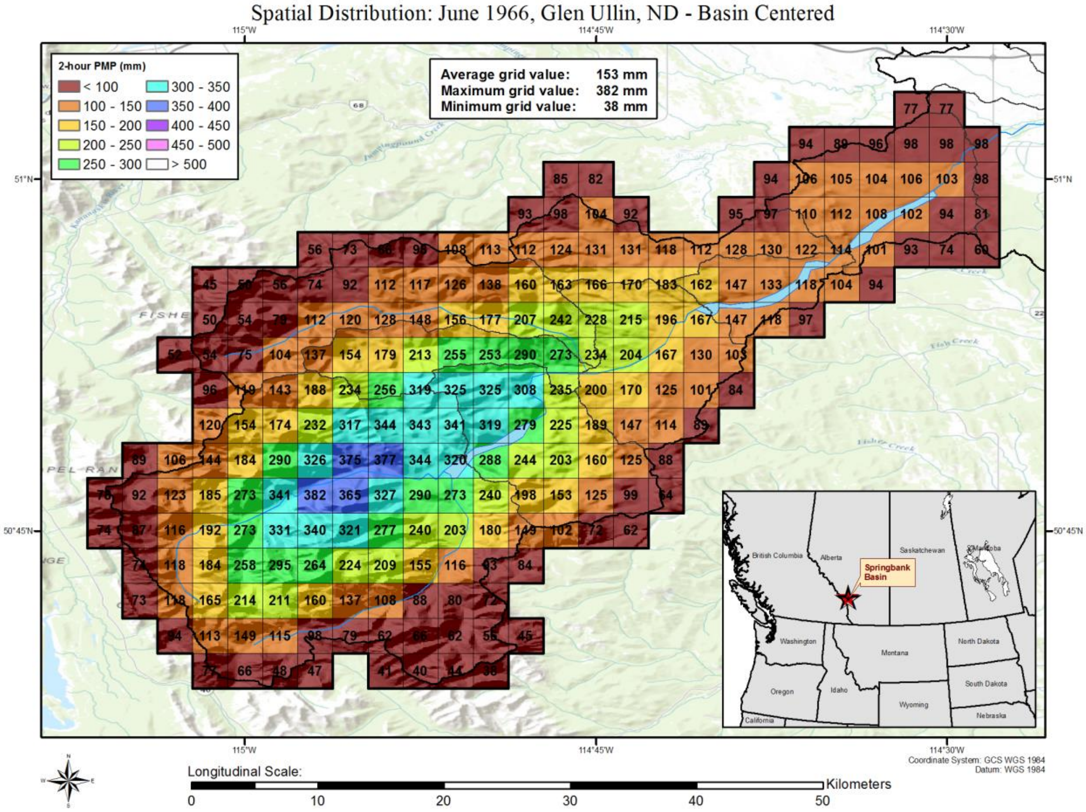
Local Storm PMP

Drainage above SR1 Diversion (863 km^2)

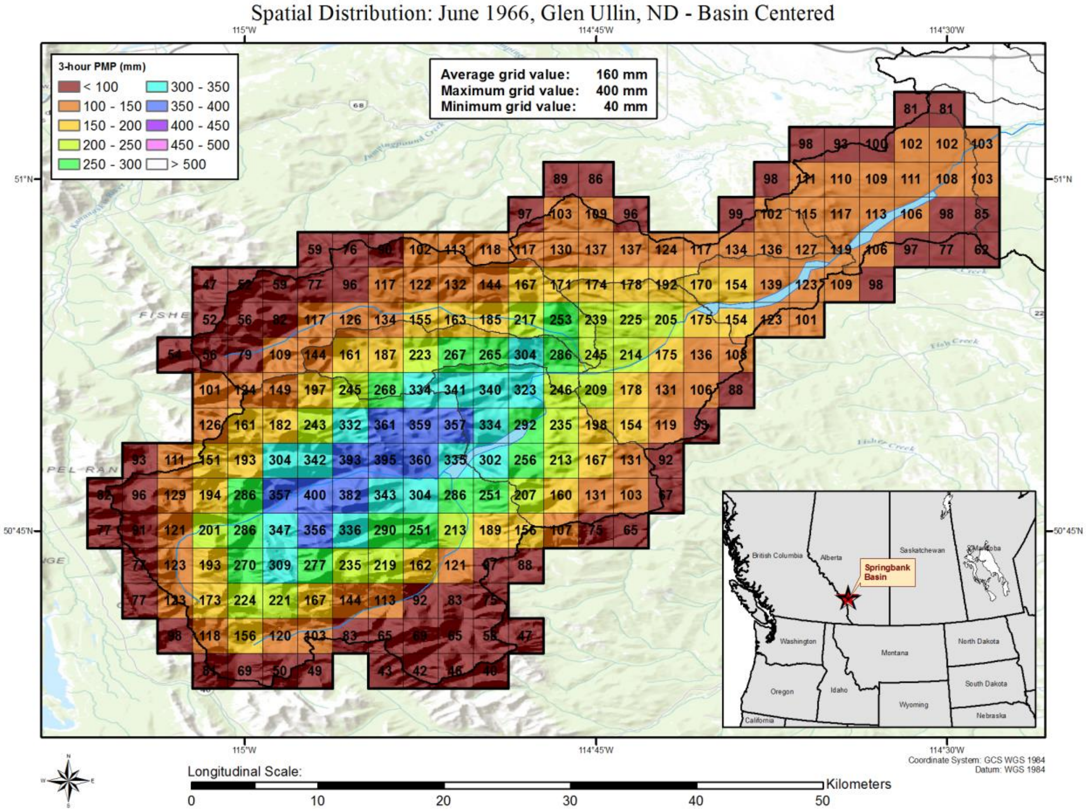
1-hour Gridded Local Storm Point PMP - Upstream of SR1 Diversion
Spatial Distribution: June 1966, Glen Ullin, ND - Basin Centered



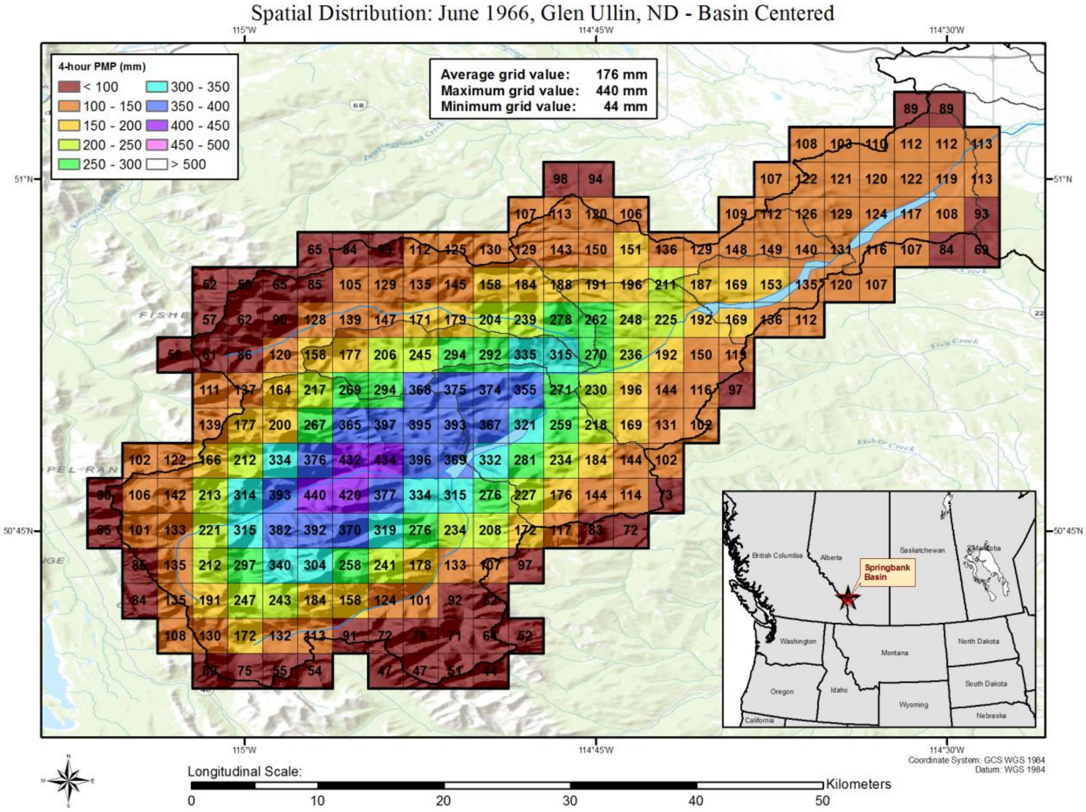
2-hour Gridded Local Storm Point PMP - Upstream of SR1 Diversion
Spatial Distribution: June 1966, Glen Ullin, ND - Basin Centered



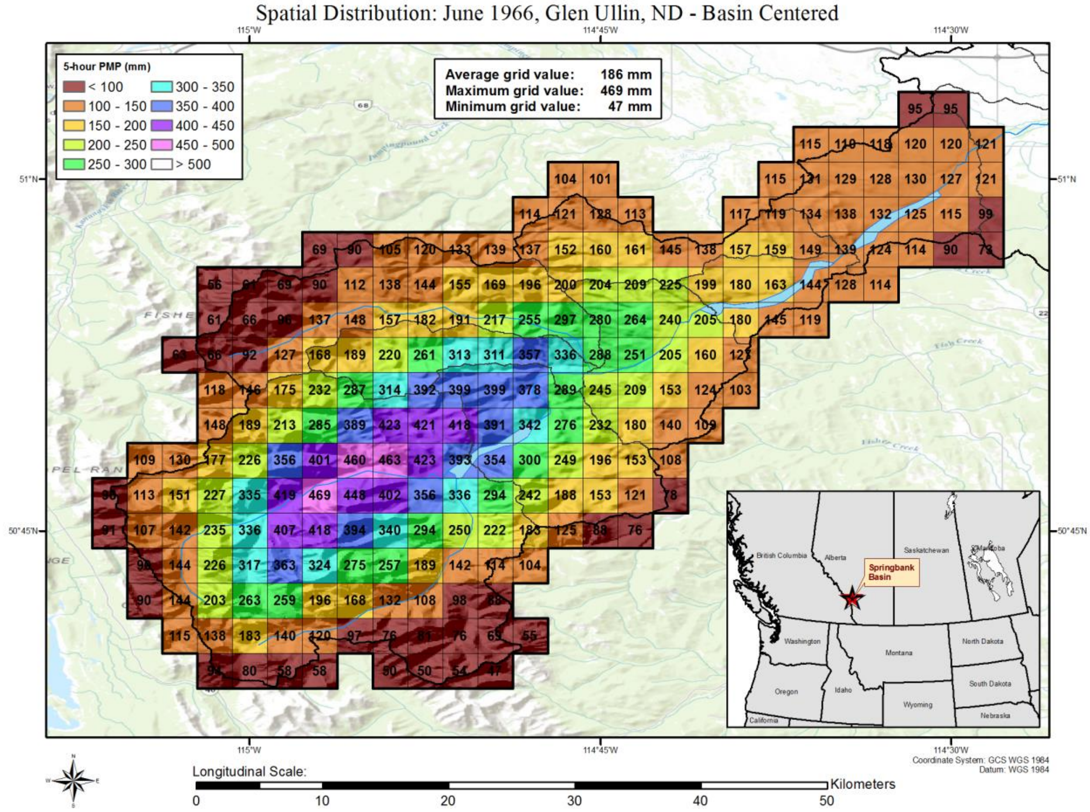
3-hour Gridded Local Storm Point PMP - Upstream of SR1 Diversion
Spatial Distribution: June 1966, Glen Ullin, ND - Basin Centered



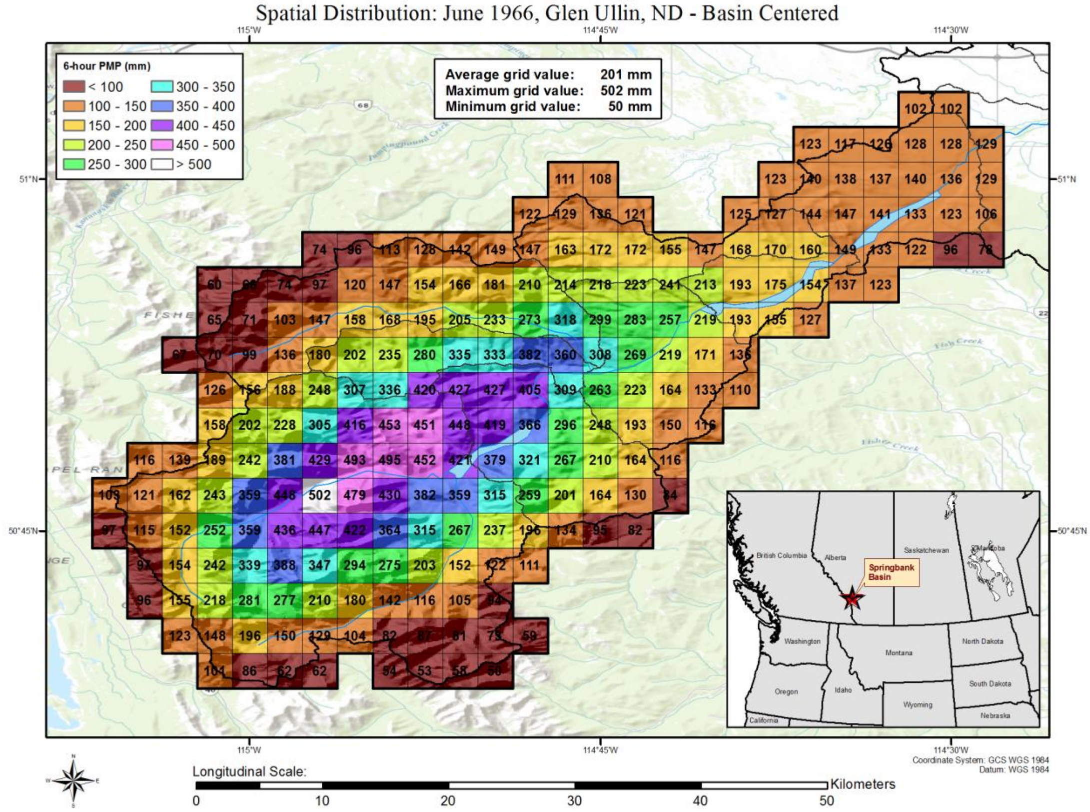
4-hour Gridded Local Storm Point PMP - Upstream of SR1 Diversion
Spatial Distribution: June 1966, Glen Ullin, ND - Basin Centered



5-hour Gridded Local Storm Point PMP - Upstream of SR1 Diversion
Spatial Distribution: June 1966, Glen Ullin, ND - Basin Centered



6-hour Gridded Local Storm Point PMP - Upstream of SR1 Diversion
Spatial Distribution: June 1966, Glen Ullin, ND - Basin Centered

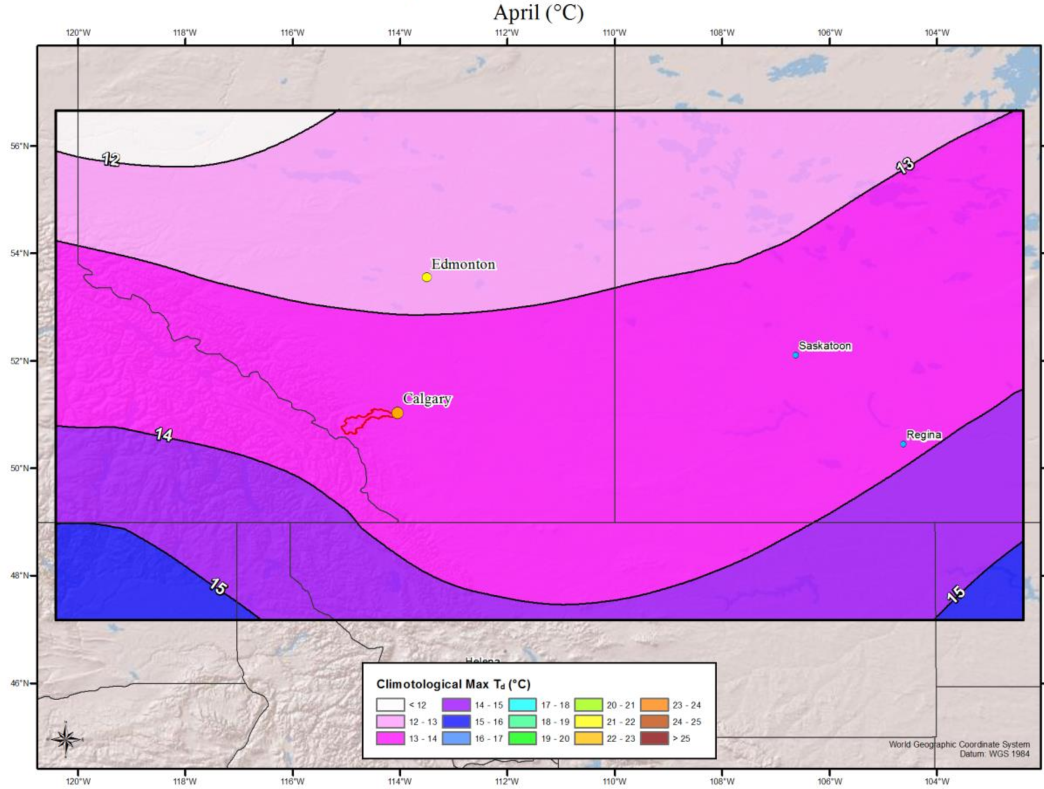


Appendix B

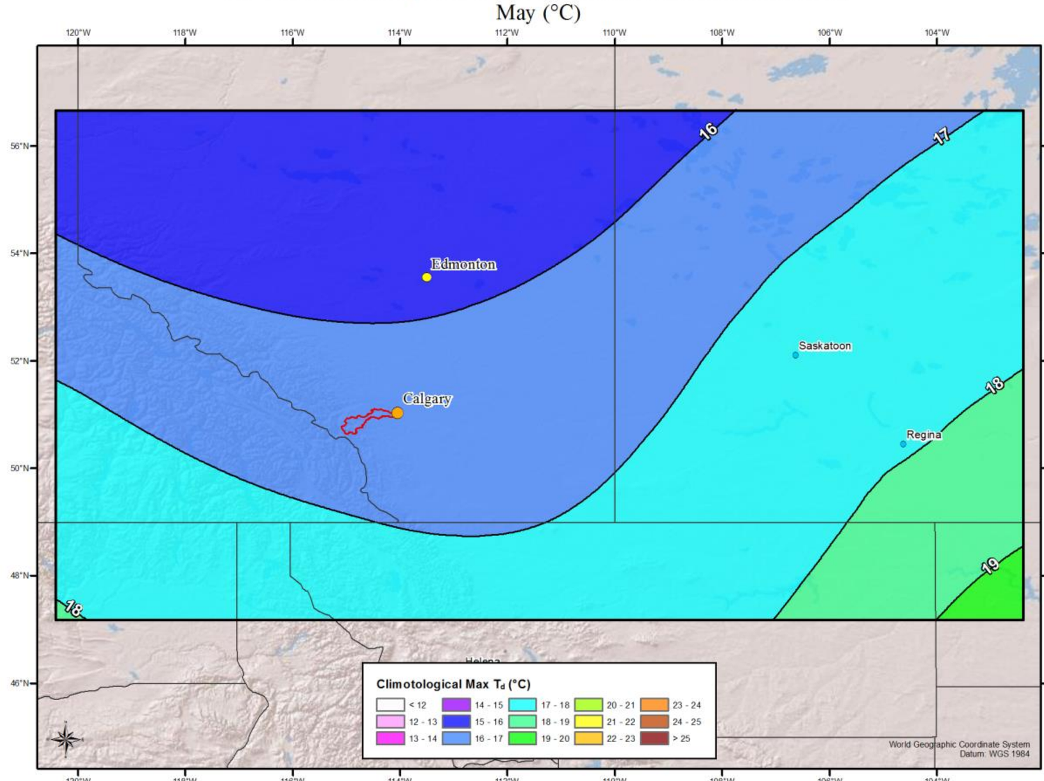
100-year Return Frequency Maximum Dew Point Temperature Climatology Maps at 100mb (April through September)

6-hour 1000mb Dew Point Maps

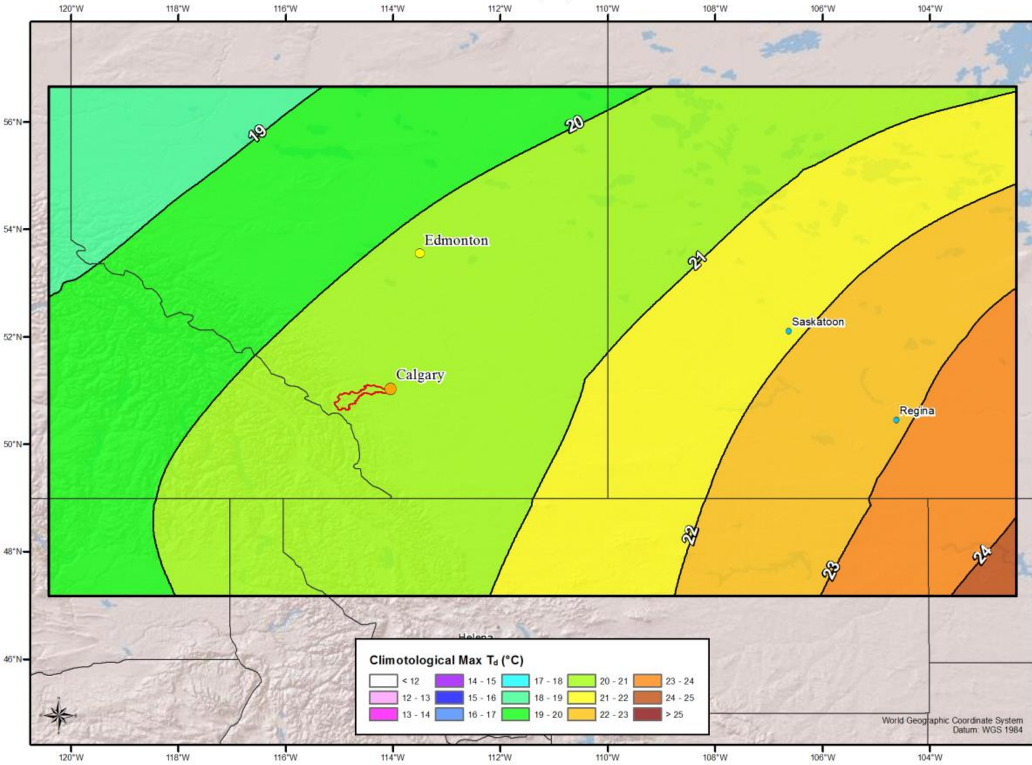
100-year Return Frequency 6-hour Maximum Dew Point Climatology
April (°C)



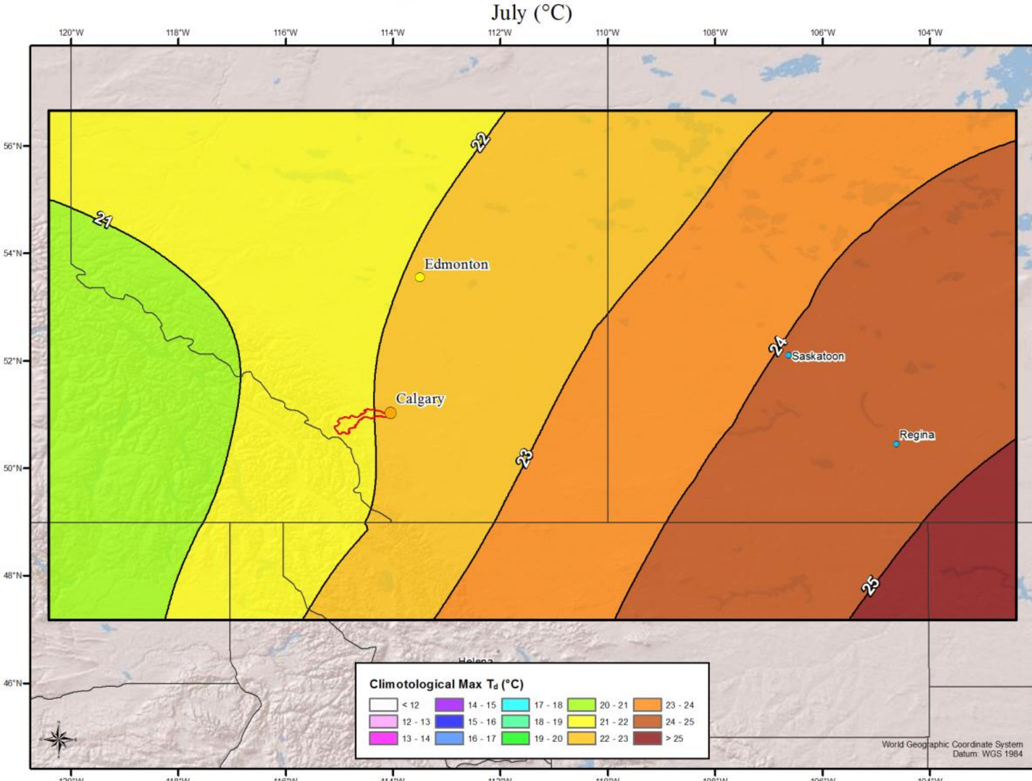
100-year Return Frequency 6-hour Maximum Dew Point Climatology
May (°C)



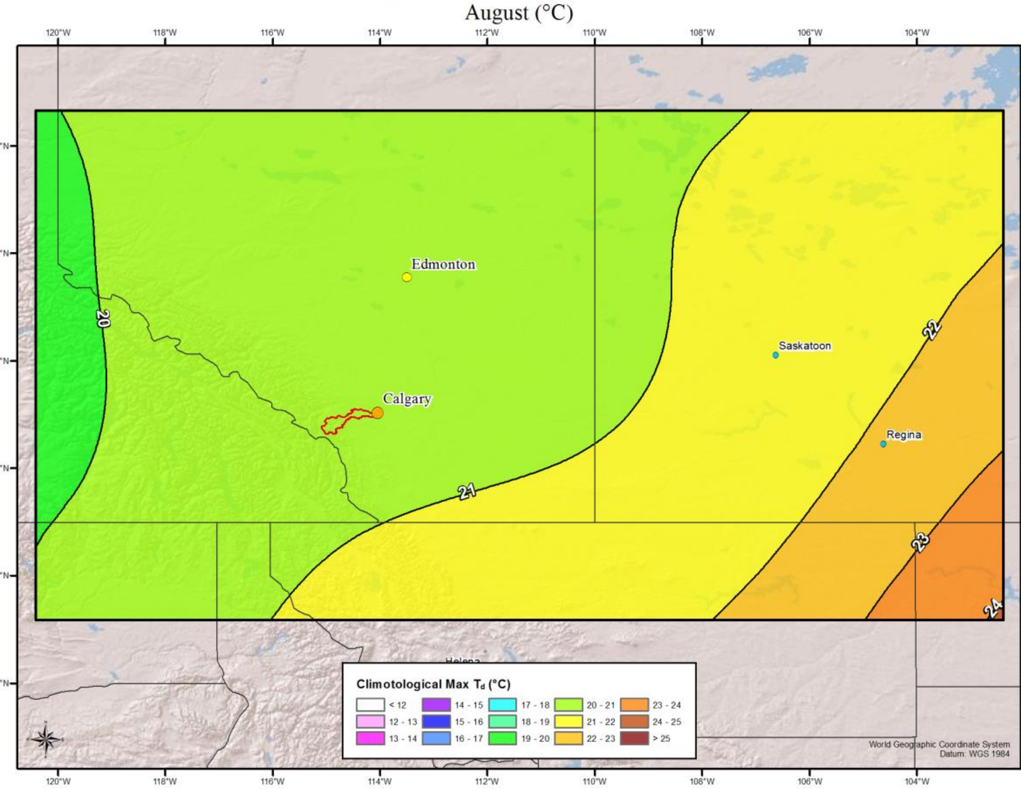
100-year Return Frequency 6-hour Maximum Dew Point Climatology
June (°C)



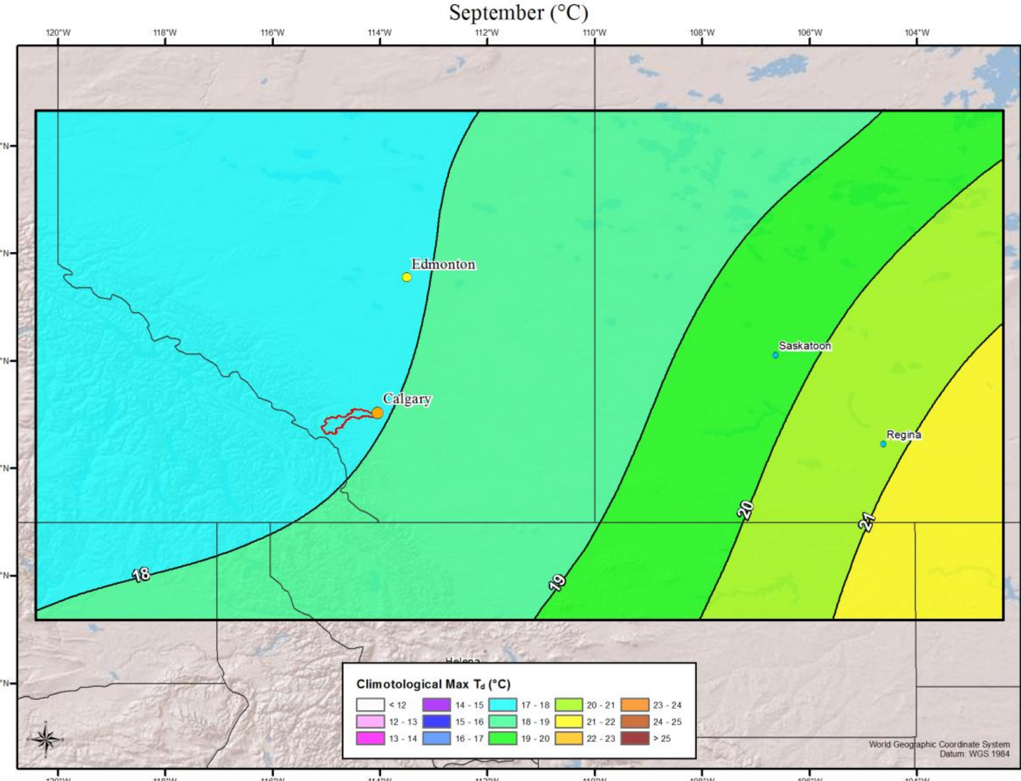
100-year Return Frequency 6-hour Maximum Dew Point Climatology
July (°C)



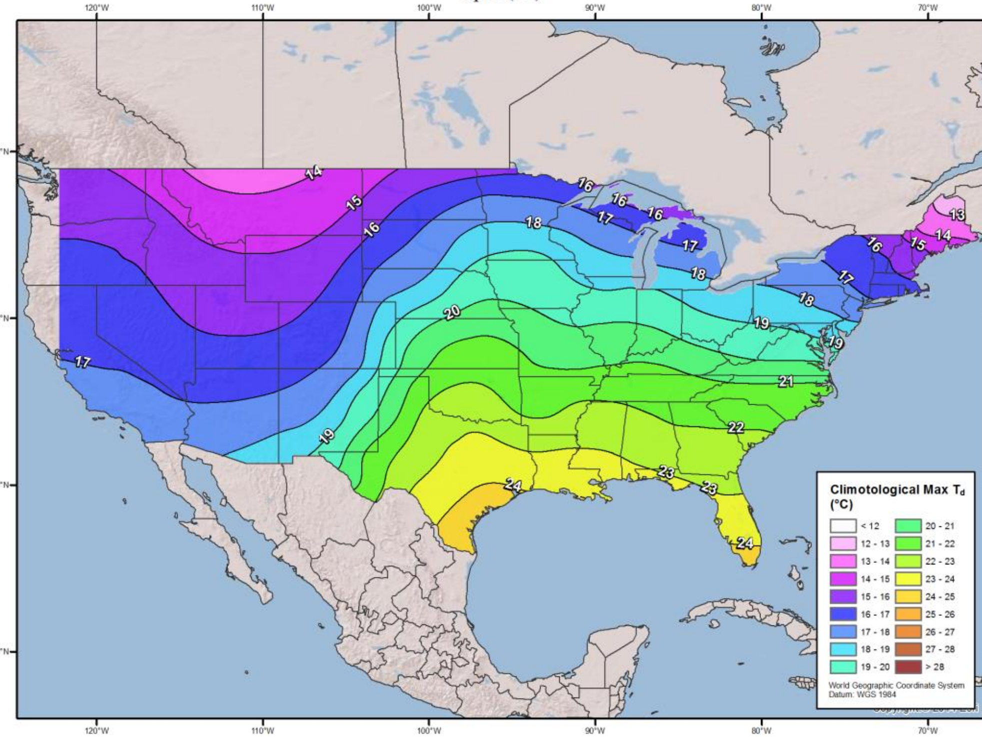
100-year Return Frequency 6-hour Maximum Dew Point Climatology
August (°C)



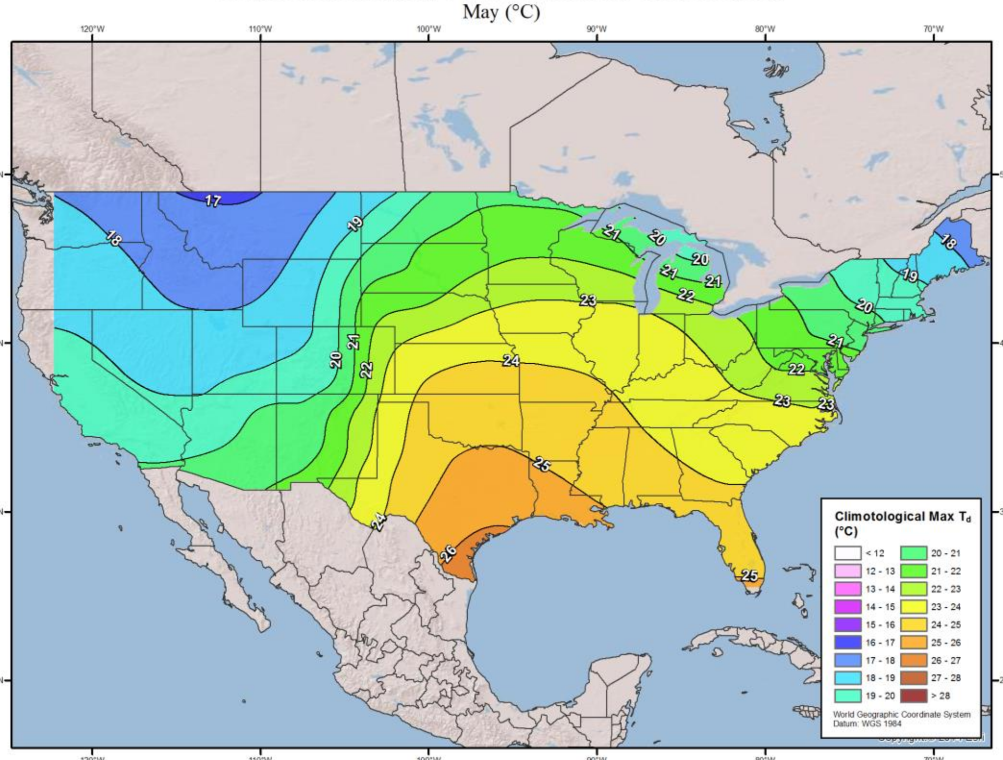
100-year Return Frequency 6-hour Maximum Dew Point Climatology
September (°C)



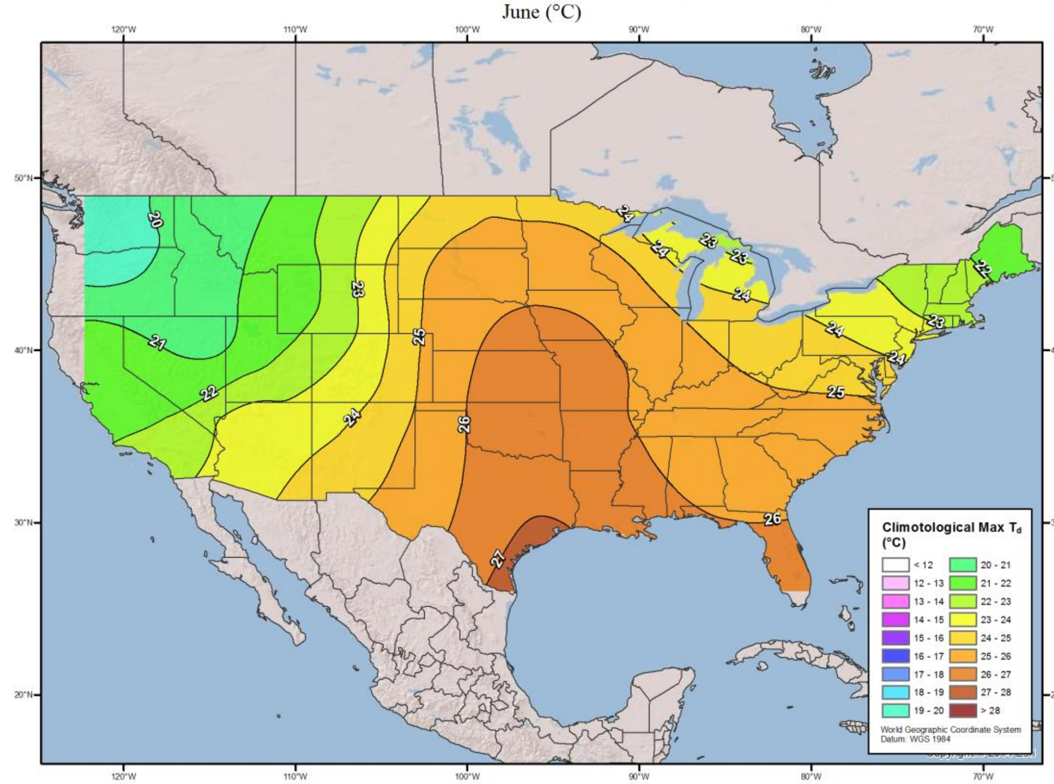
100-year Return Frequency 6-hour Maximum Dew Point Climatology
April (°C)



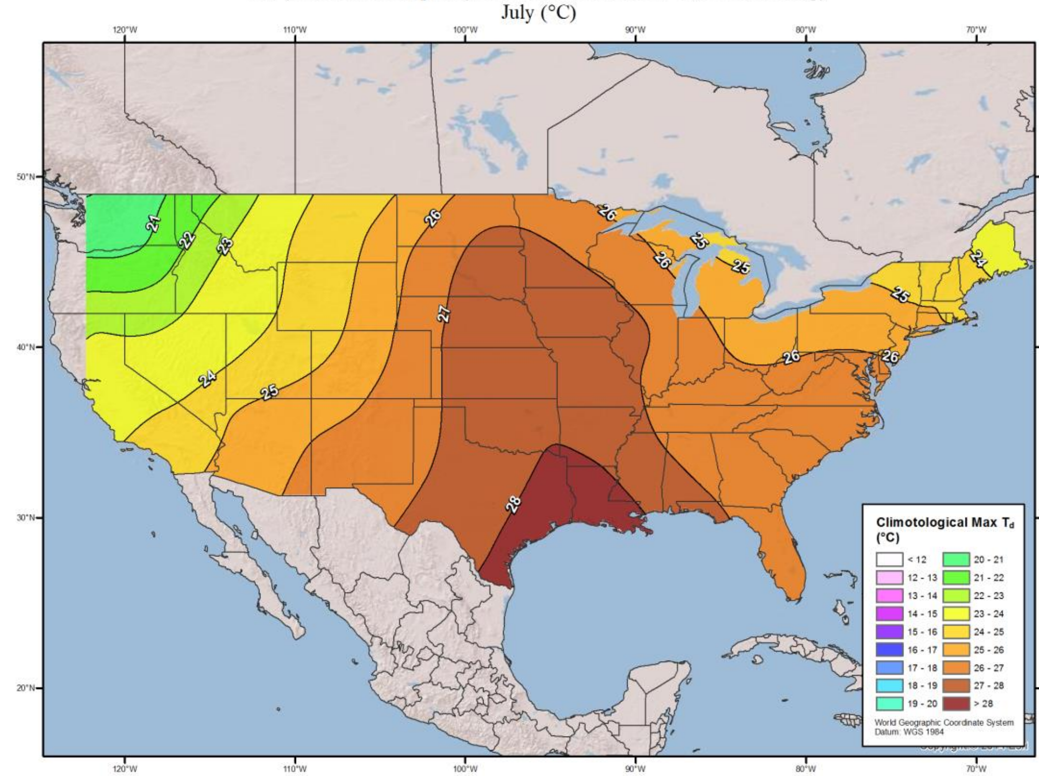
100-year Return Frequency 6-hour Maximum Dew Point Climatology
May (°C)



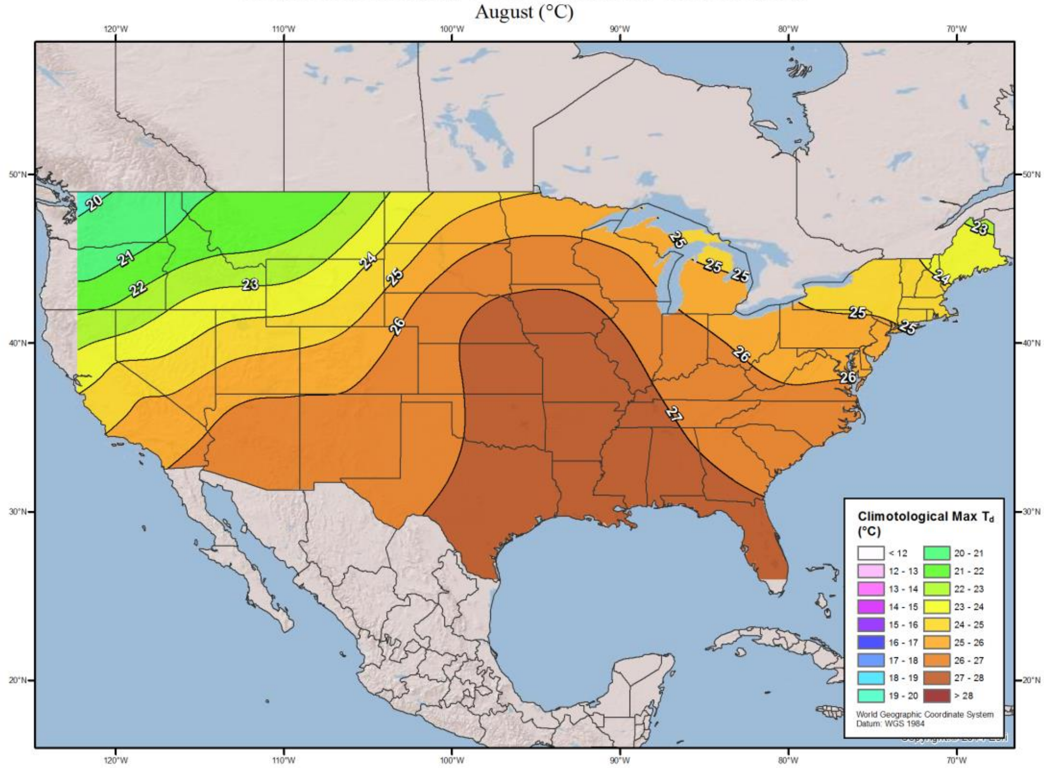
100-year Return Frequency 6-hour Maximum Dew Point Climatology
June (°C)



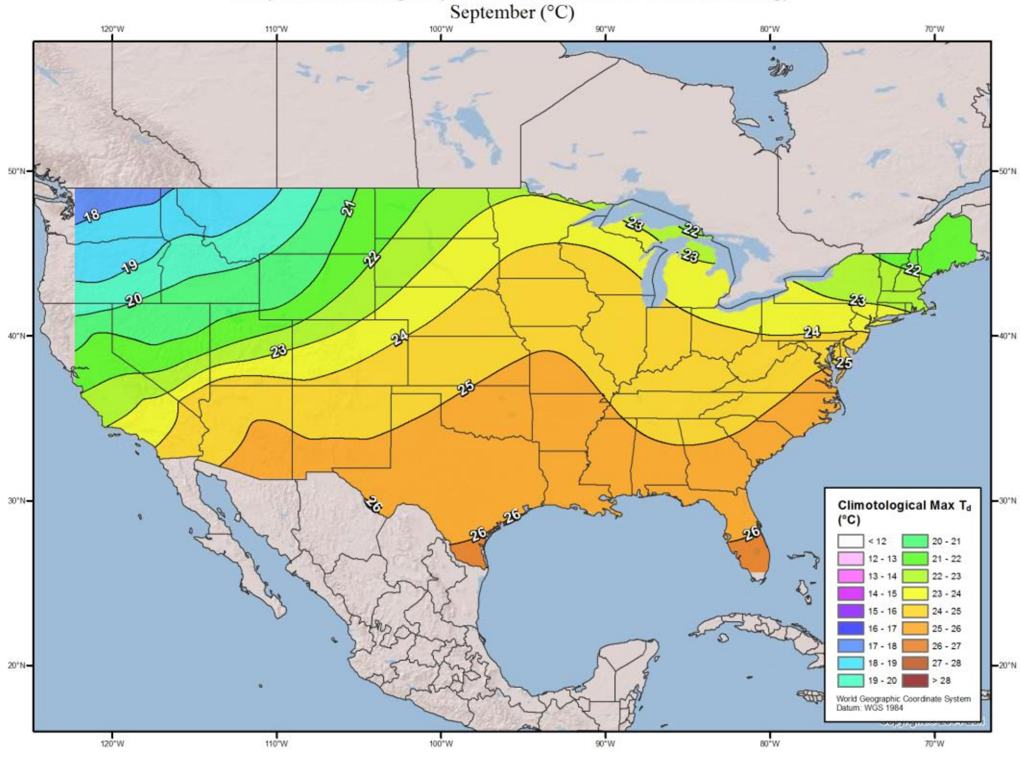
100-year Return Frequency 6-hour Maximum Dew Point Climatology
July (°C)



100-year Return Frequency 6-hour Maximum Dew Point Climatology
August (°C)

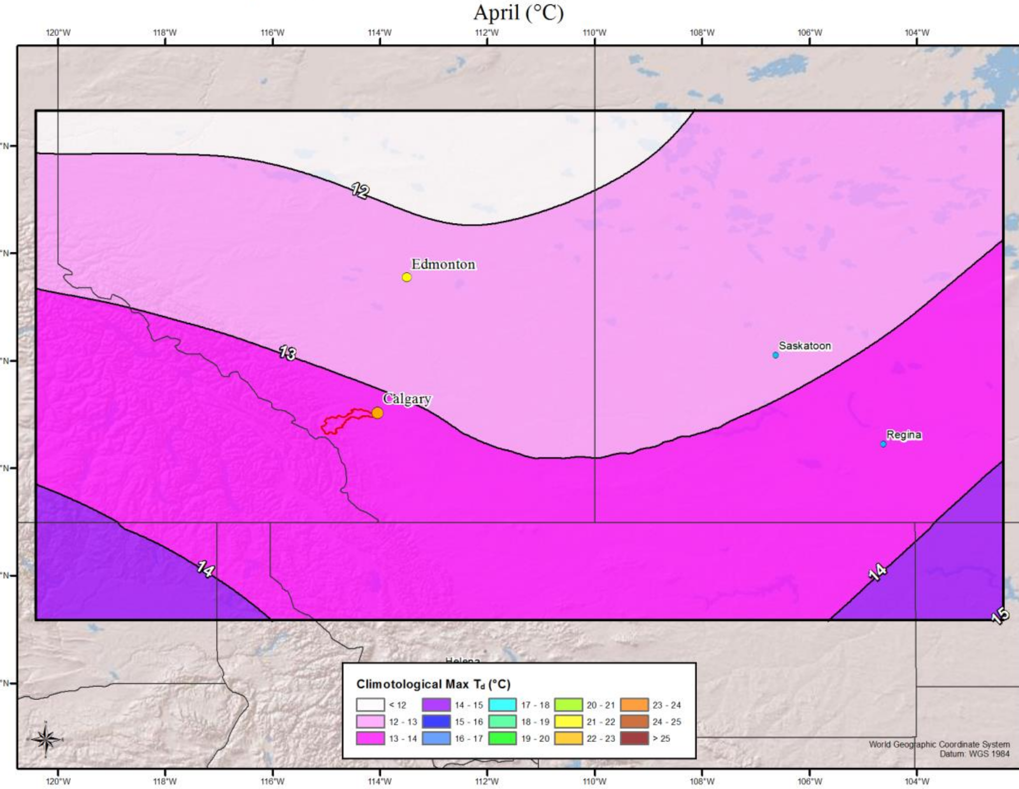


100-year Return Frequency 6-hour Maximum Dew Point Climatology
September (°C)

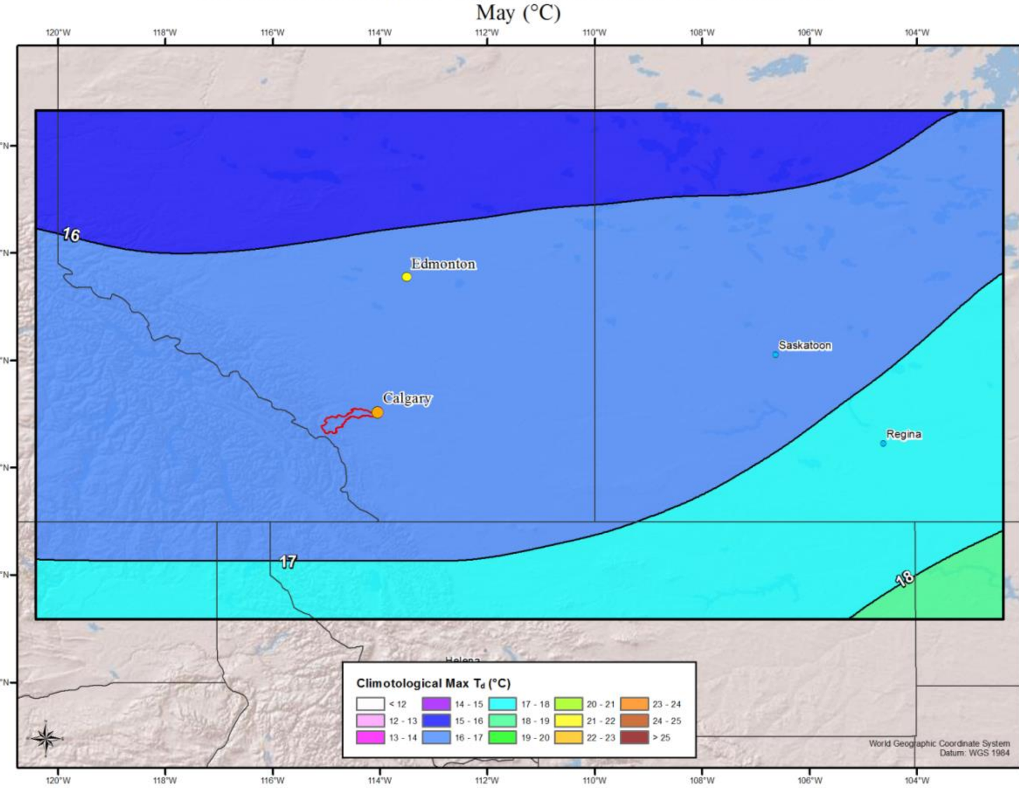


12-hour 1000mb Dew Point Maps

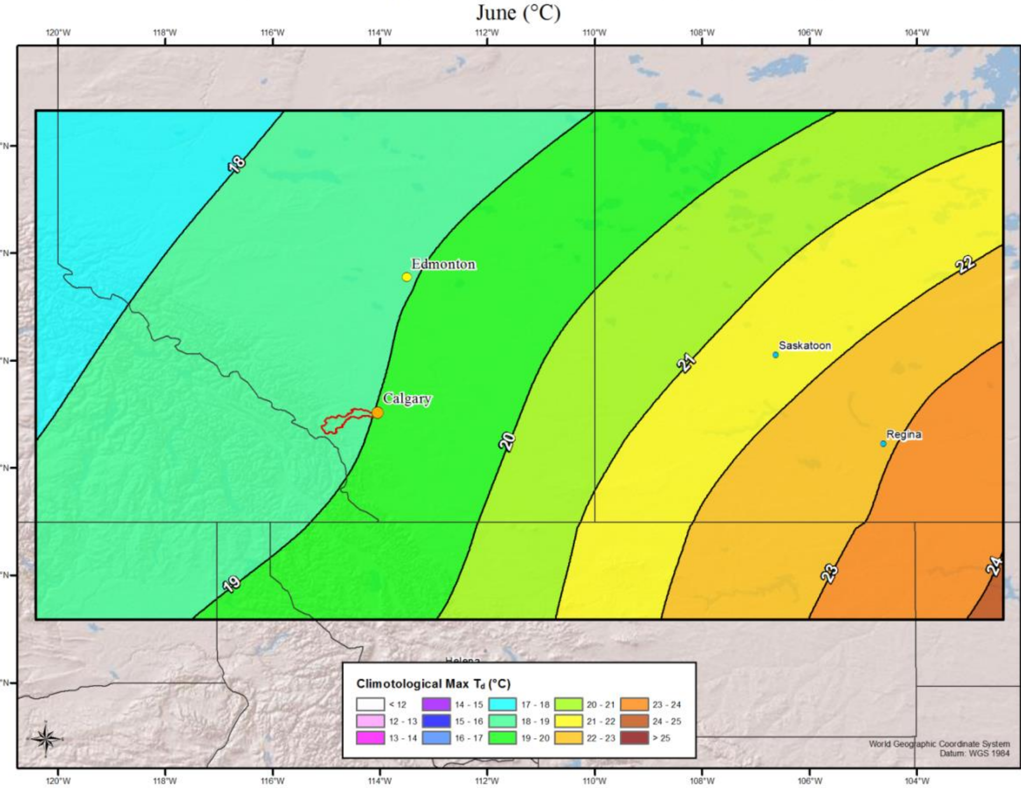
100-year Return Frequency 12-hour Maximum Dew Point Climatology
April (°C)



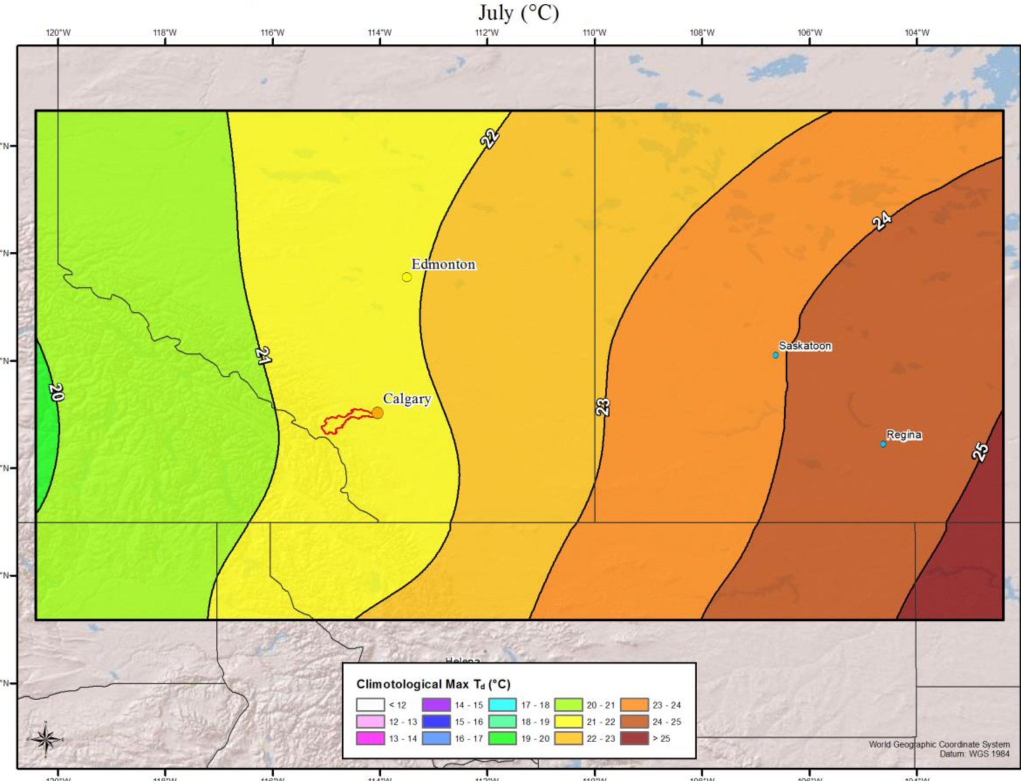
100-year Return Frequency 12-hour Maximum Dew Point Climatology
May (°C)



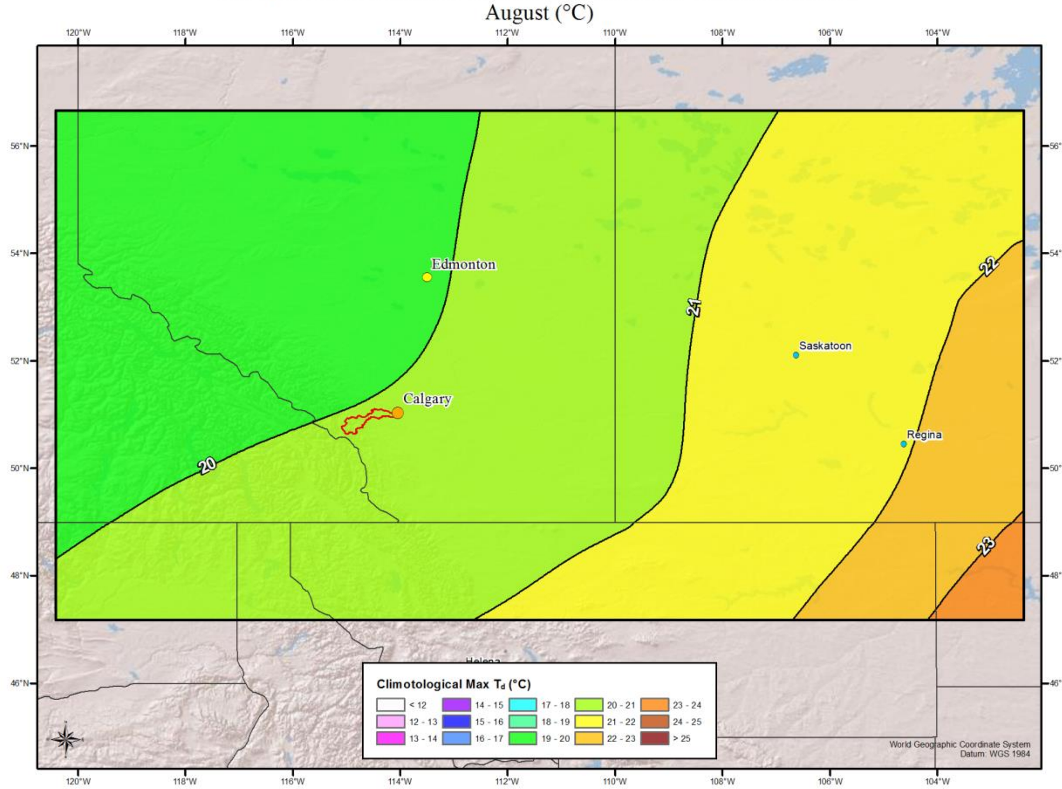
100-year Return Frequency 12-hour Maximum Dew Point Climatology
June (°C)



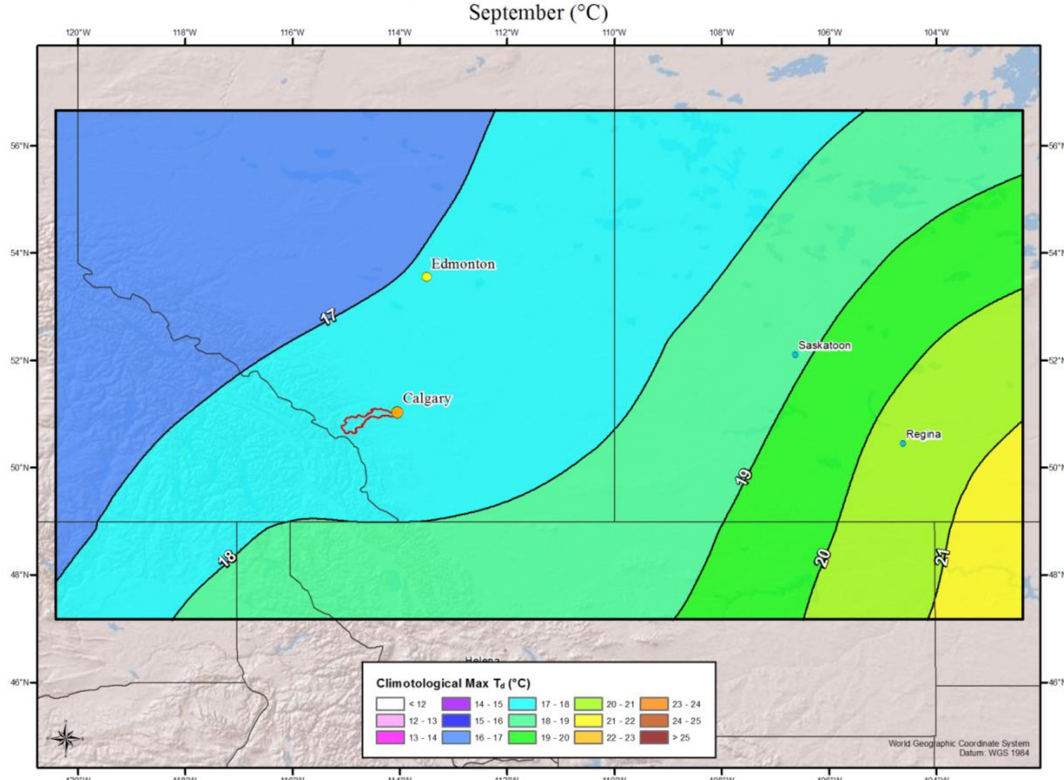
100-year Return Frequency 12-hour Maximum Dew Point Climatology
July (°C)



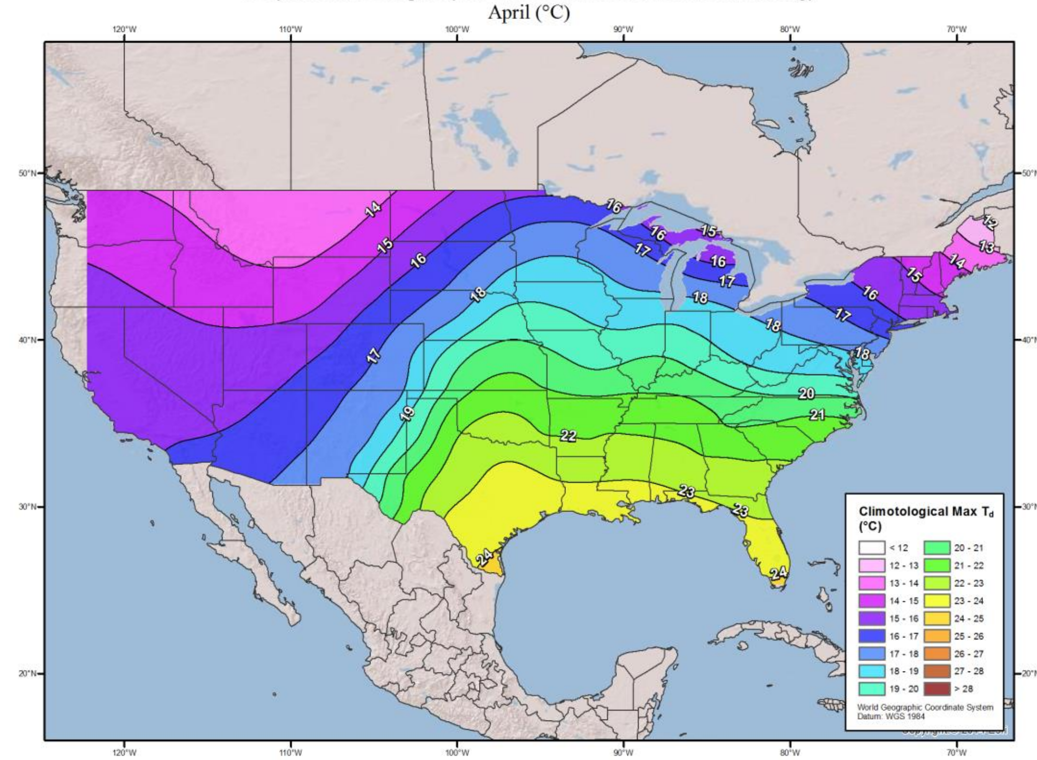
100-year Return Frequency 12-hour Maximum Dew Point Climatology
August (°C)



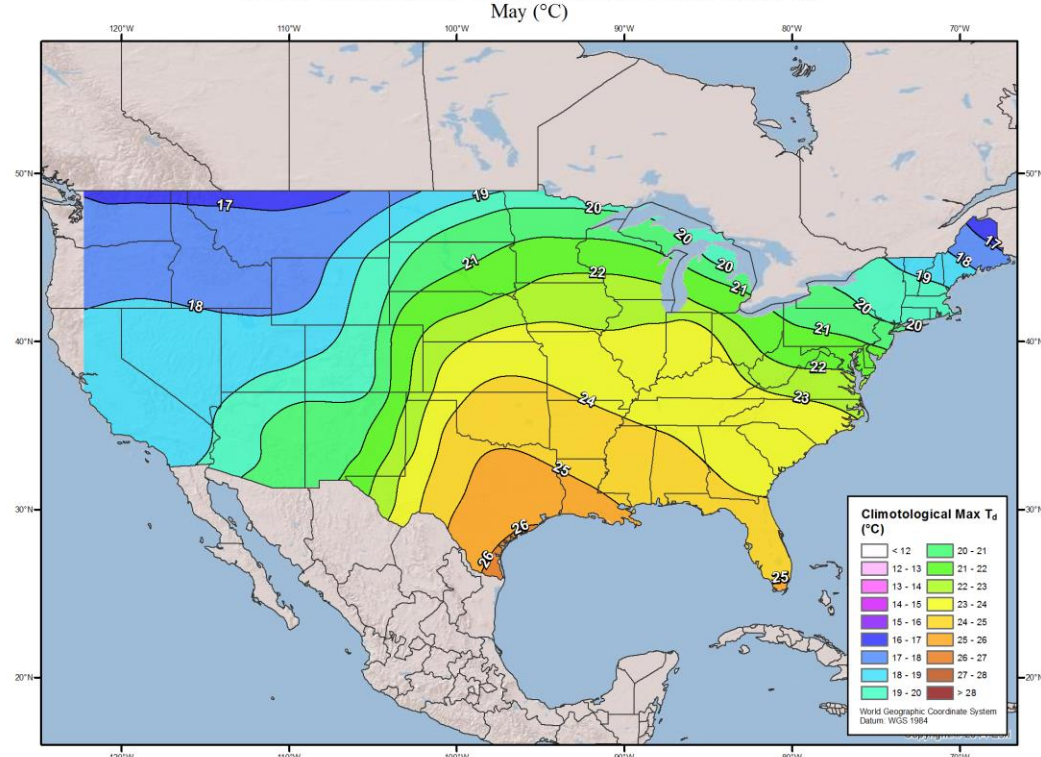
100-year Return Frequency 12-hour Maximum Dew Point Climatology
September (°C)



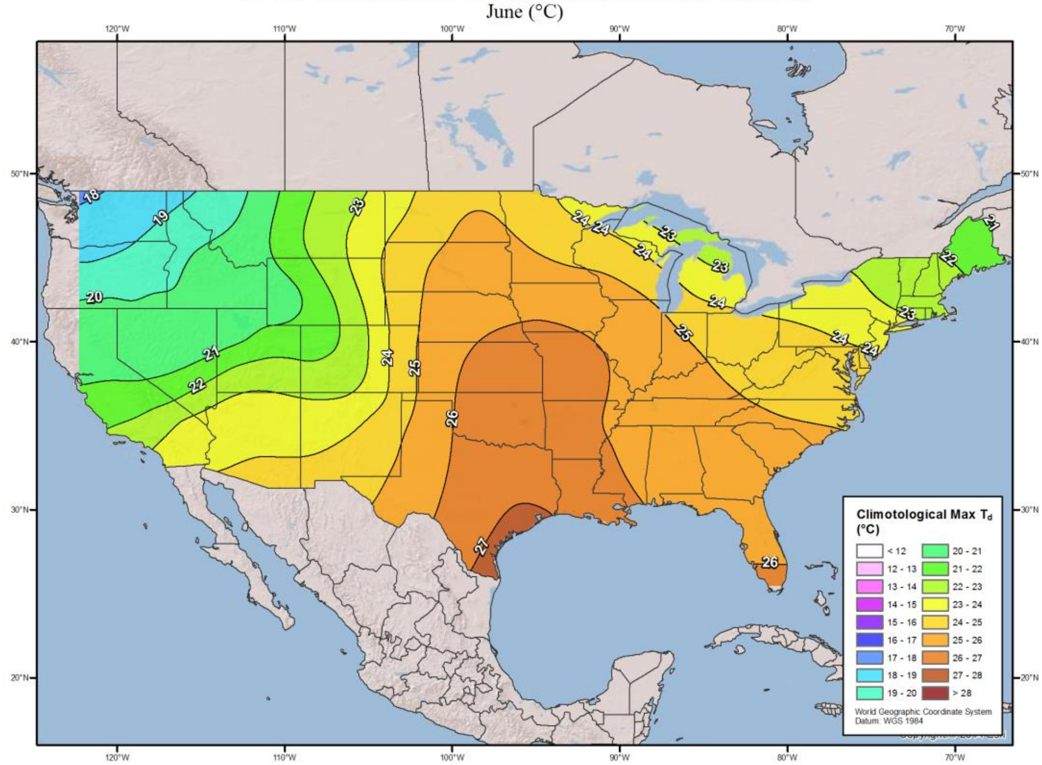
100-year Return Frequency 12-hour Maximum Dew Point Climatology
April (°C)



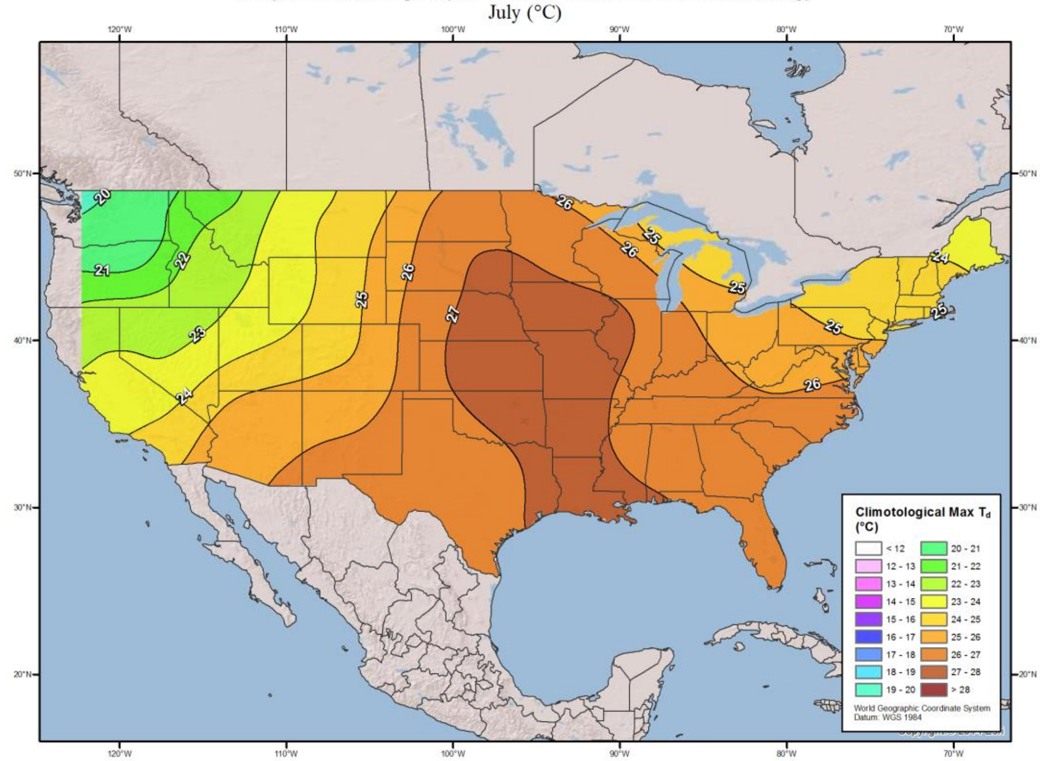
100-year Return Frequency 12-hour Maximum Dew Point Climatology
May (°C)



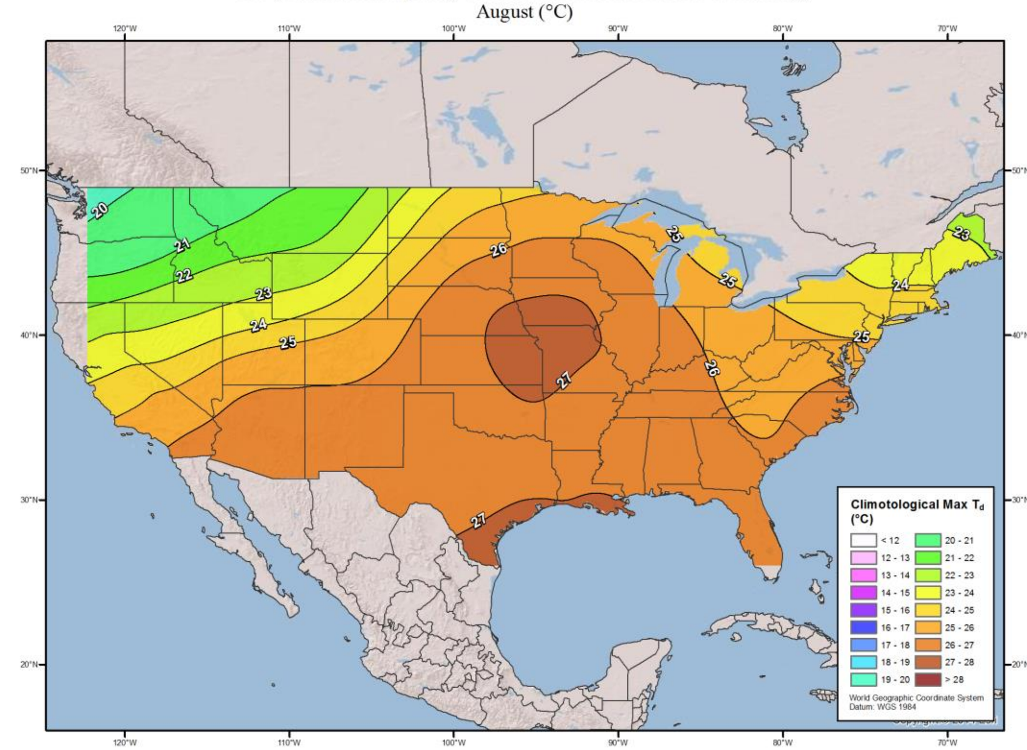
100-year Return Frequency 12-hour Maximum Dew Point Climatology
June (°C)



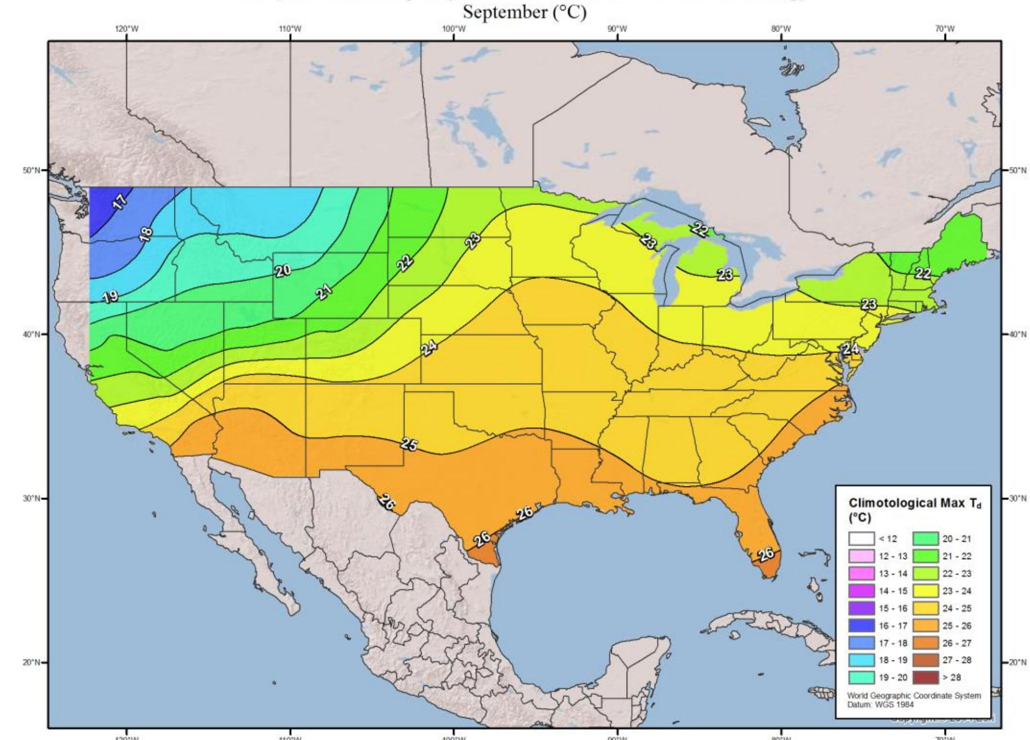
100-year Return Frequency 12-hour Maximum Dew Point Climatology
July (°C)



100-year Return Frequency 12-hour Maximum Dew Point Climatology
August (°C)

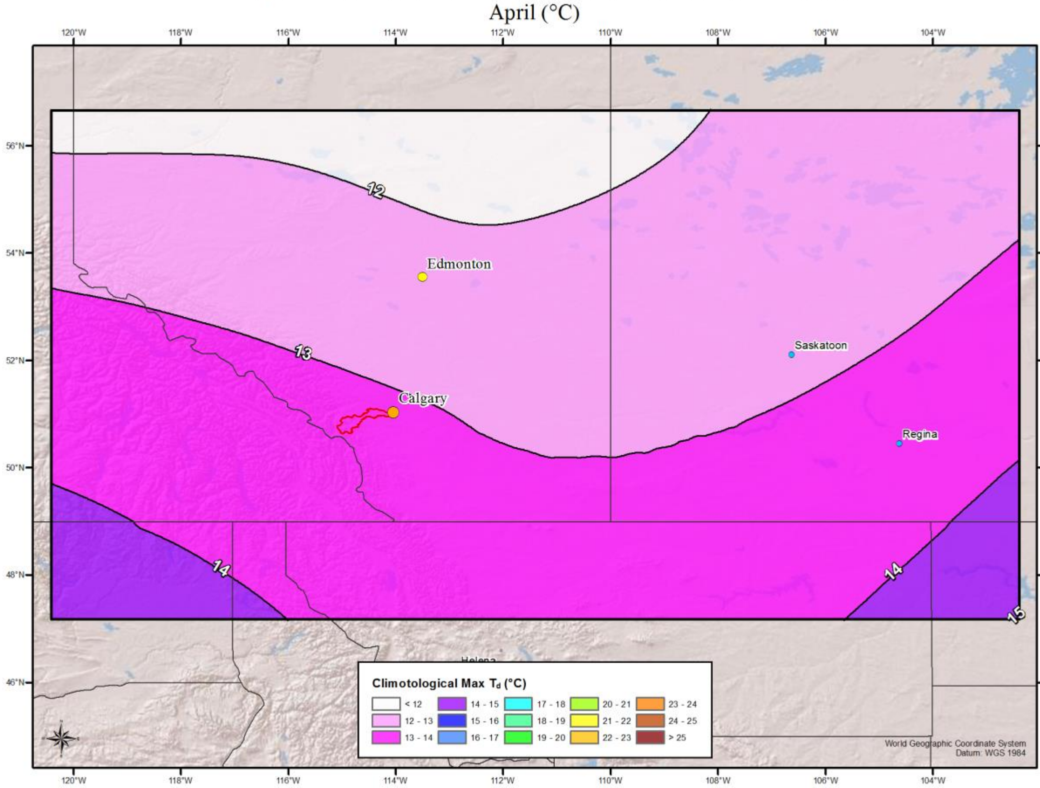


100-year Return Frequency 12-hour Maximum Dew Point Climatology
September (°C)

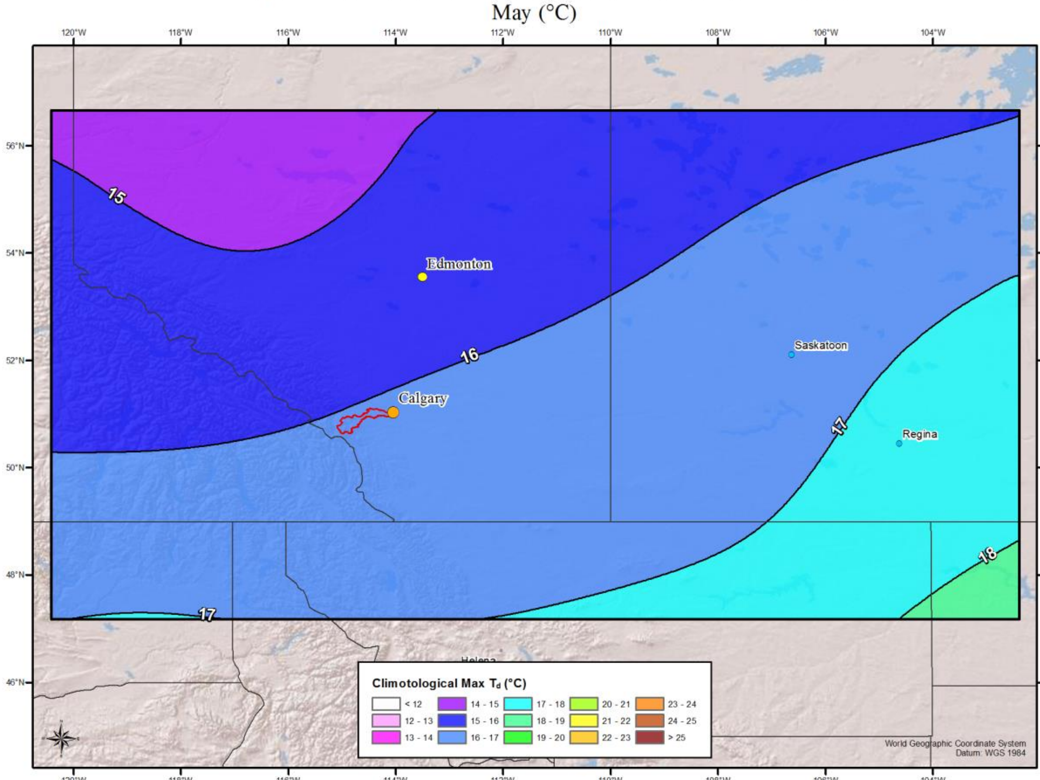


24-hour 1000mb Dew Point Maps

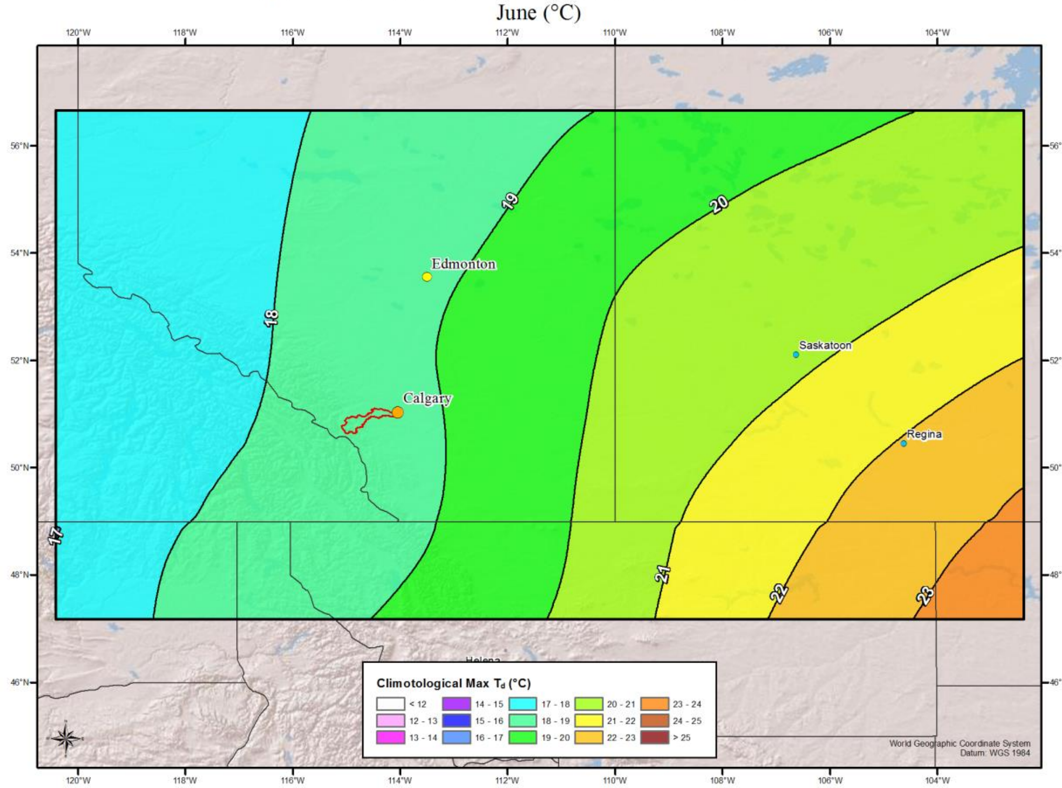
100-year Return Frequency 24-hour Maximum Dew Point Climatology
April (°C)



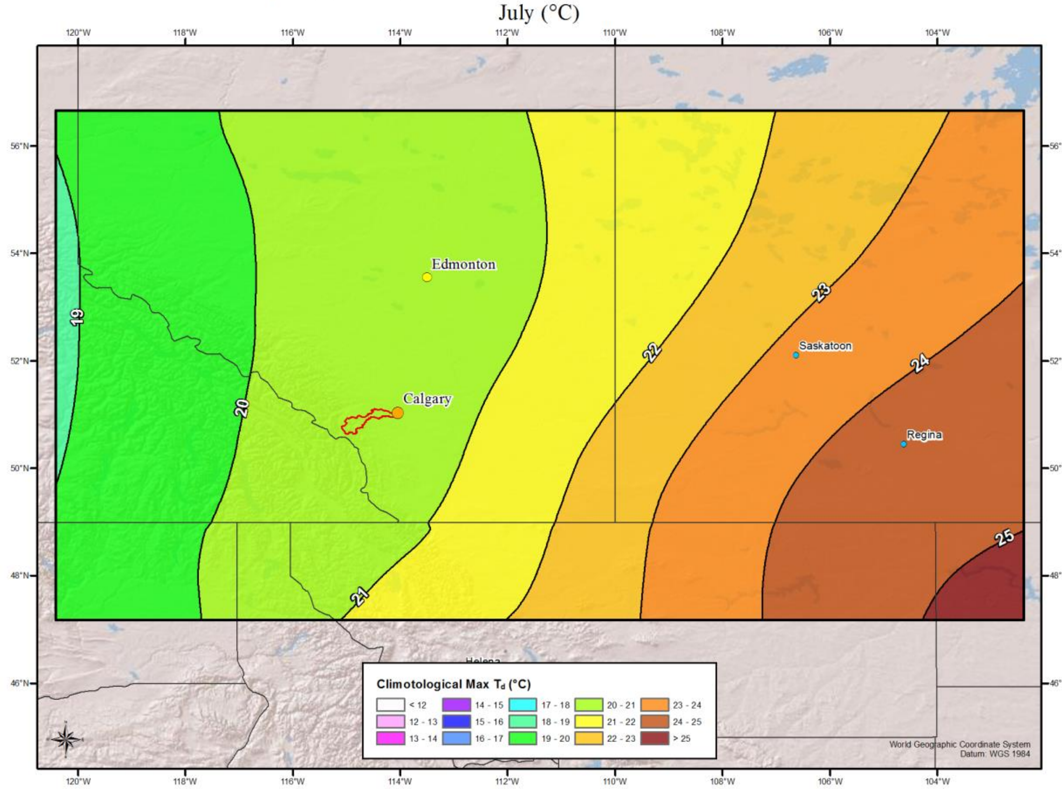
100-year Return Frequency 24-hour Maximum Dew Point Climatology
May (°C)



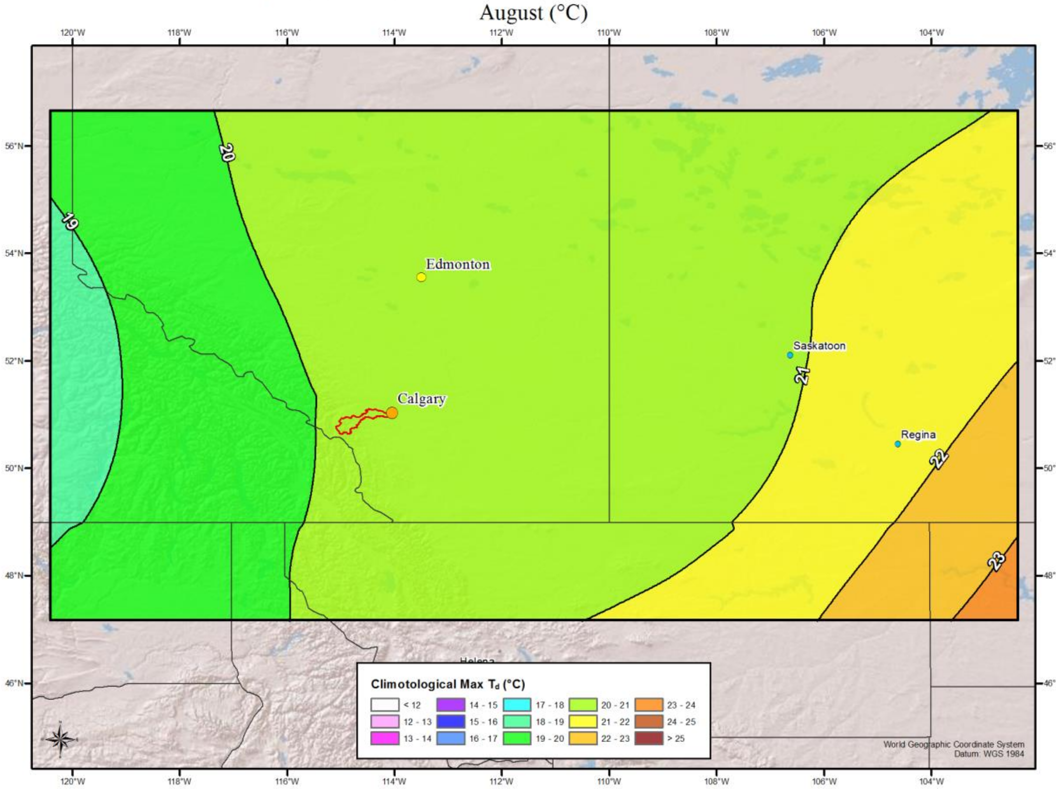
100-year Return Frequency 24-hour Maximum Dew Point Climatology
June (°C)



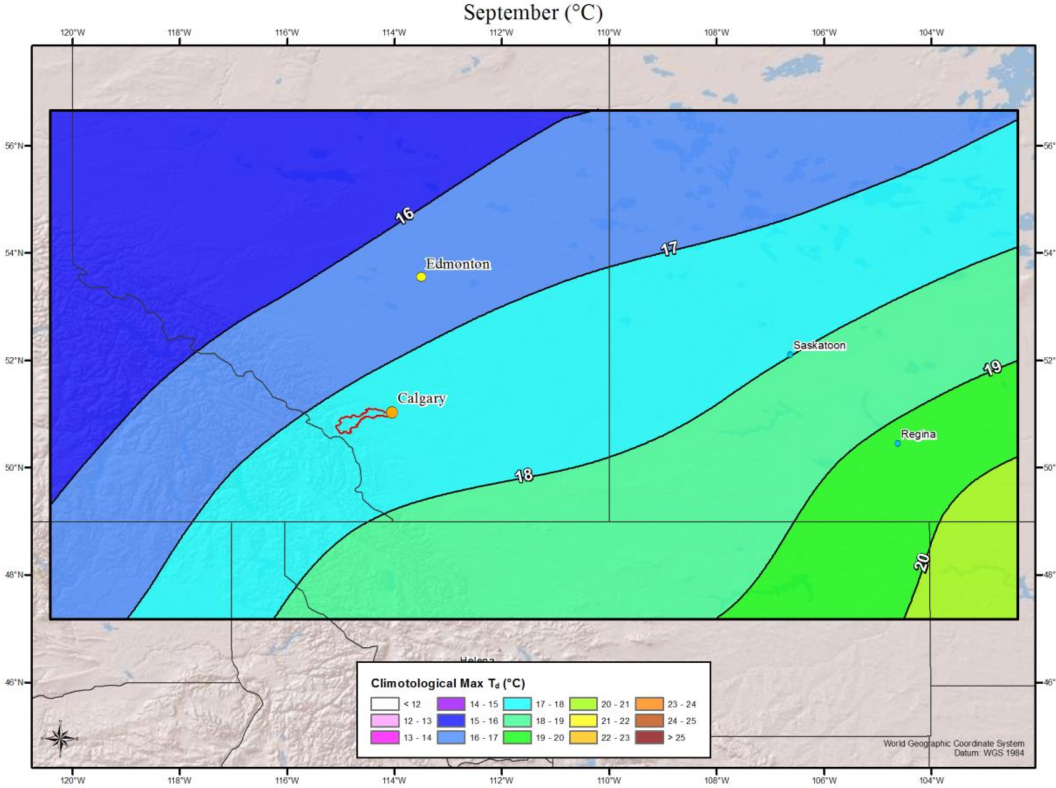
100-year Return Frequency 24-hour Maximum Dew Point Climatology
July (°C)



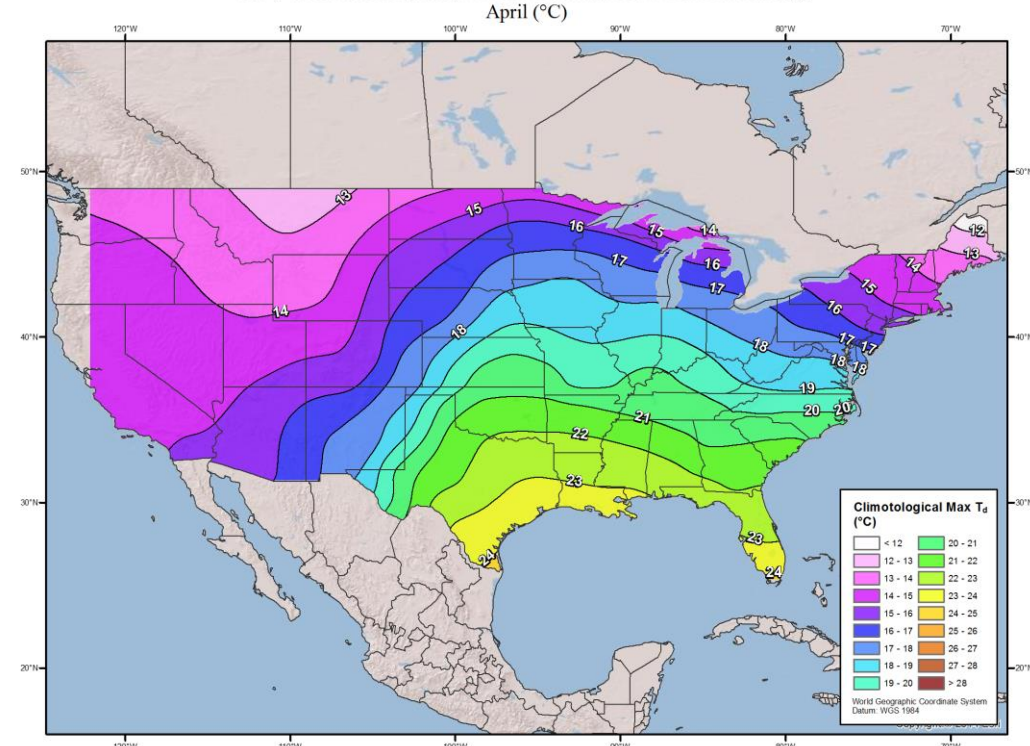
100-year Return Frequency 24-hour Maximum Dew Point Climatology
August (°C)



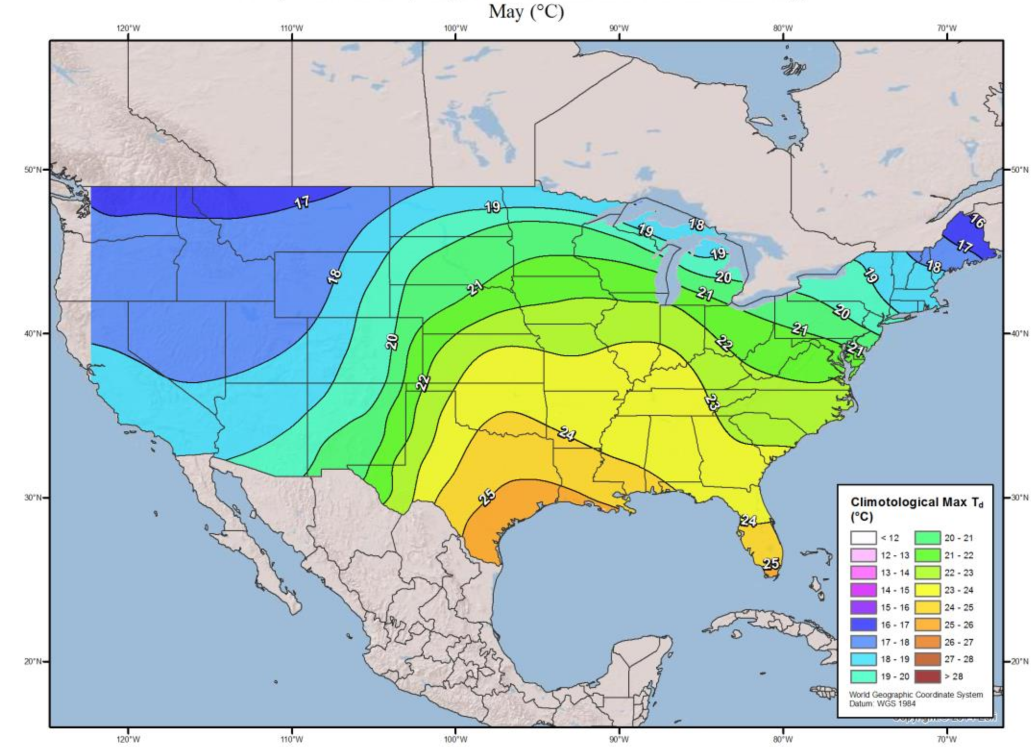
100-year Return Frequency 24-hour Maximum Dew Point Climatology
September (°C)



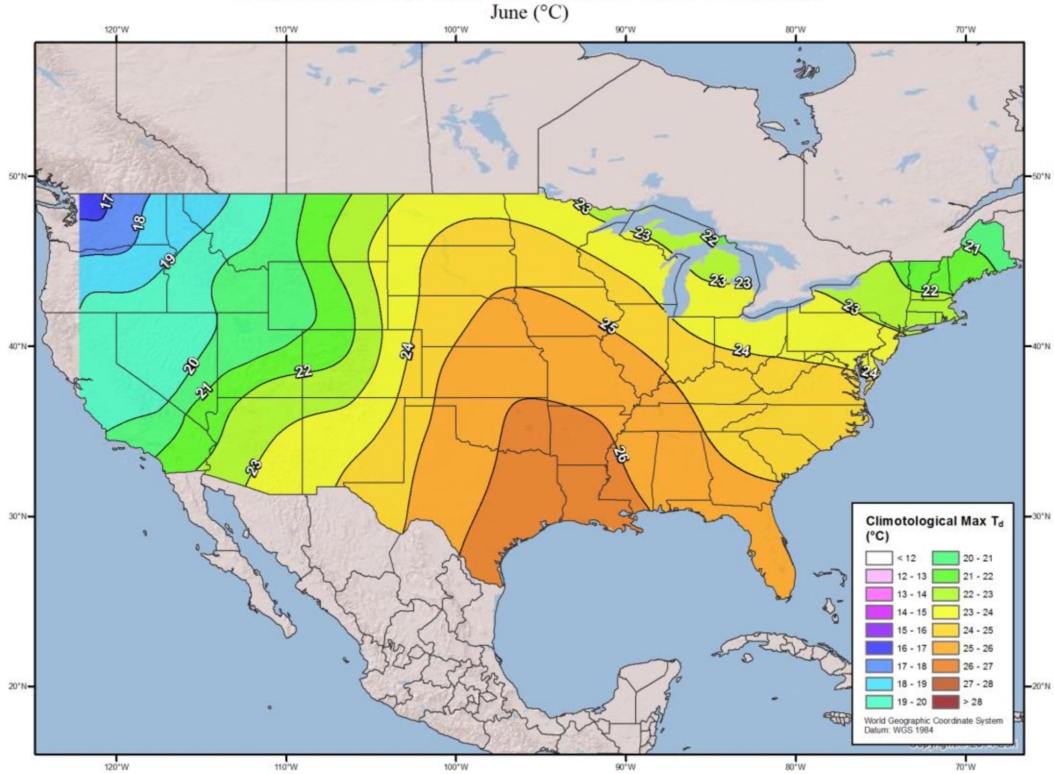
100-year Return Frequency 24-hour Maximum Dew Point Climatology
April (°C)



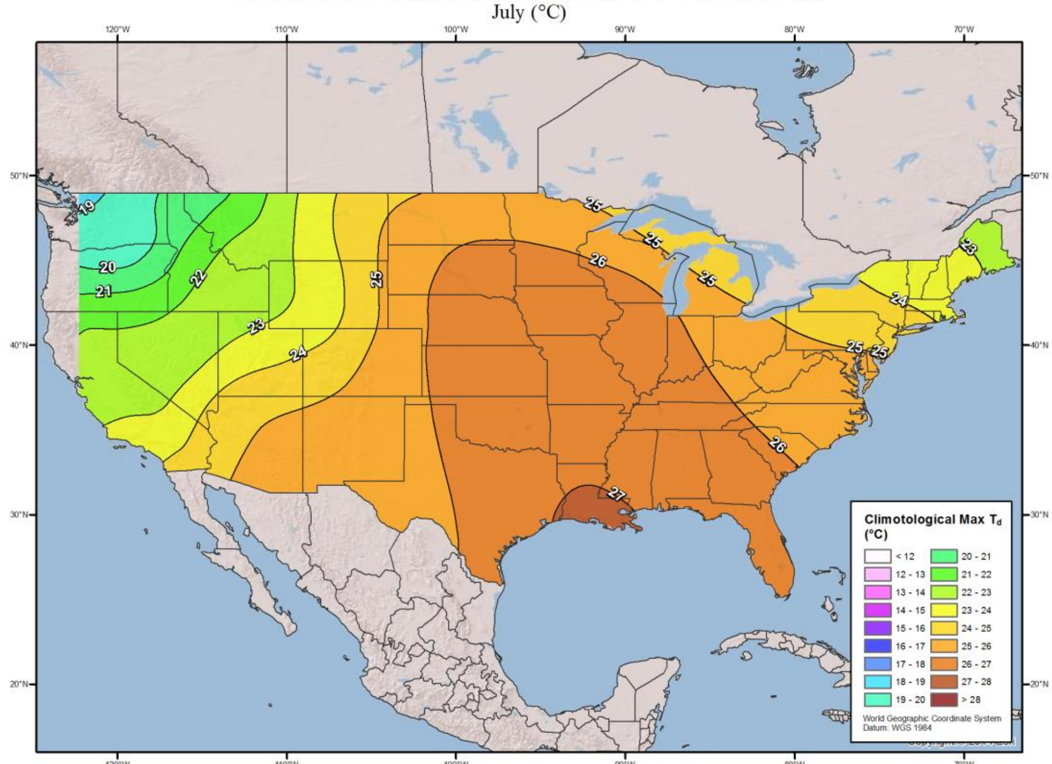
100-year Return Frequency 24-hour Maximum Dew Point Climatology
May (°C)



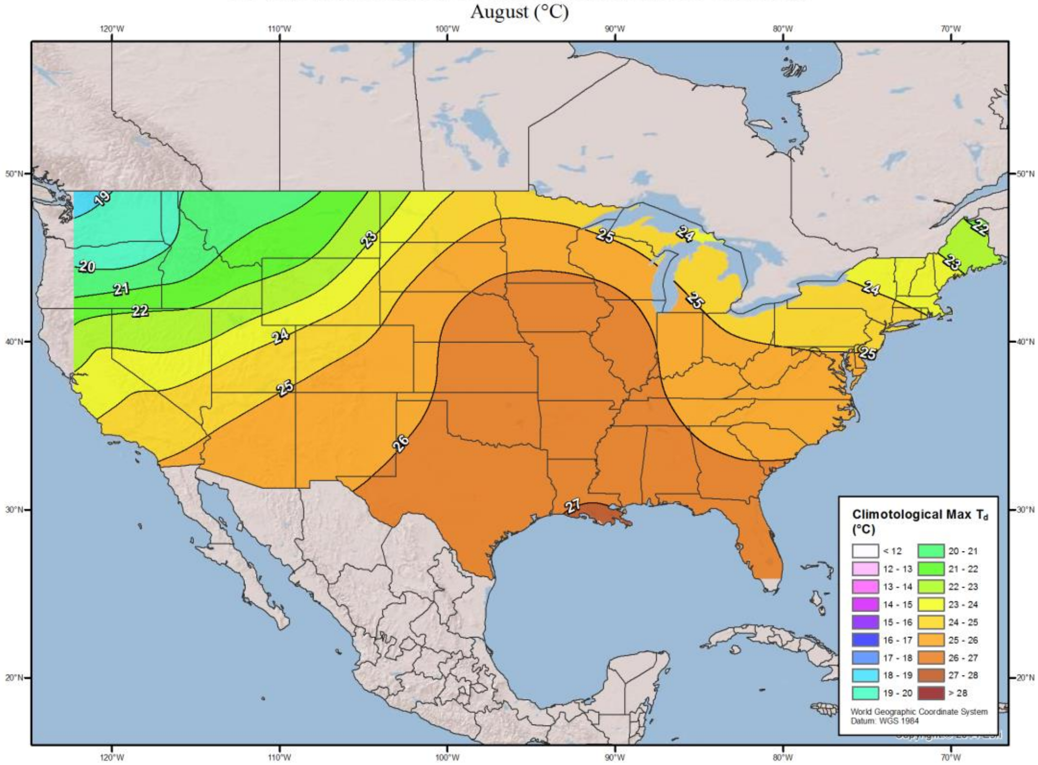
100-year Return Frequency 24-hour Maximum Dew Point Climatology
June (°C)



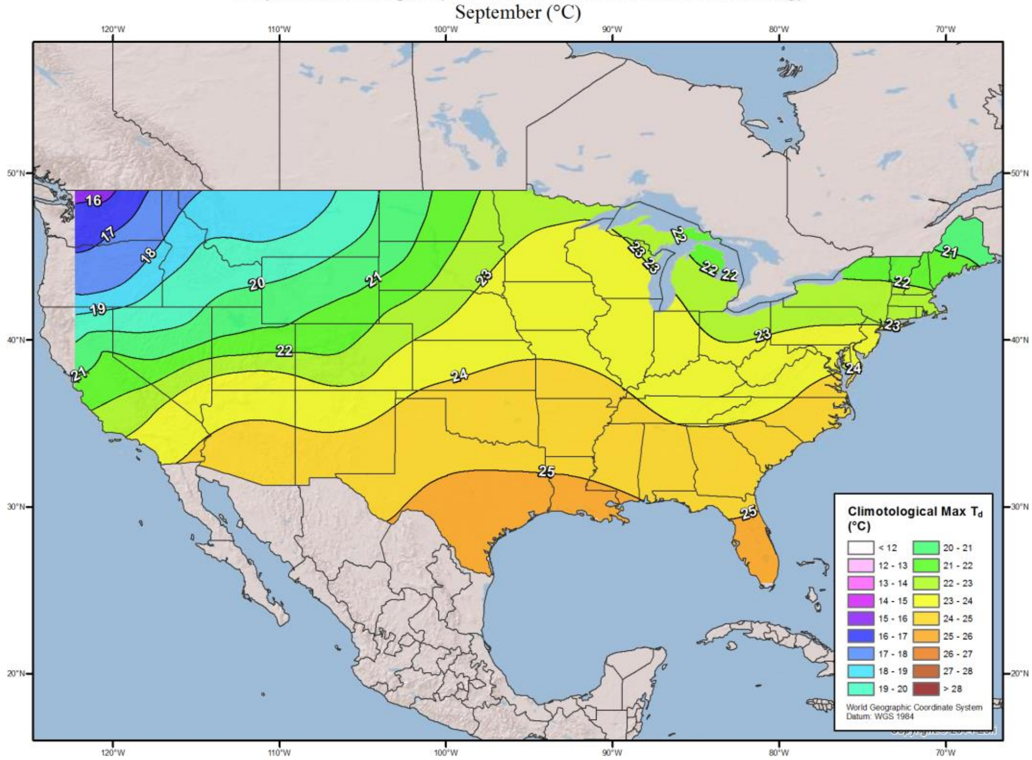
100-year Return Frequency 24-hour Maximum Dew Point Climatology
July (°C)



100-year Return Frequency 24-hour Maximum Dew Point Climatology
August (°C)



100-year Return Frequency 24-hour Maximum Dew Point Climatology
September (°C)



Appendix C

Procedure for using Dew Point Temperatures for Storm Maximization and Transposition

Maximum dew point temperatures (hereafter referred to as dew points) have historically been used for two primary purposes in the PMP computation process:

1. Increase the observed rainfall amounts to a maximum value based on a potential increase in atmospheric moisture available to the storm.
2. Adjust the available atmospheric moisture to account for any increases or decreases associated with the maximized storm potentially occurring at another location within the transposition limits for that storm.

HMR and WMO procedures for storm maximization use a representative storm dew point as the parameter to represent available moisture to a storm. Prior to the mid-1980s, maps of maximum dew point values from the *Climatic Atlas of the United States*, Environmental Data Services, Department of Commerce (1968), were the source for maximum dew point values. HMR 55 published in 1984 updated maximum dew point values for a portion of the United States from the Continental Divide eastward into the central plains. A regional PMP study for Michigan and Wisconsin produced return frequency maps using the L-moments method (Tomlinson, 1993). The Review Committee for that study included representatives from NWS, FERC, Bureau of Reclamation, and others. They agreed that the 50-year return frequency values were appropriate for use in PMP calculations. HMR 57 was published in 1994 and HMR 59 in 1999. These latest NWS publications also updated the maximum dew point climatology but used maximum observed dew points instead of return frequency values. For this study, the 100-year return frequency dew point climatology maps were appropriate because they added a layer of conservatism along with an extra 17 years of data available since the Electric Power Research Institute (EPRI) and Nebraska studies, allowing the 100-year return frequency to be more reliable. Storm precipitation amounts are maximized using the ratio of precipitable water for the maximum observed dew point to precipitable water for the storm representative dew point, assuming a vertically saturated atmosphere. This procedure was followed in this study using the updated maximum dew point climatology developed during recent and ongoing PMP studies. The climatological maximum 100-year return frequency maps for the 3-, 6-, 12-, and 24-hour durations are given in Appendix B.

The procedure for determining a storm representative dew point begins with the determination of the inflow wind vector (direction and magnitude) for the air mass that contains the atmospheric moisture available to the storm. Beginning and ending times of the rainfall event at locations of the most extreme rainfall amounts are determined using rainfall mass curves from those locations.

The storm inflow wind vector is determined using available wind data. The inflow wind vector has historically been determined using winds reported by weather stations, together with upper air winds, when available. Recently, re-analyzed weather model data representing various atmospheric parameters including wind direction and speed in the atmosphere have become available for use from the HYSPLIT trajectory model and the North American Reanalysis Project (Kalnay et al., 1996). These analyses are available back to 1948. Use of these wind fields in the lower portion of the atmosphere provides much improved reliability in the determination of the storm inflow wind vectors. The program is available through an online interface through the Air Resources Laboratory section of NOAA. Users are able to enter in specific parameters that then produce a trajectory from a starting point going backwards (or forwards) for a specified amount of time. Users can define variables such as the starting point (using latitude and longitude or a map interface), the date and time to start the trajectory, the length of time to run the trajectory, and the pressure level at which to delineate the inflow vector. Figure C.1 shows example inflow vectors generated by HYSPLIT at three levels: 700mb, 850mb, and surface for an example storm event, Rapid City, SD, June 1972. The data generated from the HYSPLIT runs is then used in conjunction with standard methods to help delineate the source region of the air mass responsible for the storm precipitation. Also, this serves as another tool to determine from which weather stations to derive hourly dew point data for storm representative dew point analysis.

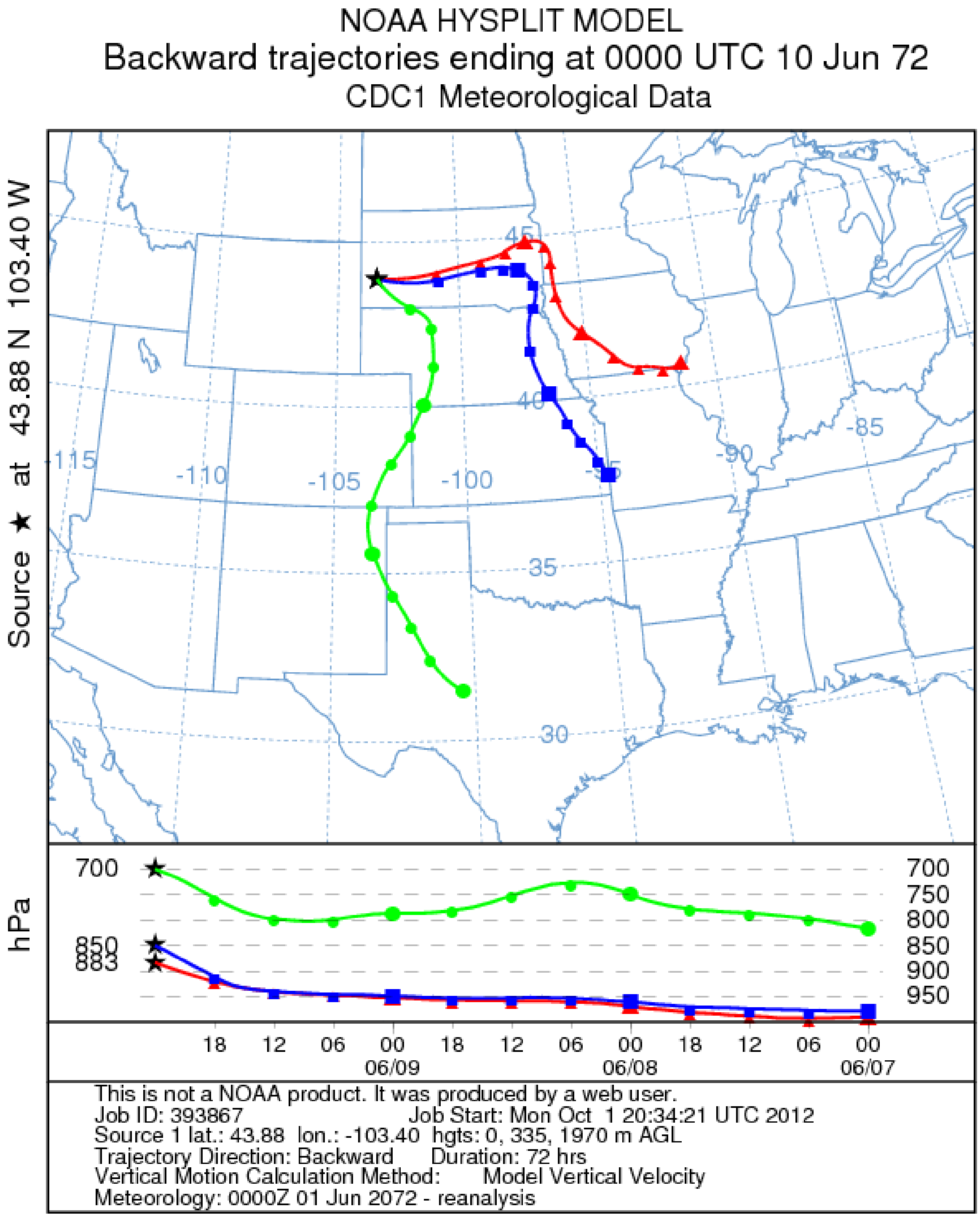


Figure C.1 HYSPLIT trajectory model results for Rapid City, SD June 1972.

The inflow wind vector is followed upwind until a location is reached that is outside of the storm rainfall. The nearest weather stations that report dew point values are identified. At least two stations are desired but a single station with reliable dew points observations can be used. The time period used to identify the appropriate dew point values is determined by computing the time required for the air mass to be transported from the location of the weather station(s) to the location of maximum rainfall. The start time of the extreme rainfall is then adjusted back in time to account for transit time from the dew point observing station(s) to the maximum rainfall location.

For example, consider the following case:

1. Rainfall begins at 11:00am and ends at 6:00pm the following day at the location of maximum rainfall,
2. The storm representative dew point location (the location of the weather stations observing the dew points) is 160.93 kilometers from the maximum rainfall location in the direction of the inflow wind vector, and
3. The inflow wind speed is 32.19 kph.

The transit time for the air mass from the weather stations to the maximum rainfall location is five hours (160.93 km divided by 32.19 kph). The time to begin using the dew point observations is five hours before the rainfall began (11:00am minus 5 hours = 6:00am) and the time to stop using the dew point observations is five hours before the rainfall ended (6:00pm minus 5 hours = 1:00pm the following day). Dew point observations taken between these times are used to determine the storm representative average 24-hour 1000mb dew point value. The storm representative dew point location can come from a single location if only one station is used or from a location between the reporting weather stations if more than one station is used. The vector connecting this location and the location of maximum rainfall becomes the wind inflow vector used for storm transpositioning.

The storm representative dew point determined from the hourly dew point observations needs to be corrected to the 1000mb level. The elevation of the storm representative dew point location is used in this correction. The correction factor of 2.4ºC per 304.8 meters of elevation is used. This is the same correction factor used in the *Climatic Atlas of the United States* (Environmental Data Services, Department of Commerce, 1968). For example, a storm representative dew point of 22.2ºC at a station location with an elevation of 243.84 meters above sea level is corrected with a factor of 243.84 X 2.4 /304.8 = 1.9ºC. The dew point value corrected to 1000mb (sea level) is 22.22ºC + 1.9ºC = 24.12ºC after rounding.

The procedure that computes the in-place maximized rainfall for a storm provides an estimate of the maximum amount of rainfall that could have been produced by the same storm at the same location if the maximum amount of atmospheric moisture had been available. This procedure requires that a maximum value for the storm representative dew point be determined. The maximum dew point value is selected at the same location where the storm dew point was determined using a maximum dew point climatology. The maximum dew point values must be corrected to 1000mb. The precipitable water in the atmosphere is determined using the storm representative and maximum dew point values. Precipitable water is defined in this study as the total amount of moisture in a column of the atmosphere from sea level to 9,144 meters assuming a vertically saturated atmosphere. Values of atmospheric precipitable water are determined using the moist pseudo-adiabatic assumption, i.e. assume that for the given 1000mb dew point value, the atmosphere holds the maximum amount of moisture possible. The ratio of the precipitable water in the column above ground level associated with the maximum 1000mb dew point to the precipitable water in the column above ground level associated with the 1000-mb storm representative dew point is the maximization factor.

For example, consider the following case:

1000mb storm representative dew point:	22.22°C
1000mb maximum dew point:	24.44°C
Precipitable water associated with a 1000mb dew point of 22.22°C:	62.74mm
Precipitable water associated with a 1000mb dew point of 24.44°C:	75.95mm

Maximization factor: PW(24.44°C)/PW(22.22°C) = 75.95mm/62.74mm = 1.21

In this example, the storm is considered to have occurred at sea level (1000mb). If the elevation of the storm had occurred above sea level, then the amount of precipitable water associated with the storm representative dew point and the climatological maximum dew point up to that elevation would need to be subtracted out of the equation. This is because that amount of precipitable water would not be available in the atmospheric column below the elevation used.

For transpositioning, the storm inflow vector (determined by connecting the storm representative dew point location with the location of maximum rainfall) is moved to the basin location being studied. The new location of the upwind end of the vector is determined. The maximum dew point associated with that location is then selected using the same maximum dew point climatology map used for in-place maximization. The transpositioning factor is the ratio of the precipitable water associated with the maximum 1000mb dew point value at the transpositioned location to the precipitable water associated with the maximum 1000mb dew point for the storm representative dew point location.

An example is provided.

1000mb maximum dew point at the storm representative dew point location:	24.44°C
1000mb maximum dew point at the transpositioned location:	23.33°C
Precipitable water associated with a 1000mb dew point of 24.44°C:	75.95mm
Precipitable water associated with a 1000mb dew point of 23.33°C:	69.34mm

Transposition factor: PW(23.33°C)/PW(24.44°C) = 69.34mm/75.95mm = 0.91

In this example, the transpositioned location is considered to be at sea level (1000mb). If the elevation of the transpostion location had was above sea level, then the amount of precipitable water associated with the climatological maximum dew point up to that elevation would need to be subtracted out of the equation. This is because that amount of precipitable water would not be available in the atmospheric column below the elevation used.

Appendix D

Storm Precipitation Analysis Program Description

Introduction

The Storm Precipitation Analysis System (SPAS) is grounded on years of scientific research with a demonstrated reliability in hundreds of post-storm precipitation analyses. It has evolved into a trusted hydrometeorological tool that provides accurate precipitation data at a high spatial and temporal resolution for use in a variety of sensitive hydrologic applications (Faulkner et al., 2004; Tomlinson et al., 2003-2012). Applied Weather Associates, LLC and METSTAT, Inc. initially developed SPAS in 2002 for use in producing Depth-Area-Duration values for Probable Maximum Precipitation (PMP) analyses. SPAS utilizes precipitation gauge data, "basemaps" and radar data (when available) to produce gridded precipitation at time intervals as short as 5 minutes, at spatial scales as fine as 1 km^2 and in a variety of customizable formats. To date (February 2014) SPAS has been used to analyze over 330 storm centers across all types of terrain, among highly varied meteorological settings and some occurring over 100-years ago.

SPAS output has many applications including, but not limited to: hydrologic model calibration/validation, flood event reconstruction, storm water runoff analysis, forensic cases, and PMP studies. Detailed SPAS-computed precipitation data allow hydrologists to accurately model runoff from basins, particularly when the precipitation is unevenly distributed over the drainage basin or when rain gauge data are limited or not available. The increased spatial and temporal accuracy of precipitation estimates has eliminated the need for commonly made assumptions about precipitation characteristics (such as uniform precipitation over a watershed), thereby greatly improving the precision and reliability of hydrologic analyses.

To instill consistency in SPAS analyses, many of the core methods have remained consistent from the beginning. However, SPAS is constantly evolving and improving through new scientific advancements and as new data and improvements are incorporated. This write-up describes the current inner-workings of SPAS, but the reader should realize SPAS can be customized on a case-by-case basis to account for special circumstances; these adaptations are documented and included in the deliverables. The over arching goal of SPAS is to combine the strengths of rain gauge data and radar data (when available) to provide sound, reliable and accurate spatial precipitation data.

Hourly precipitation observations are generally limited to a small number of locations, with many basins lacking observational precipitation data entirely. However, Next Generation Radar (NEXRAD) data provide valuable spatial and temporal information over data-sparse basins, which have historically lacked reliability for determining precipitation rates and reliable quantitative precipitation estimates (QPE). The improved reliability in SPAS is made possible by hourly calibration of the NEXRAD radar-precipitation relationship, combined with local hourly bias adjustments to force consistency between the final result and "ground truth" precipitation measurements. If NEXRAD radar data are available (generally for storm events since the mid-1990's), precipitation accumulation at temporal scales as frequent as 5-minutes can be analyzed. If no NEXRAD data are available, then precipitation data are analyzed in hourly increments. A summary of the general SPAS processes are shown in flow chart in Figure D.1.

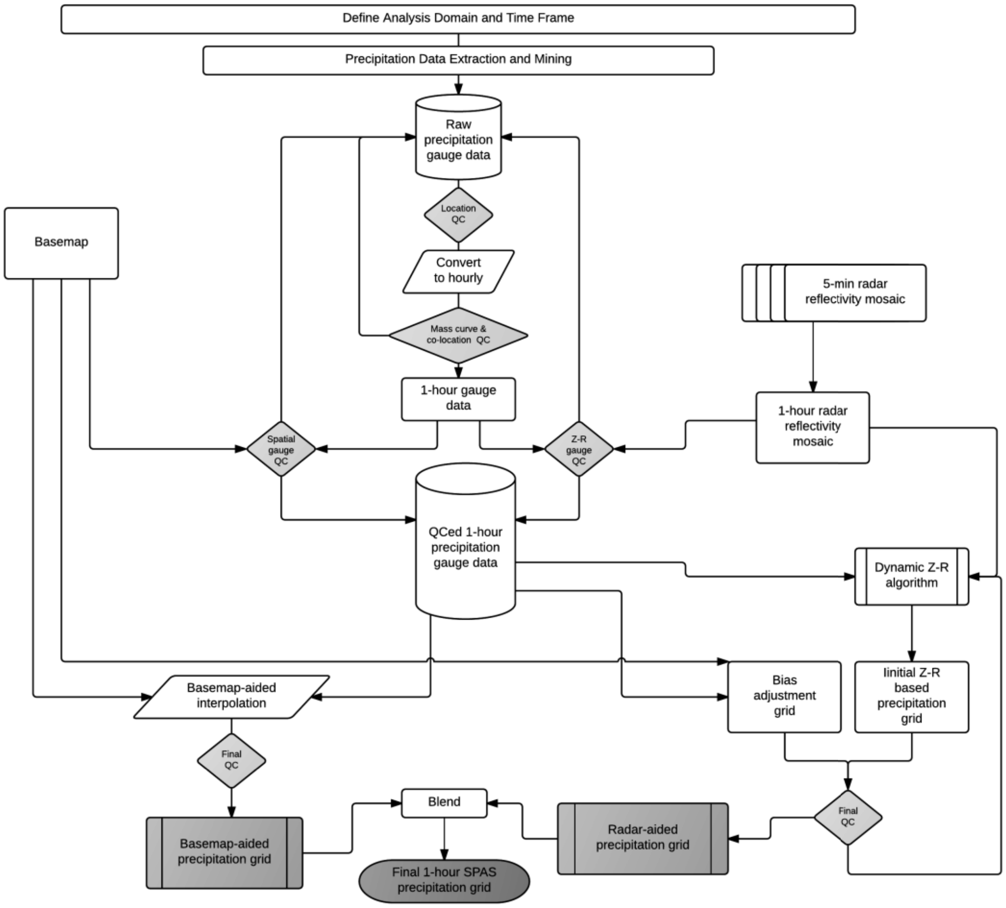


Figure D.1 SPAS flow chart

Setup

Prior to a SPAS analysis, careful definition of the storm analysis domain and time frame to be analyzed is established. Several considerations are made to ensure the domain (longitude-latitude box) and time frame are sufficient for the given application.

SPAS Analysis Domain

For PMP applications it is important to establish an analysis domain that completely encompasses a storm center, meanwhile hydrologic modeling applications are more concerned about a specific basin, watershed or catchment. If radar data are available, then it is also important to establish an area large enough to encompass enough stations (minimum of ~30) to adequately derive reliable radar-precipitation intensity relationships (discussed later). The domain is defined by evaluating existing documentation on the storm as well as plotting and evaluating initial precipitation gauge data on a map. The analysis domain is defined to include as many hourly recording gauges as possible given their importance in timing. The domain must include enough of a buffer to accurately model the nested domain of interest. The domain is defined as a longitude-latitude (upper left and lower right corner) rectangular region.

SPAS Analysis Time Frame

Ideally, the analysis time frame, also referred to as the Storm Precipitation Period (SPP), will extend from a dry period through the target wet period then back into another dry period. This is to ensure that total storm precipitation amounts can be confidently associated with the storm in question and not contaminated by adjacent wet periods. If this is not possible, a reasonable time period is selected that is bounded by relatively lighter precipitation. The time frame of the hourly data must be sufficient to capture the full range of daily gauge observational periods for the daily observations to be disaggregated into estimated incremental hourly values (discussed later). For example, if a daily gauge takes observations at 8:00 AM, then the hourly data must be available from 8:00 AM the day prior. Given the configuration of SPAS, the minimum SPP is 72 hours and aligns midnight to midnight.

The core precipitation period (CPP) is a sub-set of the SPP and represents the time period with the most precipitation and the greatest number of reporting gauges. The CPP represents the time period of interest and where our confidence in the results is highest.

Data

The foundation of a SPAS analysis is the "ground truth" precipitation measurements. In fact, the level of effort involved in "data mining" and quality control represent over half of the total level of effort needed to conduct a complete storm analysis. SPAS operates with three primary data sets: precipitation gauge data, a "basemap" and, if available, radar data. Table D.1 conveys the variety of precipitation gauges usable by SPAS. For each gauge, the following elements are gathered, entered and archived into SPAS database:

- Station ID
- Station name
- Station type (H=hourly, D=Daily, S=Supplemental, etc.)
- Longitude in decimal degrees
- Latitude in decimal degrees
- Elevation in feet above MSL
- Observed precipitation
- Observation times
- Source
- If unofficial, the measurement equipment and/or method is also noted.

Based on the SPP and analysis domain, hourly and daily precipitation gauge data are extracted from our in-house database as well as the Meteorological Assimilation Data Ingest System (MADIS). Our in-house database contains data dating back to the late 1800s, while the MADIS system (described below) contains archived data back to 2002.

Hourly Precipitation Data

Our hourly precipitation database is largely comprised of data from NCDC TD-3240, but also precipitation data from other mesonets and meteorological networks (e.g. ALERT, Flood Control Districts, etc.) that we have collected and archived as part of previous studies. Meanwhile, MADIS provides data from a large number of networks across the U.S., including NOAA's HADS (Hydrometeorological Automated Data System), numerous mesonets, the Citizen Weather Observers Program (CWOP), departments of transportation, etc. (see http://madis.noaa.gov/mesonet_providers.html for a list of providers). Although our automatic data extraction is fast, cost-effective and efficient, it never captures all of the available precipitation data for a storm event. For this reason, a thorough "data mining" effort is undertaken to acquire all available data from sources such as U.S. Geological Survey (USGS), Remote Automated Weather Stations (RAWS), Community Collaborative Rain, Hail & Snow Network (CoCoRaHS), National Atmospheric Deposition Program (NADP), Clean Air Status and Trends Network (CASTNET), local observer networks, Climate Reference Network (CRN), Global Summary of the Day (GSD) and Soil Climate Analysis Network (SCAN). Unofficial hourly precipitation are gathered to give guidance on either timing or magnitude in areas otherwise void of precipitation data. The WeatherUnderground and MesoWest, two of the largest weather databases on the Internet, contain a good deal of official data, but also includes data from unofficial gauges.

Table D.1 Different precipitation gauge types used by SPAS

Precipitation Gauge Type	Description
Hourly	Hourly gauges with complete, or nearly complete, incremental hourly precipitation data.
Hourly estimated	Hourly gauges with some estimated hourly values, but otherwise reliable.
Hourly pseudo	Hourly gauges with reliable temporal precipitation data, but the magnitude is questionable in relation to co-located daily or supplemental gauge.
Daily	Daily gauge with complete data and known observation times.
Daily estimated	Daily gauges with some or all estimated data.
Supplemental	Gauges with unknown or irregular observation times, but reliable total storm precipitation data. (E.g. public reports, storms reports, "Bucket surveys", etc.)
Supplemental estimated	Gauges with estimated total storm precipitation values based on other information (e.g. newspaper articles, stream flow discharge, inferences from nearby gauges, pre-existing total storm isohyetal maps, etc.)

Daily Precipitation Data

Our daily database is largely based on NCDC's TD-3206 (pre-1948) and TD-3200 (1948 through present) as well as SNOTEL data from NRCS. Since the late 1990s, the CoCoRaHS network of more than 15,000 observers in the U.S. has become a very important daily precipitation source. Other daily data are gathered from similar, but smaller gauge networks, for instance the High Spatial Density Precipitation Network in Minnesota.

As part of the daily data extraction process, the time of observation accompanies each measured precipitation value. Accurate observation times are necessary for SPAS to disaggregate the daily precipitation into estimated incremental values (discussed later). Knowing the observation time also allows SPAS to maintain precipitation amounts within given time bounds, thereby retaining known precipitation intensities. Given the importance of observation times, efforts are taken to insure the observation times are accurate. Hardcopy reports of "Climatological Data," scanned observational forms (available on-line from the NCDC) and/or gauge metadata forms have proven to be valuable and accurate resources for validating observation times. Furthermore, erroneous observation times are identified in the mass-curve quality-control procedure (discussed later) and can be corrected at that point in the process.

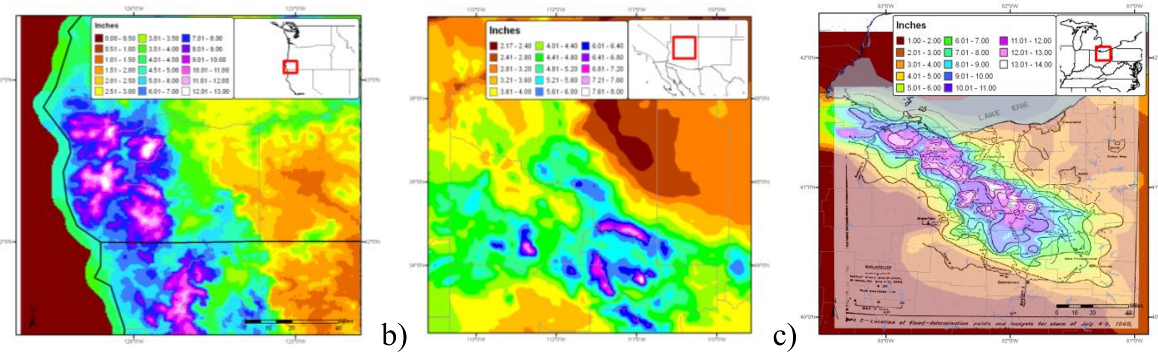
Supplemental Precipitation Gauge Data

For gauges with unknown or irregular observation times, the gauge is considered a "supplemental" gauge. A supplemental gauge can either be added to the storm database with a storm total and the associated SPP as the temporal bounds or as a gauge with the known, but irregular observation times and associated precipitation amounts. For instance, if all that is known is 3 inches fell between 0800-0900, then that information can be entered. Gauges or reports with nothing more than a storm total are often abundant, but to use them, it is important the precipitation is only from the storm period in question. Therefore, it is ideal to have the analysis time frame bounded by dry periods.

Perhaps the most important source of data, if available, is from "bucket surveys," which provide comprehensive lists of precipitation measurements collected during a post-storm field exercise. Although some bucket survey amounts are not from conventional precipitation gauges, they provide important information, especially in areas lacking data. Particularly for PMP-storm analysis applications, it is customary to accept extreme, but valid non-standard precipitation values (such as bottles and other open containers that catch rainfall) in order to capture the highest precipitation values.

Basemap

"Basemaps" are independent grids of spatially distributed weather or climate variables that are used to govern the spatial patterns of the hourly precipitation. The basemap also governs the spatial resolution of the final SPAS grids, unless radar data are available/used to govern the spatial resolution. Note that a base map is not required as the hourly precipitation patterns can be based on station characteristics and an inverse distance weighting technique (discussed later). Basemaps in complex terrain are often based on the PRISM mean monthly precipitation (Figure D.2a) or Hydrometeorological Design Studies Center precipitation frequency grids (Figure D.2b) given they resolve orographic enhancement areas and micro-climates at a spatial resolution of 30-seconds (about 800 m). Basemaps of this nature in flat terrain are not as effective given the small terrain forced precipitation gradients. Therefore, basemaps for SPAS analyses in flat terrain are often developed from pre-existing (hand-drawn) isohyetal patterns (Figure D.2c), composite radar imagery or a blend of both.



a) b) c)

Figure D.2 Sample SPAS "basemaps:" (a) A pre-existing (USGS) isohyetal pattern across flat terrain (SPAS #1209), (b) PRISM mean monthly (October) precipitation (SPAS #1192) and (c) A 100-year 24-hour precipitation grid from NOAA Atlas 14 (SPAS #1138)

Radar Data

For storms occurring since approximately the mid-1990s, weather radar data are available to supplement the SPAS analysis. A fundamental requirement for high quality radar-estimated precipitation is a high quality radar mosaic, which is a seamless collection of concurrent weather radar data from individual radar sites, however in some cases a single radar is sufficient (i.e. for a small area size storm event such as a thunderstorm). Weather radar data have been in use by meteorologists since the 1960s to estimate precipitation depths, but it was not until the early 1990s that new, more accurate NEXRAD Doppler radar (WSR88D) was placed into service across the United States. Currently, efforts are underway to convert the WSR88D radars to dual polarization (DualPol) radar. Today, NEXRAD radar coverage of the contiguous United States is comprised of 159 operational sites and there are 30 in Canada. Each U.S. radar covers an approximate 285 mile (460 km) radial extent while Canadian radars have approximately 256 km (138 nautical miles) radial extent over which their radar can detect precipitation (see Figure D.3). The primary vendor of NEXRAD weather radar data for SPAS is Weather Decision Technologies, Inc. (WDT), who accesses, mosaics, archives and quality-controls NEXRAD radar data from NOAA and Environment Canada. SPAS utilizes Level II NEXRAD radar reflectivity data in units of dBZ, available every 5-minutes in the U.S. and 10-minutes in Canada.

NEXRAD Coverage Below 10,000 Feet AGL

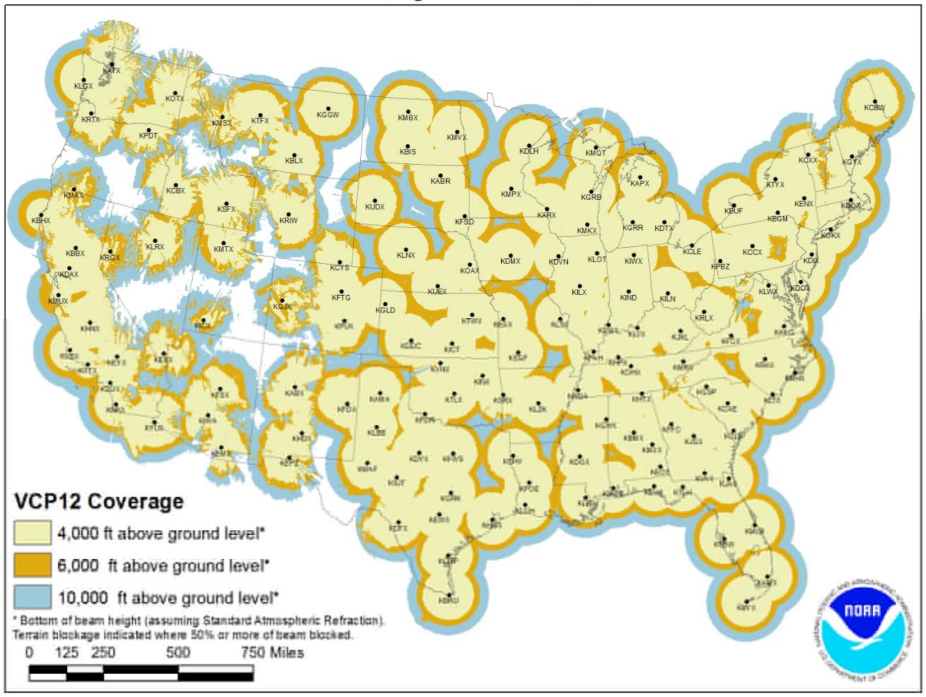


Figure D.3 U.S. radar locations and their radial extents of coverage below 10,000 feet above ground level (AGL). Each U.S. radar covers an approximate 285 mile radial extent over which the radar can detect precipitation.

The WDT and National Severe Storms Lab (NSSL) Radar Data Quality Control Algorithm (RDQC) removes non-precipitation artifacts from base Level–II radar data and remaps the data from polar coordinates to a Cartesian (latitude/longitude) grid. Non-precipitation artifacts include ground clutter, bright banding, sea clutter, anomalous propagation, sun strobes, clear air returns, chaff, biological targets, electronic interference and hardware test patterns. The RDQC algorithm uses sophisticated data processing and a Quality Control Neural Network (QCNN) to delineate the precipitation echoes caused by radar artifacts (Lakshmanan and Valente, 2004). Beam blockages due to terrain are mitigated by using 30 meter DEM data to compute and then discard data from a radar beam that clears the ground by less than 50 meters and incurs more than 50% power blockage. A clear-air echo removal scheme is applied to radars in clear-air mode when there is no precipitation reported from observation gauges within the vicinity of the radar. In areas of radar coverage overlap, a distance weighting scheme is applied to assign reflectivity to each grid cell, for multiple vertical levels. This scheme is applied to data from the nearest radar that is unblocked by terrain.

Once the data from individual radars have passed through the RDQC, they are merged to create a seamless mosaic for the United States and southern Canada as shown in Figure D.4. A multi-sensor quality control can be applied by post-processing the mosaic to remove any remaining “false echoes”. This technique uses observations of infra-red cloud top temperatures by GOES satellite and surface temperature to create a precipitation/no-precipitation mask. Figure D.4b shows the impact of WDT’s quality control measures. Upon completing all QC, WDT converts the radar data from its native polar coordinate projection (1 degree x 1.0 km) into a longitude-latitude Cartesian grid (based on the WGS84 datum), at a spatial resolution of ~1/3rdmi^2 for processing in SPAS.

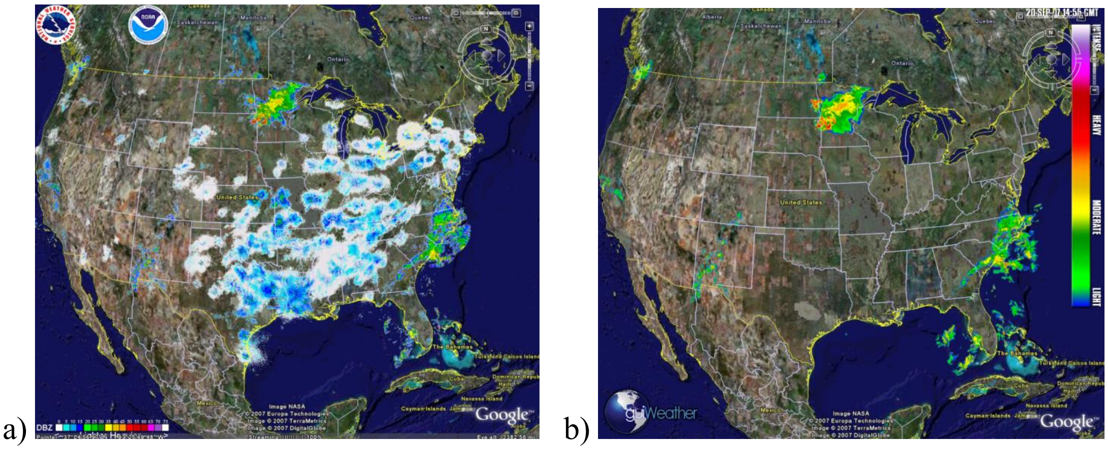


Figure D.4 (a) Level-II radar mosaic of CONUS radar with no quality control, (b) WDT quality controlled Level-II radar mosaic

SPAS conducts further QC on the radar mosaic by infilling areas contaminated by beam blockages. Beam blocked areas are objectively determined by evaluating total storm reflectivity grid which naturally amplifies areas of the SPAS analysis domain suffering from beam blockage as shown in Figure D.5.

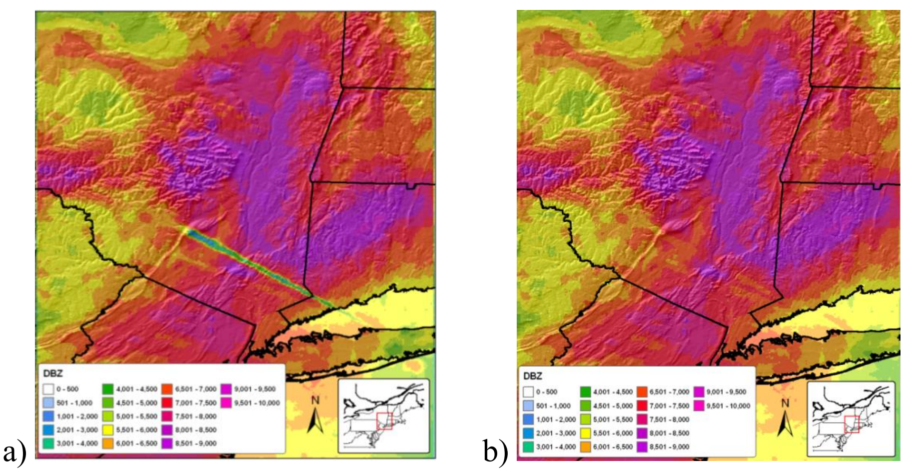


Figure D.5 Illustration of SPAS-beam blockage infilling where (a) is raw, blocked radar and (b) is filled for a 42-hour storm event

Methodology

Daily and Supplemental Precipitation to Hourly

To obtain one hour temporal resolutions and utilize all gauge data, it is necessary to disaggregate the daily and supplemental precipitation observations into estimated hourly amounts. This process has traditionally been accomplished by distributing (temporally) the precipitation at each daily/supplemental gauge in accordance to a single nearby hourly gauge (Thiessen polygon approach). However, this may introduce biases and not correctly represent hourly precipitation at daily/supplemental gauges situated in-between hourly gauges. Instead, SPAS uses a spatial approach by which the estimated hourly precipitation at each daily and supplemental gauge is governed by a distance weighted algorithm of all nearby true hourly gauges.

To disaggregate (i.e. distribute) daily/supplemental gauge data into estimate hourly values, the true hourly gauge data are first evaluated and quality controlled using synoptic maps, nearby gauges, orographic effects, gauge history and other documentation on the storm. Any problems with the hourly data are resolved, and when possible/necessary accumulated hourly values are distributed. If an hourly value is missing, the analyst can choose to either estimate it or leave it missing for SPAS to estimate later based on nearby hourly gauges. At this point in the process, pseudo (hourly) gauges can be added to represent precipitation timing in topographically complex locations, areas with limited/no hourly data or to capture localized convention. To adequately capture the temporal variations of the precipitation, a pseudo hourly gauge is sometimes necessary. A pseudo gauge is created by distributing the precipitation at a co-located daily gauge or by creating a completely new pseudo gauge from other information such as inferences from COOP observation forms, METAR visibility data (if hourly precipitation are not already available), lightning data, satellite data, or radar data. Often radar data are the best/only choice for creating pseudo hourly gauges, but this is done cautiously given the potential differences (over-shooting of the radar beam equating to erroneous precipitation) between radar data and precipitation. In any case, the pseudo hourly gauge is flagged so SPAS only uses it for timing and not magnitude. Care is taken to ensure hourly pseudo gauges represent justifiably important physical and meteorological characteristics before being incorporated into the SPAS database. Although pseudo gauges provide a very important role, their use is kept to a minimum. The importance of insuring the reliability of every hourly gauge cannot be over emphasized. All of the final hourly gauge data, including pseudos, are included in the hourly SPAS precipitation database.

Using the hourly SPAS precipitation database, each hourly precipitation value is converted into a percentage that represents the incremental hourly precipitation divided by the total SPP precipitation. The GIS-ready x-y-z file is constructed for each hour and it includes the latitude (x), longitude(y) and the percent of precipitation (z) for a particular hour. Using the GRASS GIS, an inverse-distance-weighting squared (IDW) interpolation technique is applied to each of the hourly files. The result is a continuous grid with percentage values for the entire analysis domain, keeping the grid cells on which the hourly gauge resides faithful to the observed/actual percentage. Since the percentages typically have a high degree of spatial autocorrelation, the spatial interpolation has skill in determining the percentages between gauges, especially since the percentages are somewhat independent of the precipitation magnitude. The end result is a GIS grid for each hour that represents the percentage of the SPP precipitation that fell during that hour.

After the hourly percentage grids are generated and QC'd for the entire SPP, a program is executed that converts the daily/supplemental gauge data into incremental hourly data. The timing at each of the daily/supplemental gauges is based on (1) the daily/supplemental gauge observation time, (2) daily/supplemental precipitation amount and (3) the series of interpolated hourly percentages extracted from grids (described above).

This procedure is detailed in Figure D.6 below. In this example, a supplemental gauge reported 1.40" of precipitation during the storm event and is located equal distance from the three surrounding hourly recording gauges. The procedure steps are:

Step 1. For each hour, extract the percent of SPP from the hourly gauge-based percentage at the location of the daily/supplemental gauge. In this example, assume these values are the average of all the hourly gauges.

Step 2. Multiply the individual hourly percentages by the total storm precipitation at the daily/supplemental gauge to arrive at estimated hourly precipitation at the daily/supplemental gauge. To make the daily/supplemental accumulated precipitation data faithful to the daily/supplemental observations, it is sometimes necessary to adjust the hourly percentages so they add up to 100% and account for 100% of the daily observed precipitation.

	Hour						
Precipitation	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
Hourly station 1	0.02	0.12	0.42	0.50	0.10	0.00	1.16
Hourly station 2	0.01	0.15	0.48	0.62	0.05	0.01	1.32
Hourly station 3	0.00	0.18	0.38	0.55	0.20	0.05	1.36
	Hour						
Percent of total storm precip.	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
Hourly station 1	2%	10%	36%	43%	9%	0%	100%
Hourly station 2	1%	11%	36%	47%	4%	1%	100%
Hourly station 3	0%	13%	28%	40%	15%	4%	100%
Average	*1%*	*12%*	*34%*	*44%*	*9%*	*1%*	*100%*
Storm total precipitation at daily gauge				1.40			
	Hour						
Precipitation (estimated)	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
Daily station	0.01	0.16	0.47	0.61	0.13	0.02	1.40

Figure D.6 Example of disaggregation of daily precipitation into estimated hourly precipitation based on three (3) surrounding hourly recording gauges

In cases where the hourly grids do not indicate any precipitation falling during the daily/supplemental gauge observational period, yet the daily/supplemental gauge reported precipitation, the daily/supplemental total precipitation is evenly distributed throughout the hours that make up the observational period; although this does not happen very often, this solution is consistent with NWS procedures. However, the SPAS analyst is notified of these cases in a comprehensive log file, and in most cases they are resolvable, sometimes with a pseudo hourly gauge.

Gauge Quality Control

Exhaustive quality control measures are taken throughout the SPAS analysis. Below are a few of the most significant QC measures taken.

Mass Curve Check

A mass curve-based QC-methodology is used to ensure the timing of precipitation at all gauges is consistent with nearby gauges. SPAS groups each gauge with the nearest four gauges (regardless of type) into a single file. These files are subsequently used in software for graphing and evaluation. Unusual characteristics in the mass curve are investigated and the gauge data corrected, if possible and warranted. See Figure D.7 for an example.

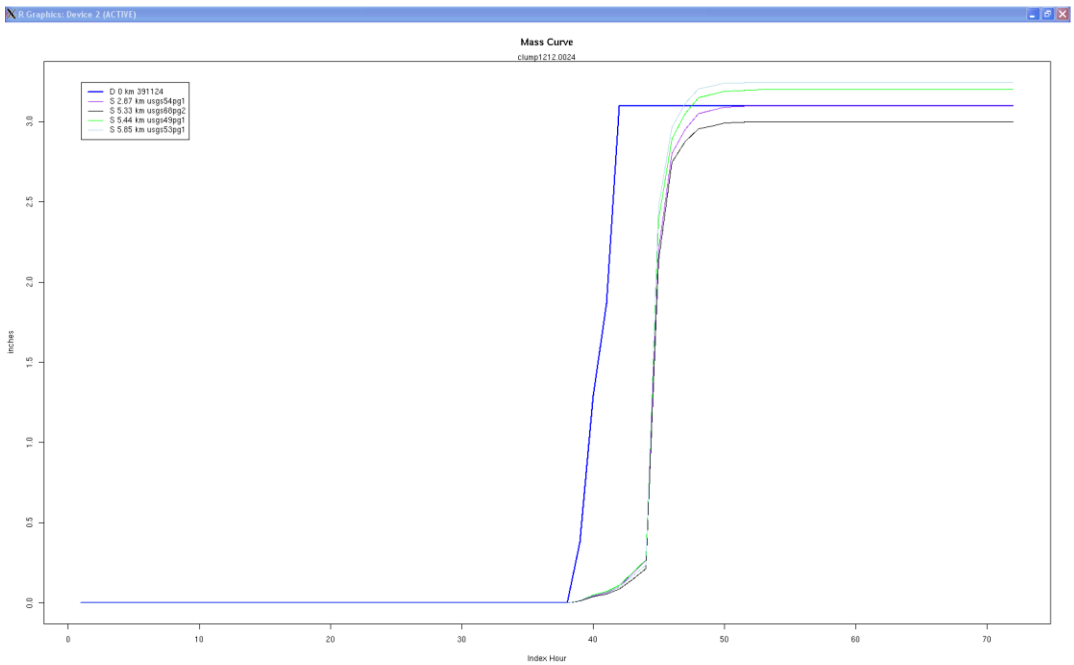


Figure D.7 Sample mass curve plot depicting a precipitation gauge with an erroneous observation time (blue line). X-axis is the SPAS index hour and the y-axis is inches. The statistics in the upper left denote gauge type, distance from target gauge (in km), and gauge ID. In this example, the center gauge (blue line) was found to have an observation error/shift of 1 day.

Gauge Mis-location Check

Although the gauge elevation is not explicitly used in SPAS, it is however used as a means of QC'ing gauge location. Gauge elevations are compared to a high-resolution 15-second DEM to identify gauges with large differences, which may indicate erroneous longitude and/or latitude values.

Co-located Gauge QC

Care is also taken to establish the most accurate precipitation depths at all co-located gauges. In general, where a co-located gauge pair exists, the highest precipitation is accepted (if deemed accurate). If the hourly gauge reports higher precipitation, then the co-located daily (or supplemental) is removed from the analysis since it would not add anything to the analysis. Often daily (or supplemental) gauges report greater precipitation than a co-located hourly station since hourly tipping bucket gauges tend to suffer from gauge under-catch, particularly during extreme events, due to loss of precipitation during tips. In these cases the daily/supplemental is retained for the magnitude and the hourly used as a pseudo hourly gauge for timing. Large discrepancies between any co-located gauges are investigated and resolved since SPAS can only utilize a single gauge magnitude at each co-located site.

Spatial Interpolation

At this point the QC'd observed hourly and disaggregated daily/supplemental hourly precipitation data are spatially interpolated into hourly precipitation grids. SPAS has three options for conducting the hourly precipitation interpolation, depending on the terrain and availability of radar data, thereby allowing SPAS to be optimized for any particular storm type or location. Figure D.8 depicts the results of each spatial interpolation methodology based on the same precipitation gauge data.

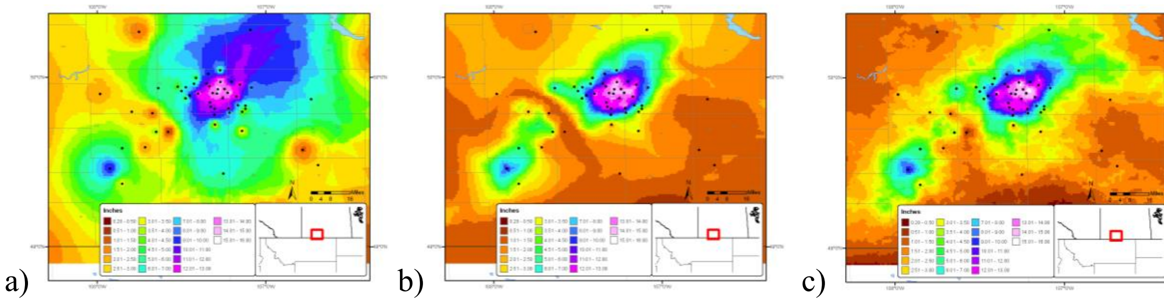


Figure D.8 Depictions of total storm precipitation based on the three SPAS interpolation methodologies for a storm (SPAS #1177, Vanguard, Canada) across flat terrain: (a) no basemap, (b) basemap-aided and (c) radar

Basic Approach

The basic approach interpolates the hourly precipitation point values to a grid using an inverse distance weighting squared GIS algorithm. This is sometimes the best choice for convective storms over flat terrain when radar data are not available, yet high gauge density instills reliable precipitation patterns. This approach is rarely used.

Basemap Approach

Another option includes use of a "basemap", also known as a climatologically-aided interpolation (Hunter, 2005). As noted before, the spatial patterns of the basemap govern the interpolation between points of hourly precipitation estimates, while the actual hourly precipitation values govern the magnitude. This approach to interpolating point data across complex terrain is widely used. In fact, it was used extensively by the NWS during their storm analysis era from the 1940s through the 1970s (USACE, 1973; Hansen et al., 1988; Corrigan et al., 1999).

In application, the hourly precipitation gauge values are first normalized by the corresponding grid cell value of the basemap before being interpolated. The normalization allows information and knowledge from the basemap to be transferred to the spatial distribution of the hourly precipitation. Using an IDW squared algorithm, the normalized hourly precipitation values are interpolated to a grid. The resulting grid is then multiplied by the basemap grid to produce the hourly precipitation grid. This is repeated each hour of the storm.

Radar Approach

The coupling of SPAS with NEXRAD provides the most accurate method of spatially and temporally distributing precipitation. To increase the accuracy of the results however, quality-controlled precipitation observations are used for calibrating the radar reflectivity to rain rate relationship (Z-R relationship) each hour instead of assuming a default Z-R relationship. Also, spatial variability in the Z-R relationship is accounted for through local bias corrections (described later). The radar approach involves several steps, each briefly described below. The radar approach cannot operate alone – either the basic or basemap approach must be completed before radar data can be incorporated.

Z-R Relationship

SPAS derives high quality precipitation estimates by relating quality controlled level–II NEXRAD radar reflectivity radar data with quality-controlled precipitation gauge data to calibrate the Z-R (radar reflectivity, Z, and precipitation, R) relationship. Optimizing the Z-R relationship is essential for capturing temporal changes in the Z-R. Most current radar-derived precipitation techniques rely on a constant relationship between radar reflectivity and precipitation rate for a given storm type (e.g. tropical, convective), vertical structure of reflectivity and/or reflectivity magnitudes. This non-linear relationship is described by the Z-R equation below:

$$Z = A R^b \qquad (1)$$

Where Z is the radar reflectivity (measured in units of dBZ), R is the precipitation (precipitation) rate (millimeters per hour), A is the "multiplicative coefficient" and b is the "power coefficient". Both A and b are directly related to the rain drop size distribution (DSD) and rain drop number distribution (DND) within a cloud (Martner and Dubovskiy, 2005). The variability in the results of Z versus R is a direct result of differing DSD, DND and air mass characteristics (Dickens, 2003). The DSD and DND are determined by complex interactions of microphysical processes that fluctuate regionally, seasonally, daily, hourly, and even within the same cloud. For these reasons, SPAS calculates an optimized Z-R relationship across the analysis domain each hour, based on observed precipitation rates and radar reflectivity (see Figure D.9).

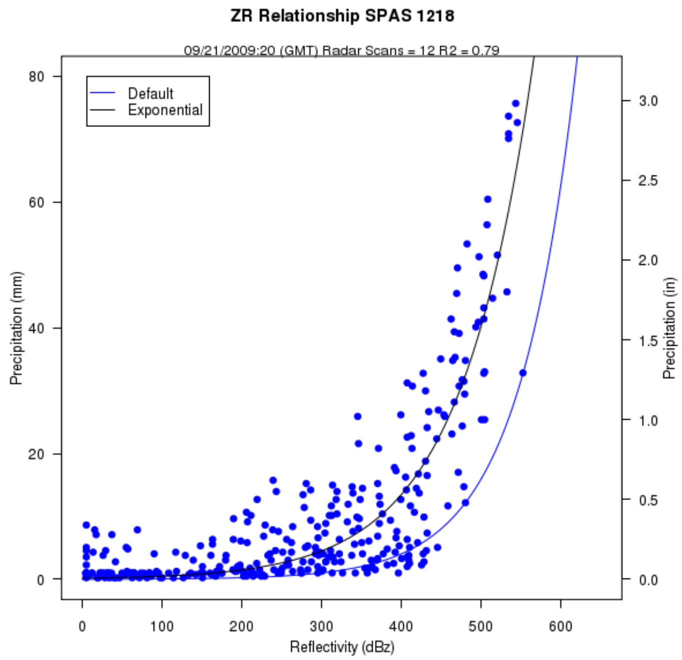


Figure D.9 Example SPAS (denoted as "Exponential") vs. default Z-R relationship (SPAS #1218, Georgia September 2009)

The National Weather Service (NWS) utilizes different default Z-R algorithms, depending on the type of precipitation event, to estimate precipitation from NEXRAD radar reflectivity data across the United States (see Figure D.10) (Baeck and Smith, 1998 and Hunter, 1999). A default Z-R relationship of Z = 300R1.4 is the primary algorithm used throughout the continental U.S. However, it is widely known that this, compared to unadjusted radar-aided estimates of precipitation, suffers from deficiencies that may lead to significant over or under-estimation of precipitation.

RELATIONSHIP	Optimum for:	Also recommended for:
Marshall-Palmer **($z=200R^{1.6}$)**	General stratiform precipitation	
East-Cool Stratiform **($z=130R^{2.0}$)**	Winter stratiform precipitation - east of continental divide	Orographic rain - East
West-Cool Stratiform **($z=75R^{2.0}$)**	Winter stratiform precipitation - west of continental divide	Orographic rain - West
WSR-88D Convective **($z=300R^{1.4}$)**	Summer deep convection	Other non-tropical convection
Rosenfeld Tropical **($z=250R^{1.2}$)**	Tropical convective systems	

Figure D.10 Commonly used Z-R algorithms used by the NWS

Instead of adopting a standard Z-R, SPAS utilizes a least squares fit procedure for optimizing the Z-R relationship each hour of the SPP. The process begins by determining if sufficient (minimum 12) observed hourly precipitation and radar data pairs are available to compute a reliable Z-R. If insufficient (<12) gauge pairs are available, then SPAS adopts the previous hour Z-R relationship, if available, or applies a user-defined default Z-R algorithm from Figure D.9.

If sufficient data are available, the one hour sum of NEXRAD reflectivity (Z) is related to the 1-hour precipitation at each gauge. A least-squares-fit exponential function using the data points is computed. The resulting best-fit, one hour-based Z-R is subjected to several tests to determine if the Z-R relationship and its resulting precipitation rates are within a certain tolerance based on the R-squared fit measure and difference between the derived and default Z-R precipitation results. Experience has shown the actual Z-R versus the default Z-R can be significantly different (Figure D.11). These Z-R relationships vary by storm type and location. A standard output of all SPAS analyses utilizing NEXRAD includes a file with each hour's adjusted Z-R relationship as calculated through the SPAS program.

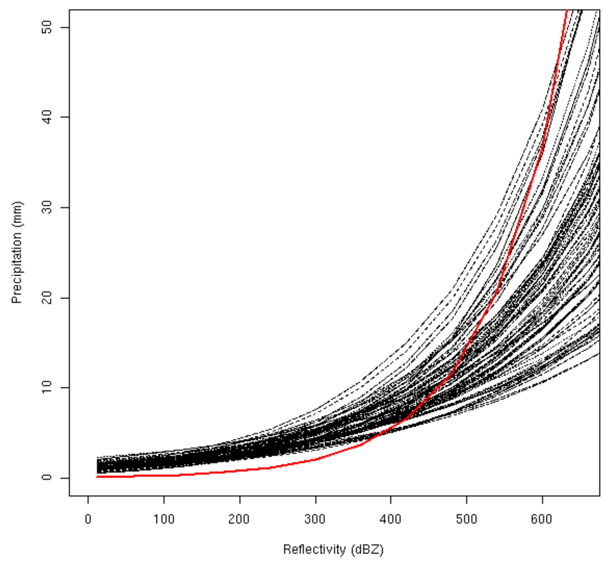


Figure D.11 Comparison of the SPAS optimized hourly Z-R relationships (black lines) versus a default Z=75R2.0 Z-R relationship (red line) for a period of 99 hours for a storm over southern California.

Radar-aided Hourly Precipitation Grids

Once a mathematically optimized hourly Z-R relationship is determined, it is applied to the total hourly Z grid to compute an initial precipitation rate (inches/hour) at each grid cell. To account for spatial differences in the Z-R relationship, SPAS computes residuals, the difference between the initial precipitation analysis (via the Z-R equation) and the actual "ground truth" precipitation (observed – initial analysis), at each gauge. The point residuals, also referred to as local biases, are normalized and interpolated to a residual grid using an inverse distance squared weighting algorithm. A radar-based hourly precipitation grid is created by adding the residual grid to the initial grid; this allows the precipitation at the grid cells for which gauges are "on" to be true and faithful to the gauge measurement. The pre-final radar-aided precipitation grid is subject to some final, visual QC checks to ensure the precipitation patterns are consistent with the terrain; these checks are particularly important in areas of complex terrain where even QC'd radar data can be unreliable. The next incremental improvement with SPAS program will come as the NEXRAD radar sites are upgraded to dual-polarimetric capability.

Radar- and Basemap-Aided Hourly Precipitation Grids

At this stage of the radar approach, a radar- and basemap-aided hourly precipitation grid exists for each hour. At locations with precipitation gauges, the grids are equal, however elsewhere the grids can vary for a number of reasons. For instance, the basemap-aided hourly precipitation grid may depict heavy precipitation in an area of complex terrain, blocked by the radar, whereas the radar-aided hourly precipitation grid may suggest little, if any, precipitation fell in the same area. Similarly, the radar-aided hourly precipitation grid may depict an area of heavy precipitation in flat terrain that the basemap-approach missed since the area of heavy precipitation occurred in an area without gauges. SPAS uses an algorithm to compute the hourly precipitation at each pixel given the two results. Areas that are completely blocked from a radar signal are accounted for with the basemap-aided results (discussed earlier). Precipitation in areas with orographically effective terrain and reliable radar data are governed by a blend of the basemap- and radar-aided precipitation. Elsewhere, the radar-aided precipitation is used exclusively. This blended approach has proven effective for resolving precipitation in complex terrain, yet retaining accurate radar-aided precipitation across areas where radar data are reliable. Figure D.12 illustrates the evolution of final precipitation from radar reflectivity in an area of complex terrain in southern California.

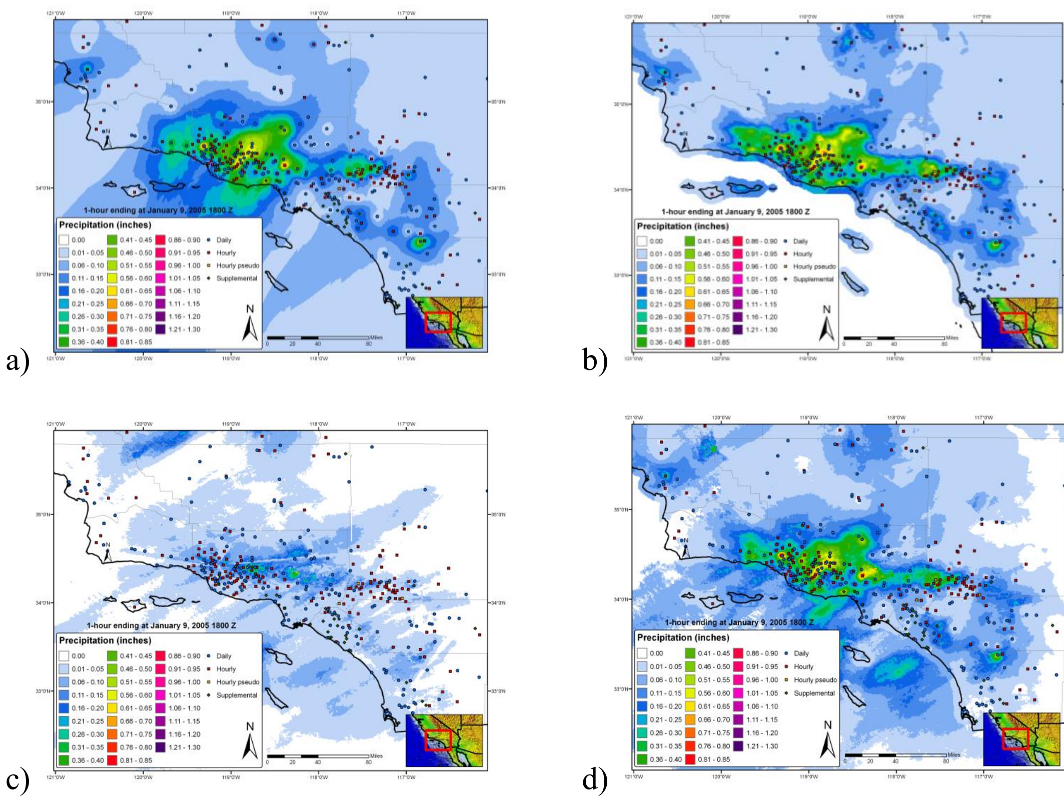


Figure D.12 A series of maps depicting 1-hour of precipitation utilizing (a) inverse distance weighting of gauge precipitation, (b) gauge data together with a climatologically-aided interpolation scheme, (c) default Z-R radar-estimated interpolation (no gauge correction) and (d) SPAS precipitation for a January 2005 storm in southern California, USA

SPAS versus Gauge Precipitation

Performance measures are computed and evaluated each hour to detect errors and inconsistencies in the analysis. The measures include: hourly Z-R coefficients, observed hourly maximum precipitation, maximum gridded precipitation, hourly bias, hourly mean absolute error (MAE), root mean square error (RMSE), and hourly coefficient of determination (r^2).

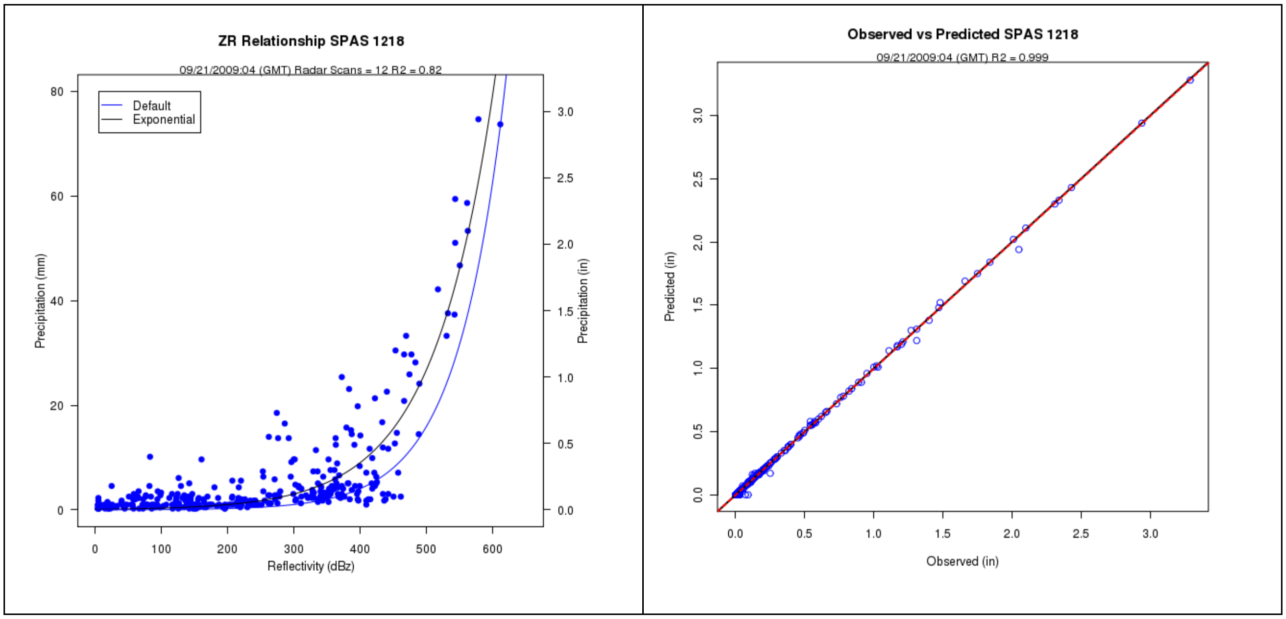


Figure D.13 Z-R plot (a), where the blue line is the SPAS derived Z-R and the black line is the default Z-R, and the (b) associated observed versus SPAS scatter plot at gauge locations.

Comparing SPAS-calculated precipitation (R_{spas}) to observed point precipitation depths at the gauge locations provides an objective measure of the consistency, accuracy and bias. Generally speaking SPAS is usually within 5% of the observed precipitation (see Figure D.13). Less-than-perfect correlations between SPAS precipitation depths and observed precipitation at gauged locations could be the result of any number of issues, including:

- **Point versus area:** A rain gauge observation represents a much smaller area than the area sampled by the radar. The area that the radar is sampling is approximately 1 km^2, whereas a standard rain gauge has an opening 8 inches in diameter, hence it only samples approximately 8.0×10^{-9} km^2. Furthermore, the radar data represents an average reflectivity (Z) over the grid cell, when in fact the reflectivity can vary across the 1 km^2 grid cell. Therefore, comparing a grid cell radar derived precipitation value to a gauge (point) precipitation depth measured may vary.
- **Precipitation gauge under-catch:** Although we consider gauge data “ground truth,” we recognize gauges themselves suffer from inaccuracies. Precipitation gauges, shielded and unshielded, inherently underestimate total precipitation due to local airflow, wind under-catch, wetting, and evaporation. The wind under-catch errors are usually around 5% but can be as large as 40% in high winds (Guo et al., 2001; Duchon and Essenberg, 2001; Ciach, 2003; Tokay et al., 2010). Tipping buckets miss a small amount of precipitation during each tip of the bucket due to the bucket travel and tip time. As precipitation intensities increase, the volumetric loss of precipitation due to tipping tends to increase. Smaller tipping buckets can have higher volumetric losses due to higher tip frequencies,

but on the other hand capture higher precision timing.

- **Radar Calibration:** NEXRAD radars calibrate reflectivity every volume scan, using an internally generated test. The test determines changes in internal variables such as beam power and path loss of the receiver signal processor since the last off-line calibration. If this value becomes large, it is likely that there is a radar calibration error that will translate into less reliable precipitation estimates. The calibration test is supposed to maintain a reflectivity precision of 1 dBZ. A 1 dBZ error can result in an error of up to 17% in R_{spas} using the default Z-R relationship $Z=300R^{1.4}$. Higher calibration errors will result in higher R_{spas} errors. However, by performing correlations each hour, the calibration issue is minimized in SPAS.
- **Attenuation:** Attenuation is the reduction in power of the radar beams' energy as it travels from the antenna to the target and back. It is caused by the absorption and the scattering of power from the beam by precipitation. Attenuation can result in errors in Z as large as 1 dBZ especially when the radar beam is sampling a large area of heavy precipitation. In some cases, storm precipitation is so intense (>12 inches/hour) that individual storm cells become "opaque" and the radar beam is totally attenuated. Armed with sufficient gauge data however, SPAS will overcome attenuation issues.
- **Range effects:** The curvature of the Earth and radar beam refraction result in the radar beam becoming more elevated above the surface with increasing range. With the increased elevation of the radar beam comes a decrease in Z values due to the radar beam not sampling the main precipitation portion of the cloud (i.e. "over topping" the precipitation and/or cloud altogether). Additionally, as the radar beam gets further from the radar, it naturally samples a larger and larger area, therefore amplifying point versus area differences (described above).
- **Radar Beam Occultation/Ground Clutter:** Radar occultation (beam blockage) results when the radar beam's energy intersects terrain features as depicted in Figure D.14. The result is an increase in radar reflectivity values that can result in higher than normal precipitation estimates. The WDT processing algorithms account for these issues, but SPAS uses GIS spatial interpolation functions to infill areas suffering from poor or no radar coverage.
- **Anomalous Propagation (AP):** AP is false reflectivity echoes produced by unusual rates of refraction in the atmosphere. WDT algorithms remove most of the AP and false echoes, however in extreme cases the air near the ground may be so cold and dense that a radar beam that starts out moving upward is bent all the way down to the ground. This produces erroneously strong echoes at large distances from the radar. Again, equipped with sufficient gauge data, the SPAS bias corrections will overcome AP issues.

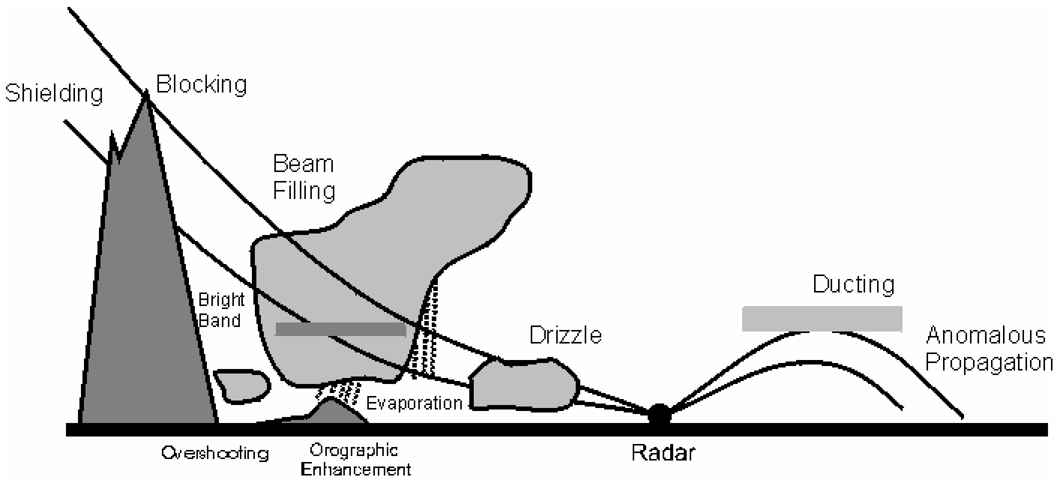


Figure D.14 Depiction of radar artifacts. (Source: Wikipedia)

SPAS is designed to overcome many of these short-comings by carefully using radar data for defining the spatial patterns and relative magnitudes of precipitation, but allowing measured precipitation values ("ground truth") at gauges to govern the magnitude. When absolutely necessary, the observed precipitation values at gauges are nudged up (or down) to force SPAS results to be consistent with observed gauge values. Nudging gauge precipitation values helps to promote better consistency between the gauge value and the gridcell value, even though these two values sometimes should not be the same since they are sampling different area sizes. For reasons discussed in the "SPAS versus Gauge Precipitation" section, the gauge value and gridcell value can vary. Plus, SPAS is designed to toss observed individual hourly values that are grossly inconsistent with radar data, hence driving a difference between the gauge and gridcell. In general, when the gauge and gridcell value differ by more than 15% and/or 0.50 inches, and the gauge data have been validated, then it is justified to artificially increase or decrease slightly the observed gauge value to "force" SPAS to derive a gridcell value equal to the observed value. Sometimes simply shifting the gauge location to an adjacent gridcell resolves the problems. Regardless, a large gauge versus gridcell difference is a "red flag" and sometimes the result of an erroneous gauge value or a mis-located gauge, but in some cases the difference can only be resolved by altering the precipitation value.

Before results are finalized, a precipitation intensity check is conducted to ensure the spatial patterns and magnitudes of the maximum storm intensities at 1-, 6-, 12-, etc. hours are consistent with surrounding gauges and published reports. Any erroneous data are corrected and SPAS re-run. Considering all of the QA/QC checks in SPAS, it typically requires 5-15 basemap SPAS runs and, if radar data are available, another 5-15 radar-aided runs, to arrive at the final output.

Test Cases

To check the accuracy of the DAD software, three test cases were evaluated.

“Pyramidville” Storm

The first test was that of a theoretical storm with a pyramid shaped isohyetal pattern. This case was called the Pyramidville storm. It contained 361 hourly stations, each occupying a single grid cell. The configuration of the Pyramidville storm (see Figure D.15) allowed for uncomplicated and accurate calculation of the analytical DA truth independent of the DAD software. The main motivation of this case was to verify that the DAD software was properly computing the area sizes and average depths.

1. Storm center: 39°N 104°W
2. Duration: 10-hours
3. Maximum grid cell precipitation: 1.00”
4. Grid cell resolution: 0.06 sq.-miles (361 total cells)
5. Total storm size: 23.11 sq-miles
6. Distribution of precipitation:

   Hour 1: Storm drops 0.10” at center (area 0.06 sq-miles)
   Hour 2: Storm drops 0.10” over center grid cell AND over one cell width around hour 1 center
   Hours 3-10:
   1. Storm drops 0.10” per hour at previously wet area, plus one cell width around previously wet area
   2. Area analyzed at every 0.10”
   3. Analysis resolution: 15-sec (~.25 square miles)

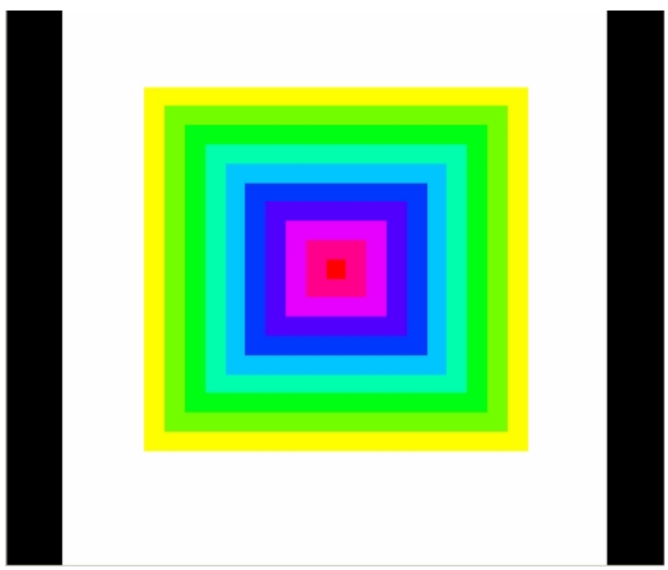


Figure D.15 "Pyramidville” Total precipitation. Center = 1.00”, Outside edge = 0.10”

The analytical truth was calculated independent of the DAD software, and then compared to the DAD output. The DAD software results were equal to the truth, thus demonstrating that the DA estimates were properly calculated (Figure D.16).

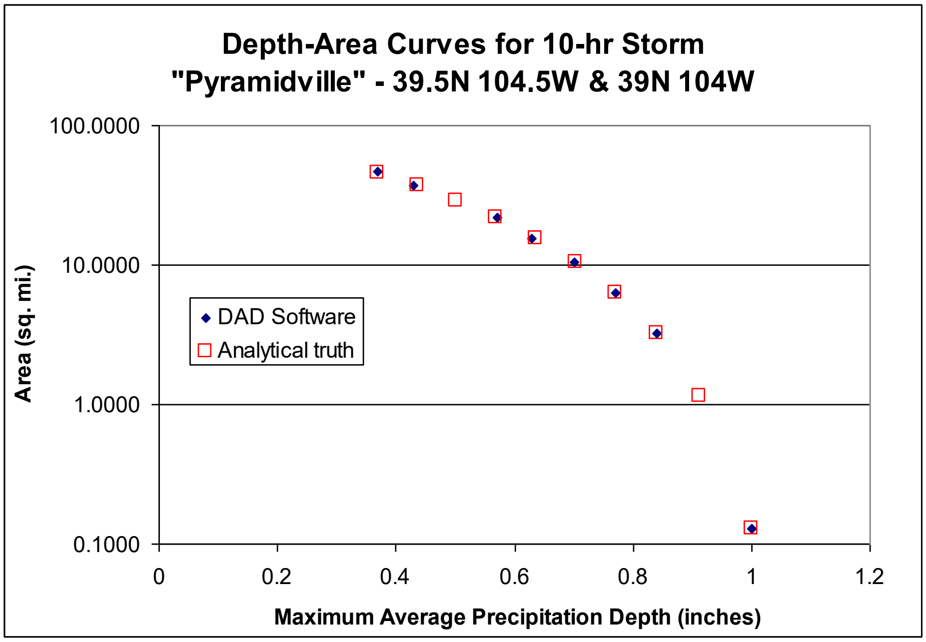


Figure D.16 10-hour DA results for "Pyramidville"; truth vs. output from DAD software

The Pyramidville storm was then changed such that the mass curve and spatial interpolation methods would be stressed. Test cases included:

- Two-centers, each center with 361 hourly stations
- A single center with 36 hourly stations, 0 daily stations
- A single center with 3 hourly stations and 33 daily stations

As expected, results began shifting from the 'truth,' but minimally and within the expected uncertainty.

Ritter, Iowa Storm, June 7, 1953

Ritter, Iowa was chosen as a test case for a number of reasons. The NWS had completed a storm analysis, with available DAD values for comparison. The storm occurred over relatively flat terrain, so orographics were not an issue. An extensive "bucket survey" provided a great number of additional observations from this event. Of the hundreds of additional reports, about 30 of the most accurate reports were included in the DAD analysis.

The DAD software results are very similar to the NWS DAD values (Table D.2).

Table D.2 The percent difference [(AWA-NWS)/NWS] between the AWA DA results and those published by the NWS for the 1953 Ritter, Iowa storm.

% Difference

	Duration (hours)				
Area (sq.mi.)		6	12	24	total
10		-15%	-7%	2%	2%
100		-7%	-6%	1%	1%
200		2%	0%	9%	9%
1000		-6%	-7%	4%	4%
5000		-13%	-8%	2%	2%
10000		-14%	-6%	0%	0%

Westfield, Massachusetts Storm, August 8, 1955

Westfield, Massachusetts was also chosen as a test case for a number of reasons. It is a probable maximum precipitation (PMP) driver for the northeastern United States. Also, the Westfield storm was analyzed by the NWS and the DAD values are available for comparison. Although this case proved to be more challenging than any of the others, the final results are very similar to those published by the NWS (Table D.3).

Table D.3 The percent difference [(AWA-NWS)/NWS] between the AWA DA results and those published by the NWS for the 1955 Westfield, Massachusetts storm

% Difference

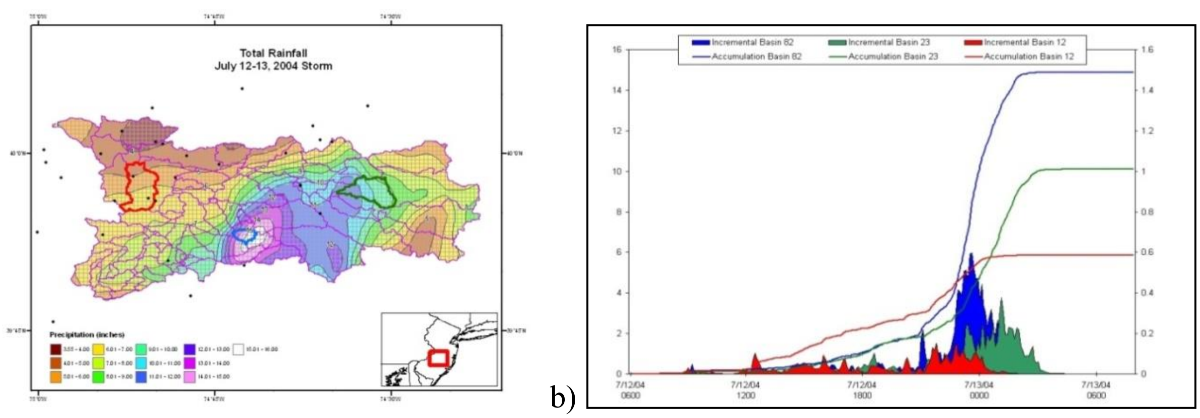
	Duration (hours)							
Area (sq. mi.)		6	12	24	36	48	60	total
10		2%	3%	0%	1%	-1%	0%	2%
100		-5%	2%	4%	-2%	-6%	-4%	-3%
200		-6%	1%	1%	-4%	-7%	-5%	-5%
1000		-4%	-2%	1%	-6%	-7%	-6%	-3%
5000		3%	2%	-3%	-3%	-5%	-5%	0%
10000		4%	9%	-5%	-4%	-7%	-5%	1%
20000		7%	12%	-6%	-3%	-4%	-3%	3%

The primary components of SPAS are: storm search, data extraction, quality control (QC), conversion of daily precipitation data into estimated hourly data, hourly and total storm precipitation grids/maps and a complete storm-centered DAD analysis.

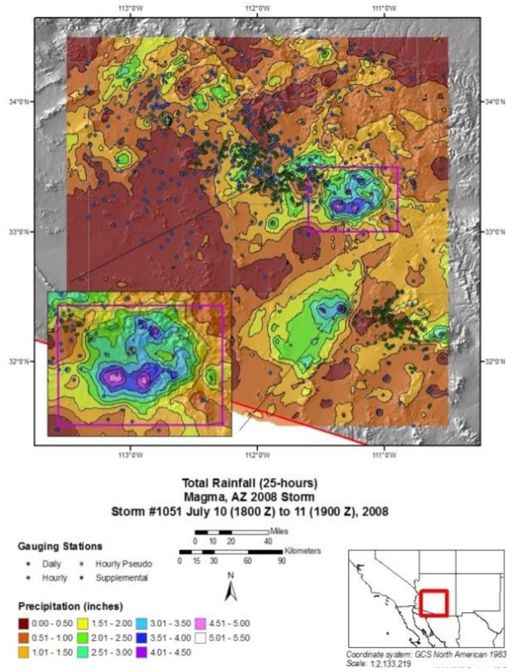
Output

Armed with accurate, high-resolution precipitation grids, a variety of customized output can be created (see Figures D.17A-D). Among the most useful outputs are sub-hourly precipitation grids for input into hydrologic models. Sub-hourly (i.e. 5-minute) precipitation grids are created by applying the appropriate optimized hourly Z-R (scaled down to be applicable for instantaneous Z) to each of the individual 5-minute radar scans; 5-minutes is often the native scan rate of the radar in the US. Once the scaled Z-R is applied to each radar scan, the resulting precipitation is summed up. The proportion of each 5-minute precipitation to the total 1-hour radar-aided precipitation is calculated. Each 5-minute proportion (%) is then applied to the quality controlled, bias corrected 1-hour total precipitation (created above) to arrive at the final 5 minute precipitation for each scan. This technique ensures the sum of 5-minute precipitation equals that of the quality controlled, bias corrected 1-hour total precipitation derived initially.

Depth-area-duration (DAD) tables/plots, shown in Figure D.17d, are computed using a highly-computational extension to SPAS. DADs provide an objective three dimensional (magnitude, area size, and duration) perspective of a storms' precipitation. SPAS DADs are computed using the procedures outlined by the NWS Technical Paper 1 (1946).



a) b)

c) 

d)

Storm 1048 - Hokah, MN August 18 - August 21, 2007

MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)

Area (mi^2)	Duration (hours)									
	1	3	6	12	18	24	36	48	72	Total
0.24	2.45	4.77	7.85	11.89	14.88	17.31	17.55	18.19	18.26	18.26
1	2.12	4.53	7.56	11.64	14.59	17.05	17.31	17.95	18.02	18.02
10	2.12	4.53	7.49	11.10	13.88	15.96	16.31	17.03	17.15	17.17
25	2.12	4.53	6.92	10.42	12.86	14.89	15.34	16.23	16.45	16.46
50	2.11	4.40	6.64	9.65	12.13	14.05	14.46	15.49	15.79	15.79
100	2.09	4.10	6.33	9.37	11.52	13.27	13.93	14.76	15.14	15.14
200	2.03	3.79	6.00	8.87	10.96	12.62	13.37	14.22	14.52	14.52
300	1.95	3.61	5.74	8.55	10.64	12.06	12.99	13.74	14.04	14.04
500	1.79	3.35	5.47	8.13	10.11	11.60	12.27	13.01	13.29	13.30
1,000	1.53	2.99	4.95	7.33	9.17	10.51	11.13	11.84	12.07	12.07
2,000	0.95	2.55	4.36	6.18	8.09	9.30	9.85	10.54	10.75	10.76
5,000	0.87	2.02	3.45	5.19	6.53	7.61	8.18	8.79	8.96	8.98
10,000	0.63	1.54	2.69	4.02	5.39	6.09	6.78	7.31	7.53	7.55
20,000	0.41	0.95	1.84	3.02	3.97	4.53	5.13	5.63	5.87	5.90

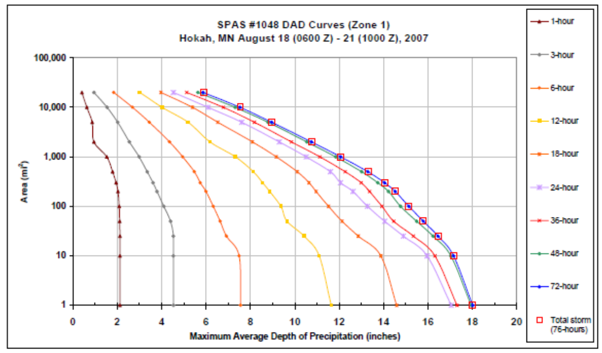


Figure D.17 Various examples of SPAS output, including (a) total storm map and its associated (b) basin average precipitation time series, (c) total storm precipitation map, (d) depth-area-duration (DAD) table and plot

Summary

Grounded on years of scientific research with a demonstrated reliability in post-storm analyses, SPAS is a hydro-meteorological tool that provides accurate precipitation analyses for a variety of applications. SPAS has the ability to compute precise and accurate results by using sophisticated timing algorithms, “basemaps”, a variety of precipitation data and most importantly NEXRAD weather radar data (if available). The approach taken by SPAS relies on hourly, daily and supplemental precipitation gauge observations to provide quantification of the precipitation amounts while relying on basemaps and NEXRAD data (if available) to provide the spatial distribution of precipitation between precipitation gauge sites. By determining the most appropriate coefficients for the Z-R equation on an hourly basis, the approach anchors the precipitation amounts to accepted precipitation gauge data while using the NEXRAD data to distribute precipitation between precipitation gauges for each hour of the storm. Hourly Z-R coefficient computations address changes in the cloud microphysics and storm characteristics as the storm evolves. Areas suffering from limited or no radar coverage are estimated using the spatial patterns and magnitudes of the independently created basemap precipitation grids. Although largely automated, SPAS is flexible enough to allow hydro-meteorologists to make important adjustments and adapt to any storm situation.

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Appendix E

HMR Storm Separation Method (SSM)

Applied Weather Associates (AWA) has reviewed the Storm Separation Method (SSM) as described in detail in HMR 55A and its application in HMR 57 and HMR 59. The SSM is used in hydrometeorological analysis to arrive at an approximation of the non-orographic component of precipitation from storms centered in orographic areas. The SSM was originally developed for HMR 55A (1988) as a standardized procedure to isolate and quantify orographic from non-orographic factors in record setting storms (HMR 59, Section 5.4). HMRs 57 and 59 refer to HMR 55A for details of the development of the SSM. The application of the SSM is described in HMR 57 and HMR 59 with some examples of the maps developed for each publication provided in various figures in Chapter 7 of HMR 57 and Chapter 6 of HMR 59. An attempt was made to acquire copies of the actual maps and data used in the computation of PMP for these publications. AWA visited the Hydrometeorology Design Studies Center (HDSC) December 8-10, 2008 to review archives of maps and working papers for HMRs 55A, 57 and 59. No maps or working papers are available for the SSM applications in those documents. Therefore, the review of the SSM is based entirely on information in HMRs 55A, 57 and 59.

Introduction

The initial review discussion describes the procedure presented in HMR 55A in detail. Maps from HMR 57 were digitized and computations completed based on the discussions in HMR 57. Results from these computations are compared with the HMR 57 PMP maps. Maps in HMR 59 were also digitized but not all maps for the SSM were available. Results from the limited information available are discussed.

The following discussion is extracted from the information provided in HMR 55A for the determination of Free Atmospheric Forced Precipitation (FAFP). The information is condensed to present major discussions. The complete text is available in Sections 6 and 7 of HMR 55A.

HMR 55A Section 6. APPROACHES

1.1 Introduction

HMR 55A states that estimation of PMP in orographic regions is difficult and storm data are limited. This is the result of a low population density that restricts the number of regular observing stations and also limits the effectiveness of supplementary precipitation surveys. In addition, the complicating effects of terrain on storm structure and precipitation must be considered. In HMR 55A, several procedures were investigated, but primary reliance was placed on a procedure that separates the effect of orography from the dynamic effects of the storm.

6.4 Storm Separation Method

It was necessary to find a procedure which would enable the precipitation potential for this diverse terrain to be analyzed in a consistent fashion. The precipitation that results from atmospheric forces (convergence precipitation) involved in the major storms in the region is defined. Convergence precipitation amounts were determined for the 24-hr 10-mi^2 precipitation amounts for all major storms in the region. These rainfall values were moisture maximized and transposed to locations where similar storms have occurred. The moisture maximized, transposed values were then analyzed to develop a generalized map of convergence PMP throughout the region.

Values of convergence rainfall were increased for orographic effects that occur over the region. The orographic intensification factor is developed from the 100-yr 24-hr precipitation-frequency amounts of NOAA Atlas 2. Since the dynamic strength of a storm varies from the most intense 1-, 2-, 3-, or 6-hr period through the end of the storm, it is not appropriate to apply the same orographic intensification factor throughout the entire storm. To vary this intensification factor, a storm intensity factor was developed. The storm intensification factor reduced the effect of the orographic factor during the most intense rainfall period of the maximum 24 hours of the storm.

After determining the 24-hr 10-mi^2 PMP, 6-/24- and 72-/24-hr ratio maps were used to develop PMP values for these two other index durations for the 10-mi^2 area. Finally, a 1-hr 10-mi^2 PMP map was developed using a 1-/6-hr ratio map. These four maps provide the key estimates of general-storm PMP for the region.

6.5 Depth-Area Relations

The technique discussed in sections 6.3 and 6.4 provide 10-mi^2, or point, estimates of general-storm PMP for four index durations. Depth-area relations were developed utilizing data from the important storms of record in and near the study region to permit estimates for larger areas. These relations provide percentages to estimate PMP for areas as large as 5,000 mi^2. Different depth-area relations are required for disparate regions. Differences also exist between orographic and non-orographic portions of the study region. These differences resulted in a set of depth-area relations.

HMR 55A Section 7. STORM SEPARATION METHOD (SSM)

7.1 Introduction

It was considered necessary to find a property of observed major storm precipitation events that is only minimally affected by terrain so transposition of observed precipitation amounts would not be limited to places where the terrain characteristics are the same as those at the place where the storm occurred. The name given to this idealized property is "free atmospheric forced precipitation" (FAFP) which has been called “convergence only" precipitation in publications such as HMR No. 49. The definition of FAFP is the precipitation not caused by orographic forcing; i.e. it is precipitation caused by the dynamic, thermodynamic, and microphysical processes of the atmosphere. It is all the precipitation from a storm occurring in an area where terrain influence or forcing is negligible, termed a non-orographic area. In areas classified as orographic, it is that part of the total precipitation which remains when amounts attributable to orographic forcing have been removed. Factors involved in the production of FAFP are:

1. Convergence at middle and low tropospheric levels and often, divergence at high levels
2. Buoyancy arising from heating and instability
3. Forcing mesoscale systems, i.e., pseudo fronts, squall lines, bubble highs, etc.

4. Storm structure, especially at the thunderstorm scale involving the interaction of precipitation unloading with the storm sustaining updraft
5. Lastly, condensation efficiency involving the role of hydroscopic nuclei and the heights of the condensation and freezing levels.

It is emphasized that FAFP is an idealized property of precipitation since no experiment has yet been devised to identify in nature which raindrops were formed by orographic forcing and which by atmospheric forcing.

7.2 Glossary of Terms (partial list)

A_o: See P_a. It is the term for the effectiveness of orographic forcing used in module 3.

Bi: It is the term representing the "triggering effects" of orography. It is used in module 2. Bi is a number between 0 and 1.0 representing the degree of FAFP implied by the relative positioning of the 1st through i-th isohyetal maxima with those terrain features (steepest slopes, prominences, converging upslope valleys) generally thought to induce or "stimulate" precipitation. A high positive correlation between terrain features and isohyetal maxima yields a low value for Bi.

BFAC: 0.95 (RCAT). It represents an upper limit for FAFP in modules 2 and 5. See also the definition for PX.

DADRF: The depth-area-duration reduction factor is the ratio of two average depths of precipitation. DADRF: RCAT/MXVATS

DADFX: DADFX = (HIFX)(DADRF).

It is used in module 2 to represent the largest amount of non-orographic precipitation caused by the same atmospheric mechanism that produced MXVATS.

F_i: See PCTHIFX: The largest isohyetal value in the non-orographic part of the storm. The same atmospheric forces (storm mechanism) must be the cause of precipitation over the areas covered by the isohyet used to determine HIFX and MXVATS.

Im: That part of RCAT attributed solely to atmospheric processes and having the dimension of depth. Since it is postulated that FAFP cannot be directly observed in an orographic area, some finite portion of it was caused by forcing other than free atmospheric. The FAFP component of the total depth must always be derived by making one or more assumptions about how the precipitation was caused. The subscript "m" identifies the single assumption or set of assumptions used to derive the amount designated by I. For example, a subscript of 2 will refer to the assumptions used in module 2.

LOFACA: LOFACA is the lowest isohyetal value at which it first becomes clear to the analyst that the topography is influencing the distribution of precipitation depths. Confirmation of this influence is assumed to occur when good correlation is observed between the LOFACA isohyet and one or more elevation contours in the orographic part of the storm.

The significance of LOFACA is that precipitation depths at and below this value are assumed to have been produced solely by atmospheric forces without any additional precipitation resulting from topographic effects; i.e., they represent the "minimum level of FAFP for the storm.

LOFAC: $$LOFAC = LOFACA + \frac{AI}{2}\left(PB^{\frac{(AI)}{2}} - 1\right).$$

It is a refinement to LOFACA based on the concept that AI may prejudice the assigning of a minimum level of FAFF.

MXVATS: The average depth of precipitation for the total storm duration for the smallest area size analyzed, provided that it is not larger than 100 sq mi.

OSL: Orographic Separation Line is a line which separates the region into two distinct regions. In one region, the non-orographic, it is assumed no more than a 5 percent change (in either increasing or decreasing the precipitation amount for any storm or series of storms) results from terrain effect. In contrast, the other region is one where the influence of terrain on the precipitation process is significant. An upper limit of 95 percent and a lower limit of no less than 5 percent is allowed. The line may exist anywhere from a few to 20 miles upwind (where the wind direction is that which is judged to prevail in typical record setting storms.

P_a (and A_a) is a ratio in which the effectiveness of an actual storm in producing precipitation is compared with a conceptualized storm of "perfect" effectiveness.

The SSM was developed because four distinct sets of precipitation were available for record-setting storms.

1. Reported Total storm precipitation, used in Module 1
2. Isohyet and depth-area-duration analyses of total storm precipitation, including Part I and Part II Summaries, used in Module 2
3. Meteorological data and analyses, used in Module 3
4. Topographic charts, used in all modules

It is noted that clearly the SSM depends on the validity of the input information.

The mechanics of the procedure used to arrive at FAFP are accomplished by completing the tasks symbolically represented in a MAIN FLOWCHART for the SSM along with its associated SSM MODULE FLOWCHARTS.

The validity of the techniques in the SSM depends on the validity of the concepts upon which they are based.

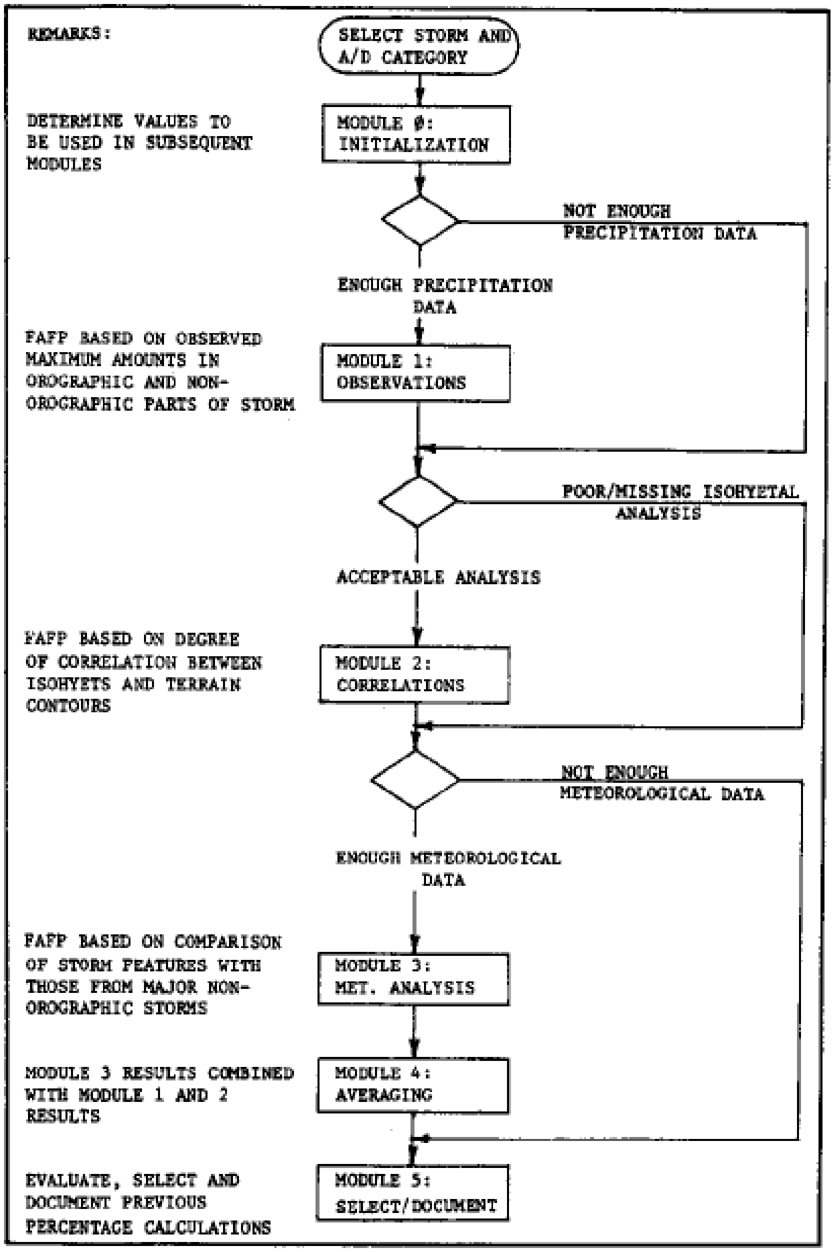


Figure 7.2.—Main flowchart for SSM.

SSM Modules from HMR 55A

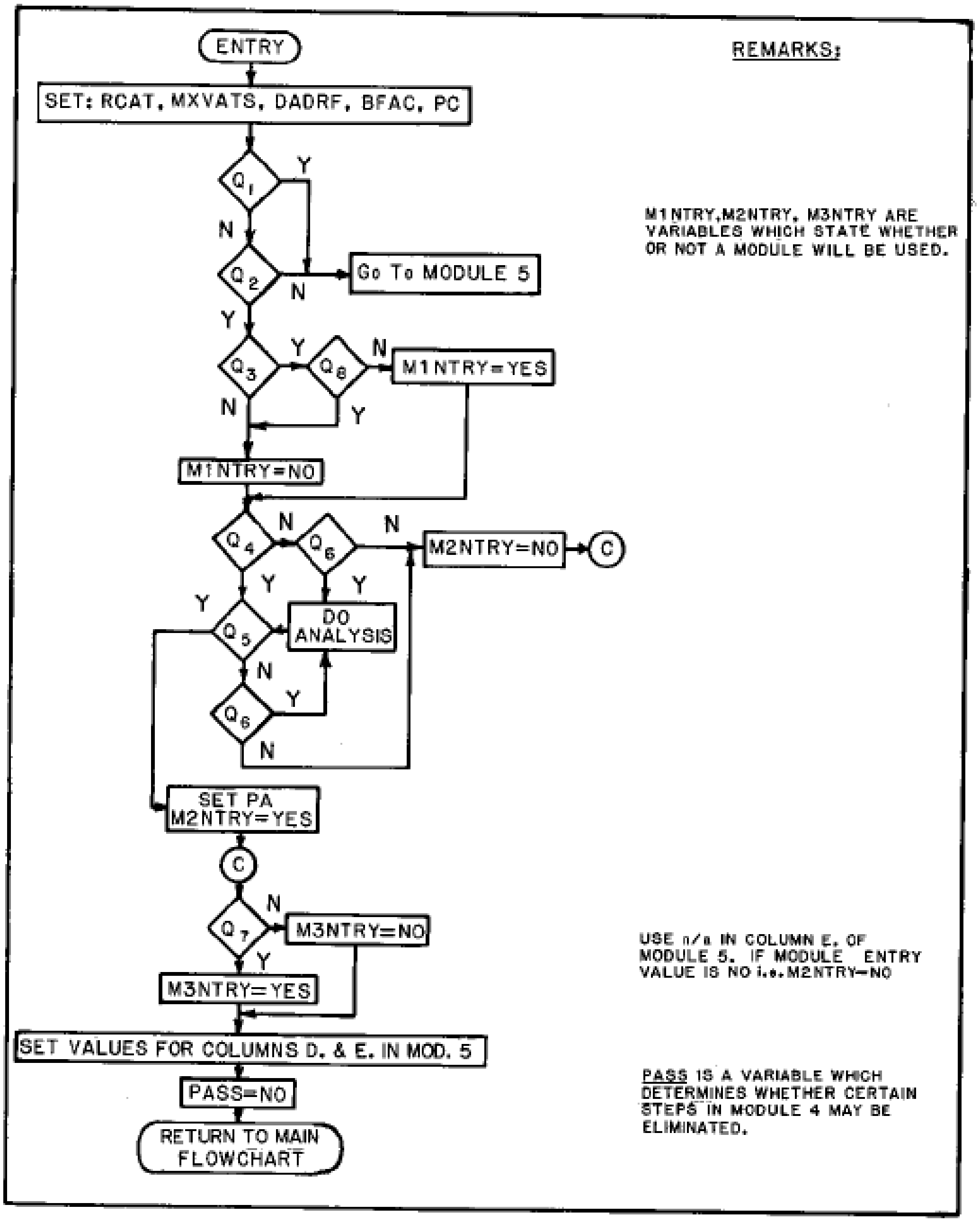


Figure 7.3.--Flowchart for module 0, SSM.

7.4.1.1 Module 0.

Module 0 is used to decide if there is adequate data available. A decision is made by the analyst if there are no data available, if the data are judged to be adequate or if the data are judged to be highly adequate. Values range from 1 for the lowest level to 9 for the highest level. The analyst assigns the value that is considered most applicable. Questions that are asked include the following:

1. Is the isohyetal analysis reliable?
2. Is there adequate data in non-orographic areas to select a reliable value for non-orographic precipitation?
3. Is the highest observed precipitation in the non-orographic part of the storm equal to zero?
4. Are the data adequate to determine a ratio of the effectiveness of the actual storm in producing precipitation to a conceptual storm of "perfect" effectiveness?

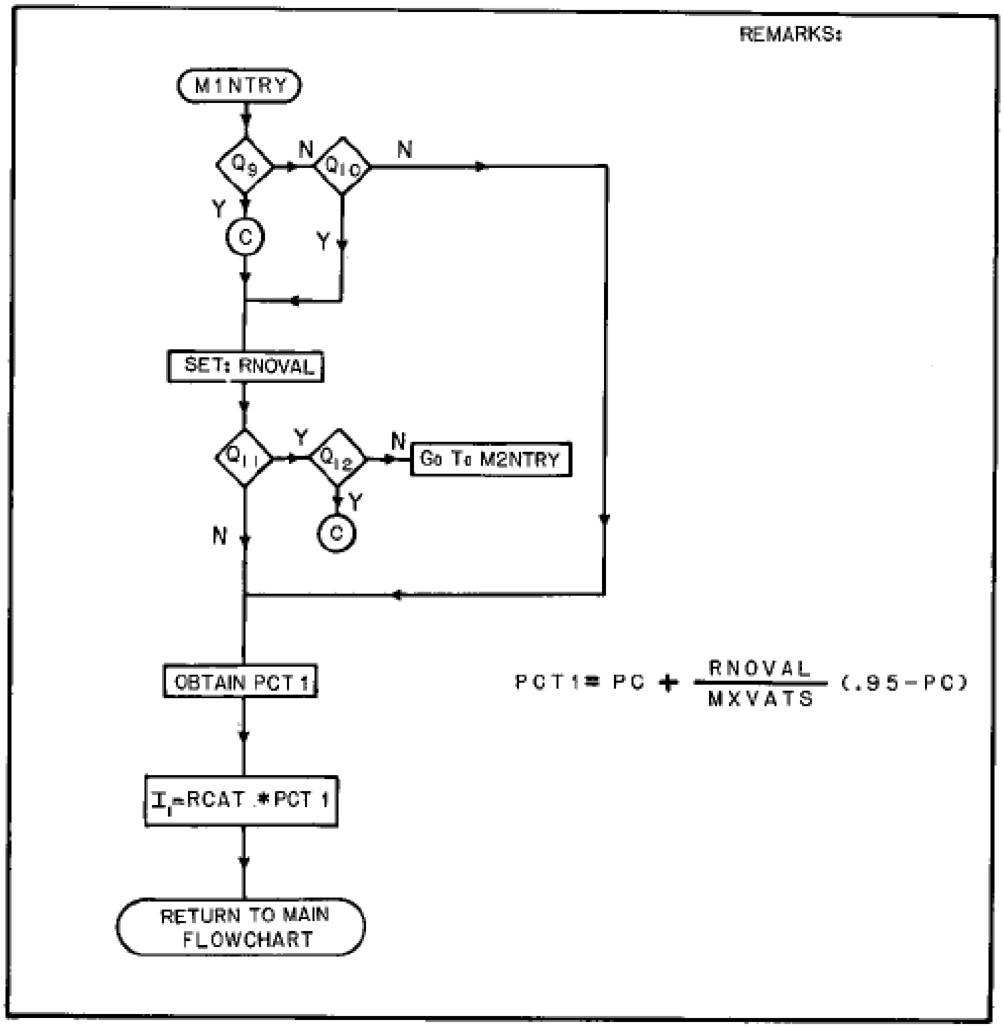


Figure 7.4.--Flowchart for module 1, SSM.

7.4.1.2 Module 1.

An analytical judgment must be made concerning the storm mechanism that resulted in the maximum precipitation over orographic regions and over non orographic regions. Questions asked include the following:

1. Is a review of the data needed?
2. Is the precipitation in the non-orographic region equal to the precipitation in the orographic region?

The reliability of the result of this module depends on the density of good precipitation observations on the date the storm occurred.

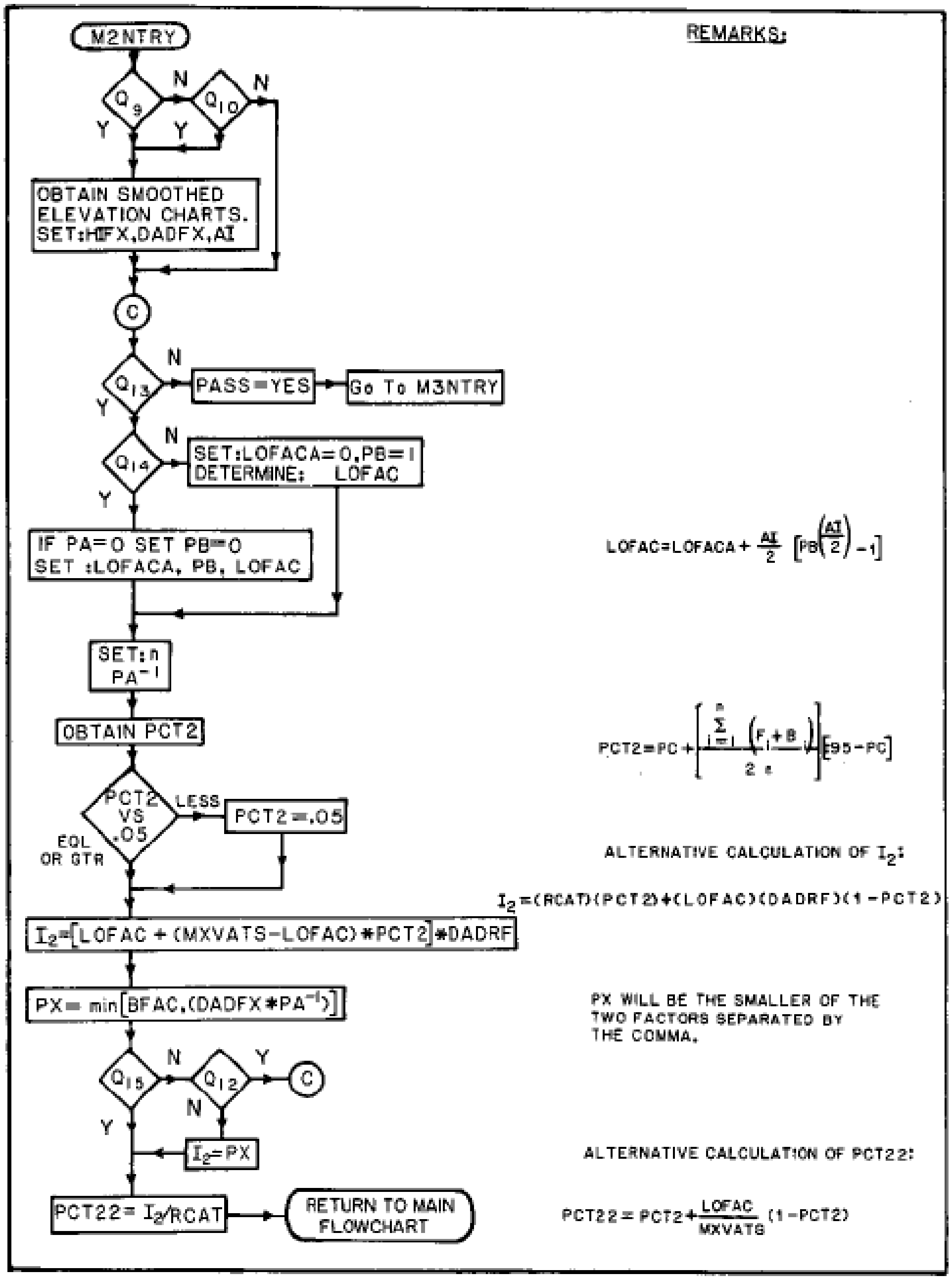
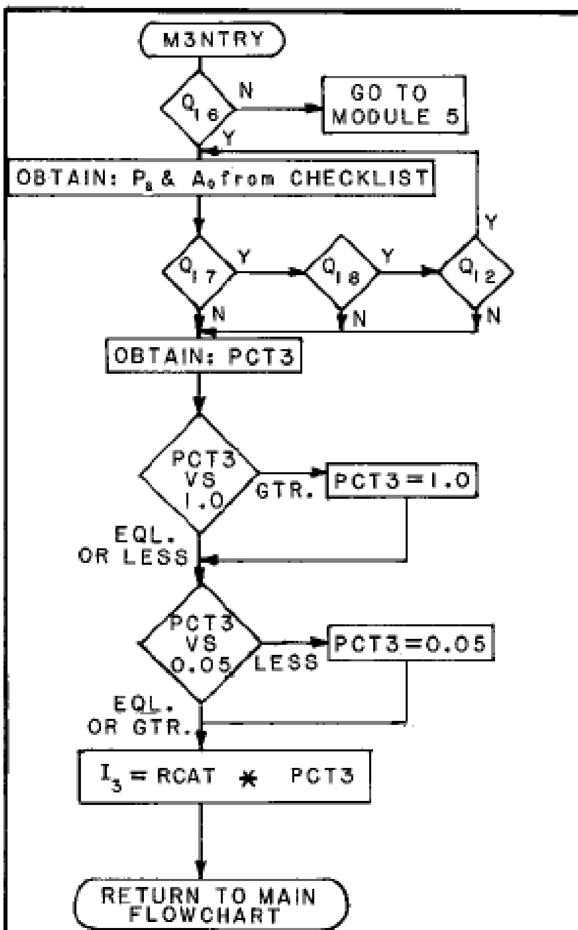


Figure 7.5.--Flowchart for module 2, SSM.

7.4.1.2 Module 2.

In this module, the average depth of precipitation is conceived of a column of water comprised of top and bottom sections. The limit to the top of the bottom section is set by the lowest isohyetal value at which it first becomes clear to the analyst that the topography is influencing the distribution of precipitation depths. The bottom section is conceived to contain only a minimum level of FAFP. The top section contains precipitation that results from orographic forcing or perhaps additional atmospheric forcing. A complex set of judgment questions are asked to evaluate each section. As in module 1, an analytical judgment must be made. Some of questions asked are as follows:

1. Is a review of the data needed?
2. Can it be determined which isohyetal maxima controls the average depth?
3. Is there a good correlation between some isohyet and the elevation contours in the orographic part of the storm?
4. Is the average depth of precipitation that is FAFP less than or equal to the smaller of either the upper limit for FAFP in module 2 or the largest amount of non-orographic precipitation caused by the same atmospheric mechanism that produced the average depth of precipitation for the total storm duration for the smallest area size analyzed, provided that it is no larger than 100 square miles?



REMARKS

$$PCT3 = PC + \frac{P_a}{P_a + A_o}(.95 - PC)$$

LEGEND

PVA = Positive Vorticity Advection
MCC = Mesoscale Convective Complex
LEWP = Line Echo Wave Pattern

P_a CHECKLIST

Cat. Data	Parameter	A (√)	B .05-.95	C 1-3	D B*C
Surface	Iso.Ptn. Fronts Waves Sq.Ln. Other				
Upper Air	PVA/SW Cutoff Blocking JetStm Other				
Rawinsonde	Stability Shear Other				
Satellite	Diver. Merger MCC Other				
Radar	LEWP Merger Others				
Other					
Duration (%)					
Totals =					
P_a = Total D/Total C =					

A_o CHECKLIST

Parameter	A Phys. Val.	B 0-±.95	C 1-3	D B*C
Inflow Direct				
Inflow Speed				
Gradient of Elevation				
Stability				
Other				
Duration (%)				
Totals =				
A_o = Total D/Total C =				

Figure 7.6.—Flowchart for module 3, SSM.

7.4.1.2 Module 3.

This module uses meteorological and terrain information to evaluate an appropriate level of FAFP. This is accomplished through evaluation of the ratio in which the effectiveness of an actual storm in producing precipitation is compared with a conceptualized storm of "perfect" effectiveness. In such a conceptual model, features known by experience to be highly correlated with positive vertical motions, or an efficient storm structure, would be numerous and exist at an optimum (not always the largest or strongest) intensity level. The presence of one or more features that infer positive vertical motion, or which may contribute toward an efficient storm structure are identified. Then take as a basis for comparison an idealized storm which contains the same features or phenomena and indicate by selecting a number between 0.05 and 0.95, the degree to which the effectiveness of the selected actual storm features/phenomena approaches the effectiveness of the same features/phenomena in the idealized storm. If the quality and quantity of the information permits, the degree of convective-scale forcing may be distinguished from forcing due to larger scale mechanisms. Features may be assigned a weighted value in relationship to others. Meteorological data categories, for which there is not sufficient information from a particular storm, are disregarded in the ratio calculations.

The effectiveness of orographic forcing effects is determined. A vertical displacement parameter is determined using the component of the wind perpendicular to terrain slopes and the slope. The effectiveness is then compared with an idealized value representing 100 percent effectiveness. A stability effectiveness is assigned and combined with the vertical displacement parameter to determine a combined effect. The "model" in module 3 follows the concept that FAFP is directly proportional to the effectiveness of atmospheric forcing and inversely proportional to the effectiveness of the orographic forcing mechanisms.

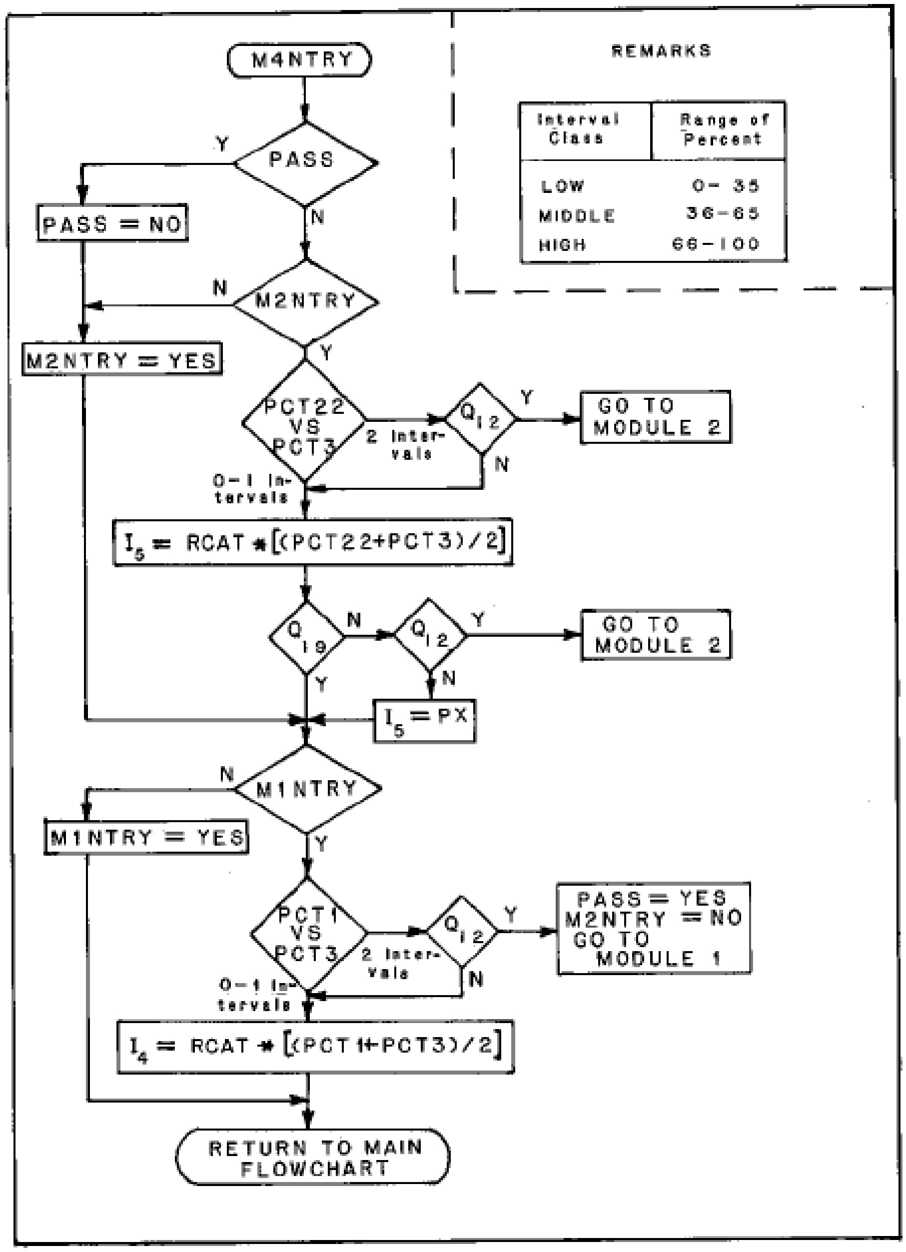


Figure 7.7.--Flowchart for module 4, SSM.

7.4.1.5 Module 4.

A basic assumption underlying the use of module 4 is that better results can be obtained by combining information; i.e., averaging the percentages obtained from the isohyetal analysis with the meteorological analysis and those obtained from analysis of the precipitation observations with the meteorological analysis. Better estimates are produced by averaging when there is little difference in the expressed preference for any one of the techniques or sources of information and, also, when the calculated percentage of FAFP from each of the modules exhibits wide differences.

Little is to be gained from use of the averaging technique over estimates produced by one of the individual analyses of modules 1, 2, or 3 when:

1. There are large differences in the expressed preference for the techniques of one module
2. The sources of information for one of the individual modules is definitely superior
3. The calculated percentages among the modules are in close agreement

DOCUMENTATION AND INDEX SELECTION

STORM ID/DATE, REMARKS:						
MODULE	PARAMETER	VALUE	EVALUATION SCALE: COL.D 0-9; COL.E 1-9 MODULES 1-3: COL.F: IS THE SUM OF COLS. D&E. COL.D: HOW ADEQUATE IS THE INPUT INFORMATION FOR THE REQUIREMENTS SET BY MODULE'S TECHNIQUE. COL.E: HOW LIKELY IT IS THAT THIS TECHNIQUE WILL ESTIMATE THE CORRECT INDEX VALUE BASED ON ITS ASSUMPTIONS? FOR MODULE 4 SEE SELECTION RULE. OVERALL RULE: SELECT INDEX VALUE WITH LARGEST COL. F SCORE. LARGEST SUBSCRIPT BREAKS TIES.			
			REMARKS	D	E	F
Ø	CATEGORY RCAT BFAC MXVATS DADRF PA PC					
1	RNOVAL PCT1 I_1					
2	AI LOFACA PB LOFAC HIFX DADFX PA^{-1} PX $\sum^{n} (F_i + B_i)$ PCT2 I_2 PCT22					
3	COLUMN: A / B / C INFLOW DIR. INFLOW SPD. GRAD. ELEV. W_o STABILITY A_o SURFACE UPPER AIR RAOB SATELLITE RADAR P_a PCT3 I_3					
4	(PCT22 + PCT3)/2 I_5 (PCT1 + PCT3)/2 I_4		RETURN TO MAIN FLOWCHART			

Figure 7.8.--Documentation form for SSM, module 5.

7.4.1.6 Module 5.

Module 5 is used for documentation. Values from the other modules are entered into the module 5 sheet. Assigning values involves subjectivity which must be the case because the “correct” value cannot be known and, hence, there is no way to know which of the various techniques used produces “correct” results most frequently. After a storm has been evaluated in each of the modules, all information is available to assign a value to the question “How likely is it that this technique will estimate the correct value based on the assumptions?” If confidence is high, assign a value of either 7, 8 or 9. If confidence is lower, assign a lower number. The scheme is designed to permit selection of one of the module results when there is a strong preference of one of them. The analyst must make a decision as to which module is to be preferred.

The final value selected for FAFP is determined by the largest value in module 5.

AWA Discussion on HMR 55A Modules

After reviewing the information provided above from Sections 6 and 7 of HMR 55A, several observations and conclusions have been made.

1. The procedures presented in HMR 55A are very detailed and following the procedures is at best very difficult since many of the parameters used are not standard meteorological parameters and their physical meaning is rarely intuitive.
2. The definition of terms in most cases includes other terms unique to this procedure and the relationship among parameters, even when a mathematical formula is provided, is not obvious when trying to associate physical characteristics to the combinations of parameters.
3. The formulas provided appear to have been subjectively derived with no obvious physical parameter associations connected through physical meteorological processes. In some cases, the process can be completed but other than a number to plug into a module, there is no meaning to the numbers that can be associated with the physical processes associated with extreme precipitation.
4. There are numerous places in the procedures where subjective evaluations are quantified with some explicit number where the number is no more than the opinion of the analyst. Then that number is used later in the procedure. In the final module, one of the critical inputs is, in the opinion of the analyst, how likely is it that the technique will estimate the correct value based on the assumptions? Examples of subjective decisions are as follows:
    1) Bi is the "triggering effect" of orography. It is a number between 0.0 and 1.0 representing the degree of FAFP implied by the relative positioning of isohyetal maxima lines with terrain features.
    2) Im is that part of the average depth of precipitation solely attributed to atmospheric processes
    3) LOFACA is the lowest isohyetal value where it first becomes clear to the analyst that topography is influencing the distribution of rainfall depths.
    4) P_a and A_a are ratios in which the effectiveness of an actual storm in producing precipitation is compared with a conceptual storm of "perfect" effectiveness. This is a very interesting subjective decision since if the analyst knew the effectiveness of the conceptual storm of "perfect" effectiveness, then one of the major unknowns in PMP determination is no longer an unknown.
    5) The statement is made that the validity of the techniques in the SSM depends on the validity of the concepts upon which they are based. Since the concepts involve many subjective judgments, the SSM procedure is only as valid as

those subjective judgments. Unfortunately the validity of those judgments vary from analyst to analyst with no way of objectively evaluating their reliability.

6) Module 4 makes seemingly contradicting statements.

    A basic assumption underlying the use of module 4 is that *better results can be obtained by combining information*; i.e., averaging the percentages obtained from the isohyetal analysis with the meteorological analysis and those obtained from analysis of the precipitation observations with the meteorological analysis. *Better estimates are produced by averaging when there is little difference* in the expressed preference for any one of the techniques or sources of information and, *also*, when the calculated percentage of FAFP from each of the modules exhibits *wide differences*.

    Little is to be gained from use of the averaging technique over estimates produced by one of the individual analyses of modules 1, 2, or 3 when:

    There are *large differences* in the expressed preference for the techniques of one module
    The sources of information for one of the individual modules is definitely superior
    The calculated percentages among the modules are *in close agreement*

The following discussion is extracted from the information provided in HMR 55A for the determination of the orographic factor. The information is condensed to present major discussions. The complete text is available in Section 9 of HMR 55A.

HMR 55A Section 9.2 Orographic Factor, T/C

Maps of 100-yr 24-hr precipitation from NOAA Atlas 2 were used to form a ratio of total 100-yr to convergence component 100-yr rainfall, T/C, and it was assumed that this ratio related to a ratio of similar parameters for PMP. The ratio of T/C can be used as a representative index of orographic effects.

The availability of the 100-yr 24-hr maps provides only part of the needed ratio, the total rainfall or numerator in the fraction, and it remains to determine how to obtain the convergence component, C. The rationale followed was that isopleths of the convergence component would exhibit a smooth, gradually varying geographic pattern. The gradients and general geographic variation would be somewhat similar to the FAFP component. HMR 51 has smooth PMP lines east of the 105^{th} meridian and is assumed to be convergence only PMP, so NOAA Atlas 2 isopluvials for this region are also assumed to be convergence only.

The approach taken to determine C is to look at the 100-yr precipitation analysis for zones of least topographic effect. These zones would be tied together in some form of smooth analysis. A rough pattern of smooth contours was sketched. This provides a map of C. Using NOAA Atlas 2 and the map of C, T/C can be computed.

HMR 55A Section 9.3 Storm Intensity Factor, M

A storm intensity factor adjustment, M, was developed to relate the amount of precipitation that could be expected during the most intense precipitation period to the total amount of precipitation for a period. M varies with storm type.

The 6-hr interval was determined as the duration of the most intense precipitation period with the base period being the 24-hr duration. The storm intensity factor was defined as the ratio of rainfall in the maximum 6-hr period to the rainfall in the basic 24-hr period. M is obtained by dividing the FAFP for 6 hours by the FAFP for 24 hours.

By combining the results of the FAFP, T/C and M evaluations, then PMP can be computed using the FAFP and an orographic influence parameter, K. K is a function of the orographic factor, T/C. PMP is represented as the sum of two parts representing the core period and the remaining period. Through some mathematical combinations,

$PMP = (FAFP)\ (K) = (FAFP)(M^2\ (1\text{-}T/C) + T/C)$

AWA Discussion on HMR 55A Section 9

After reviewing the information provided above from Section 9 of HMR 55A, several observations and conclusions have been made.

1. NOAA Atlas 2 is based on statistical analyses of precipitation data observed within the NOAA Atlas 2 domain. Although NOAA Atlas 2 is being updated for various regions in the United States, it is the current return frequency analysis for this region and is based on evaluation of rainfall data, and hence has a basis for being objectively derived from rainfall observations.
2. C is the 100-year 24-hour convergence only component of rainfall. It is assumed that for regions where there is least orographic influence, NOAA Atlas 2 values approximate C. For regions where there is significant orographic influences, C is subjectively estimated since there are no observational data that provide only the convergence component of observed rainfall. Hence, C much like FAFP, is derived using very limited data and subjective analyses over regions where orographic influences are significant.
3. The M factor also has subjective decisions incorporated into its determination. The duration of the core rainfall period seems to be subjectively derived. For locations where a core period cannot be identified, M = 0.
4. For storms without large core precipitation periods, i.e. where M is small or 0, PMP is primarily dependent on FAFP, T and C. While T has basis for being objectively derived,

FAFP and C are largely subjective determined. Hence PMP values computed using the SSM provide highly subjective PMP values.

HMR 57 SSM Application

Section 6 Storm Separation Method

The technique for developing FAFP used in HMR 55A is complex and involves the analyst tracking through a set of modules in which knowledge of observed conditions and experience are used to arrive at estimates of FAFP. The estimates are in turn weighted, based on the analyst's judgment of the amount and quality of overall information to obtain a result.

The SSM has undergone minor refinements since its development in HMR 55A. A decision about the level of FAFP for a storm may have to accommodate a fair amount of uncertainty. The questions asked in the SSM modules are formulated in such a way that analysts with different levels of experience could estimate different amounts of FAFP. Under such circumstances a consensus among analysts often leads to the best FAFP estimate for a storm, but the consensus process is not a necessary part of the SSM.

The SSM technique was considered most appropriate for the present study (HMR 57). The technique was applied directly according to original guidance, subject to modifications. A discussion is provided in HMR 57 with the comment that the discussion covers specific changes in details that may be beyond the casual reader's interest. Module 2 was not used to analyze any of the storms but the other modules were used to determine FAFP.

A map of C was constructed using regions of relative minima in the 100-year return frequency map. This was used together with the 100-year return frequency map to compute T/C. For some locations, the T/C maps were subjectively adjusted. The M-Factor for western Washington was determined to be zero so the K factors became T/C.

AWA Discussion on HMR 57 SSM Application

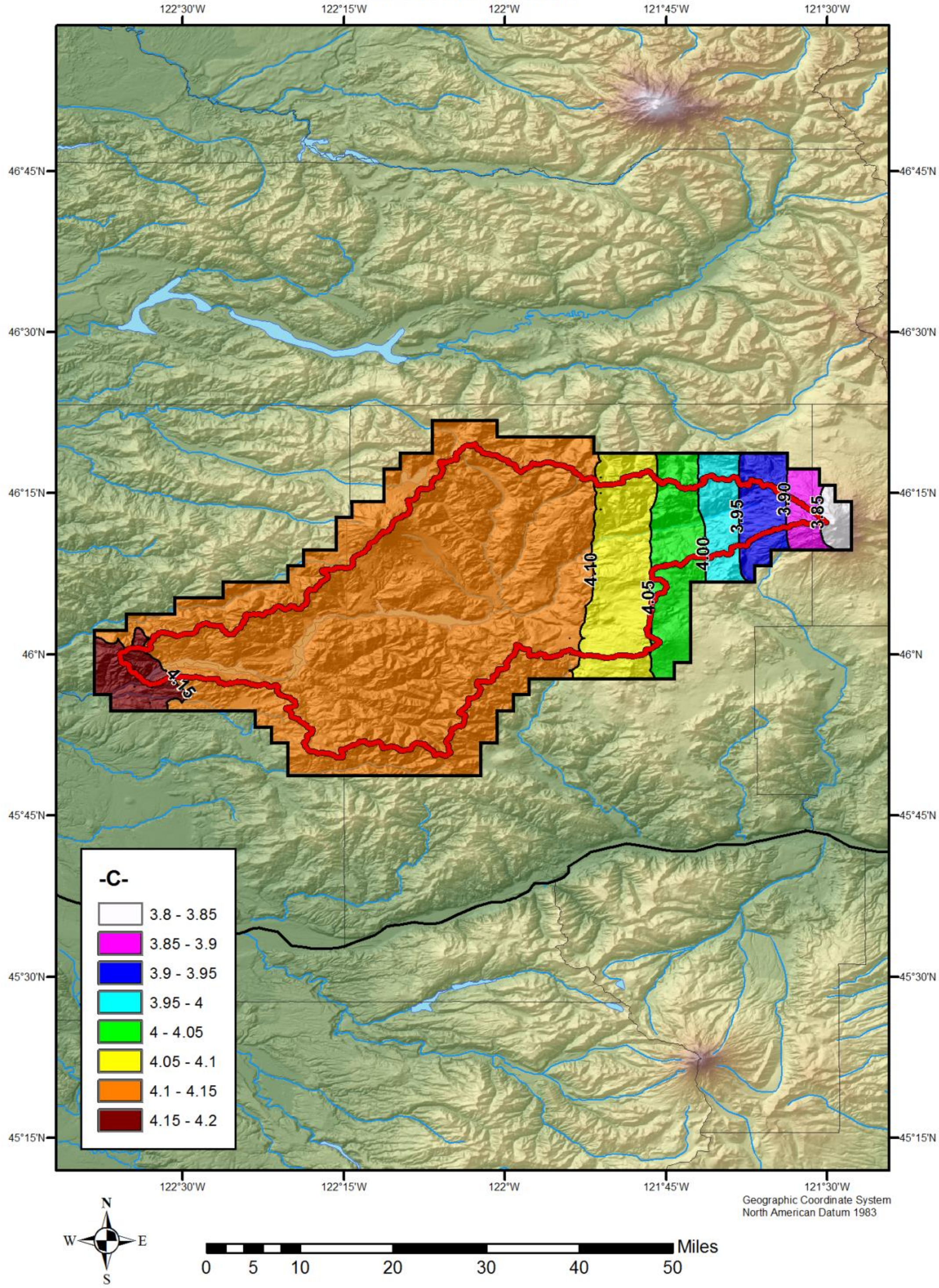
After reviewing the information provided above from Sections 6, 7 and 8 of HMR 57, several observations and conclusions have been made.

1. The discussion in Section 6 emphasizes that the SSM is complex, involves tracking through a set of modules in which knowledge of observed conditions and experience are used to arrive at estimates of FAFP, estimates are based on the analyst's judgment, and that there is a fair amount of uncertainty indicating that the authors of HMR 57 recognized major issues with the SSM. However, it was applied directly according to the original guidance in HMR 57.
2. The T/C maps were adjusted subjectively with no documentation on what adjustments were made or why.

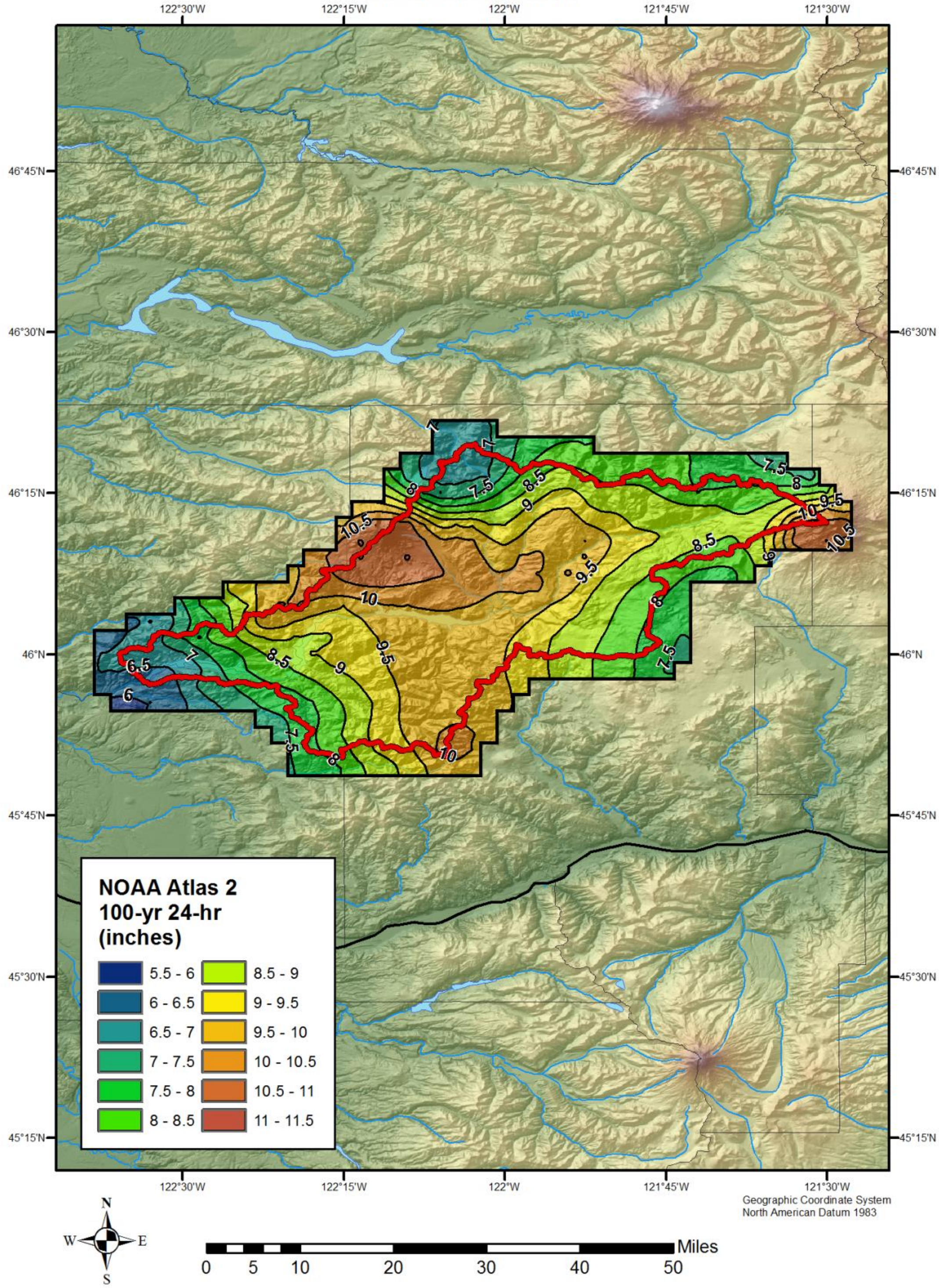
As discussed earlier, the maps used for FAFP, C and M for computation of PMP in HMR 57 are not available from the HSDC. However, low resolution example maps are published in HMR 57 for these parameters that cover western Washington. Figure 8.1 shows the C map, Figure 8.2 shows the T/C map, Figure 8.3 shows the M factor map and Figure 8.4 shows the orographic factor K map for the Lewis River basin in southern Cascades of Washington state. These maps were digitized in GIS for analysis. Using the formulas in HMR 57 Chapter 8, maps were produced from the digitized figure maps to compare with the maps shown in HMR 57. The Lewis River drainage basin in southern Washington was the domain used for the comparisons.

NOAA Atlas 2 provides the map for the 100-year 24-hour T values. Using the map of C from HMR 57 Figure 8.1, a map of T/C was computed. Since HMR 57 Figure 8.3 shows that M=0 for the Lewis River Basin, K=T/C. The computed T/C map was compared with HMR 57 Figure 8.4 (HMR 57 K). The NOAA Atlas 2 map, the HMR 57 maps for C and K, and the computed maps for K are shown below. The HMR 57 K map was compared with the computed K map and a percentage difference map is shown.

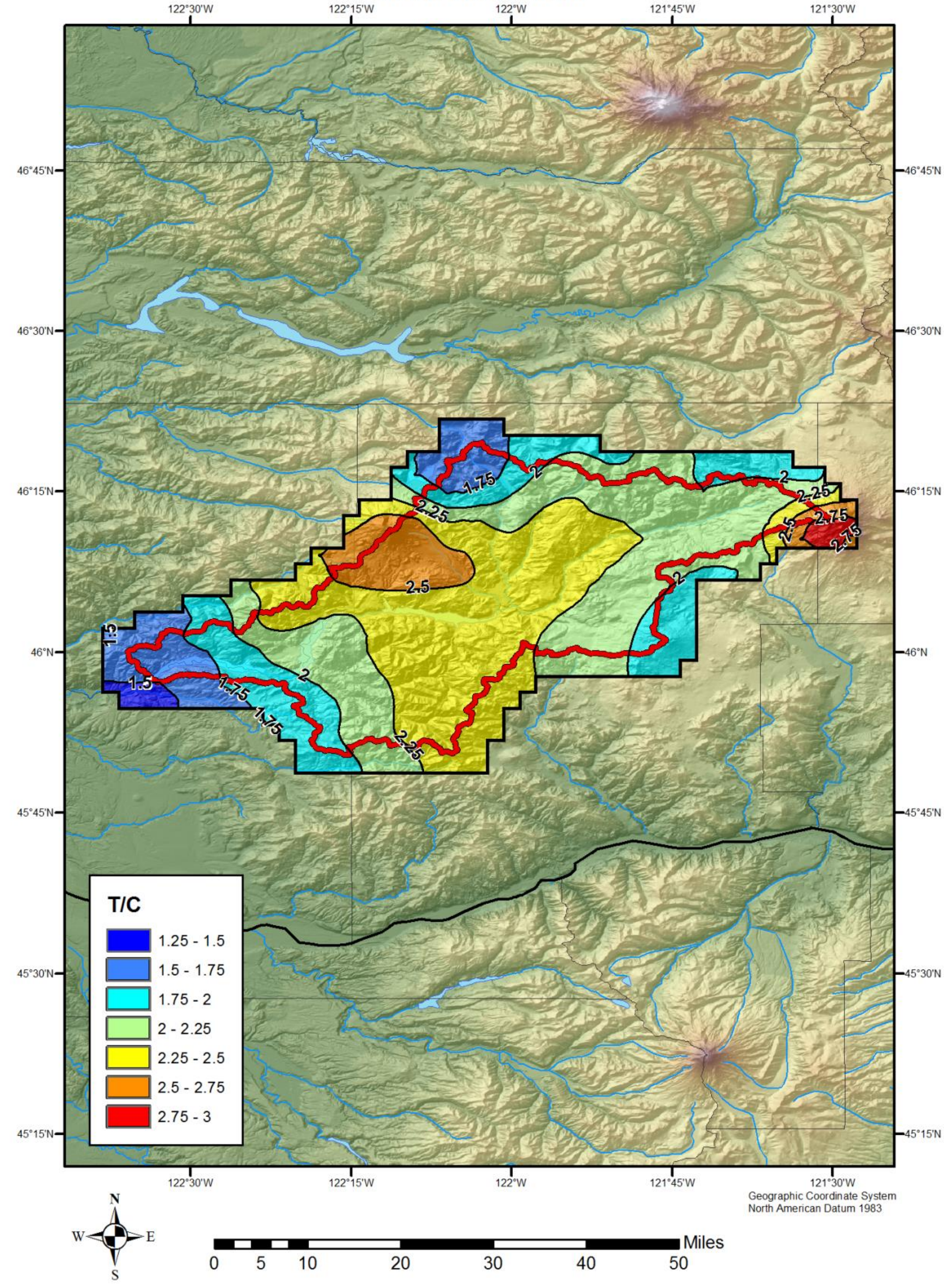
HMR-57 C (from fig 8.1)
Lewis River Basin



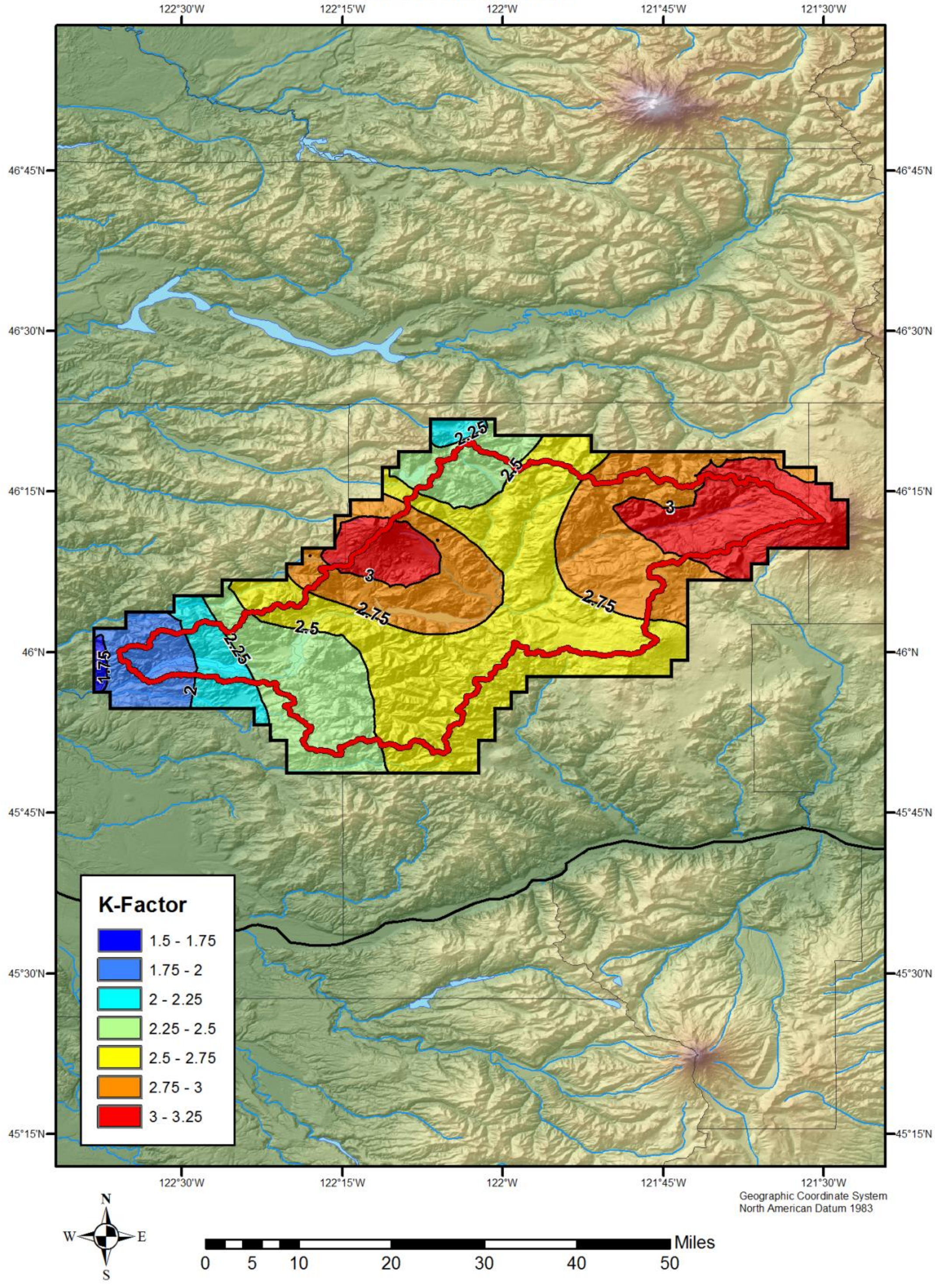
NOAA Atlas 2 100-year 24-hour Precipitation
Lewis River Basin



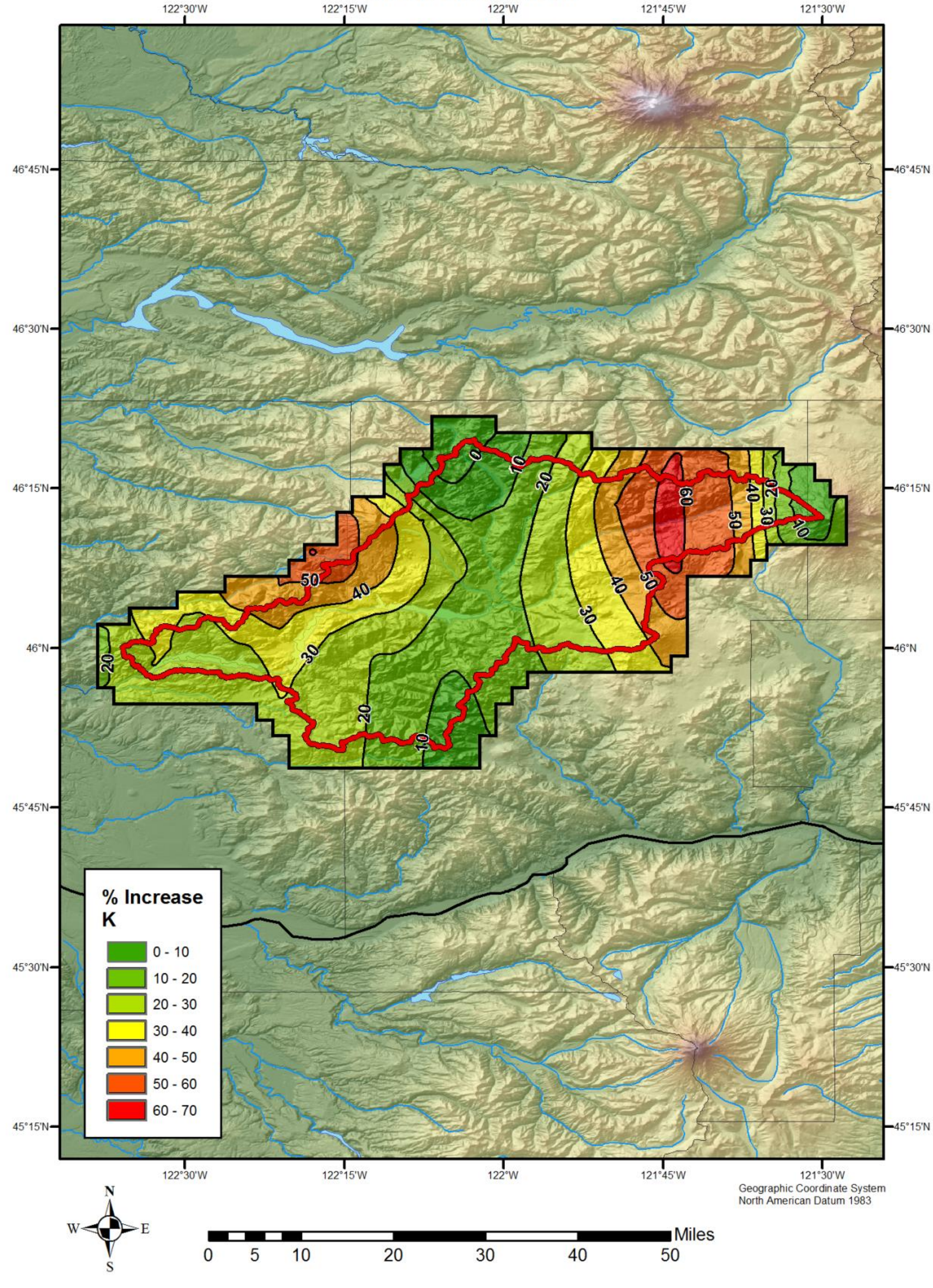
T/C - (NOAA Atlas 2 100-year 24-hour Precipitation ÷ HMR 57 C)
Lewis River Basin



HMR-57 K-Factor (from fig 8.4)
Lewis River Basin



Percent Increase of HMR 57 K Values from T/C Values
Lewis River Basin

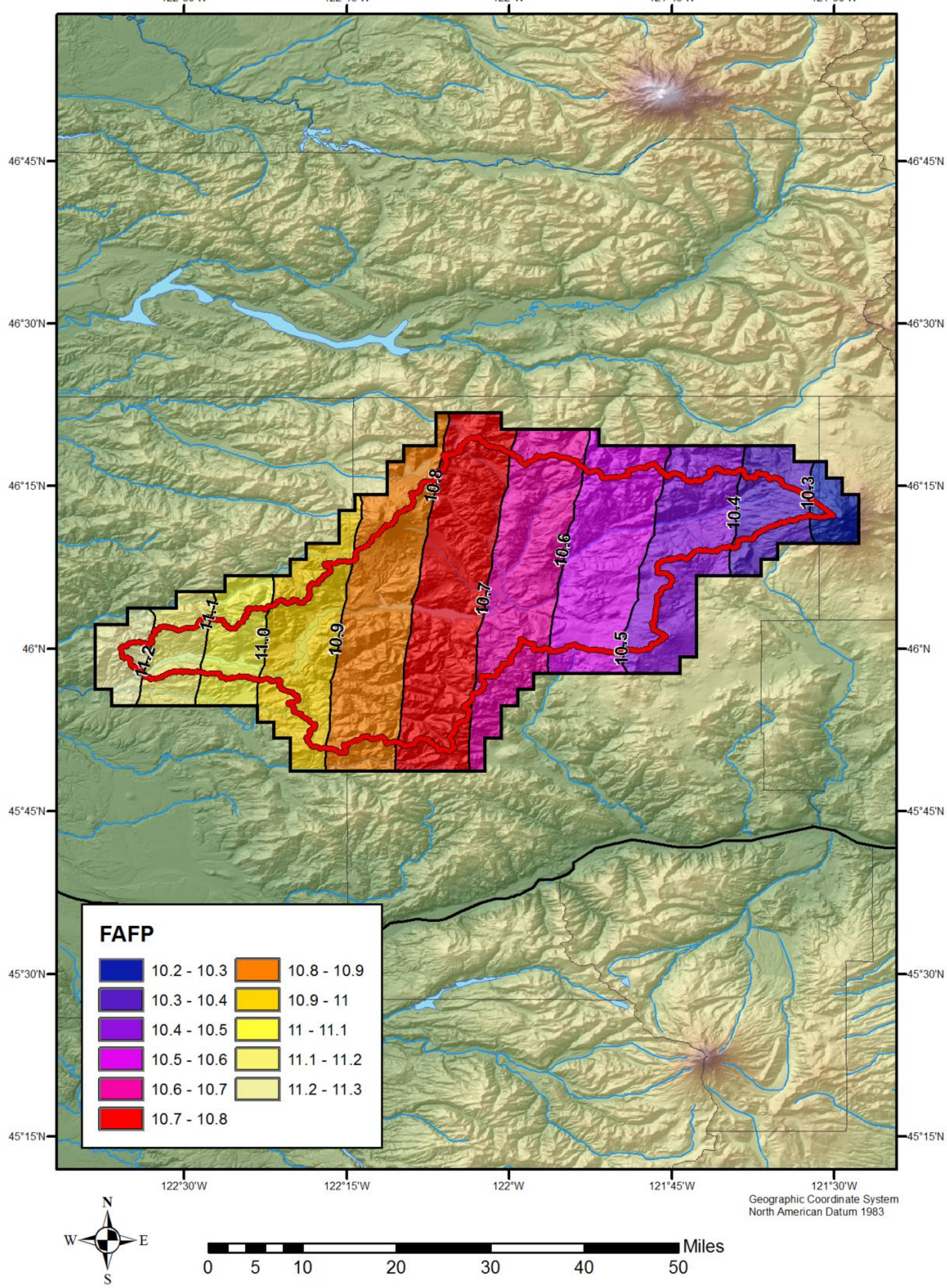


The comparison between the computed K map and the HMR 57 K map shows significant differences. Overall the computed K values are significantly smaller than the K values from

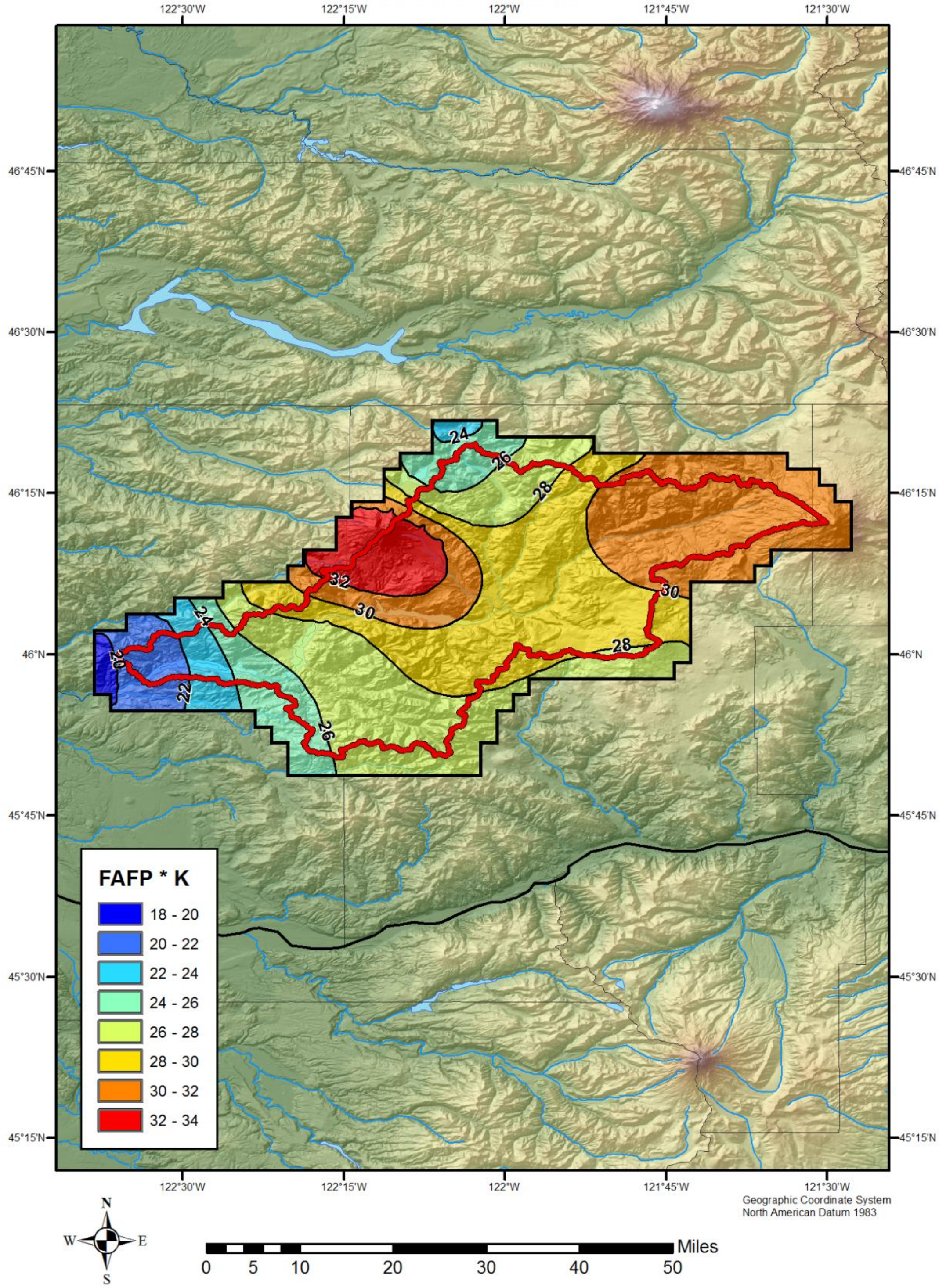
HMR 57. The differences range from about 10% to over 60% with the HMR 57 values being consistently larger.

Having values for FAFP from HMR 57 Figure 7.2 and values for K from Figure 8.4, a map of PMP can be constructed using PMP = (FAFP) (K). Figures showing these values are show below along with HMR 24-hour 10-mi^2 PMP values.

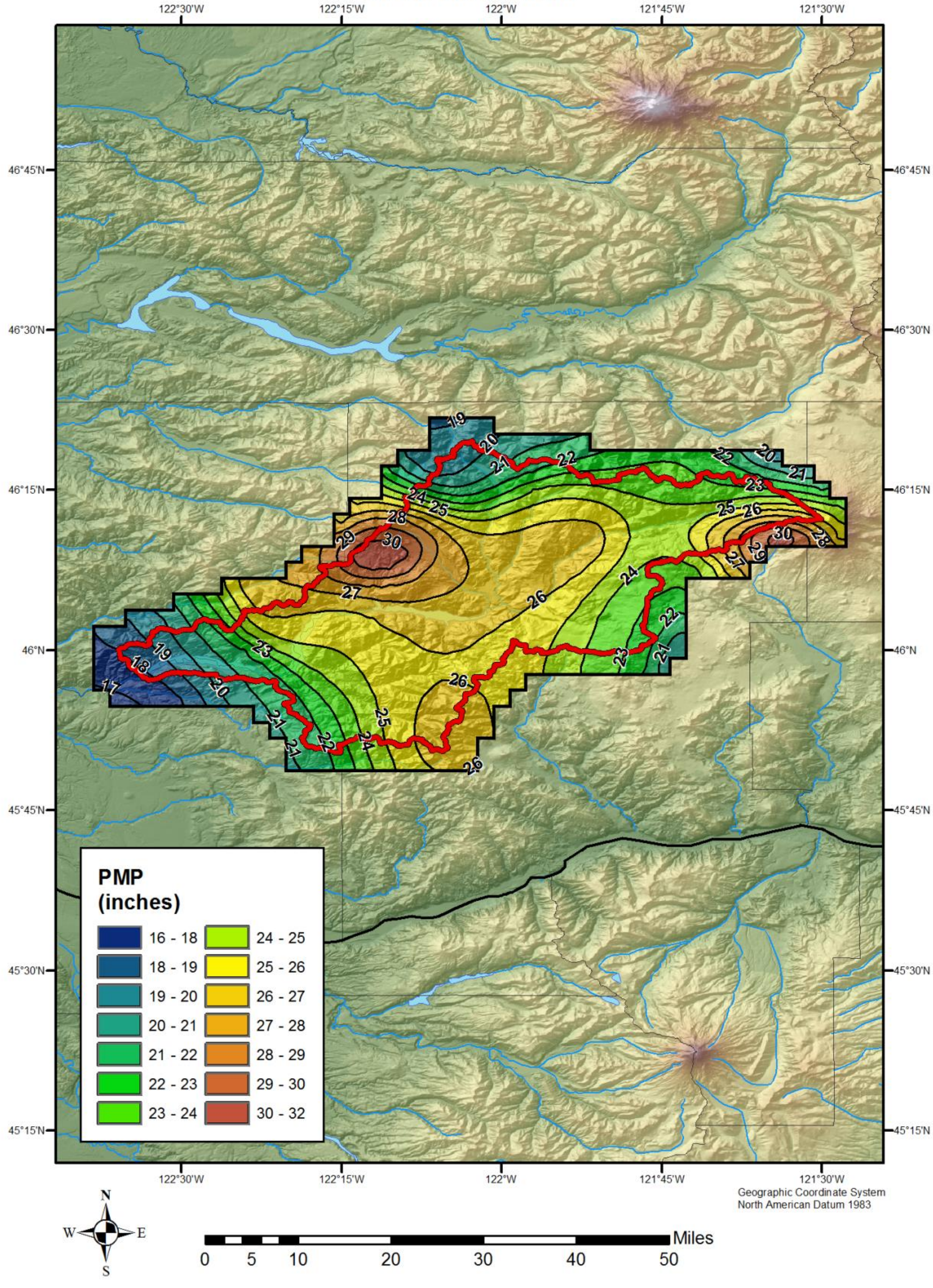
HMR-57 FAFP (from fig 7.2)
Lewis River Basin



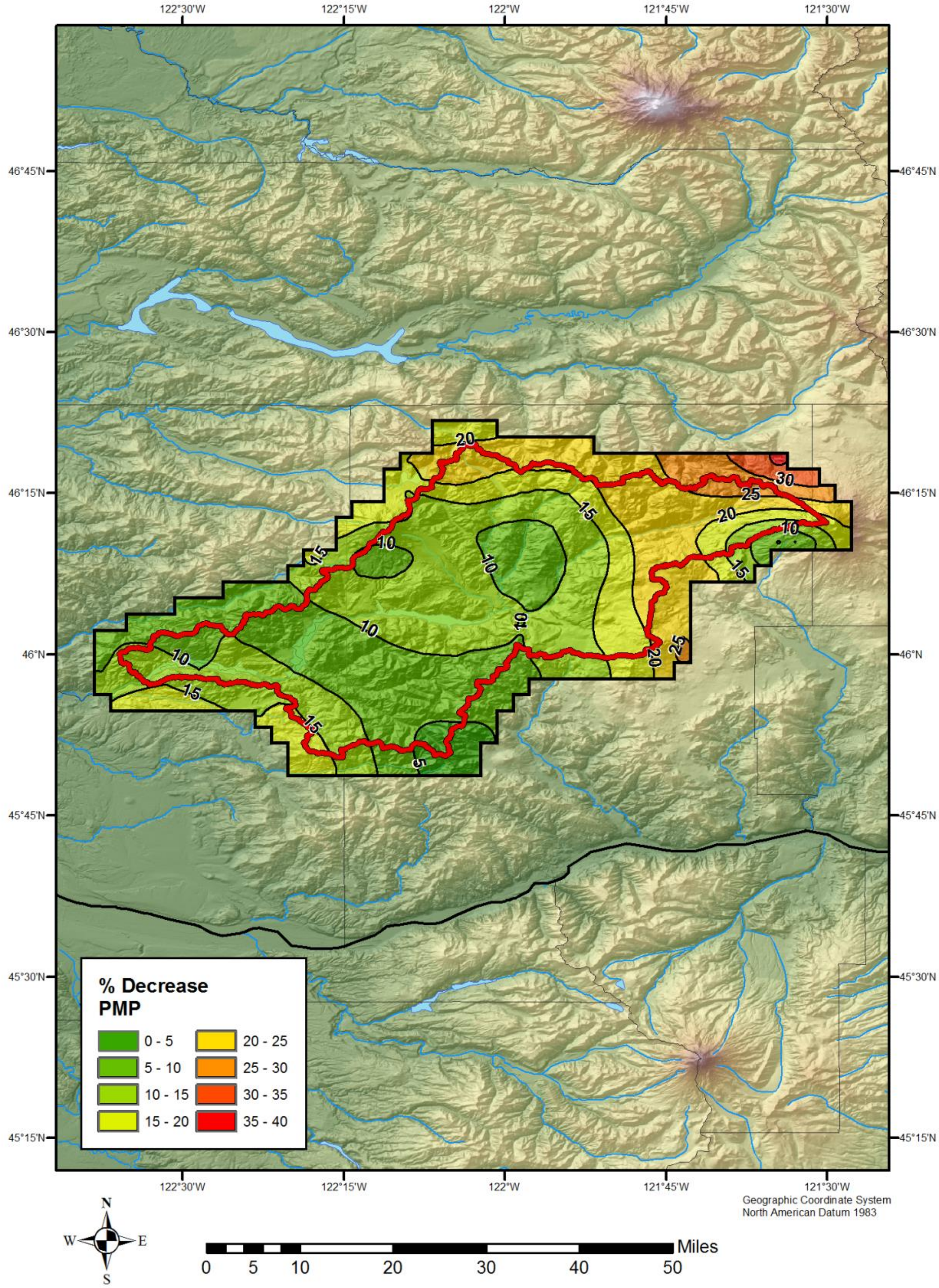
[HMR 57 FAFP] * [HMR 57 K]
Lewis River Basin



HMR-57 24-hour PMP
Lewis River Basin



Percent Decrease in HMR 57 24-hr PMP Values from HMR 57 (FAFP * K) Values
Lewis River Basin



The comparison between the computed PMP map and the HMR 57 PMP map also shows significant differences. Overall the computed PMP values are larger than the PMP values from

HMR 57. The differences range from about 7% to over 25% with the HMR 57 values being consistently smaller.

The reasons for these differences are not known. It appears that after the highly subjective SSM procedure is followed, significant changes are manually made to the SSM maps and to the resulting maps of PMP produced using the SSM maps. The conclusion is made that for the Lewis River drainage basin domain, the SSM maps published in HMR 57 cannot be objectively duplicated and using the HMR 57 maps of SSM parameters, the HMR 57 PMP values cannot be objective duplicated.

HMR 59 SSM Application

A similar exercise was completed in the HMR 59 domain in and around the Piru Creek region and the Piru Creek drainage basin in southern California was used as the domain to compare computed maps with HMR 59 maps. Again none of the HMR 59 maps used to compute PMP was available from HDSC. Example low resolution maps for T/C (Figure 6.4), M-factor (Figure 6.5), and the K factor (Figure 6.6) for southern California are included in HMR 59. Unfortunately, the example map for FAFP (Figure 6.3) was for northern California and no example map of C is included in HMR 59. Therefore comparisons of computed maps with HMR 59 maps are limited.

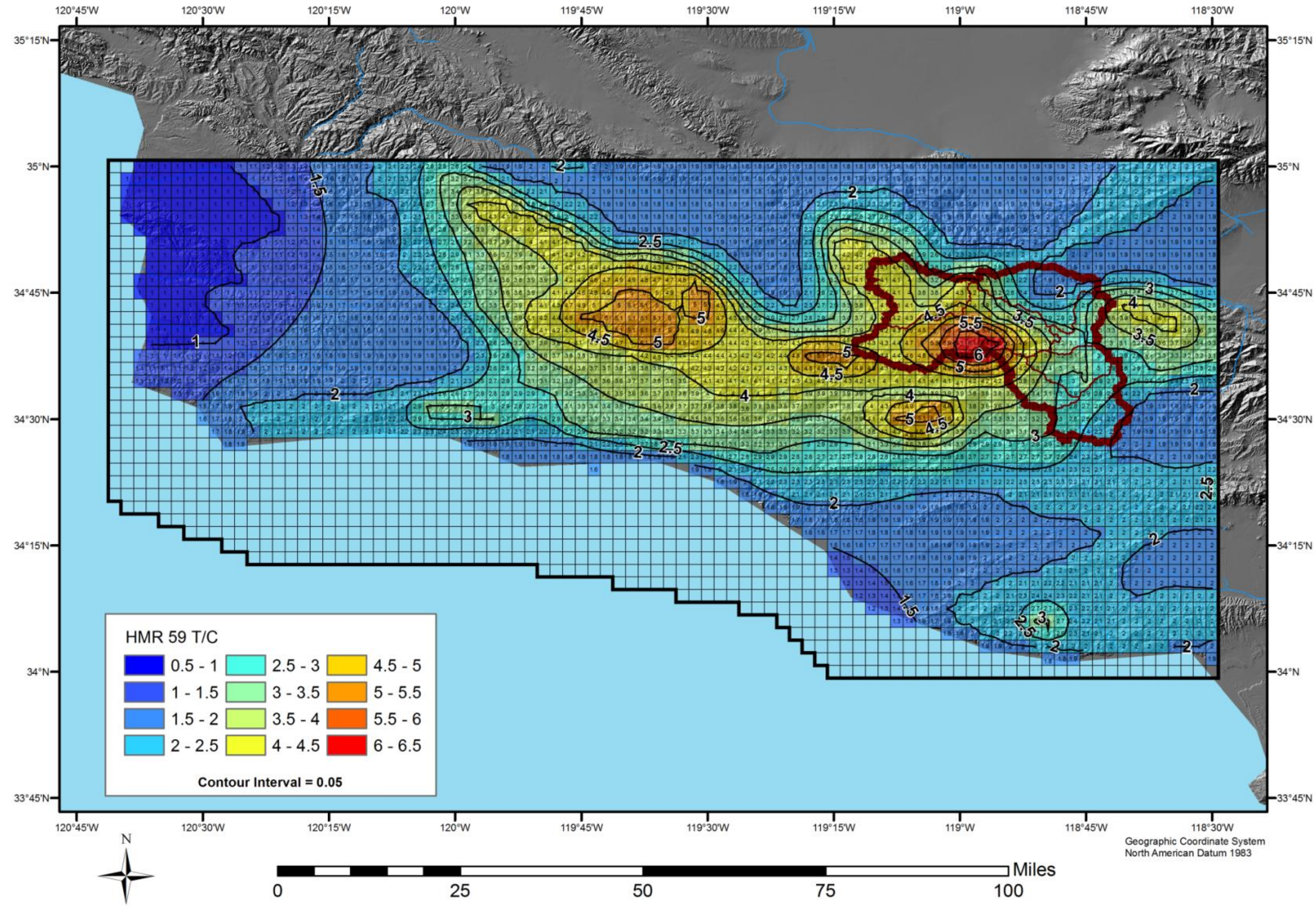
Using the example maps in HMR 59, maps for C and FAFP can be constructed. Unfortunately by constructing these maps, independent comparisons with HMR 59 maps is not possible. Figure 6.4 provides a map of T/C. By inverting the values on this map, a map of C/T was produced. That map is then multiplied by the NOAA Atlas 2 map (T) to produce a map of C. The M-factors for the Piru Creek drainage basin can be determined from Figure 6.5 and of course the PMP values for the Piru Creek domain are available from the HMR 59 PMP maps. Using Equation 6-5 from HMR 59,

$$K = M^2 (1 - (T/C)) + T/C$$

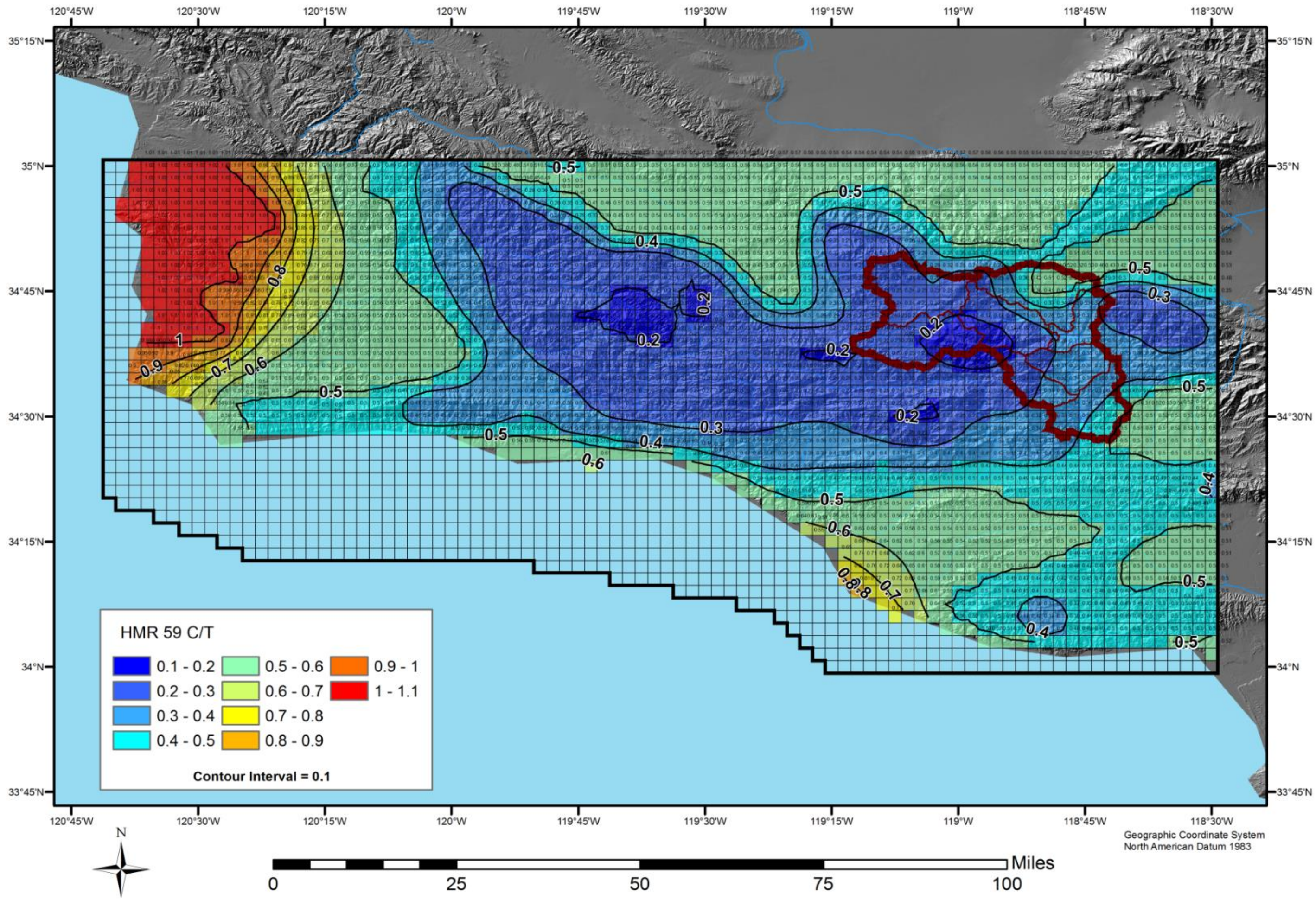
a computed map of K can be constructed.

HMR 59 maps and computed maps are shown below:

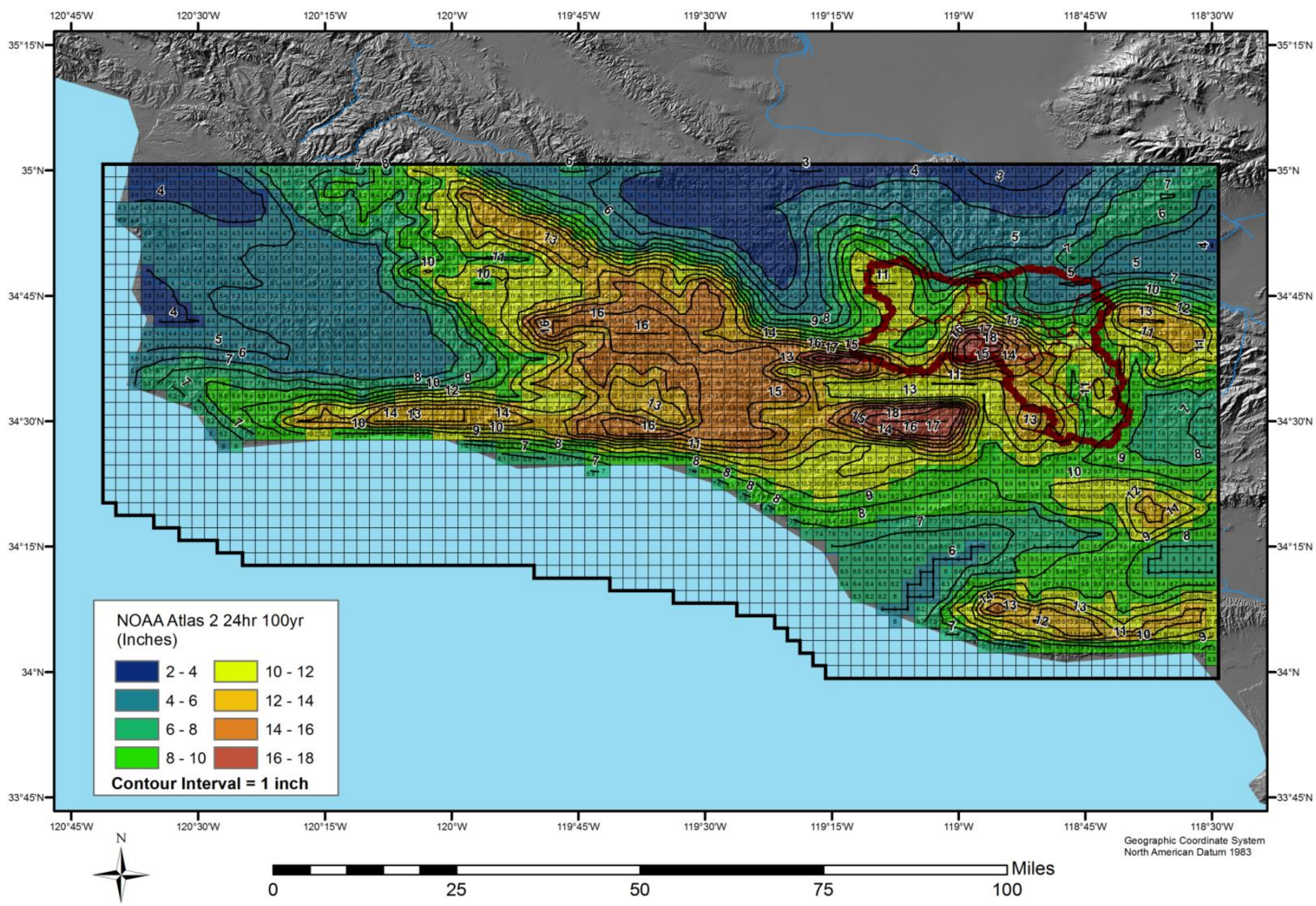
HMR 59 T/C


120°45'W
120°30'W
120°15'W
120°W
119°45'W
119°30'W
119°15'W
119°W
118°45'W
118°30'W
35°15'N
35°N
34°45'N
34°30'N
34°15'N
34°N
33°45'N
HMR 59 T/C
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
5 - 5.5
5.5 - 6
6 - 6.5
Contour Interval = 0.05
N
Miles
0
25
50
75
100
Geographic Coordinate System
North American Datum 1983

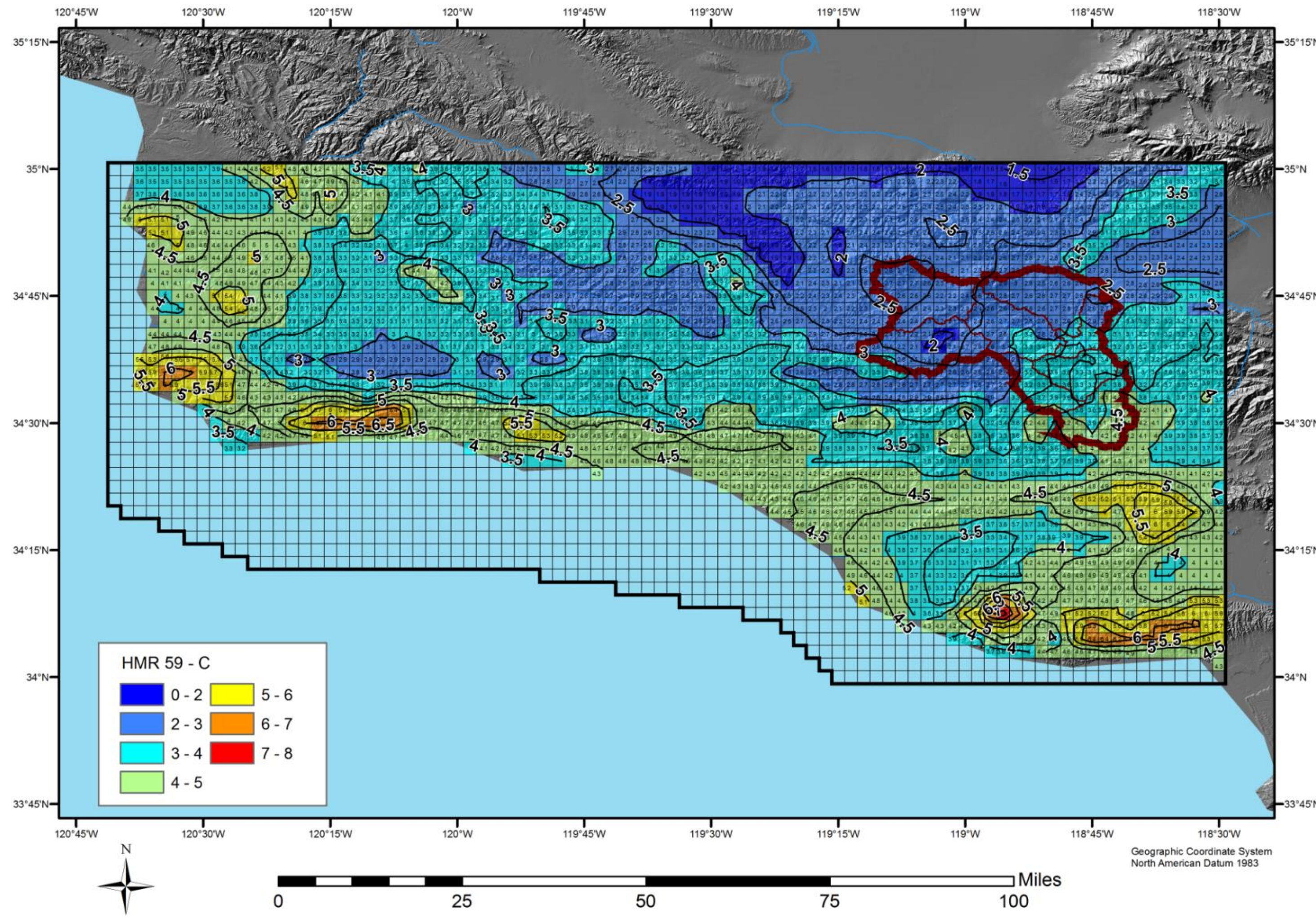
HMR 59 C/T


HMR 59 C/T
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 1.1
Contour Interval = 0.1
120°45'W
120°30'W
120°15'W
120°W
119°45'W
119°30'W
119°15'W
119°W
118°45'W
118°30'W
35°15'N
35°N
34°45'N
34°30'N
34°15'N
34°N
33°45'N
Geographic Coordinate System
North American Datum 1983
N
Miles
0
25
50
75
100

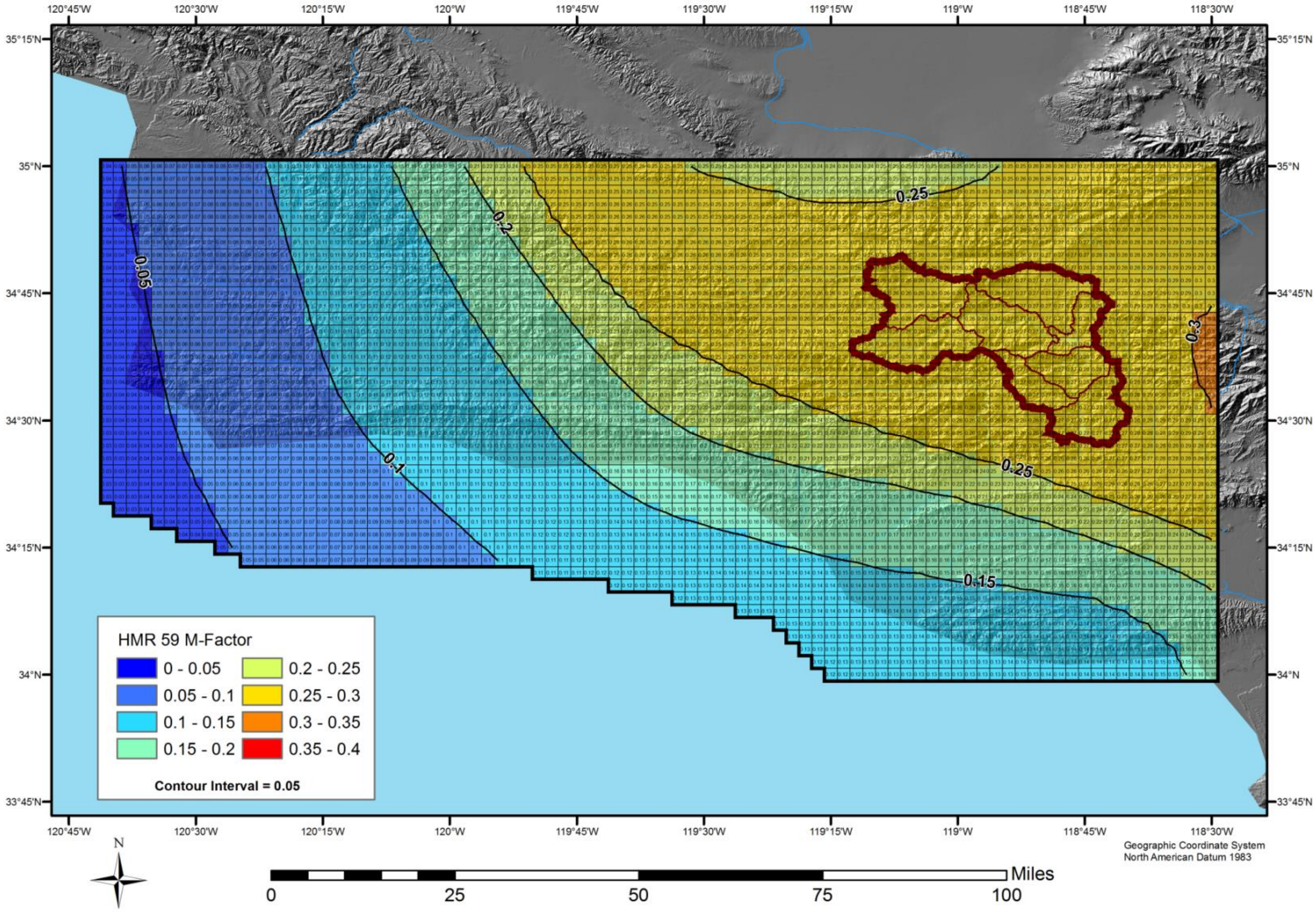
NOAA Atlas 2 - 24-hour 100-year Precipitation Frequency Estimates



HMR 59 100-year Convergence Component "C"

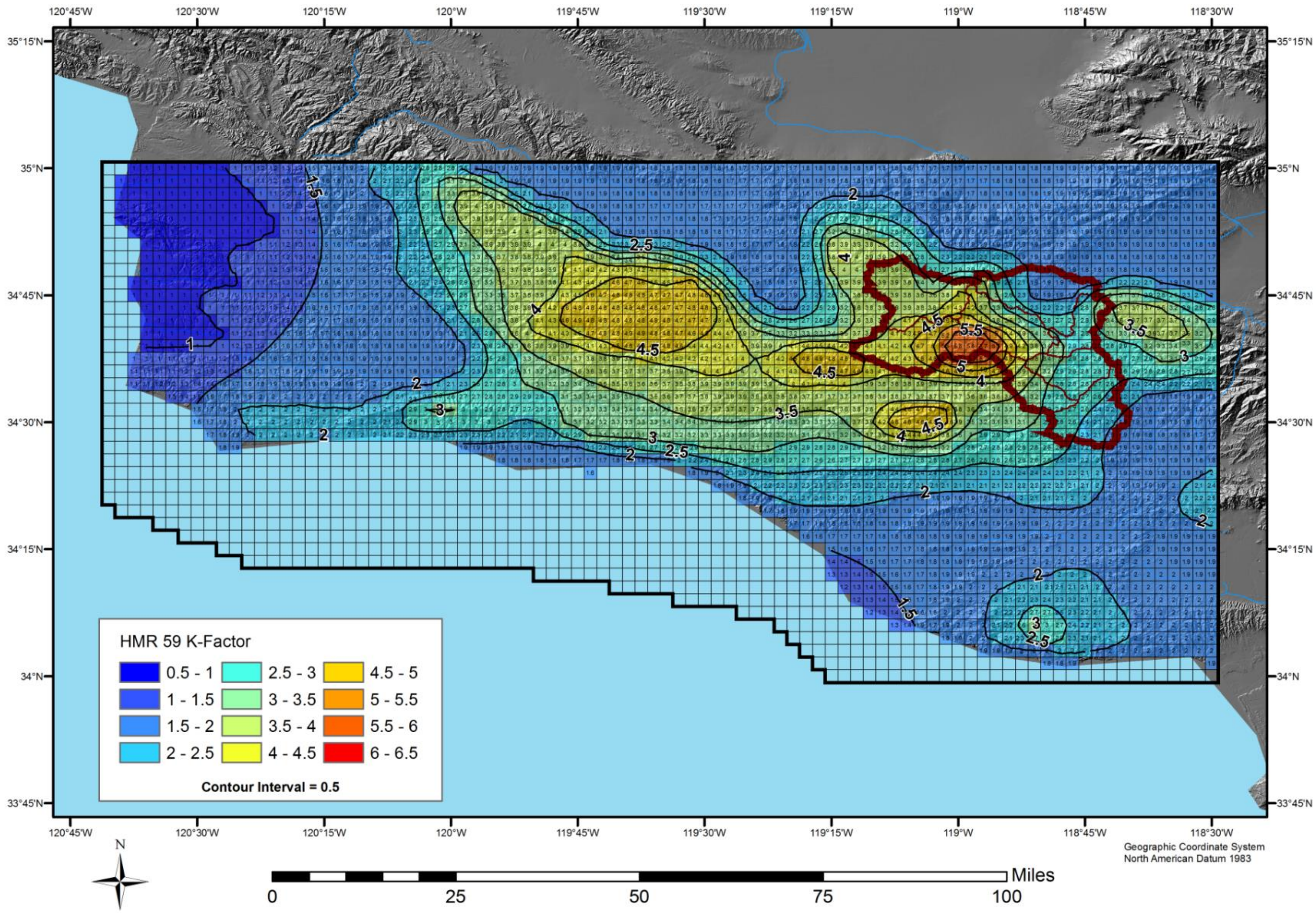


HMR 59 M-Factor

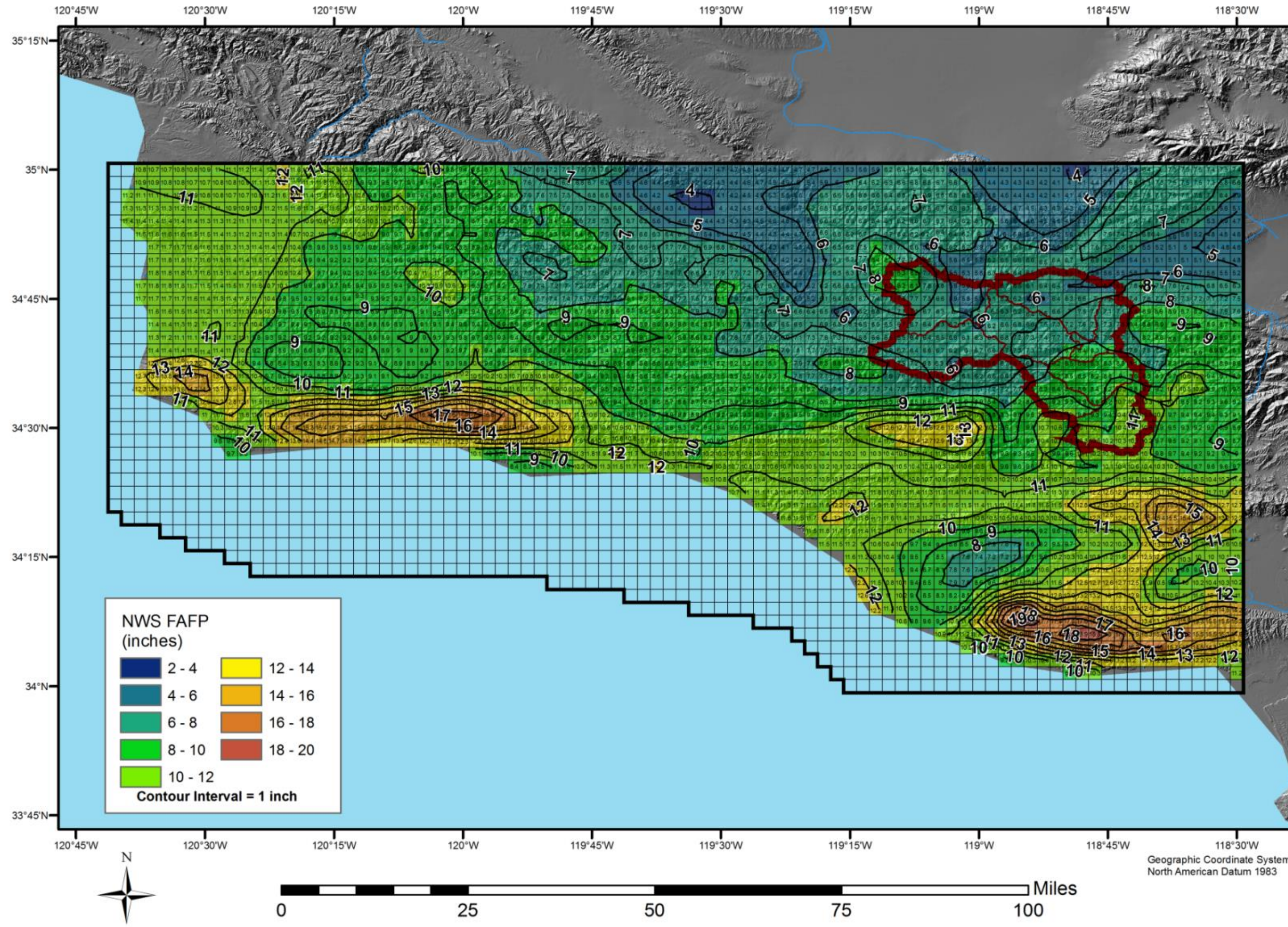


AWA Produced K-Factor

$K = M^2 (1- (T/C)) + (T/C)$



NWS FAFP = PMP ÷ K



There are several significant observations from these maps. The 100-year C map has been constructed using the HMR 59 T/C map and the NOAA Atlas 2 map for T. Since this map is the 100-year rainfall produced from storm dynamics without any influence from underlying terrain, the gradients of rainfall should be relatively smooth. The C map from HMR 57 shown previously shows a relatively smooth analysis. The constructed C map from the HMR 59 data shows areas of large gradients, especially for coastal regions. Since this map is subjectively constructed in the SSM procedure, the large gradient areas were manually introduced into the analysis for unknown reasons.

A similar observation is made for the constructed FAFP map. FAFP is the rainfall produced by a storm from atmospheric dynamics without the influence of the underlying topography. The FAFP map from HMR 57 shown previously shows a relatively smooth analysis. The large rainfall gradient areas in the FAFP map (HMR 59 Figure 6.3-see below) indicate that subjective adjustments were made to the FAFP map which introduced artificial gradients from the coast through the Central Valley and into the Sierra Nevada.

The K factor map in HMR 59 was compared to the computed K factor map using values for M, C and T from HMR 59 and from NOAA Atlas 2. The comparison resulted in good agreement for the region surrounding the Piru Creek drainage basin.

An interesting region to look at is the relatively non-orographic region between Lompoc and Santa Maria, approximately 120.5W and 34.75N. Both the HMR 59 K factor map and the computed K factor map identify values of M to be approximately 0 and K to be approximately 1. Hence for this area PMP is approximately equal to FAFP.

According to the discussions related to the SSM, the FAFP map is constructed using storm data for regions where K is approximately equal to 1, i.e. regions where orographic influences are at a minimum. This region seems appropriate for K to be approximately 1. The FAFP values in this region are between 11 inches and 12 inches, consistent with the HMR 59 PMP values of approximately 12 inches. However, the largest maximized storm rainfall from storms analyzed for the Piru Creek site-specific PMP study for this region is 4.5 inches from the January 1943 storm. It is not obvious how the largest maximized storm rainfall was increased from 4.5 inches to 11.5 inches resulting significantly larger FAFP values than those from maximized storm rainfall values. It can only be assumed that use of the various subject producers and decisions was applied. These subjective changes drastically affect the final PMP values developed for HMR 59 and of course or not reproducible.

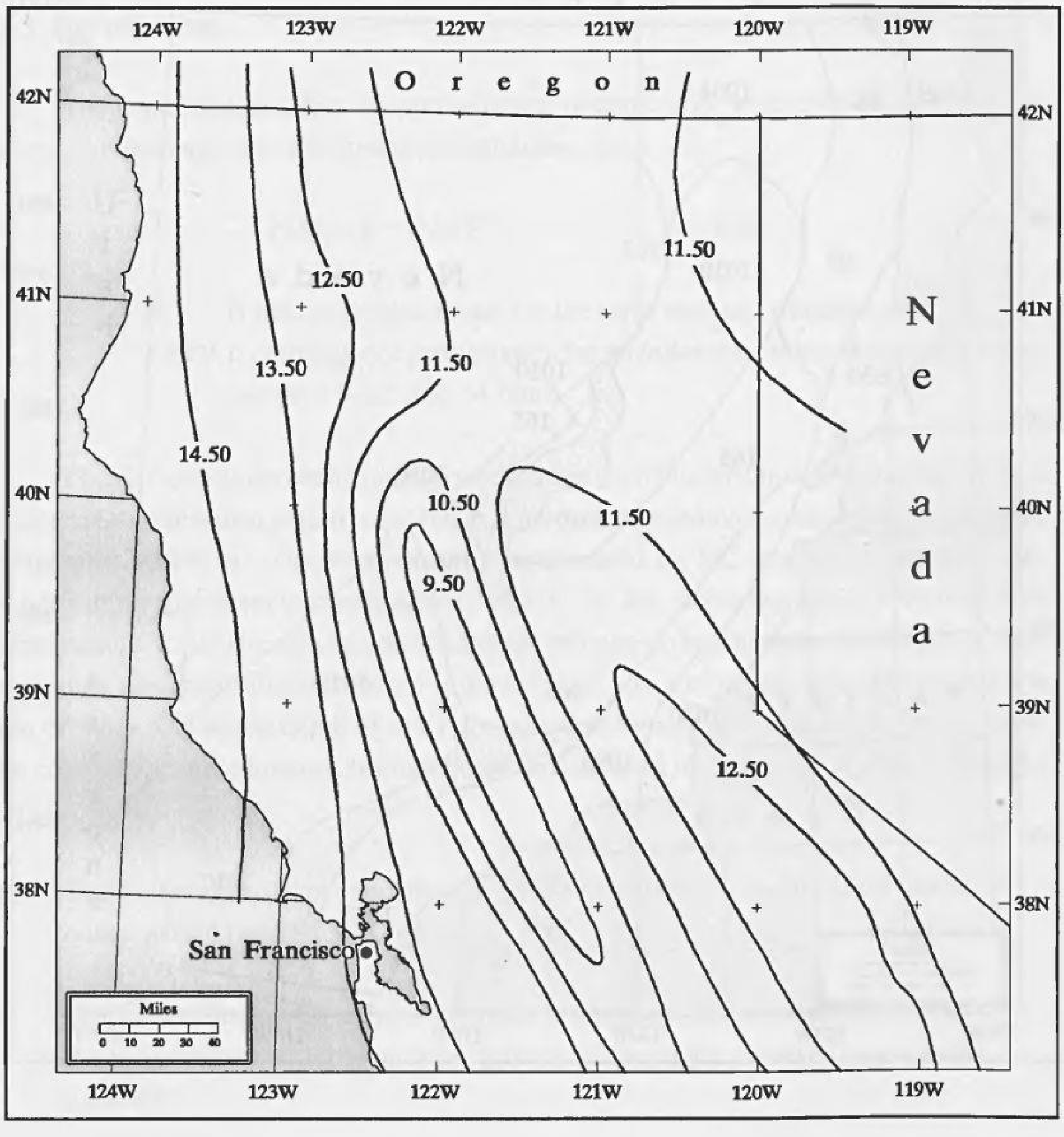


Figure 6.3. *Non-orographic PMP (FAFP) at 1000 mb (inches of rainfall).*

HMR 59 Figure 6.3 FAFP map for northern California

Summary

Discussions on the development of the SSM from HMR 55A have been provided which show the subjectivity associated with the SSM, especially with the development of FAFP and C in the computations. Example maps from HMR 57 and HMR 59 have been compared with computed maps using information in the HMRs. Significant differences between the HMR maps and the computed maps have been shown for HMR 57 in the K factor maps and the PMP maps. For HMR 59, example maps were not available for all parameters so independent comparisons could not be made. However, the FAFP values for the region where K is approximately equal to one shows that the FAFP values for that region are significantly larger than available storm data indicate. Additionally there are large rainfall gradient areas in the HMR 59 FAFP and C maps that are not generally expected and do not show up in the HMR 57 FAFP and C maps. Because of this, serious questions are raised as to the validity of the treatment of orographic influence on rainfall in HMRs 55A, 57, and 59 and the resulting PMP values. Specifically, any values for PMP given in those documents in areas that are orographically influenced should at the very least be re-evaluated to verify their accuracy.

Appendix F

Short Storm List Analysis Data Used For PMP Development

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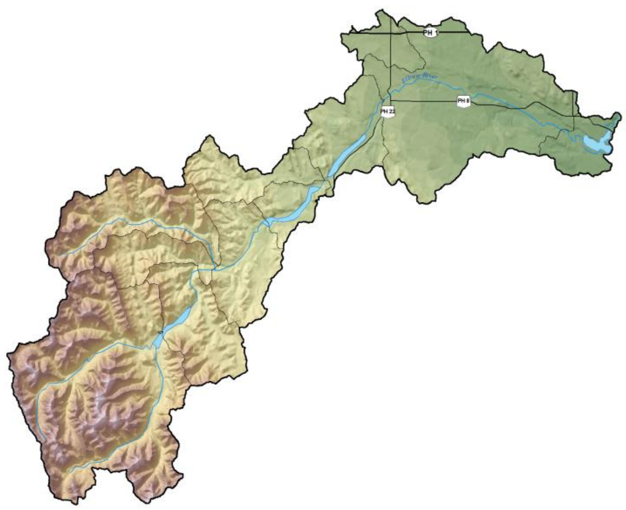
http://www.appliedweatherassociates.com

Site-Specific Probable Maximum Precipitation Study for the Elbow River Basin-Springbank Off-Stream Storage Project

Appendix F-Storm Analysis Data



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July 2015

Notice

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Conversion Factors

millimeters	x	0.03937	=	inches
meters	x	3.28083	=	feet
kilometers	x	0.6215	=	miles
square kilometers	x	0.38610	=	square miles

List of Storms Analyzed

Storm files were made for the 22 storms used to derive the PMP values. This includes 6 local storms and 16 general storms (Table F.1). Storm files and SPAS analysis results for each of these storms are contained in this appendix. All storm data and values provided in this Appendix are in English units, as that was the native data set during the original development of each data set. Please utilize the conversion information above if needed. Note, in table F.1 and in the Table of Contents in this appendix, only the location name associated with the highest SPAS analyzed rainfall is listed. However, for many of the SPAS storm analyses, more than one SPAS DAD zones were analyzed. These DAD zone delineations, if any, are displayed on the total storm isohyetal maps provided in this Appendix. Note, daily synoptic weather maps are provided for a period starting a few days before each storm and continuing to a few days after each storm. Daily weather maps covering the period from 1871 through 2002 are from the U.S. Daily Weather Maps Archive, NOAA Climate Database Modernization Program (CDMP), National Climatic Data Center, Asheville, NC, and the NOAA Central Library Data Imaging Project. Daily synoptic weather maps from 2002 through 2014 are from the NOAA Weather Prediction Center Daily Weather Maps web page, http://www.hpc.ncep.noaa.gov/dailywxmap/index.html.

Table F.1 Springbank PMP Short Storm List

Storm Name	State	Latitude in °	Longitude in °	Year	Month	Day	Total Rainfall (mm)	Elevation (meters)	Storm Type
WARRICK	MT	48.0791	-109.7041	1906	6	5	348	1260	General
SAVAGETON	WY	43.8458	-105.8042	1923	9	27	446	1460	General
BASSANO	AB	50.4375	-114.3042	1923	5	29	167	1340	General
GIBSON DAM	MT	48.3542	-113.3708	1964	6	6	487	2440	General
PEKISKO	AB	50.2375	-114.2708	1969	6	19	257	1480	General
PELICAN MOUNTAIN	AB	55.5542	-113.6625	1970	6	26	286	830	General
NOSE MOUNTAIN	AB	54.5375	-119.5542	1972	6	9	207	1490	General
VETERAN	AB	51.8625	-110.4292	1973	6	13	243	670	General
WATERTON RED ROCK	AB	49.0875	-114.0458	1975	6	14	367	2390	General
NOSE MOUNTAIN	AB	54.5125	-120.0292	1982	7	12	188	1370	General
PARKMAN	SK	49.7020	-101.8958	1985	8	3	400	630	General
SIMONETTE LO	AB	54.2375	-118.4042	1987	7	30	334	1280	General
SPIONKOP CREEK	AB	49.1708	-114.1625	1995	6	4	368	1630	General
CALGARY	AB	50.4350	-114.3850	2005	6	1	325	1480	General
CRYSTAL LAKE	MT	45.3150	-107.1750	2011	5	19	232	1520	General
CALGARY	AB	50.6350	-114.8550	2013	6	19	350	2590	General
SPRINGBROOK	MT	47.3642	-105.7778	1921	6	17	386	820	Local
PEKISKO	AB	50.7792	-112.5708	1923	5	29	196	820	Local
BUFFALO GAP	SK	49.1146	-105.2896	1961	5	30	267	790	Local
GLEN ULLIN	ND	47.3041	-101.3875	1966	6	24	327	530	Local
RAPID CITY	SD	43.8875	-103.4042	1972	6	8	401	1440	Local
VANGUARD	SK	49.9218	-107.2100	2000	7	3	388	760	Local

Table of Contents

General Storms

Gibson Dam, MT

June 6-10, 1964

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1211

General Storm Location: Gibson Dam and Summit, Montana (a.k.a. HMR 57 #155)

Storm Dates: June 6-9, 1964 (6/6/1964 0600 UTC – 6/10/1964 0500 – 96-hours)

Event: Mid-latitude cyclone/upslope

DAD Zone 1

Latitude: 48.35416°

Longitude: -113.37083°

Max. Grid Rainfall Amount: 487mm

Max. Observed Rainfall Amount: 393.7mm at Summit, MT (Marias Pass)

Number of Stations: 510 (87 daily, 26 hourly, 1 hourly estimated, 1 hourly estimated pseudo, 5 hourly pseudos, 387 supplemental and 3 supplemental estimated)

SPAS Version: 8.5

Base Map Used: PRISM mean 1971-2000 June precipitation

Spatial resolution: 30 seconds (degree: minute: second, WGS84, ~ 0.2 mi^2, 0.52 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: Over most of the storm analysis domain, abundant gauge data and well positioned hourly rain gauges provided better than average confidence in the results. At the time this analysis was completed, no hourly recording stations were available in southern Alberta, therefore we have lower confidence in the temporal distribution of precipitation across the northern portion of the analysis domain. And although we generally had abundant gauge data, the wettest mountain locations were not well covered by observations, therefore the maximum storm precipitation centers are driven by the basemap (PRISM mean 1971-2000 June precipitation).

Storm Name:	**SPAS 1211 Gibson Dam and Summit, MT**	**Storm Adjustment Summary**
Storm Date:	**6/6-9/1964**	
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **22-Jun**

	Lat	Long
Storm Center Location	**48.35 N**	**113.37 W**
Storm Rep Dew Point Location	**48.40 N**	**106.52 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**E @ 507**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**2,438**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**18.9 °C**	with total precipitable water above sea level of		**47**	millimeters.
The in-place maximum dew point is	**22.8 °C**	with total precipitable water above sea level of		**66**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**2,438**	which subtracts	**29**	millimeters of precipitable water at	**18.9 °C**
The in-place storm elevation is	**2,438**	which subtracts	**37**	millimeters of precipitable water at	**22.8 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.30**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Used 24hr average from KGSG. In-place max faxtor calculated at 1.54, held to 1.30 based on average IPMF from similar events.

Observed Storm Depth-Area-Duration (millimeters)

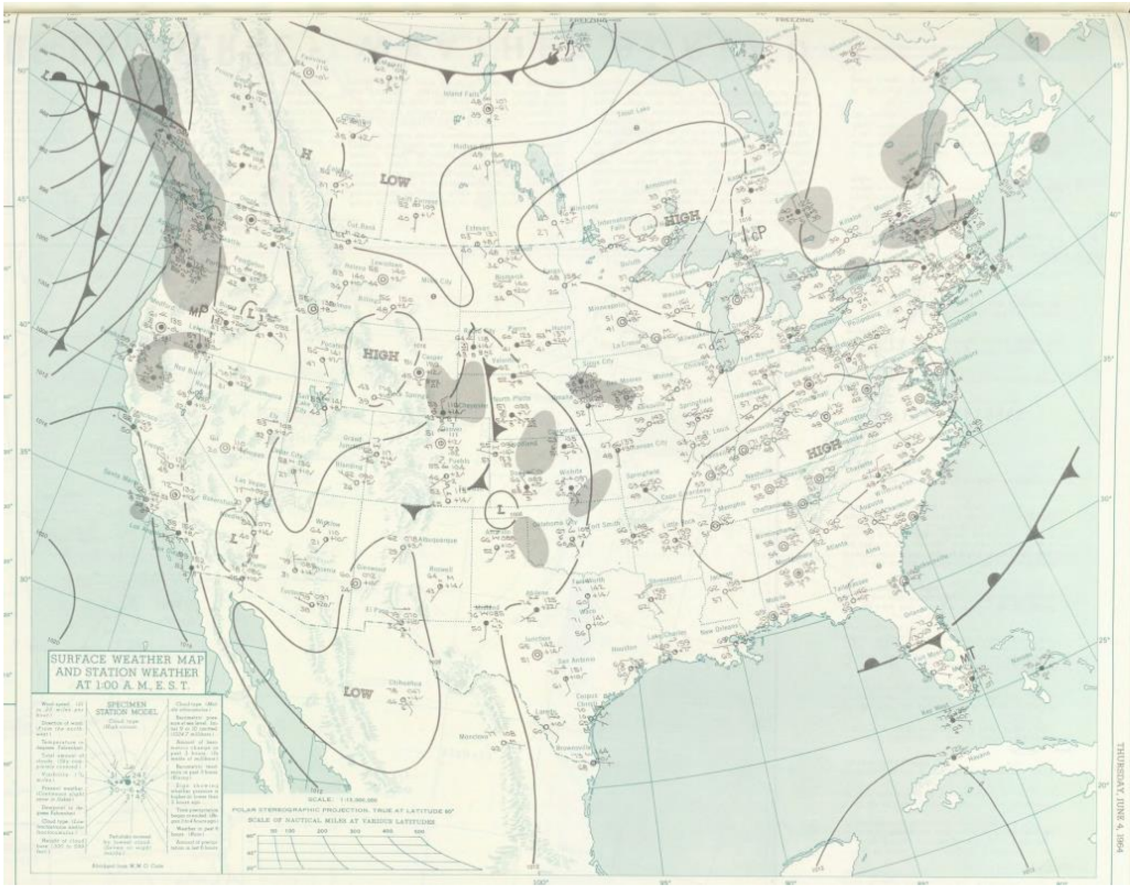
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**30**	**61**	**89**			**173**	**305**	**437**	**483**
26 km^2 (10 mi^2)	**28**	**58**	**84**			**163**	**290**	**422**	**467**
259 km^2 (100 mi^2)	**25**	**53**	**76**			**147**	**264**	**386**	**432**
518 km^2 (200 mi^2)	**25**	**51**	**74**			**142**	**251**	**371**	**414**
1,295 km^2 (500 mi^2)	**23**	**46**	**69**			**124**	**229**	**335**	**381**
2,590 km^2 (1,00 mi^2)	**20**	**41**	**61**			**114**	**208**	**307**	**343**
5,180 km^2 (2,000 mi^2)	**18**	**38**	**53**			**102**	**185**	**274**	**310**
12.950 km^2 (5000 mi^2)	**15**	**28**	**43**			**8**	**145**	**226**	**259**
25,900 km^2 (10,000 mi^2)	**13**	**23**	**33**			**61**	**112**	**175**	**198**
51,800 km^2 (20,000 mi^2)	**8**	**15**	**25**			**43**	**74**	**117**	**150**

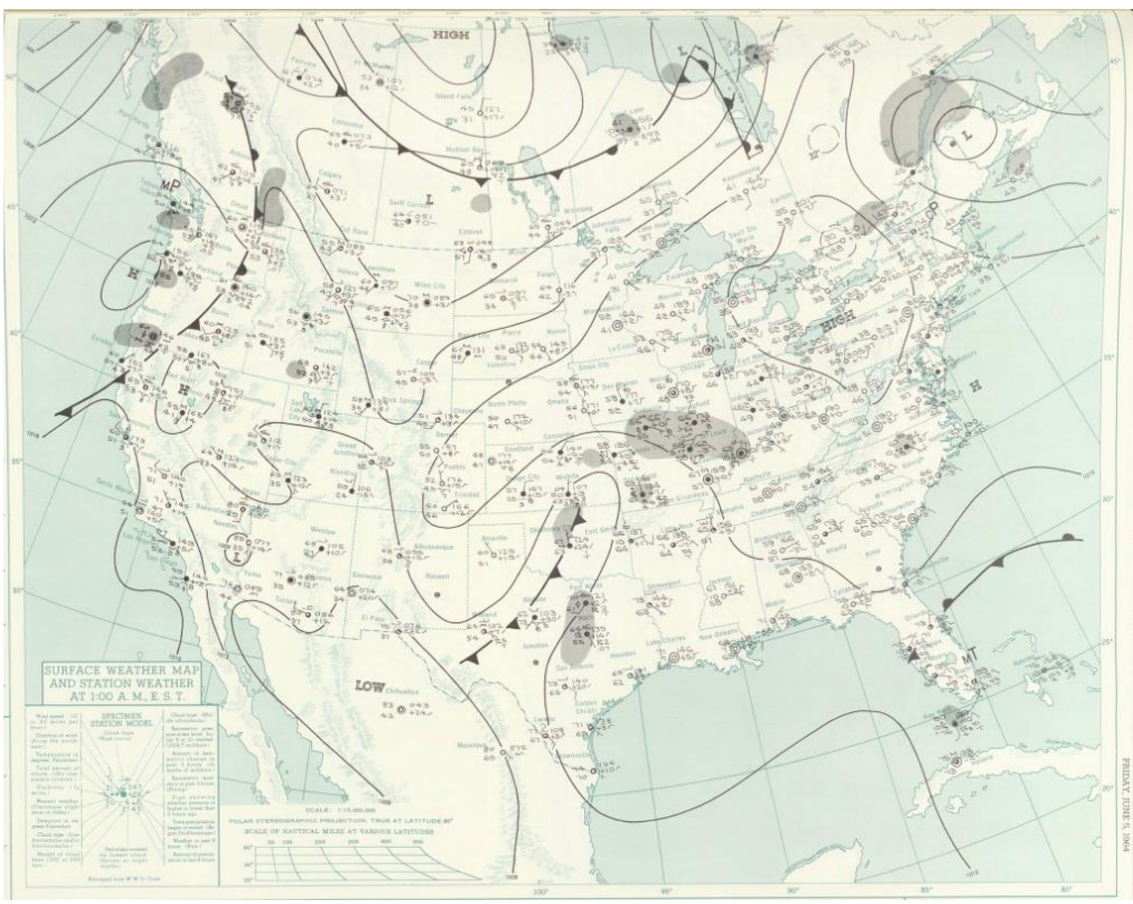
Adjusted Storm Depth-Area-Duration (millimeters)

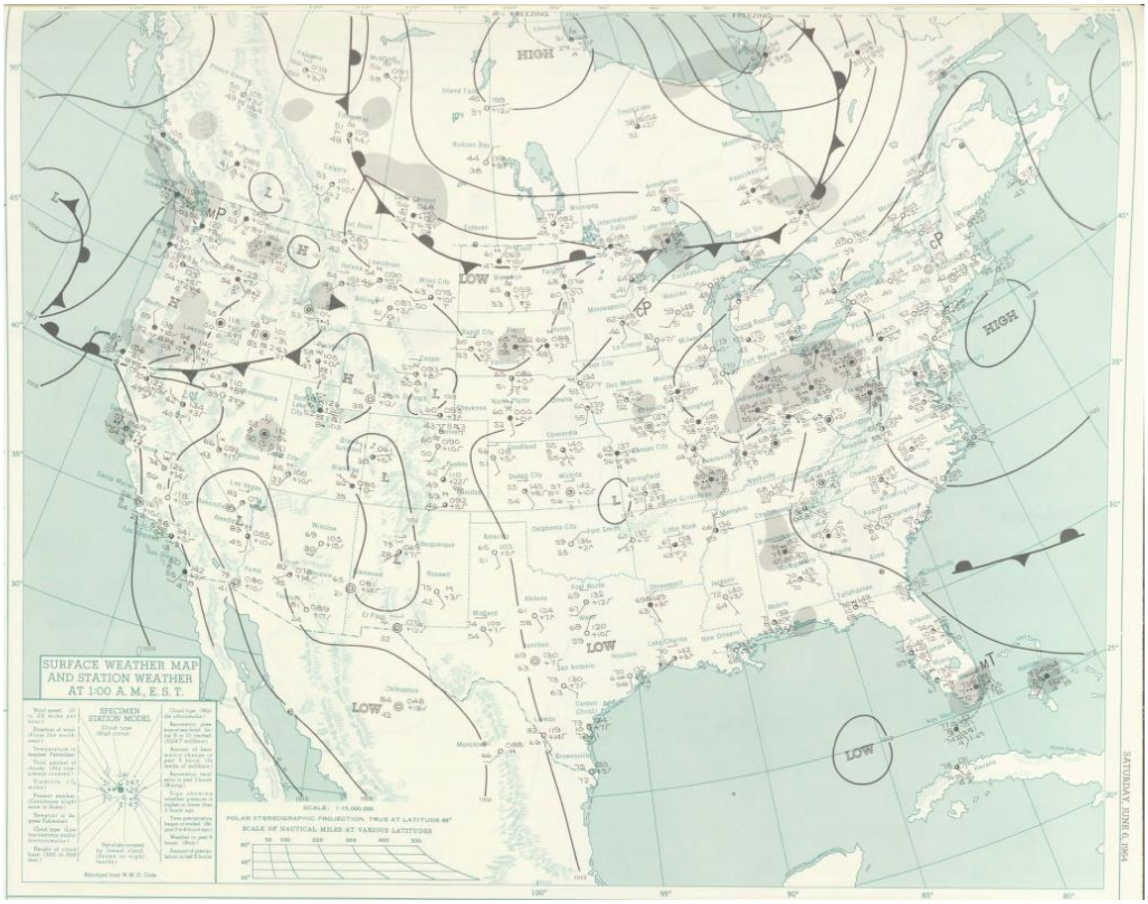
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***	**N/A***	**N/A***			**N/A***	**N/A***	**N/A***	**N/A***

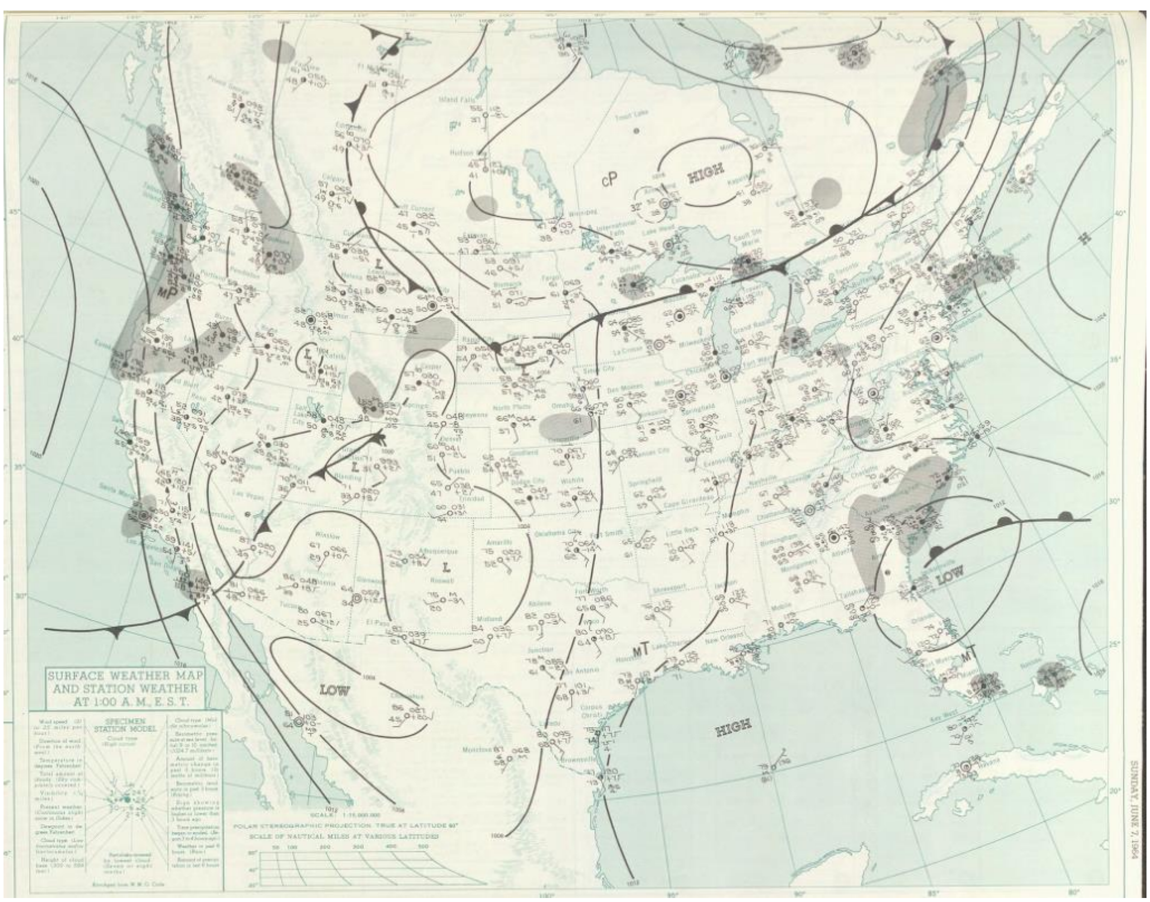
Storm or Storm Center Name	**SPAS 1211 Gibson Dam and Summit, MT**	
Storm Date(s)	6/6-9/1964	
Storm Type	Synoptic	
Storm Location	48.35 N	113.37 W
Storm Center Elevation	2,438	meters
Precipitation Total & Duration	487	Millimeters 96-hours
Storm Representative Dew Point	18.9 °C	24
Storm Representative Dew Point Location	48.40 N	106.52 W
Maximum Dew Point	22.8 °C	
Moisture Inflow Vector	E @ 507	kilometers
In-place Maximization Factor	**1.30**	
Temporal Transposition (Date)	22-Jun	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

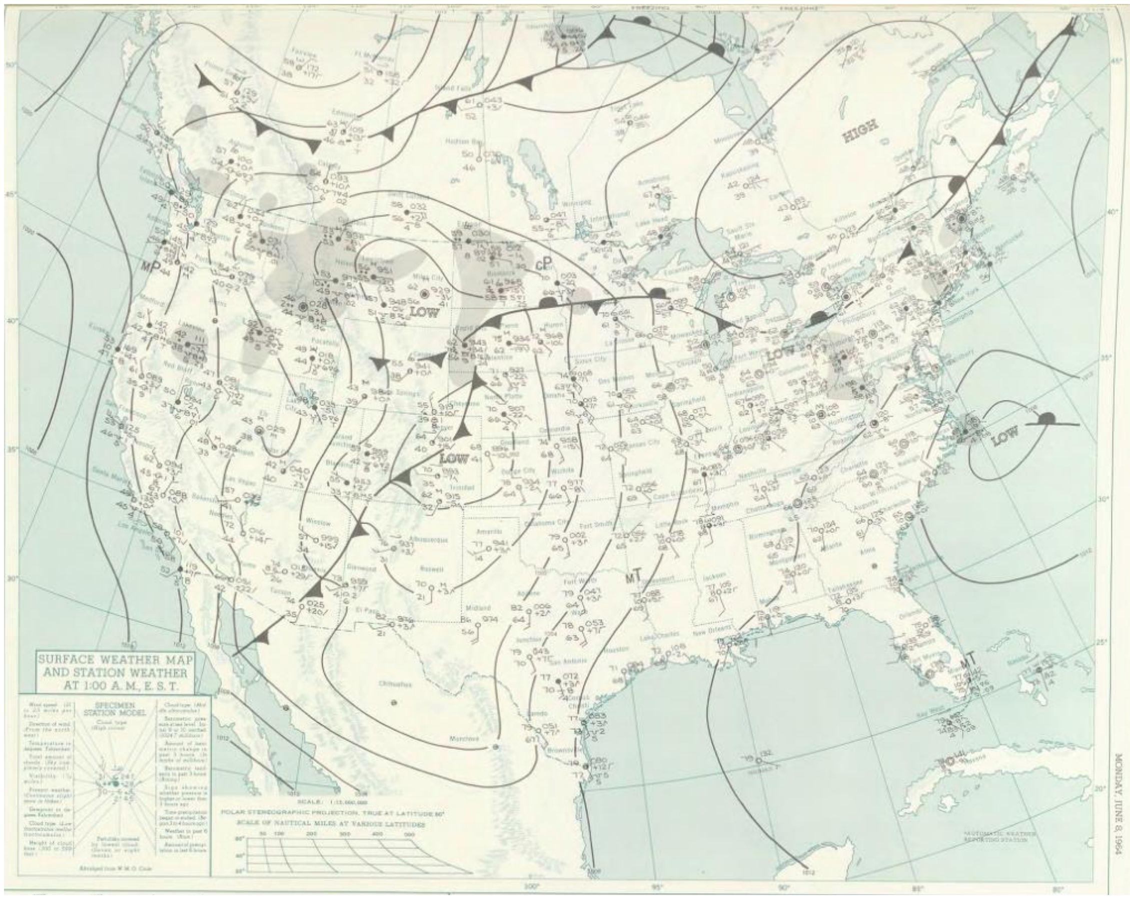
*Variable dependent on transposition location

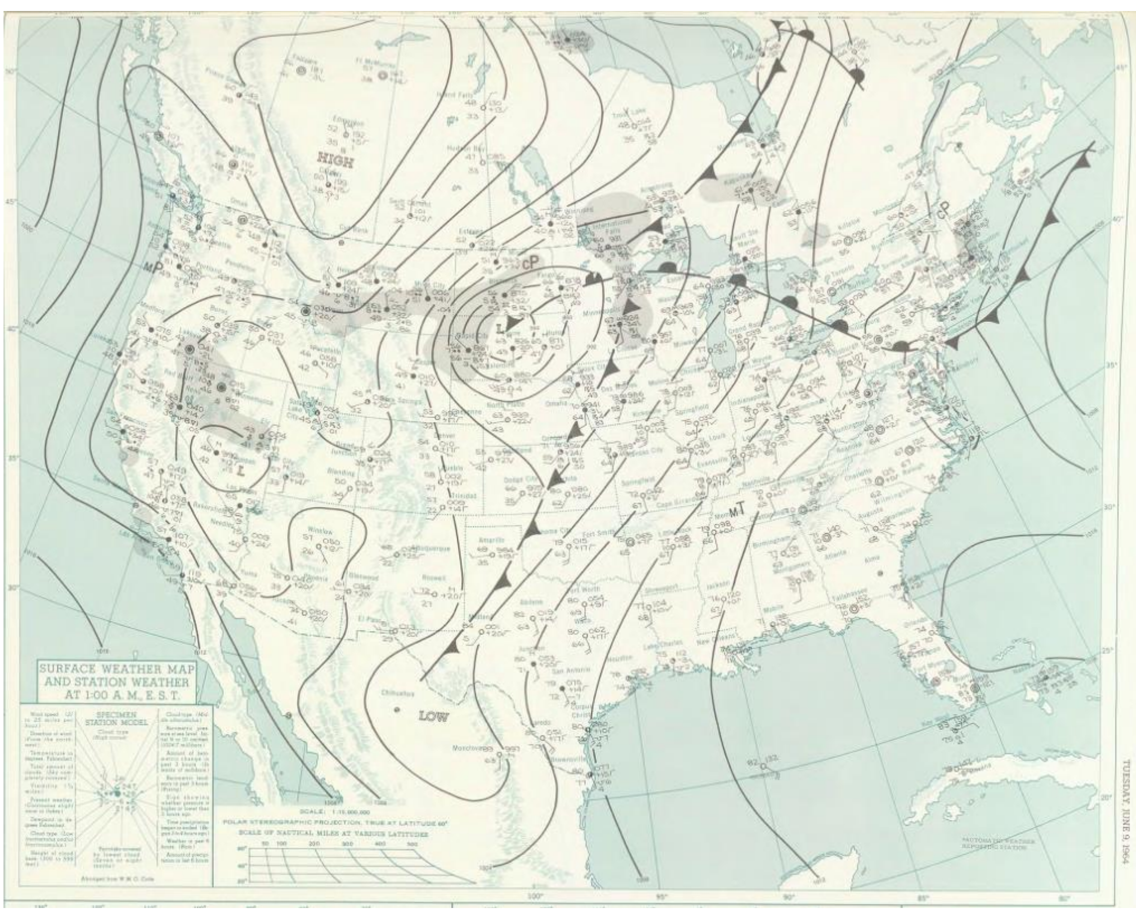

SURFACE WEATHER MAP
AND STATION WEATHER
AT 1:00 A.M., E.S.T.
HIGH
LOW
POLAR STEREOGRAPHIC PROJECTION, TRUE AT LATITUDE 60°
SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES
THURSDAY, JUNE 4, 1964

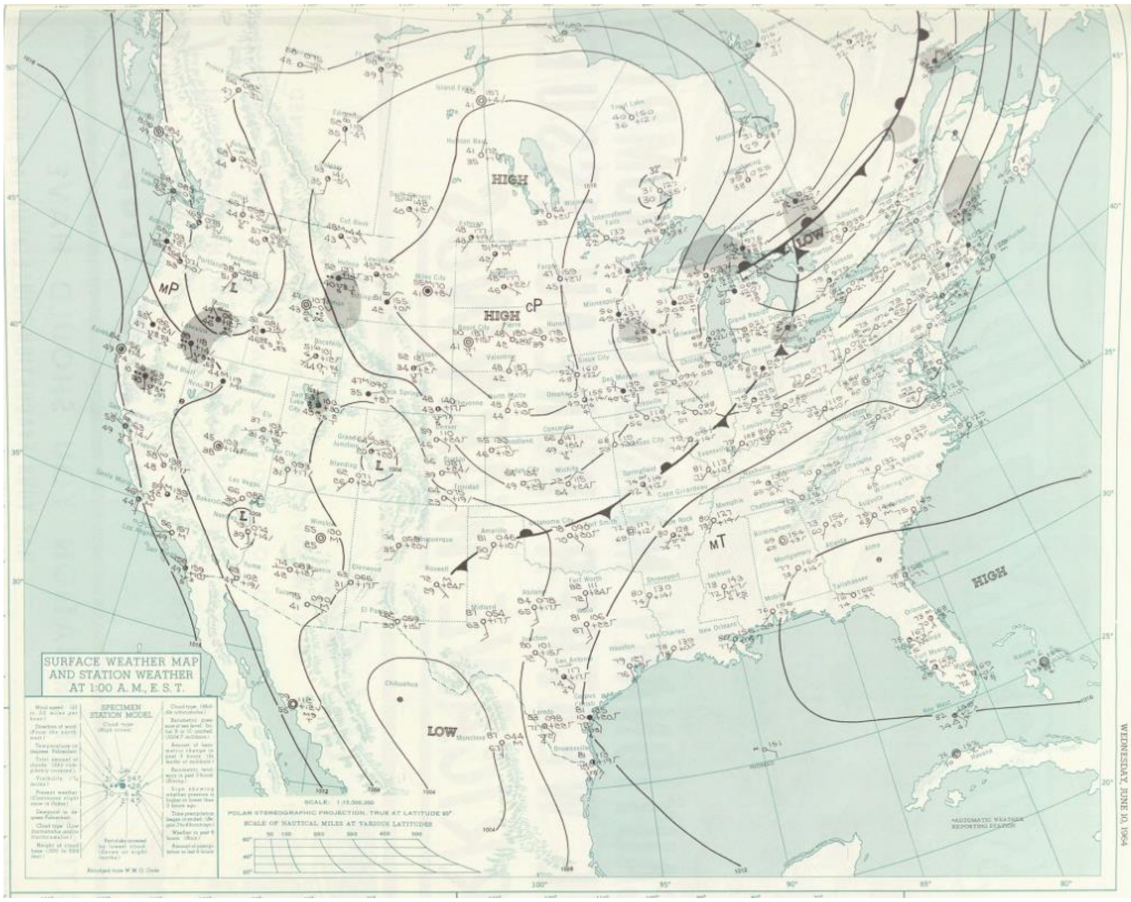

SURFACE WEATHER MAP
AND STATION WEATHER
AT 1:00 A.M., E.S.T.
HIGH
LOW
POLAR STEREOGRAPHIC PROJECTION, TRUE AT LATITUDE 60°
SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES
FRIDAY, JUNE 5, 1964

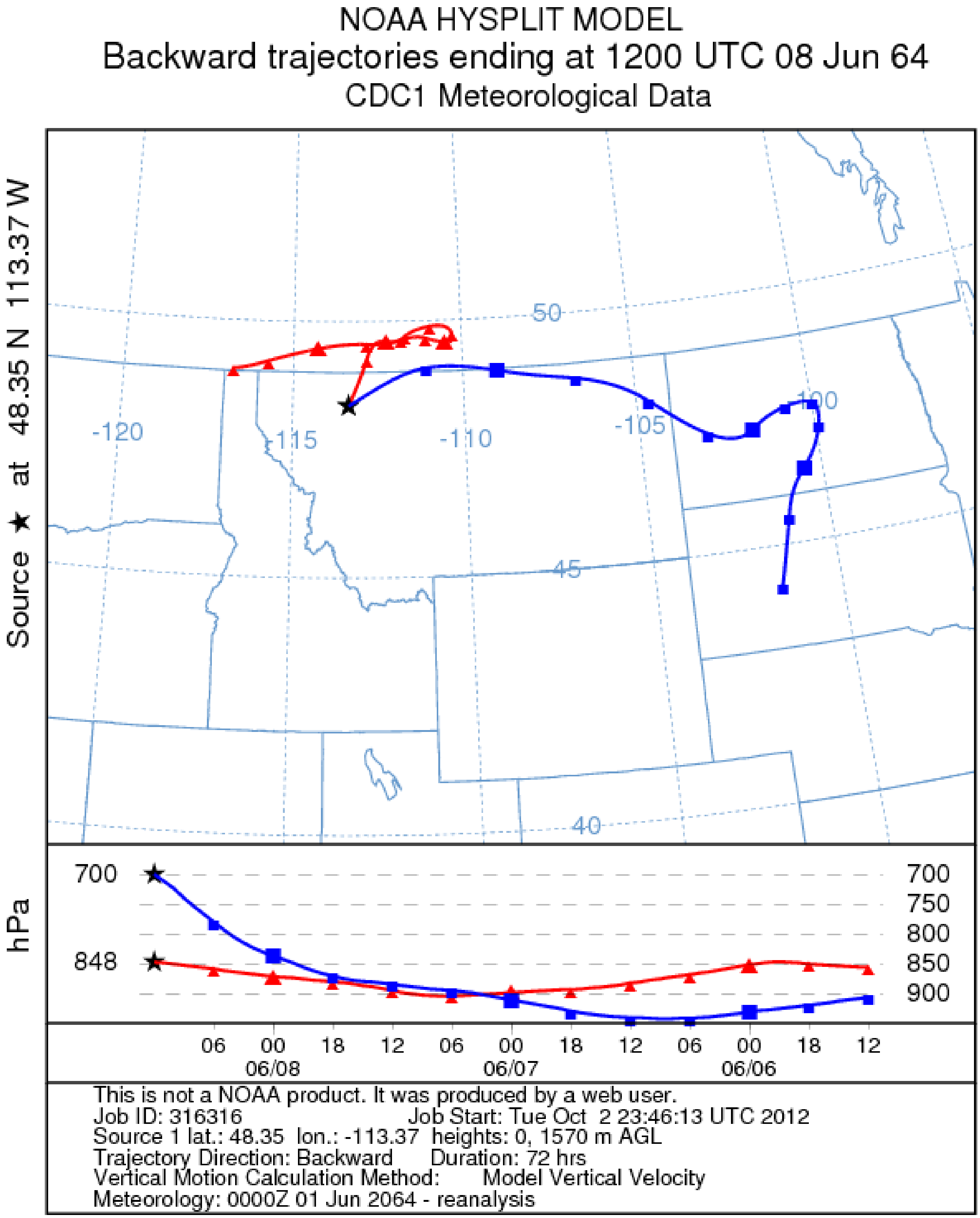

SURFACE WEATHER MAP
AND STATION WEATHER
AT 1:00 A.M., E.S.T.
SPECIMEN
STATION MODEL
HIGH
LOW
LOW
LOW
LOW
HIGH
SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES
SATURDAY, JUNE 6, 1964

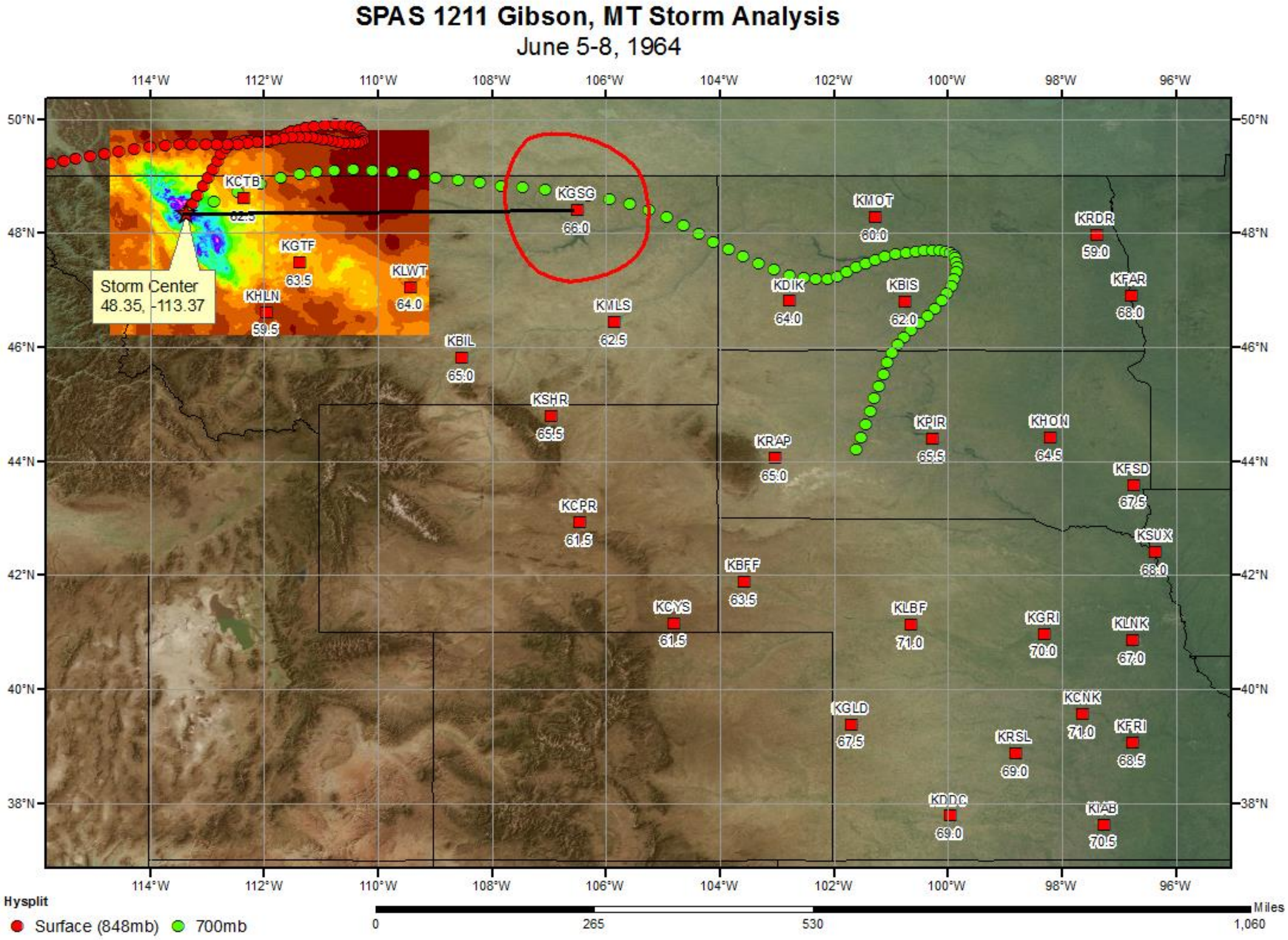

SURFACE WEATHER MAP
AND STATION WEATHER
AT 1:00 A.M., E.S.T.
SPECIMEN
STATION MODEL
HIGH
HIGH
LOW
LOW
SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES
SUNDAY, JUNE 7, 1964


SURFACE WEATHER MAP
AND STATION WEATHER
AT 1:00 A.M., E.S.T.
MONDAY, JUNE 8, 1964
HIGH
LOW
LOW
LOW
LOW
mP
cP
mT
mT

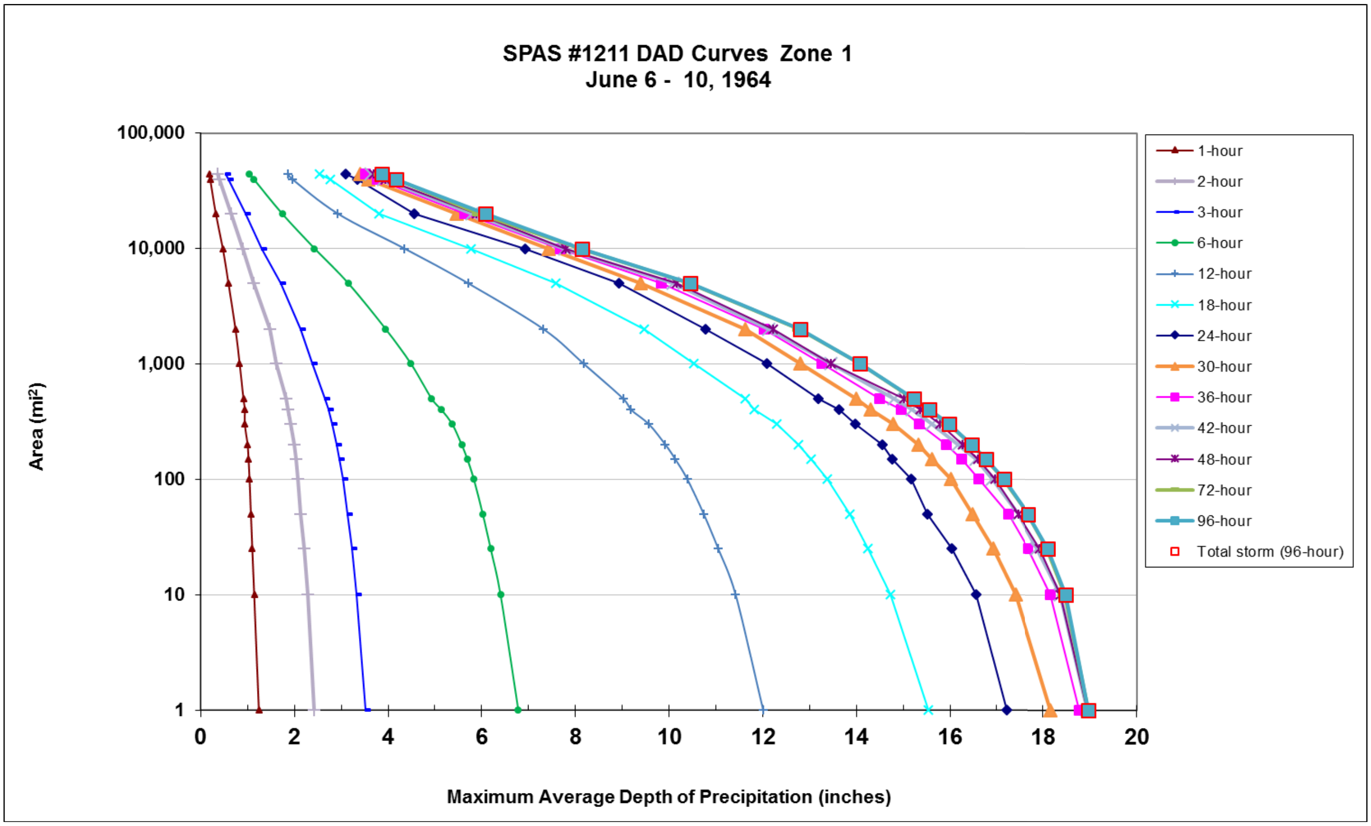

SURFACE WEATHER MAP
AND STATION WEATHER
AT 1:00 A.M., E.S.T.
TUESDAY, JUNE 9, 1964
HIGH
LOW
mP
cP
cP
mT

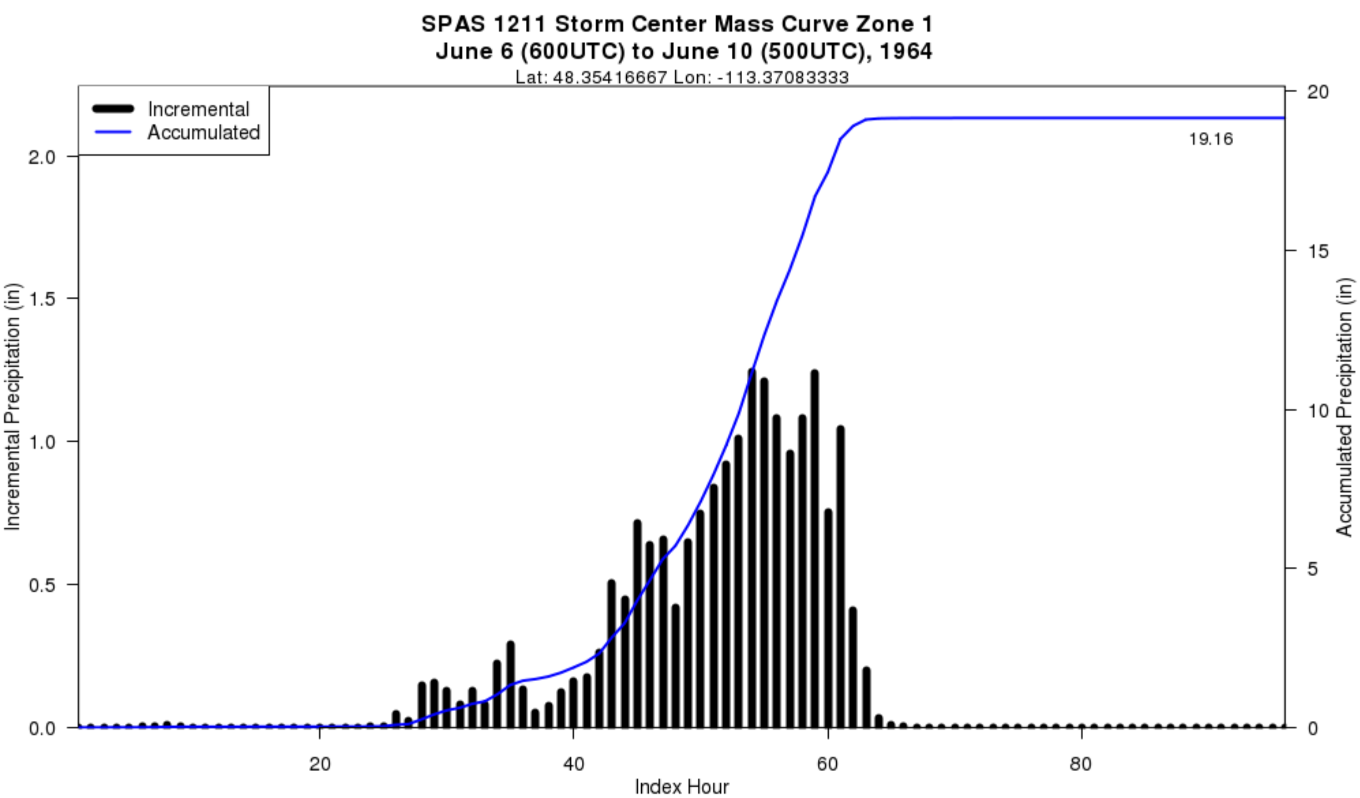

SURFACE WEATHER MAP
AND STATION WEATHER
AT 1:00 A.M., E.S.T.
SPECIMEN
STATION MODEL
HIGH
LOW
POLAR STEREOGRAPHIC PROJECTION, TRUE AT LATITUDE 60°
SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES
WEDNESDAY, JUNE 10, 1964

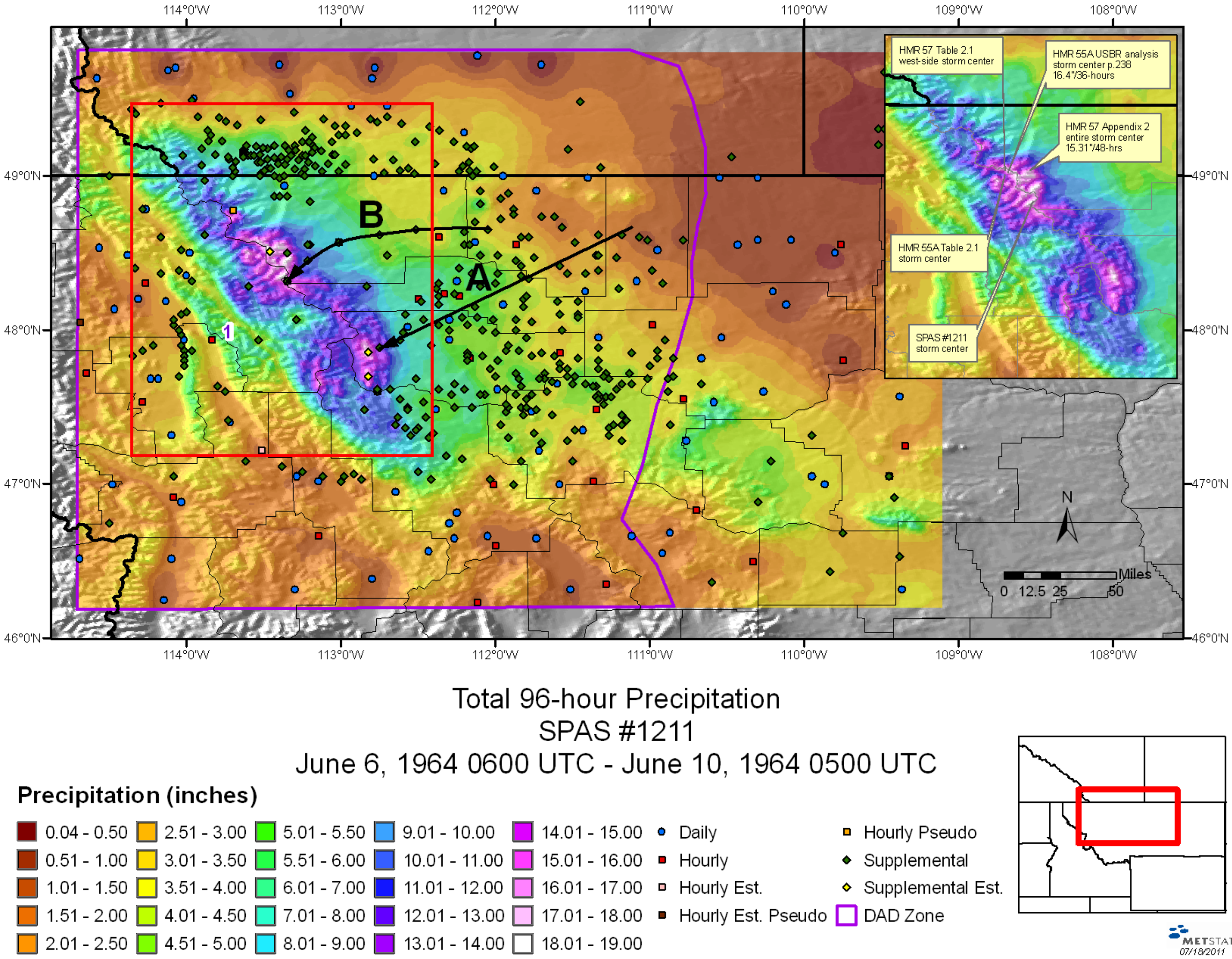

NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 08 Jun 64
CDC1 Meteorological Data
Source ★ at 48.35 N 113.37 W
50
-120
-115
-110
-105
-100
45
40
hPa
700
848
700
750
800
850
900
06 00 18 12 06 00 18 12 06 00 18 12
06/08
06/07
06/06
This is not a NOAA product. It was produced by a web user.
Job ID: 316316 Job Start: Tue Oct 2 23:46:13 UTC 2012
Source 1 lat.: 48.35 lon.: -113.37 heights: 0, 1570 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 01 Jun 2064 - reanalysis



Storm 1211 - June 6 (0600 UTC) - June 10 (0500 UTC), 1964														
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)														
	Duration (hours)													
Area (mi^2)	1	2	3	6	12	18	24	30	36	42	48	72	96	Total
0.2	1.25	2.46	3.54	6.82	12.13	15.66	17.38	18.28	19	19.12	19.13	19.15	19.16	19.16
1	1.24	2.42	3.52	6.78	12.01	15.54	17.22	18.16	18.78	18.94	18.95	18.96	18.96	18.96
10	1.14	2.29	3.33	6.4	11.42	14.72	16.56	17.4	18.15	18.37	18.37	18.47	18.48	18.48
25	1.1	2.2	3.22	6.19	11.05	14.24	16.04	16.92	17.68	17.86	17.93	18.08	18.09	18.09
50	1.07	2.14	3.13	6.02	10.74	13.86	15.51	16.48	17.25	17.46	17.46	17.67	17.68	17.68
100	1.04	2.08	3.03	5.83	10.39	13.38	15.17	16.01	16.61	16.9	16.96	17.14	17.15	17.15
150	1.02	2.03	2.96	5.69	10.13	13.04	14.77	15.61	16.24	16.55	16.59	16.76	16.77	16.77
200	1	1.99	2.91	5.57	9.92	12.77	14.55	15.32	15.93	16.18	16.27	16.46	16.47	16.47
300	0.94	1.92	2.81	5.37	9.57	12.3	13.98	14.79	15.34	15.61	15.79	15.96	15.97	15.97
400	0.94	1.87	2.73	5.14	9.19	11.81	13.63	14.31	14.95	15.19	15.37	15.55	15.56	15.56
500	0.91	1.82	2.66	4.93	9.02	11.63	13.18	14	14.5	14.8	15.02	15.2	15.22	15.22
1,000	0.83	1.61	2.39	4.49	8.18	10.52	12.09	12.8	13.26	13.46	13.46	14.07	14.08	14.08
2,000	0.74	1.47	2.13	3.95	7.32	9.47	10.77	11.63	12.03	12.12	12.23	12.78	12.8	12.80
5,000	0.59	1.13	1.71	3.15	5.71	7.58	8.93	9.4	9.83	10.08	10.17	10.44	10.45	10.45
10,000	0.47	0.9	1.31	2.43	4.35	5.78	6.93	7.42	7.67	7.78	7.79	8.13	8.14	8.14
20,000	0.32	0.64	0.95	1.74	2.93	3.81	4.56	5.46	5.64	5.8	5.88	5.95	6.08	6.08
40,000	0.2	0.39	0.59	1.13	1.95	2.77	3.34	3.58	3.76	3.9	3.95	4.17	4.17	4.17
44,374	0.18	0.36	0.54	1.04	1.86	2.54	3.09	3.41	3.52	3.64	3.7	3.85	3.86	3.86


SPAS #1211 DAD Curves Zone 1
June 6 - 10, 1964
Area (mi²)
Maximum Average Depth of Precipitation (inches)
1-hour
2-hour
3-hour
6-hour
12-hour
18-hour
24-hour
30-hour
36-hour
42-hour
48-hour
72-hour
96-hour
Total storm (96-hour)


SPAS 1211 Storm Center Mass Curve Zone 1
June 6 (600UTC) to June 10 (500UTC), 1964
Lat: 48.35416667 Lon: -113.37083333
Incremental
Accumulated
19.16
Incremental Precipitation (in)
Accumulated Precipitation (in)
Index Hour


114°0'W
113°0'W
112°0'W
111°0'W
110°0'W
109°0'W
108°0'W
49°0'N
48°0'N
47°0'N
46°0'N
HMR 57 Table 2.1
west-side storm center
HMR 55A USBR analysis
storm center p.238
16.4"/36-hours
HMR 57 Appendix 2
entire storm center
15.31"/48-hrs
HMR 55A Table 2.1
storm center
SPAS #1211
storm center
A
B
1
N
Miles
0 12.5 25 50
Total 96-hour Precipitation
SPAS #1211
June 6, 1964 0600 UTC - June 10, 1964 0500 UTC
Precipitation (inches)
0.04 - 0.50
0.51 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 2.50
2.51 - 3.00
3.01 - 3.50
3.51 - 4.00
4.01 - 4.50
4.51 - 5.00
5.01 - 5.50
5.51 - 6.00
6.01 - 7.00
7.01 - 8.00
8.01 - 9.00
9.01 - 10.00
10.01 - 11.00
11.01 - 12.00
12.01 - 13.00
13.01 - 14.00
14.01 - 15.00
15.01 - 16.00
16.01 - 17.00
17.01 - 18.00
18.01 - 19.00
Daily
Hourly
Hourly Est.
Hourly Est. Pseudo
Hourly Pseudo
Supplemental
Supplemental Est.
DAD Zone
METSTAT
07/18/2011

Waterton Red Rock, AB

June 14-21, 1975

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1252

General Storm Location: Alberta/Montana

Storm Dates: June 14-21, 1975

Event: Convective

DAD Zone 1

Latitude: 49.0875°

Longitude: -114.0458°

Max. Grid Rainfall Amount: 367mm

Max. Observed Rainfall Amount: 350mm

Number of Stations: 179 (143 Daily, 23 Hourly, 6 Hourly Pseudo, and 7 Supplemental)

SPAS Version: 9.5

Basemap: PRISM mean (1971-2000) June precipitation blended with Canadian based Basemap derived on elevation.

Spatial resolution: 00:00:30 (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, and supplemental data. We have a high degree of confidence in the station based results, and spatial pattern is dependent on the basemap. An hourly pseudo station was added at Waterton Red Rock, this station was based on timing at Summit MT. An hourly pseudo station is a gauge with reliable temporal precipitation data, but the magnitude is questionable in relation to co-located daily or supplemental gauges

Storm Name:	SPAS 1252 Waterton Red Rock, AB	**Storm Adjustment Summary**
Storm Date:	6/14-21/1975	
AWA Analysis Date:	7/20/2015	

Temporal Transposition Date **1-Jul**

	Lat	Long
Storm Center Location	**49.09 N**	**114.05 W**
Storm Rep Dew Point Location	**43.15 N**	**99.95 W**
Transposition Dew Point Location	N/A*	N/A*
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**ESE @ 1,304**	kilometers
Basin Average Elevation	N/A*	meters
Storm Center Elevation	**2,438**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**21.7 °C**	with total precipitable water above sea level of		**60**	millimeters.
The in-place maximum dew point is	**25.6 °C**	with total precipitable water above sea level of		**84**	millimeters.
The transpositioned maximum dew point is	N/A*	with total precipitable water above sea level of		N/A*	millimeters.
The in-place storm elevation is	**2,438**	which subtracts	**35**	millimeters of precipitable water at	**21.7 °C**
The in-place storm elevation is	**2,438**	which subtracts	**44**	millimeters of precipitable water at	**25.6 °C**
The transposition basin elevation at	N/A*	which subtracts	N/A*	millimeters of precipitable water at	N/A*

The in-place storm maximization factor is	**1.50**
The transposition/elevation to basin factor is	N/A*
The barrier adjustment factor is	N/A*
The total adjustment factor is	N/A*

Notes: Storm rep Td value used from KMCK, KLBF, and KPIR 24hr ave and 24hr 100yr Td climatology. IPMF calculated at 1.55 and held to 1.50.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	23		33			58	104	183	267
26 km^2 (10 mi^2)	20		33			58	104	183	267
259 km^2 (100 mi^2)	15		28			51	91	157	234
518 km^2 (200 mi^2)	10		25			46	86	145	216
1,295 km^2 (500 mi^2)	10		23			43	79	130	193
2,590 km^2 (1,00 mi^2)	10		23			41	76	119	183
5,180 km^2 (2,000 mi^2)	8		20			38	69	109	165
12.950 km^2 (5000 mi^2)	8		18			33	64	97	142
25,900 km^2 (10,000 mi^2)	8		15			30	56	81	119
51,800 km^2 (20,000 mi^2)	5		13			25	46	64	91

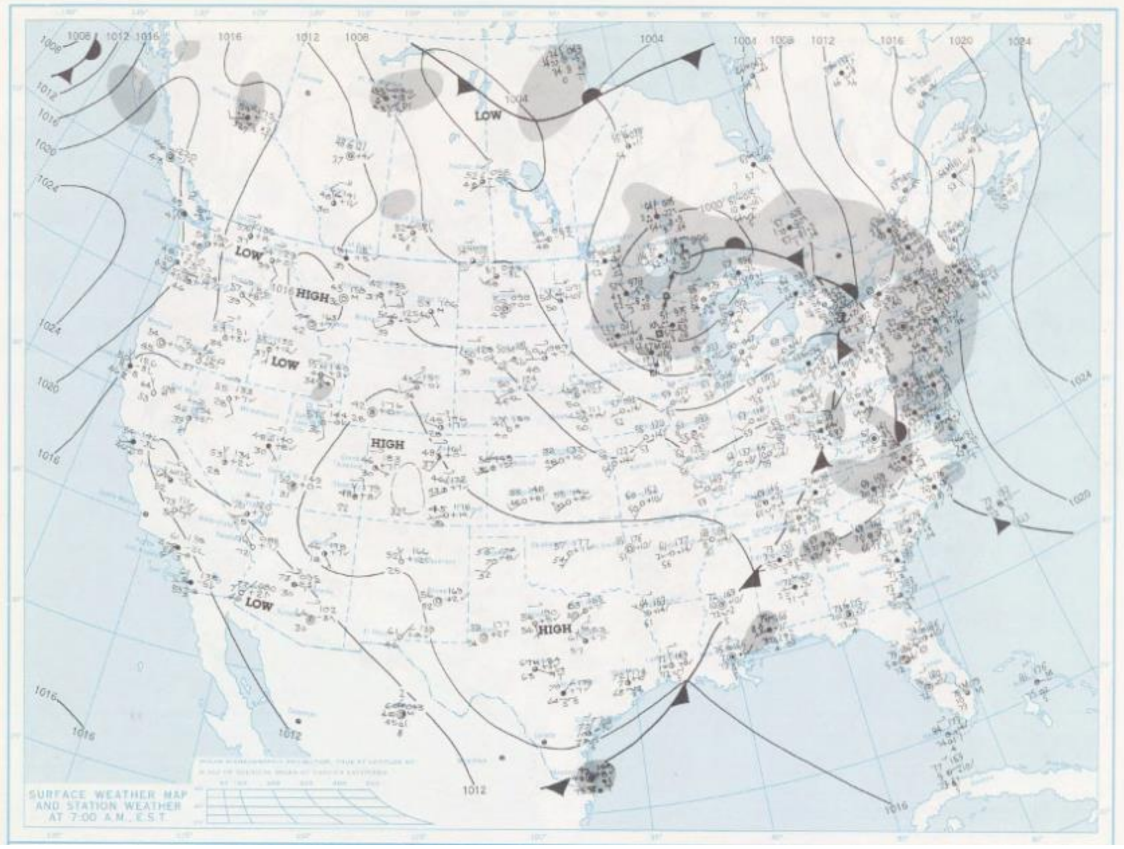
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
26 km2 (10 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
259 km2 (100 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
518 km2 (200 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
1,295 km2 (500 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
2,590 km2 (1,00 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
5,180 km2 (2,000 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
12.950 km2 (5000 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
25,900 km2 (10,000 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
51,800 km2 (20,000 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*

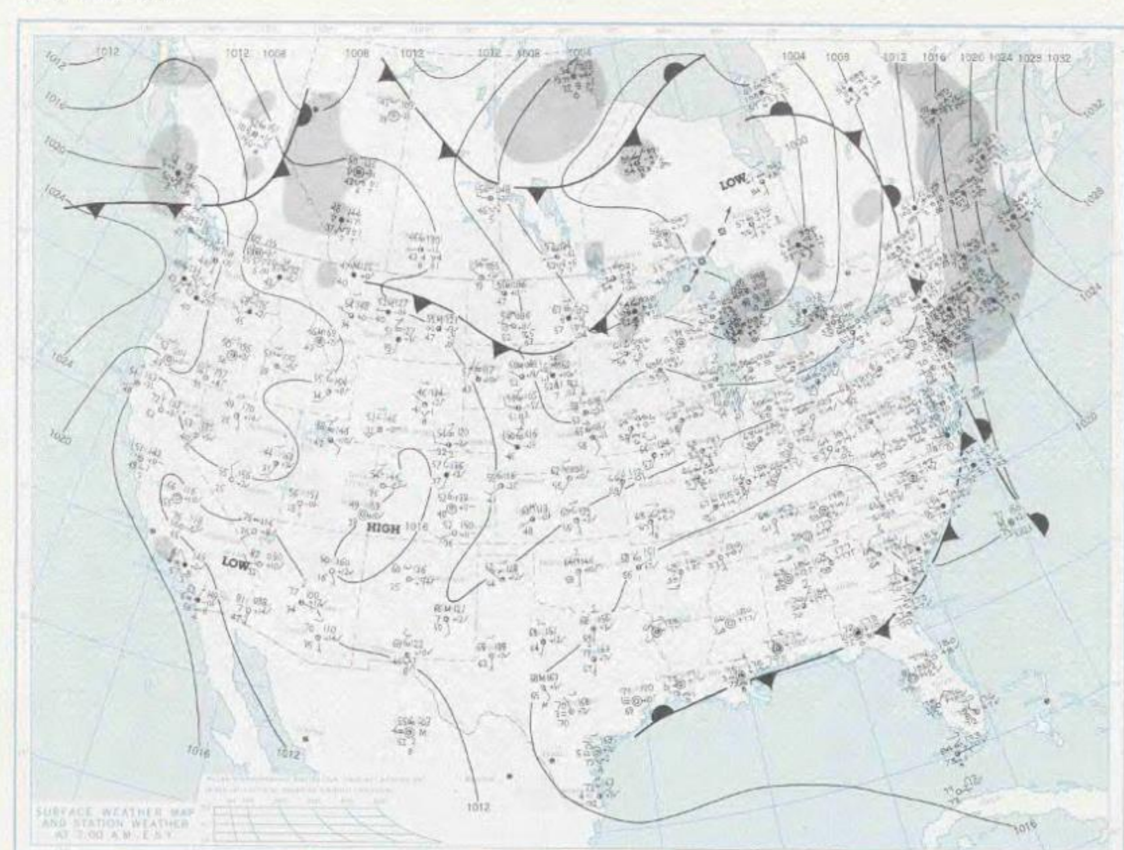
Storm or Storm Center Name	**SPAS 1252 Waterton Red Rock, AB**	
Storm Date(s)	6/14-21/1975	
Storm Type	Synoptic	
Storm Location	49.09 N	114.05 W
Storm Center Elevation	2,438	meters
Precipitation Total & Duration	367	millimeters 144 hours
Storm Representative Dew Point	21.7 °C	24
Storm Representative Dew Point Location	43.15 N	99.95 W
Maximum Dew Point	25.6 °C	
Moisture Inflow Vector	ESE @ 1,304 kilometers	
In-place Maximization Factor	**1.50**	
Temporal Transposition (Date)	1-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

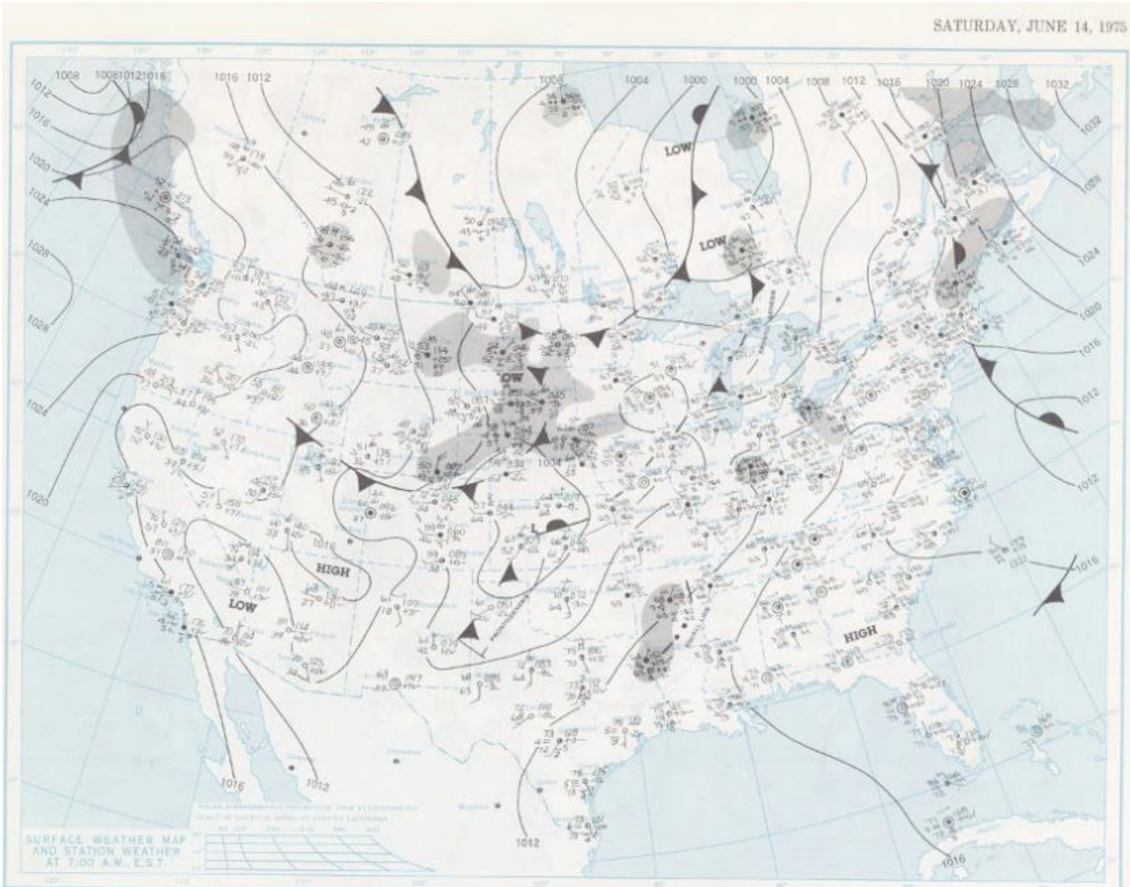
*Variable dependent on transposition location

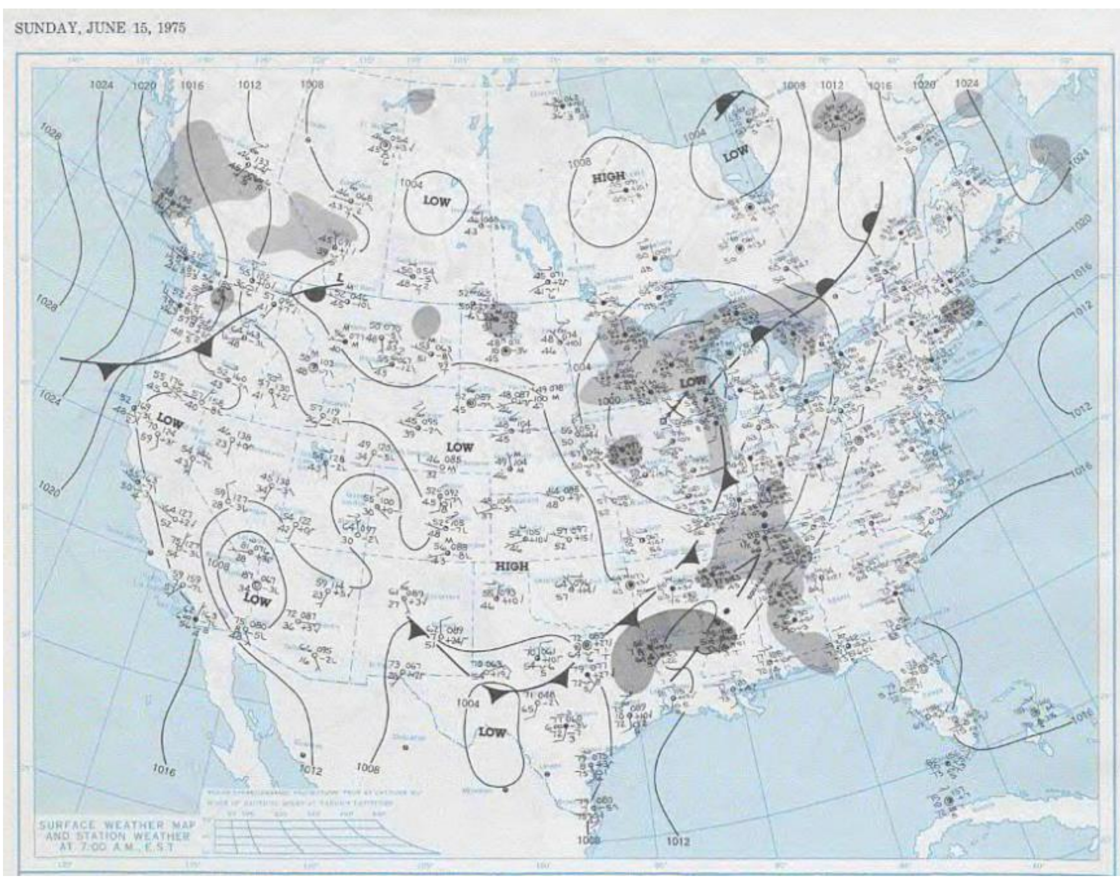
THURSDAY, JUNE 12, 1975



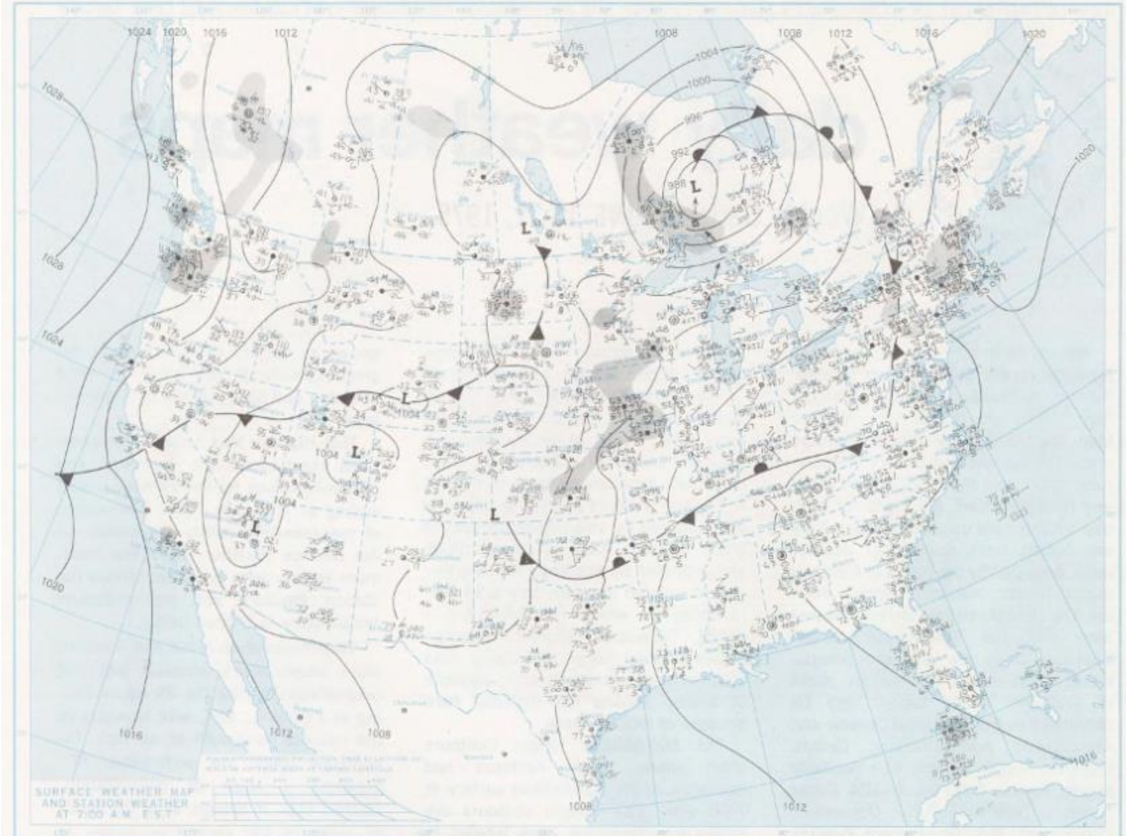
FRIDAY, JUNE 13, 1975



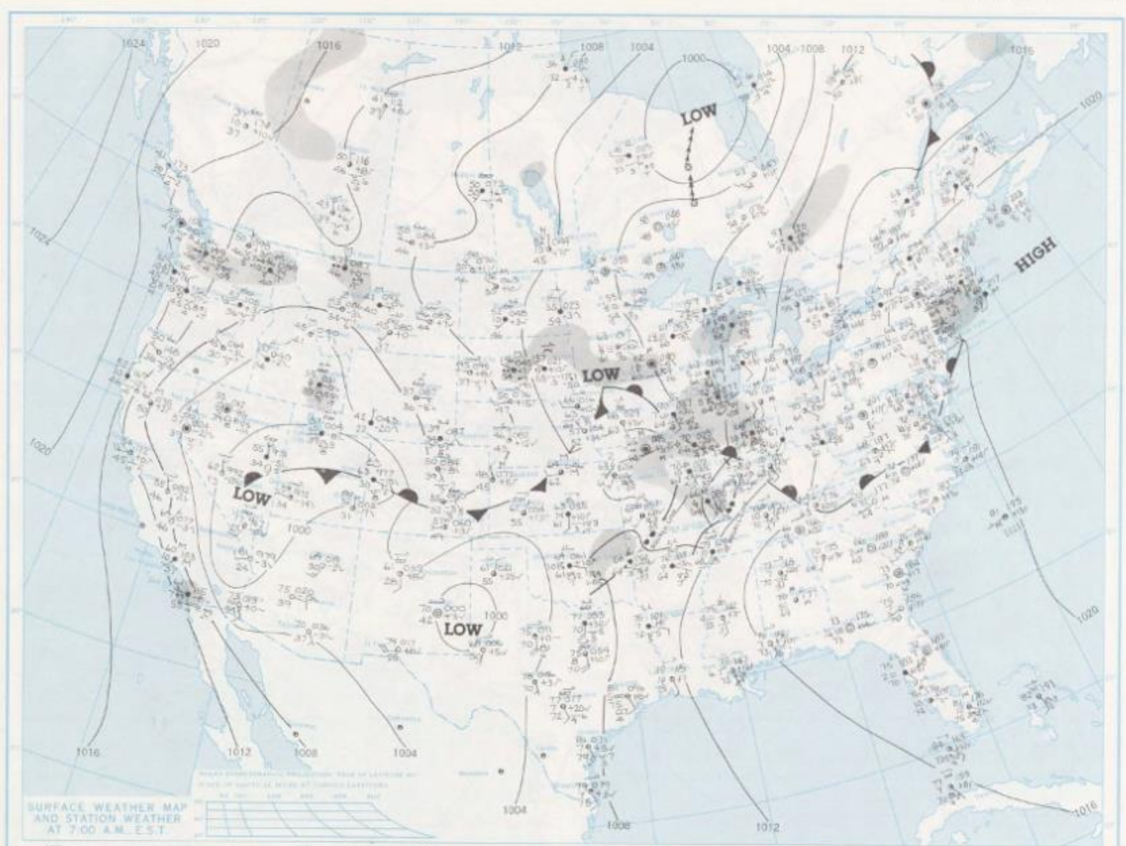

SATURDAY, JUNE 14, 1975
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M., E.S.T.
HIGH
LOW
HIGH
LOW
LOW
LOW


SUNDAY, JUNE 15, 1975
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M., E.S.T.
HIGH
LOW
LOW
LOW
LOW
LOW
HIGH
LOW

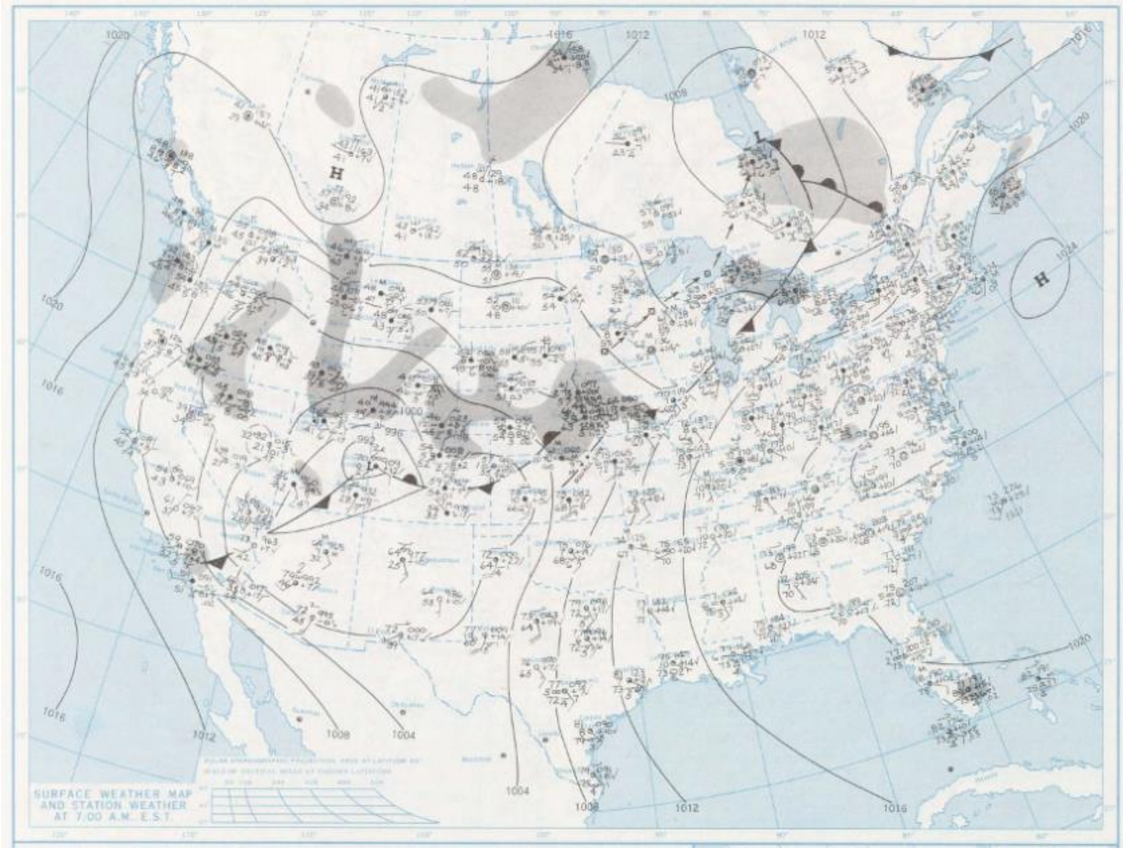
MONDAY, JUNE 16, 1975



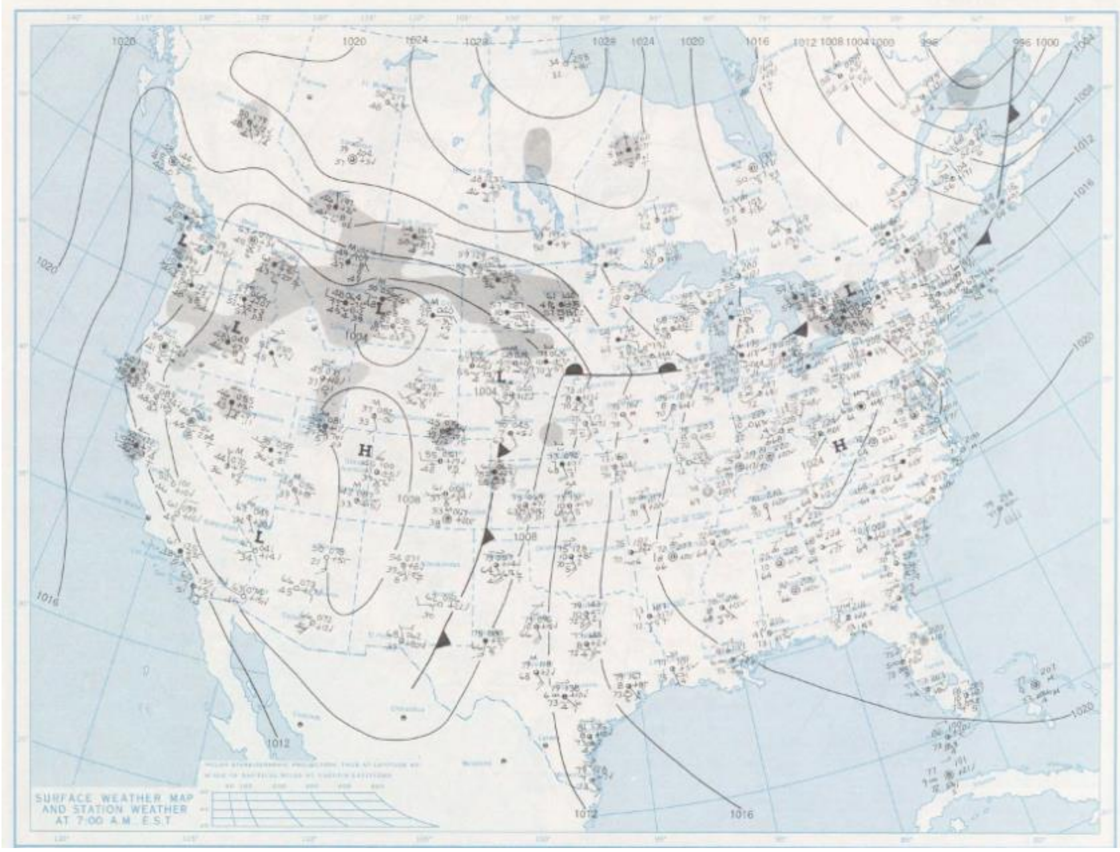
TUESDAY, JUNE 17, 1975



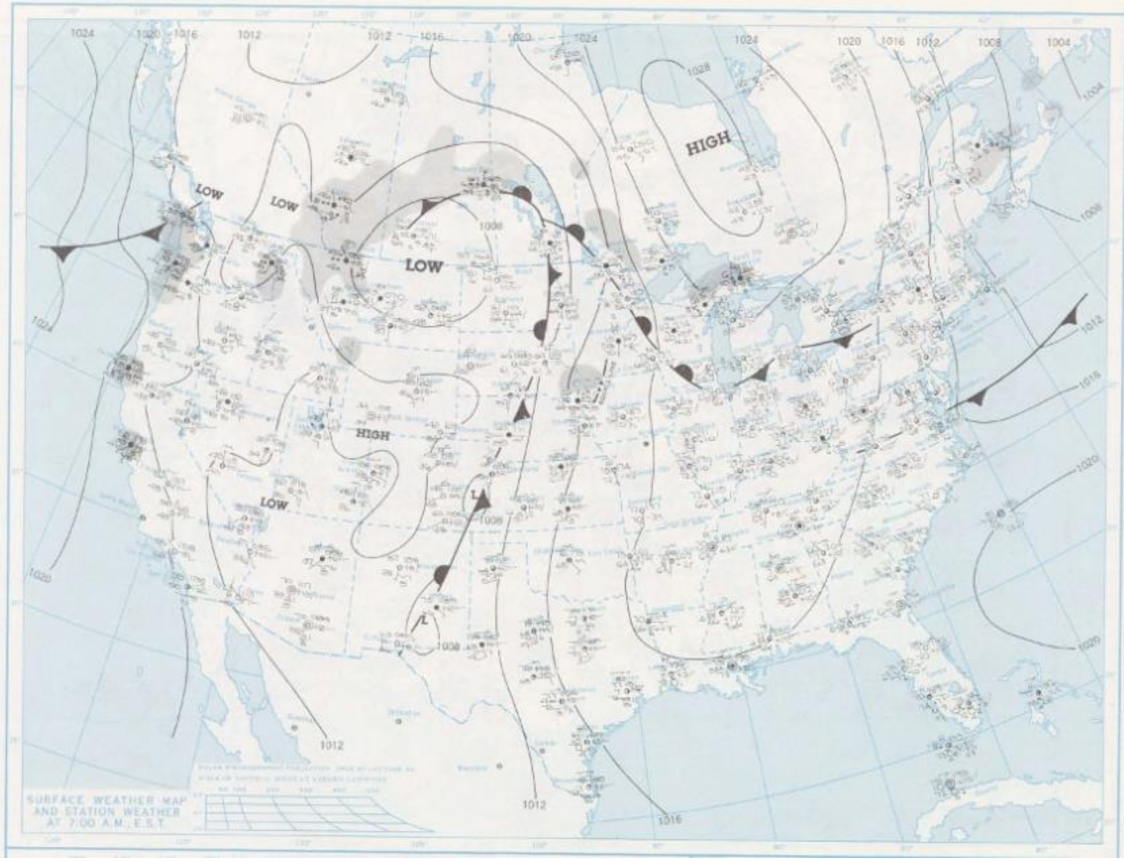
WEDNESDAY, JUNE 18, 1975



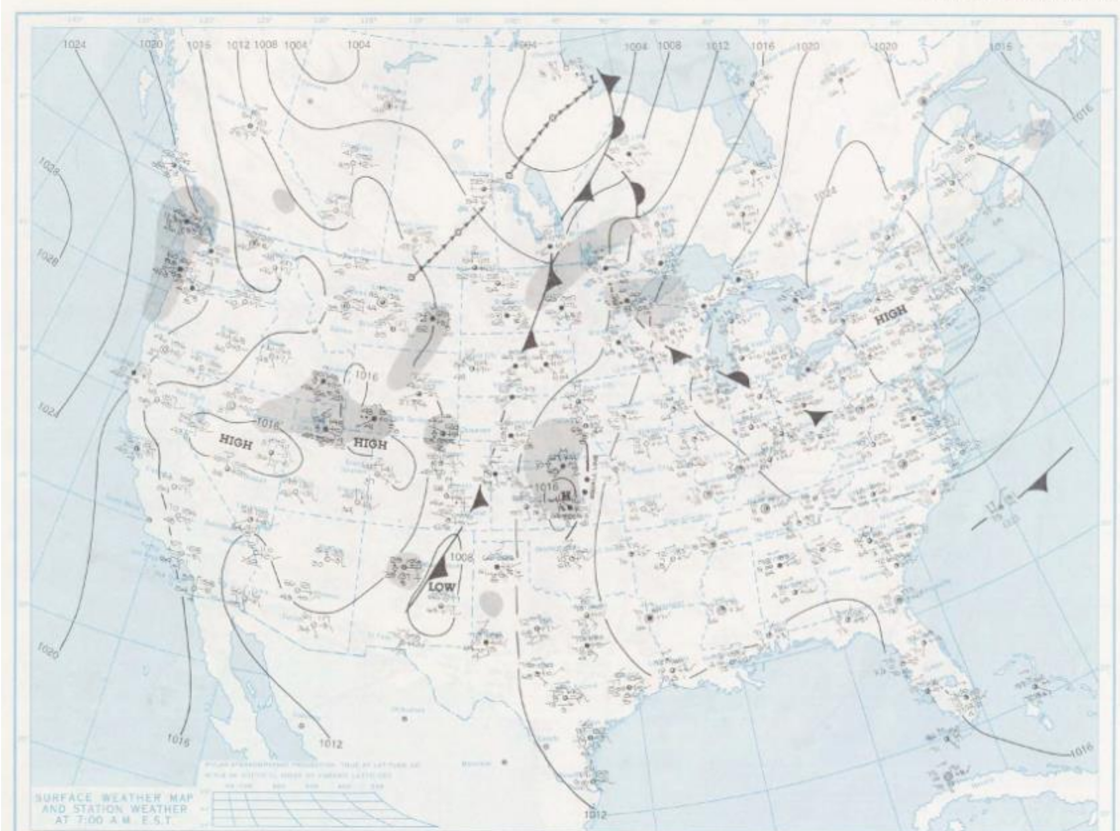
THURSDAY, JUNE 19, 1975

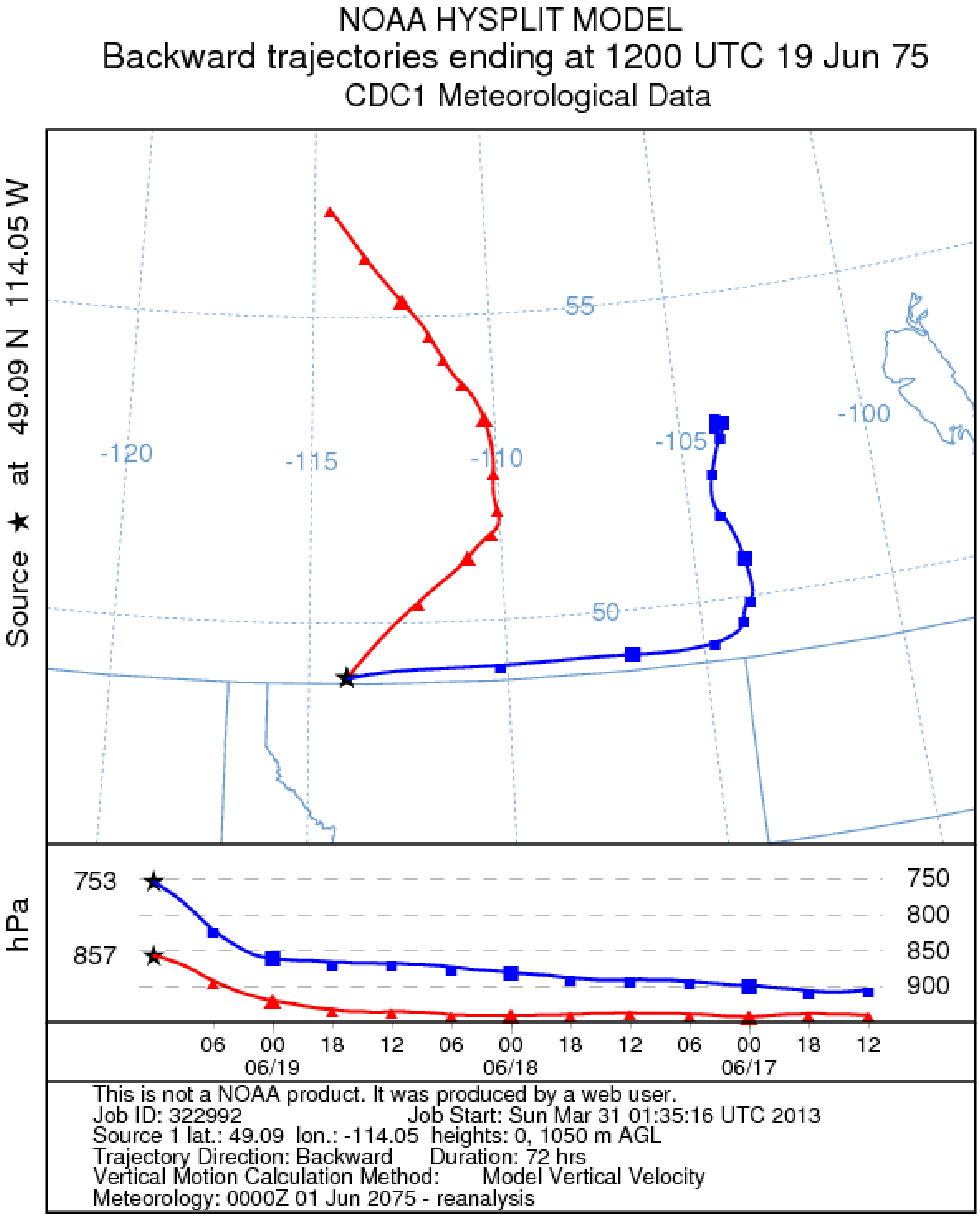


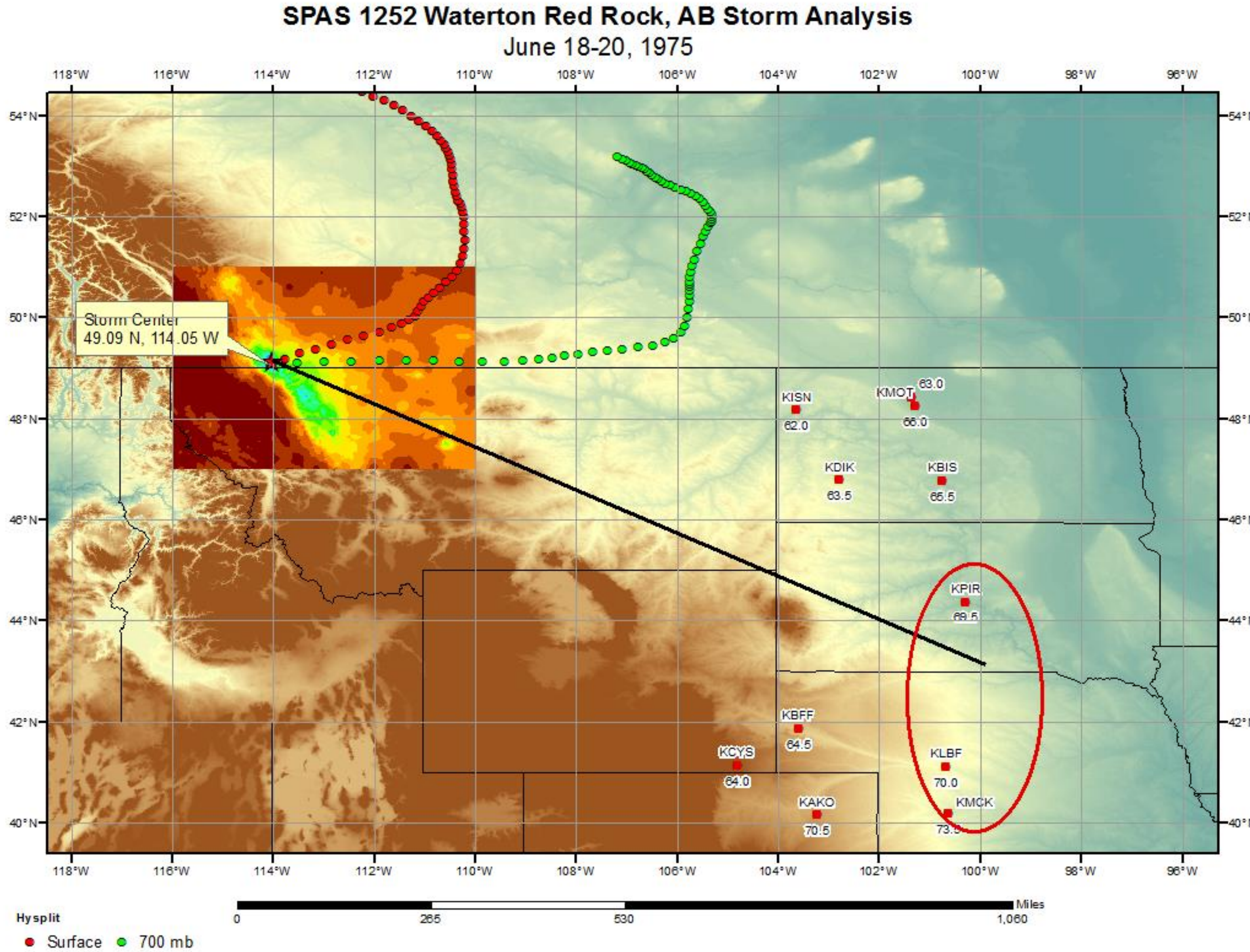
FRIDAY, JUNE 20, 1975



SATURDAY, JUNE 21, 1975




NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 19 Jun 75
CDC1 Meteorological Data
Source ★ at 49.09 N 114.05 W
55
50
-120
-115
-110
-105
-100
hPa
753
857
750
800
850
900
06 00 18 12 06 00 18 12 06 00 18 12
06/19
06/18
06/17
This is not a NOAA product. It was produced by a web user.
Job ID: 322992 Job Start: Sun Mar 31 01:35:16 UTC 2013
Source 1 lat.: 49.09 lon.: -114.05 heights: 0, 1050 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 01 Jun 2075 - reanalysis

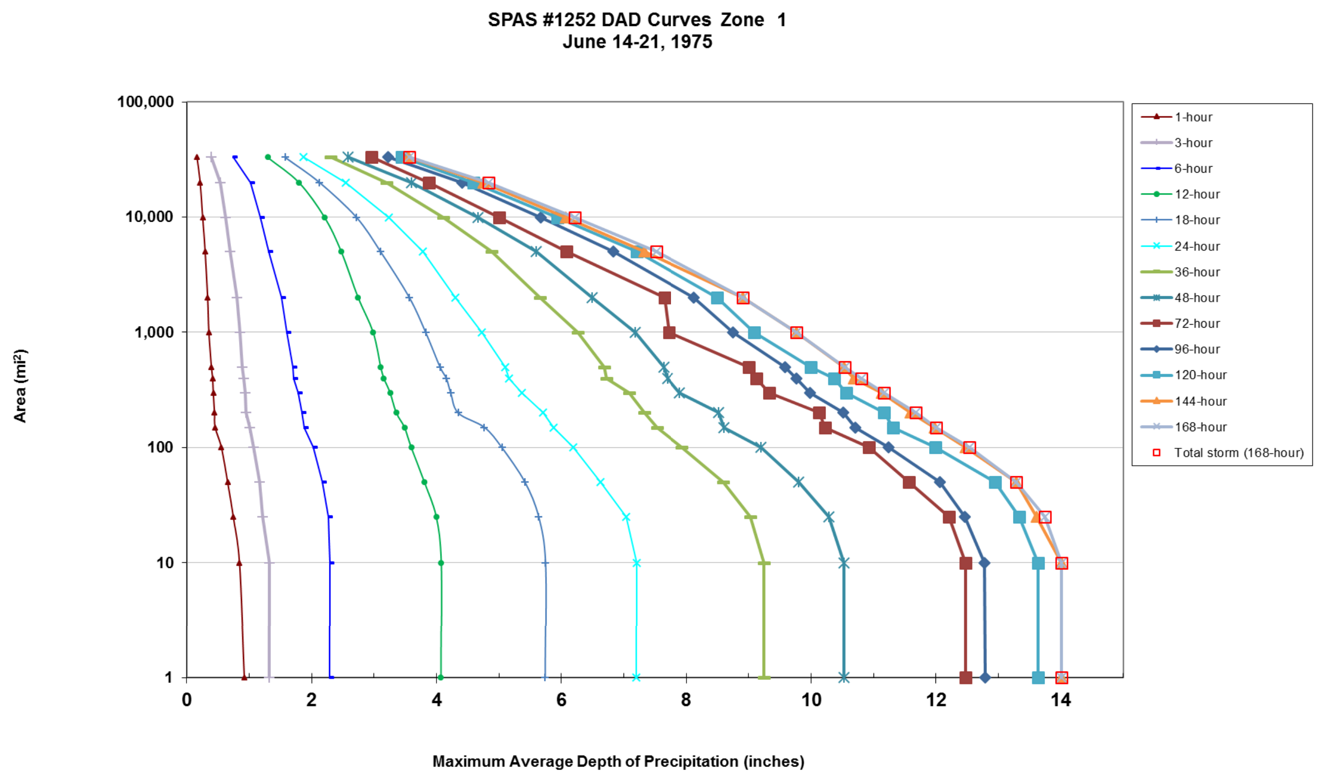


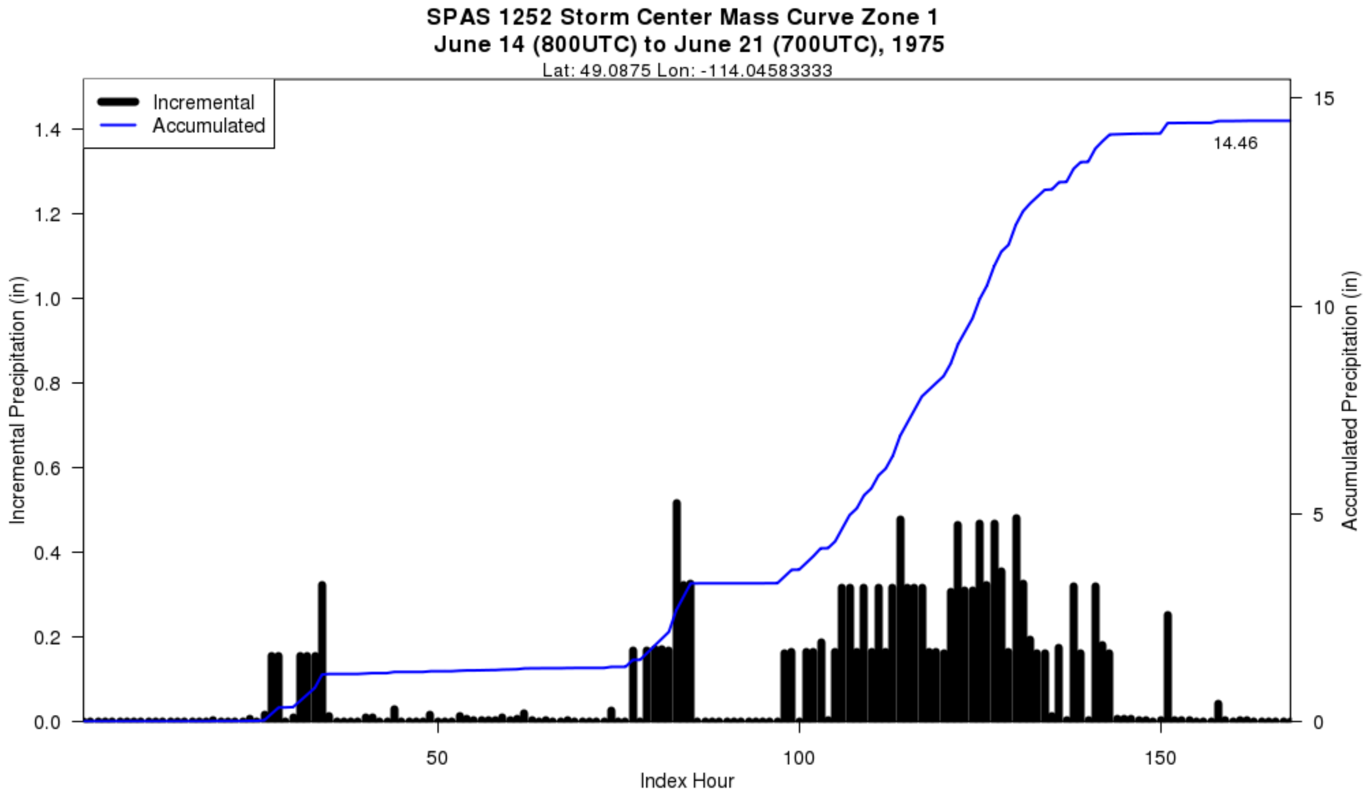
SPAS 1252 Waterton Red Rock, AB Storm Analysis
June 18-20, 1975
Storm Center
49.09 N, 114.05 W
KISN
62.0
KMOT
63.0
66.0
KDIK
63.5
KBIS
65.5
KPIR
69.5
KBFF
64.5
KCYS
64.0
KLBF
70.0
KAKO
70.5
KMCK
73.5
Hysplit
Surface
700 mb
Miles
0
265
530
1,060

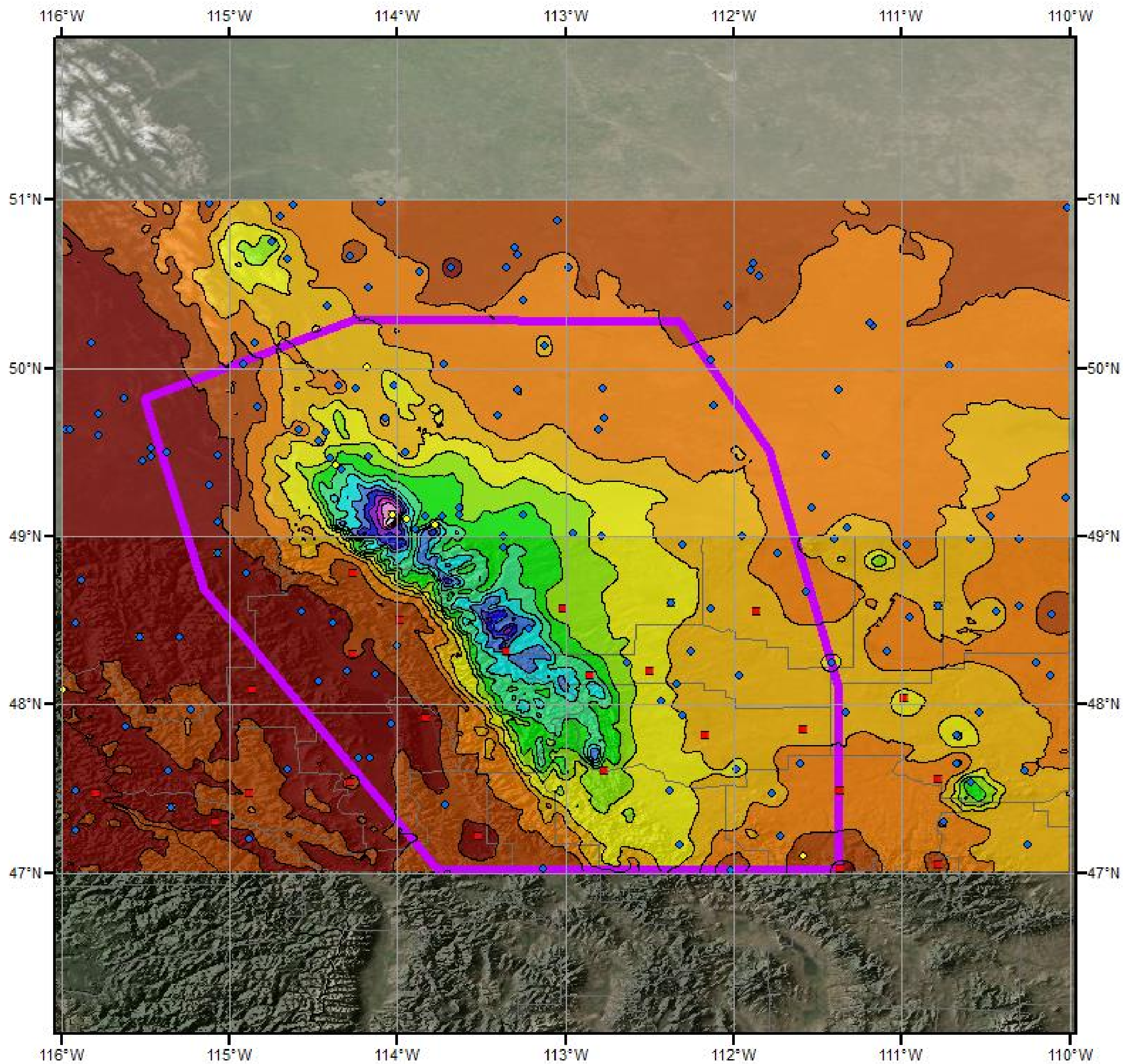
SPAS 1252 - June 14 (800 UTC) - June 21 (700 UTC), 1975

MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)

	Duration (hours)													
Area (mi^2)	**1**	**3**	**6**	**12**	**18**	**24**	**36**	**48**	**72**	**96**	**120**	**144**	**168**	**Total**
0.2	0.94	1.37	2.38	4.19	5.93	7.4	9.51	10.87	12.88	13.18	14.13	14.46	14.46	14.46
1	0.92	1.32	2.29	4.07	5.74	7.2	9.24	10.53	12.47	12.79	13.64	14.01	14.01	14.01
10	0.84	1.32	2.29	4.07	5.74	7.2	9.24	10.53	12.47	12.78	13.64	14.01	14.01	14.01
25	0.74	1.21	2.26	3.99	5.63	7.03	9.03	10.29	12.21	12.46	13.33	13.61	13.74	13.74
50	0.65	1.16	2.17	3.8	5.41	6.62	8.59	9.8	11.57	12.06	12.95	13.28	13.29	13.29
100	0.55	1.07	2.02	3.59	5.04	6.18	7.93	9.19	10.92	11.24	11.99	12.48	12.53	12.53
150	0.45	1.01	1.88	3.48	4.76	5.87	7.53	8.6	10.22	10.71	11.31	11.98	12	12.00
200	0.44	0.95	1.84	3.35	4.34	5.7	7.32	8.52	10.13	10.51	11.17	11.59	11.67	11.67
300	0.42	0.93	1.78	3.25	4.22	5.36	7.08	7.89	9.33	9.98	10.56	11.13	11.17	11.17
400	0.41	0.91	1.71	3.15	4.15	5.15	6.72	7.7	9.12	9.77	10.37	10.68	10.81	10.81
500	0.39	0.89	1.69	3.1	4.05	5.09	6.68	7.63	9	9.58	9.99	10.53	10.54	10.54
1,000	0.35	0.85	1.6	2.98	3.82	4.72	6.25	7.17	7.72	8.75	9.09	9.76	9.76	9.76
2,000	0.33	0.8	1.51	2.74	3.56	4.3	5.65	6.48	7.65	8.12	8.49	8.91	8.91	8.91
5,000	0.29	0.69	1.31	2.47	3.1	3.78	4.88	5.59	6.07	6.83	7.2	7.32	7.51	7.51
10,000	0.25	0.62	1.17	2.2	2.71	3.23	4.1	4.66	5	5.66	5.93	6.06	6.21	6.21
20,000	0.21	0.53	1.02	1.79	2.12	2.54	3.2	3.59	3.87	4.41	4.59	4.74	4.83	4.83
33,046	0.16	0.39	0.74	1.29	1.57	1.86	2.3	2.58	2.95	3.22	3.44	3.55	3.56	3.56




SPAS 1252 Storm Center Mass Curve Zone 1
June 14 (800UTC) to June 21 (700UTC), 1975
Lat: 49.0875 Lon: -114.04583333
Incremental
Accumulated
Incremental Precipitation (in)
Accumulated Precipitation (in)
Index Hour
14.46
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
5
10
15
50
100
150



Total Precipitation (168-hours)
SPAS 1252 - Waterton Red Rock, AB
6/14/1975 0800 GMT - 6/21/1975 0700 GMT

Gauges

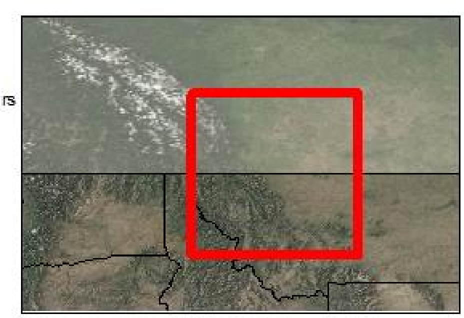
- Daily
- Hourly
- Hourly Pseudo
- Supplemental

Miles: 0, 25, 50, 100

Kilometers: 0, 60, 120, 240

Precipitation (inches)

0.12 - 1.00	3.01 - 4.00	6.01 - 7.00	9.01 - 10.00	12.01 - 13.00
1.01 - 2.00	4.01 - 5.00	7.01 - 8.00	10.01 - 11.00	13.01 - 14.00
2.01 - 3.00	5.01 - 6.00	8.01 - 9.00	11.01 - 12.00	14.01 - 15.00



11/2/2012

Calgary, AB

June 19-23, 2013

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1320

General Storm Location: Calgary, Alberta Canada

Storm Dates: June 19-22, 2013

Event: Synoptic

DAD Zone 1

> **Latitude**: 50.635°
>
> **Longitude**: -114.855°
>
> **Max. Grid Rainfall Amount**: 350mm
>
> **Max. Observed Rainfall Amount**: 345mm

Number of Stations: 193 (80 Daily, 84 Hourly, 13 Hourly Pseudo, and 16 Supplemental)

SPAS Version: 9.5

Basemap: PRISM September 1971-2000 Precipitation Climatology

Spatial resolution: 0.01 (decimal degrees, WGS84) (~ 0.40 mi^2) (1.04 km^2)

Radar Included: Yes

Depth-Area-Duration (DAD) analysis: No

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and NEXRAD Radar. The radar data was not of highest quality in that the radar data had issues with beam blockage, lower quality radar scans (high angle/elevation scan), and missing scan periods. The radar data were a blend of three elevational scan levels. We have a good degree of confidence in the radar/station based storm total results, the spatial pattern is dependent on the radar data and basemap, and the timing is based on hourly and hourly pseudo stations. The 5-minute radar data is not recommended for use.

Storm Name:	**SPAS 1320 Calgary, AB**	
Storm Date:	**6/19-22/2013**	**Storm Adjustment Summary**
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **10-Jul**

	Lat	Long
Storm Center Location	**50.64 N**	**114.86 W**
Storm Rep Dew Point Location	**49.00 N**	**112.50 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**SE @ 241**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**2,591**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**18.6 °C**	with total precipitable water above sea level of			**46**	millimeters.
The in-place maximum dew point is	**20.8 °C**	with total precipitable water above sea level of			**56**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of			**N/A***	millimeters.
The in-place storm elevation is	**2,591**	which subtracts	**29**	millimeters of precipitable water at	**18.6 °C**	
The in-place storm elevation is	**2,591**	which subtracts	**34**	millimeters of precipitable water at	**20.8 °C**	
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***	

The in-place storm maximization factor is	**1.29**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Storm rep dew point taken from 24hr ave at CYQL and KCTB 0100Z 19th to 0100Z 20th.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**43**		**76**			**112**	**180**	**257**	**333**
26 km^2 (10 mi^2)	**41**		**74**			**109**	**180**	**254**	**333**
259 km^2 (100 mi^2)	**41**		**64**			**102**	**165**	**229**	**307**
518 km^2 (200 mi^2)	**38**		**58**			**94**	**152**	**213**	**290**
1,295 km^2 (500 mi^2)	**33**		**53**			**79**	**140**	**188**	**262**
2,590 km^2 (1,00 mi^2)	**28**		**51**			**76**	**124**	**175**	**246**
5,180 km^2 (2,000 mi^2)	**20**		**43**			**69**	**119**	**152**	**229**
12.950 km^2 (5000 mi^2)	**15**		**36**			**58**	**99**	**140**	**201**
25,900 km^2 (10,000 mi^2)	**10**		**28**			**51**	**86**	**114**	**152**
51,800 km^2 (20,000 mi^2)	**8**		**20**			**36**	**66**	**94**	**124**

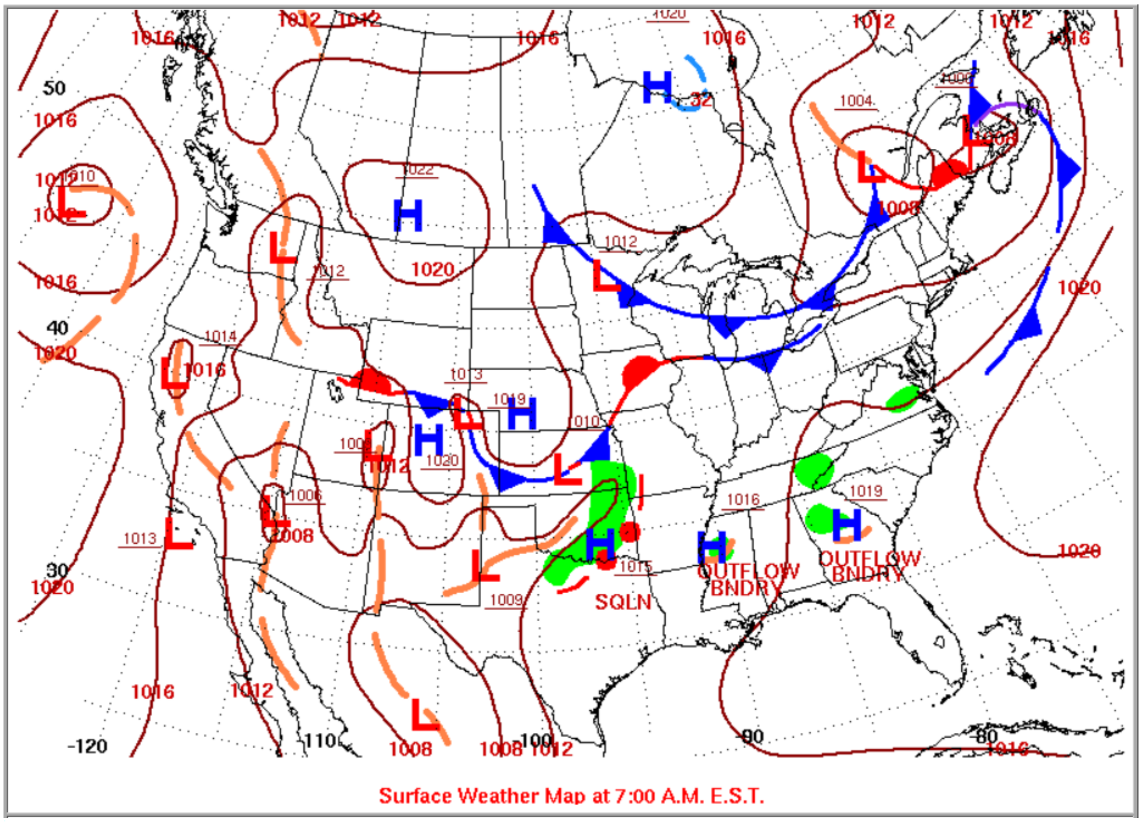
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***		**N/A***	**N/A***			**N/A***	**N/A***	**N/A***

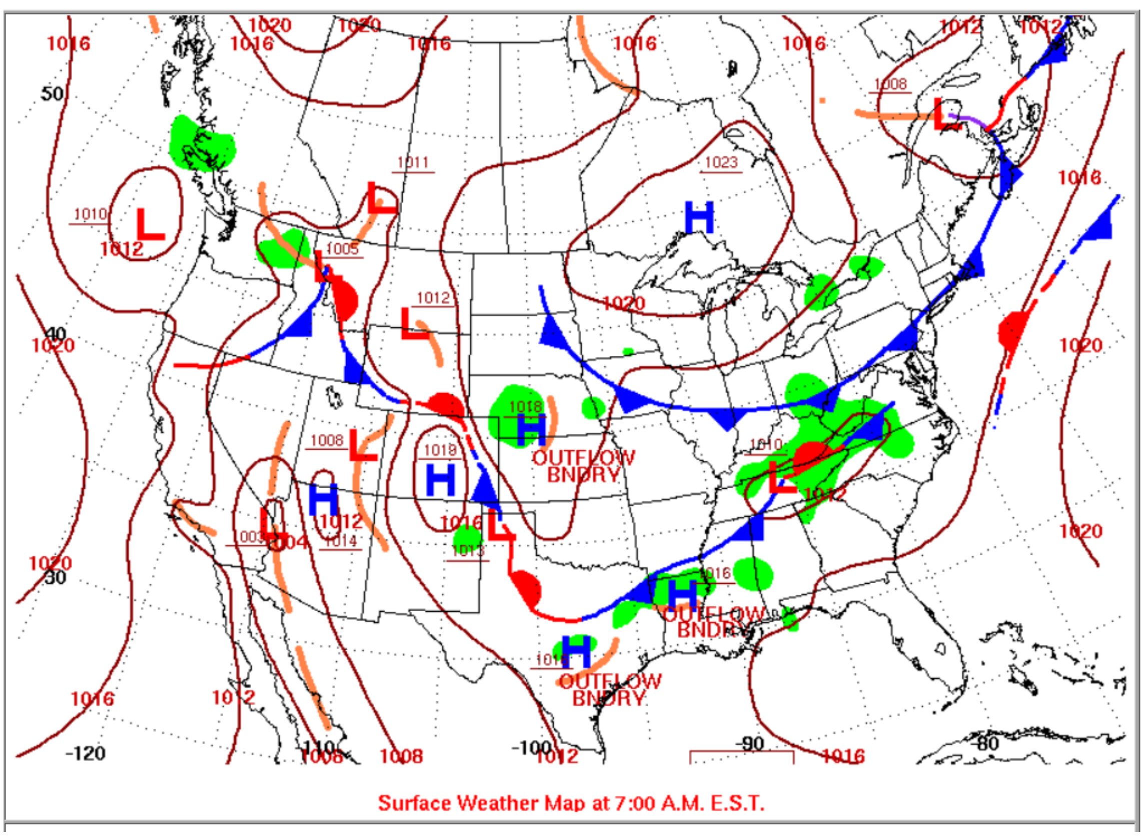
Storm or Storm Center Name	**SPAS 1320 Calgary, AB**	
Storm Date(s)	6/19-22/2013	
Storm Type	Synoptic	
Storm Location	50.64 N	114.86 W
Storm Center Elevation	2,591	meters
Precipitation Total & Duration	350	millimeters
Storm Representative Dew Point	18.6 °C	24
Storm Representative Dew Point Location	49.00 N	112.50 W
Maximum Dew Point	20.8 °C	
Moisture Inflow Vector	SE @ 241	kilometers
In-place Maximization Factor	**1.29**	
Temporal Transposition (Date)	10-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

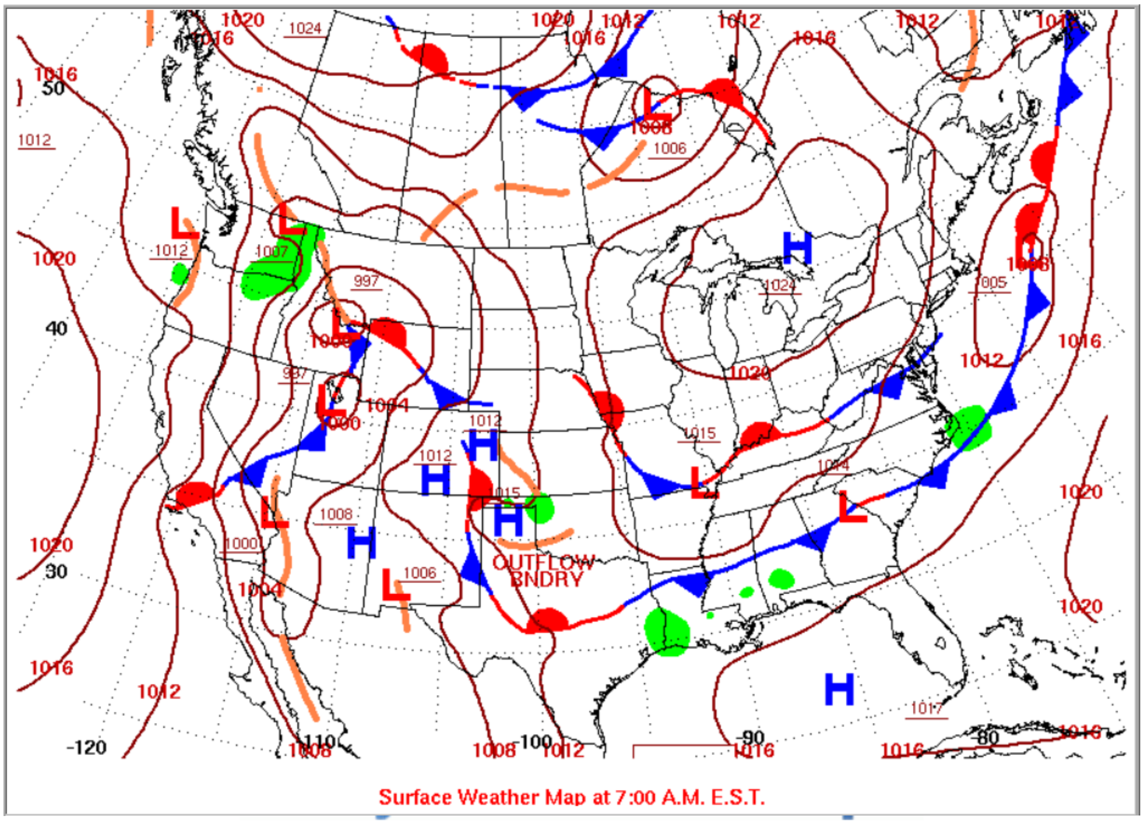
MONDAY JUNE 17, 2013



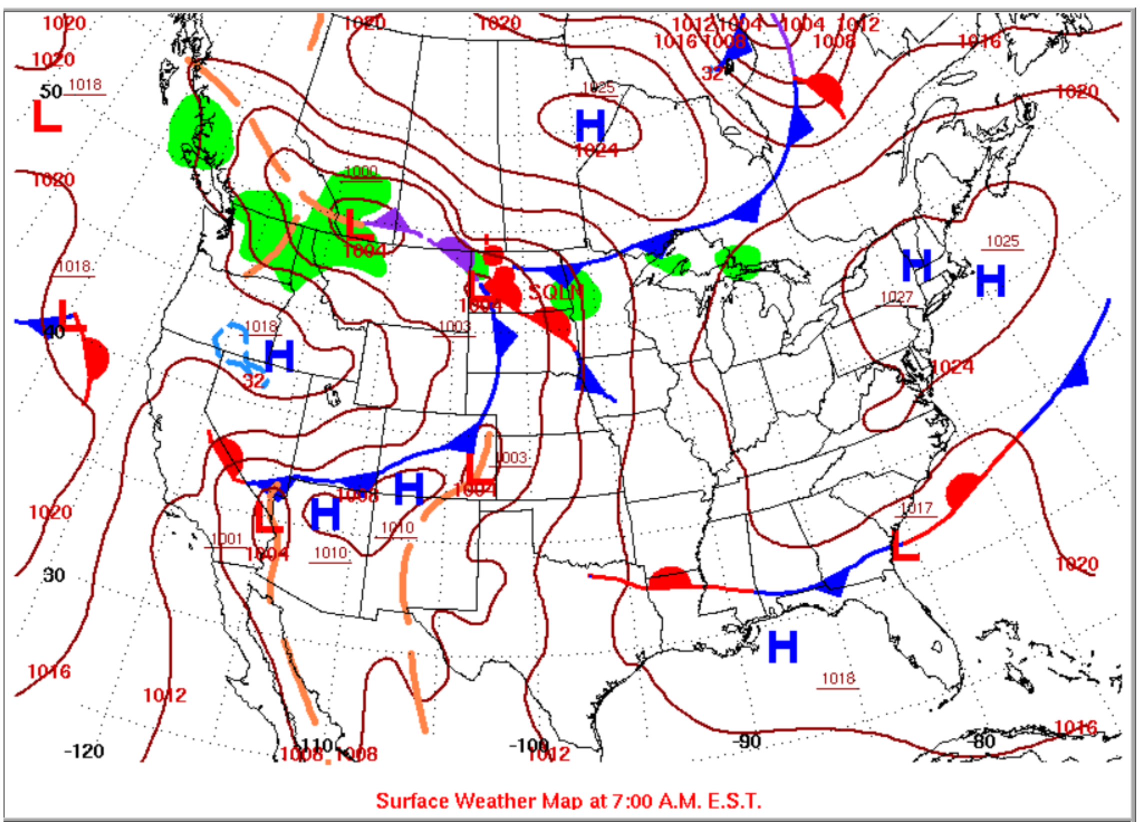
TUESDAY JUNE 18, 2013



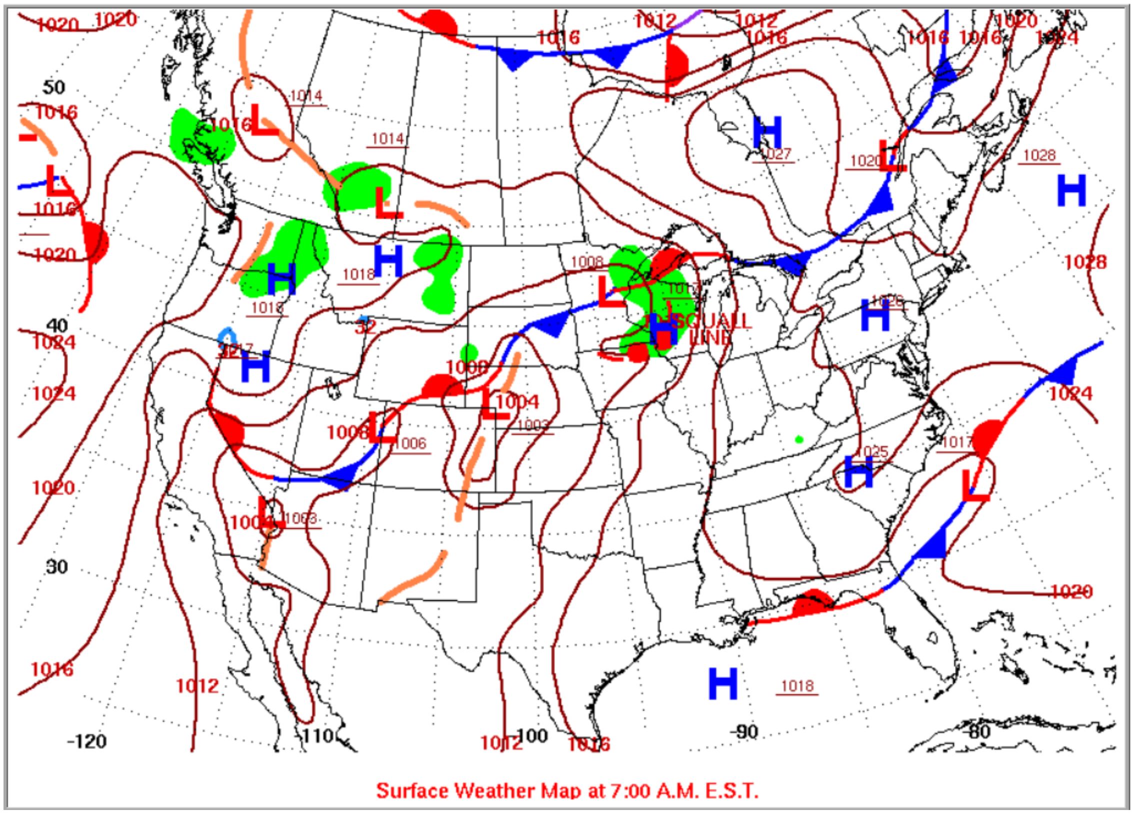
WEDNESDAY JUNE 19, 2013



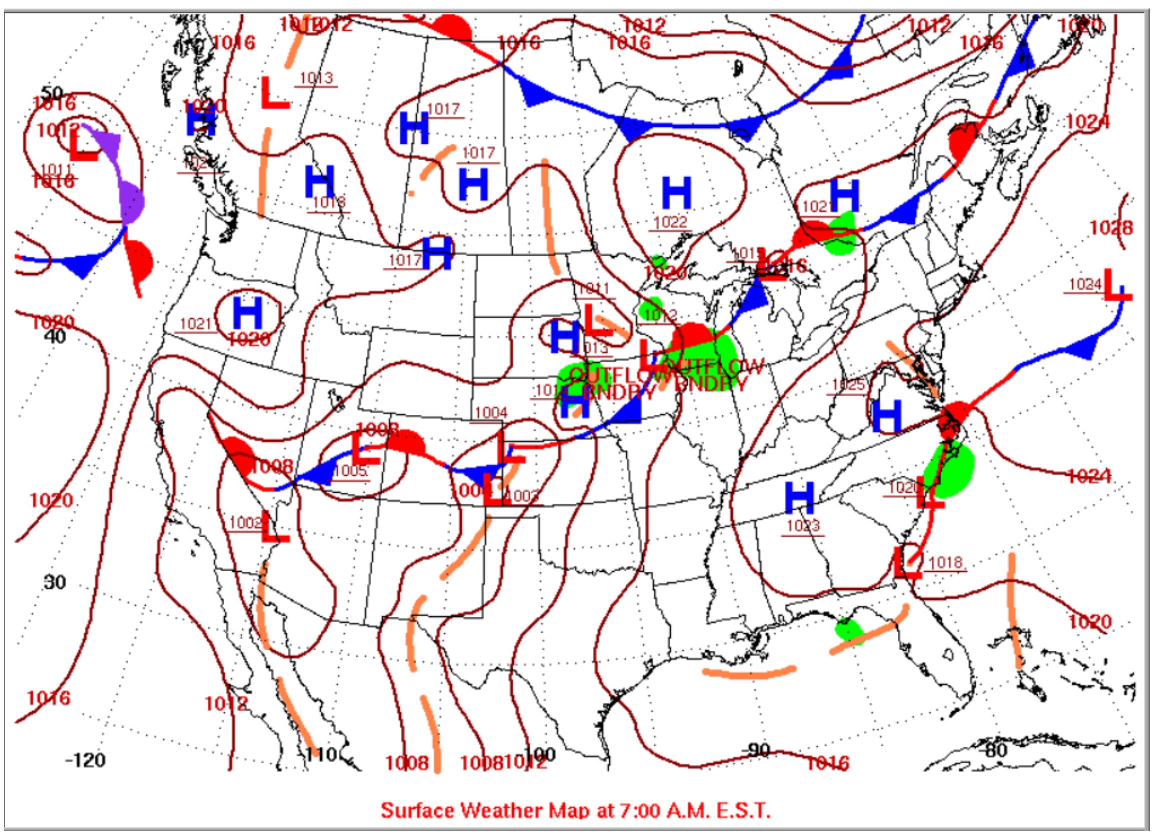
THURSDAY JUNE 20, 2013

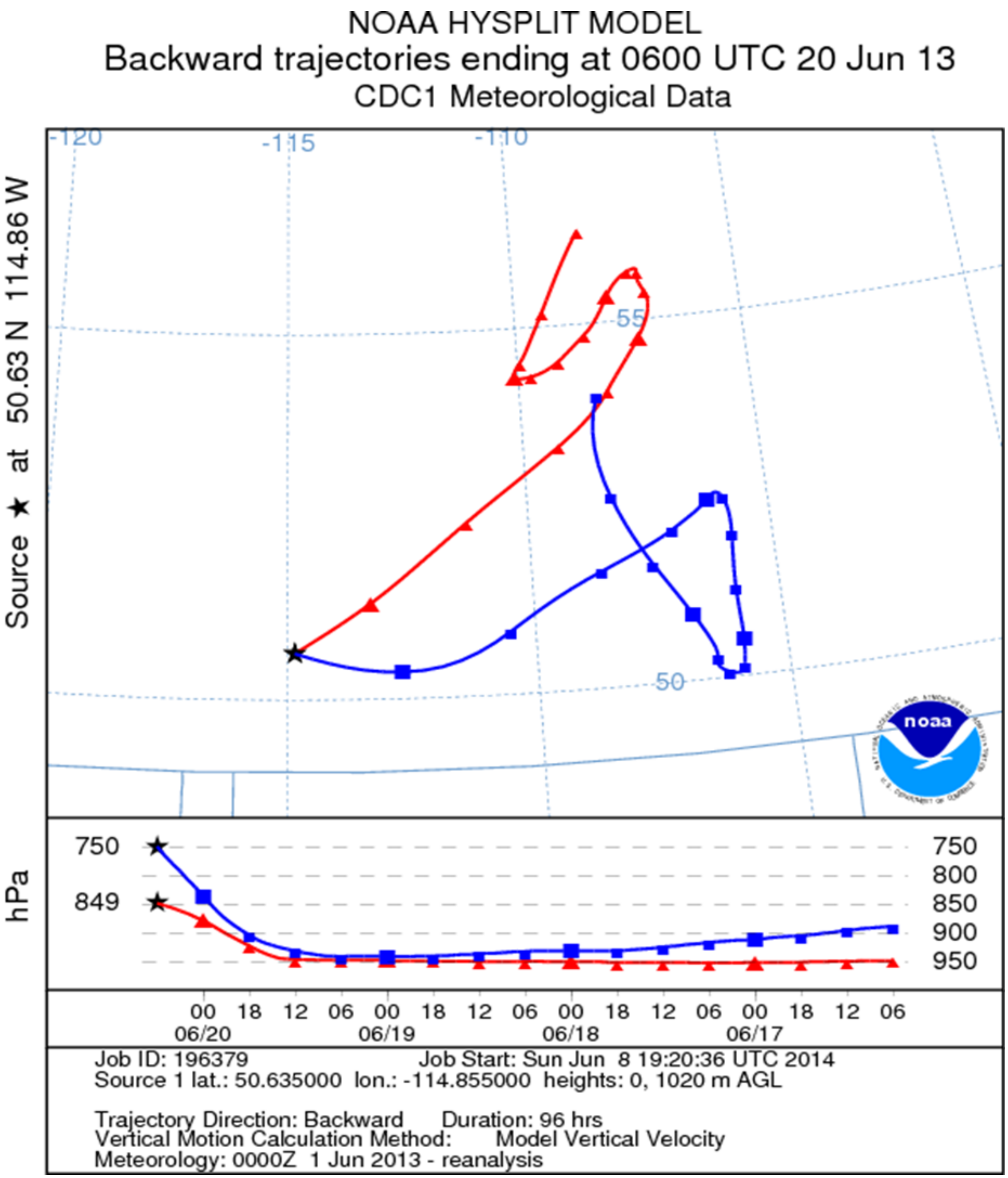


FRIDAY JUNE 21, 2013



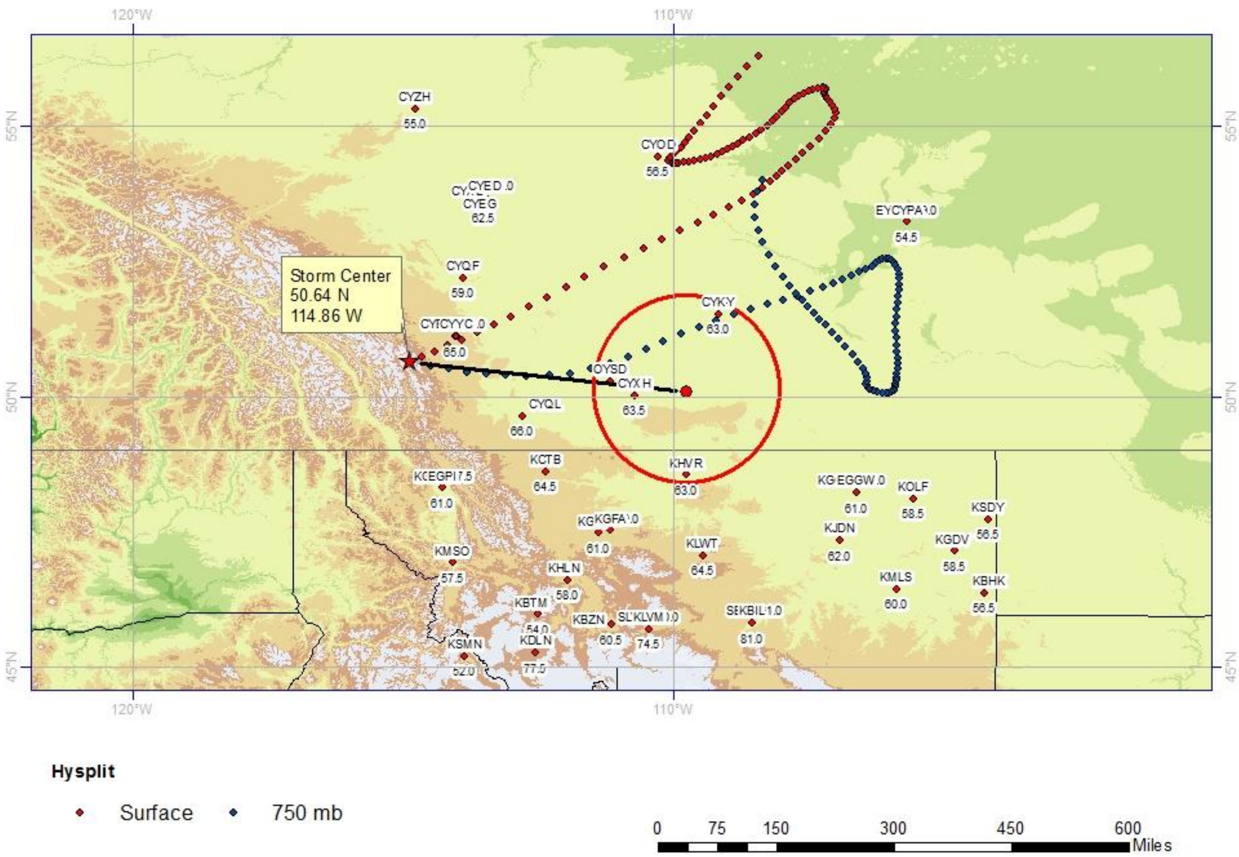
SATURDAY JUNE 22, 2013



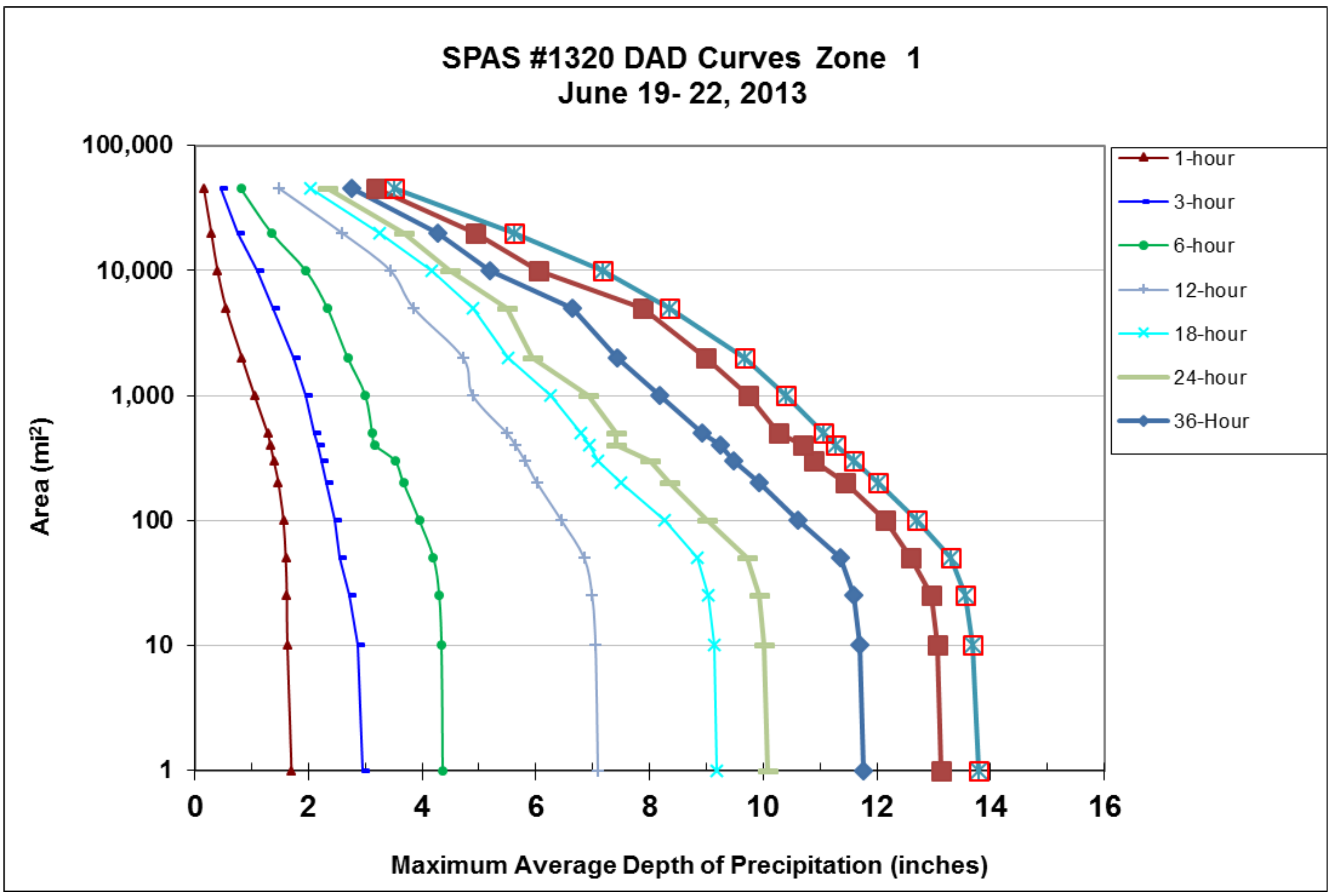

NOAA HYSPLIT MODEL
Backward trajectories ending at 0600 UTC 20 Jun 13
CDC1 Meteorological Data
Source ★ at 50.63 N 114.86 W
-120
-115
-110
55
50
hPa
750
849
750
800
850
900
950
00 18 12 06 00 18 12 06 00 18 12 06 00 18 12 06
06/20
06/19
06/18
06/17
Job ID: 196379 Job Start: Sun Jun 8 19:20:36 UTC 2014
Source 1 lat.: 50.635000 lon.: -114.855000 heights: 0, 1020 m AGL
Trajectory Direction: Backward Duration: 96 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jun 2013 - reanalysis

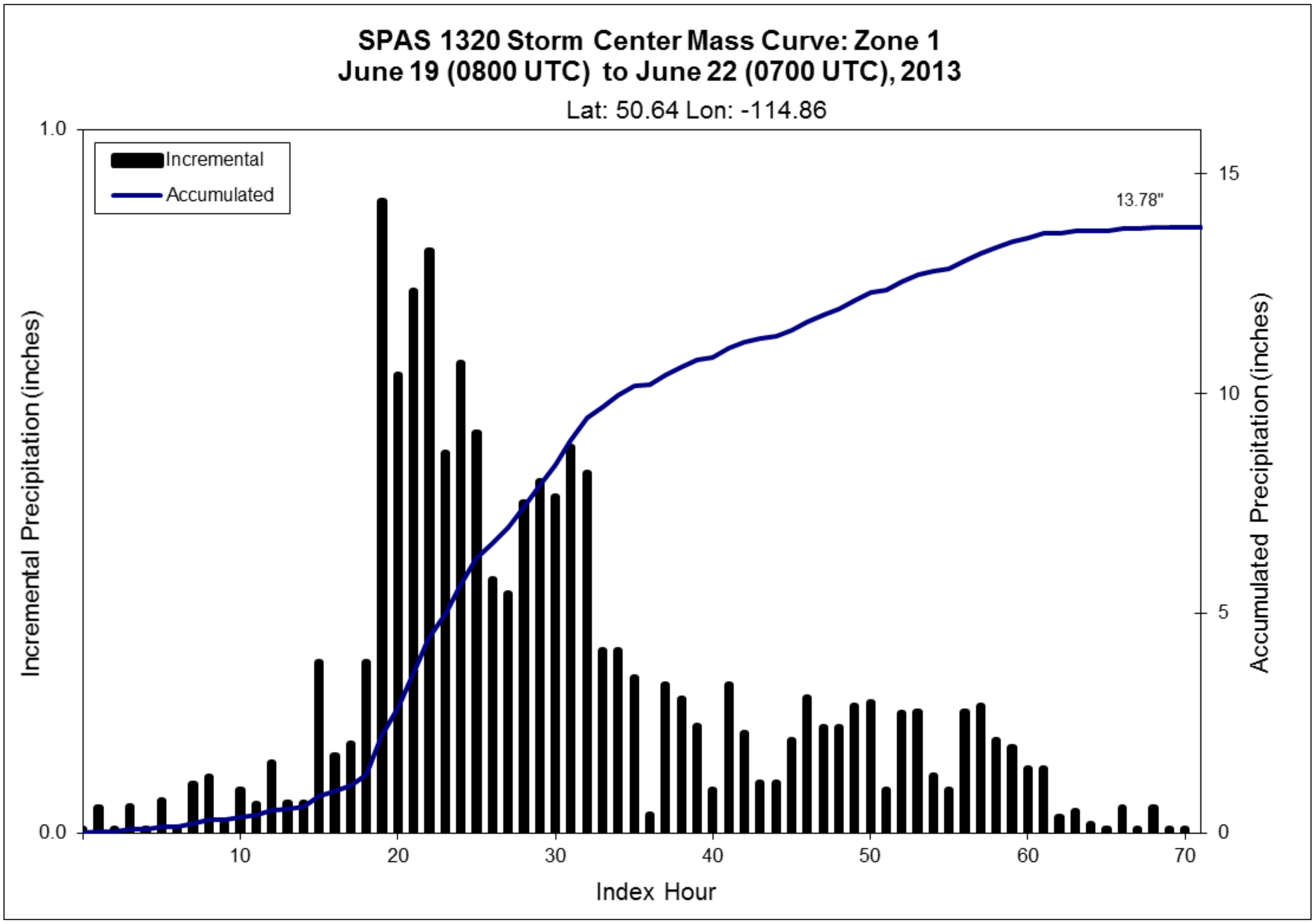
SPAS 1320

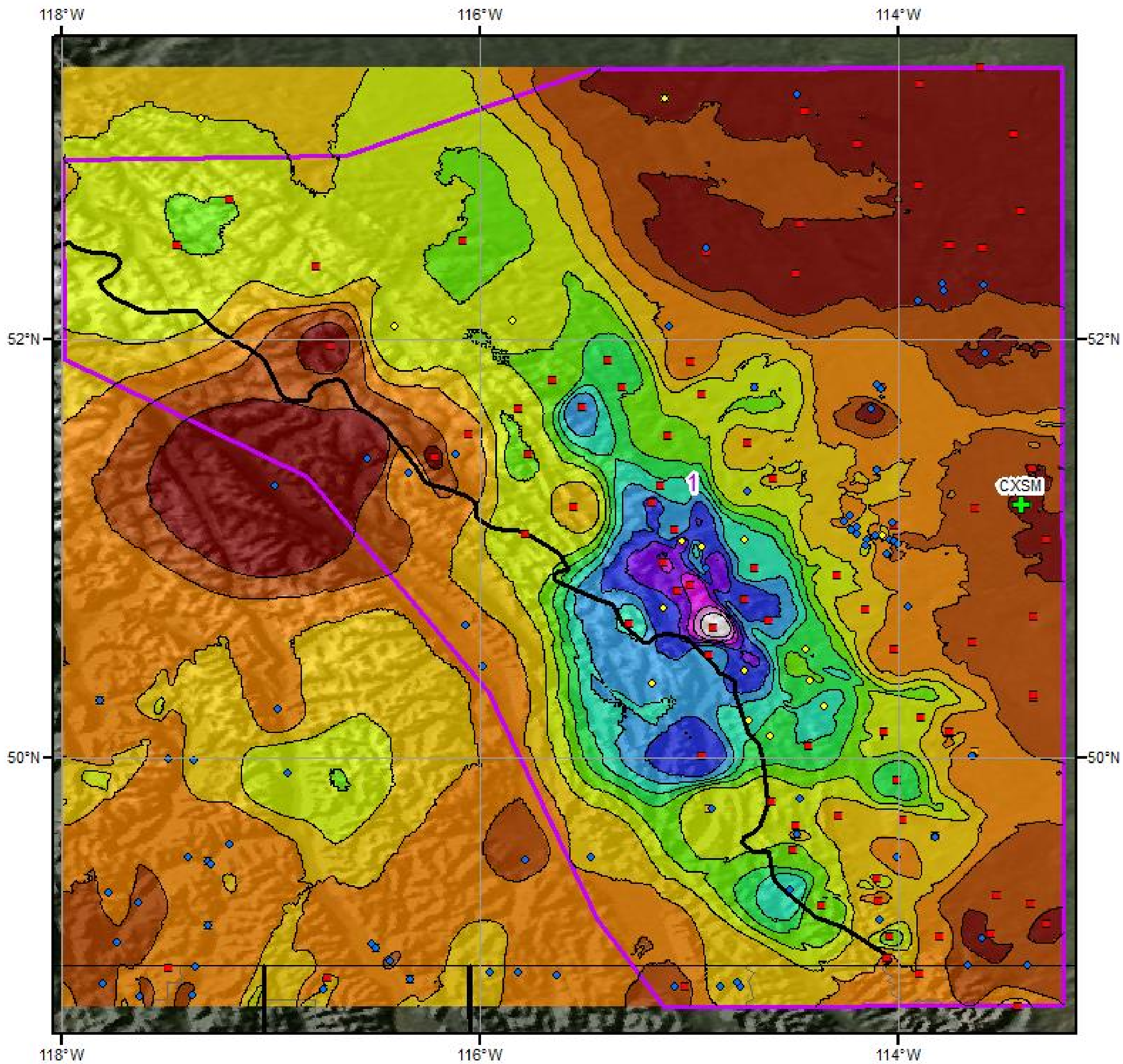
June 19 - 22, 2013



Storm 1320 - June 19 (0800 UTC) - June 22 (0700 UTC), 2013										
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)										
	Duration (hours)									
Area (mi²)	1	3	6	12	18	24	36	48	72	Total
0.3	1.70	2.95	4.36	7.09	9.18	10.08	11.77	13.13	13.78	13.78
1	1.70	2.95	4.36	7.09	9.18	10.08	11.77	13.12	13.78	13.78
10	1.63	2.86	4.34	7.05	9.13	10.02	11.70	13.06	13.69	13.69
25	1.62	2.71	4.30	6.99	9.04	9.93	11.60	12.95	13.55	13.55
50	1.60	2.54	4.20	6.85	8.84	9.71	11.35	12.60	13.29	13.29
100	1.56	2.47	3.95	6.45	8.27	9.01	10.61	12.14	12.70	12.70
200	1.47	2.32	3.67	6.02	7.50	8.35	9.94	11.44	12.02	12.02
300	1.39	2.22	3.52	5.81	7.09	8.02	9.49	10.90	11.59	11.59
400	1.33	2.17	3.17	5.64	6.95	7.42	9.25	10.70	11.27	11.27
500	1.28	2.09	3.12	5.49	6.80	7.41	8.93	10.27	11.07	11.07
1,000	1.05	1.95	3.00	4.89	6.26	6.92	8.18	9.73	10.40	10.40
2,000	0.83	1.74	2.69	4.72	5.51	5.95	7.44	9.00	9.67	9.67
5,000	0.55	1.38	2.33	3.85	4.90	5.49	6.65	7.89	8.36	8.36
10,000	0.40	1.09	1.95	3.44	4.16	4.50	5.19	6.04	7.17	7.17
20,000	0.29	0.75	1.35	2.59	3.26	3.67	4.27	4.93	5.63	5.63
45,132	0.16	0.45	0.81	1.49	2.03	2.34	2.76	3.18	3.51	3.51




SPAS 1320 Storm Center Mass Curve: Zone 1
June 19 (0800 UTC) to June 22 (0700 UTC), 2013
Lat: 50.64 Lon: -114.86
Incremental
Accumulated
13.78"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour
1.0
0.0
15
10
5
0
10
20
30
40
50
60
70

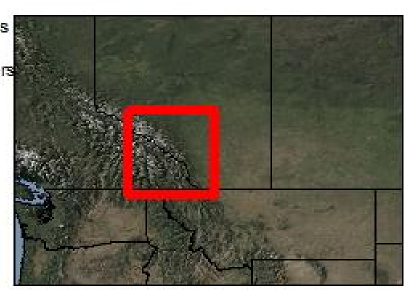


Total Storm (72-hr) Precipitation (inches)
6/19/2013 (0800 UTC) - 6/22/2013 (0700 UTC)
SPAS-NEXRAD 1320

Gauges

- Daily
- Hourly
- Hourly Pseudo
- Supplemental

Miles: 0, 35, 70, 140
Kilometers: 0, 55, 110, 220



6/07/2014

Precipitation (inches)

0.00 - 1.00	3.01 - 4.00	6.01 - 7.00	9.01 - 10.00	12.01 - 13.00
1.01 - 2.00	4.01 - 5.00	7.01 - 8.00	10.01 - 11.00	13.01 - 14.00
2.01 - 3.00	5.01 - 6.00	8.01 - 9.00	11.01 - 12.00	

Savageton, WY

September 27 – October 1, 1923

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1325

General Storm Location: Savageton, Wyoming

Storm Dates: Sept. 27-Oct. 1, 1923

Event: Mid-latitude cyclone

DAD Zone 1

Latitude: 43.8458°

Longitude: -105.8042°

Max. grid rainfall amount: 446mm

Max. observed rainfall amount: 434mm (SAVAGETON WY)

Number of Stations: 111

SPAS Version: 9.5

Base Map Used: Based on digitized HMR Isohyetal Map (storm total Sept. 27-Oct. 1, 1923) and PRISM Sept/Oct monthly mean maps

Spatial resolution: 30 seconds (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of Results: The complex terrain and limited number of hourly and daily data near the primary small storm center diminish the reliability of these results. In particular, there were only 5 hourly stations and their hourly data were estimated from USACE's smoothed mass rainfall curves. We theorize that the hourly data at these storm centers were estimated by USBR based on information (non-gauge data) available to them at the time. However, given this was a synoptic storm with large areas of nearly continuous precipitation (rainfall), it's believed the temporal distribution of precipitation is fairly reliable. The use of the U.S. Army Corps of Engineers' isohyetal pattern coupled with the monthly mean maps for September and October provides some confidence in the spatial patterns and magnitudes of precipitation. Lastly, orographic effects (accounted for in the PRISM maps) have created a maxima in the grid (17.56") that is slightly higher than the maximum observed at a station (17.10") in the storm center; the effect at the storm center was constrained by editing the basemap.

Storm Name:	SPAS 1325 Savageton, WY	Storm Adjustment Summary
Storm Date:	9/27-30/1923	
AWA Analysis Date:	7/20/2015	

Temporal Transposition Date 15-Sep

	Lat	Long
Storm Center Location	43.85 N	105.80 W
Storm Rep Dew Point Location	38.90 N	100.08 W
Transposition Dew Point Locatio	N/A*	N/A*
Basin Location	50.89 N	114.69 W

Moisture Inflow Direction	SE @ 724	kilometers
Basin Average Elevation	N/A*	meters
Storm Center Elevation	1,455	meters
Storm Analysis Duration	24	hours

The storm representative dew point is	21.9 °C	with total precipitable water above sea level of		61	millimeters.
The in-place maximum dew point is	23.6 °C	with total precipitable water above sea level of		71	millimeters.
The transpositioned maximum dew point is	N/A*	with total precipitable water above sea level of		N/A*	millimeters.
The in-place storm elevation is	1,455	which subtracts	24	millimeters of precipitable water at	21.9 °C
The in-place storm elevation is	1,455	which subtracts	26	millimeters of precipitable water at	23.6 °C
The transposition basin elevation at	N/A*	which subtracts	N/A*	millimeters of precipitable water at	N/A*

The in-place storm maximization factor is	1.18
The transposition/elevation to basin factor is	N/A*
The barrier adjustment factor is	N/A*
The total adjustment factor is	N/A*

Notes: DAD values taken from SPAS 1325. Storm representative dew point value was based on maximum 24-hr Td values on September 26-29, 1923 at KLBF and KDDC. Values were selected in region where temperature did not vary more than a 1-degree over a large area.

Observed Storm Depth-Area-Duration (millimeters)

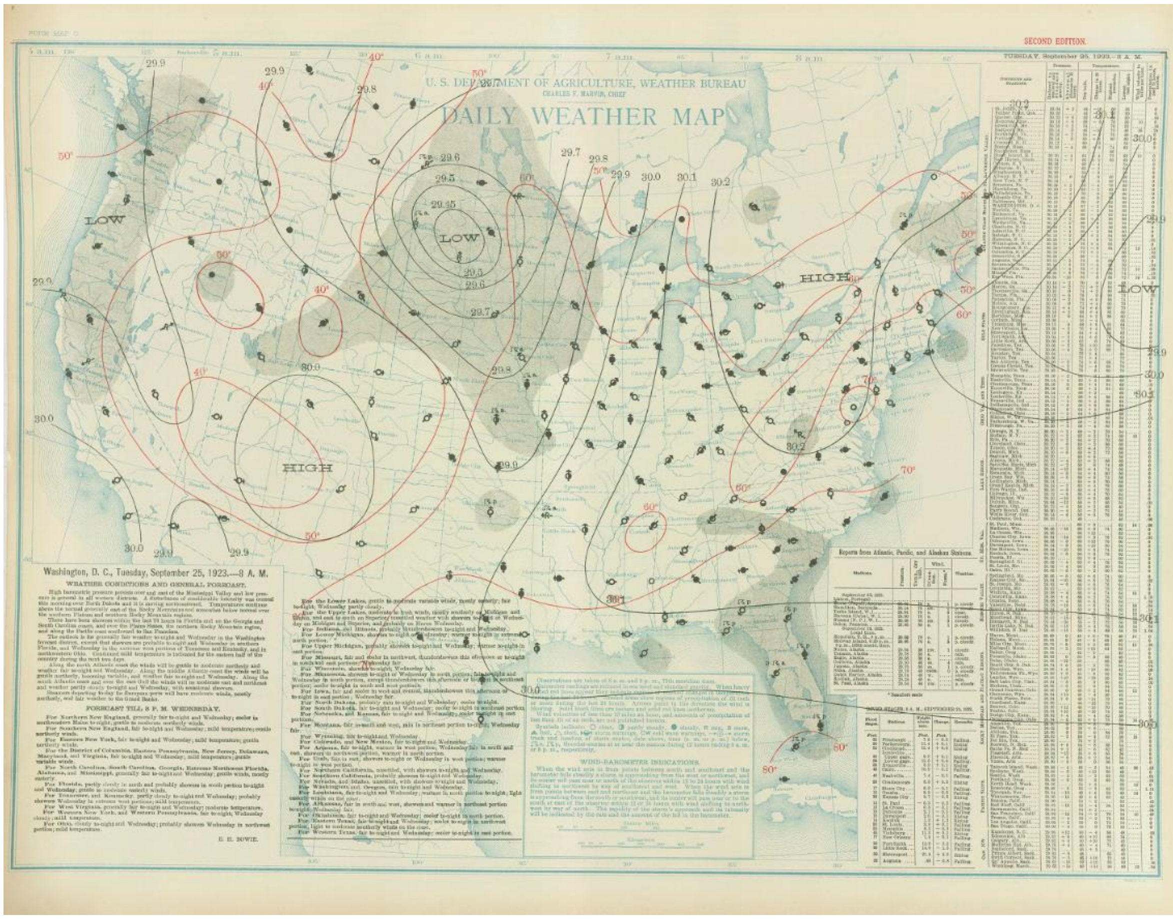
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	30		91			114	218	262	442
26 km^2 (10 mi^2)	30		91			114	216	262	439
259 km^2 (100 mi^2)	28		84			107	206	246	409
518 km^2 (200 mi^2)	28		79			102	196	236	396
1,295 km^2 (500 mi^2)	23		64			91	165	206	353
2,590 km^2 (1,00 mi^2)	18		48			74	147	170	305
5,180 km^2 (2,000 mi^2)	18		38			69	99	135	234
12.950 km^2 (5000 mi^2)	13		30			51	81	99	165
,900 km^2 (10,000 mi^2)	10		28			46	69	89	132
,800 km^2 (20,000 mi^2)	10		20			36	58	76	112

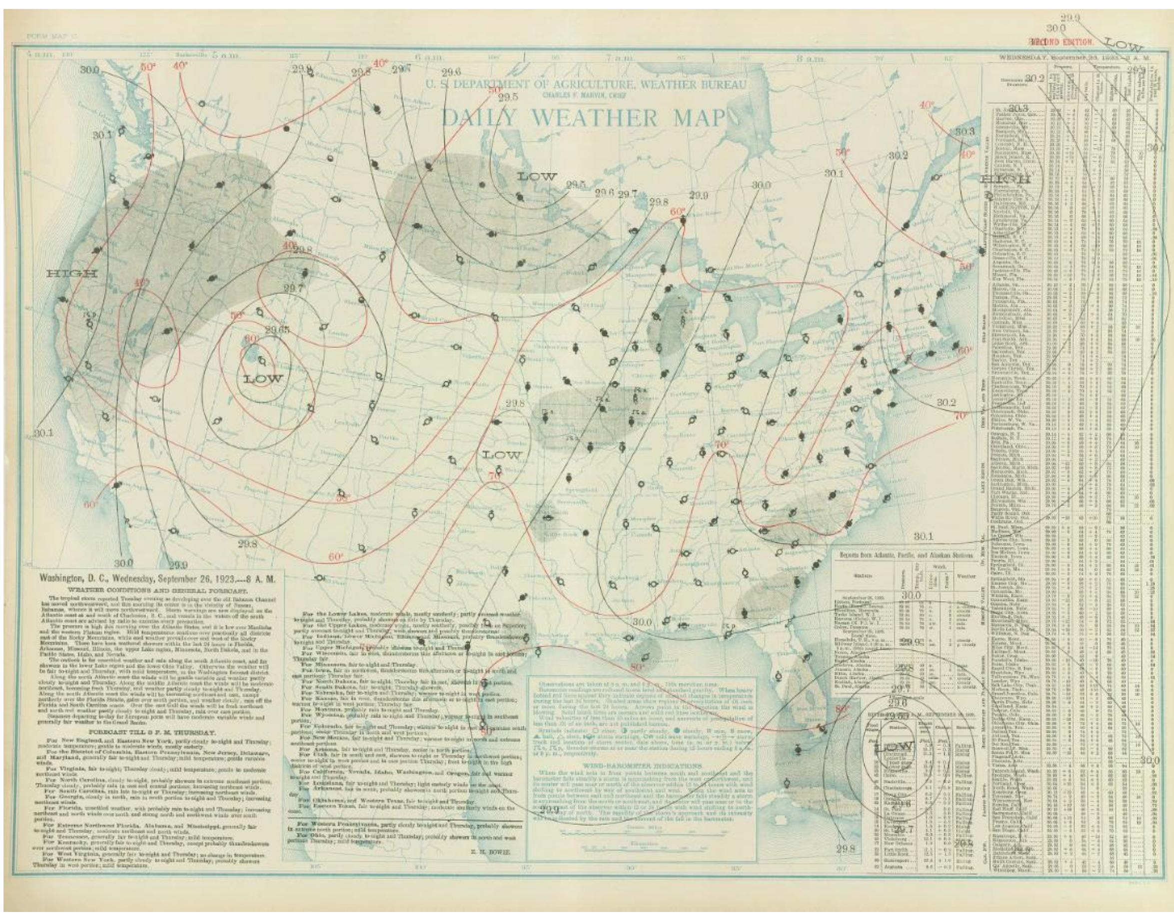
Adjusted Storm Depth-Area-Duration (millimeters)

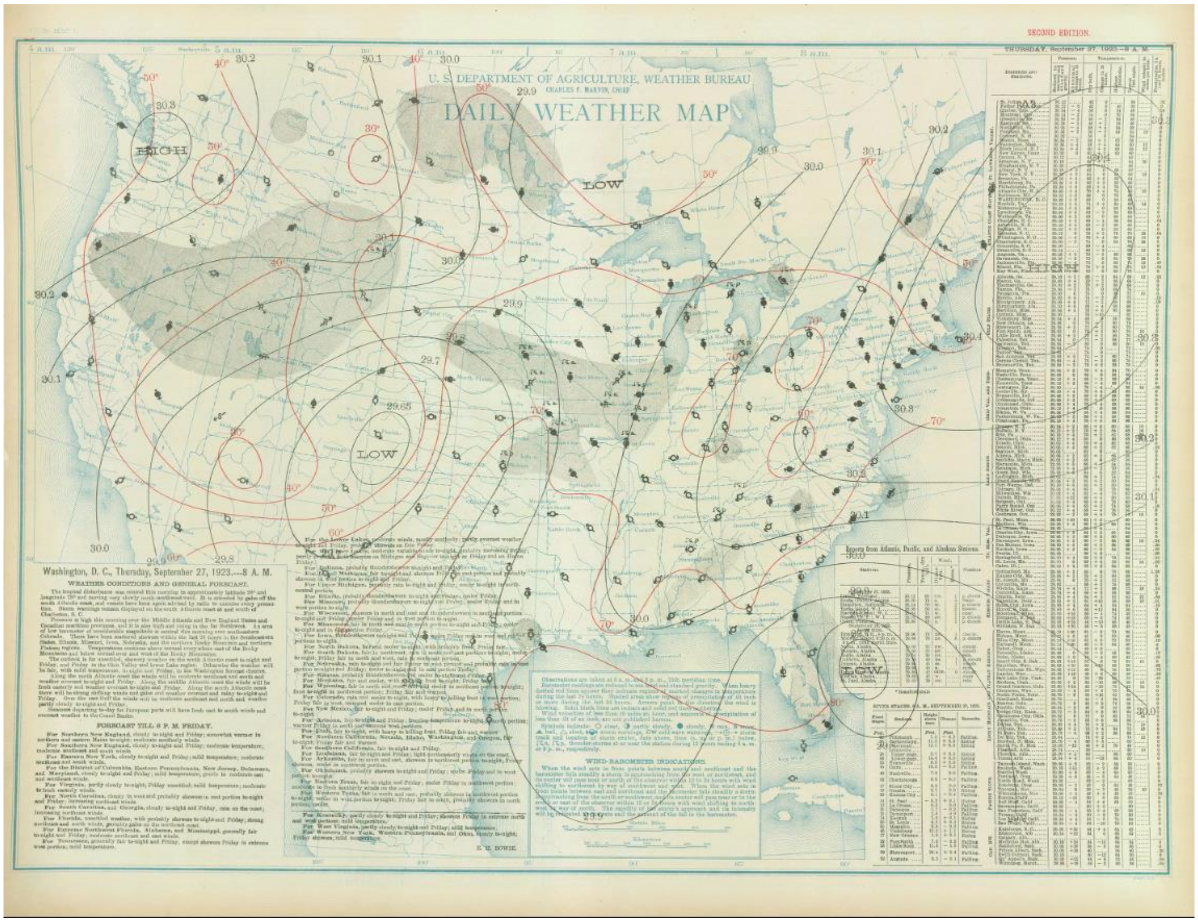
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
26 km2 (10 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
259 km2 (100 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
518 km2 (200 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
1,295 km2 (500 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
2,590 km2 (1,00 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
5,180 km2 (2,000 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
2.950 km2 (5000 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
900 km2 (10,000 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*
800 km2 (20,000 mi2)	N/A*		N/A*			N/A*	N/A*	N/A*	N/A*

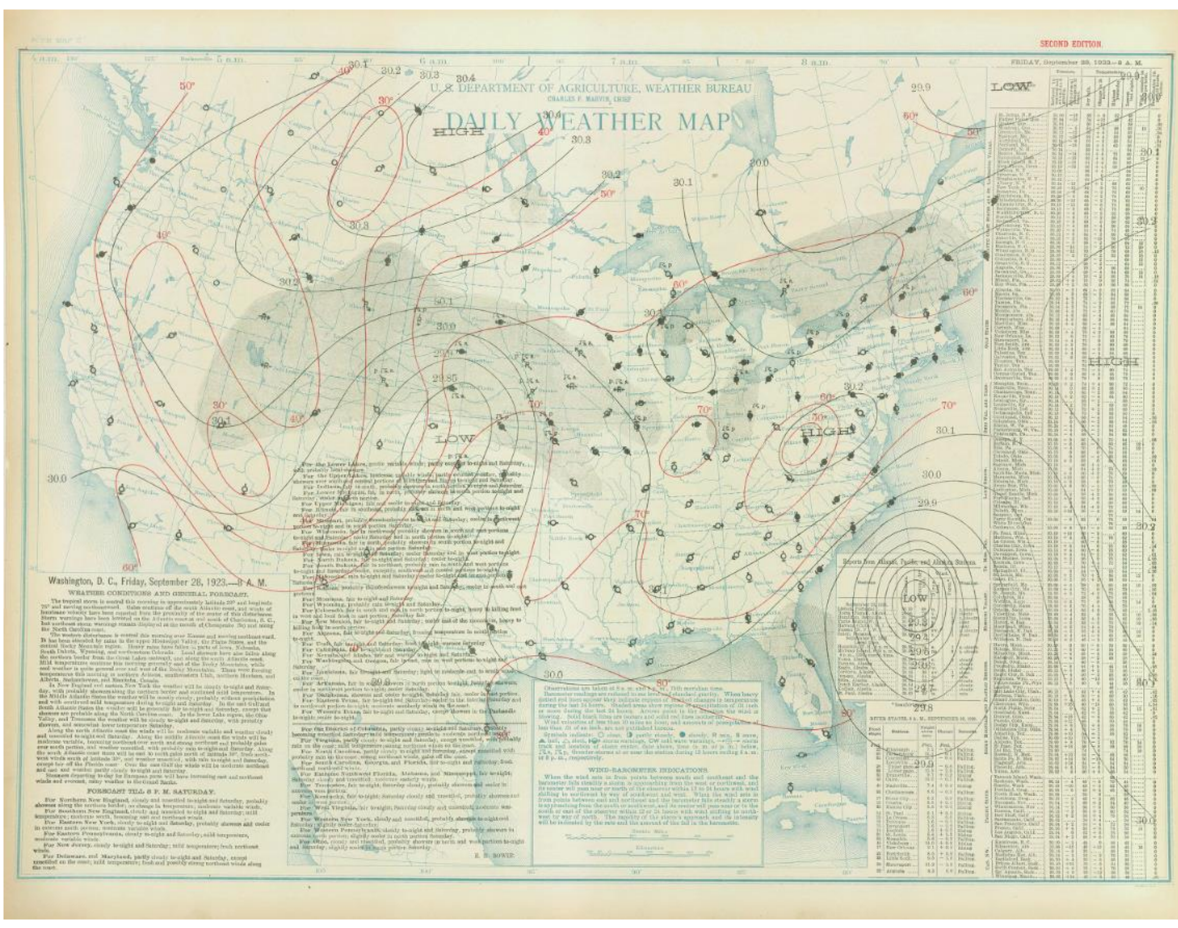
Storm or Storm Center Name	**SPAS 1325 Savageton, WY**	
Storm Date(s)	9/27-30/1923	
Storm Type	Synoptic	
Storm Location	43.85 N	105.80 W
Storm Center Elevation	1,455	meters
Precipitation Total & Duration	446	millimeters 96 hours
Storm Representative Dew Point	21.9 °C	24
Storm Representative Dew Point Location	38.90 N	100.08 W
Maximum Dew Point	23.6 °C	
Moisture Inflow Vector	SE @ 724	kilometers
In-place Maximization Factor	**1.18**	
Temporal Transposition (Date)	15-Sep	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

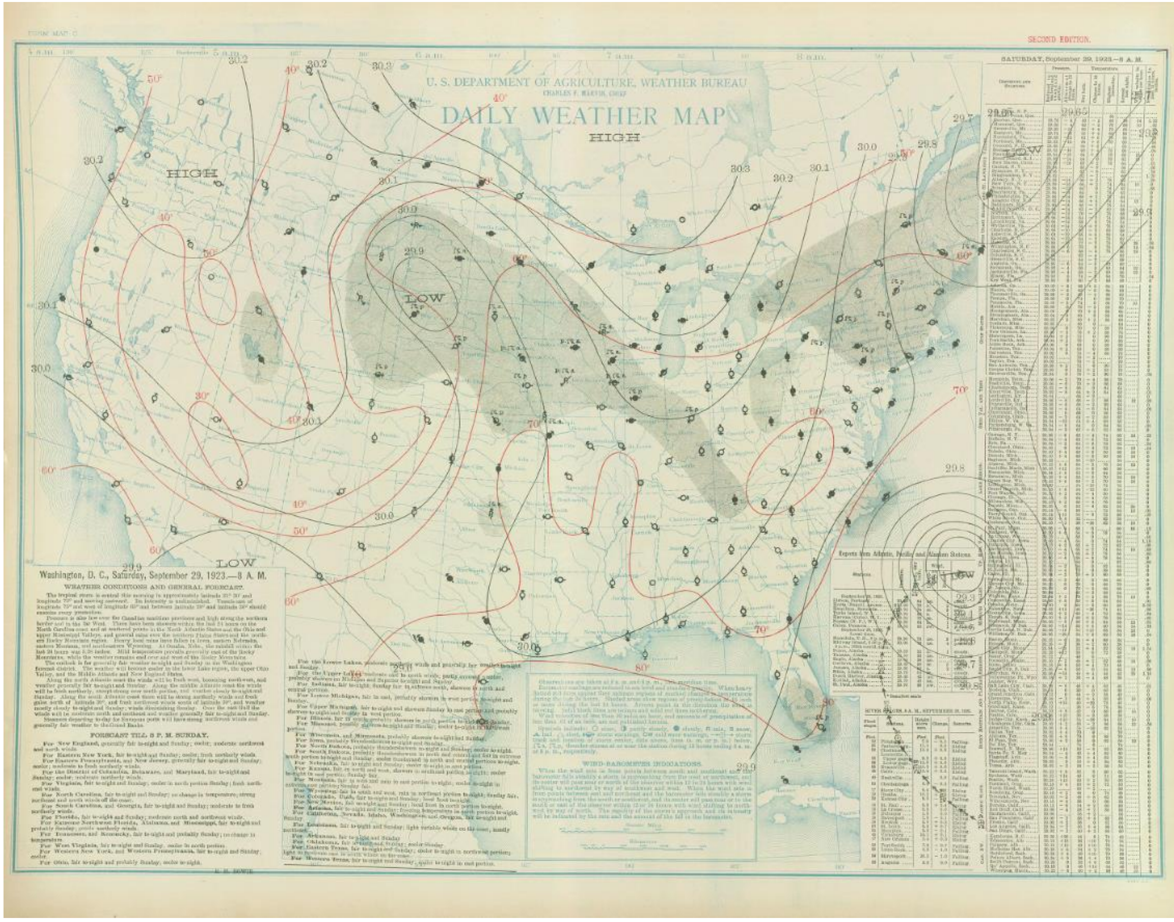
*Variable dependent on transposition location

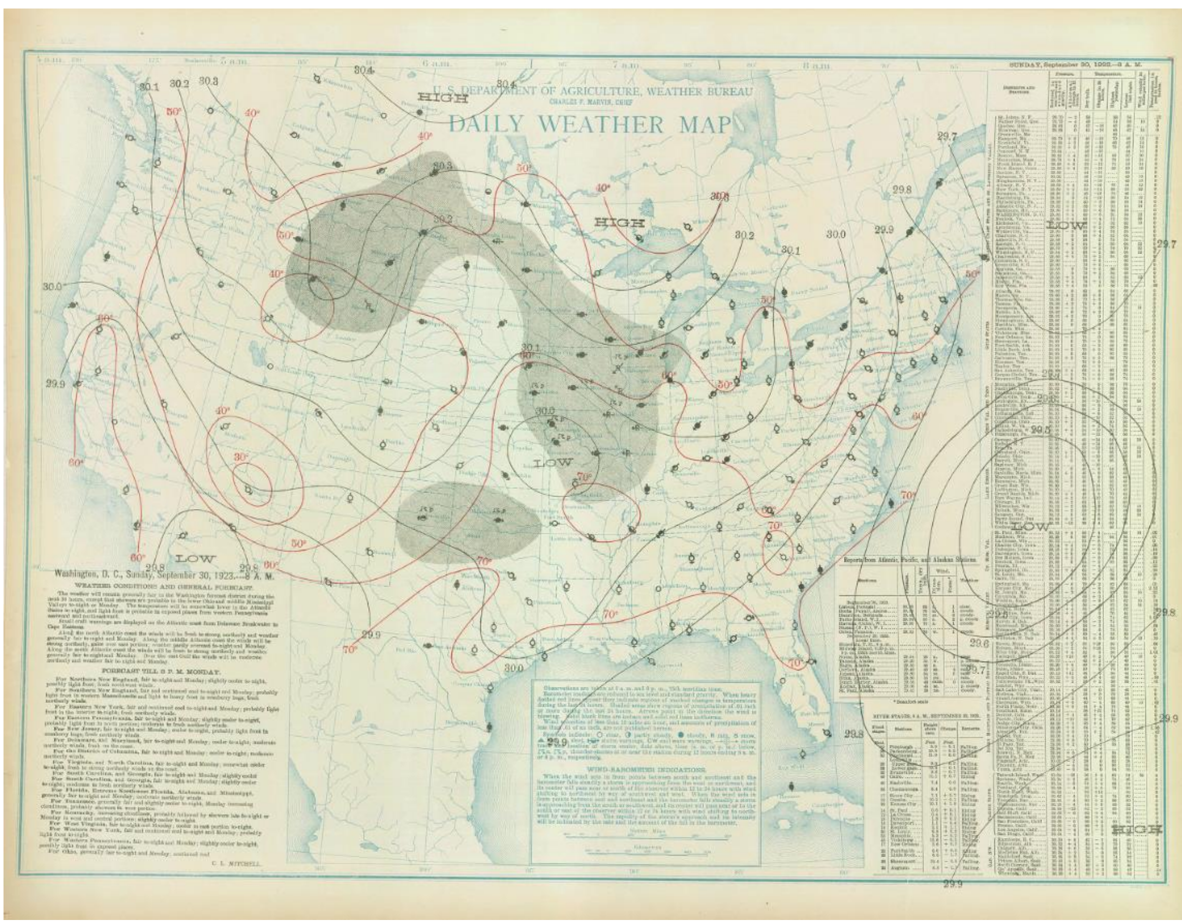

SECOND EDITION.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
LOW
HIGH
Washington, D. C., Tuesday, September 25, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. WEDNESDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations

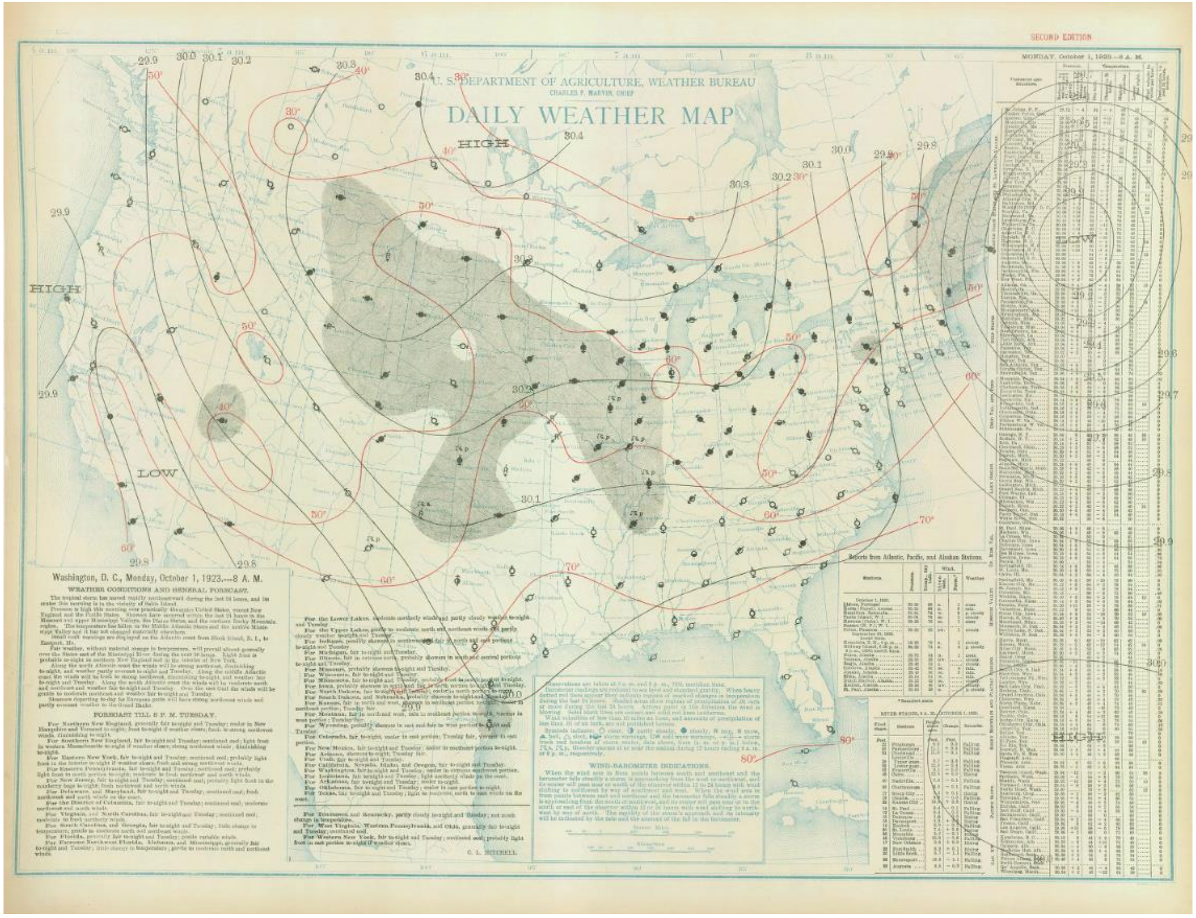

SECOND EDITION.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
LOW
HIGH
Washington, D. C., Wednesday, September 26, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. THURSDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations


SECOND EDITION.
THURSDAY, September 27, 1923—8 A. M.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
HIGH
LOW
LOW
HIGH
LOW
Washington, D. C., Thursday, September 27, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. FRIDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations.
E. B. GARRIOTT

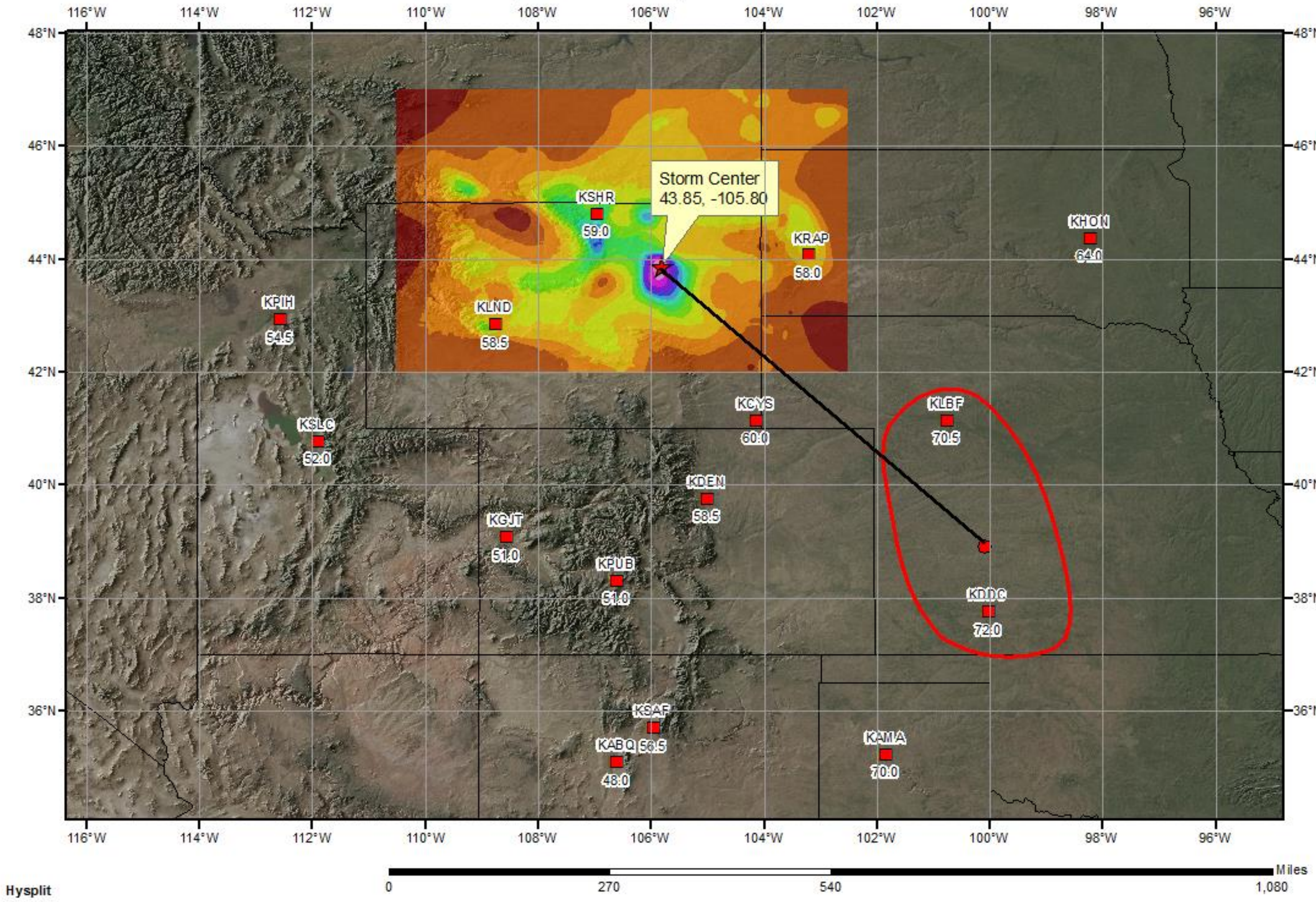

SECOND EDITION.
FRIDAY, September 28, 1923—8 A. M.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
HIGH
LOW
LOW
HIGH
HIGH
LOW
Washington, D. C., Friday, September 28, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SATURDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations.


SECOND EDITION.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
SATURDAY, September 29, 1923—8 A. M.
HIGH
LOW
Washington, D. C., Saturday, September 29, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SUNDAY.
WIND-BAROMETER INDICATIONS.

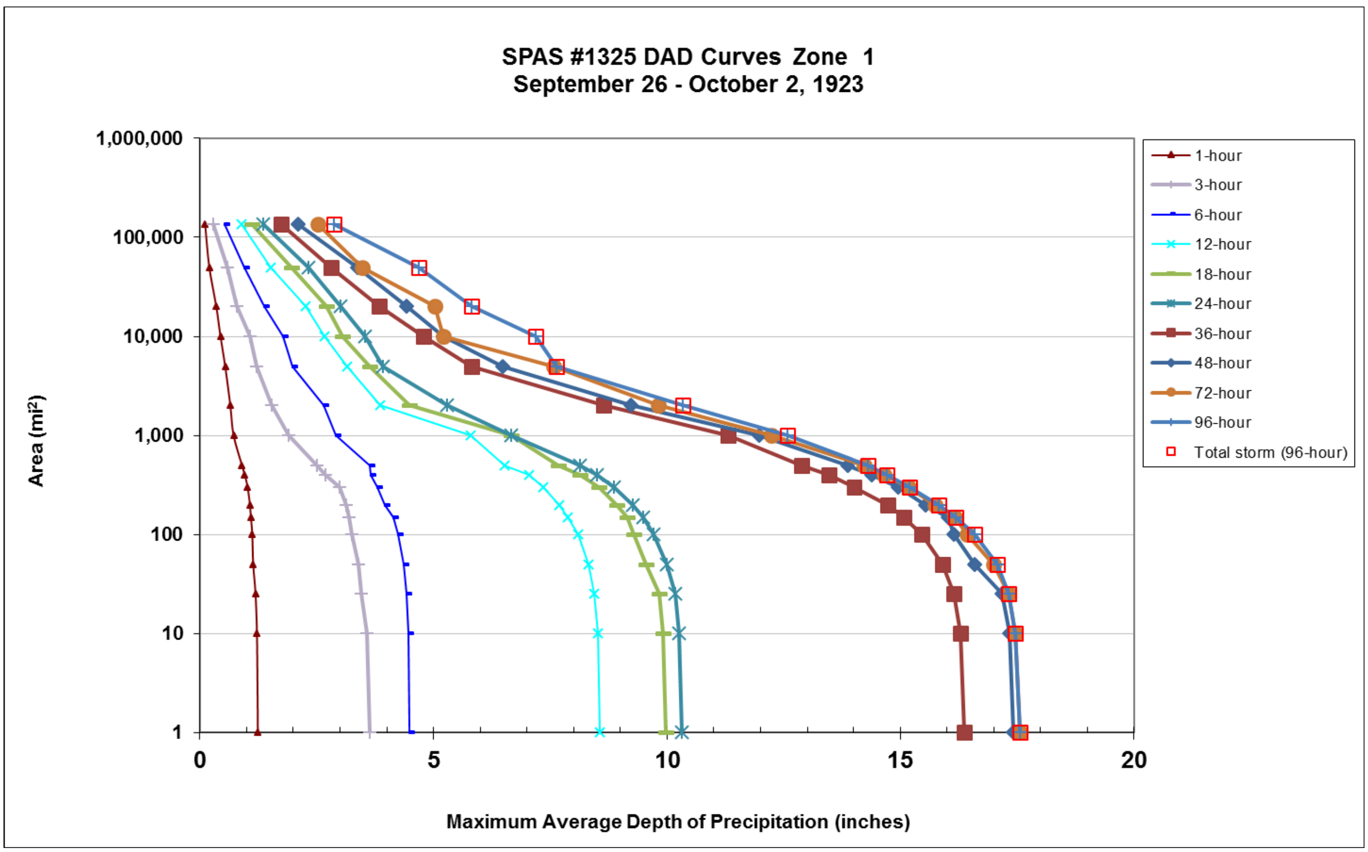

U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
SUNDAY, September 30, 1923—8 A. M.
HIGH
LOW
Washington, D. C., Sunday, September 30, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. MONDAY.
WIND-BAROMETER INDICATIONS.


SECOND EDITION
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Monday, October 1, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. TUESDAY.
WIND-BAROMETER INDICATIONS.

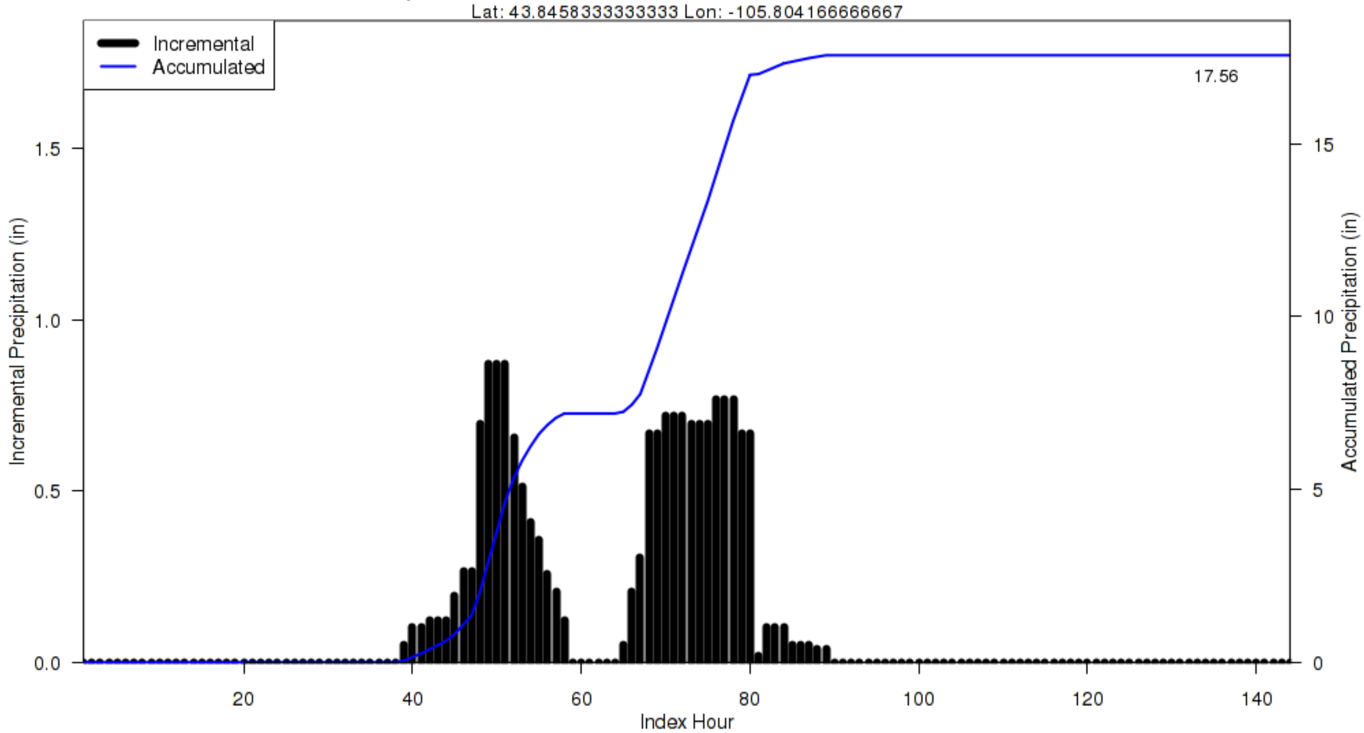
SPAS 1325 Savageton, WY Storm Analysis
September 26-29, 1923

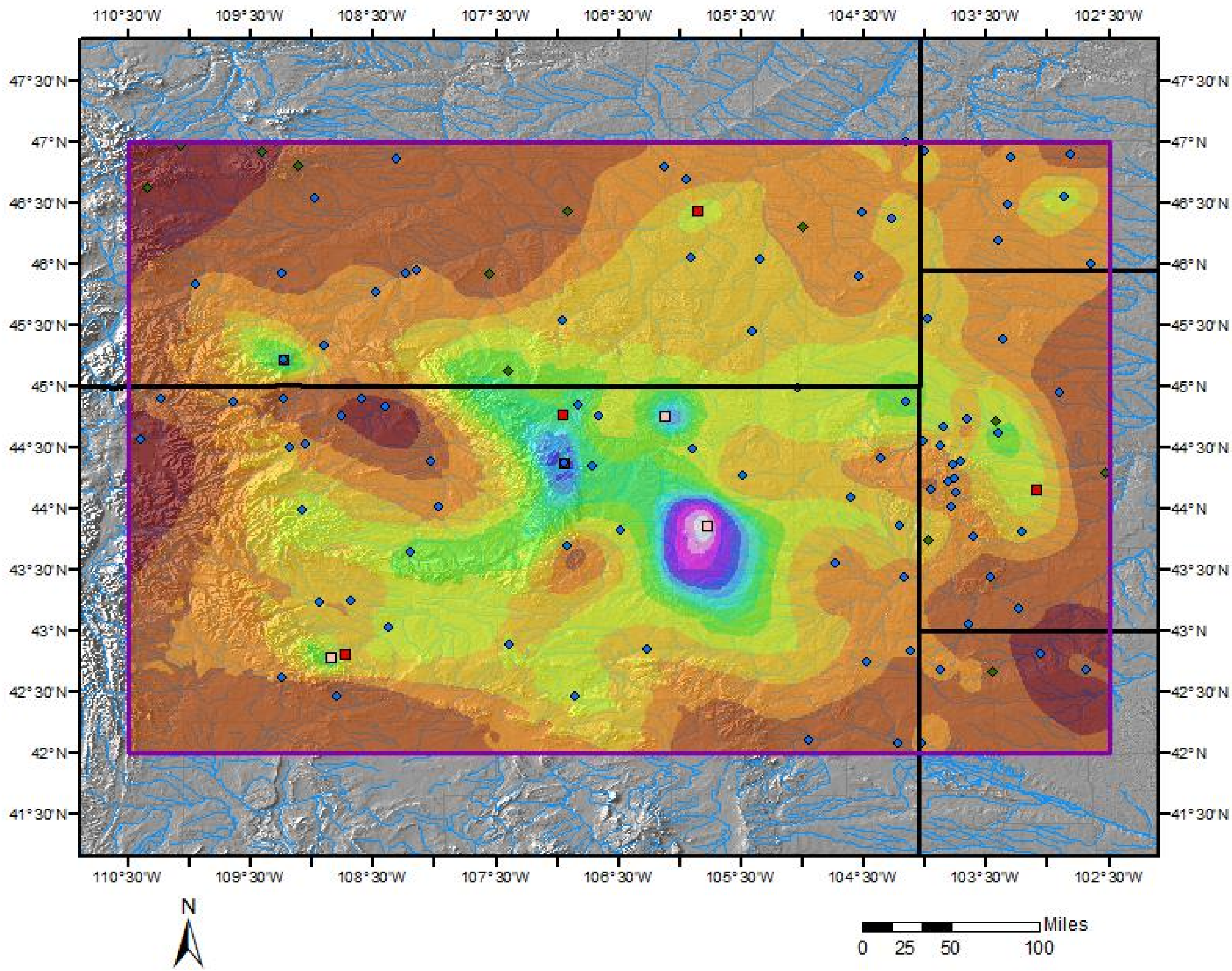


SPAS 1325 - September 26 (0800 UTC) - October 2 (0700 UTC), 1923											
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)											
	Duration (hours)										
Area (mi^2)	1	3	6	12	18	24	36	48	72	96	Total
0.2	1.24	3.65	4.59	8.56	9.97	10.32	16.37	17.43	17.56	17.56	17.56
1	1.24	3.64	4.49	8.56	9.97	10.32	16.36	17.42	17.55	17.55	17.55
10	1.22	3.57	4.47	8.52	9.92	10.26	16.28	17.33	17.46	17.46	17.46
25	1.19	3.46	4.43	8.44	9.83	10.17	16.14	17.18	17.31	17.31	17.31
50	1.14	3.39	4.36	8.32	9.55	9.99	15.91	16.60	16.99	17.07	17.07
100	1.12	3.26	4.24	8.09	9.28	9.71	15.47	16.14	16.43	16.60	16.60
150	1.09	3.20	4.14	7.88	9.15	9.49	15.08	16.03	16.17	16.19	16.19
200	1.07	3.13	3.96	7.69	8.92	9.26	14.73	15.55	15.74	15.83	15.83
300	1.02	2.98	3.80	7.35	8.54	8.86	14.00	14.96	15.18	15.20	15.20
400	0.96	2.69	3.66	7.05	8.13	8.49	13.46	14.40	14.66	14.71	14.71
500	0.90	2.50	3.63	6.53	7.67	8.14	12.88	13.87	14.23	14.32	14.32
1,000	0.72	1.91	2.91	5.79	6.66	6.66	11.31	11.97	12.24	12.58	12.58
2,000	0.65	1.53	2.65	3.86	4.48	5.30	8.63	9.22	9.81	10.34	10.34
5,000	0.54	1.21	1.99	3.16	3.64	3.92	5.82	6.48	7.57	7.64	7.64
10,000	0.44	1.08	1.77	2.66	3.05	3.53	4.78	5.20	5.20	7.19	7.19
20,000	0.35	0.79	1.37	2.26	2.71	3.01	3.83	4.43	5.02	5.81	5.81
50,000	0.20	0.58	0.96	1.52	1.97	2.32	2.81	3.37	3.47	4.69	4.69
136,442	0.11	0.29	0.52	0.90	1.12	1.35	1.74	2.11	2.52	2.87	2.87

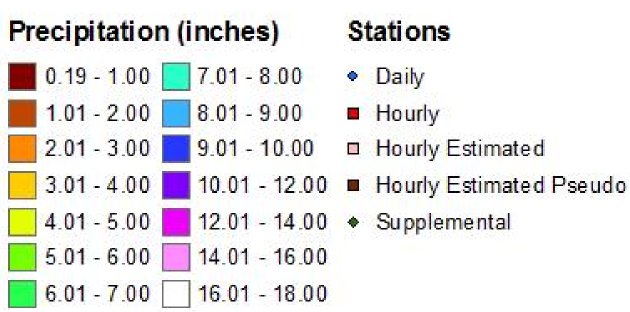


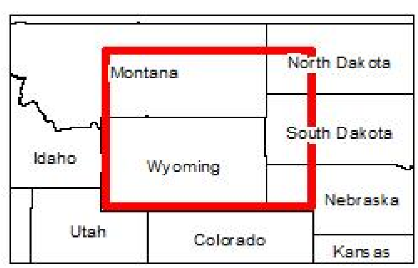
SPAS 1325 Storm Center Mass Curve Zone 1
September 26 (0800UTC) to October 2 (0700UTC), 1923
Lat: 43.8458333333333 Lon: -105.804166666667





Total 144-hr Precipitation (inches)
September 26, 1923 0800 UTC - October 2,1923 0800 UTC
SPAS #1325





DLM 04/10/2014

Warrick, MT

June 5-9, 1906

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1335

General Storm Location: Warrick, MT

Storm Dates: June 5-9, 1906

Event: Mid-latitude cyclone with embedded convection

DAD Zone 1

Latitude: 48.0791°

Longitude: -109.7041°

Max. grid rainfall amount: 348mm

Max. observed rainfall amount: 338mm (Warrick, MT)

Number of Stations: 50

SPAS Version: 9.5

Base Map Used: Digitized HMR Isohyetal Map (plus some manual edits)

Spatial resolution: 30 seconds (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of Results: Very strong winds accompanied this storm, especially the morning of June 6^{th} through the morning of June 8^{th}, likely resulted in severe gauge under-catch. Only 5 hourly gauges (some estimated) were utilized, therefore casting higher than usual uncertainly on the timing of precipitation during this large storm. The timing is most reliable at 6-hour intervals; use caution with the 1-5 hour DAD results. Very few daily/supplemental stations were available for this storm, so the precipitation magnitudes are somewhat uncertain as well. The results are consistent with USACE/NWS analysis (MR 5-13) of this storm. This storm was analyzed as part of HMR55A. The influence of orographically significant terrain near Warrick (and the wind-induced under-catch) justified a slight increase in the measured storm maximum from 13.31” to 13.69”.

Storm Name:	**SPAS 1335 Warrick, MT**	
Storm Date:	**6/5-9/1906**	**Storm Adjustment Summary**
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **20-Jun**

	Lat	Long
Storm Center Location	**48.08 N**	**109.70 W**
Storm Rep Dew Point Location	**45.92 N**	**102.20 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**ESE @ 612**	kilometers
Basin Average Elevation	N/A*	meters
Storm Center Elevation	**1,250**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**18.9 °C**	with total precipitable water above sea level of			**47**	millimeters.
The in-place maximum dew point is	**24.2 °C**	with total precipitable water above sea level of			**74**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of			**N/A***	millimeters.
The in-place storm elevation is	**1,250**	which subtracts	**17**	millimeters of precipitable water at	**18.9 °C**	
The in-place storm elevation is	**1,250**	which subtracts	**24**	millimeters of precipitable water at	**24.2 °C**	
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***	

The in-place storm maximization factor is	**1.50**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Storm rep Td taken from USACE/NWS analysis and added 2°F to convert 12-hr persisting to 24-hr average value. In-place max factor calcualted at 1.68, held to 1.50 based on HMR guidance.

Observed Storm Depth-Area-Duration (millimeters)

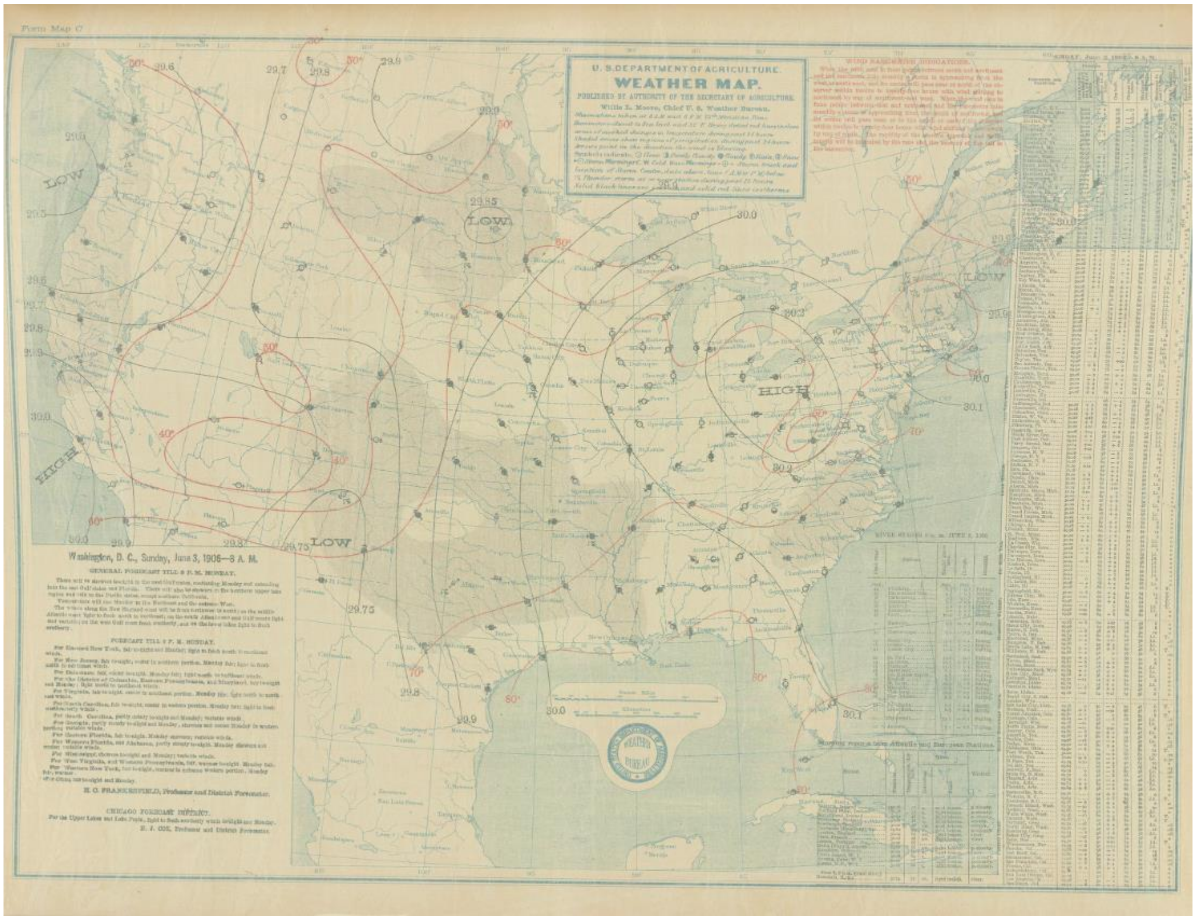
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**36**		**94**			**152**	**193**	**251**	**348**
26 km^2 (10 mi^2)	**36**		**94**			**150**	**188**	**249**	**345**
259 km^2 (100 mi^2)	**33**		**86**			**137**	**170**	**231**	**318**
518 km^2 (200 mi^2)	**30**		**79**			**130**	**163**	**218**	**295**
1,295 km^2 (500 mi^2)	**25**		**69**			**109**	**142**	**193**	**269**
2,590 km^2 (1,00 mi^2)	**20**		**51**			**91**	**117**	**160**	**229**
5,180 km^2 (2,000 mi^2)	**15**		**41**			**71**	**81**	**122**	**180**
12.950 km^2 (5000 mi^2)	**13**		**36**			**58**	**76**	**97**	**135**
25,900 km^2 (10,000 mi^2)	**13**		**28**			**46**	**61**	**86**	**130**
51,800 km^2 (20,000 mi^2)	**10**		**23**			**36**	**53**	**69**	**107**

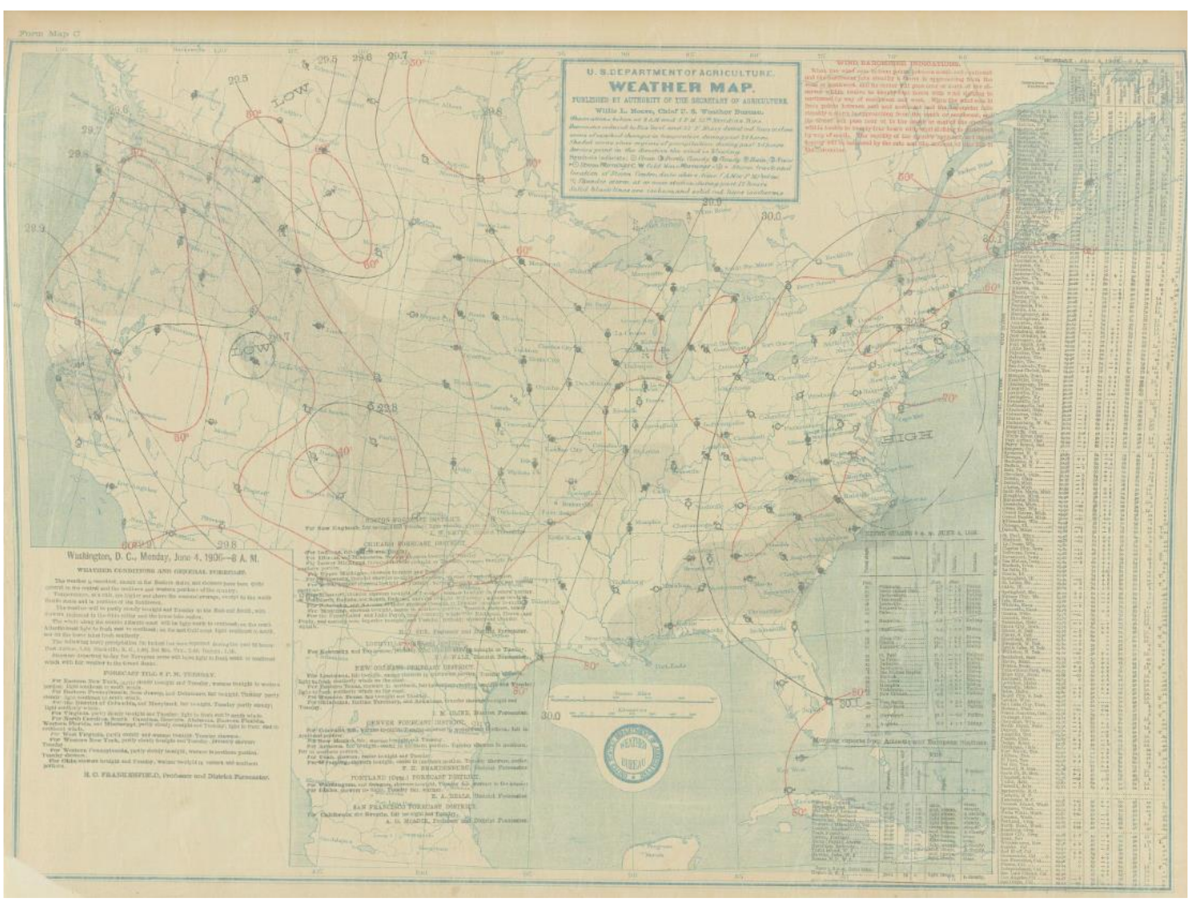
Adjusted Storm Depth-Area-Duration (millimeters)

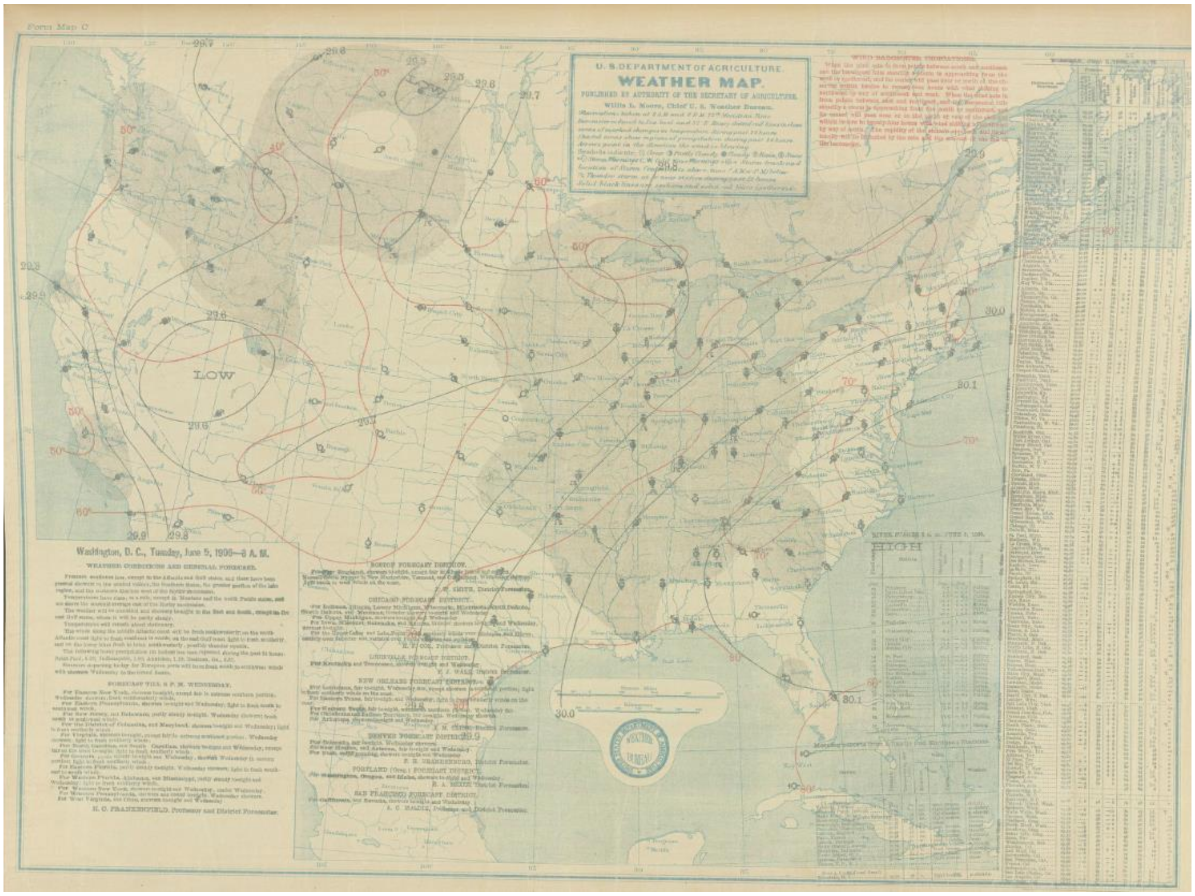
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***

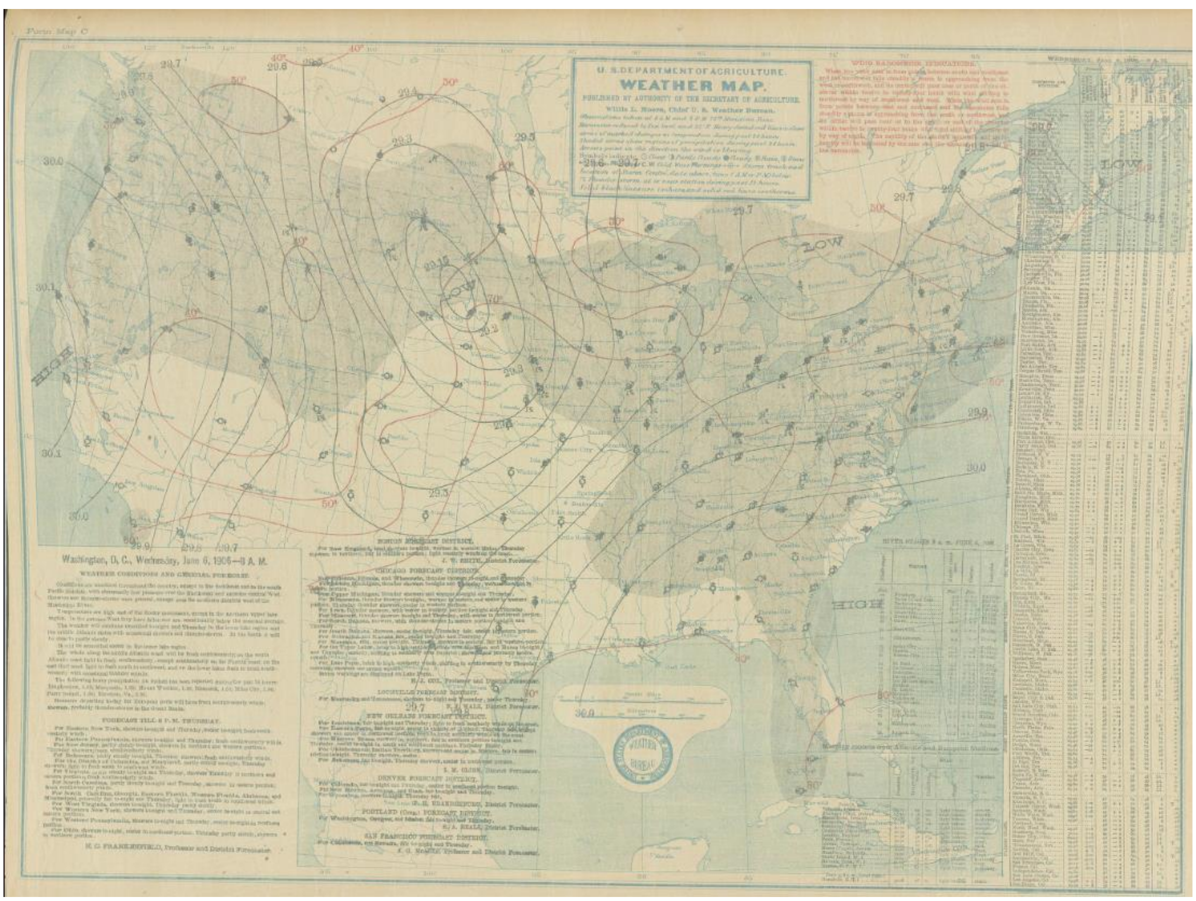
Storm or Storm Center Name	**SPAS 1335 Warrick, MT**	
Storm Date(s)	6/5-9/1906	
Storm Type	MCC/Synoptic	
Storm Location	48.08 N	109.70 W
Storm Center Elevation	1,250	meters
Precipitation Total & Duration	348	millimeters 48 hours
Storm Representative Dew Point	18.9 °C	24
Storm Representative Dew Point Location	45.92 N	102.20 W
Maximum Dew Point	24.2 °C	
Moisture Inflow Vector	ESE @ 612 kilometers	
In-place Maximization Factor	**1.50**	
Temporal Transposition (Date)	20-Jun	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

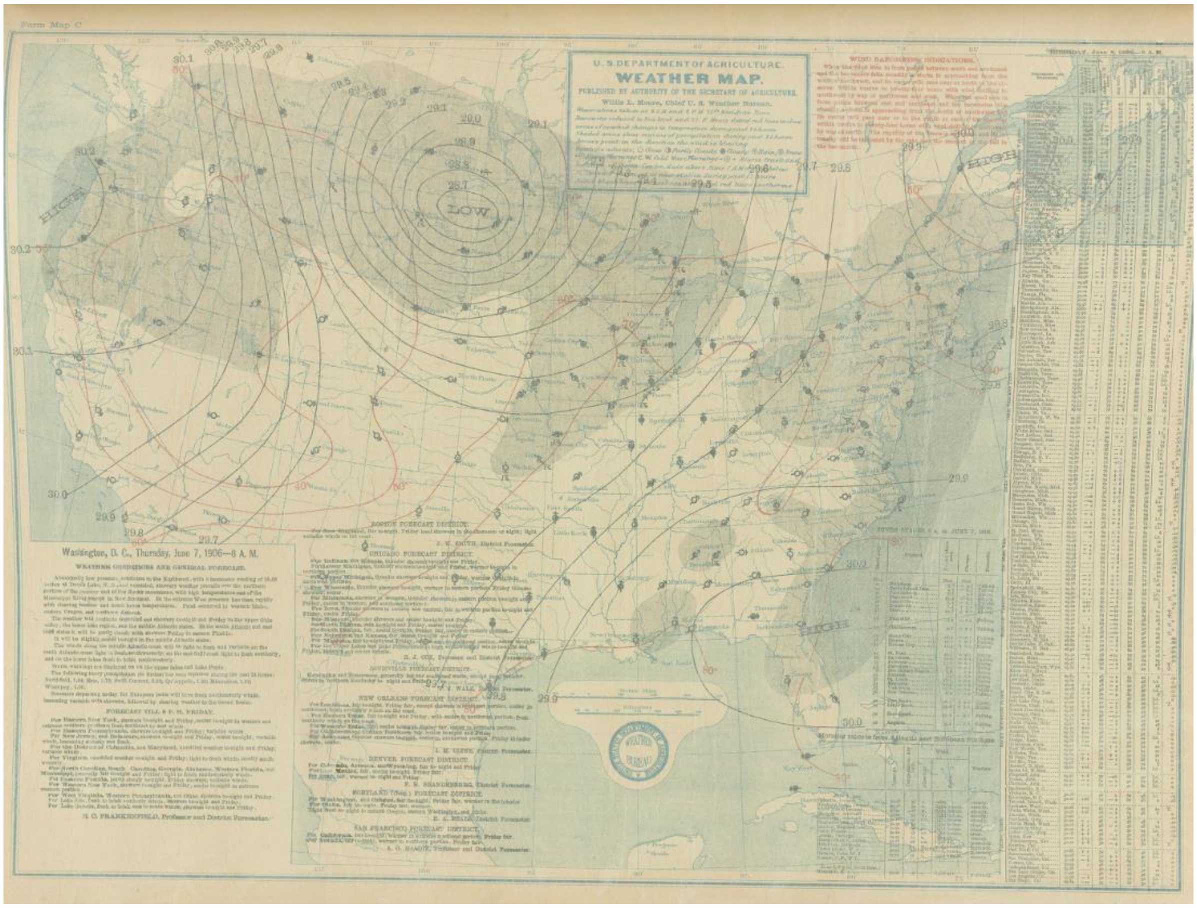
*Variable dependent on transposition location


Form Map C
U. S. DEPARTMENT OF AGRICULTURE.
WEATHER MAP.
PUBLISHED BY AUTHORITY OF THE SECRETARY OF AGRICULTURE.
Willis L. Moore, Chief U. S. Weather Bureau.
LOW
HIGH
Washington, D. C., Sunday, June 3, 1906—8 A. M.
GENERAL FORECAST TILL 8 P. M. MONDAY.
FORECAST TILL 8 P. M. MONDAY.
H. C. FRANKENFIELD, Professor and District Forecaster.
CHICAGO FORECAST DISTRICT.
WEATHER BUREAU


Form Map C
U. S. DEPARTMENT OF AGRICULTURE.
WEATHER MAP.
PUBLISHED BY AUTHORITY OF THE SECRETARY OF AGRICULTURE.
Willis L. Moore, Chief U. S. Weather Bureau.
LOW
HIGH
Washington, D. C., Monday, June 4, 1906—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. TUESDAY.
H. C. FRANKENFIELD, Professor and District Forecaster.
WEATHER BUREAU


U. S. DEPARTMENT OF AGRICULTURE.
WEATHER MAP.
LOW
HIGH
Washington, D. C., Tuesday, June 5, 1906—8 A. M.


U. S. DEPARTMENT OF AGRICULTURE.
WEATHER MAP.
LOW
HIGH
Washington, D. C., Wednesday, June 6, 1906—8 A. M.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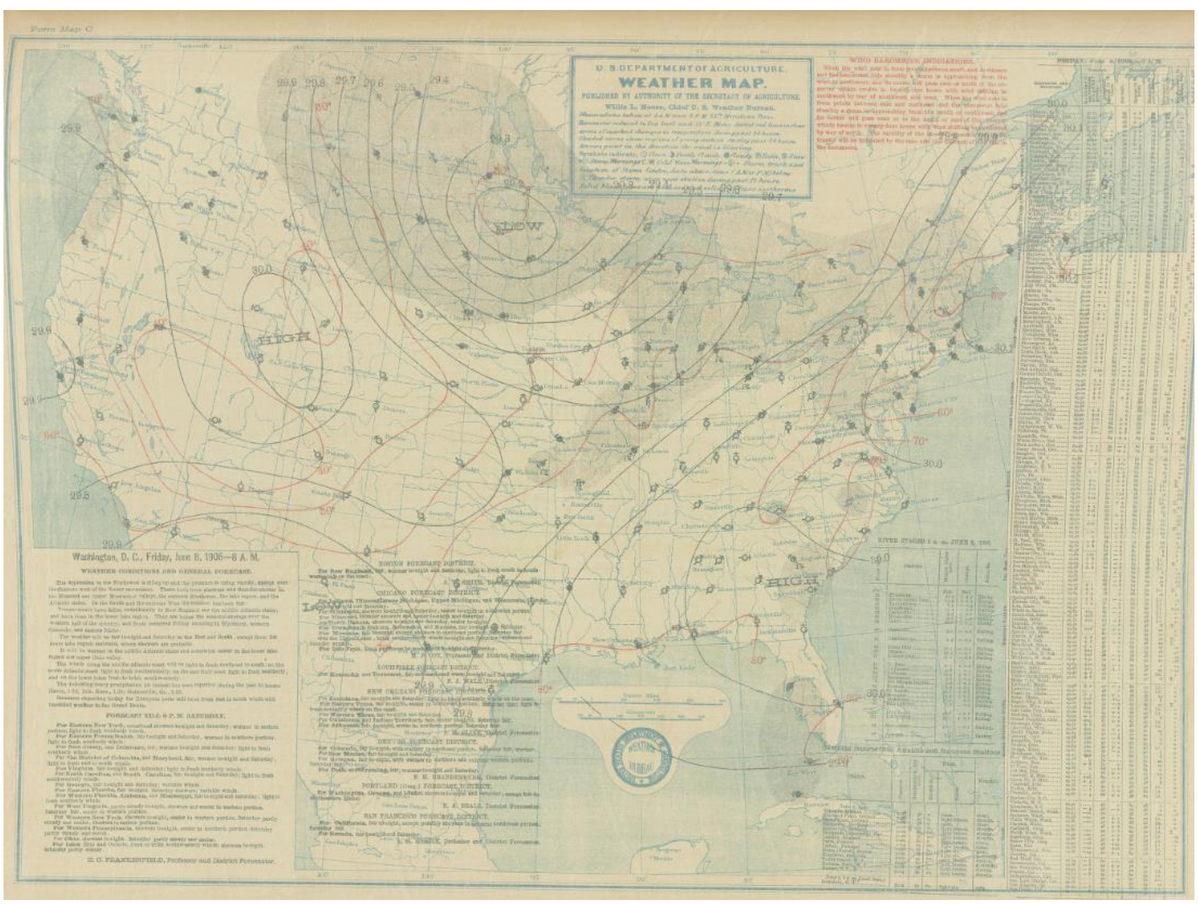
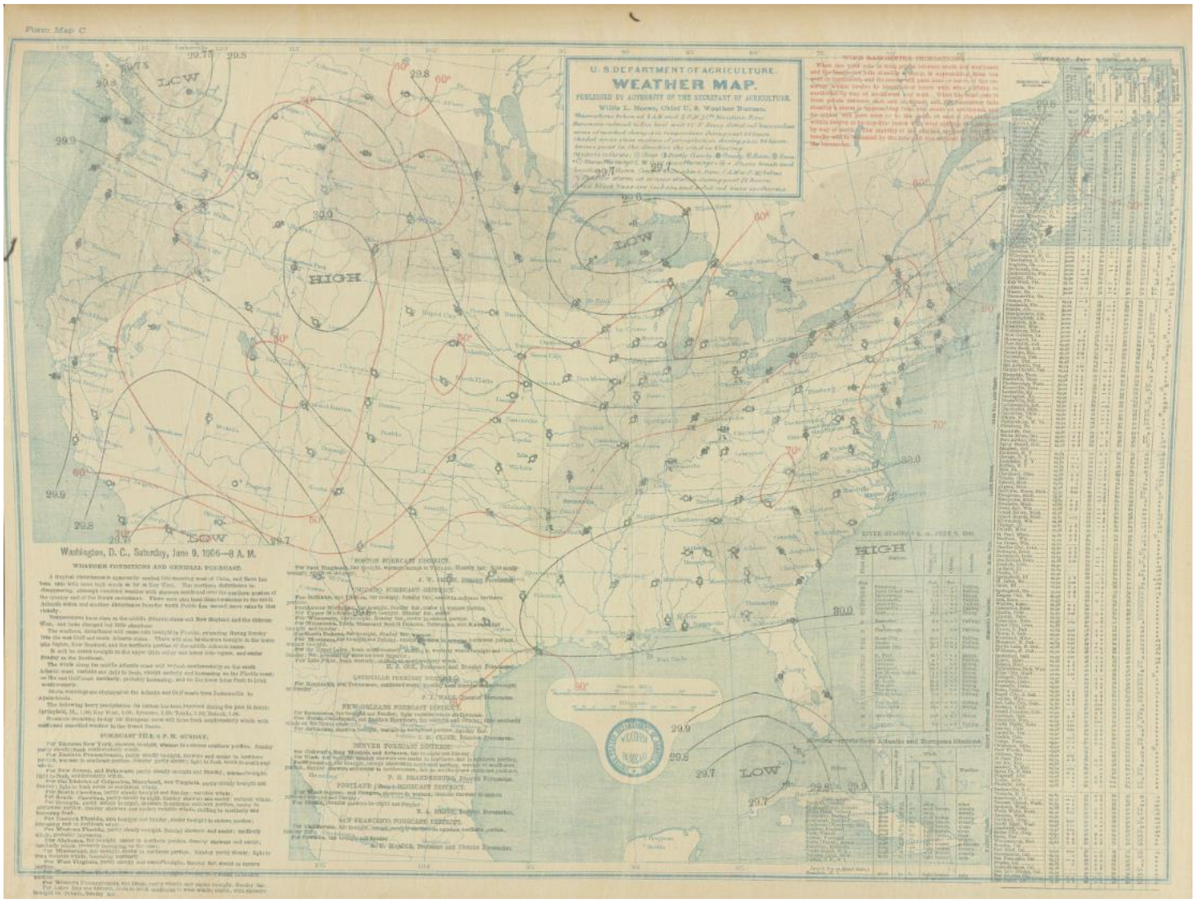
U. S. DEPARTMENT OF AGRICULTURE.
WEATHER MAP.
PUBLISHED BY AUTHORITY OF THE SECRETARY OF AGRICULTURE.
Willis L. Moore, Chief U. S. Weather Bureau.
HIGH
LOW
Washington, D. C., Thursday, June 7, 1906—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. FRIDAY.
WIND BAROMETER INDICATIONS.


Form Map C
U. S. DEPARTMENT OF AGRICULTURE.
WEATHER MAP.
PUBLISHED BY AUTHORITY OF THE SECRETARY OF AGRICULTURE.
Willis L. Moore, Chief U. S. Weather Bureau.
HIGH
LOW
Washington, D. C., Friday, June 8, 1906—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SATURDAY.
WIND BAROMETER INDICATIONS.



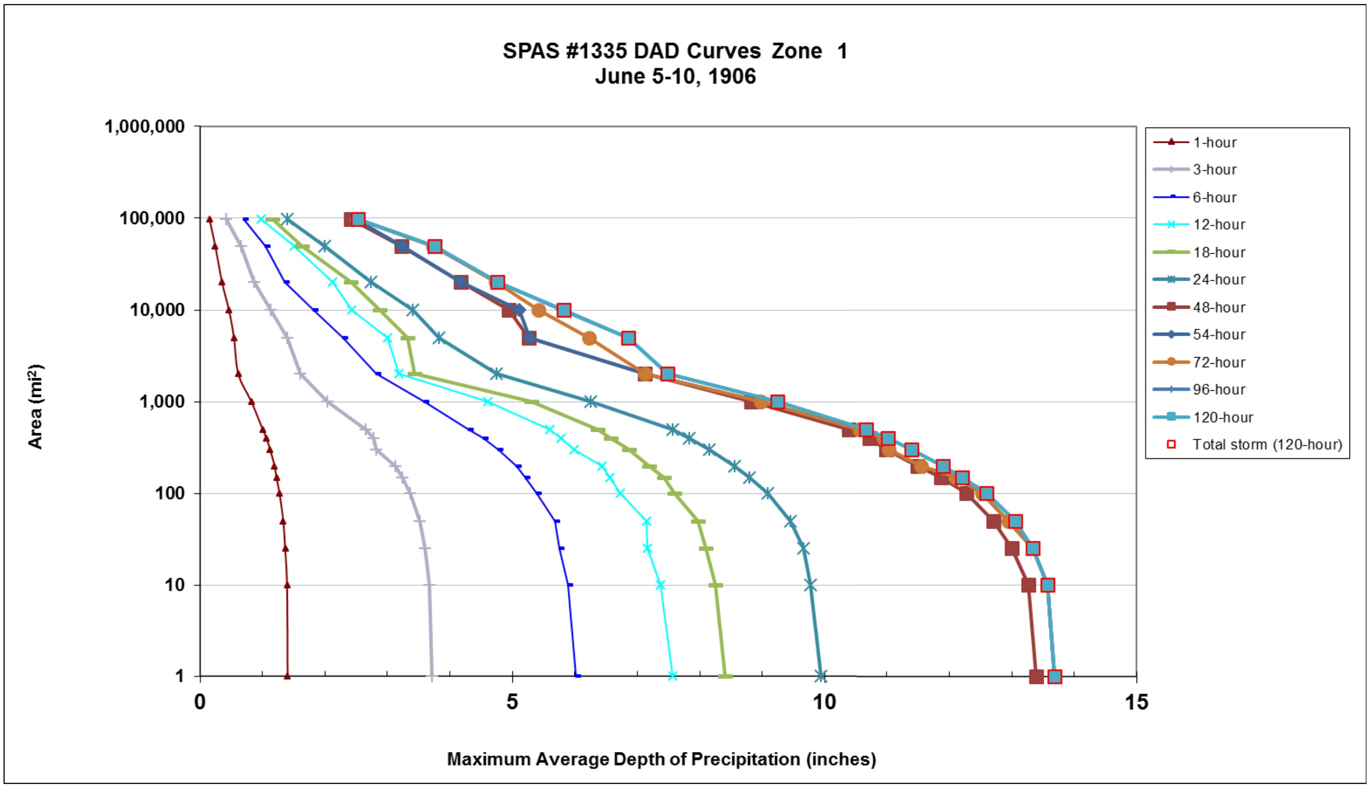
U. S. DEPARTMENT OF AGRICULTURE.
WEATHER MAP.
PUBLISHED BY AUTHORITY OF THE SECRETARY OF AGRICULTURE.
Willis L. Moore, Chief U. S. Weather Bureau.
HIGH
LOW
Washington, D. C., Saturday, June 9, 1906—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.

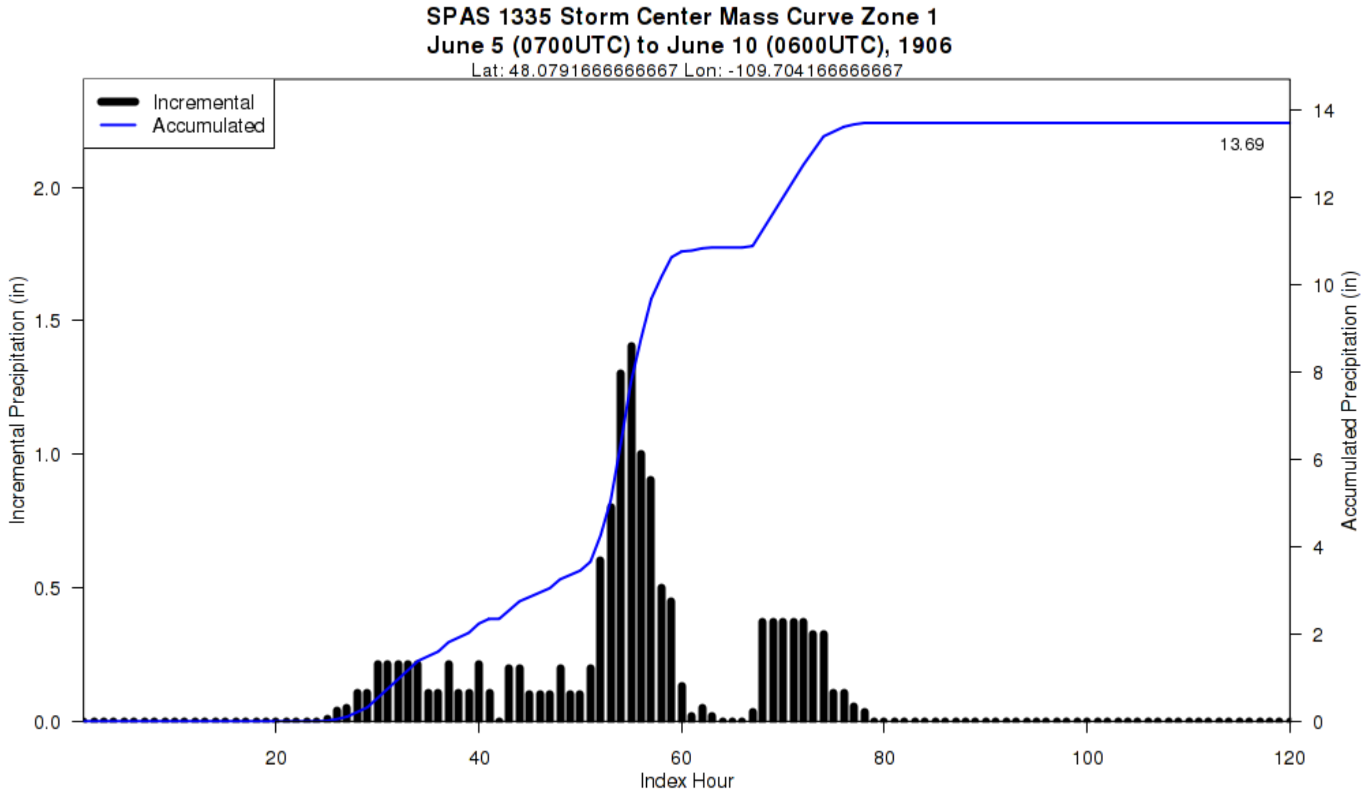
Table 5.1.--Representative persisting 12-hr 1000-mb storm and maximum dew points for important storms in and near study region

Storm No.	Name	Storm T_d Old	Storm T_d New	Date+	Ref. Old	Loc. New	Max. T_d Old	Max. T_d New	Stations
1.	Ward District, CO	62	64	30	325SE	350SE	75	77	AMA, DDC
6.	Boxelder, CO	60	60	4	350SE	320SE	72	74	DEN, PUB, DDC, OKC, ICT
8.	Rociada, NM	72	72	28	170SSE	300ESE	76	77	ABI, AMA
10.	Warrick, MT	64	64	6	380ESE	380ESE	73	75	ISN, PIR
13.	Evans, MT	65	65	4	510ESE	510ESE	75	76	BIS, RAP, PIR, VTN, HON
86.	May Valley, CO	67	67	18	450SSE	450SSE	76	76	AMA, ABI, FTW, SAT
20.	Clayton, NM	68	69	1	550SE	560SSE	76	77	SAT, DRT, CRP
23.	Tajique, NM	69	69	21	80SE	160SSE	77	78	ELP, ROW
25.	Lakewood, NM	-	76	7	-	350SE	-	79	DRT, SAT
27.	Meek, NM	72	72	15	390ESE	400ESE	78	79	AMA, ABI, FTW, OKC, SAT, GBK
30.	Fry's Ranch, CO	56	63	15	550ESE	700SE	71	74	FWH, DAL
31.	Penrose, CO	67	70	4	400SE	350SE	77	77	AMA, OKC
32.	Springbrook, MT	71	72	18	500ESE	370ESE	76	77	PIR, HON, FAR
35.	Virsylvia, NM (Cerro)	-	66	17	-	120SW	-	77	ABQ
38.	Savageton, WY	68	72	28	550SE	530SE	75	76	FRI, CNK
44.	Porter, NM	70	71	11	540SE	380SE	78	77	DRT, AUS, FTW, ABI
46.	Kassler, CO	71	66	10	440SE	420SE	77	77	OKC, DDC
47.	Cherry Creek, CO	72	71	30	540SE	560SE	76	79	ABI, ACT, FTW, SPS
101.	Hale, CO	72	71	30	540SE	560SE	76	79	ABI, ACT, FTW, SPS
48.	Las Cruces, NM*	-	71	30	-	-	-	78	ELP
105.	Broome, TX	77	77	14	350SSE	350SSE	78	80	CRP, BRO
53.	Loveland, CO	71	71	1	180SE	210SE	76	76	PUB, GLD
55.	Masonville, CO*	-	65	10	-	-	-	74	AKO
108.	Snyder, TX	73	75	19	100SE	340SSE	78	79	SAT, CRP
56.	Prairieview, NM	70	73	20	390SE	370SE	77	78	SAT, AUS
58.	McColleum Ranch, NM	72	72	21	50SE	300SE	77	79	ELP, DRT, SAT, CRP
60.	Rancho Grande, NM	74	75	31	250SE	250SE	77	78	LBB, BGS, ABI
66.	Ft. Collins, CO	66	67	30	570SE	600SE	78	78	GAG, TUL
67.	Golden, CO*	65	65	7	-	-	76	75	AMA

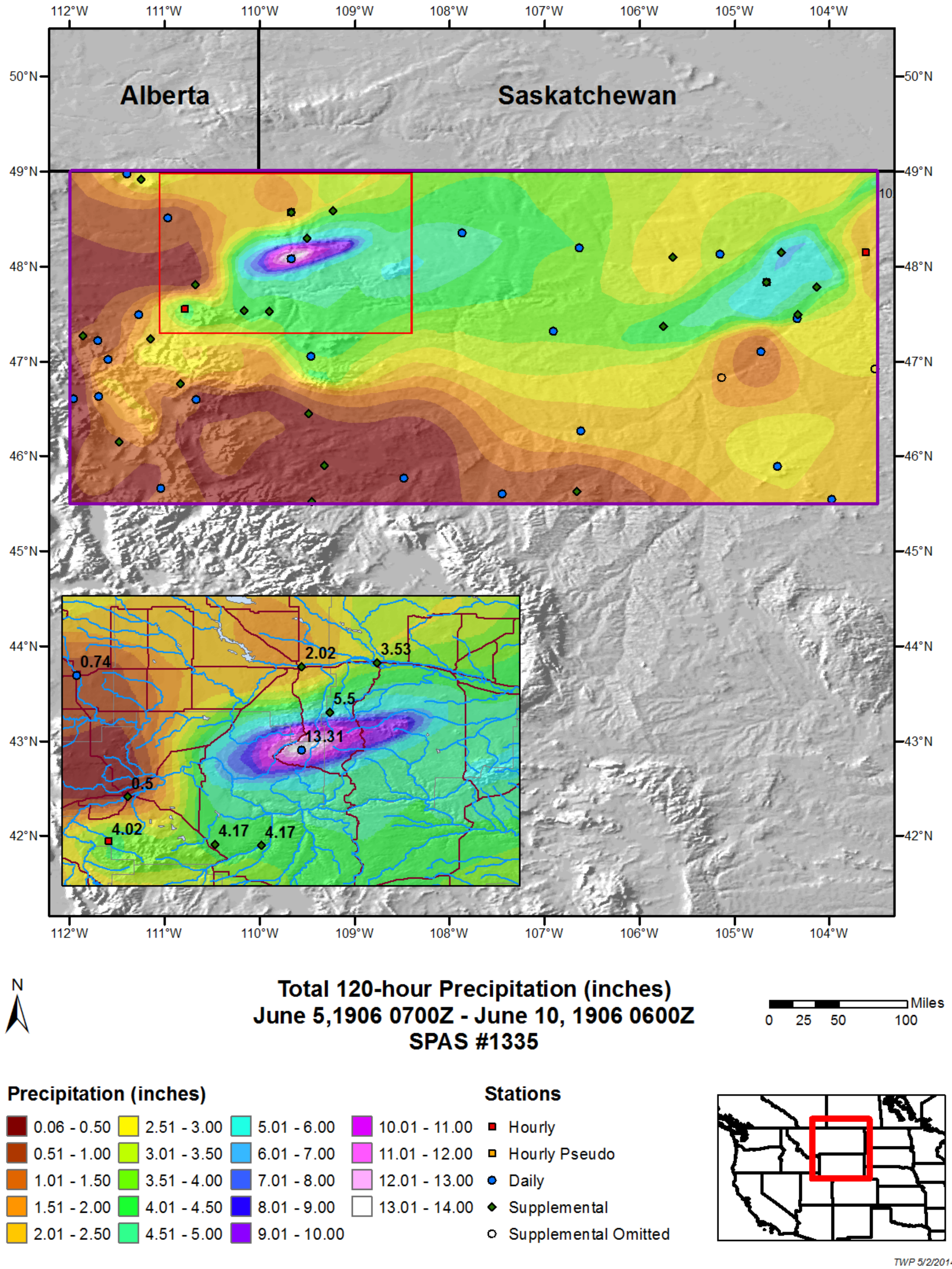
Note, this table is copied from HMR 55A and therefore units are in °F and miles.

SPAS 1335 - June 5 (0700 UTC) - June 10 (0600 UTC), 1906												
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)												
	Duration (hours)											
Area (mi^2)	1	3	6	12	18	24	48	54	72	96	120	Total
0.2	1.40	3.71	6.02	7.57	8.41	9.94	13.39	13.69	13.69	13.69	13.69	13.69
1	1.40	3.71	6.02	7.57	8.41	9.94	13.39	13.69	13.69	13.69	13.69	13.69
10	1.39	3.67	5.89	7.37	8.25	9.78	13.26	13.57	13.57	13.57	13.57	13.57
25	1.36	3.60	5.75	7.16	8.10	9.66	13.00	13.33	13.33	13.34	13.34	13.34
50	1.33	3.51	5.68	7.15	7.97	9.45	12.70	12.94	12.95	13.06	13.06	13.06
100	1.27	3.36	5.39	6.73	7.59	9.09	12.28	12.53	12.53	12.59	12.59	12.59
150	1.22	3.24	5.20	6.56	7.43	8.80	11.87	12.10	12.10	12.21	12.21	12.21
200	1.19	3.13	5.07	6.43	7.19	8.56	11.49	11.55	11.55	11.89	11.89	11.89
300	1.12	2.82	4.77	5.99	6.87	8.16	10.99	11.03	11.03	11.40	11.40	11.40
400	1.06	2.78	4.53	5.78	6.58	7.83	10.72	10.95	10.95	11.01	11.01	11.01
500	1.00	2.65	4.30	5.60	6.37	7.57	10.39	10.55	10.55	10.67	10.67	10.67
1,000	0.82	2.04	3.58	4.60	5.31	6.25	8.82	8.98	8.98	9.24	9.24	9.24
2,000	0.61	1.60	2.82	3.18	3.43	4.75	7.12	7.12	7.12	7.48	7.48	7.48
5,000	0.54	1.40	2.29	3.00	3.32	3.82	5.26	5.28	6.23	6.85	6.86	6.86
10,000	0.46	1.13	1.81	2.43	2.87	3.41	4.94	5.11	5.41	5.80	5.82	5.82
20,000	0.35	0.86	1.35	2.12	2.41	2.74	4.17	4.17	4.73	4.76	4.76	4.76
50,000	0.24	0.65	1.05	1.50	1.63	2.00	3.23	3.24	3.73	3.75	3.75	3.75
96,655	0.15	0.41	0.69	0.98	1.15	1.40	2.41	2.49	2.51	2.52	2.52	2.52





SPAS 1335 Storm Center Mass Curve Zone 1
June 5 (0700UTC) to June 10 (0600UTC), 1906
Lat: 48.0791666666667 Lon: -109.704166666667
Incremental
Accumulated
13.69
Incremental Precipitation (in)
Accumulated Precipitation (in)
Index Hour


112°W
111°W
110°W
109°W
108°W
107°W
106°W
105°W
104°W
50°N
49°N
48°N
47°N
46°N
45°N
44°N
43°N
42°N
Alberta
Saskatchewan
10
0.74
2.02
3.53
5.5
13.31
0.5
4.02
4.17
4.17
N
Total 120-hour Precipitation (inches)
June 5,1906 0700Z - June 10, 1906 0600Z
SPAS #1335
Miles
0 25 50 100
Precipitation (inches)
0.06 - 0.50
0.51 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 2.50
2.51 - 3.00
3.01 - 3.50
3.51 - 4.00
4.01 - 4.50
4.51 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
8.01 - 9.00
9.01 - 10.00
10.01 - 11.00
11.01 - 12.00
12.01 - 13.00
13.01 - 14.00
Stations
Hourly
Hourly Pseudo
Daily
Supplemental
Supplemental Omitted
TWP 5/2/2014

Parkman, SK

August 3-4, 1985

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1337

General Storm Location: Wilson, Saskatchewan

Storm Dates: August 3-4, 1985

Event: Convective event

DAD Zone 1

> **Latitude**: 49.7020°
>
> **Longitude**: -101.8958°
>
> **Max. grid rainfall amount**: 400mm
>
> **Max. observed rainfall amount**: 381mm (Wilson, SK)

Number of Stations: 142

SPAS Version: 9.5

Base Map Used: Based on digitized Canadian Climate Centre of Environment Canada's SASK-8-85 Isohyetal Map (storm total)

Spatial resolution: 30 seconds (decimal degrees, WGS84, ~ 0.30 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of Results: Environment Canada was asked about the full storm report, SASK-8-85 for this event, but they could not locate the report. There were a limited number of recording gauges and none were located in or near the storm center. Estimates of the hourly data for the maximum daily observation at WILSON SK were developed. Effort was taken to conform the maximum 6-hour, 12-hour and 24-hour amounts to the "point" DAD amounts derived from the Environment Canada figure and consideration was given to the influence of the three nearest hourly stations (ESTEVAN AIRPORT SK, BROADVIEW SK, and BRANDON AIRPORT MB). The reliability of the timing has significant uncertainty as a result. Results are consistent with the published DAD estimates (those for 100 square miles are within +/- 2").

Storm Name:	**SPAS 1337 Parkman, SK**	
Storm Date:	**8/3-4/1985**	**Storm Adjustment Summary**
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **21-Jul**

	Lat	Long
Storm Center Location	**49.70 N**	**101.90 W**
Storm Rep Dew Point Location	**39.60 N**	**102.75 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**S @ 1,125**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**610**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**24.2 °C**	with total precipitable water above sea level of		**74**	millimeters.
The in-place maximum dew point is	**25.6 °C**	with total precipitable water above sea level of		**84**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**610**	which subtracts	**12**	millimeters of precipitable water at	**24.2 °C**
The in-place storm elevation is	**610**	which subtracts	**13**	millimeters of precipitable water at	**25.6 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.14**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Storm rep Td taken from 24hr aveage at KLIC and K4LJ on August 2nd.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**64**		**135**			**193**	**300**	**378**	**396**
26 km^2 (10 mi^2)	**64**		**135**			**193**	**297**	**378**	**396**
259 km^2 (100 mi^2)	**64**		**124**			**180**	**277**	**351**	**366**
518 km^2 (200 mi^2)	**61**		**114**			**165**	**254**	**328**	**333**
1,295 km^2 (500 mi^2)	**56**		**94**			**137**	**211**	**272**	**277**
2,590 km^2 (1,00 mi^2)	**51**		**76**			**109**	**168**	**218**	**224**
5,180 km^2 (2,000 mi^2)	**43**		**56**			**76**	**91**	**152**	**157**
12.950 km^2 (5000 mi^2)	**30**		**43**			**51**	**66**	**86**	**107**
25,900 km^2 (10,000 mi^2)	**20**		**33**			**38**	**51**	**74**	**79**
51,800 km^2 (20,000 mi^2)	**15**		**23**			**28**	**38**	**46**	**66**

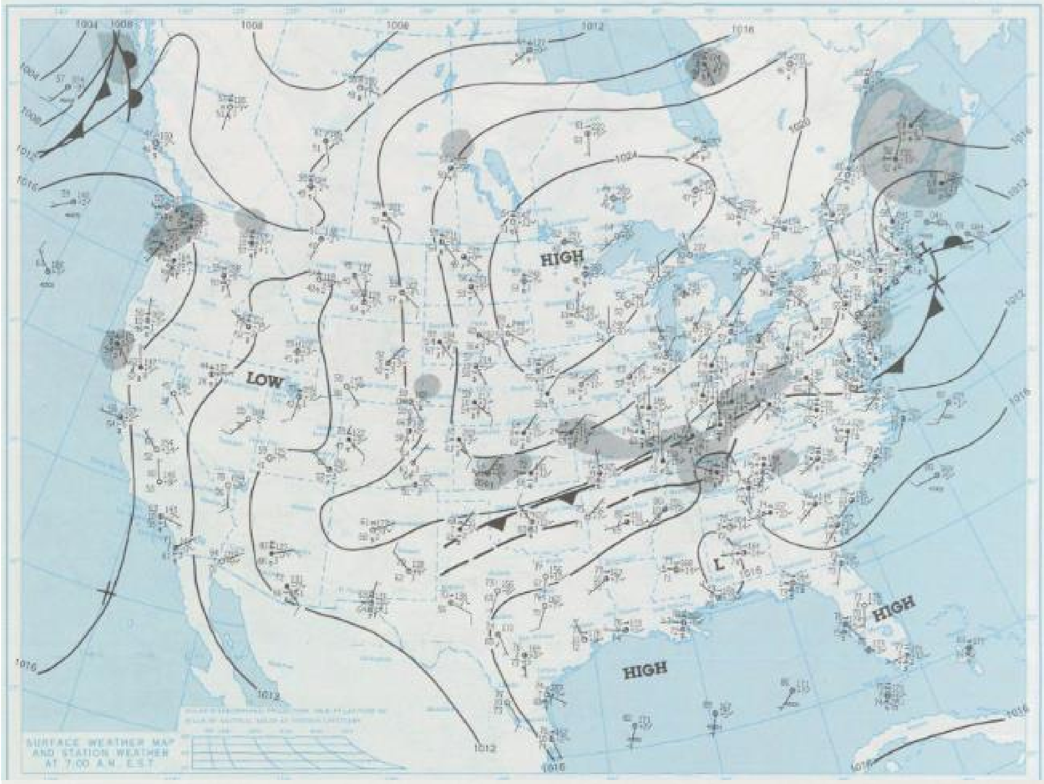
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
5,900 km2 (10,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
1,800 km2 (20,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***

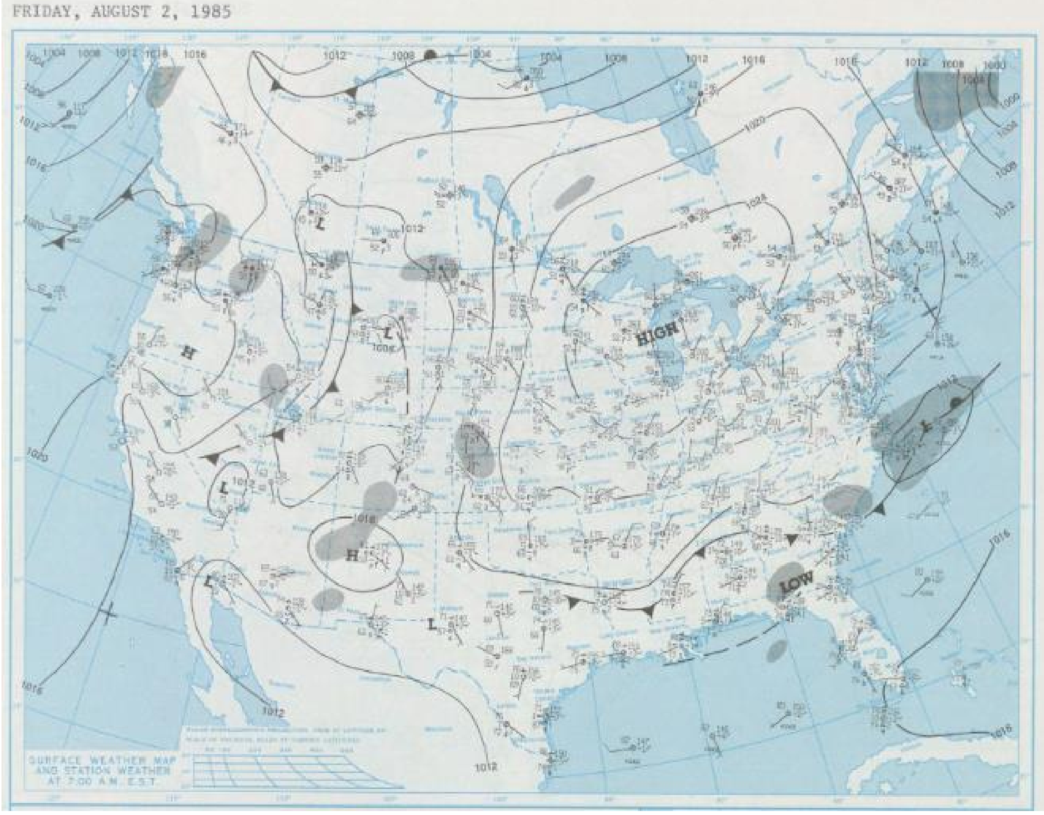
Storm or Storm Center Name	**SPAS 1337 Parkman, SK**	
Storm Date(s)	8/3-4/1985	
Storm Type	Synoptic	
Storm Location	49.70 N	101.90 W
Storm Center Elevation	610	meters
Precipitation Total & Duration	400	millimeters 104 hours
Storm Representative Dew Point	24.2 °C	24
Storm Representative Dew Point Location	39.60 N	102.75 W
Maximum Dew Point	25.6 °C	
Moisture Inflow Vector	S @ 1,125	kilometers
In-place Maximization Factor	**1.14**	
Temporal Transposition (Date)	21-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

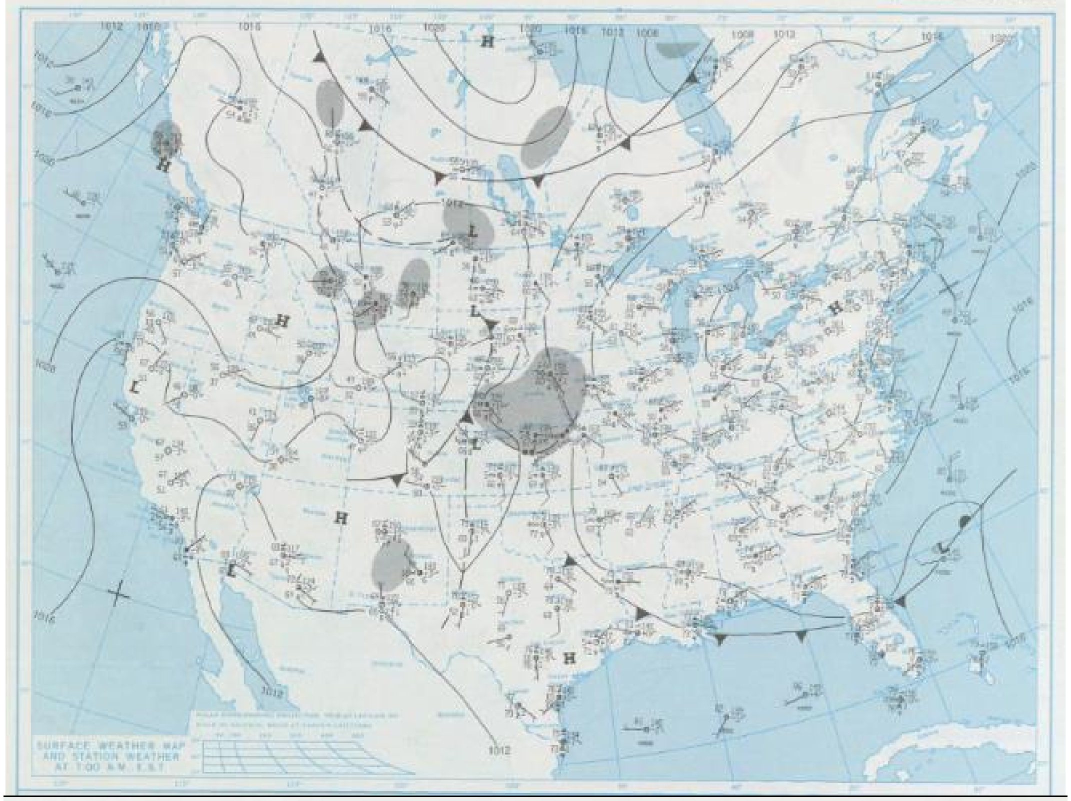
THURSDAY, AUGUST 1, 1985



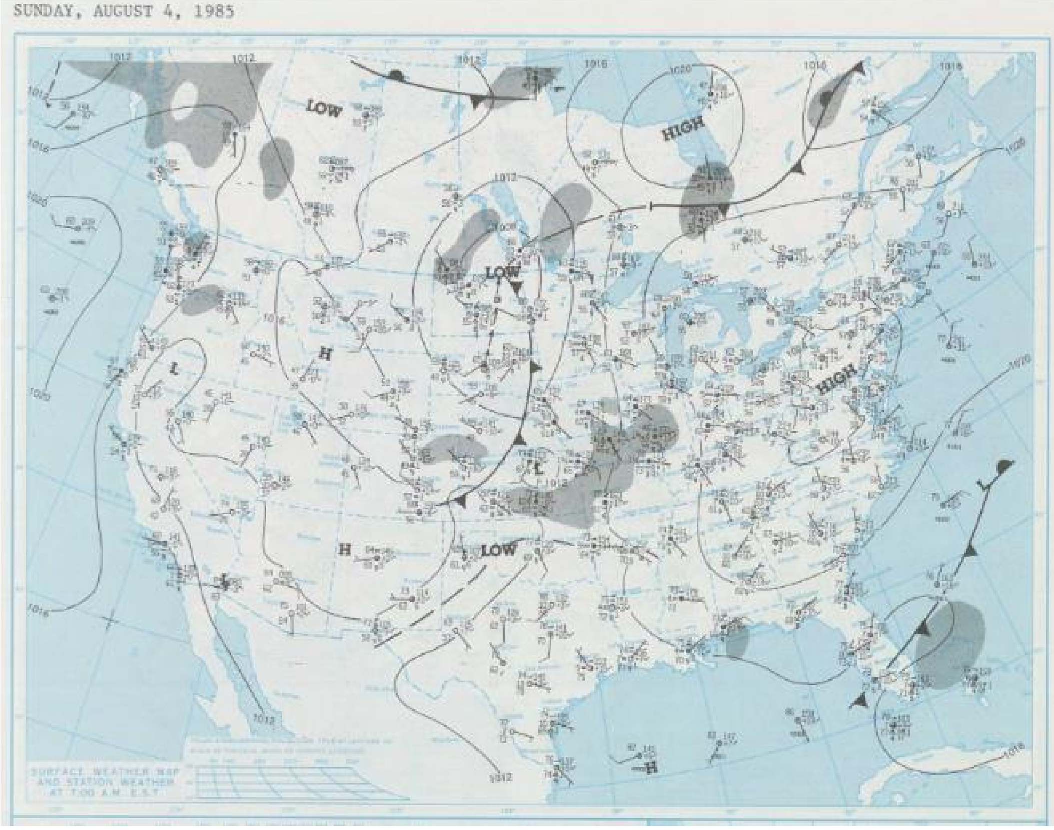
FRIDAY, AUGUST 2, 1985

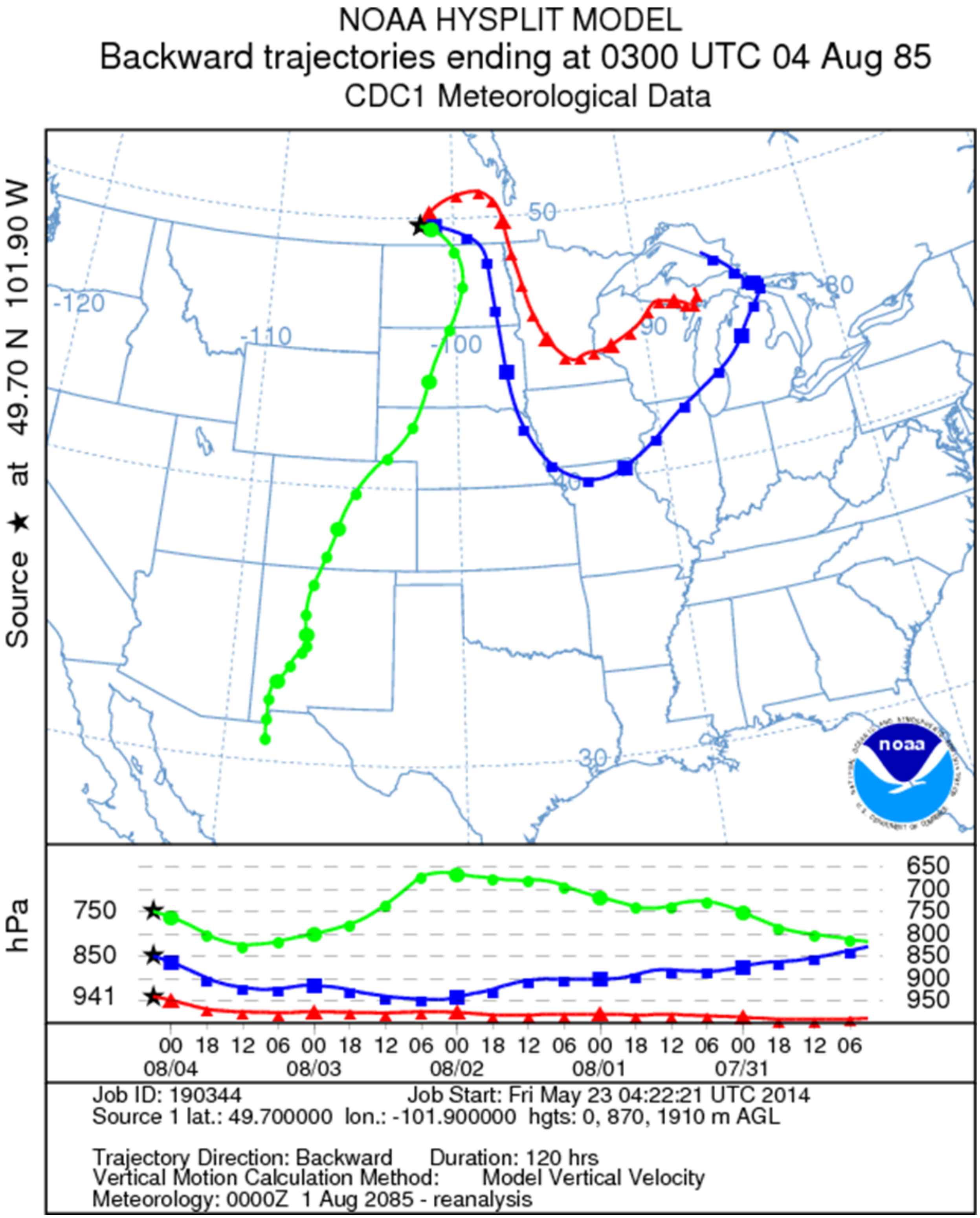


SATURDAY, AUGUST 3, 1985



SUNDAY, AUGUST 4, 1985

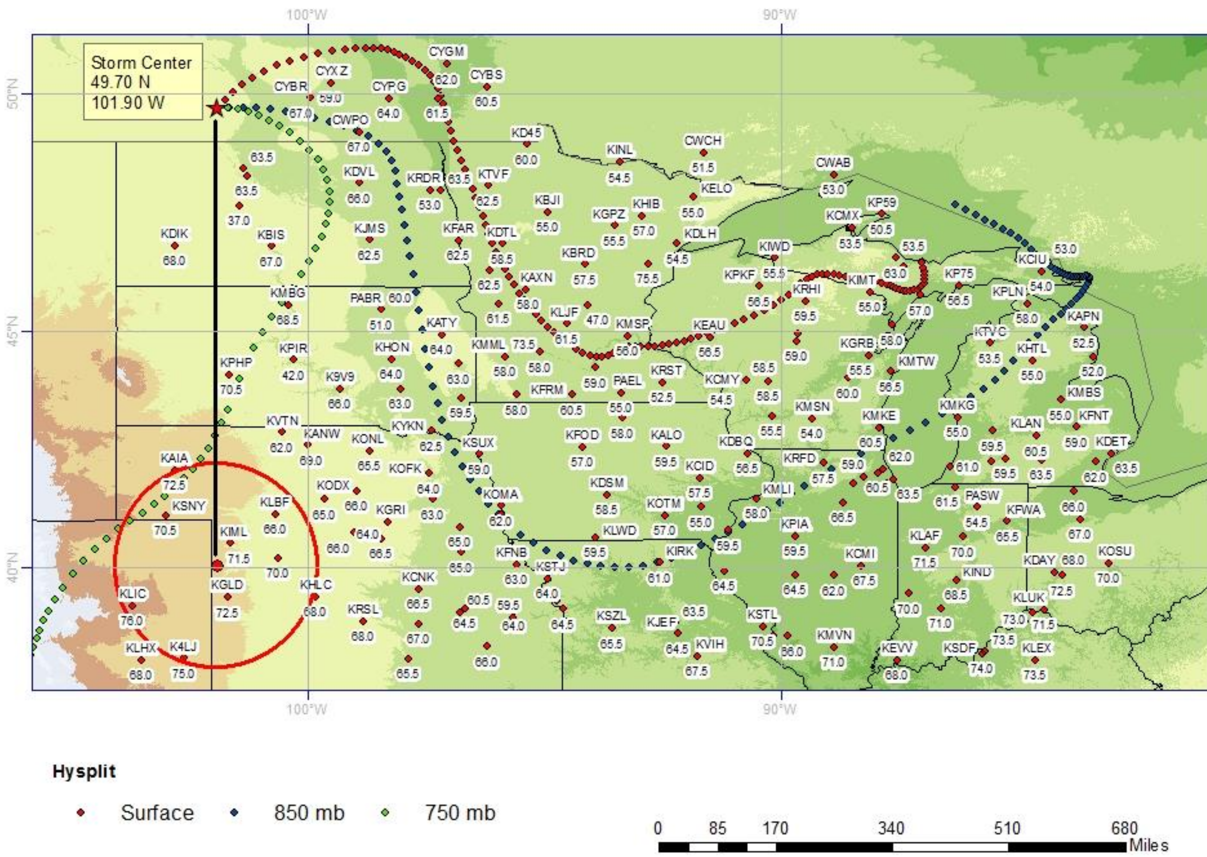




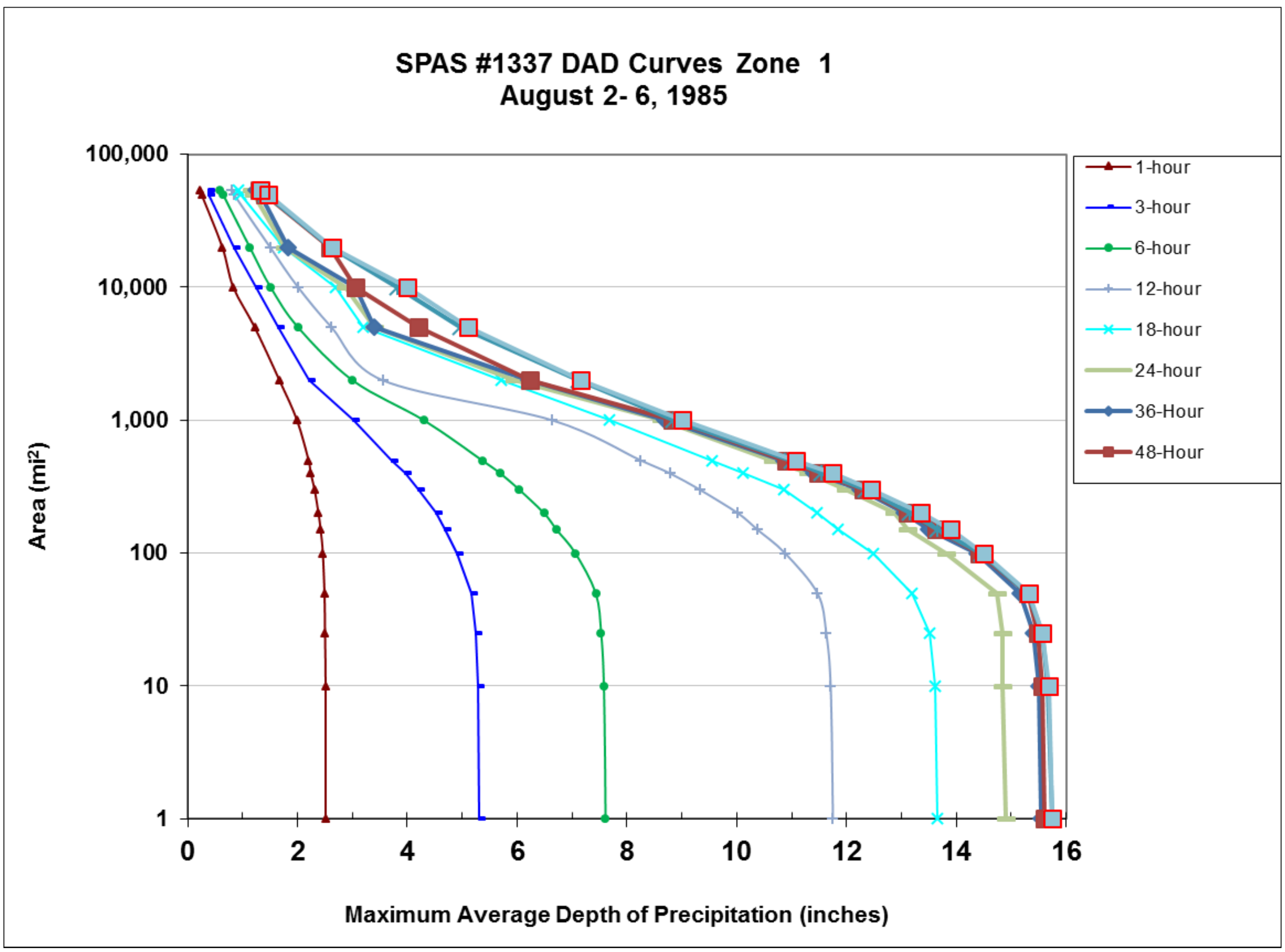
NOAA HYSPLIT MODEL
Backward trajectories ending at 0300 UTC 04 Aug 85
CDC1 Meteorological Data
Source ★ at 49.70 N 101.90 W
hPa
750
850
941
650
700
750
800
850
900
950
00 18 12 06 00 18 12 06 00 18 12 06 00 18 12 06 00 18 12 06
08/04 08/03 08/02 08/01 07/31
Job ID: 190344 Job Start: Fri May 23 04:22:21 UTC 2014
Source 1 lat.: 49.700000 lon.: -101.900000 hgts: 0, 870, 1910 m AGL
Trajectory Direction: Backward Duration: 120 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Aug 2085 - reanalysis

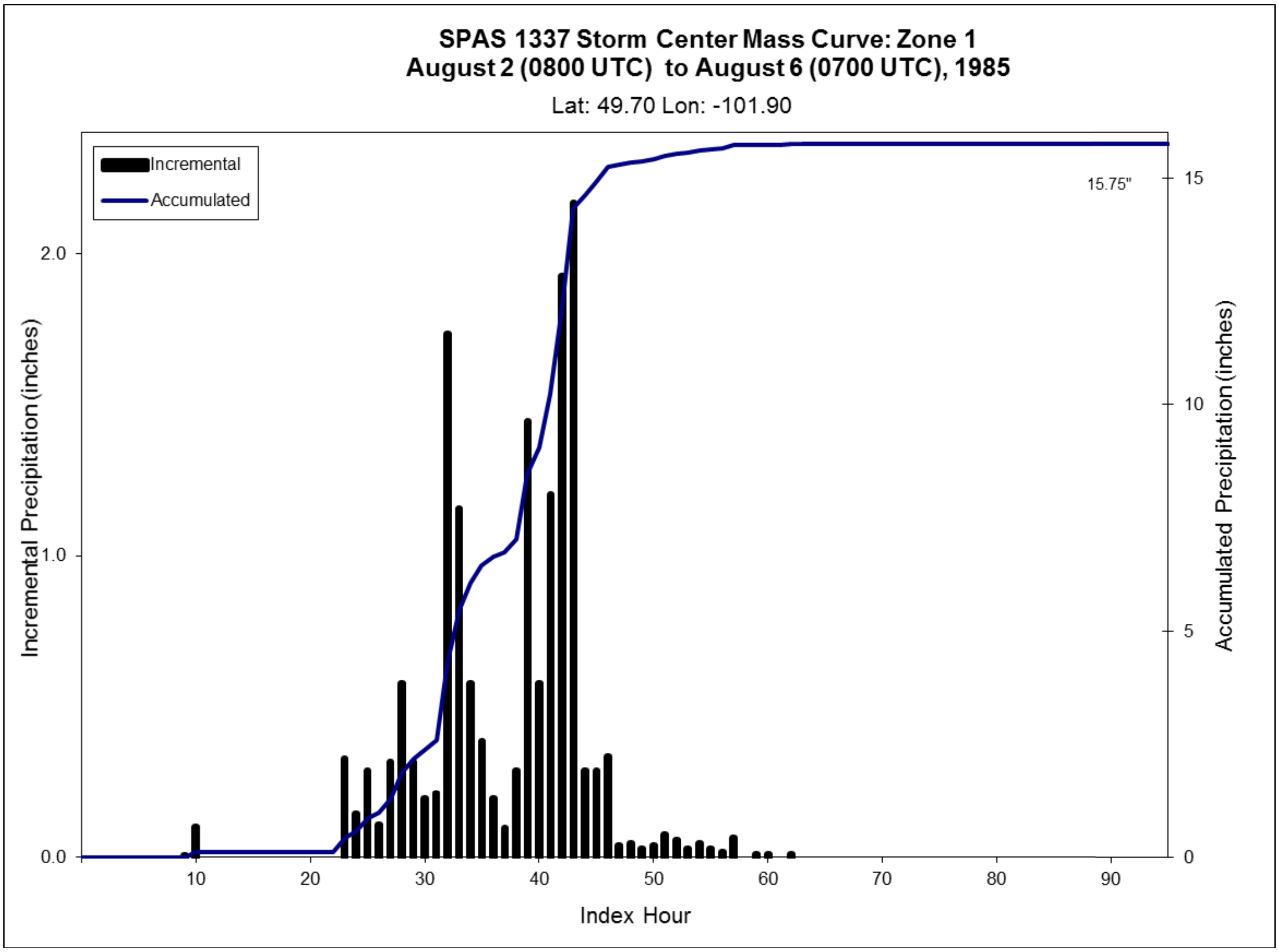
SPAS 1337

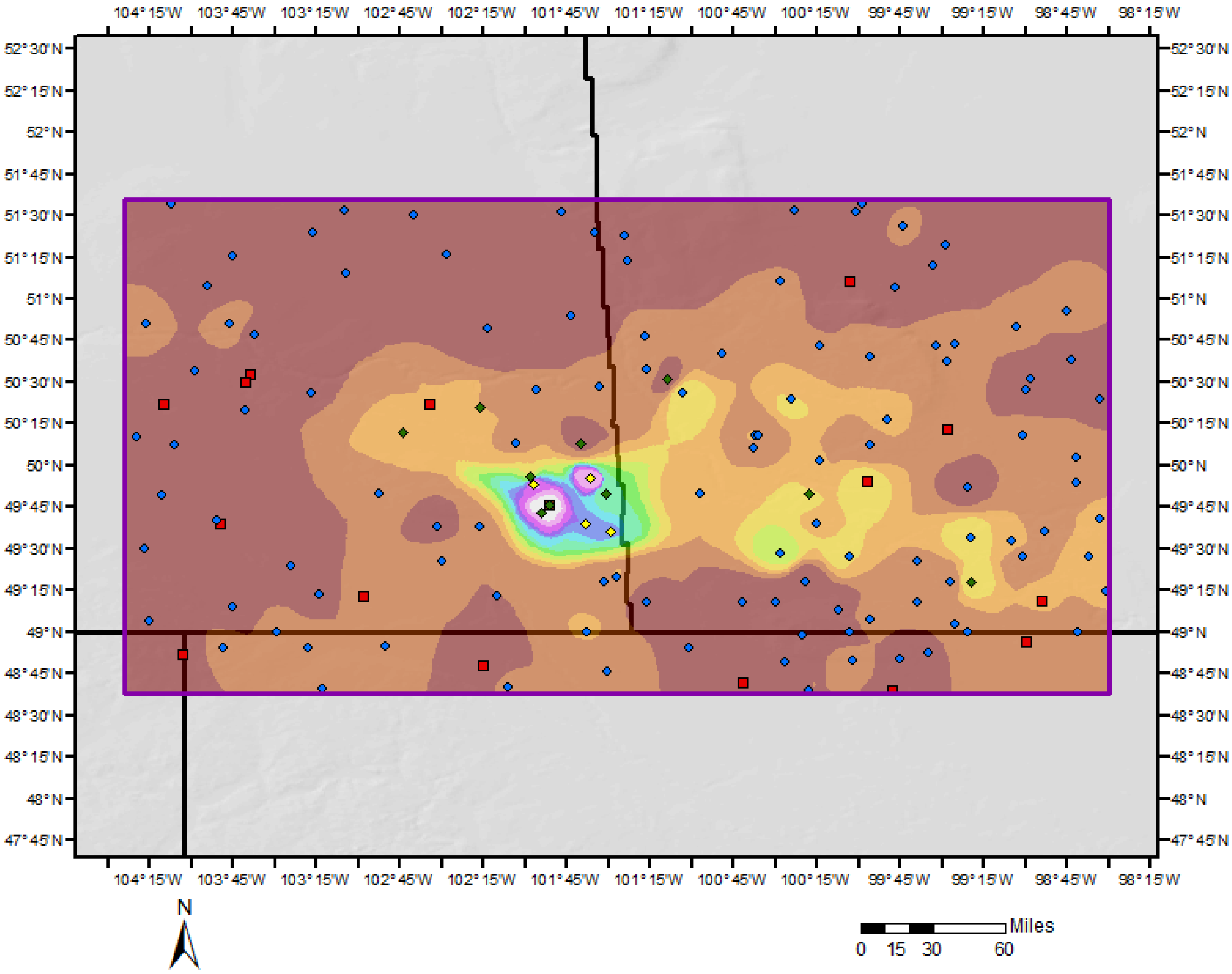
August 2 - 6, 1985



Storm 1337 - August 2 (0800 UTC) - August 6 (0700 UTC), 1985 MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)											
	Duration (hours)										
Area (mi^2)	1	3	6	12	18	24	36	48	72	96	Total
0.2	2.51	5.30	7.61	11.75	13.66	15.15	15.62	15.72	15.75	15.75	15.75
1	2.51	5.30	7.61	11.75	13.66	14.90	15.55	15.61	15.74	15.74	15.74
10	2.51	5.28	7.58	11.71	13.61	14.85	15.50	15.56	15.67	15.68	15.68
25	2.50	5.24	7.53	11.63	13.51	14.84	15.41	15.48	15.56	15.56	15.56
50	2.49	5.17	7.43	11.47	13.20	14.75	15.17	15.30	15.30	15.33	15.33
100	2.46	4.90	7.06	10.88	12.48	13.81	14.37	14.42	14.46	14.50	14.50
150	2.42	4.69	6.72	10.38	11.85	13.11	13.49	13.63	13.65	13.90	13.90
200	2.38	4.52	6.49	10.02	11.47	12.87	13.05	13.12	13.16	13.36	13.36
300	2.31	4.21	6.04	9.33	10.85	11.99	12.25	12.30	12.34	12.44	12.44
400	2.24	3.96	5.69	8.78	10.11	11.30	11.41	11.49	11.55	11.74	11.74
500	2.20	3.72	5.36	8.25	9.56	10.65	10.86	10.89	11.00	11.07	11.07
1,000	1.99	3.02	4.30	6.64	7.69	8.62	8.68	8.83	8.84	9.00	9.00
2,000	1.67	2.22	3.00	3.55	5.70	5.96	6.21	6.23	7.11	7.16	7.16
5,000	1.22	1.65	2.01	2.62	3.20	3.39	3.39	4.20	4.96	5.11	5.11
10,000	0.83	1.25	1.51	2.01	2.69	2.88	3.06	3.06	3.82	4.00	4.00
20,000	0.63	0.85	1.13	1.50	1.74	1.76	1.82	2.60	2.62	2.63	2.63
50,000	0.25	0.39	0.64	0.84	0.97	1.20	1.33	1.41	1.42	1.47	1.47
53,819	0.22	0.39	0.59	0.81	0.92	1.16	1.25	1.30	1.32	1.32	1.32




SPAS 1337 Storm Center Mass Curve: Zone 1
August 2 (0800 UTC) to August 6 (0700 UTC), 1985
Lat: 49.70 Lon: -101.90
Incremental
Accumulated
15.75"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour
0.0
1.0
2.0
0
5
10
15
10
20
30
40
50
60
70
80
90



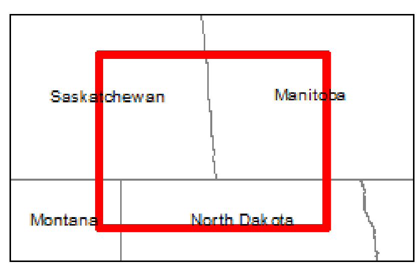
Total 96-hr Precipitation (inches)
August 2-5, 1985 0800 UTC
SPAS #1337

Precipitation (inches)

- 0.00 - 1.00
- 1.01 - 2.00
- 2.01 - 3.00
- 3.01 - 4.00
- 4.01 - 5.00
- 5.01 - 6.00
- 6.01 - 7.00
- 7.01 - 8.00
- 8.01 - 9.00
- 9.01 - 10.00
- 10.01 - 12.00
- 12.01 - 14.00
- 14.01 - 16.00

Stations

- Daily
- Hourly
- Hourly Estimated Pseudo
- Supplemental
- Supplemental Estimated



DLM 05/09/2014

Spionkop Creek, AB

June 4-7, 1995

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1338

General Storm Location: Spionkop Creek, Alberta Canada

Storm Dates: June 4-7, 1995 (96-hours)

Event: Mid-latitude cyclone

DAD Zone 1

> **Latitude**: 49.1708°
>
> **Longitude**: -114.1625°
>
> **Max. grid rainfall amount**: 368mm
>
> **Max. observed rainfall amount**: 333mm (Spionkop Creek, Alberta Canada)

Number of Stations: 120

SPAS Version: 9.5

Base Map Used: Mean PRISM (1961-90) June Precipitation from:

http://www.ualberta.ca/~ahamann/data/climatewna.html

Spatial resolution: 30 seconds (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of Results: Although the magnitude of precipitation north of 49.5 degrees North is considered reliable, the timing is highly unreliable due to the lack of hourly data. The magnitude and temporal details of the precipitation in/around the storm center and in areas across Montana are considered reliable. Five key hourly stations in Canada (near the storm center) were drawn from digital mass curves from EC, however the exact start time of the data was not clear and therefore estimated from nearby hourly stations in the U.S. (see below for details).

Storm Name:	SPAS 1338 Spionkop Creek, AB
Storm Date:	6/4-7/1995
AWA Analysis Date:	7/20/2015

Storm Adjustment Summary

Temporal Transposition Date **21-Jun**

	Lat	Long
Storm Center Location	**49.17 N**	**114.16 W**
Storm Rep Dew Point Location	**46.55 N**	**111.50 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**SE @ 354**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**1,676**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**18.9 °C**	with total precipitable water above sea level of			**47**	millimeters.
The in-place maximum dew point is	**20.6 °C**	with total precipitable water above sea level of			**54**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of			**N/A***	millimeters.
The in-place storm elevation is	**1,676**	which subtracts	**22**	millimeters of precipitable water at	**18.9 °C**	
The in-place storm elevation is	**1,676**	which subtracts	**24**	millimeters of precipitable water at	**20.6 °C**	
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***	

The in-place storm maximization factor is	**1.19**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: 24hr average dew point taken from KBTM, KBZN, K3HT from the 4th-5th.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**29**		**82**			**143**	**242**	**335**	**362**
26 km^2 (10 mi^2)	**26**		**74**			**137**	**233**	**314**	**343**
259 km^2 (100 mi^2)	**25**		**69**			**122**	**211**	**287**	**305**
518 km^2 (200 mi^2)	**25**		**62**			**113**	**190**	**262**	**280**
1,295 km^2 (500 mi^2)	**23**		**56**			**94**	**156**	**220**	**244**
2,590 km^2 (1,00 mi^2)	**21**		**51**			**84**	**137**	**191**	**216**
5,180 km^2 (2,000 mi^2)	**18**		**41**			**69**	**105**	**167**	**188**
12.950 km^2 (5000 mi^2)	**15**		**36**			**60**	**92**	**138**	**145**
25,900 km^2 (10,000 mi^2)	**13**		**30**			**51**	**79**	**102**	**114**
51,800 km^2 (20,000 mi^2)	**9**		**24**			**40**	**64**	**78**	**108**

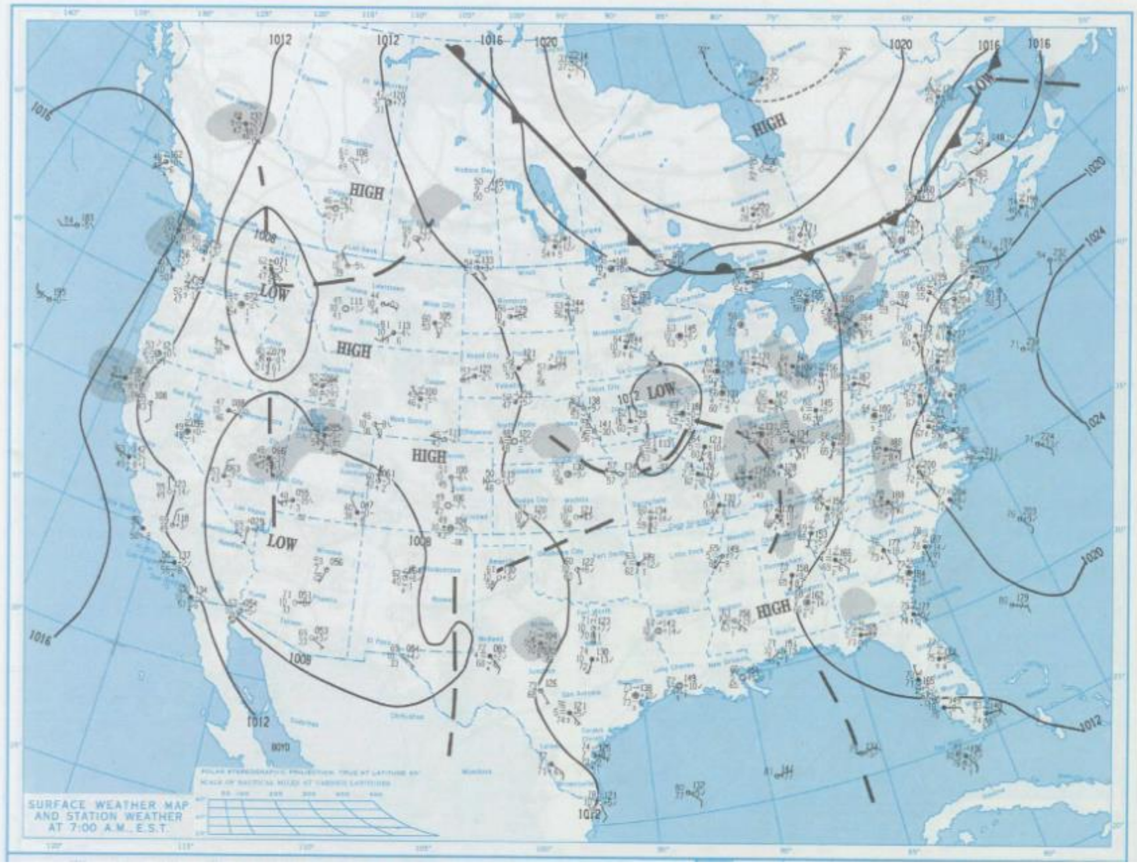
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***

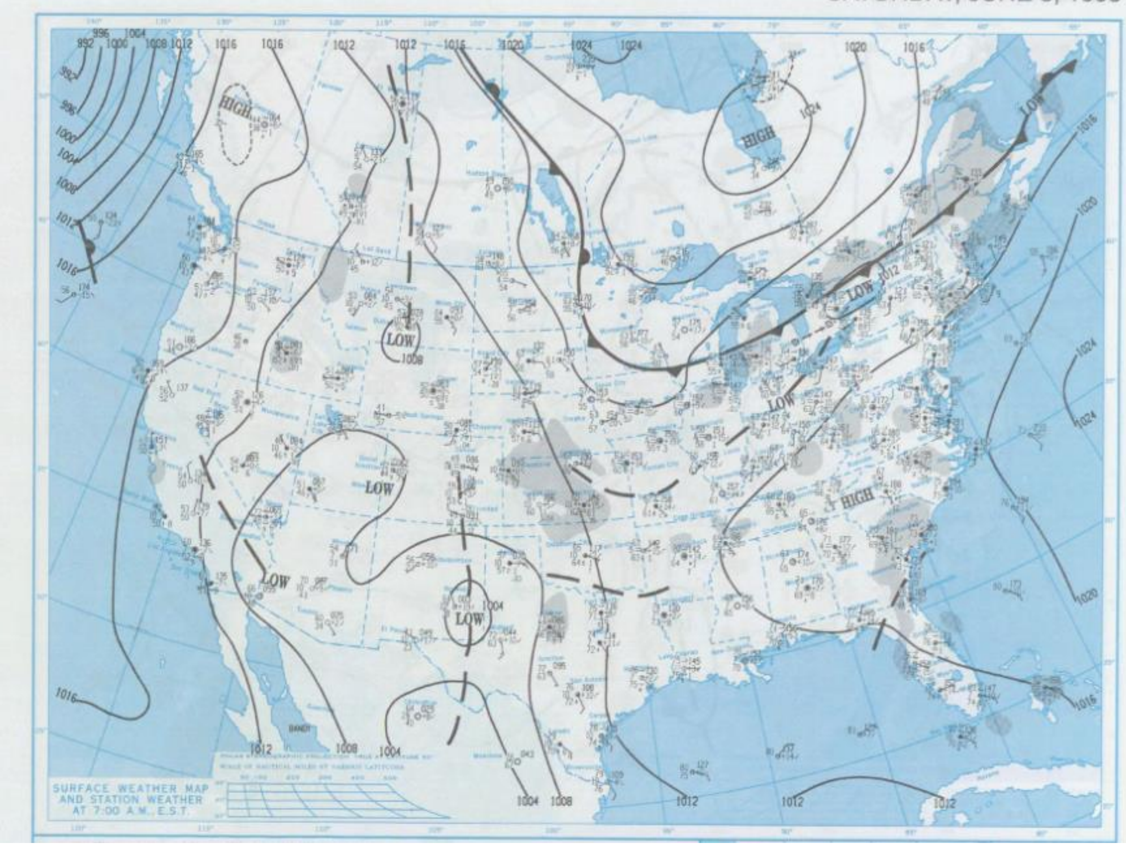
Storm or Storm Center Name	**SPAS 1338 Spionkop Creek, AB**	
Storm Date(s)	6/4-7/1995	
Storm Type	Synoptic	
Storm Location	49.17 N	114.16 W
Storm Center Elevation	1,676	meters
Precipitation Total & Duration	368	millimeters
Storm Representative Dew Point	18.9 °C	24
Storm Representative Dew Point Location	46.55 N	111.50 W
Maximum Dew Point	20.6 °C	
Moisture Inflow Vector	SE @ 354	kilometers
In-place Maximization Factor	**1.19**	
Temporal Transposition (Date)	21-Jun	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

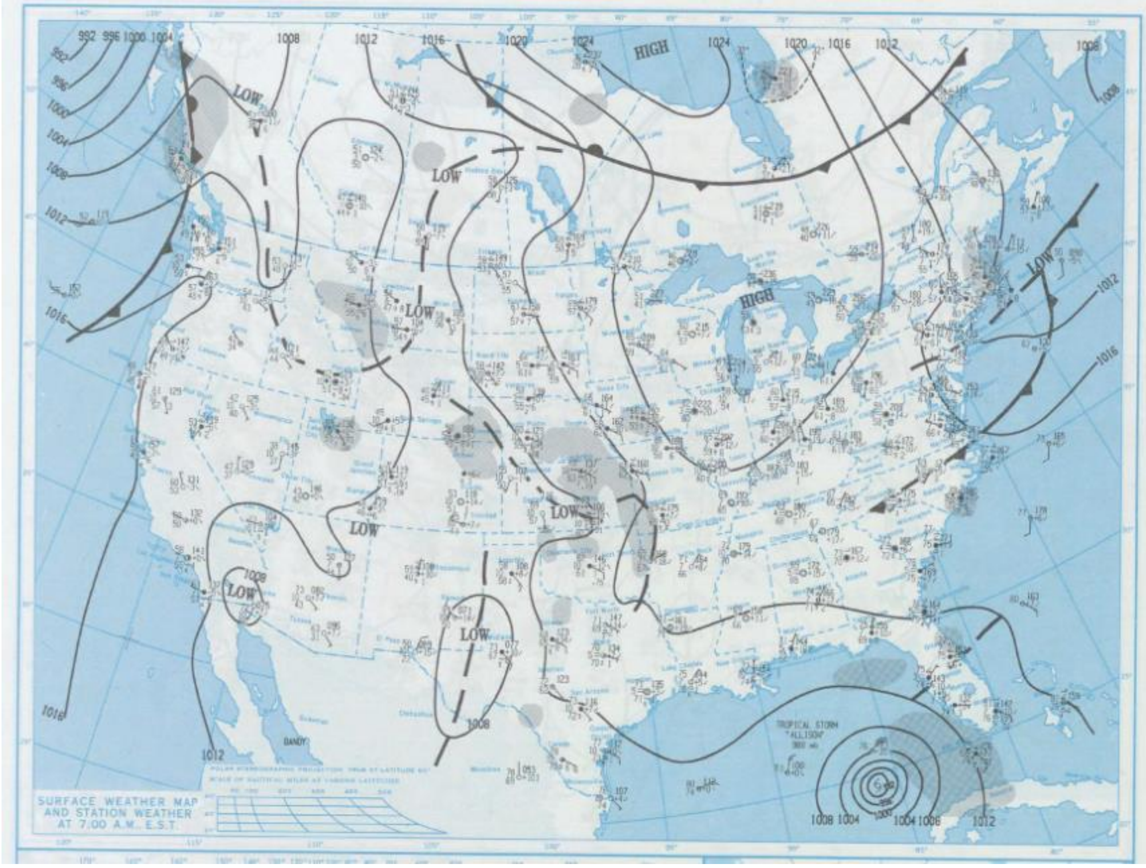
FRIDAY, JUNE 2, 1995



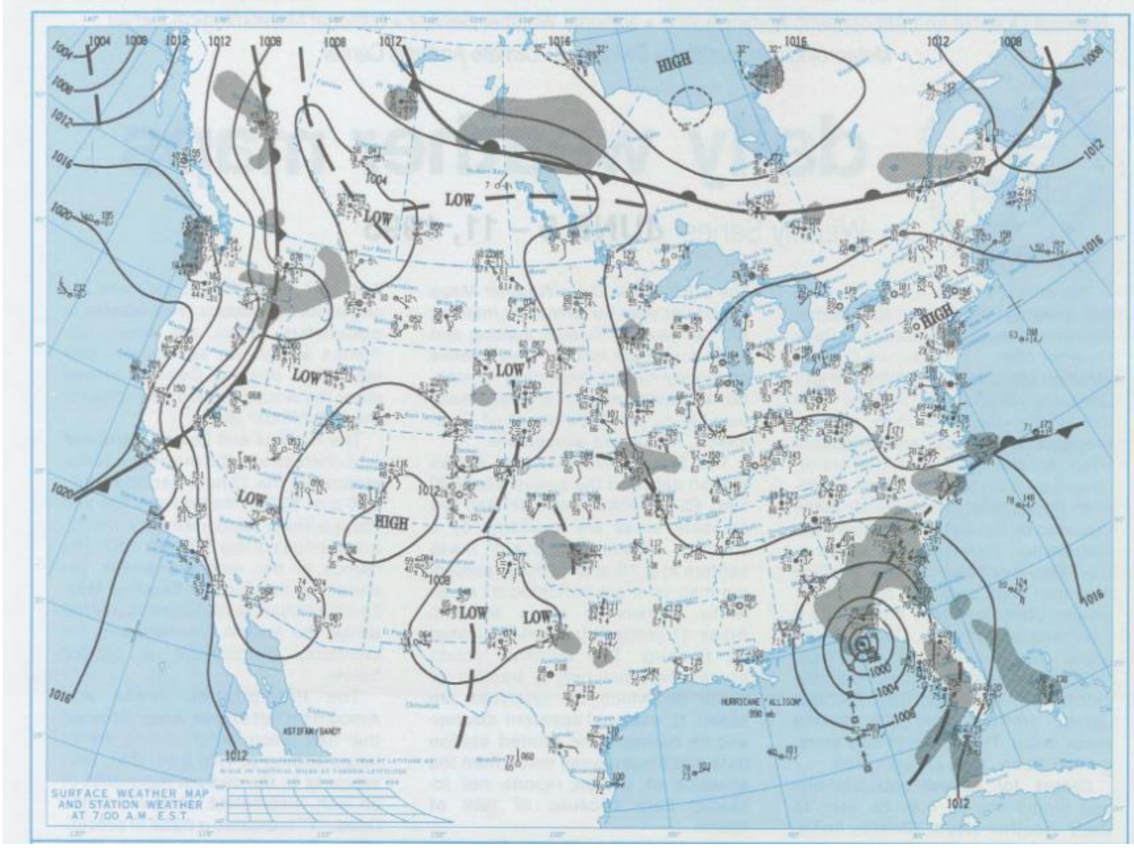
SATURDAY, JUNE 3, 1995



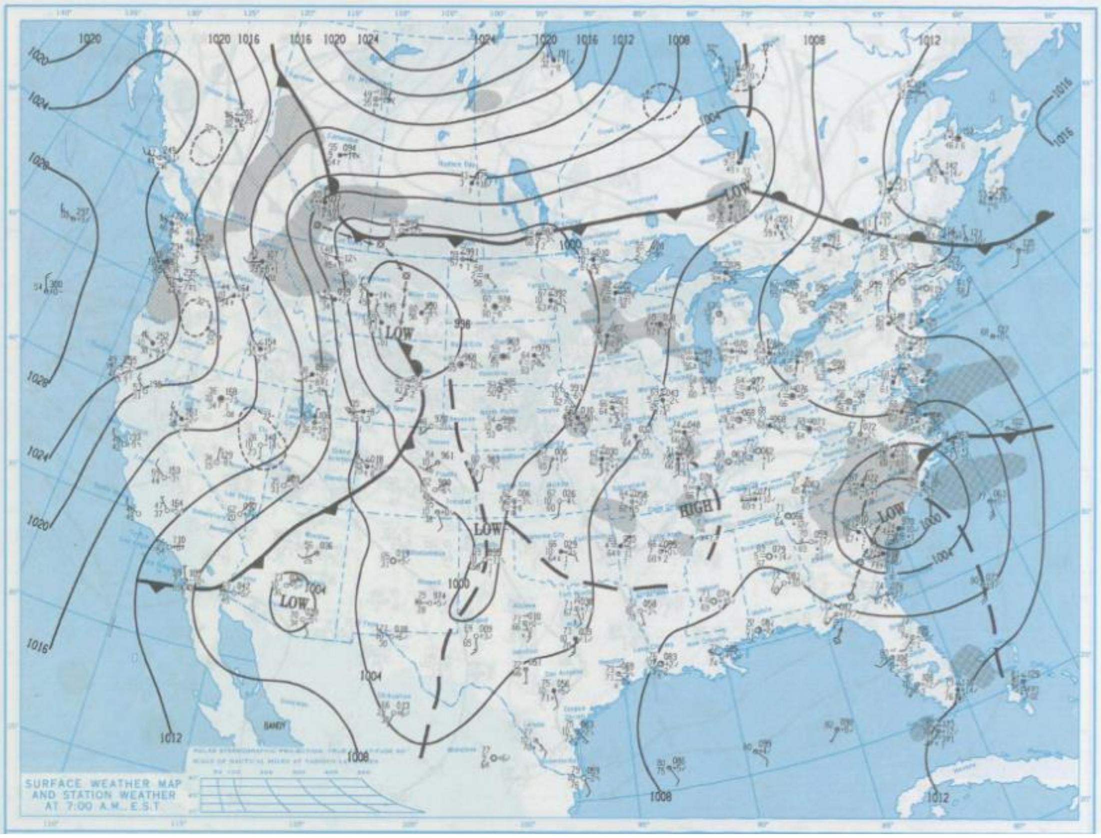
SUNDAY, JUNE 4, 1995



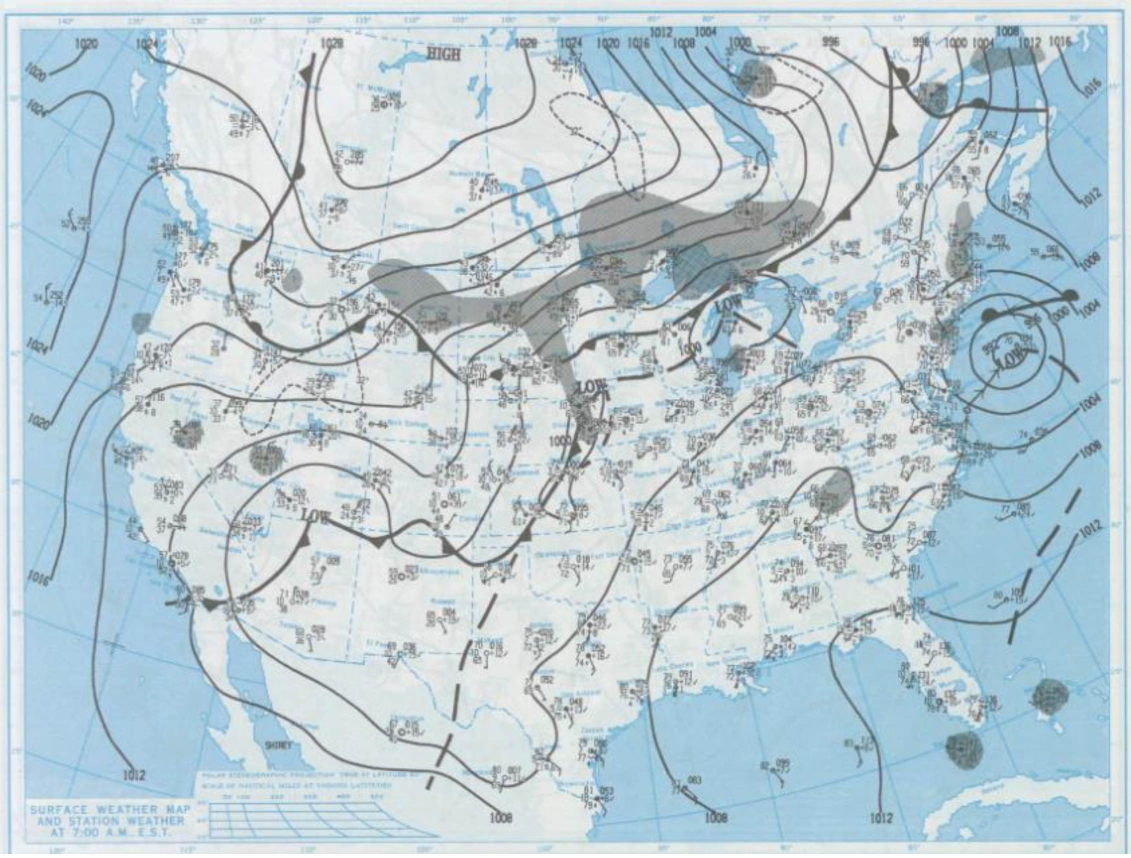
MONDAY, JUNE 5, 1995

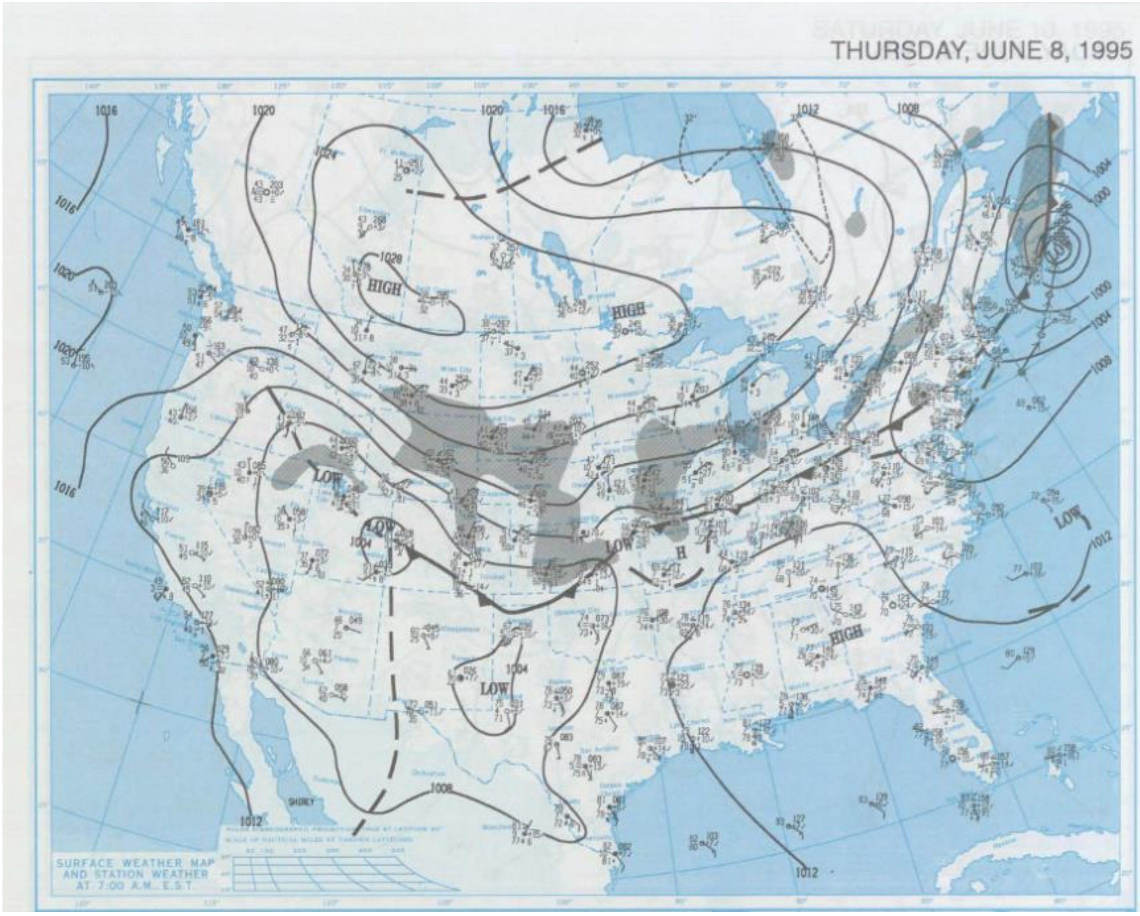


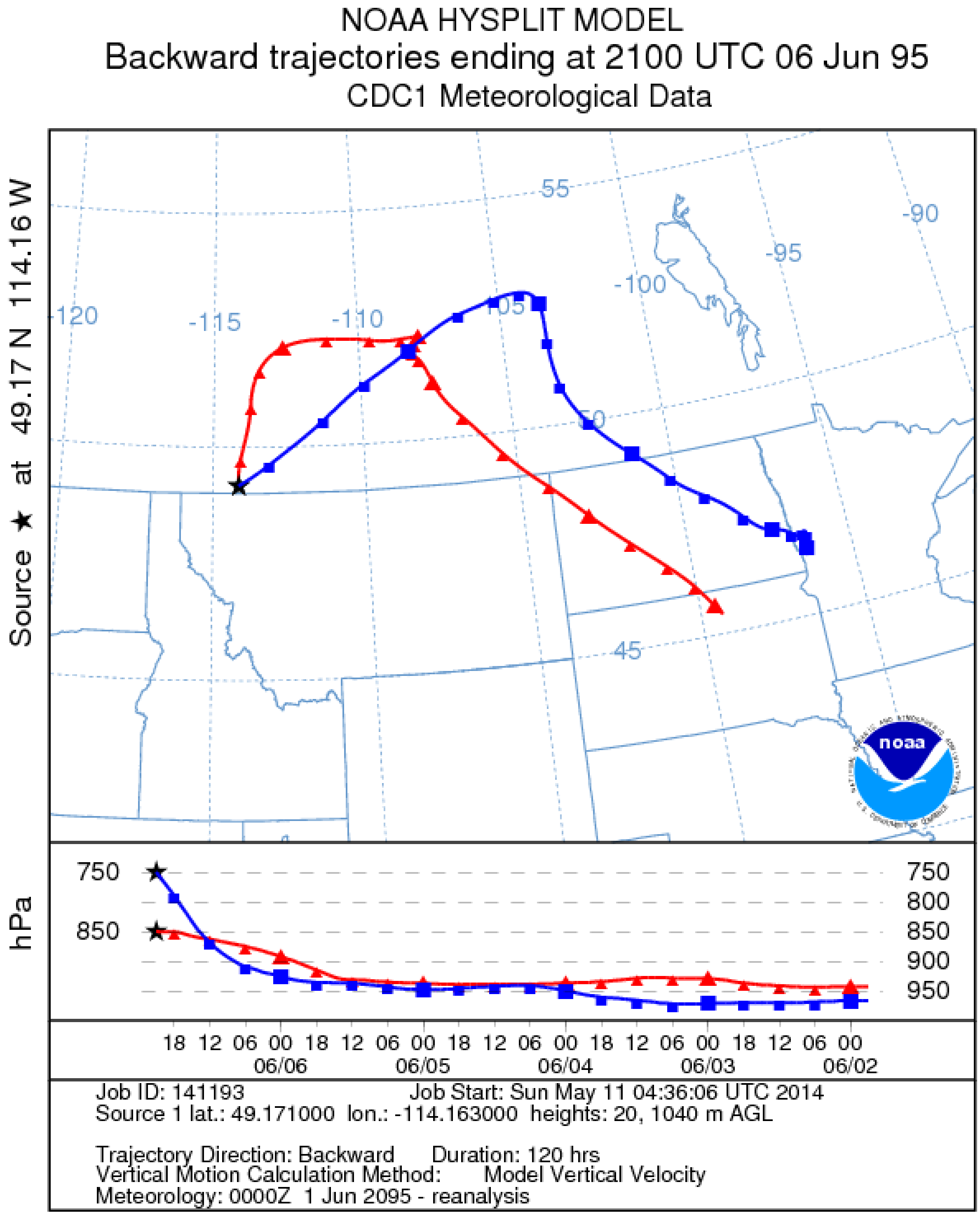
TUESDAY, JUNE 6, 1995



WEDNESDAY, JUNE 7, 1995

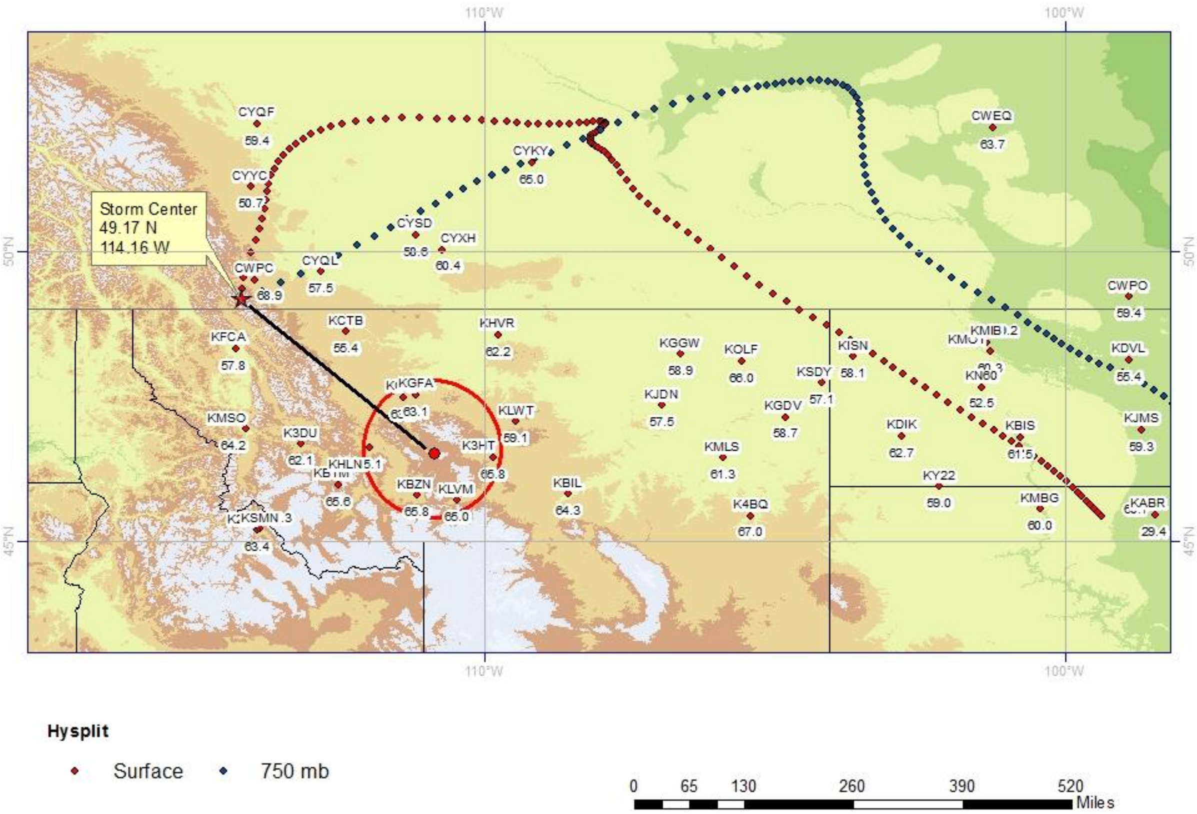



THURSDAY, JUNE 8, 1995
HIGH
HIGH
HIGH
LOW
LOW
LOW
LOW
LOW
LOW
SURFACE WEATHER MAP
AND STATION WEATHER
AT 7:00 A.M., E.S.T.

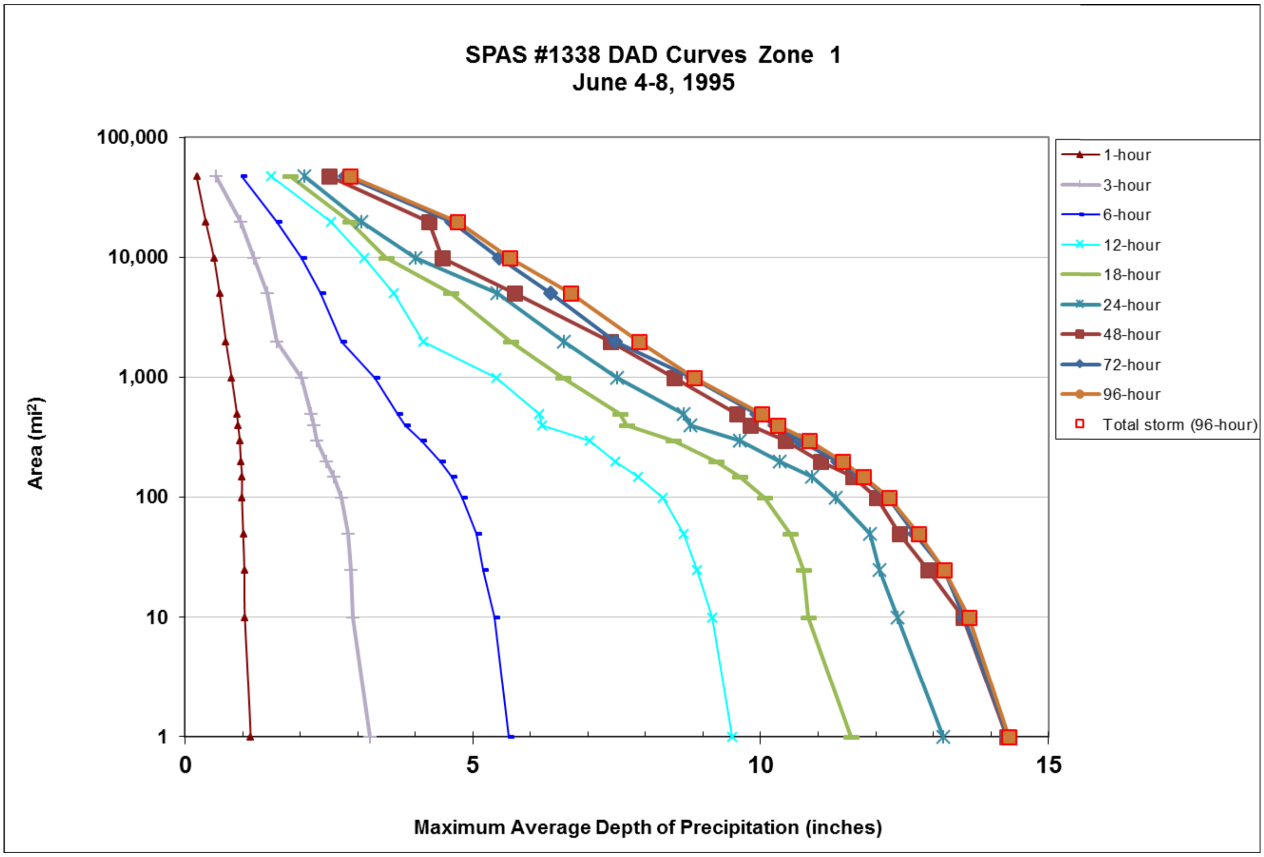

NOAA HYSPLIT MODEL
Backward trajectories ending at 2100 UTC 06 Jun 95
CDC1 Meteorological Data
Source ★ at 49.17 N 114.16 W
55
-90
-95
-100
-120
-115
-110
-105
50
45
noaa
hPa
750
850
750
800
850
900
950
18 12 06 00 18 12 06 00 18 12 06 00 18 12 06 00 18 12 06 00
06/06
06/05
06/04
06/03
06/02
Job ID: 141193
Job Start: Sun May 11 04:36:06 UTC 2014
Source 1 lat.: 49.171000 lon.: -114.163000 heights: 20, 1040 m AGL
Trajectory Direction: Backward
Duration: 120 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jun 2095 - reanalysis

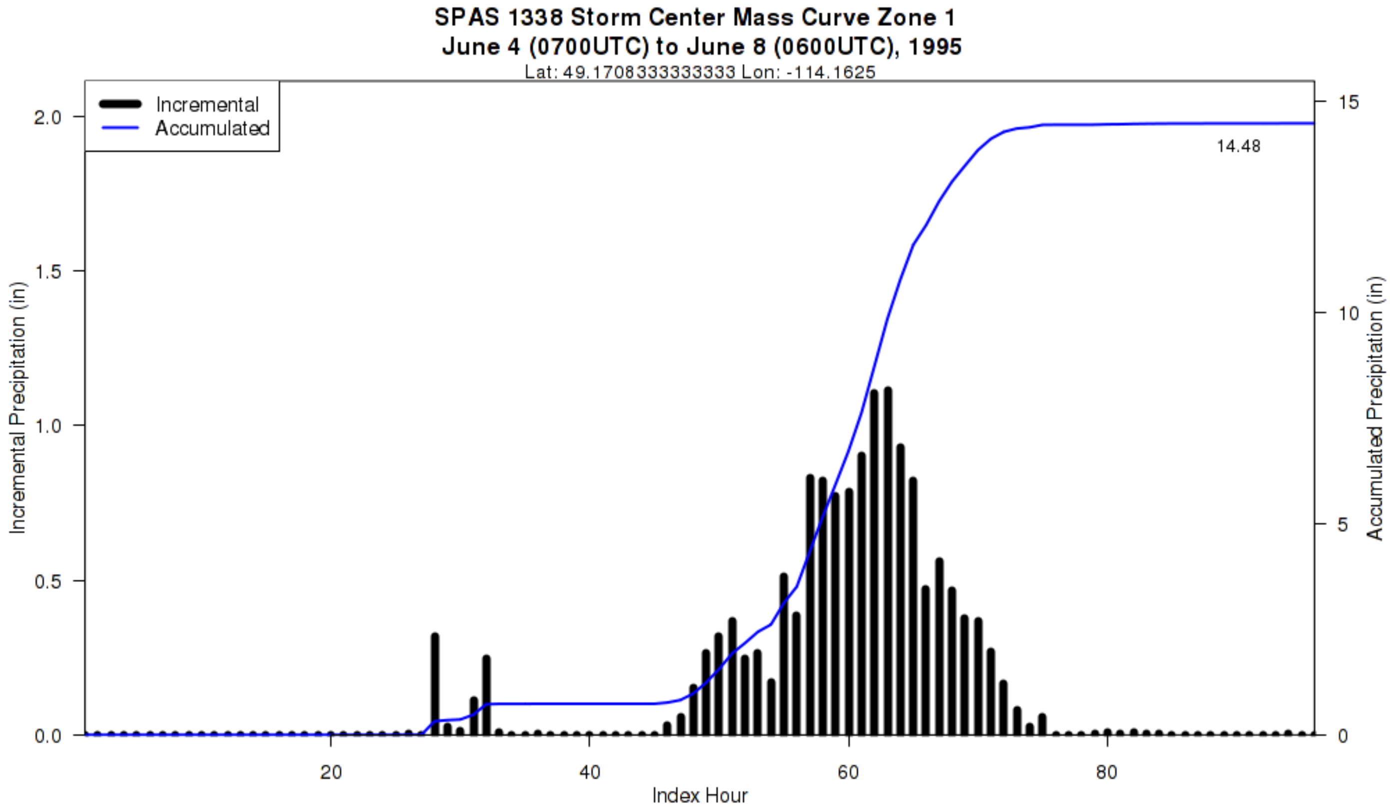
SPAS 1338

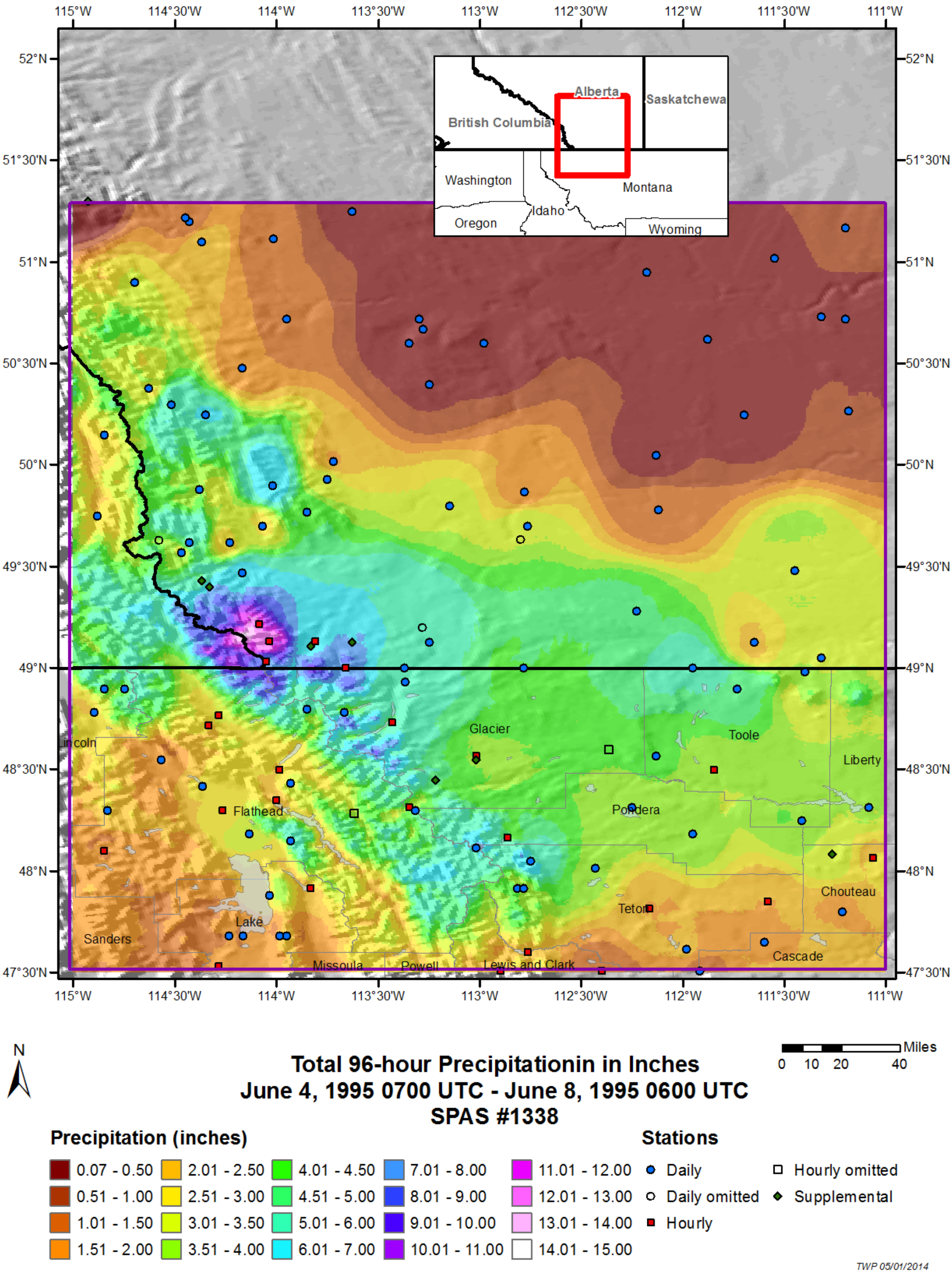
June 4 - June 8, 1995



SPAS 1338 - June 4 (0700 UTC) - June 8 (0600 UTC), 1995										
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)										
	Duration (hours)									
Area (mi^2)	1	3	6	12	18	24	48	72	96	Total
0.2	1.16	3.26	5.66	9.59	11.67	13.30	14.44	14.48	14.48	14.48
1	1.14	3.22	5.62	9.51	11.57	13.17	14.27	14.30	14.31	14.31
10	1.04	2.91	5.38	9.16	10.83	12.38	13.51	13.53	13.61	13.61
25	1.03	2.89	5.17	8.90	10.75	12.07	12.91	13.19	13.19	13.19
50	1.01	2.83	5.07	8.66	10.51	11.90	12.41	12.67	12.75	12.75
100	0.99	2.72	4.82	8.30	10.07	11.31	12.01	12.21	12.23	12.23
150	0.99	2.58	4.63	7.87	9.64	10.89	11.60	11.74	11.78	11.78
200	0.97	2.46	4.43	7.47	9.22	10.33	11.04	11.34	11.42	11.42
300	0.95	2.29	4.10	7.02	8.48	9.63	10.43	10.67	10.85	10.85
400	0.92	2.24	3.83	6.20	7.68	8.78	9.82	10.25	10.29	10.29
500	0.90	2.19	3.69	6.16	7.56	8.66	9.59	9.94	10.01	10.01
1,000	0.81	2.02	3.30	5.41	6.56	7.50	8.50	8.81	8.84	8.84
2,000	0.71	1.60	2.72	4.13	5.66	6.58	7.39	7.47	7.89	7.89
5,000	0.60	1.43	2.35	3.62	4.62	5.42	5.72	6.35	6.70	6.70
10,000	0.50	1.20	2.02	3.11	3.49	4.00	4.47	5.46	5.64	5.64
20,000	0.36	0.96	1.59	2.53	2.86	3.06	4.24	4.63	4.74	4.74
47,367	0.20	0.53	0.98	1.49	1.82	2.07	2.51	2.78	2.87	2.87


SPAS #1338 DAD Curves Zone 1
June 4-8, 1995
Area (mi²)
Maximum Average Depth of Precipitation (inches)
100,000
10,000
1,000
100
10
1
0
5
10
15
1-hour
3-hour
6-hour
12-hour
18-hour
24-hour
48-hour
72-hour
96-hour
Total storm (96-hour)


SPAS 1338 Storm Center Mass Curve Zone 1
June 4 (0700UTC) to June 8 (0600UTC), 1995
Lat: 49.1708333333333 Lon: -114.1625
Incremental
Accumulated
Incremental Precipitation (in)
Accumulated Precipitation (in)
Index Hour
14.48
2.0
1.5
1.0
0.5
0.0
15
10
5
0
20
40
60
80



Total 96-hour Precipitationin in Inches
June 4, 1995 0700 UTC - June 8, 1995 0600 UTC
SPAS #1338

Crystal Lake, MT

May 19-23, 2011

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1404

General Storm Location: Calgary, Alberta Canada

Storm Dates: May 19-23, 2011

Event: Synoptic

DAD Zone 1

Latitude: 45.315°

Longitude: -107.175°

Max. Grid Rainfall Amount: 232mm

Max. Observed Rainfall Amount: 232mm

Number of Stations: 413 (65 Daily, 111 Hourly, 8 Hourly Pseudo, 224 Supplemental, and 5 Supplemental Estimated)

SPAS Version: 9.5

Basemap: PRISM September 1971-2000 Precipitation Climatology

Spatial resolution: 0.01 second (degree: minute: second, WGS84, ~ 0.4 mi^2, 1.04 km^2)

Radar Included: Yes

Depth-Area-Duration (DAD) analysis: No

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and NEXRAD Radar. The radar data was not of highest quality in that the radar data had issues with beam blockage, lower quality radar scans (high angle/elevation scan), and missing scan periods. We have a good degree of confidence in the radar/station based storm total results, the spatial pattern is dependent on the radar data and basemap, and the timing is based on hourly and hourly pseudo stations. The 5-minute radar data is not recommended for use.

Storm Name:	SPAS 1404 Crystal Lake, MT	**Storm Adjustment Summary**
Storm Date:	5/19-23/2011	
AWA Analysis Date:	7/20/2015	

Temporal Transposition Date 2-Jun

	Lat	Long
Storm Center Location	45.32 N	107.18 W
Storm Rep Dew Point Location	43.40 N	97.11 W
Transposition Dew Point Location	N/A*	N/A*
Basin Location	50.89 N	114.69 W

Moisture Inflow Direction	ESE @ 829	kilometers
Basin Average Elevation	N/A*	meters
Storm Center Elevation	1,524	meters
Storm Analysis Duration	24	hours

The storm representative dew point is	17.5 °C	with total precipitable water above sea level of		42	millimeters.
The in-place maximum dew point is	23.3 °C	with total precipitable water above sea level of		69	millimeters.
The transpositioned maximum dew point is	N/A*	with total precipitable water above sea level of		N/A*	millimeters.
The in-place storm elevation is	1,524	which subtracts	18	millimeters of precipitable water at	17.5 °C
The in-place storm elevation is	1,524	which subtracts	27	millimeters of precipitable water at	23.3 °C
The transposition basin elevation at	N/A*	which subtracts	N/A*	millimeters of precipitable water at	N/A*

The in-place storm maximization factor is	1.50
The transposition/elevation to basin factor is	N/A*
The barrier adjustment factor is	N/A*
The total adjustment factor is	N/A*

Notes: DAD values taken from SPAS 1404. Storm representative Td value was based on maximum 24-hr Td values on May 21, 2011 at using KATY, KMHE, KFSD, KLRJ, KOFK. In-place max factor calculated as 1.85, held to 1.50.

Observed Storm Depth-Area-Duration (millimeters)

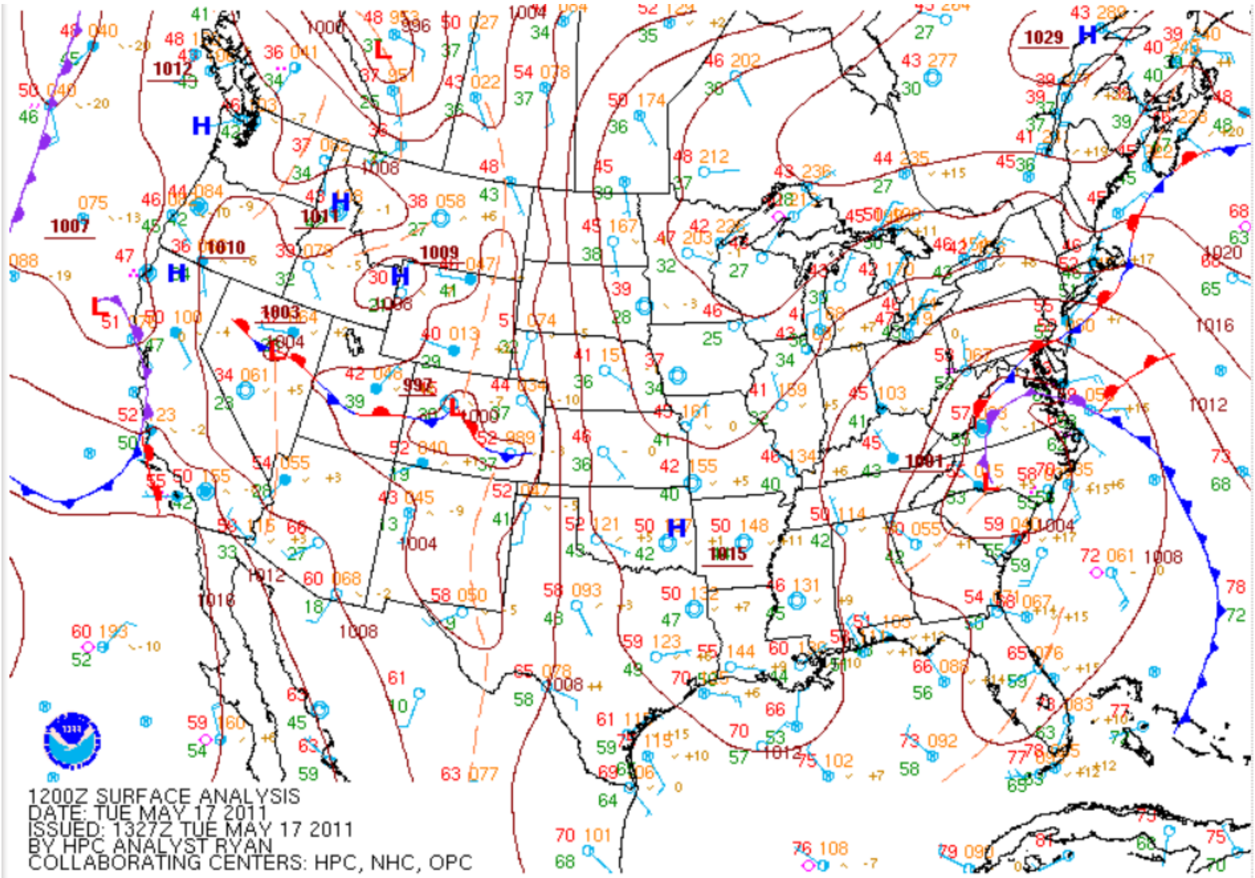
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	23					67	119	149	216
26 km^2 (10 mi^2)	23					63	110	145	208
259 km^2 (100 mi^2)	21					57	86	137	186
518 km^2 (200 mi^2)	19					53	80	129	179
1,295 km^2 (500 mi^2)	15					45	73	108	163
2,590 km^2 (1,00 mi^2)	10					41	67	103	151
5,180 km^2 (2,000 mi^2)									
12.950 km^2 (5000 mi^2)	7					26	49	74	115
25,900 km^2 (10,000 mi^2)	6					23	38	62	103
51,800 km^2 (20,000 mi^2)	4					19	33	50	90

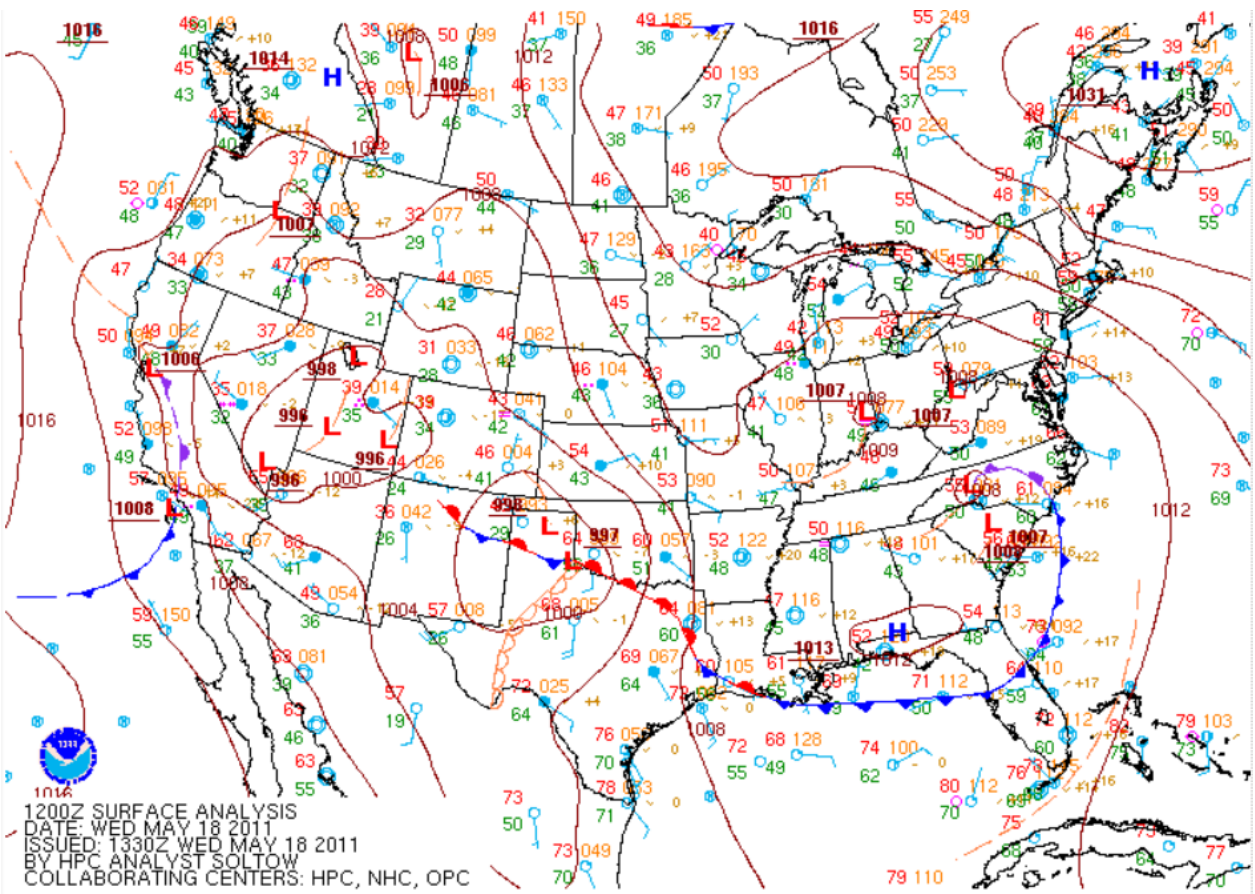
Adjusted Storm Depth-Area-Duration (millimeters)

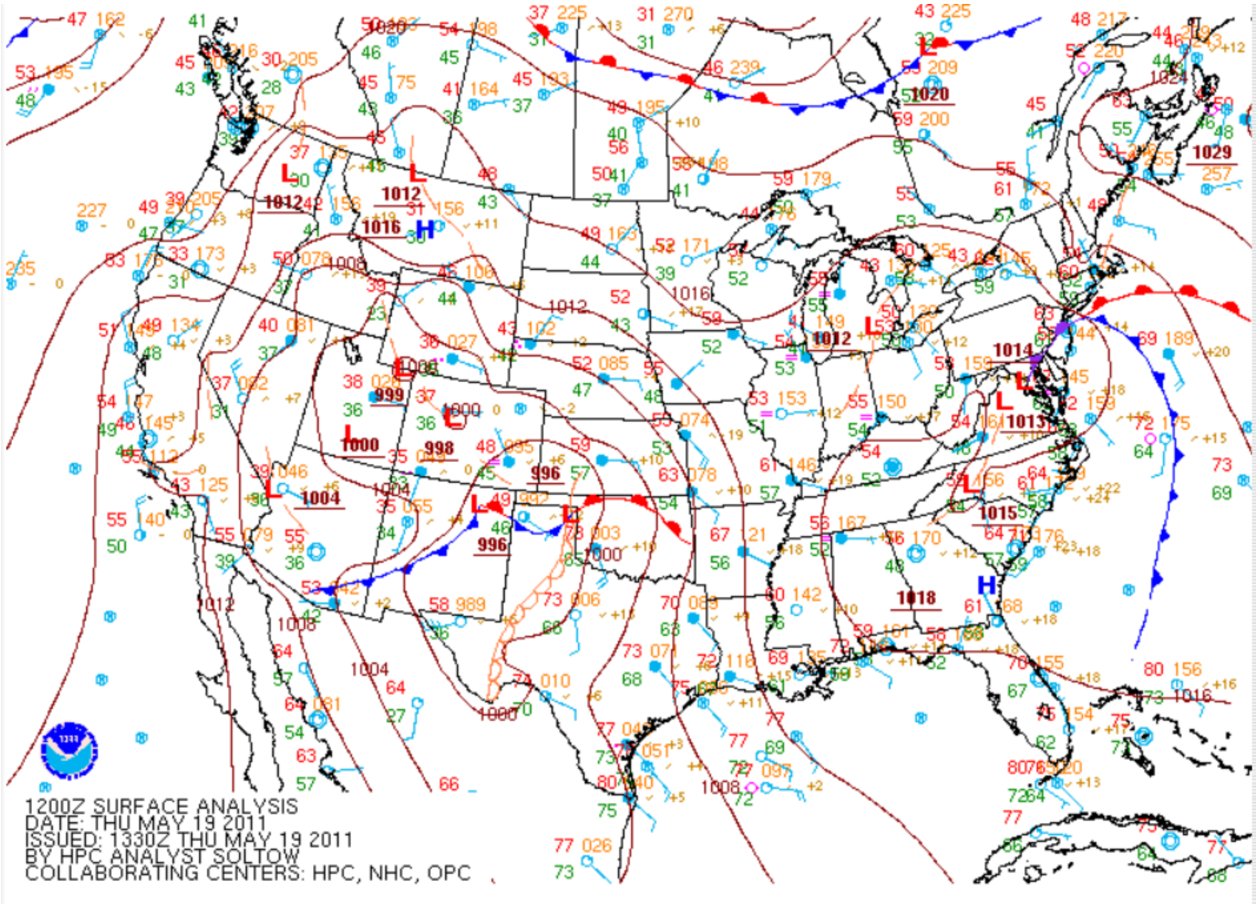
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*
26 km2 (10 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*
259 km2 (100 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*
518 km2 (200 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*
1,295 km2 (500 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*
2,590 km2 (1,00 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*
5,180 km2 (2,000 mi2)									
12.950 km2 (5000 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*
25,900 km2 (10,000 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*
51,800 km2 (20,000 mi2)	N/A*					N/A*	N/A*	N/A*	N/A*

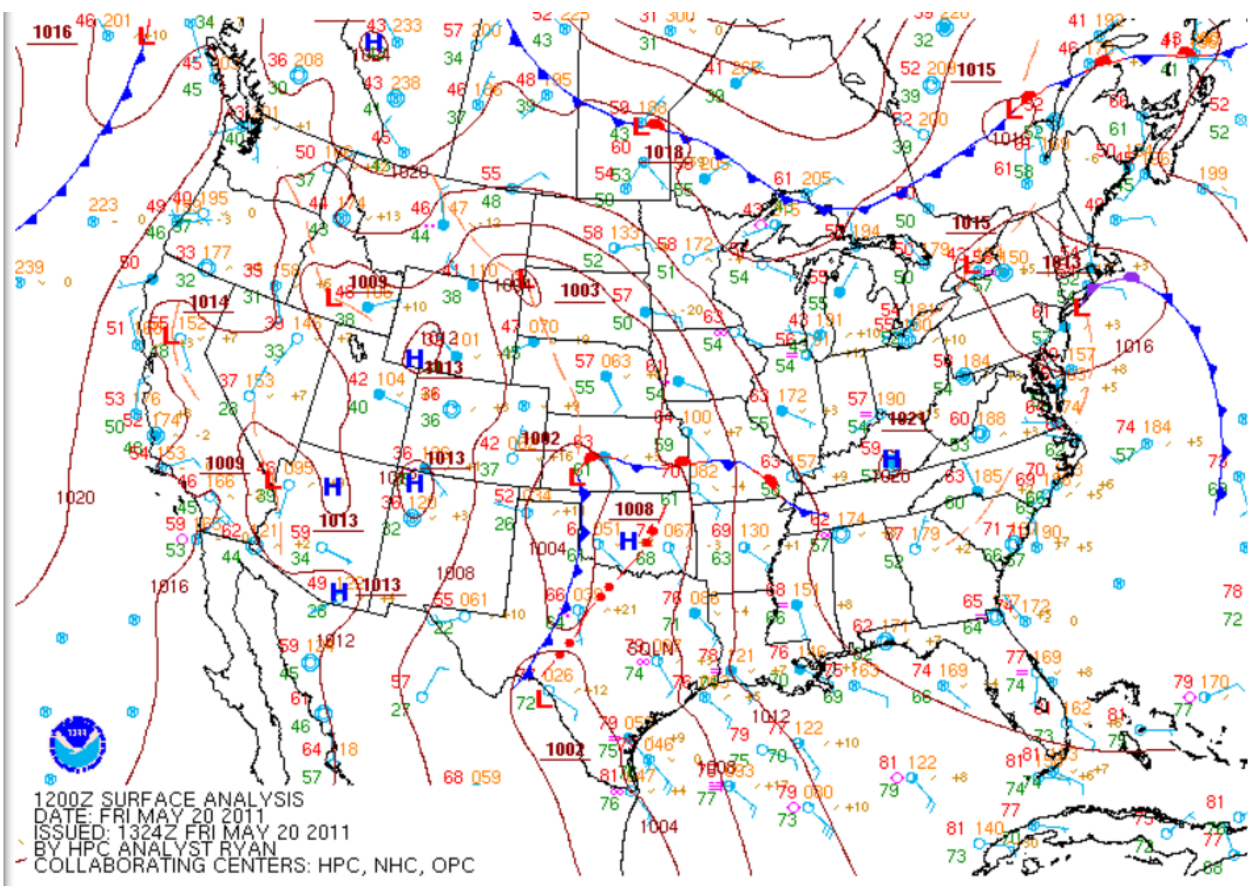
Storm or Storm Center Name	**SPAS 1404 Crystal Lake, MT**		
Storm Date(s)	5/19-23/2011		
Storm Type	Synoptic		
Storm Location	45.32 N	107.18 W	
Storm Center Elevation	1,524	meters	
Precipitation Total & Duration	232	millimeters	
Storm Representative Dew Point	17.5 °C		24
Storm Representative Dew Point Location	43.40 N	97.11 W	
Maximum Dew Point	23.3 °C		
Moisture Inflow Vector	ESE @ 829 kilometers		
In-place Maximization Factor	**1.50**		
Temporal Transposition (Date)	2-Jun		
Transposition Dew Point Location	N/A*	N/A*	
Transposition Maximum Dew Point	N/A*		
Transposition Adjustment Factor	N/A*		
Average Basin Elevation	N/A*		
Barrier Adjustment Factor	N/A*		
Total Adjustment Factor	**N/A***		

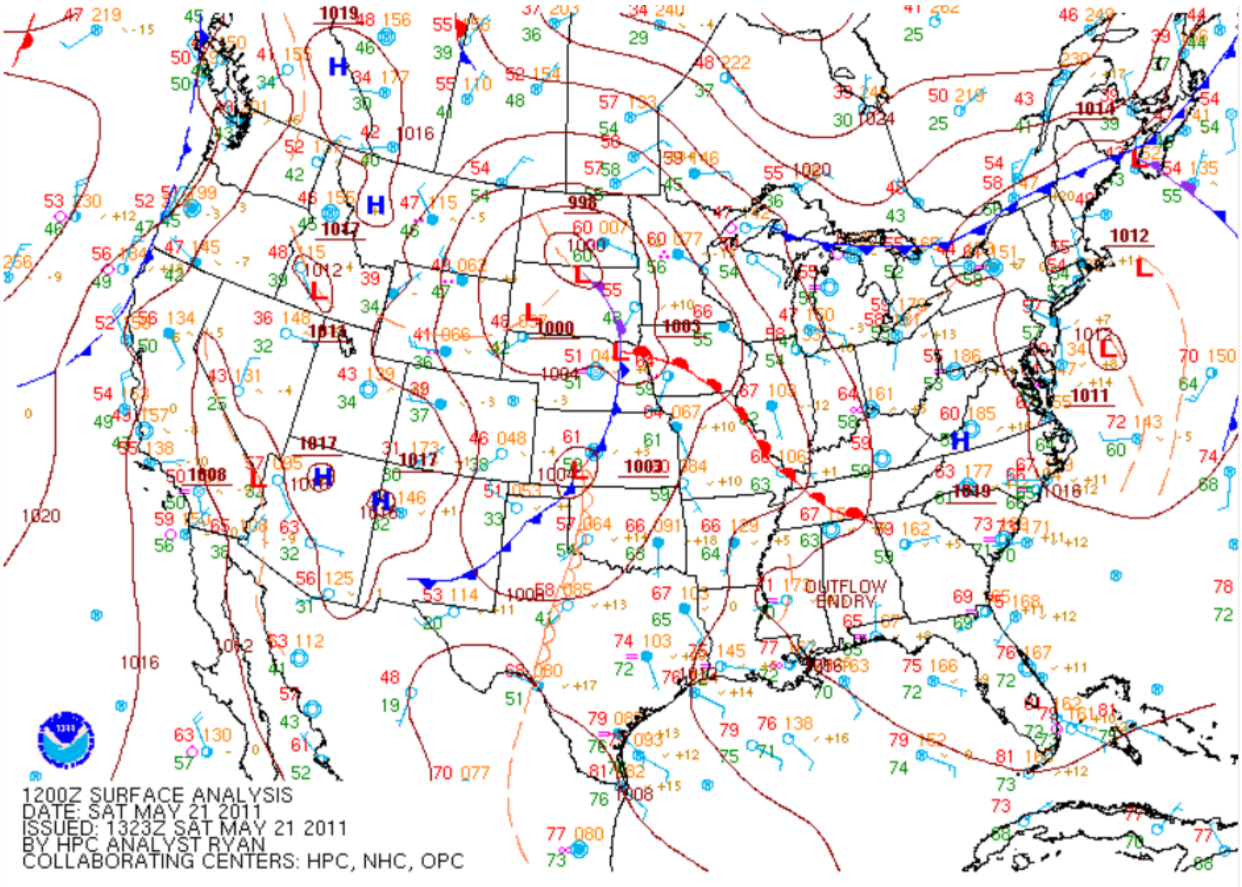
*Variable dependent on transposition location

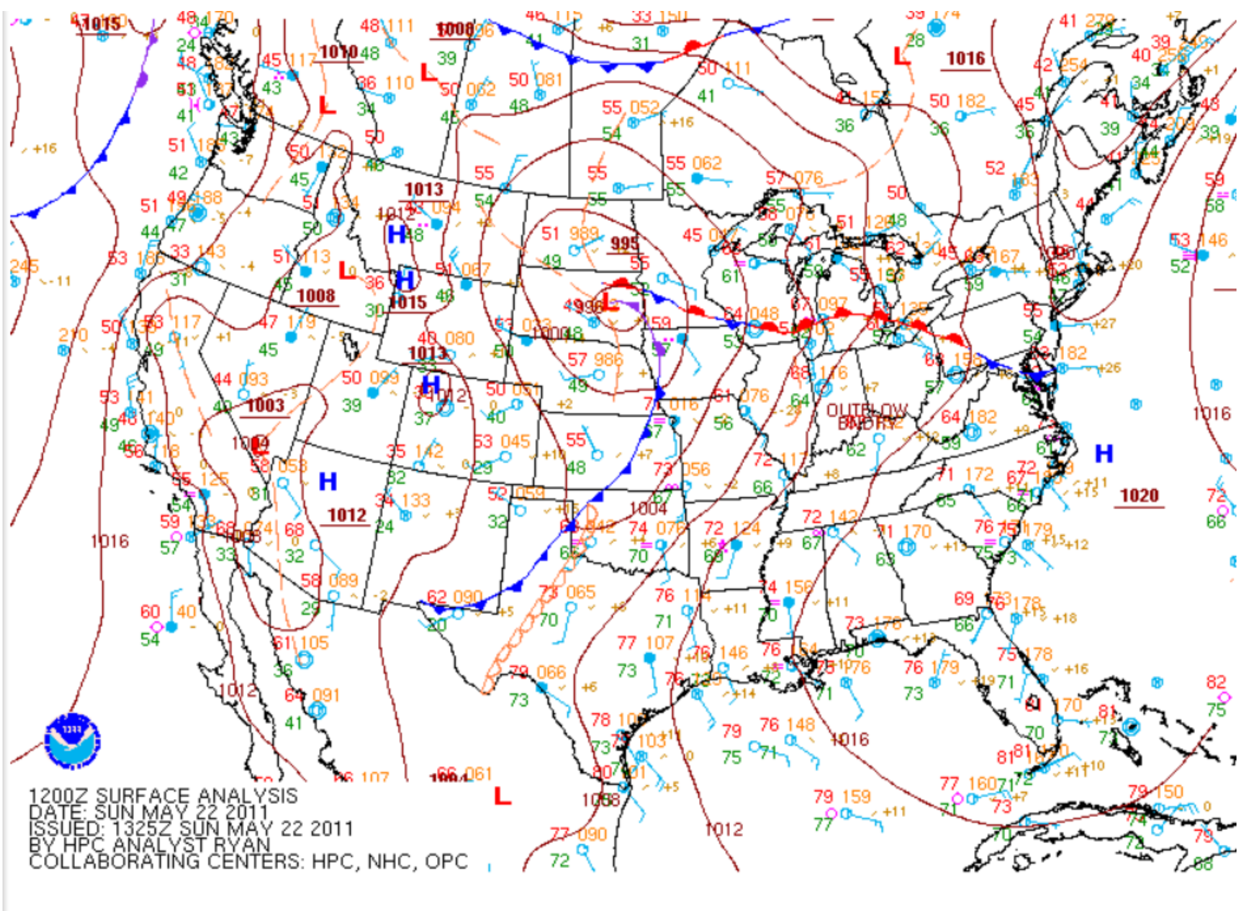

1200Z SURFACE ANALYSIS
DATE: TUE MAY 17 2011
ISSUED: 1327Z TUE MAY 17 2011
BY HPC ANALYST RYAN
COLLABORATING CENTERS: HPC, NHC, OPC

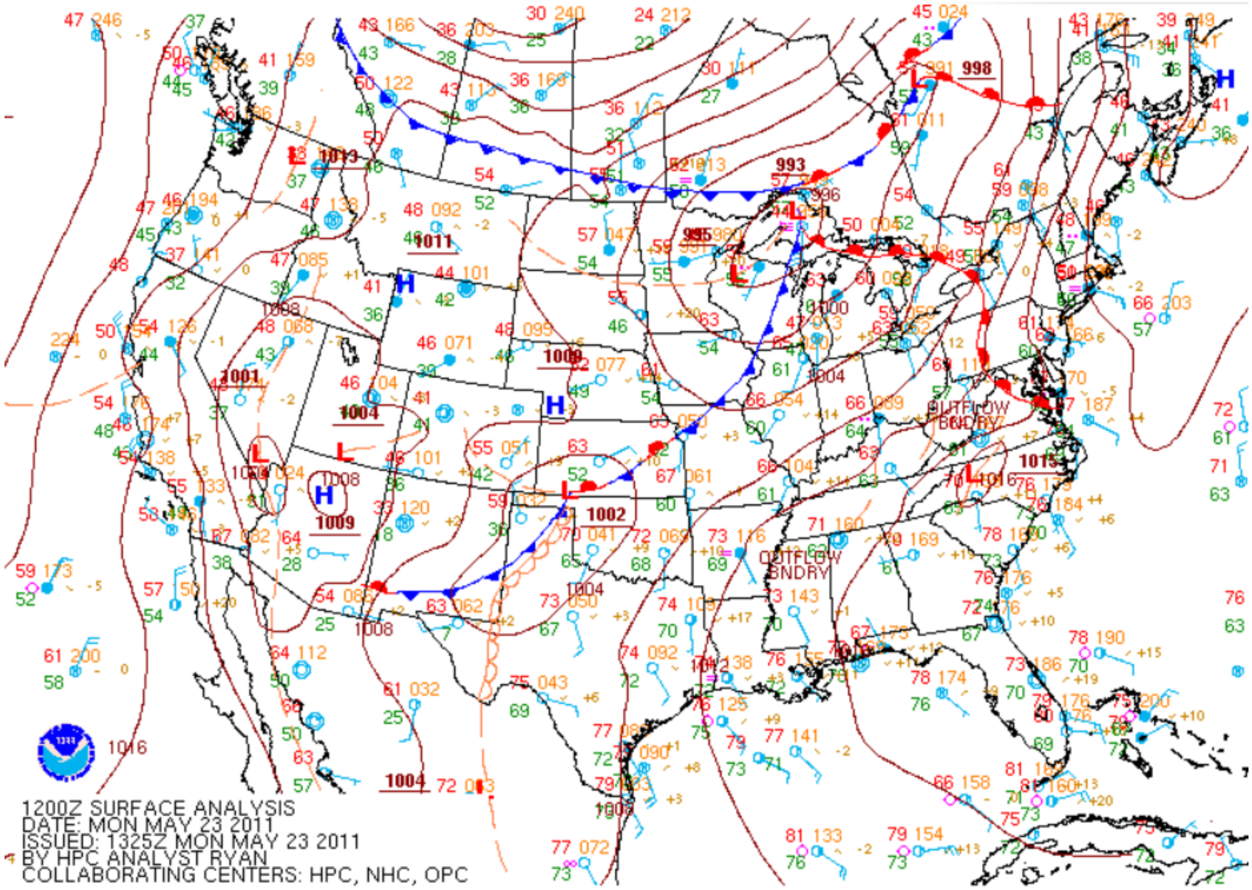

1200Z SURFACE ANALYSIS
DATE: WED MAY 18 2011
ISSUED: 1330Z WED MAY 18 2011
BY HPC ANALYST SOLTOW
COLLABORATING CENTERS: HPC, NHC, OPC

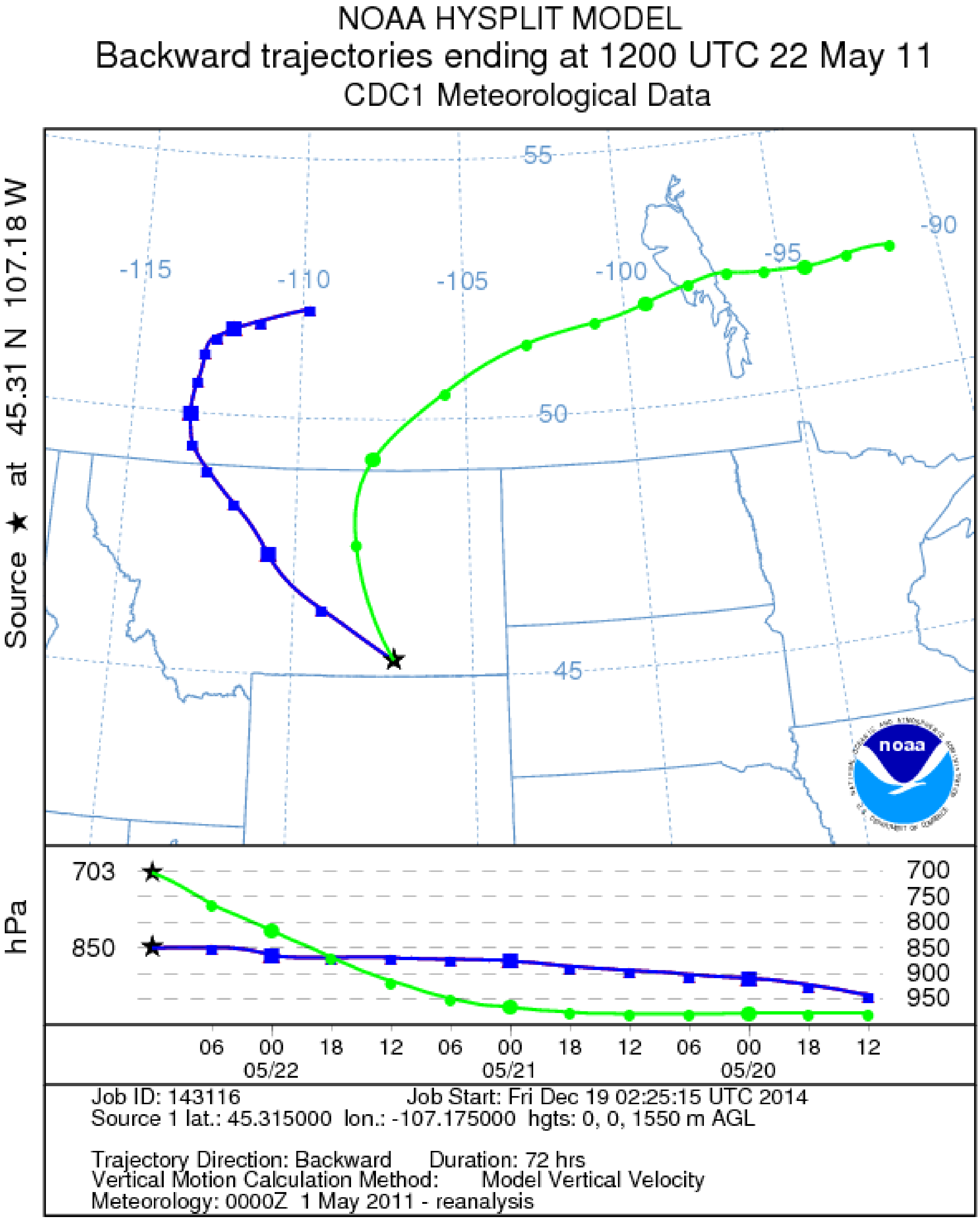

1200Z SURFACE ANALYSIS
DATE: THU MAY 19 2011
ISSUED: 1330Z THU MAY 19 2011
BY HPC ANALYST SOLTOW
COLLABORATING CENTERS: HPC, NHC, OPC

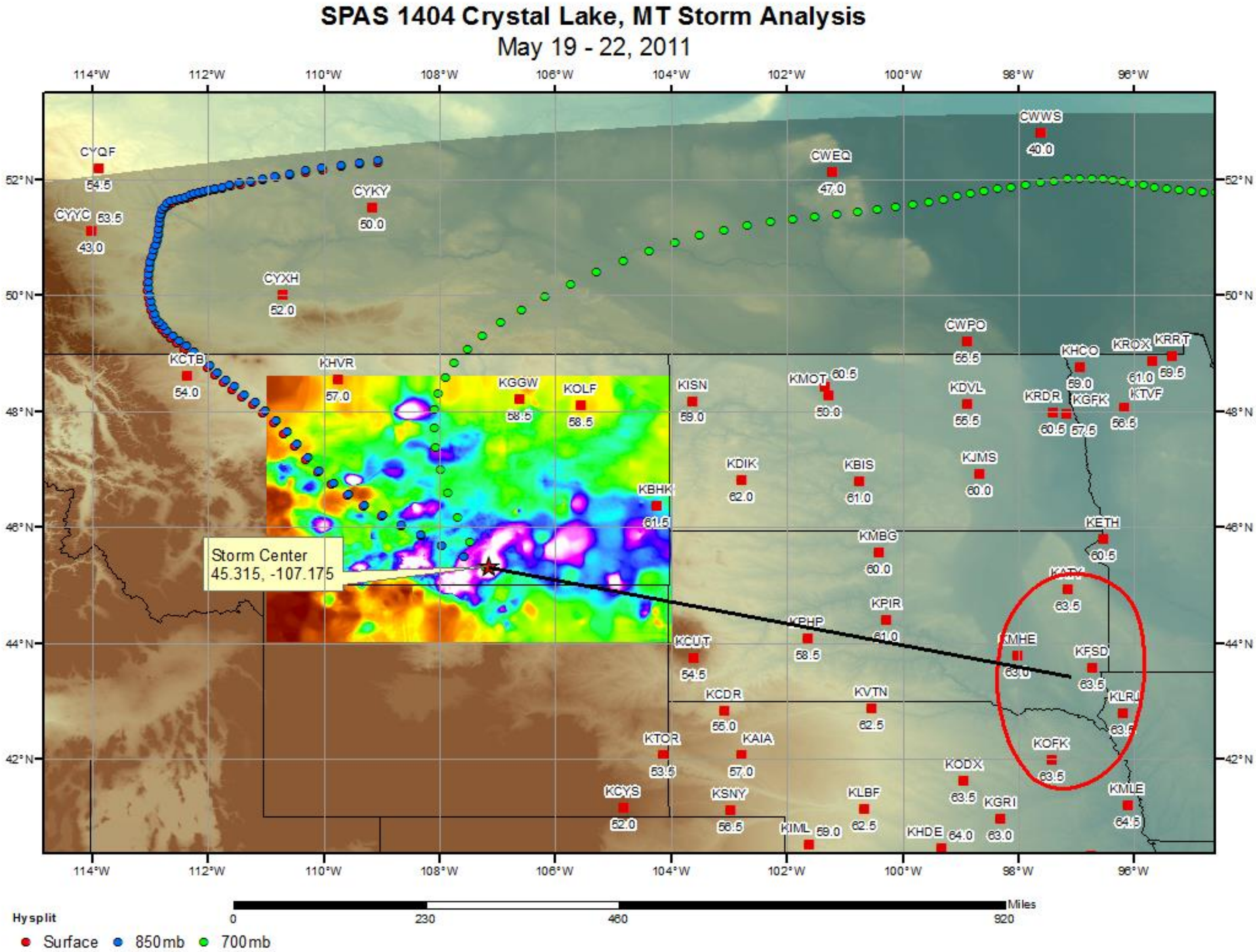

1200Z SURFACE ANALYSIS
DATE: FRI MAY 20 2011
ISSUED: 1324Z FRI MAY 20 2011
BY HPC ANALYST RYAN
COLLABORATING CENTERS: HPC, NHC, OPC


1200Z SURFACE ANALYSIS
DATE: SAT MAY 21 2011
ISSUED: 1323Z SAT MAY 21 2011
BY HPC ANALYST RYAN
COLLABORATING CENTERS: HPC, NHC, OPC
OUTFLOW BNDRY


1200Z SURFACE ANALYSIS
DATE: SUN MAY 22 2011
ISSUED: 1325Z SUN MAY 22 2011
BY HPC ANALYST RYAN
COLLABORATING CENTERS: HPC, NHC, OPC
OUTFLOW BNDRY

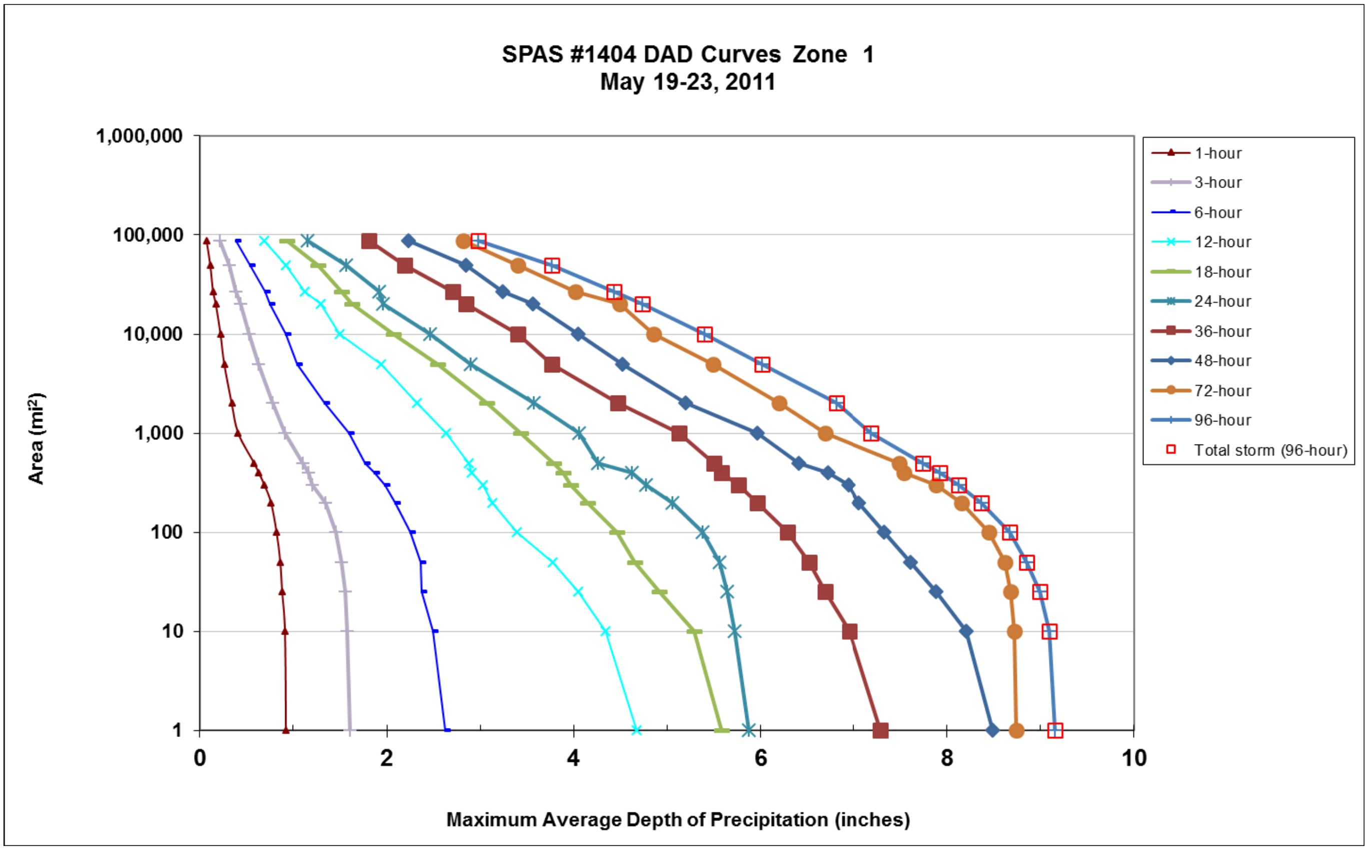

1200Z SURFACE ANALYSIS
DATE: MON MAY 23 2011
ISSUED: 1325Z MON MAY 23 2011
BY HPC ANALYST RYAN
COLLABORATING CENTERS: HPC, NHC, OPC
OUTFLOW BNDRY
OUTFLOW BNDRY

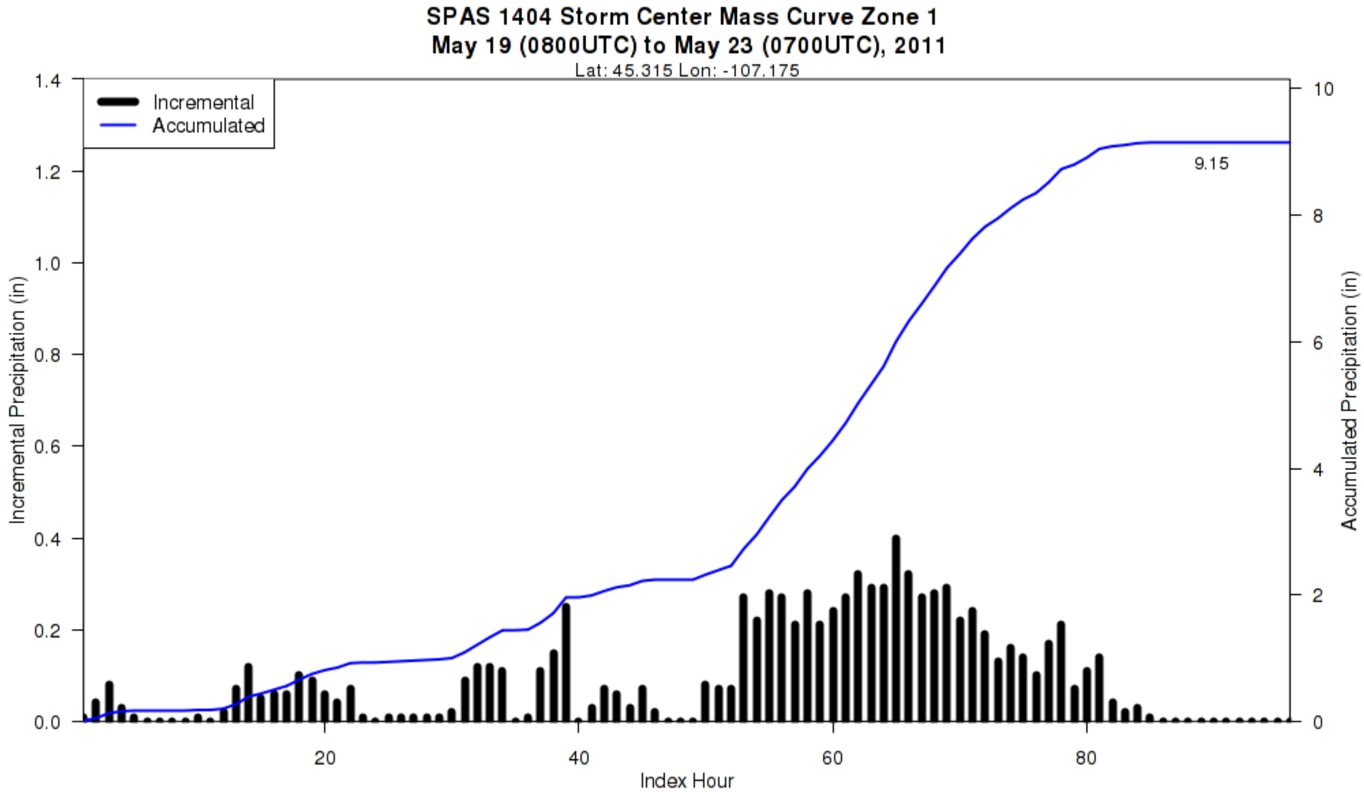

NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 22 May 11
CDC1 Meteorological Data
Source ★ at 45.31 N 107.18 W
55
50
45
-115
-110
-105
-100
-95
-90
hPa
703
850
700
750
800
850
900
950
06 00 18 12 06 00 18 12 06 00 18 12
05/22
05/21
05/20
Job ID: 143116 Job Start: Fri Dec 19 02:25:15 UTC 2014
Source 1 lat.: 45.315000 lon.: -107.175000 hgts: 0, 0, 1550 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 May 2011 - reanalysis

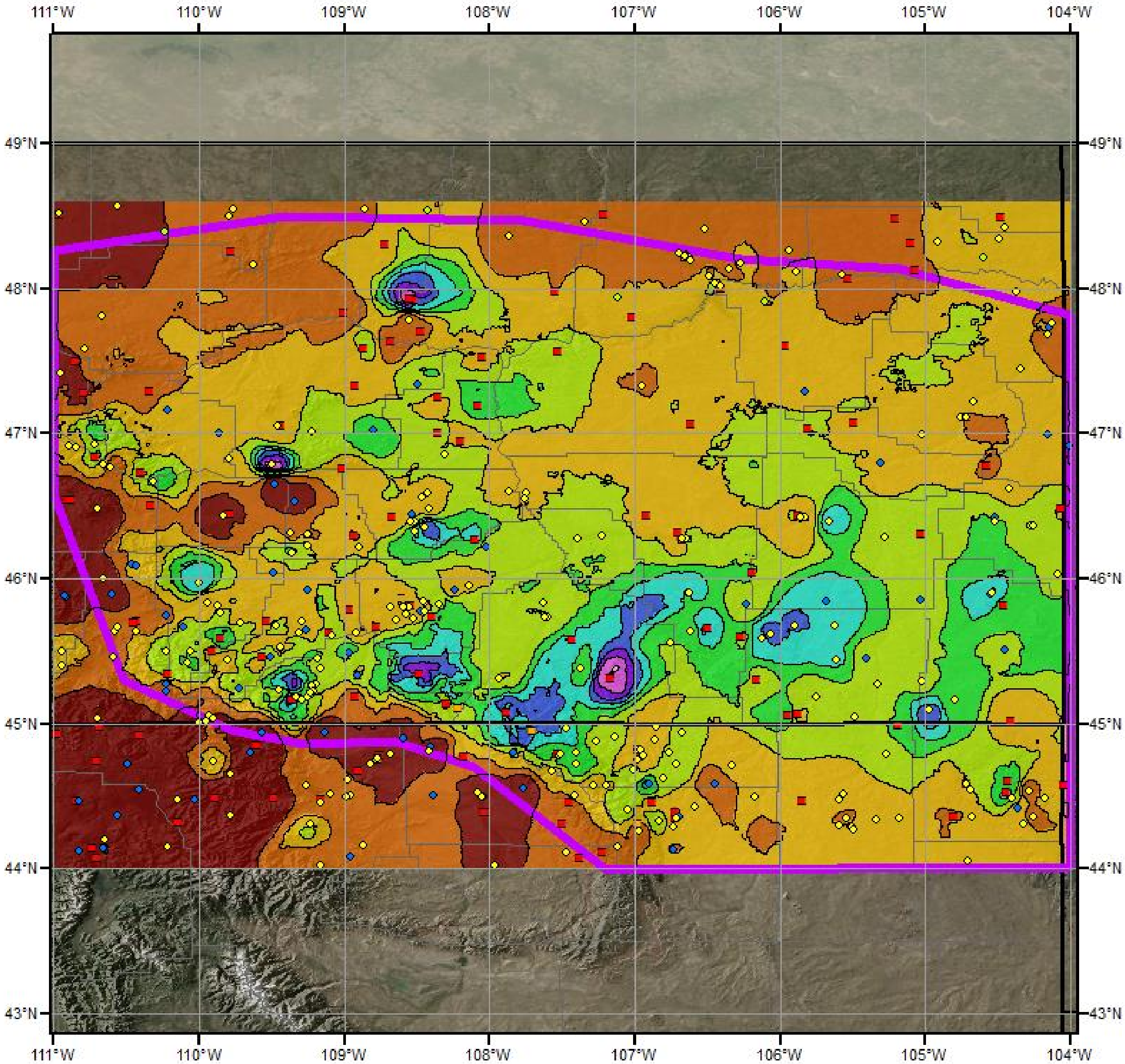


SPAS 1404 Crystal Lake, MT Storm Analysis
May 19 - 22, 2011
Storm Center
45.315, -107.175
CWWS 40.0
CYQF 54.5
CWEQ 47.0
CYKY 50.0
CYYC 53.5
43.0
CYXH 52.0
CWPO 55.5
KHCQ 59.0
KROX 61.0
KRRT 59.5
KCTB 54.0
KHVR 57.0
KGGW 58.5
KOLF 58.5
KISN 59.0
KMOT 60.5
50.0
KDVL 55.5
KRDR 60.5
KGFK 57.5
KTVF 56.5
KDIK 62.0
KBIS 61.0
KJMS 60.0
KBHK 61.5
KETH 60.5
KMBG 60.0
KATY 63.5
KPIR 61.0
KPHP 58.5
KMHE 63.0
KFSD 63.5
KCUT 54.5
KCDR 55.0
KVTN 62.5
KLRJ 63.5
KTOR 53.5
KAIA 57.0
KOFK 63.5
KODX 63.5
KGRI 63.0
KCYS 52.0
KSNY 56.5
KLBF 62.5
KMLE 64.5
KIML 59.0
KHDE 64.0
114°W 112°W 110°W 108°W 106°W 104°W 102°W 100°W 98°W 96°W
52°N 50°N 48°N 46°N 44°N 42°N
Miles
0 230 460 920
Hysplit
Surface 850mb 700mb

SPAS 1404 - May 19 (0800 UTC) - May 23 (0700 UTC), 2011											
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)											
	Duration (hours)										
Area (mi^2)	1	3	6	12	18	24	36	48	72	96	Total
0.3	0.92	1.63	2.65	4.69	5.60	5.89	7.31	8.51	8.94	9.15	9.15
1	0.92	1.61	2.63	4.67	5.58	5.87	7.29	8.49	8.74	9.15	9.15
10	0.91	1.58	2.49	4.34	5.29	5.72	6.95	8.20	8.72	9.09	9.09
25	0.88	1.56	2.37	4.05	4.92	5.64	6.69	7.88	8.68	8.99	8.99
50	0.86	1.52	2.36	3.78	4.65	5.56	6.52	7.61	8.62	8.85	8.85
100	0.82	1.45	2.25	3.39	4.46	5.38	6.29	7.33	8.45	8.67	8.67
200	0.76	1.34	2.09	3.13	4.15	5.06	5.96	7.05	8.15	8.37	8.37
300	0.69	1.20	1.98	3.03	3.97	4.77	5.76	6.94	7.88	8.12	8.12
400	0.63	1.16	1.87	2.91	3.89	4.62	5.58	6.72	7.54	7.92	7.92
500	0.58	1.10	1.77	2.88	3.79	4.26	5.50	6.41	7.49	7.74	7.74
1,000	0.41	0.91	1.60	2.64	3.43	4.06	5.13	5.96	6.69	7.19	7.19
2,000	0.34	0.78	1.33	2.32	3.07	3.57	4.47	5.20	6.20	6.81	6.81
5,000	0.26	0.63	1.04	1.94	2.54	2.90	3.77	4.52	5.49	6.01	6.01
10,000	0.22	0.53	0.92	1.49	2.07	2.46	3.40	4.05	4.85	5.40	5.40
20,000	0.17	0.44	0.75	1.29	1.63	1.96	2.85	3.56	4.49	4.73	4.73
27,000	0.14	0.39	0.70	1.12	1.52	1.92	2.71	3.24	4.02	4.43	4.43
50,000	0.11	0.31	0.54	0.92	1.26	1.57	2.19	2.85	3.40	3.77	3.77
87,767	0.07	0.21	0.39	0.69	0.93	1.15	1.81	2.23	2.82	2.98	2.98




SPAS 1404 Storm Center Mass Curve Zone 1
May 19 (0800UTC) to May 23 (0700UTC), 2011
Lat: 45.315 Lon: -107.175
Incremental
Accumulated
9.15
Incremental Precipitation (in)
Accumulated Precipitation (in)
Index Hour
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
2
4
6
8
10
20
40
60
80



Total Precipitation (96-hours)
SPAS-NEXRAD 1404 - Crystal Lake, MT
5/19/2011 0800 GMT - 5/23/2011 0700 GMT

Gauges

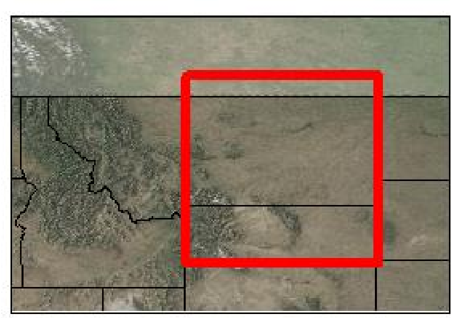
- Daily
- Hourly
- Hourly Pseudo
- Supplemental
- Supplementl Estimated

Miles: 0, 30, 60, 120

Kilometers: 0, 62.5, 125, 250

Precipitation (inches)

0.00 - 1.00
1.01 - 2.00
2.01 - 3.00
3.01 - 4.00
4.01 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
8.01 - 9.00
9.01 - 10.00



10/10/2014

Calgary, AB

June 1-9, 2005

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1492

General Storm Location: Calgary, Alberta

Storm Dates: June 1 - 9, 2005

Event: Synoptic Event

DAD Zone 1

Latitude: 50.435°

Longitude: -114.385°

Max. Grid Rainfall Amount: 325mm

Max. Observed Rainfall Amount: 309mm

Number of Stations: 223 (121 Daily, 37 Hourly, 23 Hourly Pseudo, 2 Hourly Estimated Pseudo, and 40 Supplemental)

SPAS Version: 10.0

Basemap: PRISM June 1961-1990 Climatology (Canada)

Spatial resolution: 0.01 second (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: Yes

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and radar reflectivity data. We have a good degree of confidence in the station and radar based storm total results, the spatial pattern is dependent on the station data radar reflectivity, and a basemap. The timing is based on hourly and hourly pseudo stations and radar reflectivity. *** Radar reflectivity data were good, but contained a lot of high scan levels.

Storm Name:	SPAS 1492 Calgary, AB	**Storm Adjustment Summary**
Storm Date:	6/1-9/2005	
AWA Analysis Date:	7/20/2015	

Temporal Transposition Date **20-Jun**

	Lat	Long
Storm Center Location	**50.44 N**	**114.39 W**
Storm Rep Dew Point Location	**48.00 N**	**111.00 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**SE @ 370**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**1,478**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**15.3 °C**	with total precipitable water above sea level of		**34**	millimeters.
The in-place maximum dew point is	**20.3 °C**	with total precipitable water above sea level of		**53**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**1,478**	which subtracts	**16**	millimeters of precipitable water at	**15.3 °C**
The in-place storm elevation is	**1,478**	which subtracts	**22**	millimeters of precipitable water at	**20.3 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.50**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Storm representative Td was based on the 24hr average Td from KHVR, KFGA and KLWT on June 6, 2005. IPMF calculated at 1.70 and held to 1.50.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**26**					**66**	**115**	**157**	**220**
26 km^2 (10 mi^2)	**24**					**66**	**115**	**156**	**219**
259 km^2 (100 mi^2)	**21**					**64**	**109**	**150**	**212**
518 km^2 (200 mi^2)	**19**					**61**	**104**	**144**	**202**
1,295 km^2 (500 mi^2)	**16**					**53**	**93**	**130**	**191**
2,590 km^2 (1,00 mi^2)	**13**					**48**	**85**	**116**	**187**
5,180 km^2 (2,000 mi^2)	**9**					**42**	**74**	**103**	**172**
12.950 km^2 (5000 mi^2)	**8**					**33**	**59**	**88**	**141**
25,900 km^2 (10,000 mi^2)	**5**					**28**	**50**	**77**	**123**
51,800 km^2 (20,000 mi^2)	**4**					**23**	**38**	**66**	**101**

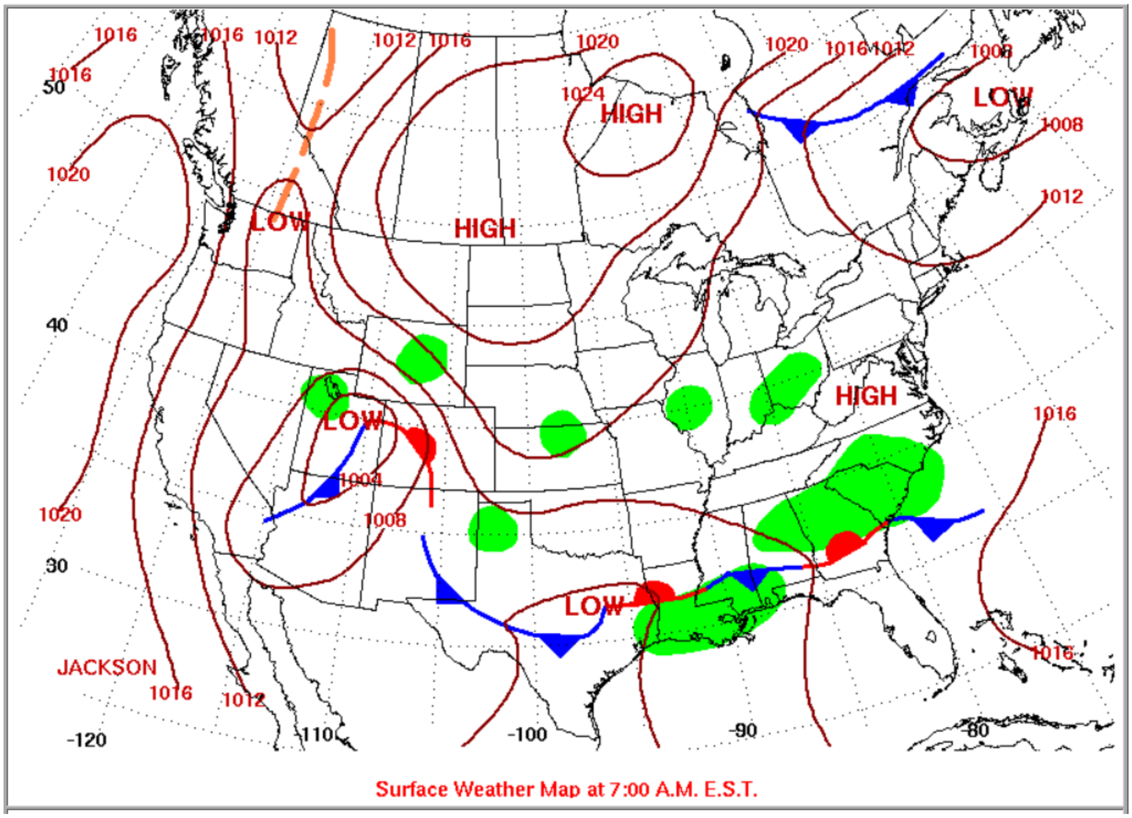
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***

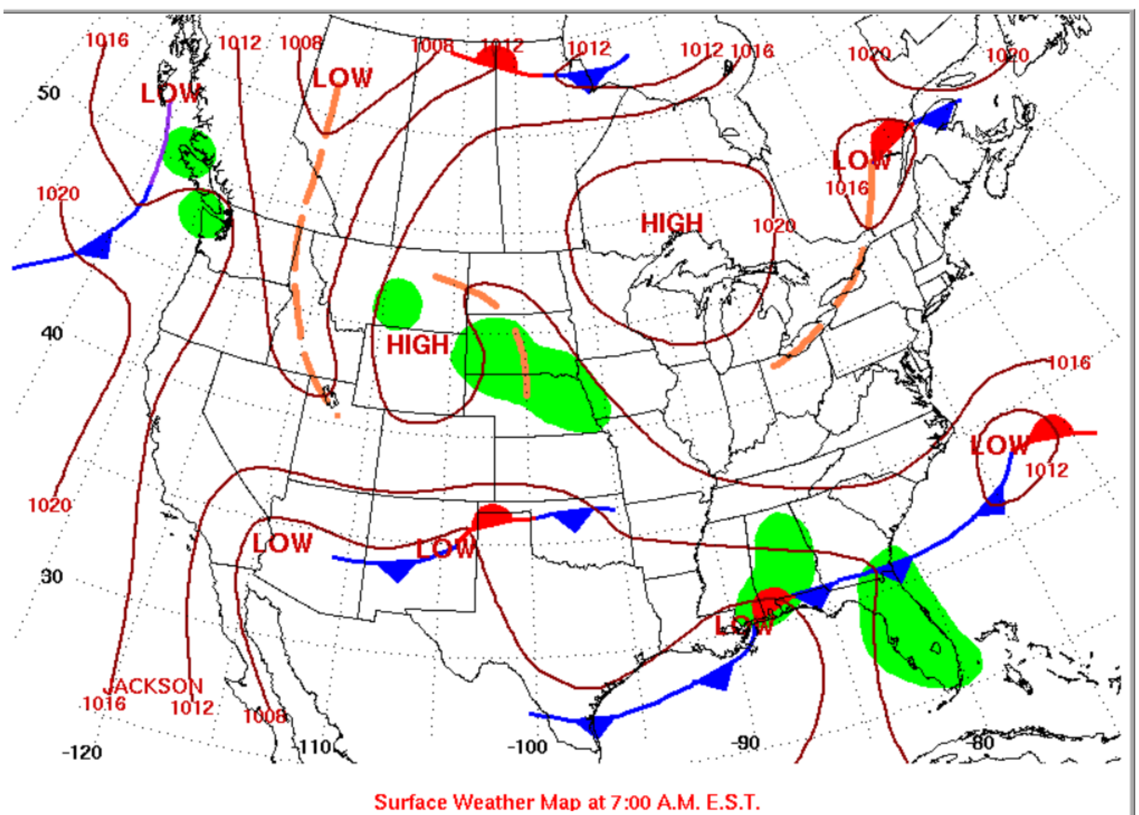
Storm or Storm Center Name	**SPAS 1492 Calgary, AB**	
Storm Date(s)	6/1-9/2005	
Storm Type	Synoptic	
Storm Location	50.44 N	114.39 W
Storm Center Elevation	1,478	meters
Precipitation Total & Duration	325	millimeters
Storm Representative Dew Point	15.3 °C	24
Storm Representative Dew Point Location	48.00 N	111.00 W
Maximum Dew Point	20.3 °C	
Moisture Inflow Vector	SE @ 370	kilometers
In-place Maximization Factor	**1.50**	
Temporal Transposition (Date)	20-Jun	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

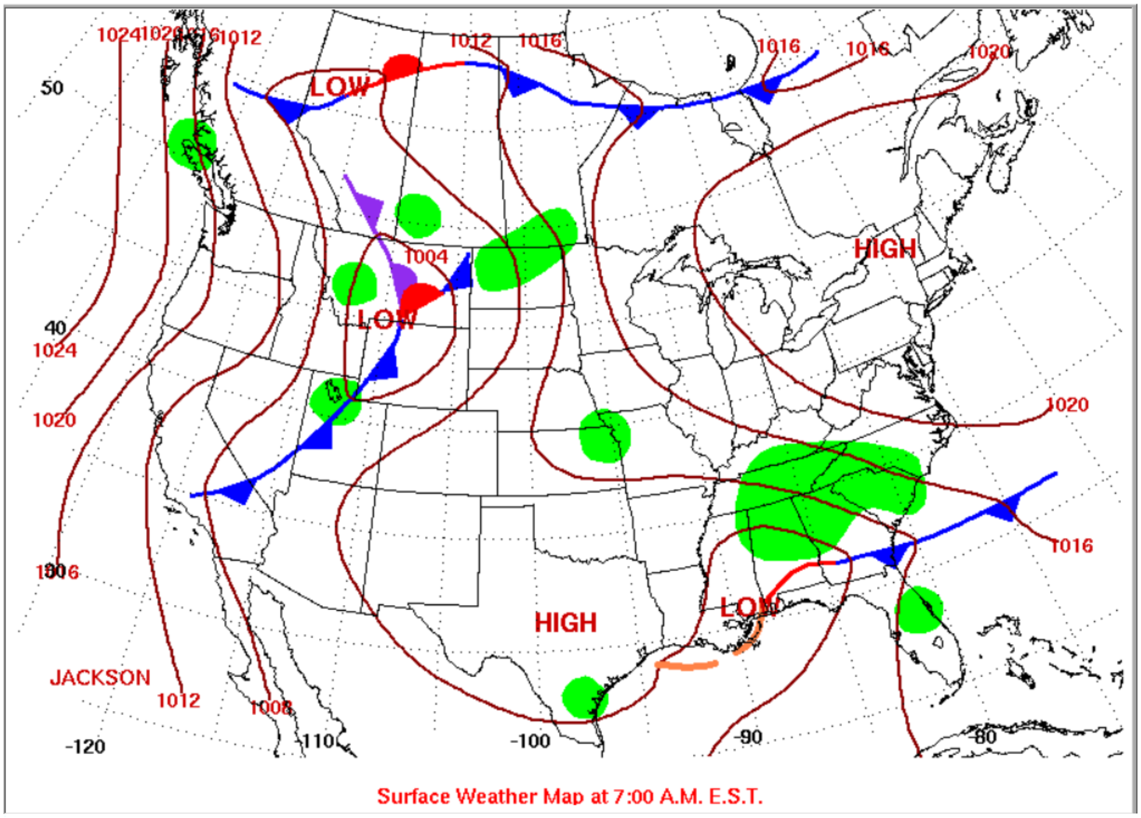
MONDAY MAY 30, 2005



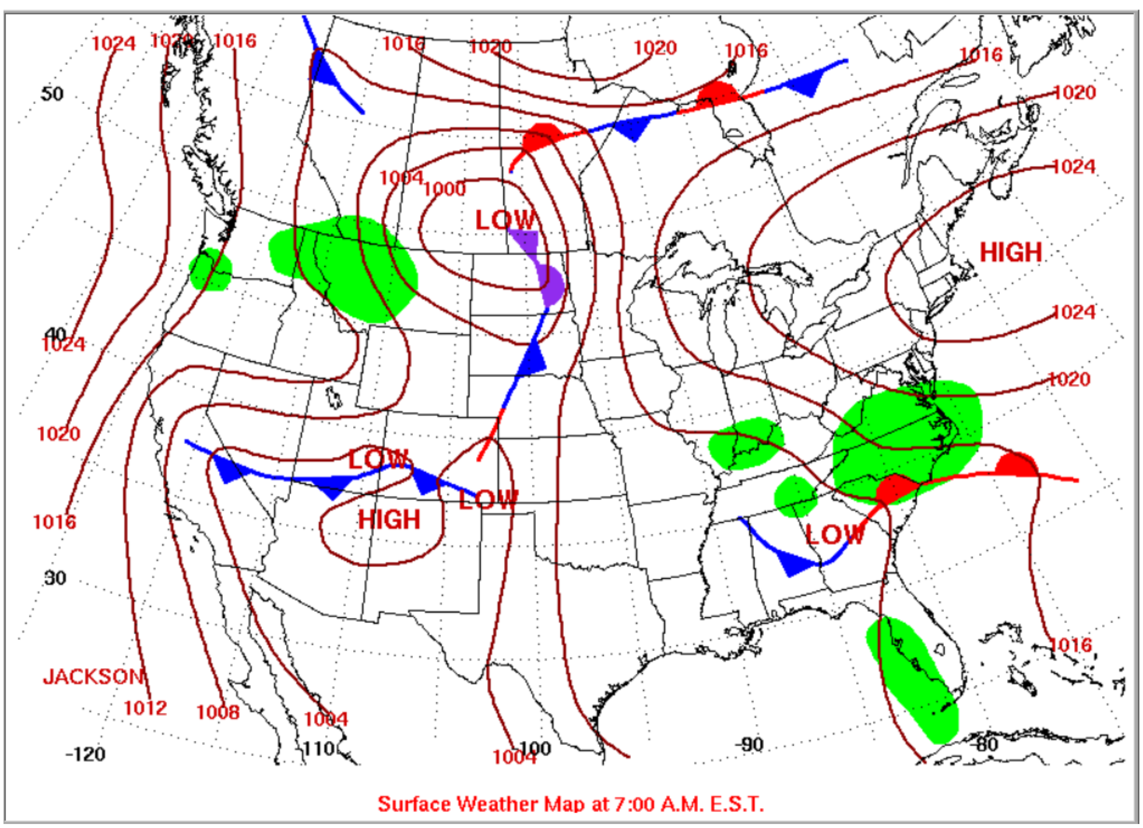
TUESDAY MAY 31, 2005



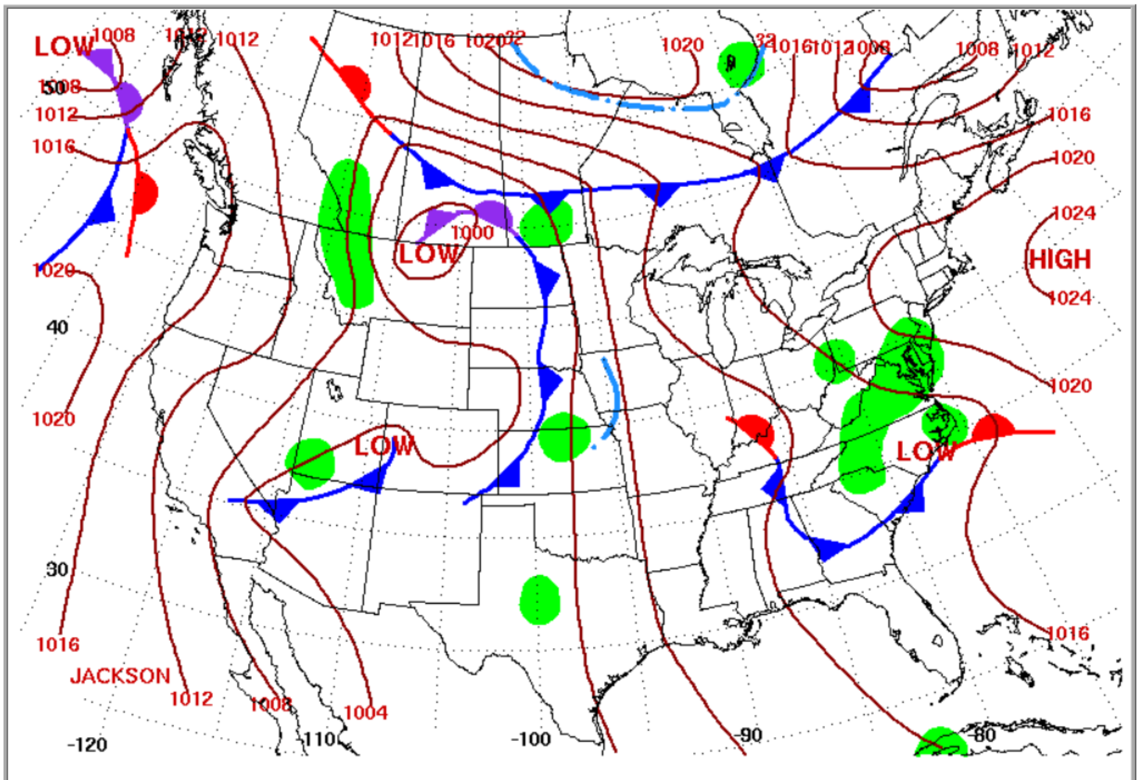
WEDNESDAY JUNE 1, 2005



THURSDAY JUNE 2, 2005

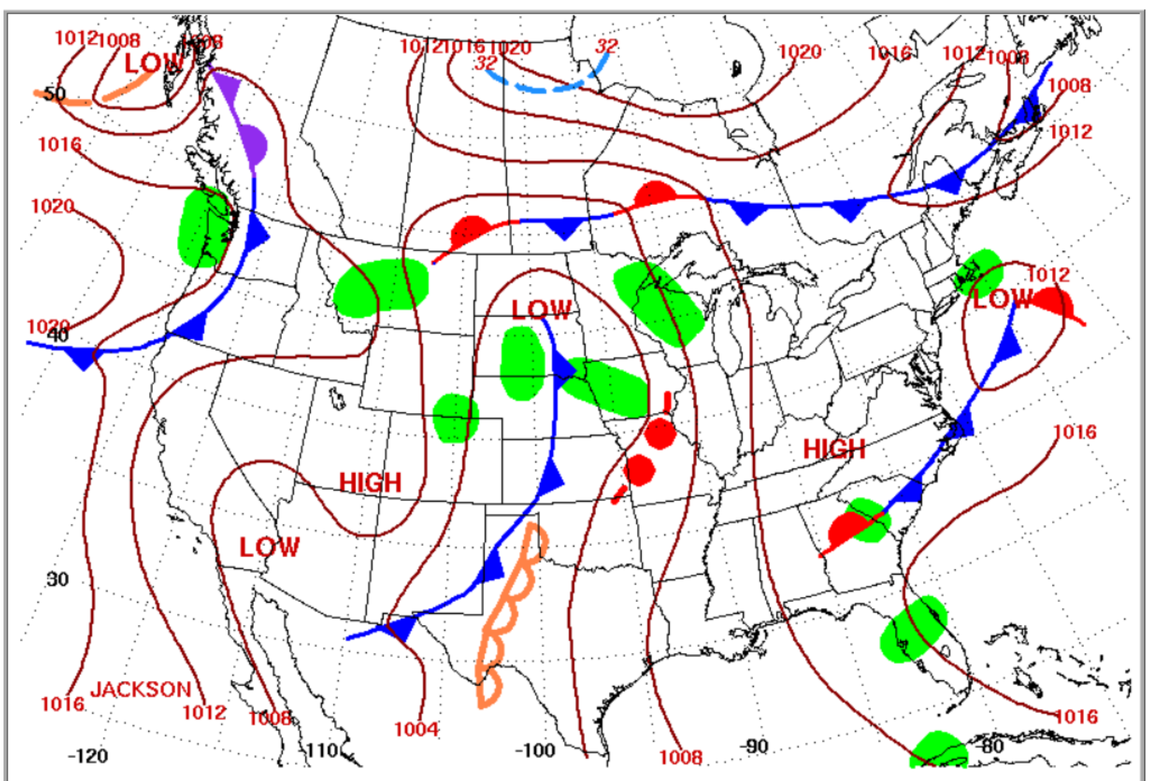


FRIDAY JUNE 3, 2005



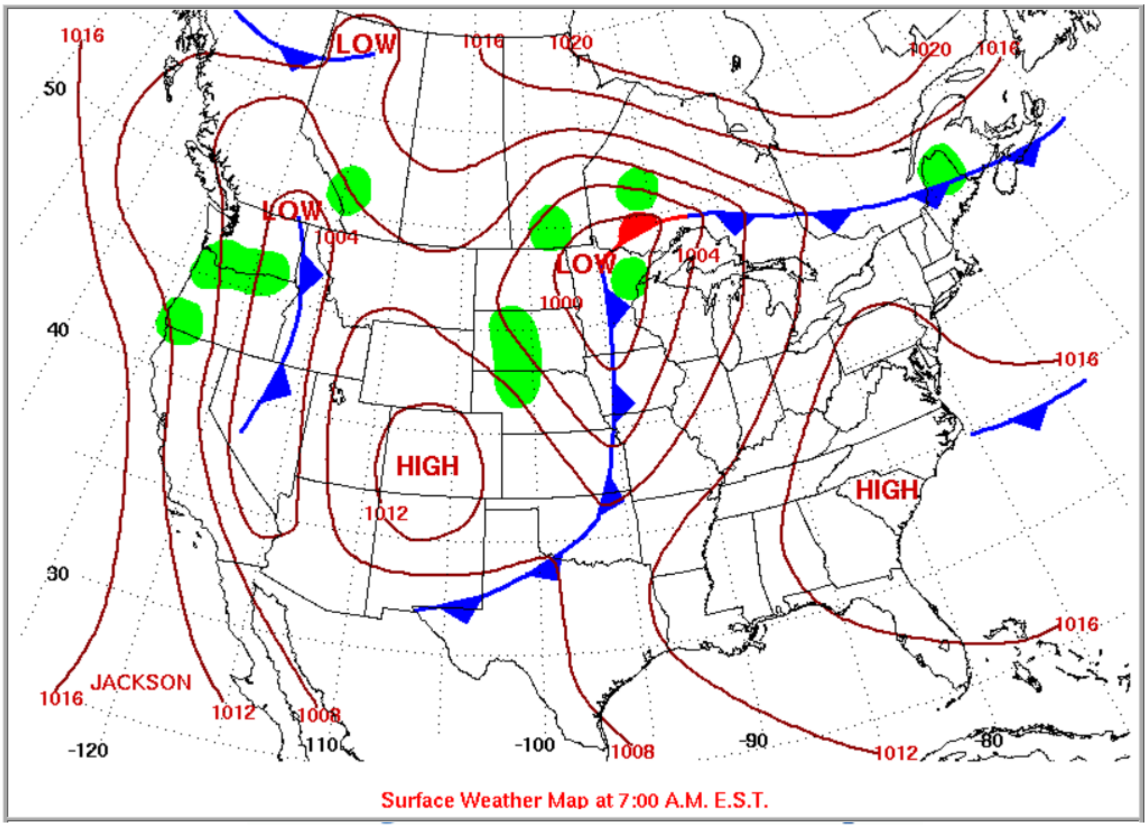
Surface Weather Map at 7:00 A.M. E.S.T.

SATURDAY JUNE 4, 2005

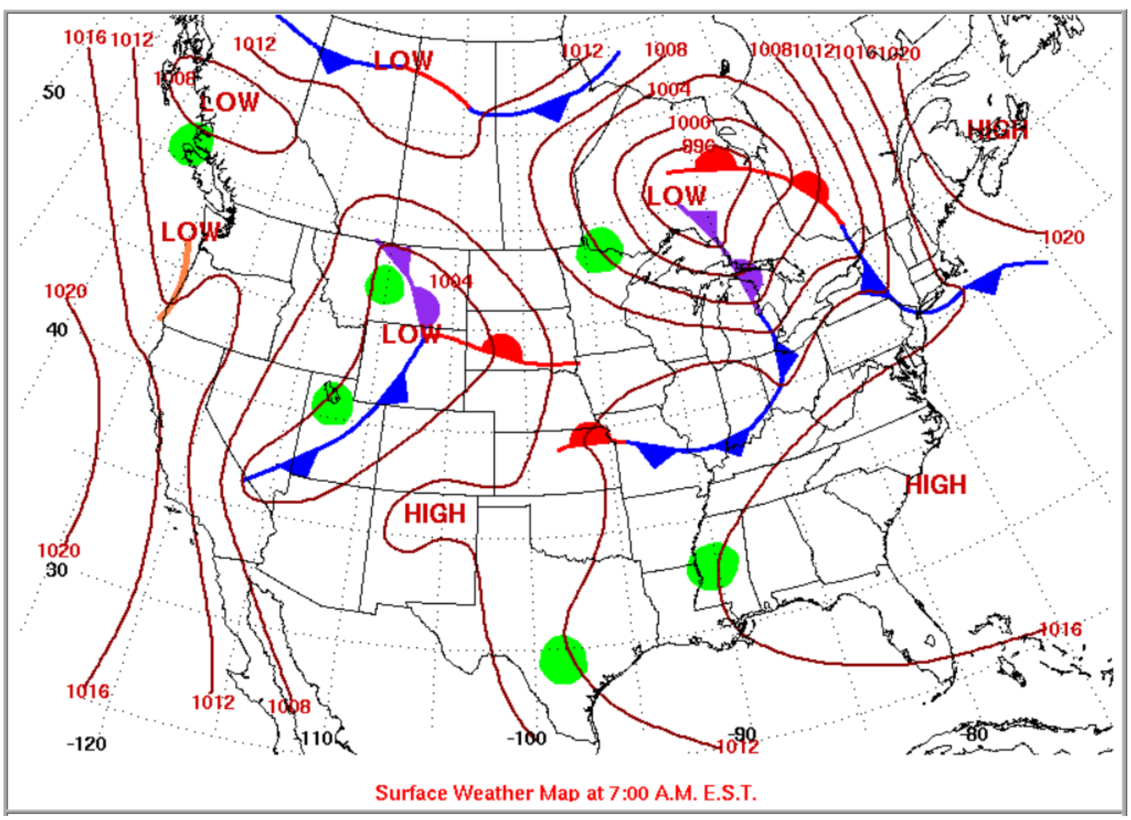


Surface Weather Map at 7:00 A.M. E.S.T.

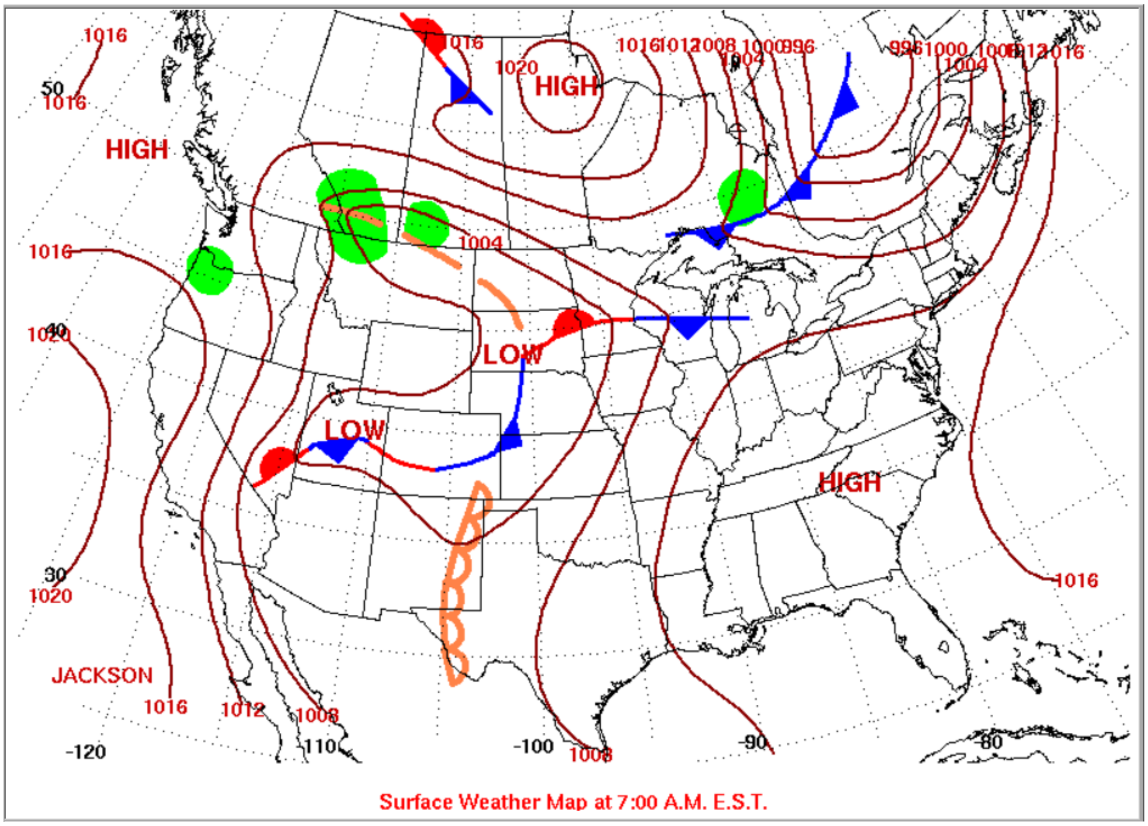
SUNDAY JUNE 5, 2005



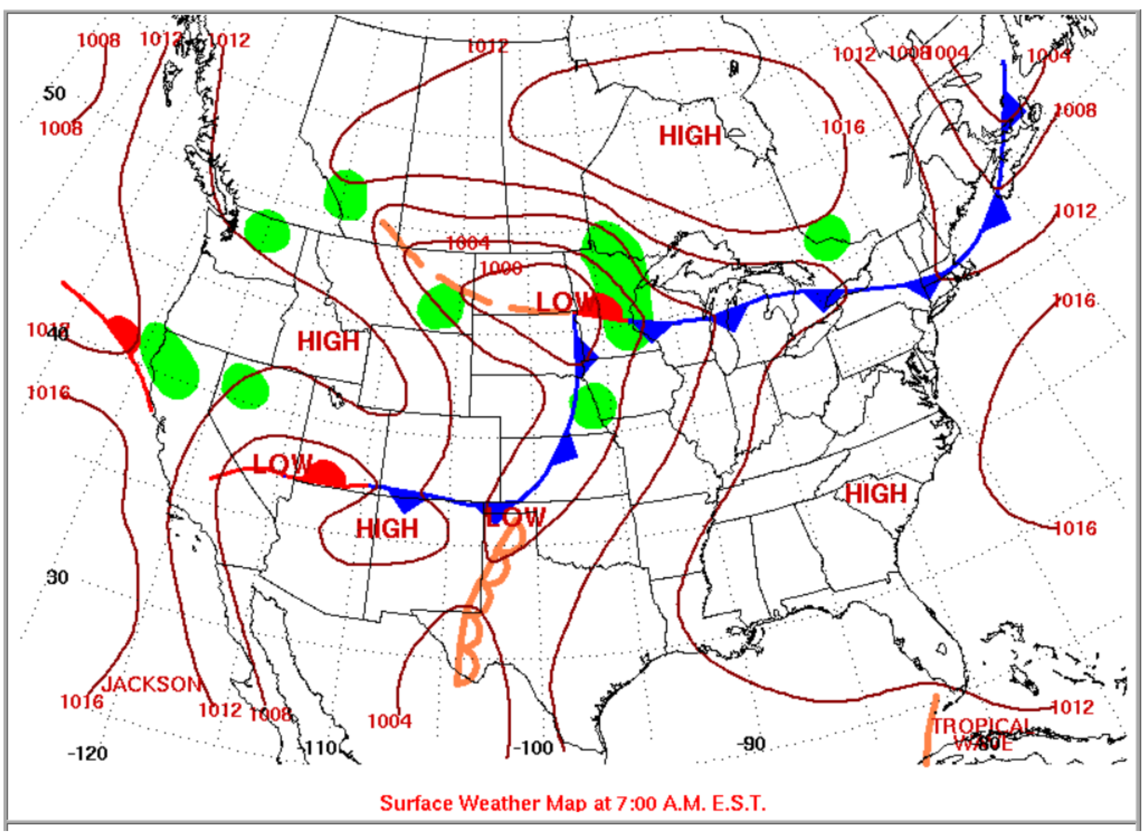
MONDAY JUNE 6, 2005



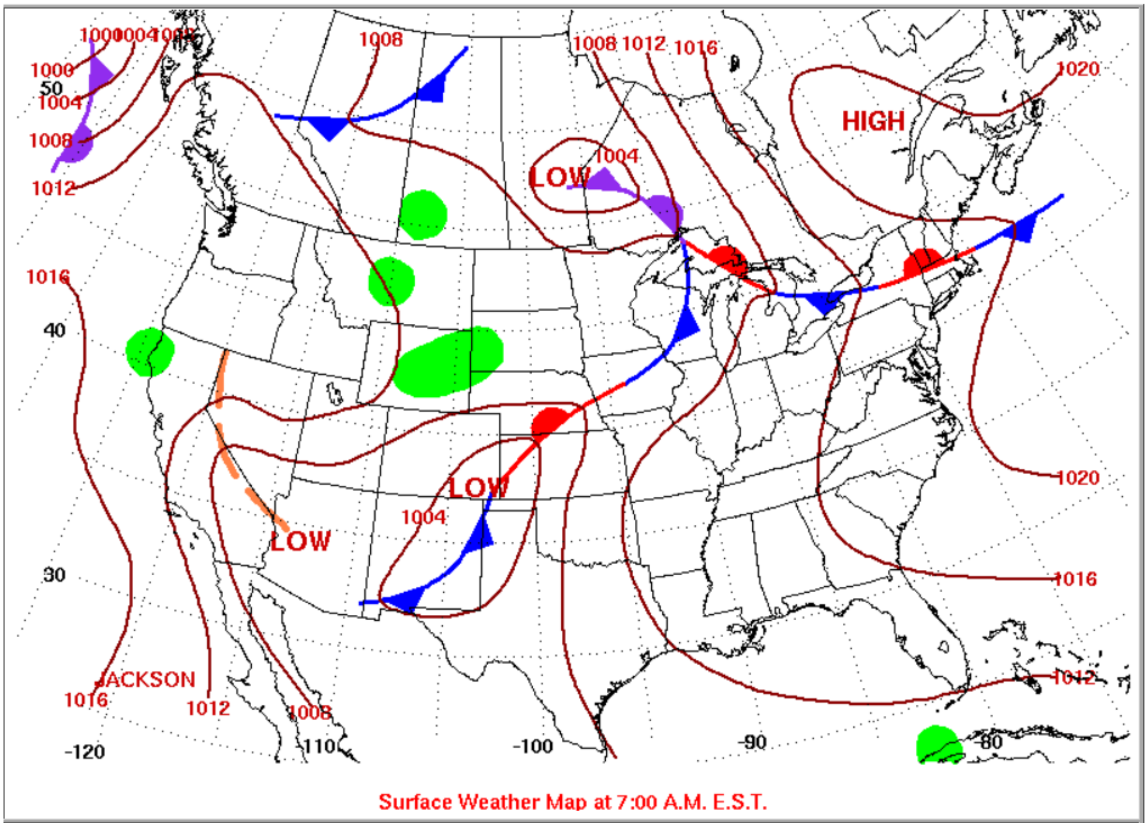
TUESDAY JUNE 7, 2005

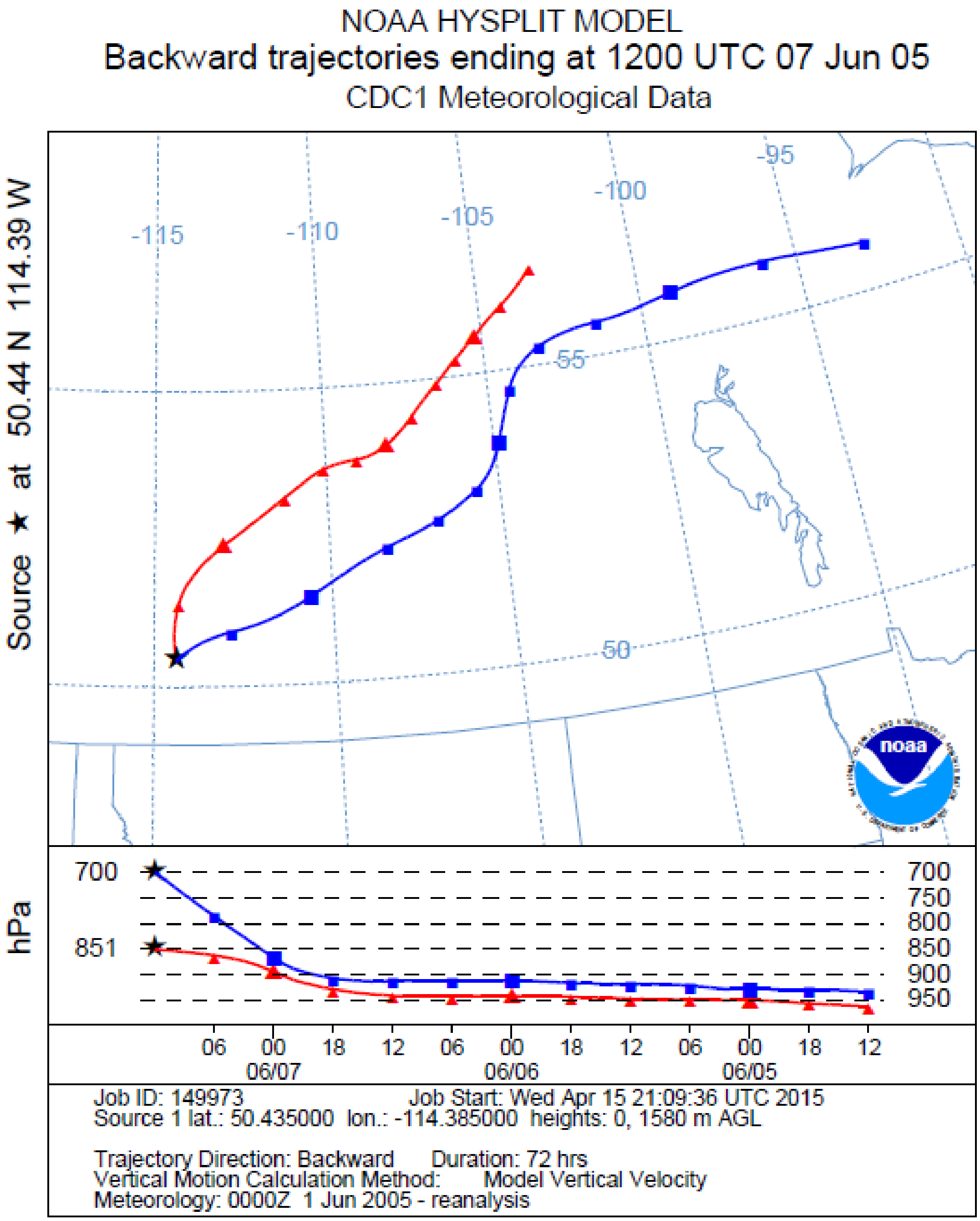


WEDNESDAY JUNE 8, 2005

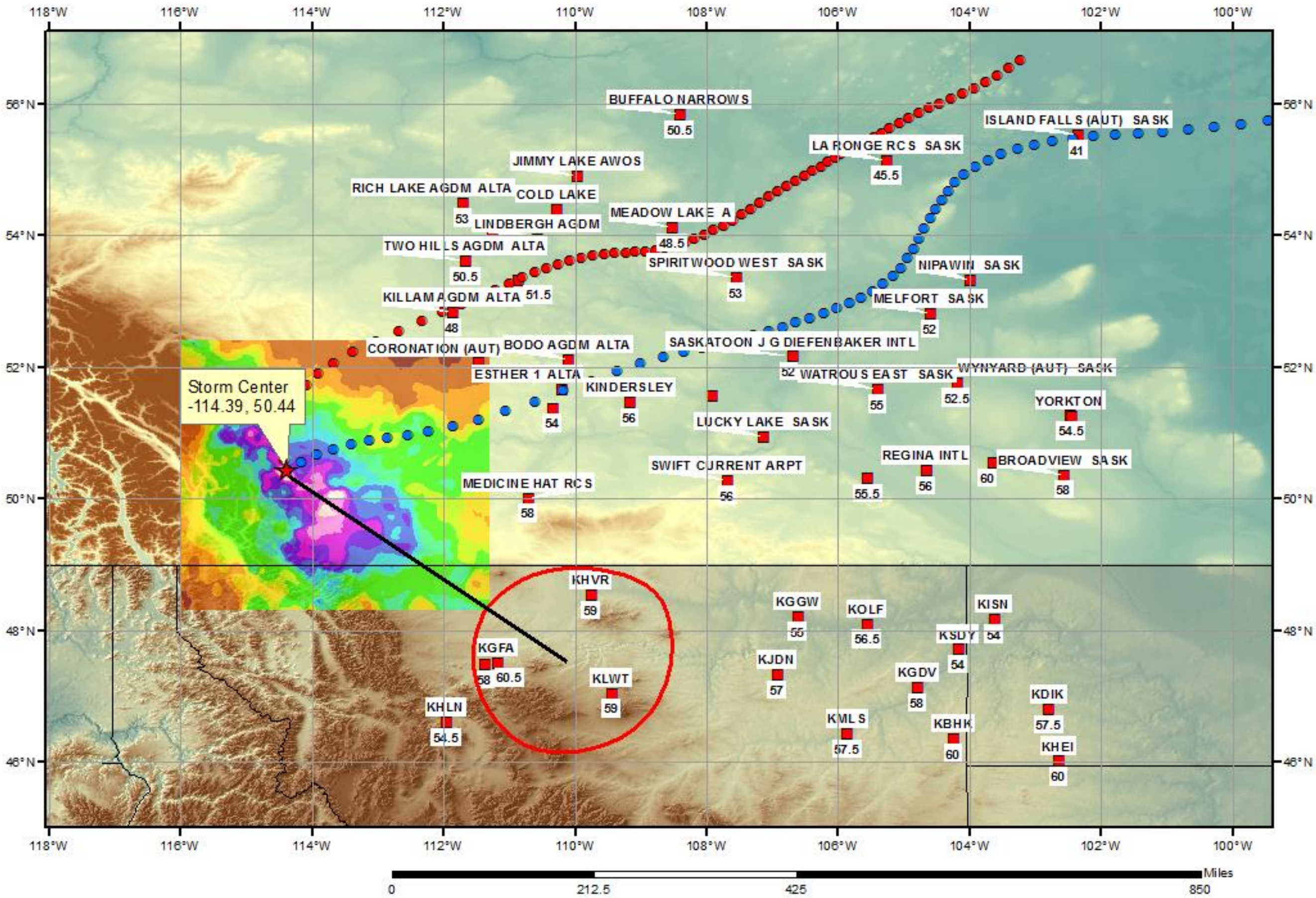


THURSDAY JUNE 9, 2005




NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 07 Jun 05
CDC1 Meteorological Data
Source ★ at 50.44 N 114.39 W
-115
-110
-105
-100
-95
55
50
noaa
hPa
700
851
700
750
800
850
900
950
06 00 18 12 06 00 18 12 06 00 18 12
06/07
06/06
06/05
Job ID: 149973
Job Start: Wed Apr 15 21:09:36 UTC 2015
Source 1 lat.: 50.435000 lon.: -114.385000 heights: 0, 1580 m AGL
Trajectory Direction: Backward
Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jun 2005 - reanalysis

SPAS 1492 Calgary, AB Storm Analysis
June 5 - 7, 2005



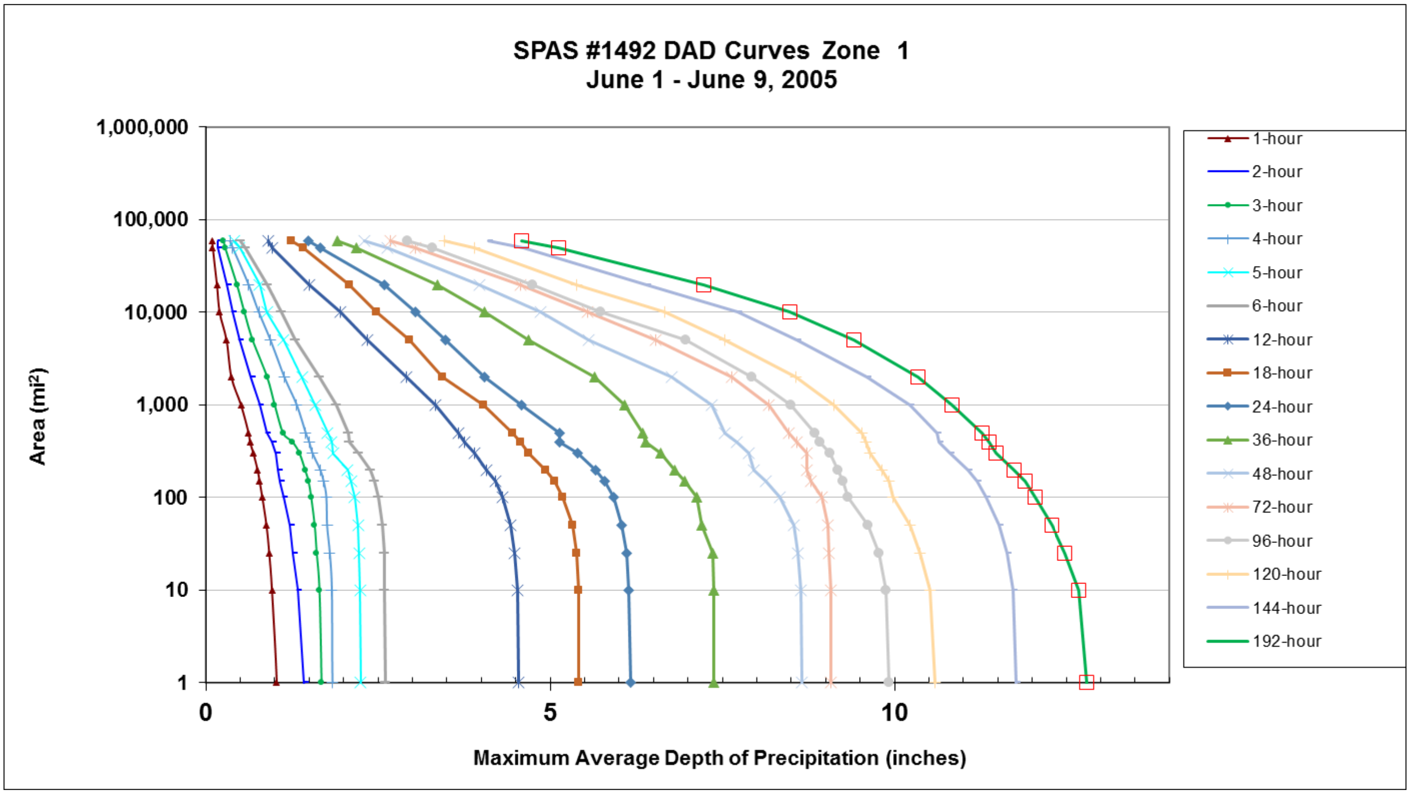
Area (mi²)	Duration (hours)															
	1	**2**	**3**	**4**	**5**	**6**	**12**	**18**	**24**	**36**	**48**	**72**	**96**	**120**	**144**	**192**	**Total**

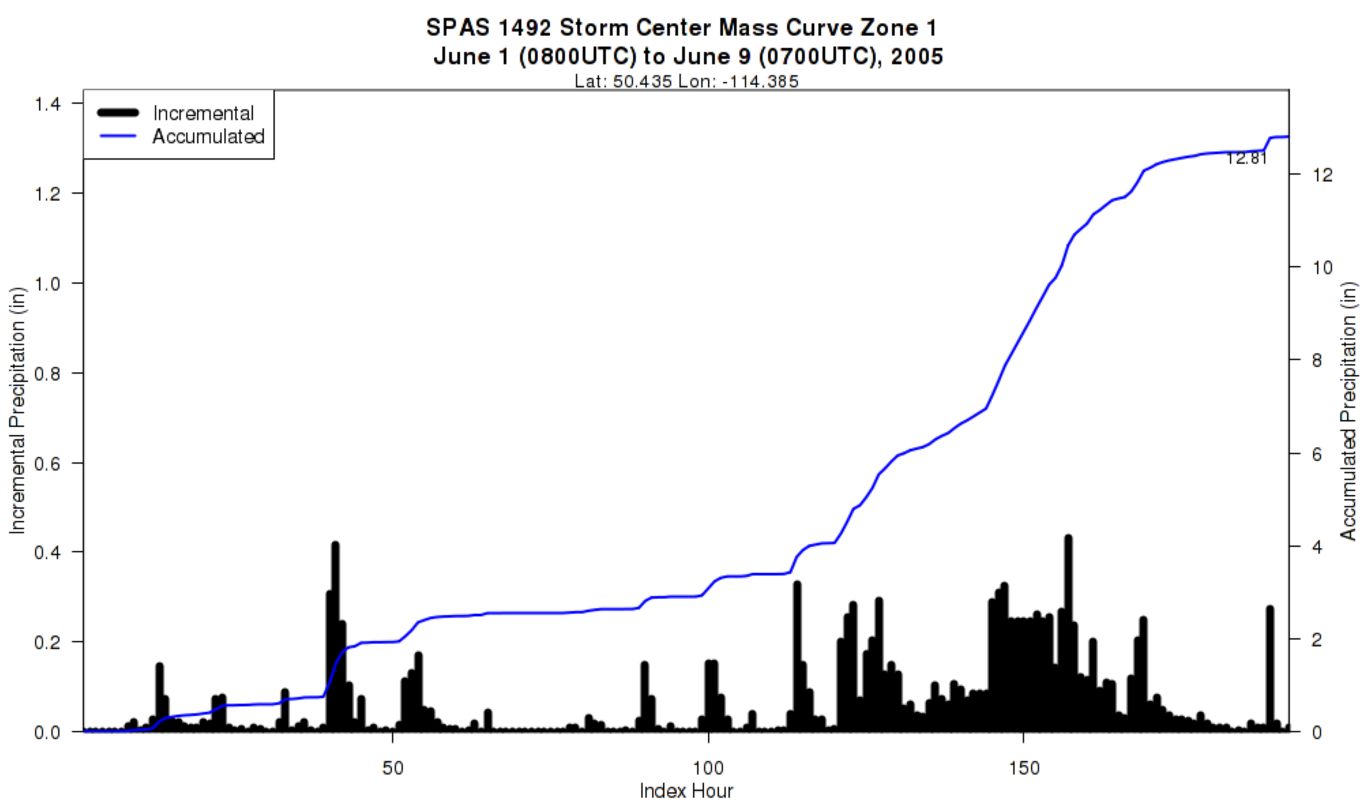
Storm 1492 - June 1 (0800 UTC) - June 9 (0700 UTC), 2005

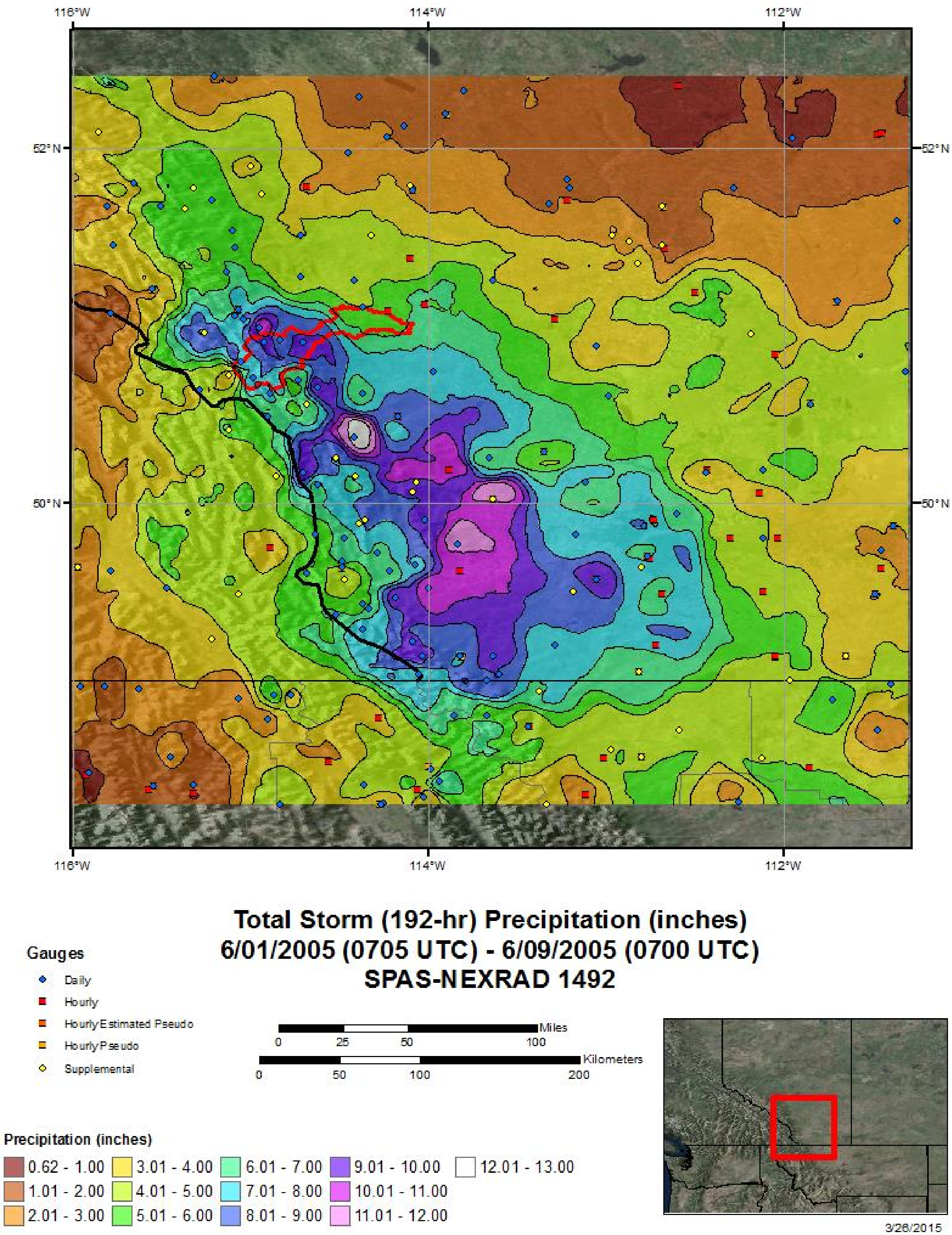
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)

Area (mi^2)	1	2	3	4	5	6	12	18	24	36	48	72	96	120	144	192	Total
0.3	1.03	1.44	1.69	1.88	2.25	2.61	4.54	5.46	6.17	7.52	8.75	9.29	9.93	10.60	11.77	12.81	12.81
1	1.03	1.43	1.68	1.84	2.25	2.61	4.54	5.42	6.17	7.37	8.66	9.07	9.92	10.59	11.77	12.80	12.80
10	0.96	1.33	1.65	1.83	2.24	2.60	4.52	5.41	6.14	7.37	8.64	9.07	9.87	10.51	11.72	12.68	12.68
25	0.92	1.27	1.61	1.80	2.23	2.59	4.49	5.38	6.11	7.36	8.60	9.05	9.77	10.37	11.64	12.47	12.47
50	0.88	1.22	1.58	1.76	2.21	2.56	4.42	5.33	6.04	7.20	8.54	9.03	9.62	10.23	11.52	12.29	12.29
100	0.82	1.13	1.53	1.75	2.16	2.51	4.31	5.18	5.92	7.13	8.33	8.94	9.33	9.97	11.33	12.04	12.04
150	0.78	1.08	1.49	1.71	2.11	2.45	4.21	5.06	5.79	6.96	8.13	8.79	9.25	9.92	11.20	11.89	11.89
200	0.75	1.05	1.44	1.66	2.06	2.39	4.08	4.94	5.66	6.81	7.95	8.72	9.18	9.82	11.06	11.74	11.74
300	0.69	1.02	1.36	1.55	1.85	2.22	3.90	4.69	5.40	6.61	7.88	8.72	9.06	9.65	10.81	11.48	11.48
400	0.64	0.96	1.26	1.50	1.83	2.09	3.75	4.57	5.14	6.39	7.71	8.58	8.92	9.59	10.64	11.37	11.37
500	0.62	0.88	1.12	1.45	1.77	2.07	3.67	4.46	5.13	6.35	7.53	8.47	8.85	9.53	10.61	11.27	11.27
1,000	0.51	0.78	1.00	1.32	1.59	1.89	3.33	4.03	4.58	6.08	7.35	8.17	8.49	9.12	10.22	10.83	10.83
2,000	0.37	0.66	0.89	1.14	1.40	1.65	2.92	3.44	4.04	5.65	6.77	7.63	7.93	8.57	9.60	10.34	10.34
5,000	0.30	0.49	0.68	0.94	1.13	1.30	2.34	2.95	3.48	4.68	5.56	6.53	6.97	7.54	8.58	9.41	9.41
10,000	0.20	0.39	0.56	0.77	0.89	1.10	1.95	2.47	3.04	4.05	4.86	5.55	5.74	6.67	7.72	8.48	8.48
20,000	0.16	0.31	0.45	0.62	0.78	0.90	1.51	2.09	2.60	3.37	3.97	4.57	4.75	5.39	6.40	7.23	7.23
50,000	0.10	0.18	0.28	0.39	0.49	0.58	0.96	1.42	1.67	2.19	2.63	3.05	3.29	3.90	4.61	5.12	5.12
58,891	0.09	0.18	0.26	0.35	0.42	0.50	0.91	1.24	1.49	1.91	2.31	2.68	2.93	3.46	4.10	4.58	4.58

Duration (hours)


SPAS #1492 DAD Curves Zone 1
June 1 - June 9, 2005
Area (mi²)
Maximum Average Depth of Precipitation (inches)
1,000,000
100,000
10,000
1,000
100
10
1
0
5
10
1-hour
2-hour
3-hour
4-hour
5-hour
6-hour
12-hour
18-hour
24-hour
36-hour
48-hour
72-hour
96-hour
120-hour
144-hour
192-hour


SPAS 1492 Storm Center Mass Curve Zone 1
June 1 (0800UTC) to June 9 (0700UTC), 2005
Lat: 50.435 Lon: -114.385
Incremental
Accumulated
Incremental Precipitation (in)
Accumulated Precipitation (in)
Index Hour
12.81
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
12
10
8
6
4
2
0
50
100
150


116°W
114°W
112°W
52° N
50° N
Total Storm (192-hr) Precipitation (inches)
6/01/2005 (0705 UTC) - 6/09/2005 (0700 UTC)
SPAS-NEXRAD 1492
Gauges
Daily
Hourly
Hourly Estimated Pseudo
Hourly Pseudo
Supplemental
Miles
0 25 50 100
Kilometers
0 50 100 200
Precipitation (inches)
0.62 - 1.00
1.01 - 2.00
2.01 - 3.00
3.01 - 4.00
4.01 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
8.01 - 9.00
9.01 - 10.00
10.01 - 11.00
11.01 - 12.00
12.01 - 13.00
3/26/2015

Nose Mountain, AB

July 12 – 17, 1982

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1501

General Storm Location: Nose Mountain, Alberta

Storm Dates: July 12 - 17, 1982

Event: Synoptic Event

DAD Zone 1

- **Latitude**: 54.5125°
- **Longitude**: -120.0292°
- **Max. Grid Rainfall Amount**: 188mm
- **Max. Observed Rainfall Amount**: 185mm

Number of Stations: 187 (114 Daily, 31 Hourly, 8 Hourly Pseudo, 2 Hourly Estimated Pseudo, and 32 Supplemental)

SPAS Version: 10.0

Basemap: Blended PRISM July 1961-1990 Climatology (Canada) and AL 7-82 Isohyetal

Spatial resolution: 30 second (degree: minute: second, WGS84, ~ 0.3 mi^2) (0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and AL 7-82 data. We have a good degree of confidence in the station based storm total results; the spatial pattern is dependent on the station data and a basemap. The timing is based on hourly and hourly pseudo stations.

Storm Name:	**SPAS 1501 Nose Mountain, AB**	
Storm Date:	**7/12-17/1982**	**Storm Adjustment Summary**
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **15-Jul**

	Lat	Long
Storm Center Location	**54.51 N**	**120.03 W**
Storm Rep Dew Point Location	**51.65 N**	**113.09 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**SE @ 563**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**1,372**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**18.6 °C**	with total precipitable water above sea level of	**46**	millimeters.	
The in-place maximum dew point is	**20.8 °C**	with total precipitable water above sea level of	**56**	millimeters.	
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of	**N/A***	millimeters.	
The in-place storm elevation is	**1,372**	which subtracts	**18**	millimeters of precipitable water at	**18.6 °C**
The in-place storm elevation is	**1,372**	which subtracts	**21**	millimeters of precipitable water at	**20.8 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.25**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Storm representative Td was based on the 24hr average Td from Coronation, Red Deer and Standard on July 13-14, 1982.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**24**		**55**			**93**	**131**	**165**	**188**
26 km^2 (10 mi^2)	**24**		**55**			**92**	**131**	**164**	**187**
259 km^2 (100 mi^2)	**24**		**54**			**91**	**127**	**160**	**186**
518 km^2 (200 mi^2)	**23**		**53**			**89**	**124**	**158**	**184**
1,295 km^2 (500 mi^2)	**22**		**49**			**84**	**117**	**155**	**179**
2,590 km^2 (1,00 mi^2)	**20**		**46**			**79**	**108**	**151**	**171**
5,180 km^2 (2,000 mi^2)	**18**		**42**			**70**	**102**	**147**	**162**
12.950 km^2 (5000 mi^2)	**15**		**34**			**60**	**88**	**132**	**146**
25,900 km^2 (10,000 mi^2)	**12**		**27**			**46**	**75**	**113**	**126**
51,800 km^2 (20,000 mi^2)	**8**		**22**			**36**	**60**	**92**	**108**

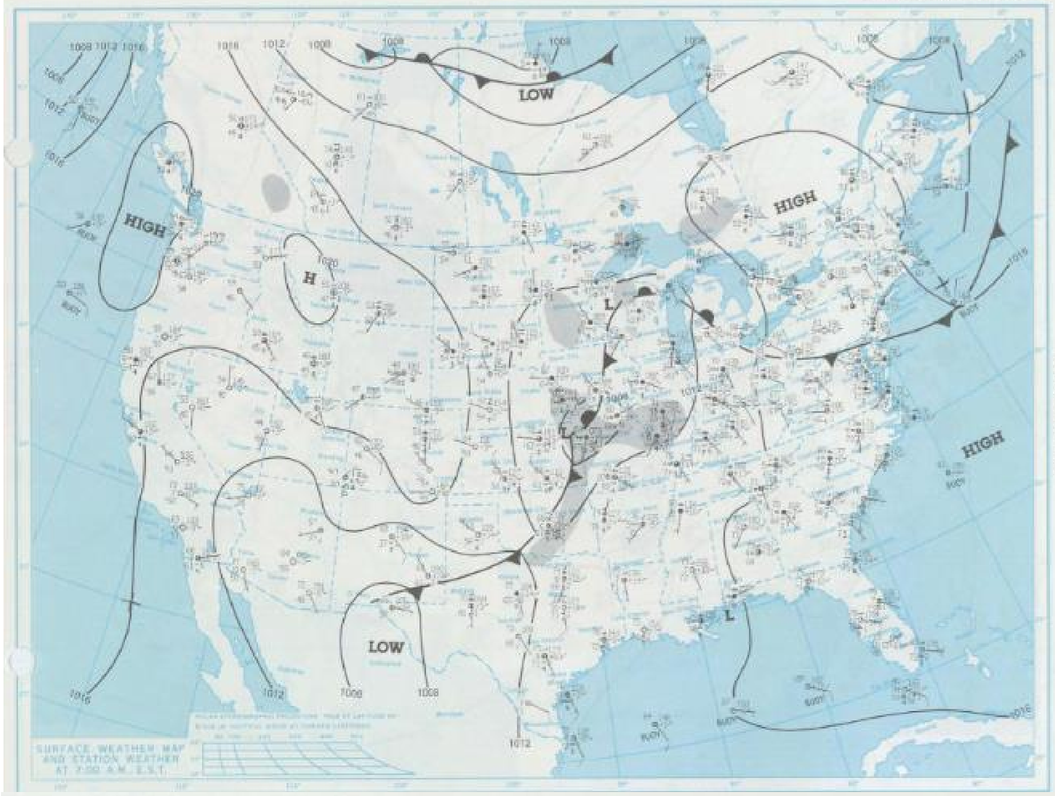
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***

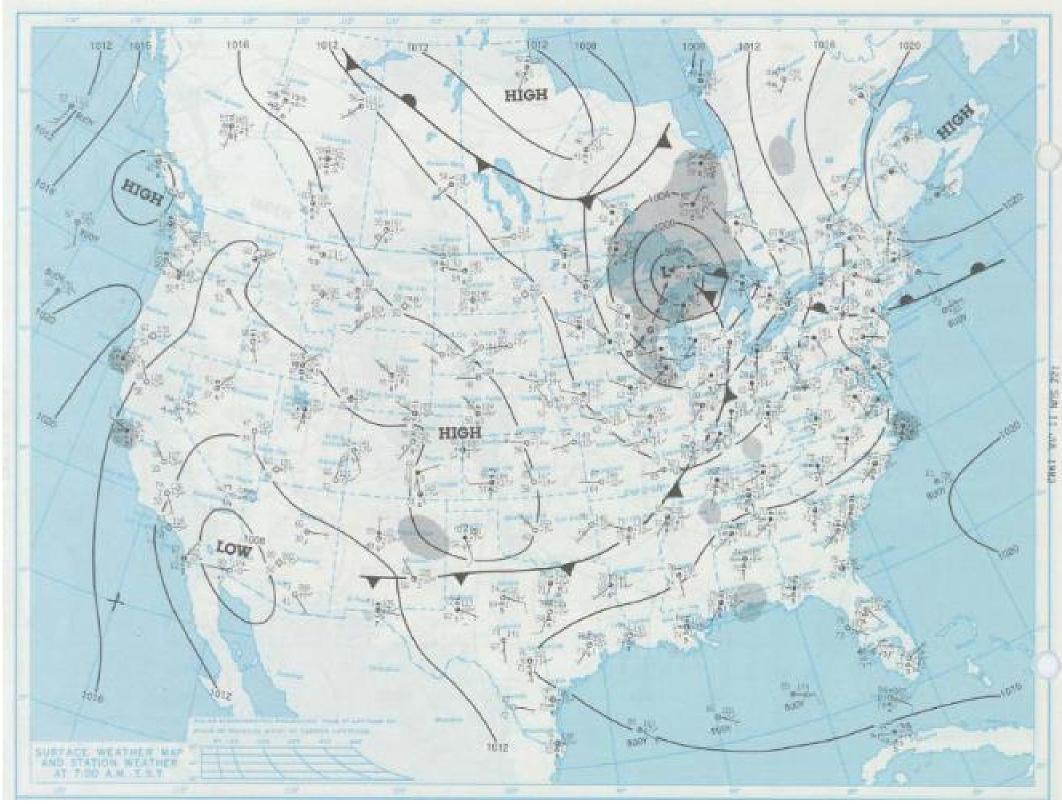
Storm or Storm Center Name	**SPAS 1501 Nose Mountain, AB**	
Storm Date(s)	7/12-17/1982	
Storm Type	Synoptic	
Storm Location	54.51 N	120.03 W
Storm Center Elevation	1,372	meters
Precipitation Total & Duration	188	millimeters
Storm Representative Dew Point	18.6 °C	24
Storm Representative Dew Point Location	51.65 N	113.09 W
Maximum Dew Point	20.8 °C	
Moisture Inflow Vector	SE @ 563	kilometers
In-place Maximization Factor	**1.25**	
Temporal Transposition (Date)	15-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

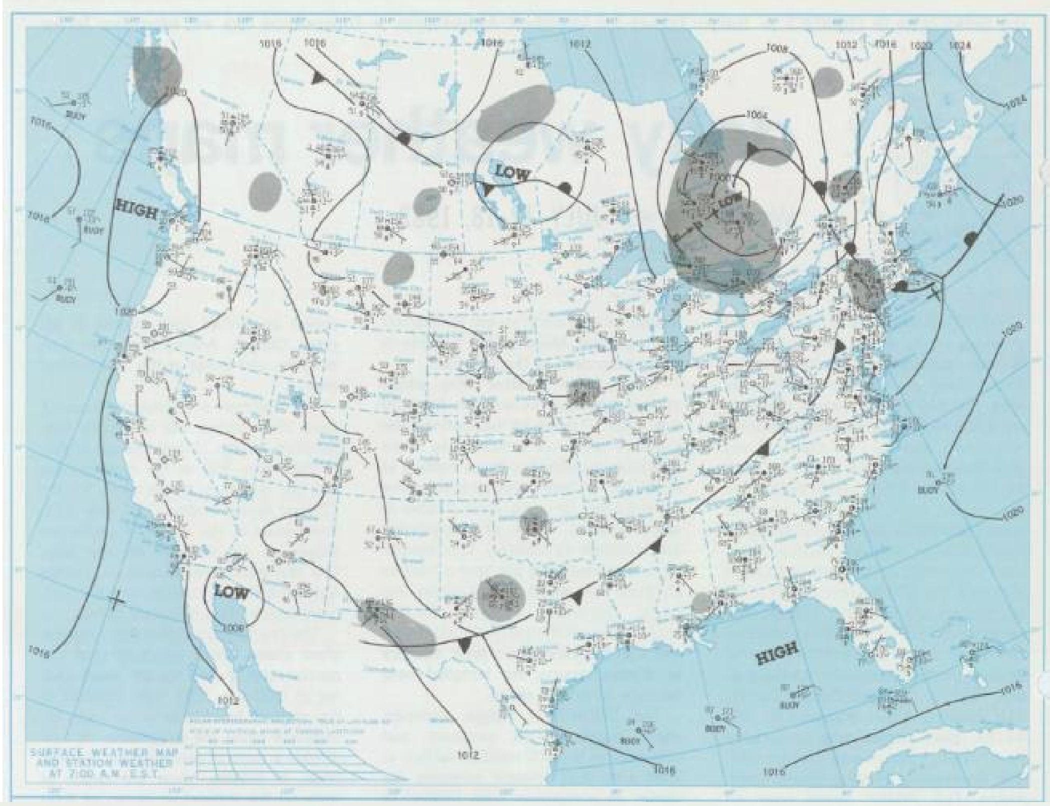
SATURDAY, JULY 10, 1982



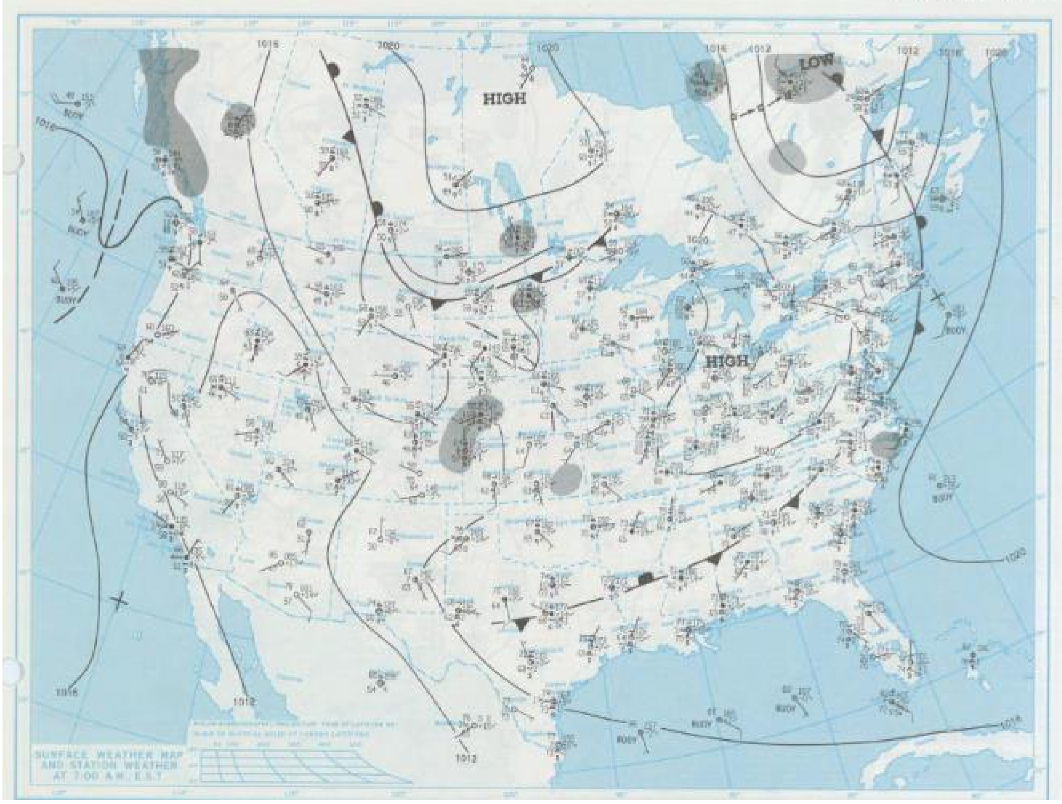
SUNDAY, JULY 11, 1982



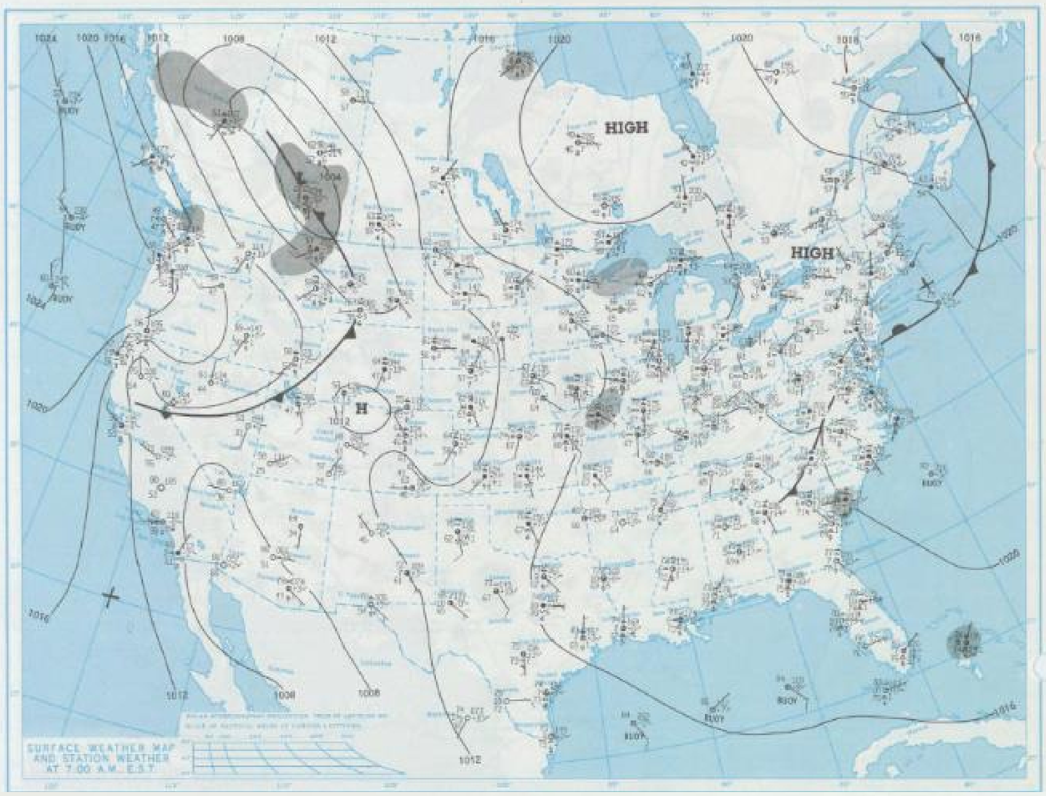
MONDAY, JULY 12, 1982



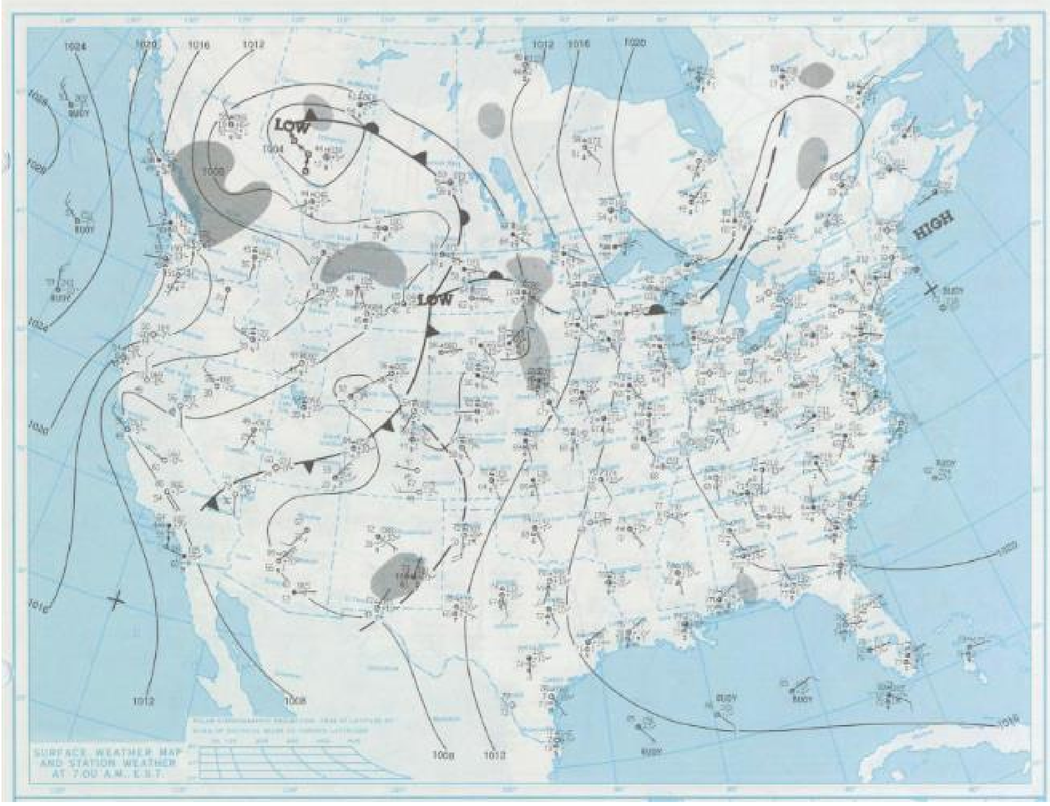
TUESDAY, JULY 13, 1982



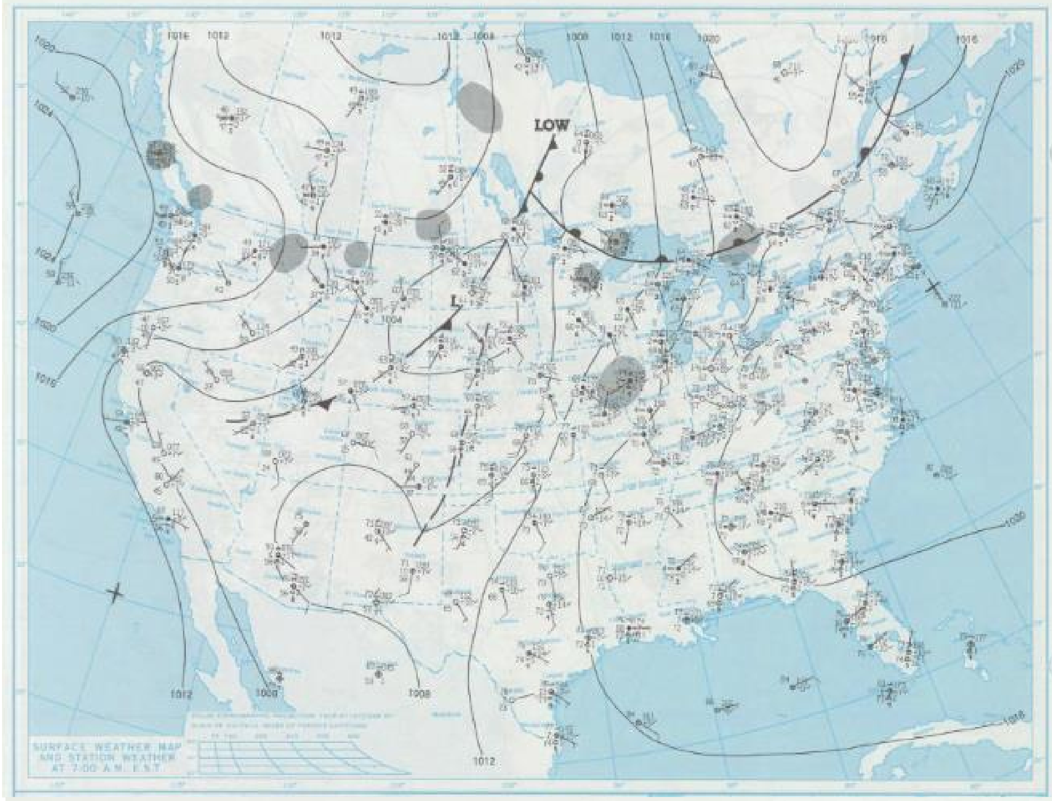
WEDNESDAY, JULY 14, 1982



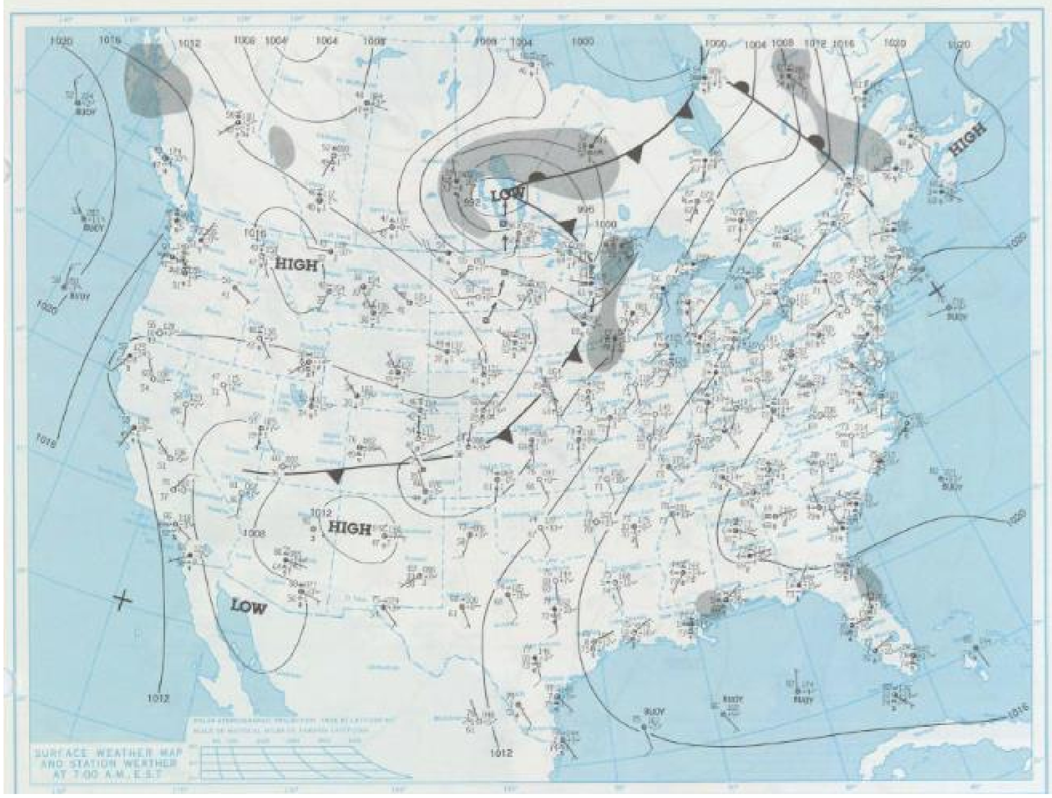
THURSDAY, JULY 15, 1982

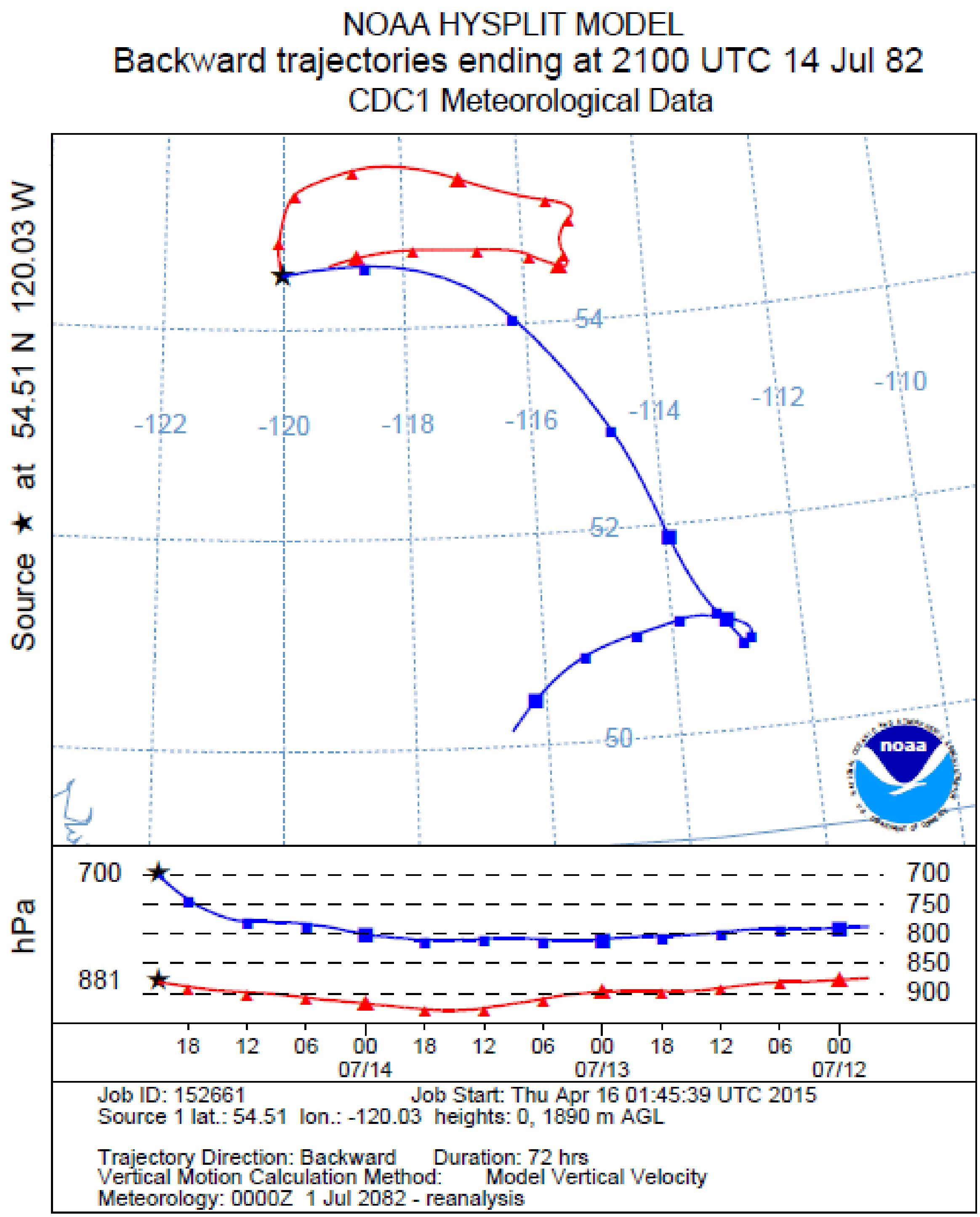


FRIDAY, JULY 16, 1982

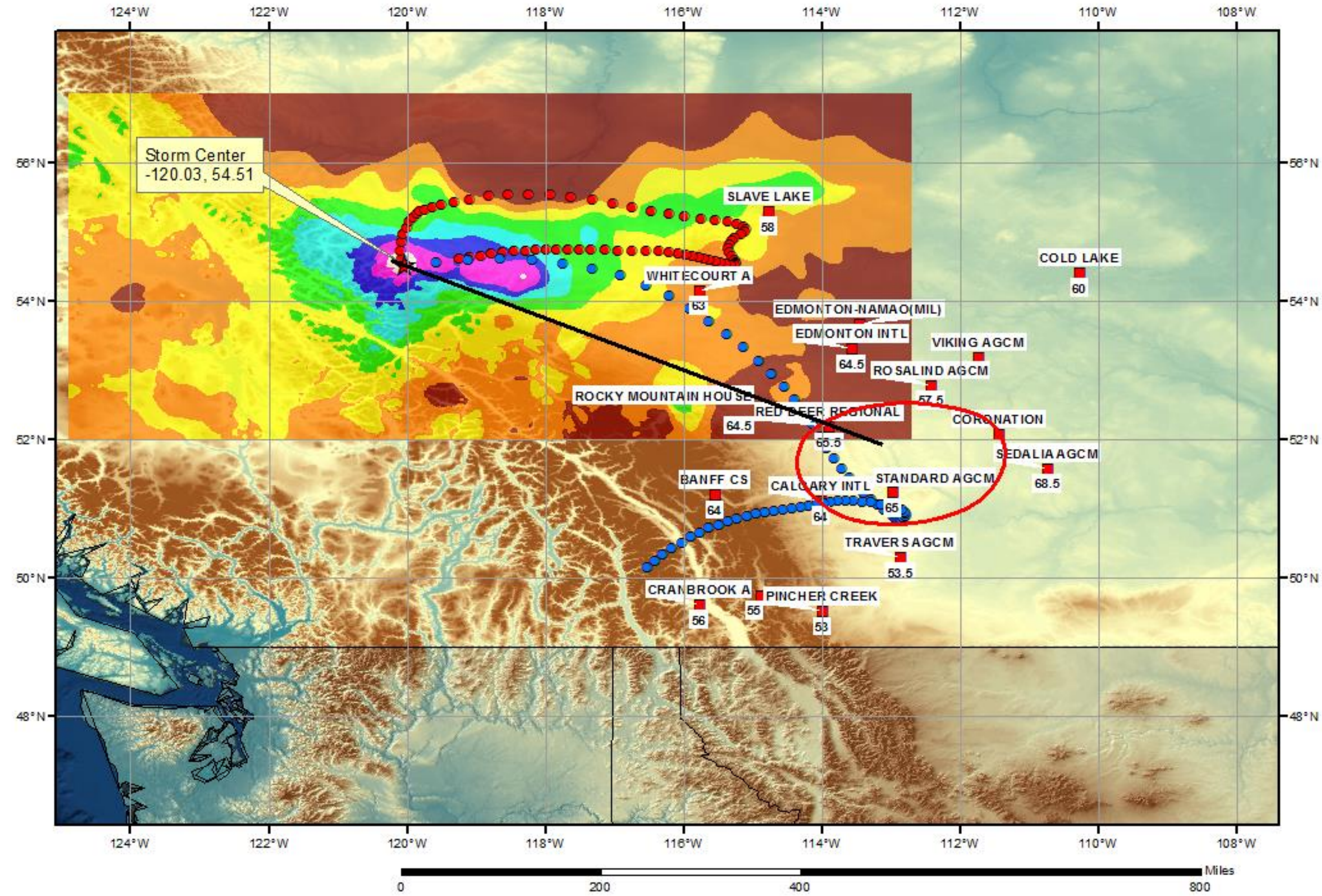


SATURDAY, JULY 17, 1982

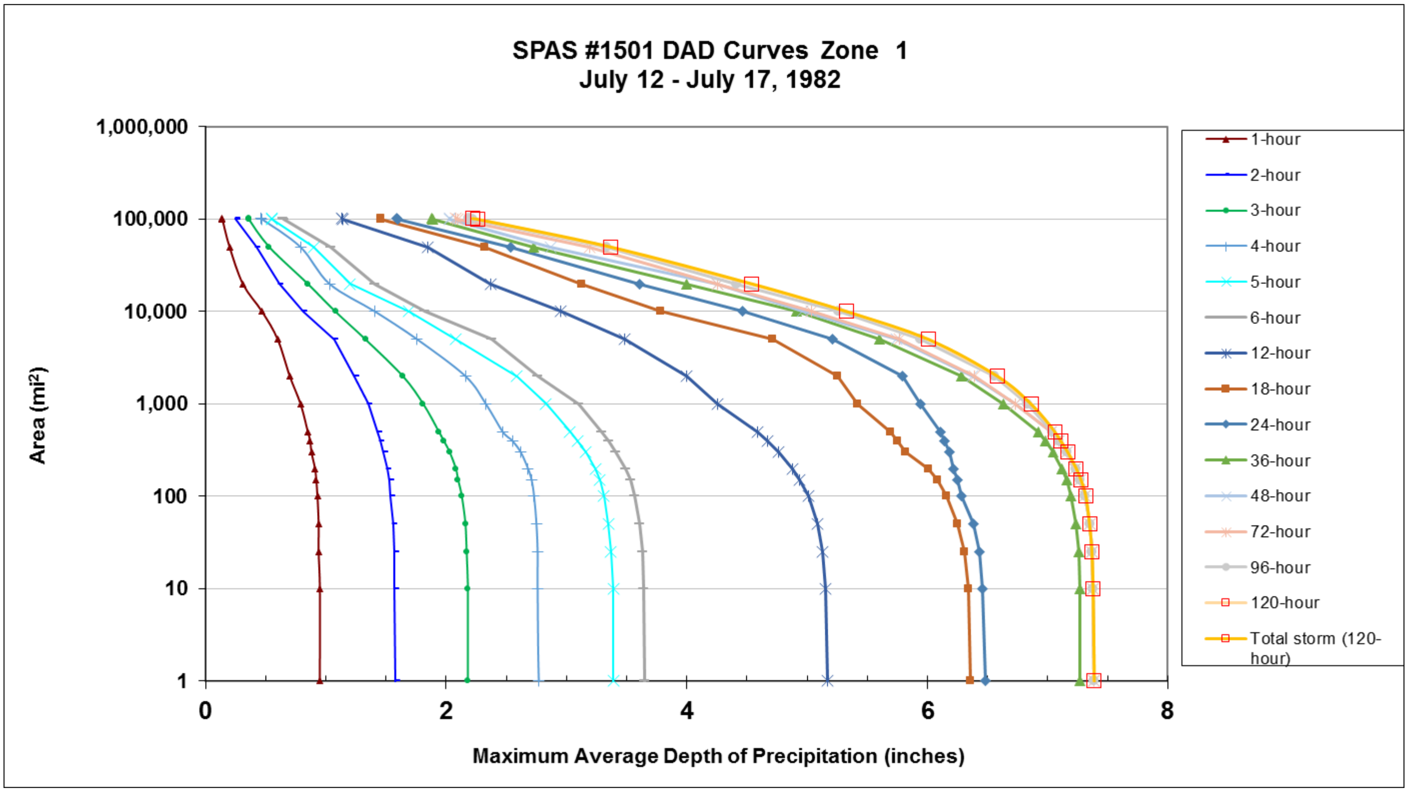



NOAA HYSPLIT MODEL
Backward trajectories ending at 2100 UTC 14 Jul 82
CDC1 Meteorological Data
Source ★ at 54.51 N 120.03 W
54
52
50
-122
-120
-118
-116
-114
-112
-110
hPa
700
881
700
750
800
850
900
18
12
06
00
07/14
18
12
06
00
07/13
18
12
06
00
07/12
Job ID: 152661 Job Start: Thu Apr 16 01:45:39 UTC 2015
Source 1 lat.: 54.51 lon.: -120.03 heights: 0, 1890 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jul 2082 - reanalysis

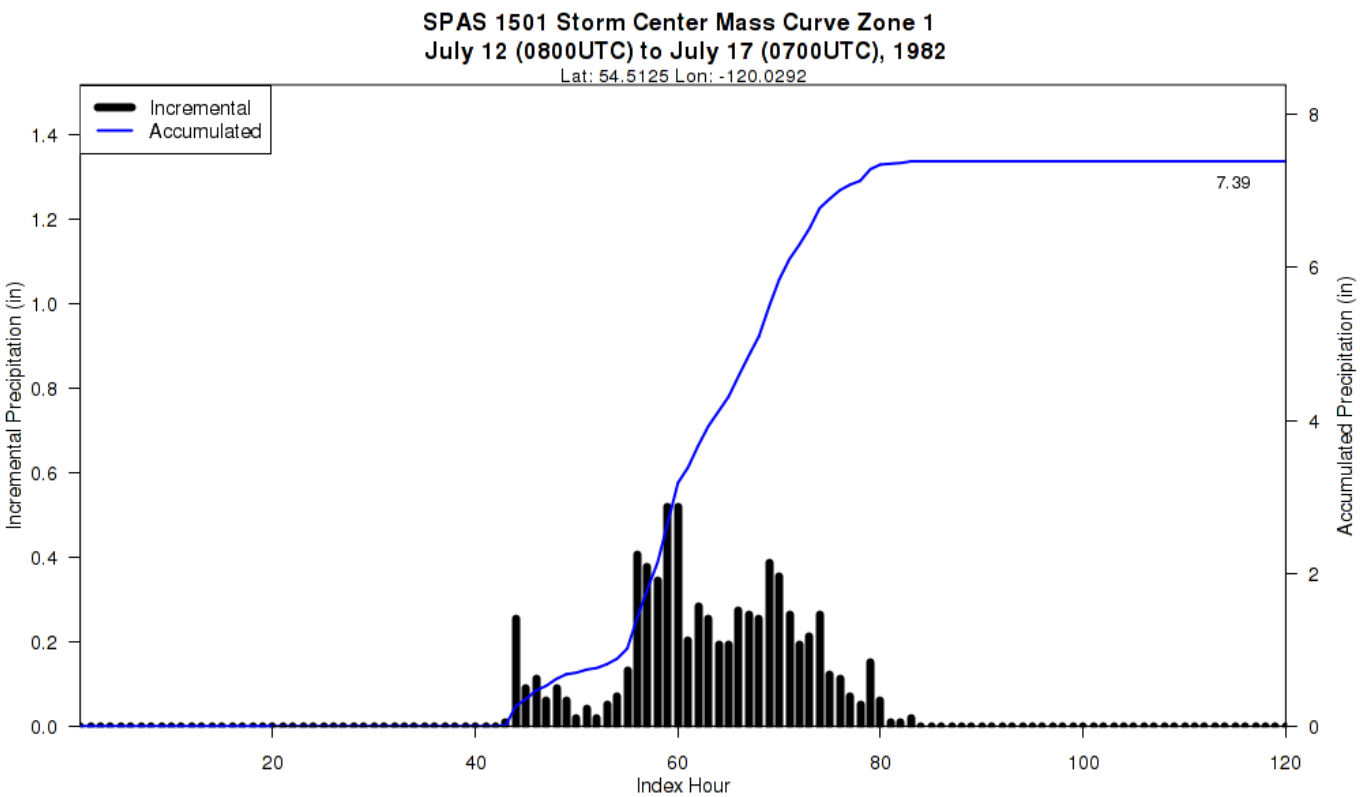
SPAS 1501 Nose Mountain, AB Storm Analysis
July 12 - 14, 1982



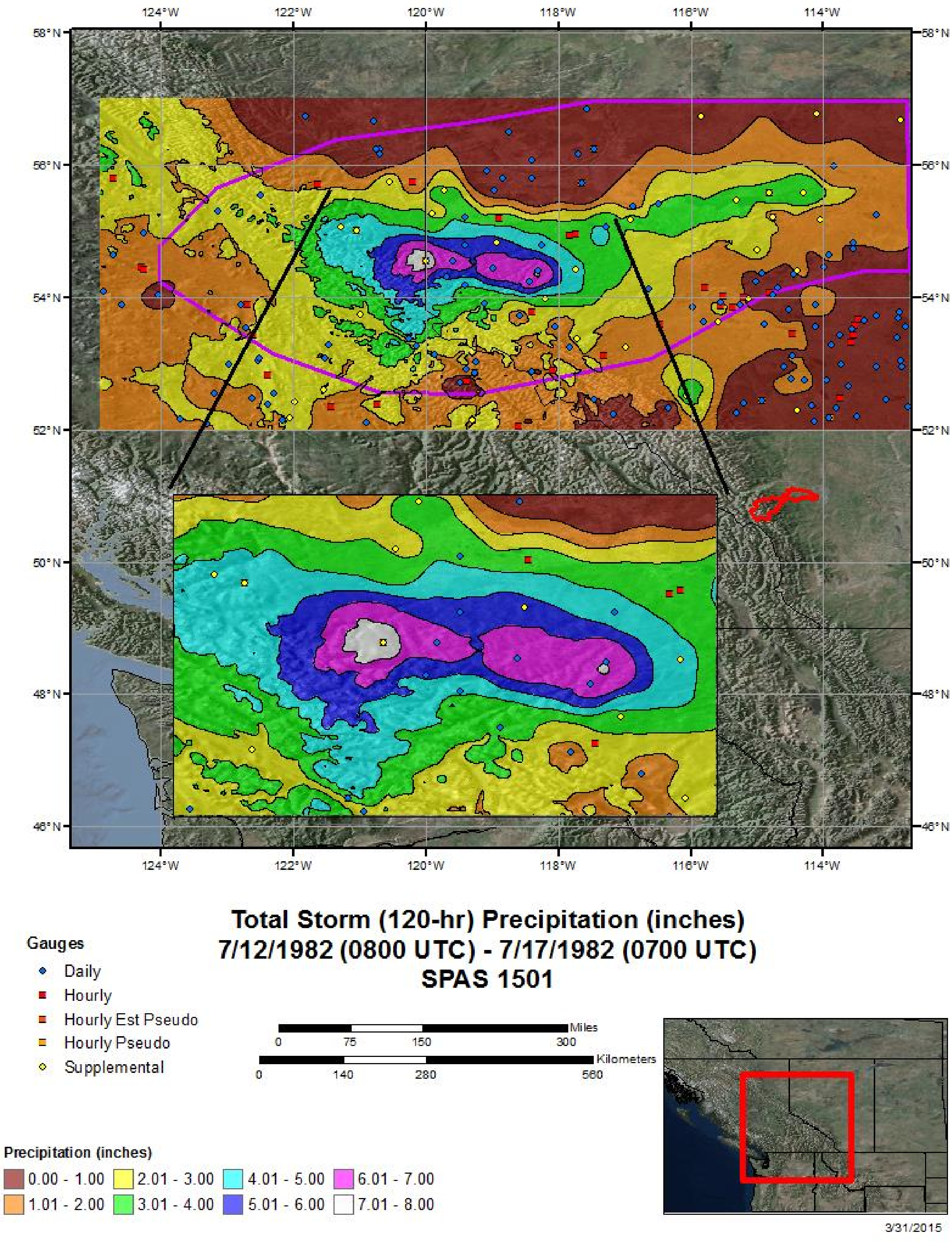
Storm 1501 - July 12 (0800 UTC) - July 17 (0700 UTC), 1982															
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)															
Area (mi^2)	Duration (hours)														
	1	2	3	4	5	6	12	18	24	36	48	72	96	120	Total
0.2	0.95	1.58	2.18	2.81	3.39	3.65	5.17	6.36	6.48	7.28	7.39	7.39	7.39	7.39	7.39
1	0.95	1.58	2.18	2.77	3.39	3.65	5.17	6.36	6.48	7.27	7.39	7.39	7.39	7.39	7.39
10	0.95	1.57	2.18	2.76	3.39	3.64	5.15	6.34	6.46	7.27	7.38	7.38	7.38	7.38	7.38
25	0.94	1.57	2.17	2.76	3.37	3.63	5.13	6.31	6.43	7.26	7.37	7.37	7.37	7.37	7.37
50	0.94	1.56	2.16	2.75	3.35	3.61	5.09	6.25	6.38	7.24	7.35	7.35	7.35	7.35	7.35
100	0.93	1.54	2.13	2.73	3.31	3.57	5.01	6.16	6.28	7.20	7.31	7.31	7.31	7.32	7.32
150	0.92	1.53	2.10	2.71	3.28	3.53	4.94	6.08	6.25	7.16	7.27	7.27	7.27	7.28	7.28
200	0.91	1.51	2.08	2.68	3.24	3.49	4.88	6.01	6.22	7.12	7.23	7.23	7.24	7.24	7.24
300	0.88	1.48	2.03	2.62	3.16	3.41	4.76	5.82	6.18	7.05	7.16	7.16	7.16	7.17	7.17
400	0.87	1.45	1.98	2.55	3.09	3.35	4.67	5.75	6.14	6.98	7.09	7.10	7.10	7.11	7.11
500	0.85	1.43	1.94	2.47	3.03	3.29	4.59	5.69	6.11	6.92	7.03	7.03	7.04	7.06	7.06
1,000	0.79	1.35	1.81	2.33	2.83	3.10	4.26	5.42	5.94	6.63	6.73	6.73	6.83	6.86	6.86
2,000	0.70	1.24	1.64	2.16	2.59	2.76	4.00	5.25	5.79	6.28	6.37	6.39	6.56	6.58	6.58
5,000	0.60	1.07	1.33	1.76	2.08	2.38	3.48	4.71	5.21	5.60	5.74	5.77	5.94	6.01	6.01
10,000	0.47	0.81	1.08	1.41	1.69	1.82	2.95	3.78	4.46	4.91	4.96	5.04	5.26	5.33	5.33
20,000	0.31	0.61	0.85	1.03	1.20	1.41	2.37	3.13	3.61	4.00	4.26	4.26	4.41	4.54	4.54
50,000	0.20	0.42	0.53	0.79	0.90	1.04	1.85	2.32	2.54	2.73	2.87	3.19	3.33	3.37	3.37
100,000	0.14	0.25	0.36	0.47	0.55	0.65	1.14	1.46	1.60	1.89	2.03	2.10	2.22	2.26	2.26
101,596	0.14	0.25	0.36	0.46	0.55	0.64	1.13	1.46	1.59	1.88	2.03	2.08	2.19	2.22	2.22



SPAS #1501 DAD Curves Zone 1
July 12 - July 17, 1982
Area (mi²)
1,000,000
100,000
10,000
1,000
100
10
1
0
2
4
6
8
Maximum Average Depth of Precipitation (inches)
1-hour
2-hour
3-hour
4-hour
5-hour
6-hour
12-hour
18-hour
24-hour
36-hour
48-hour
72-hour
96-hour
120-hour
Total storm (120-hour)



SPAS 1501 Storm Center Mass Curve Zone 1
July 12 (0800UTC) to July 17 (0700UTC), 1982
Lat: 54.5125 Lon: -120.0292
Incremental
Accumulated
Incremental Precipitation (in)
Accumulated Precipitation (in)
7.39
Index Hour


124°W
122°W
120°W
118°W
116°W
114°W
58°N
56°N
54°N
52°N
50°N
48°N
46°N
Total Storm (120-hr) Precipitation (inches)
7/12/1982 (0800 UTC) - 7/17/1982 (0700 UTC)
SPAS 1501
Gauges
Daily
Hourly
Hourly Est Pseudo
Hourly Pseudo
Supplemental
Miles
0 75 150 300
Kilometers
0 140 280 560
Precipitation (inches)
0.00 - 1.00
2.01 - 3.00
4.01 - 5.00
6.01 - 7.00
1.01 - 2.00
3.01 - 4.00
5.01 - 6.00
7.01 - 8.00
3/31/2015

Veteran, AB

June 13-18, 1973

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1502

General Storm Location: Sedalia, Alberta

Storm Dates: June 13 - 18, 1973

Event: Synoptic/Convective Event

DAD Zone 1

Latitude: 51.8625°

Longitude: -110.4292°

Max. Grid Rainfall Amount: 243mm

Max. Observed Rainfall Amount: 223mm

Number of Stations: 299 (223 Daily, 20 Hourly, 10 Hourly Pseudo, 0 Hourly Estimated Pseudo, and 46 Supplemental)

SPAS Version: 10.0

Basemap: Blended PRISM July 1961-1990 Climatology (Canada) and AL 6-73 Isohyetal

Spatial resolution: 30 second (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and AL 6-73 data. We have a good degree of confidence in the station based storm total results; the spatial pattern is dependent on the station data and a basemap. The timing is based on hourly and hourly pseudo stations.

Storm Name:	**SPAS 1502 Veteran, AB**	**Storm Adjustment Summary**
Storm Date:	**6/13-18/1973**	
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **1-Jul**

	Lat	Long
Storm Center Location	**51.86 N**	**110.43 W**
Storm Rep Dew Point Location	**49.07 N**	**103.00 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**ESE @ 612**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**671**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**20.6 °C**	with total precipitable water above sea level of		**54**	millimeters.
The in-place maximum dew point is	**23.9 °C**	with total precipitable water above sea level of		**72**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**671**	which subtracts	**11**	millimeters of precipitable water at	**20.6 °C**
The in-place storm elevation is	**671**	which subtracts	**13**	millimeters of precipitable water at	**23.9 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.36**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: DAD values taken from SPAS 1502. Storm representative Td value was based on maximum 24-hr average Td values at CYEN on June 13-16, 1973.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**31**					**115**	**158**	**211**	**238**
26 km^2 (10 mi^2)	**31**					**115**	**158**	**211**	**238**
259 km^2 (100 mi^2)	**31**					**113**	**155**	**208**	**234**
518 km^2 (200 mi^2)	**30**					**110**	**152**	**202**	**228**
1,295 km^2 (500 mi^2)	**29**					**103**	**143**	**191**	**215**
2,590 km^2 (1,00 mi^2)	**27**					**95**	**129**	**172**	**196**
5,180 km^2 (2,000 mi^2)	**24**					**84**	**107**	**158**	**176**
12.950 km^2 (5000 mi^2)	**20**					**64**	**87**	**132**	**152**
25,900 km^2 (10,000 mi^2)	**16**					**55**	**66**	**112**	**132**
51,800 km^2 (20,000 mi^2)	**12**					**45**	**64**	**93**	**119**

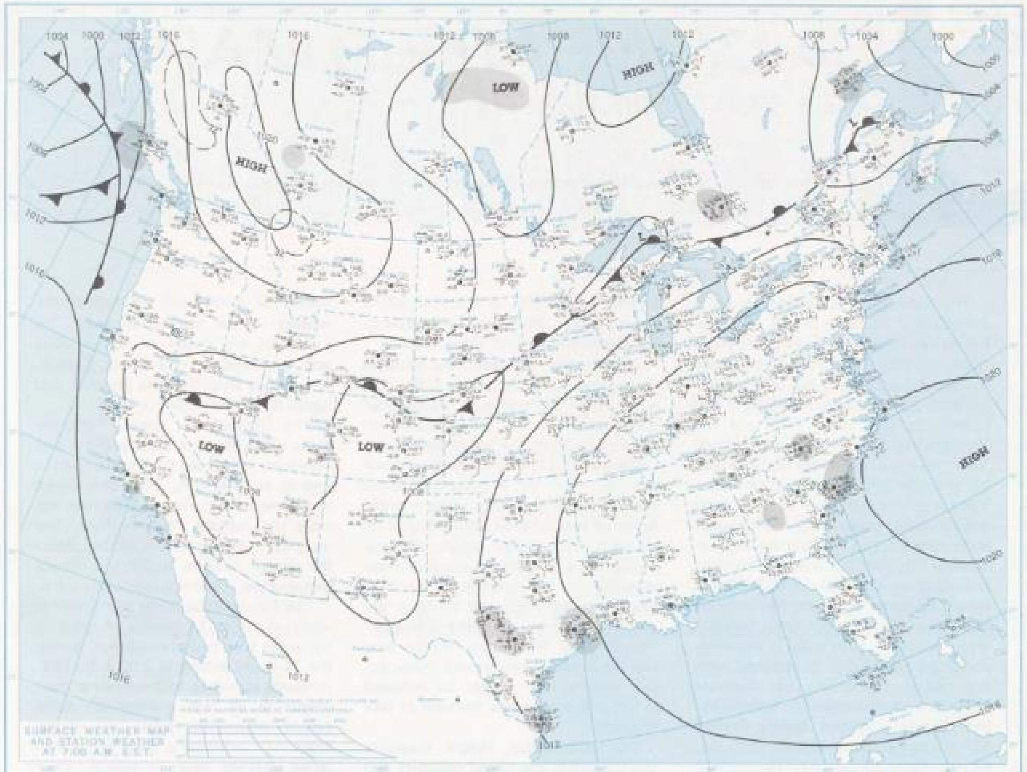
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***

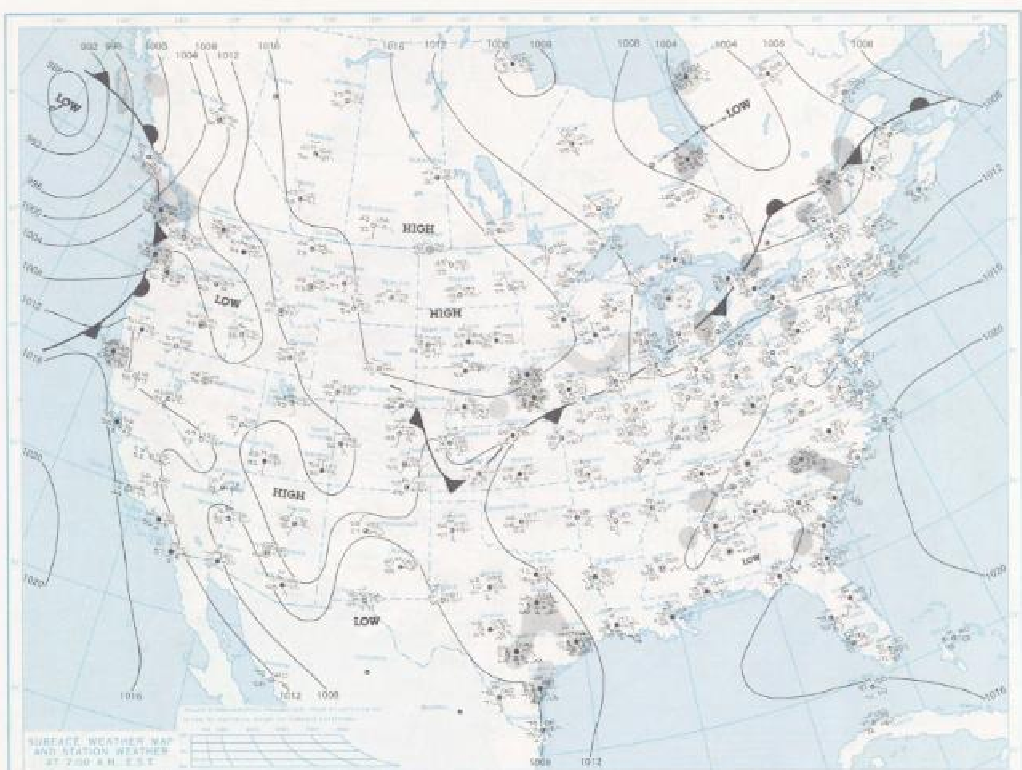
Storm or Storm Center Name	**SPAS 1502 Veteran, AB**	
Storm Date(s)	6/13-18/1973	
Storm Type	Synoptic Event	
Storm Location	51.86 N	110.43 W
Storm Center Elevation	671	meters
Precipitation Total & Duration	243	millimeters
Storm Representative Dew Point	20.6 °C	24
Storm Representative Dew Point Location	49.07 N	103.00 W
Maximum Dew Point	23.9 °C	
Moisture Inflow Vector	ESE @ 612 kilometers	
In-place Maximization Factor	**1.36**	
Temporal Transposition (Date)	1-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

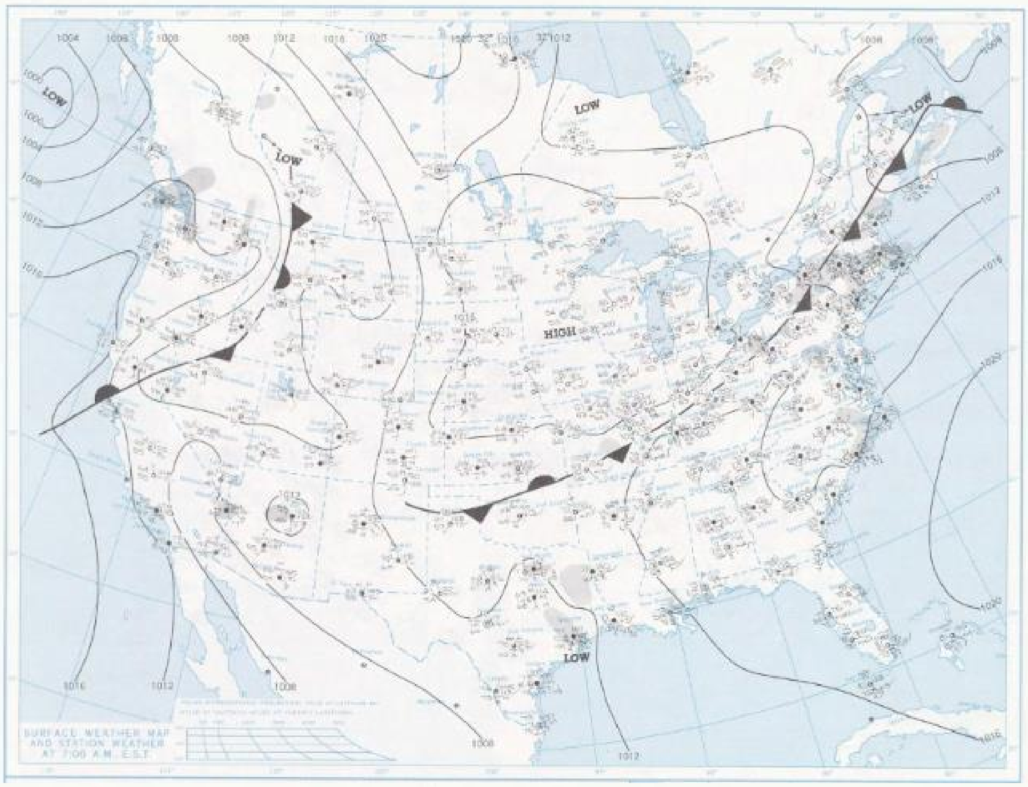
MONDAY, JUNE 11, 1973



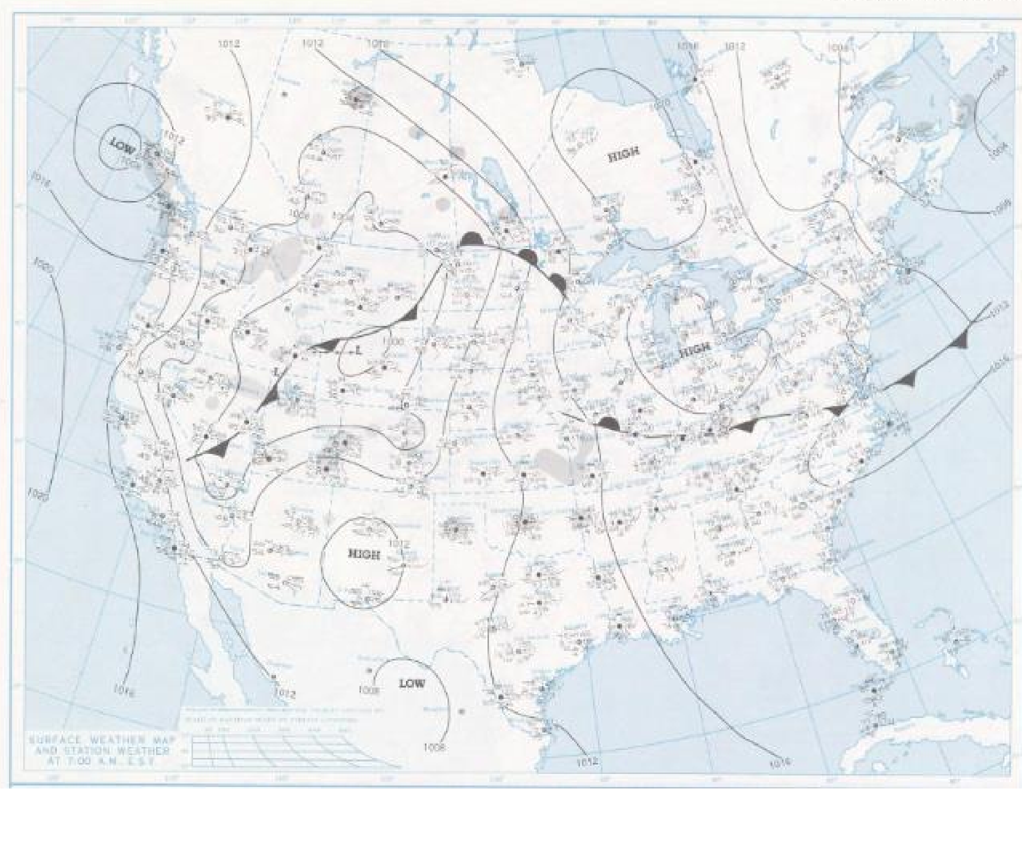
TUESDAY, JUNE 12, 1973



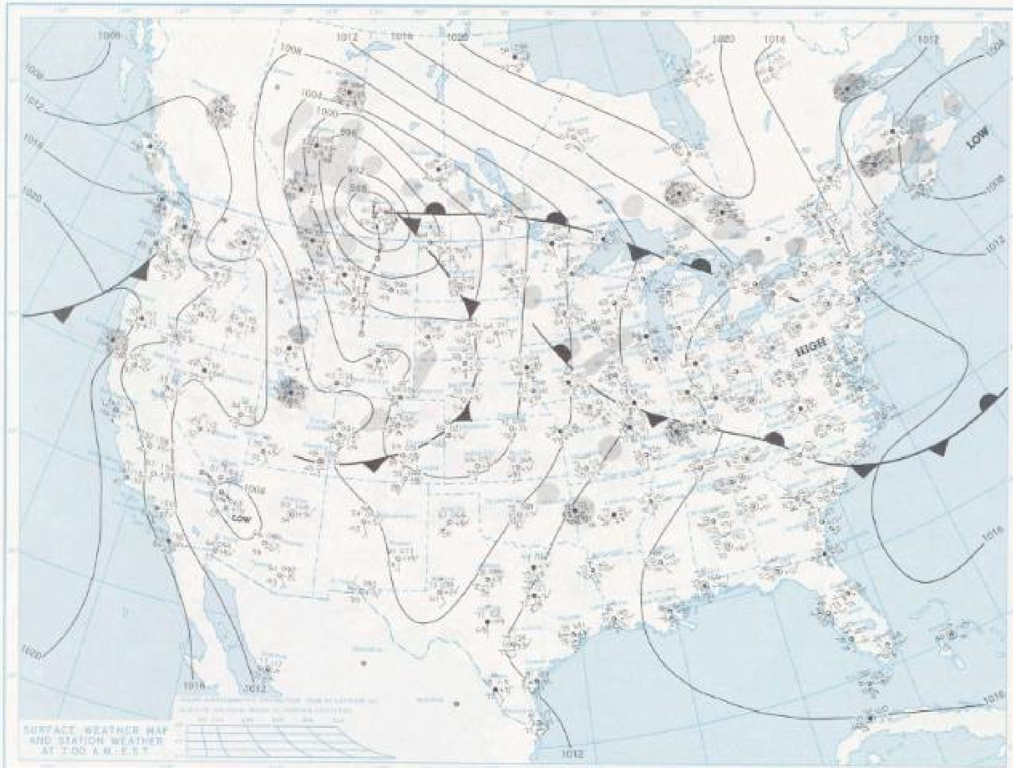
WEDNESDAY, JUNE 13, 1973



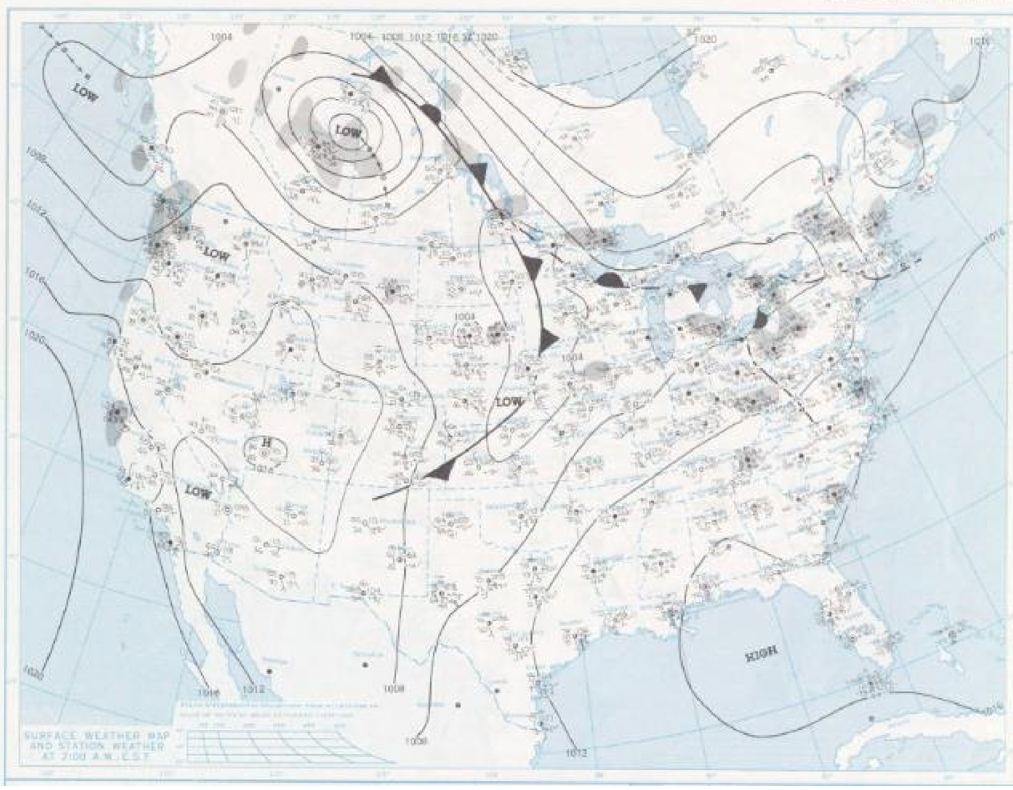
THURSDAY, JUNE 14, 1973



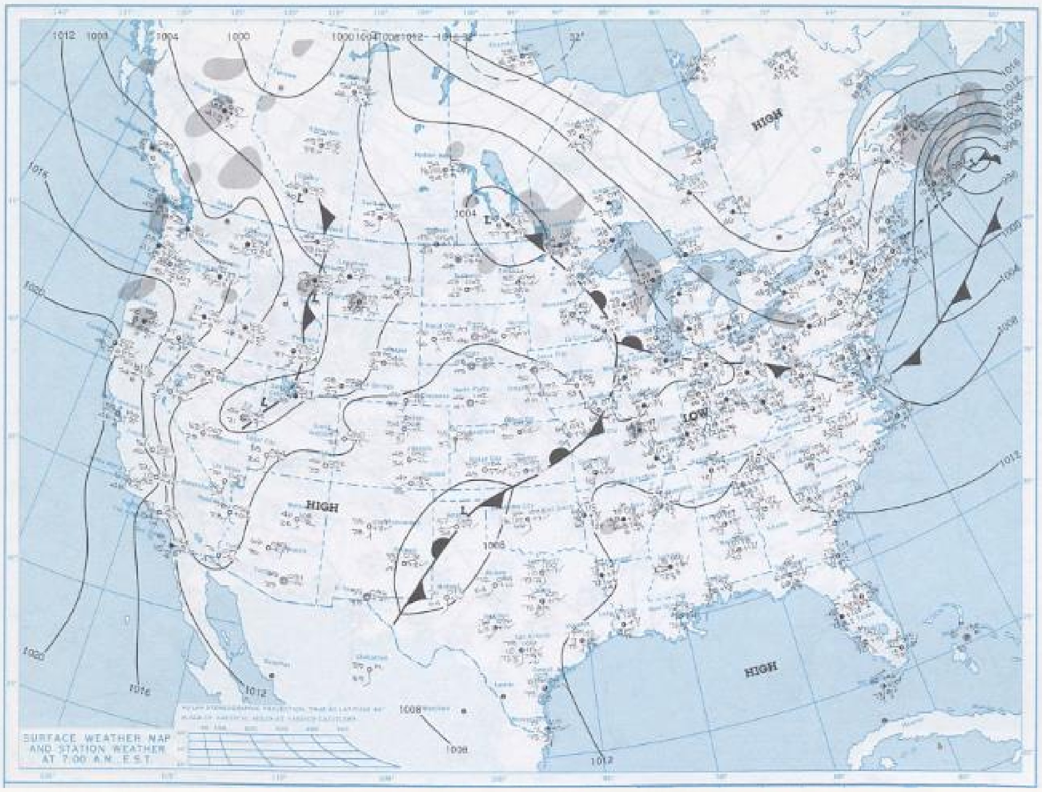
FRIDAY, JUNE 15, 1973



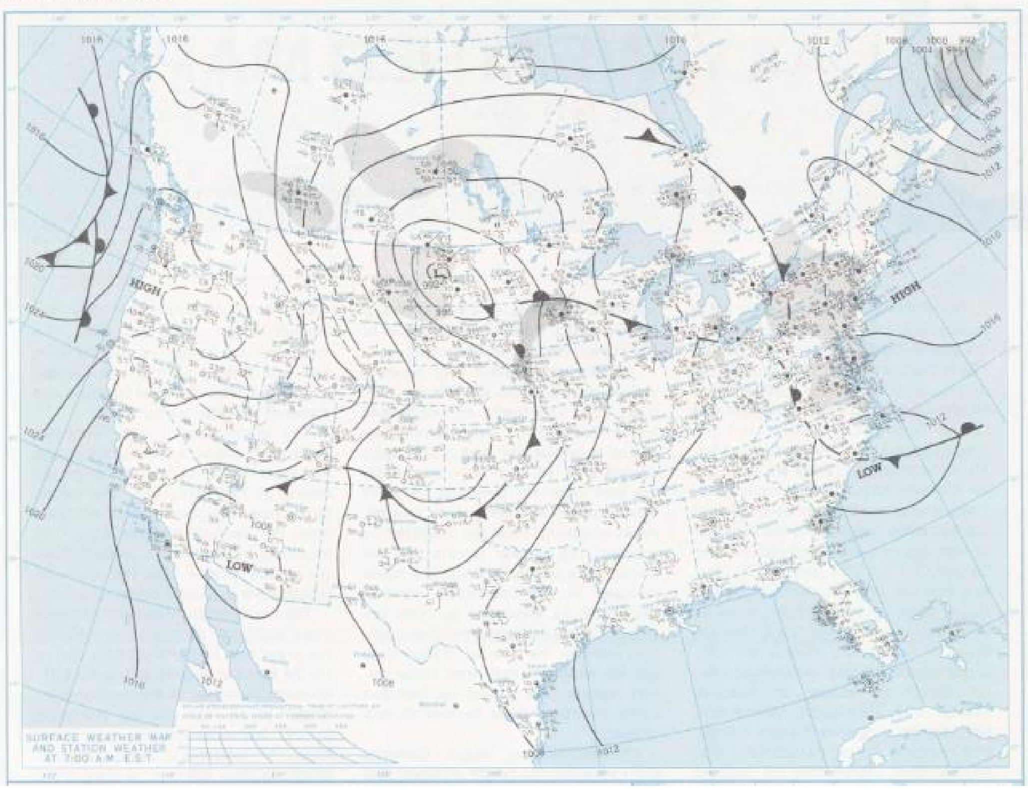
SATURDAY, JUNE 16, 1973

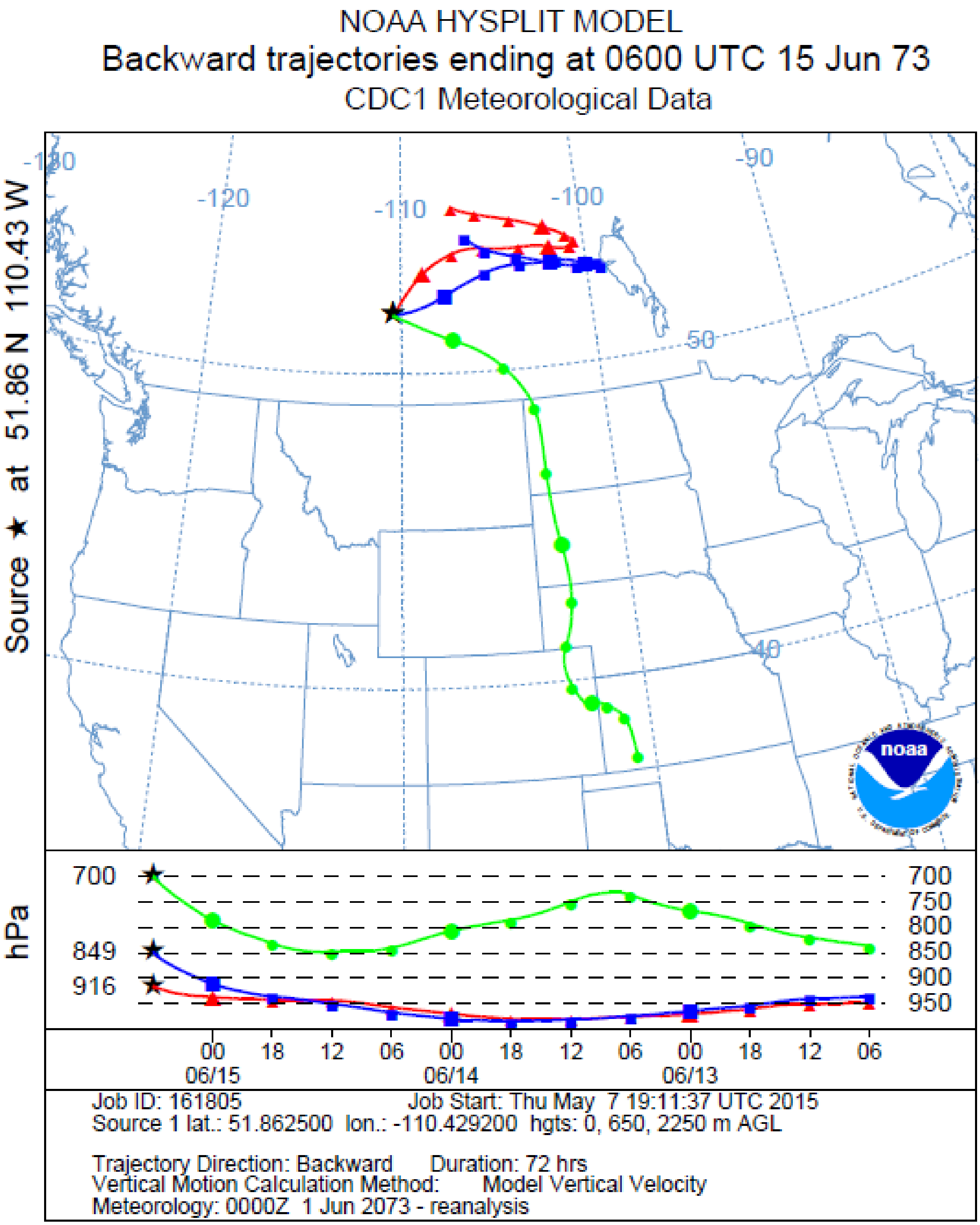


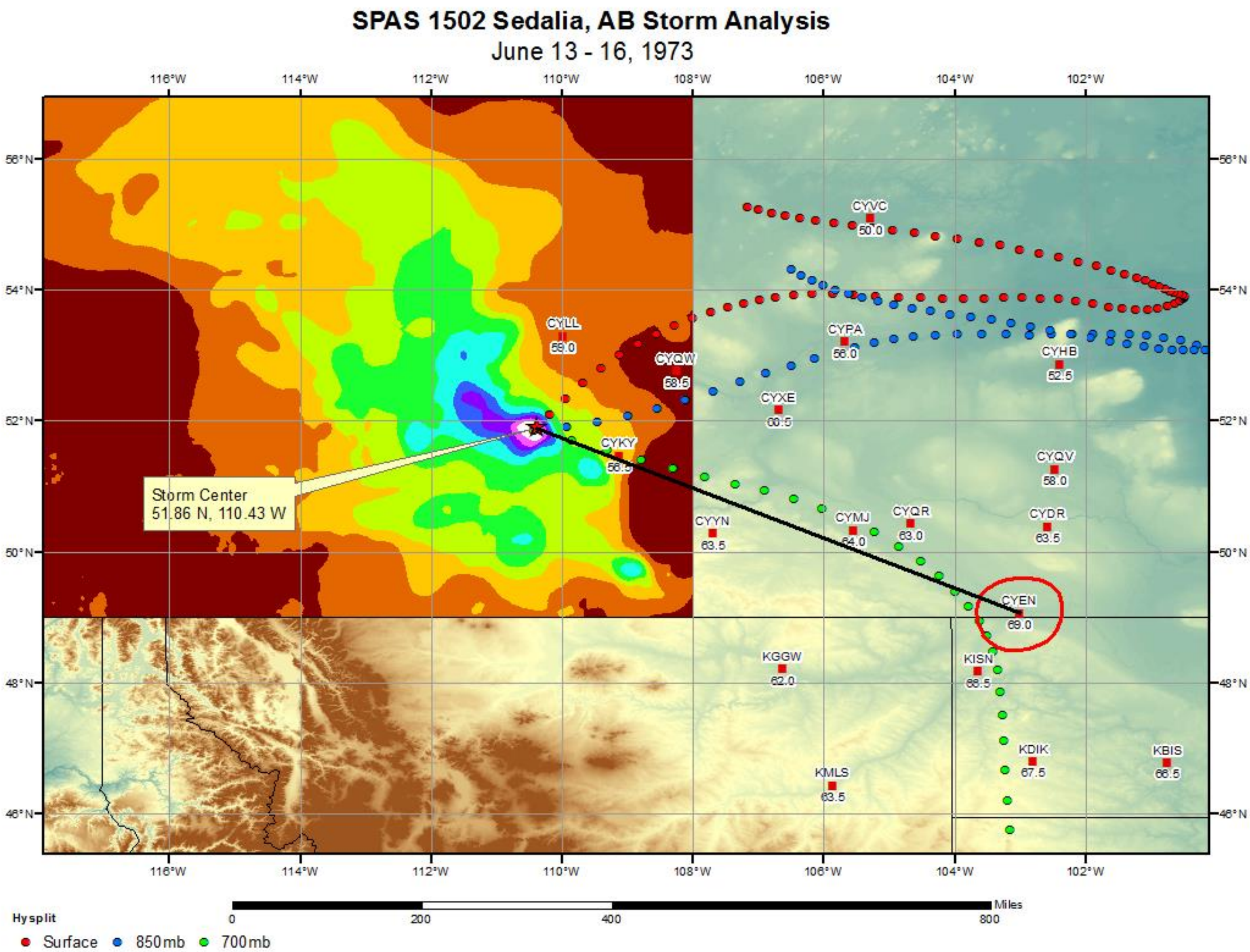
SUNDAY, JUNE 17, 1973



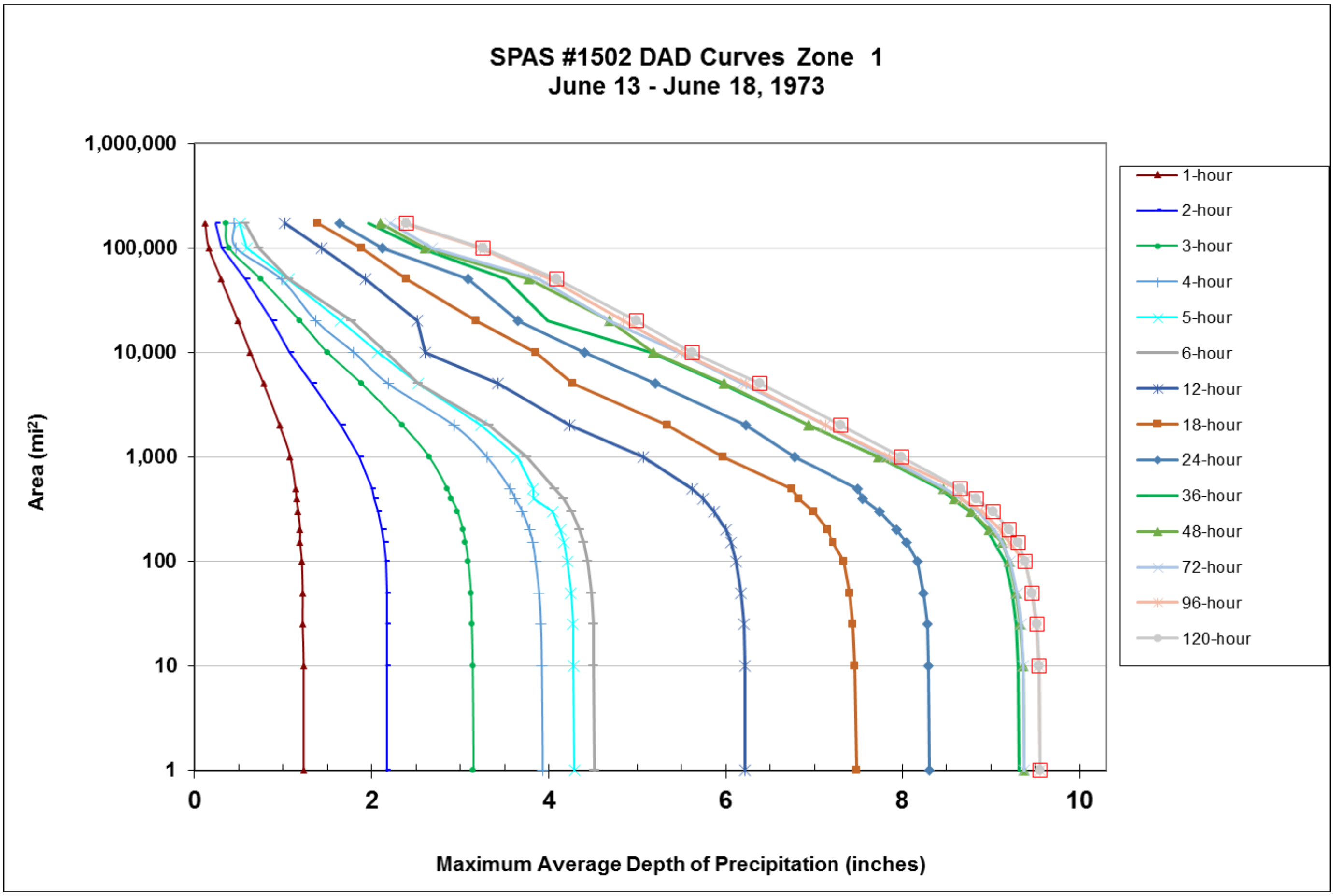
MONDAY, JUNE 18, 1973



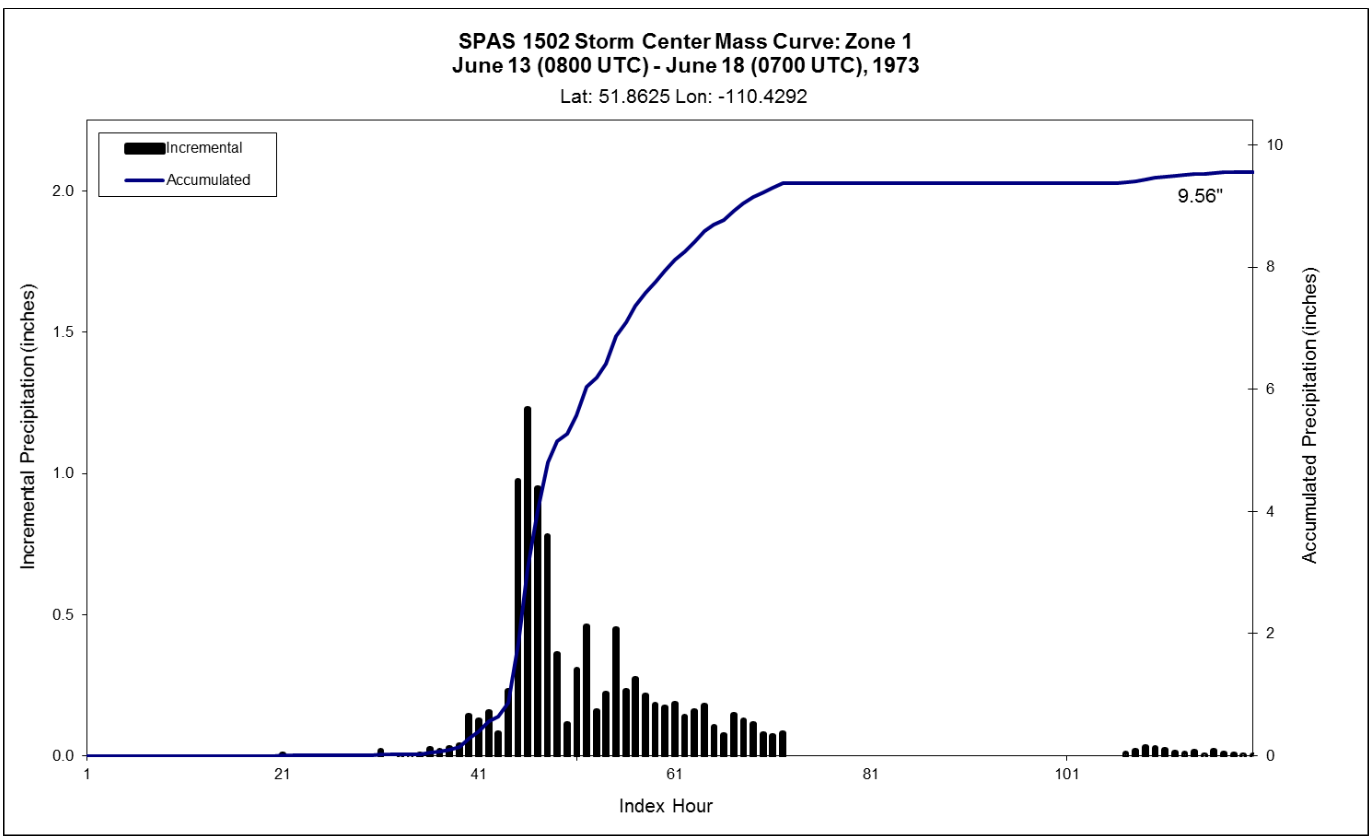

NOAA HYSPLIT MODEL
Backward trajectories ending at 0600 UTC 15 Jun 73
CDC1 Meteorological Data
Source ★ at 51.86 N 110.43 W
-120
-110
-100
-90
50
40
hPa
700
849
916
700
750
800
850
900
950
00
18
12
06
00
18
12
06
00
18
12
06
06/15
06/14
06/13
Job ID: 161805 Job Start: Thu May 7 19:11:37 UTC 2015
Source 1 lat.: 51.862500 lon.: -110.429200 hgts: 0, 650, 2250 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jun 2073 - reanalysis



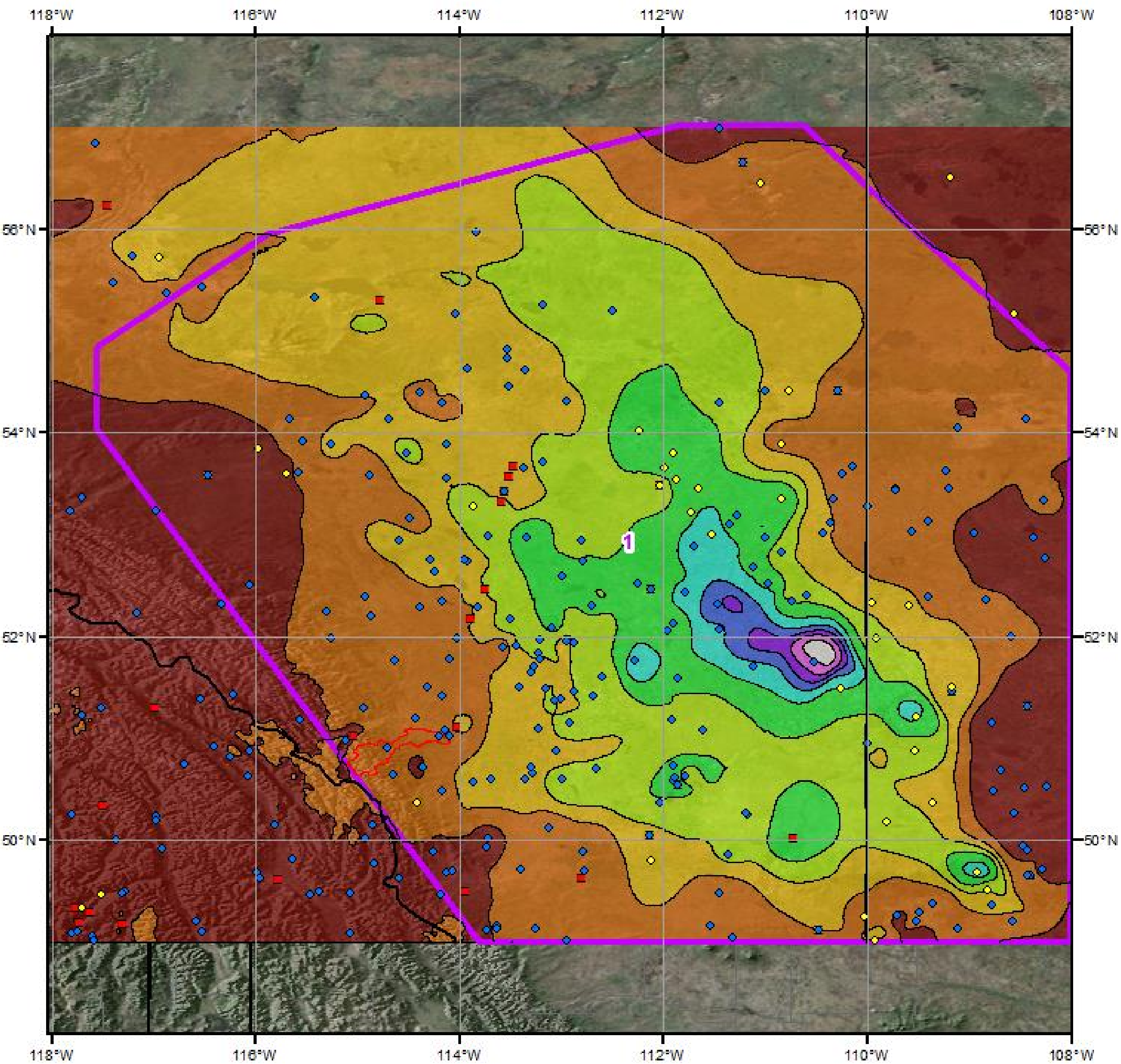
Storm 1502 - June 13 (0800 UTC) - June 18 (0700 UTC), 1973														
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)														
Area (mi^2)	Duration (hours)													
	1	2	3	4	5	6	12	18	24	36	48	72	96	120	Total
0.2	1.23	2.20	3.15	3.93	4.29	4.52	6.22	7.48	8.31	9.32	9.37	9.38	9.55	9.56	9.56
1	1.23	2.17	3.15	3.93	4.29	4.52	6.22	7.48	8.31	9.32	9.37	9.38	9.55	9.56	9.56
10	1.23	2.17	3.14	3.92	4.28	4.51	6.21	7.46	8.30	9.31	9.36	9.36	9.54	9.54	9.54
25	1.22	2.17	3.13	3.91	4.27	4.50	6.20	7.44	8.28	9.28	9.33	9.34	9.51	9.52	9.52
50	1.22	2.17	3.12	3.89	4.25	4.48	6.17	7.41	8.24	9.24	9.29	9.30	9.47	9.47	9.47
100	1.21	2.16	3.09	3.85	4.21	4.44	6.11	7.34	8.17	9.16	9.21	9.22	9.39	9.39	9.39
150	1.19	2.14	3.06	3.82	4.17	4.39	6.06	7.22	8.05	9.04	9.13	9.13	9.21	9.31	9.31
200	1.19	2.12	3.03	3.78	4.13	4.35	6.00	7.15	7.94	8.96	8.98	9.04	9.11	9.21	9.21
300	1.17	2.07	2.97	3.70	4.04	4.26	5.87	6.99	7.74	8.77	8.78	8.86	8.90	9.03	9.03
400	1.15	2.03	2.90	3.62	3.83	4.17	5.74	6.82	7.55	8.57	8.59	8.67	8.67	8.84	8.84
500	1.14	2.00	2.85	3.56	3.82	4.07	5.62	6.74	7.50	8.43	8.46	8.49	8.62	8.65	8.65
1,000	1.08	1.86	2.65	3.30	3.64	3.75	5.07	5.97	6.78	7.73	7.73	7.81	7.86	7.99	7.99
2,000	0.96	1.66	2.35	2.93	3.24	3.32	4.23	5.34	6.23	6.93	6.93	7.13	7.13	7.31	7.31
5,000	0.78	1.33	1.89	2.19	2.53	2.53	3.43	4.27	5.20	5.94	5.98	6.18	6.23	6.38	6.38
10,000	0.63	1.07	1.50	1.80	2.07	2.17	2.61	3.85	4.40	5.16	5.18	5.47	5.50	5.62	5.62
20,000	0.49	0.88	1.19	1.37	1.65	1.77	2.51	3.18	3.65	3.99	4.68	4.68	4.84	4.99	4.99
50,000	0.30	0.58	0.75	0.98	1.06	1.06	1.93	2.39	3.09	3.52	3.77	3.89	4.01	4.09	4.09
100,000	0.16	0.31	0.39	0.47	0.59	0.73	1.43	1.88	2.12	2.55	2.61	2.68	3.22	3.26	3.26
170,226	0.12	0.24	0.35	0.45	0.51	0.57	1.02	1.39	1.64	1.96	2.10	2.21	2.36	2.39	2.39



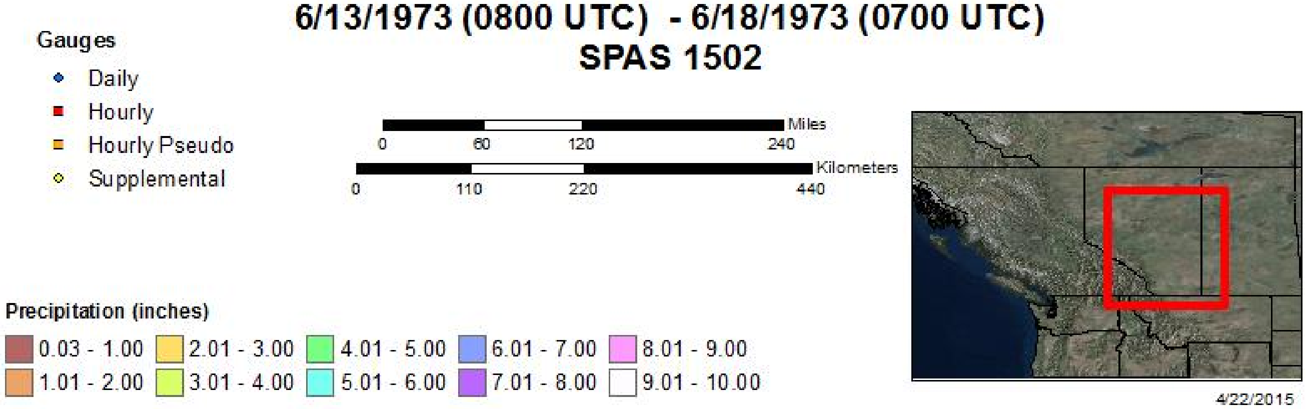
SPAS #1502 DAD Curves Zone 1
June 13 - June 18, 1973
Area (mi²)
1,000,000
100,000
10,000
1,000
100
10
1
0
2
4
6
8
10
Maximum Average Depth of Precipitation (inches)
1-hour
2-hour
3-hour
4-hour
5-hour
6-hour
12-hour
18-hour
24-hour
36-hour
48-hour
72-hour
96-hour
120-hour



SPAS 1502 Storm Center Mass Curve: Zone 1
June 13 (0800 UTC) - June 18 (0700 UTC), 1973
Lat: 51.8625 Lon: -110.4292
Incremental
Accumulated
9.56"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour
0.0
0.5
1.0
1.5
2.0
0
2
4
6
8
10
1
21
41
61
81
101



Total Storm (120-hr) Precipitation (inches)
6/13/1973 (0800 UTC) - 6/18/1973 (0700 UTC)
SPAS 1502



Nose Mountain, AB

June 9-13, 1972

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1503

General Storm Location: Nose Mtn, Alberta

Storm Dates: June 9-13, 1972

Event: Synoptic/Convective Event

DAD Zone 1

- **Latitude**: 54.5375°
- **Longitude**: -119.5542°
- **Max. Grid Rainfall Amount**: 207mm
- **Max. Observed Rainfall Amount**: 204mm

DAD Zone 2

- **Latitude**: 52.4708°
- **Longitude**: -116.0125°
- **Max. Grid Rainfall Amount**: 78mm
- **Max. Observed Rainfall Amount**: 75mm

Number of Stations: 136 (92 Daily, 13 Hourly, 2 Hourly Pseudo, 0 Hourly Estimated Pseudo, and 29 Supplemental)

SPAS Version: 10.0

Basemap: Blended PRISM June 1961-1990 Climatology (Canada) and AL 6-(2)72 Isohyetal

Spatial resolution: 30 second (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and AL 6(2)-72 data. We have a good degree of confidence in the station based storm total results; the spatial pattern is dependent on the station data and a basemap. The timing is based on hourly and hourly pseudo stations.

Storm Name:	SPAS 1503 - Nose Mountain, AB - Zone 1
Storm Date:	6/9-13/1972
AWA Analysis Date:	7/20/2015

Storm Adjustment Summary

Temporal Transposition Date **25-Jun**

	Lat	Long
Storm Center Location	**54.54 N**	**119.55 W**
Storm Rep Dew Point Location	**51.00 N**	**112.00 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**SE @ 644**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**1,494**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**18.9 °C**	with total precipitable water above sea level of		**47**	millimeters.
The in-place maximum dew point is	**20.0 °C**	with total precipitable water above sea level of		**52**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**1,494**	which subtracts	**20**	millimeters of precipitable water at	**18.9 °C**
The in-place storm elevation is	**1,494**	which subtracts	**21**	millimeters of precipitable water at	**20.0 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.13**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: DAD values taken from SPAS 1503. Storm representative Td value was based on maximum 24-hr average Td values at YYC and YQL on June 9-12, 1972.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**18**					**62**	**90**	**135**	**207**
26 km^2 (10 mi^2)	**18**					**61**	**89**	**135**	**206**
259 km^2 (100 mi^2)	**17**					**59**	**86**	**129**	**198**
518 km^2 (200 mi^2)	**16**					**57**	**83**	**125**	**191**
1,295 km^2 (500 mi^2)	**16**					**53**	**78**	**115**	**180**
2,590 km^2 (1,00 mi^2)	**15**					**51**	**72**	**107**	**168**
5,180 km^2 (2,000 mi^2)	**13**					**47**	**65**	**94**	**136**
12.950 km^2 (5000 mi^2)	**11**					**39**	**53**	**81**	**114**
25,900 km^2 (10,000 mi^2)	**9**					**33**	**45**	**69**	**97**
51,800 km^2 (20,000 mi^2)	**7**					**26**	**36**	**56**	**75**

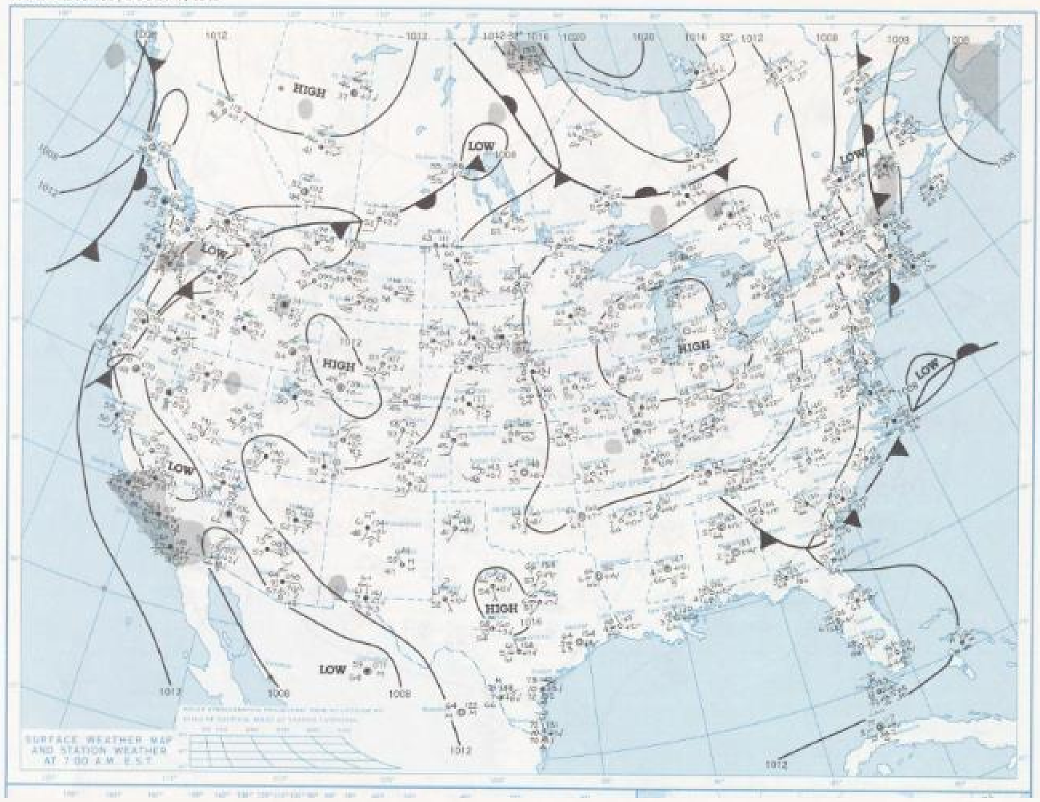
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***

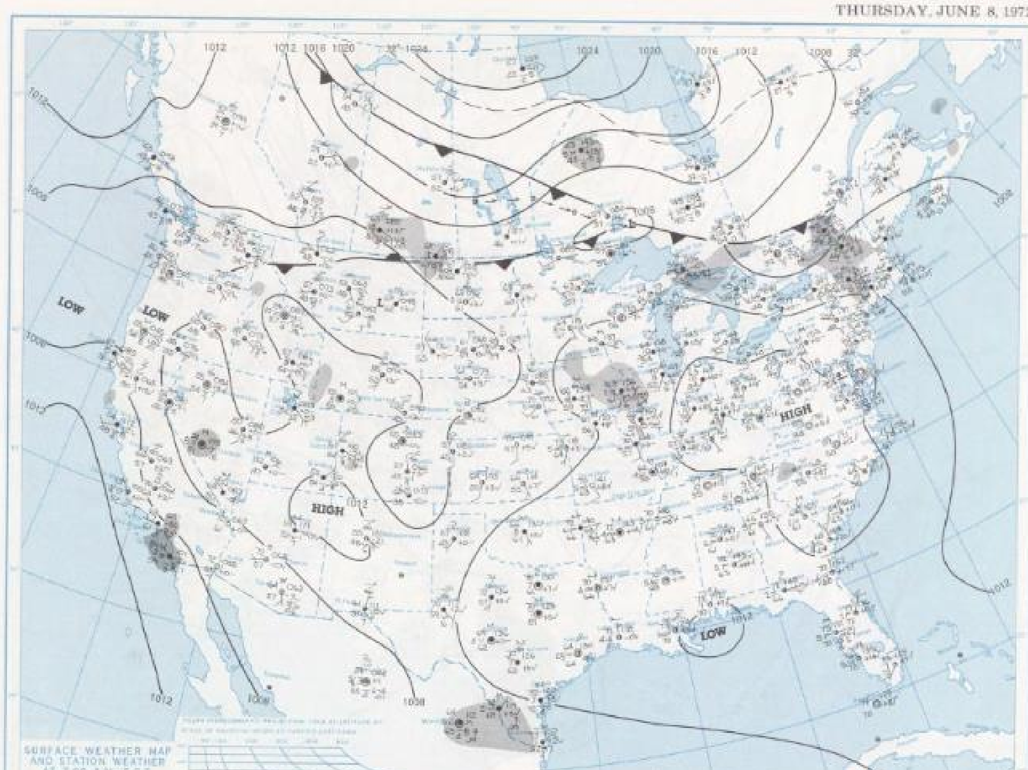
Storm or Storm Center Name	**SPAS 1503 - Nose Mountain, AB - Zone 1**	
Storm Date(s)	6/9-13/1972	
Storm Type	Synoptic	
Storm Location	54.54 N	119.55 W
Storm Center Elevation	1,494	meters
Precipitation Total & Duration	207	millimeters
Storm Representative Dew Point	18.9 °C	24
Storm Representative Dew Point Location	51.00 N	112.00 W
Maximum Dew Point	20.0 °C	
Moisture Inflow Vector	SE @ 644	kilometers
In-place Maximization Factor	**1.13**	
Temporal Transposition (Date)	25-Jun	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

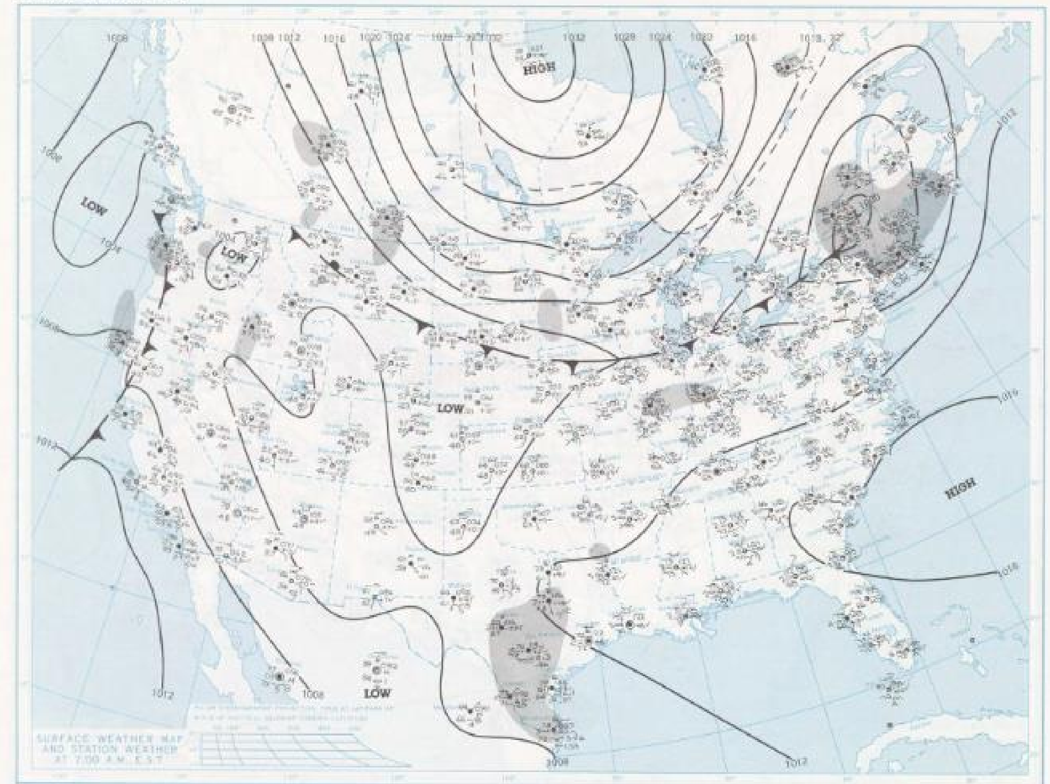
WEDNESDAY, JUNE 7, 1972



THURSDAY, JUNE 8, 1972

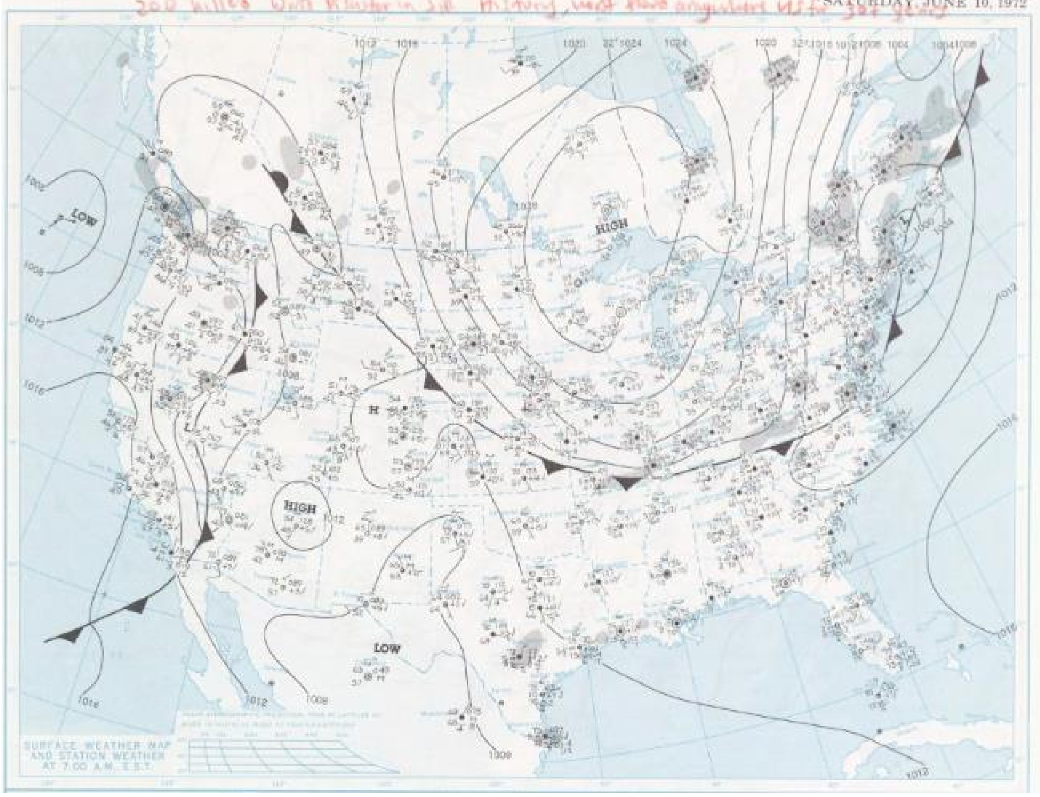


FRIDAY, JUNE 9, 1972

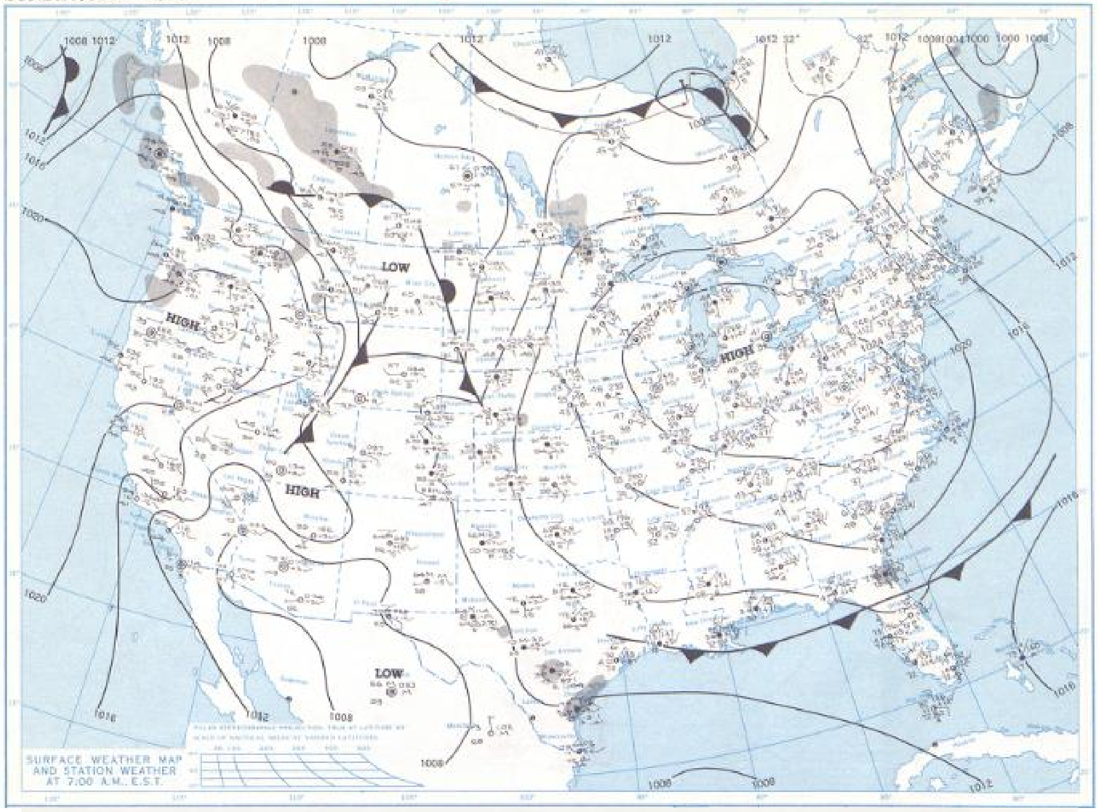


Disastrous Flash Floods Rapid City- Black Hills area, up to 7" rain in 12hr some spots. 200 killed Worst Disaster in S.D. History, worst flood anywhere US for 38 years

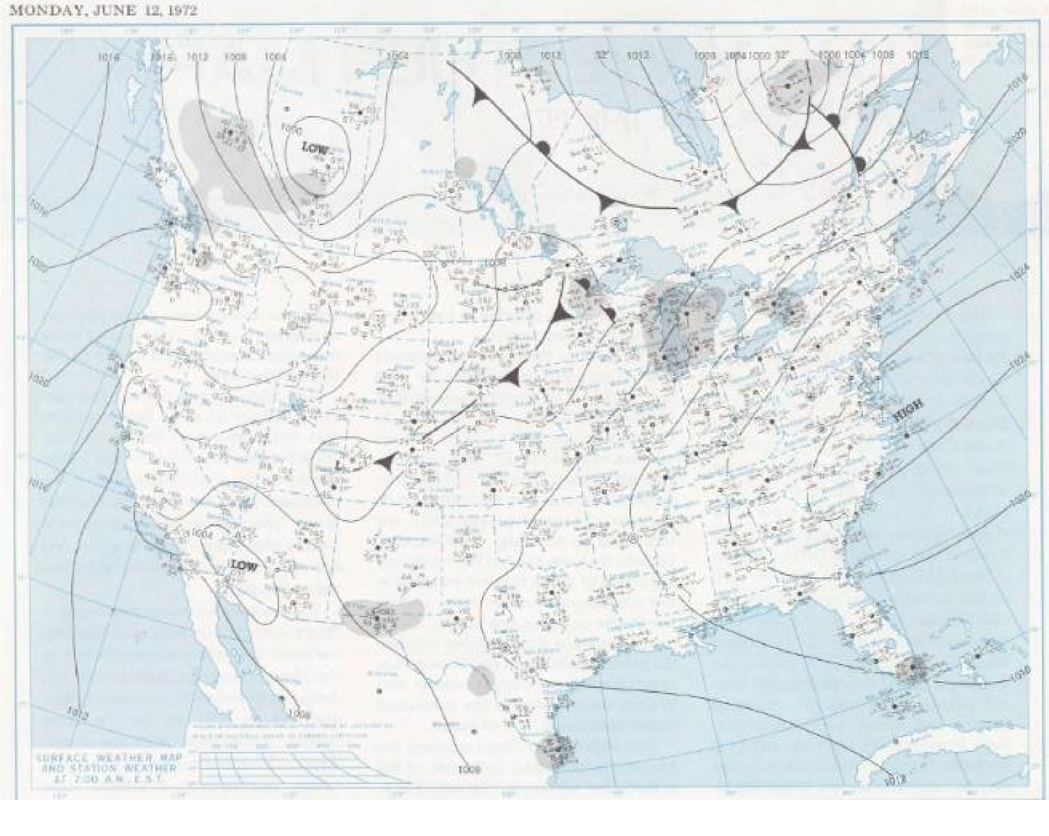
SATURDAY, JUNE 10, 1972

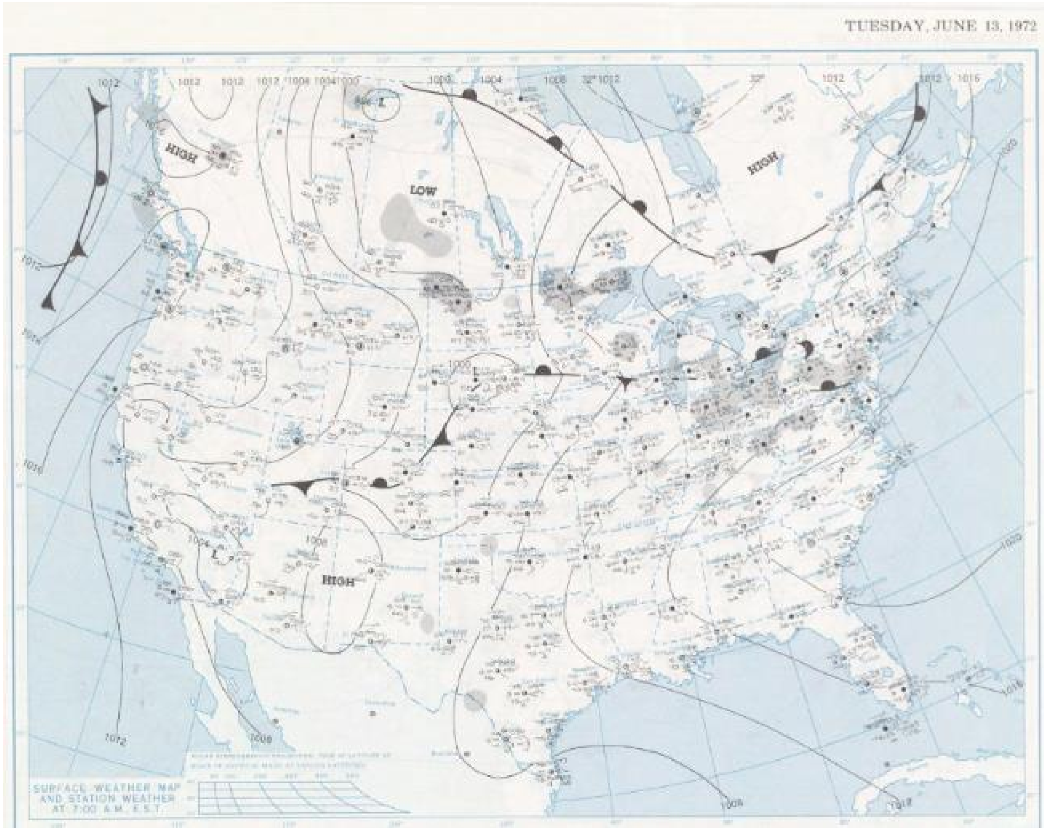


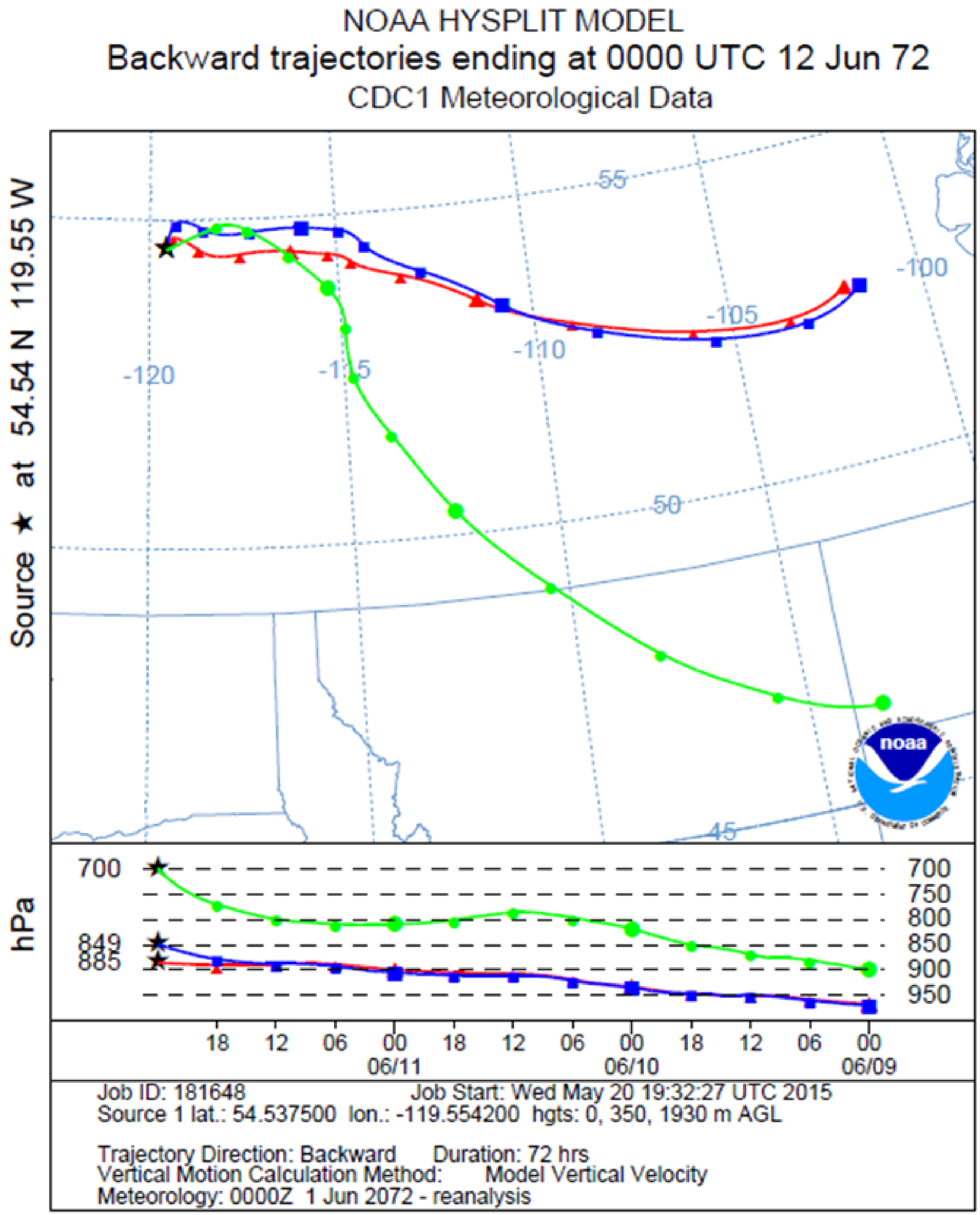
SUNDAY, JUNE 11, 1972

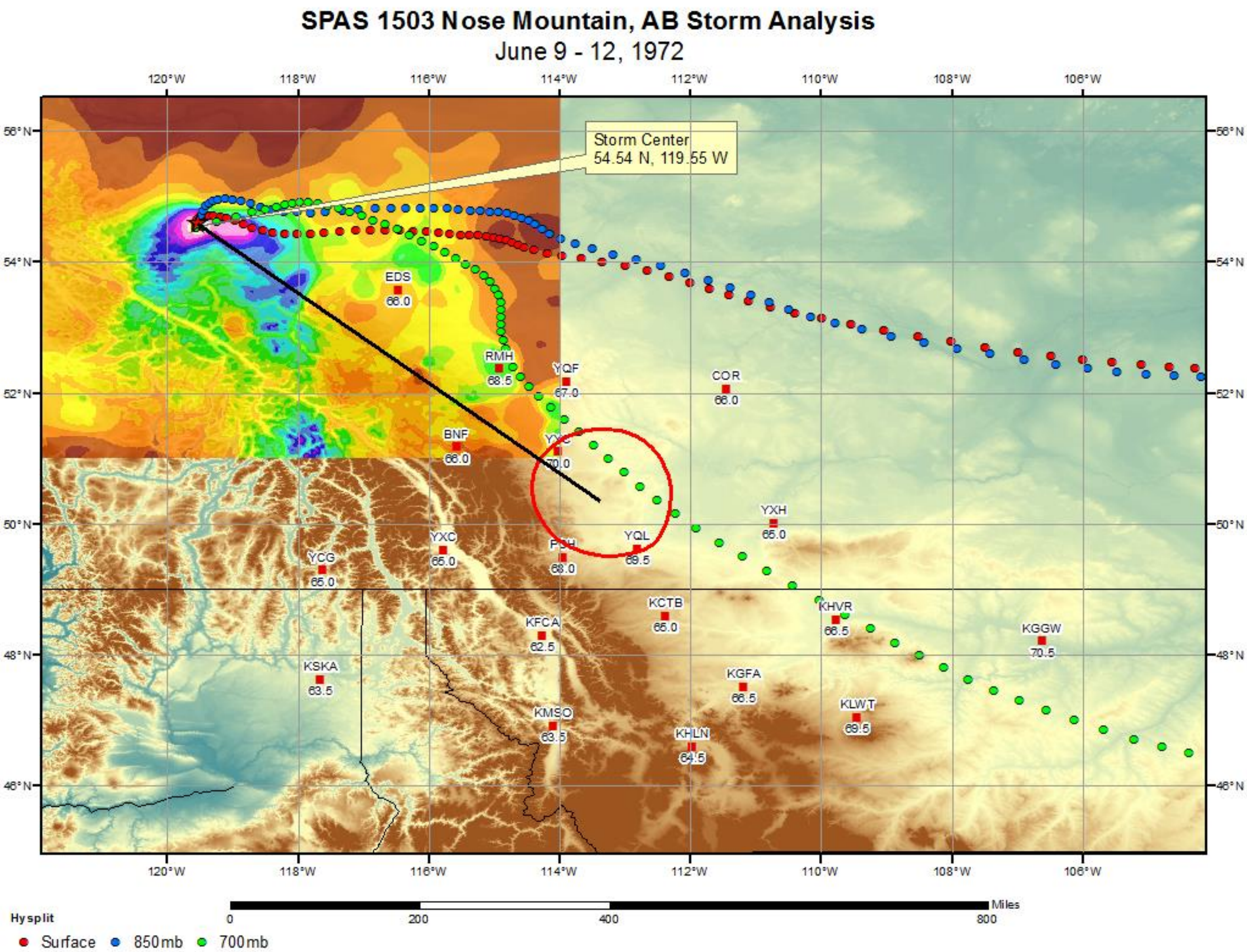


MONDAY, JUNE 12, 1972

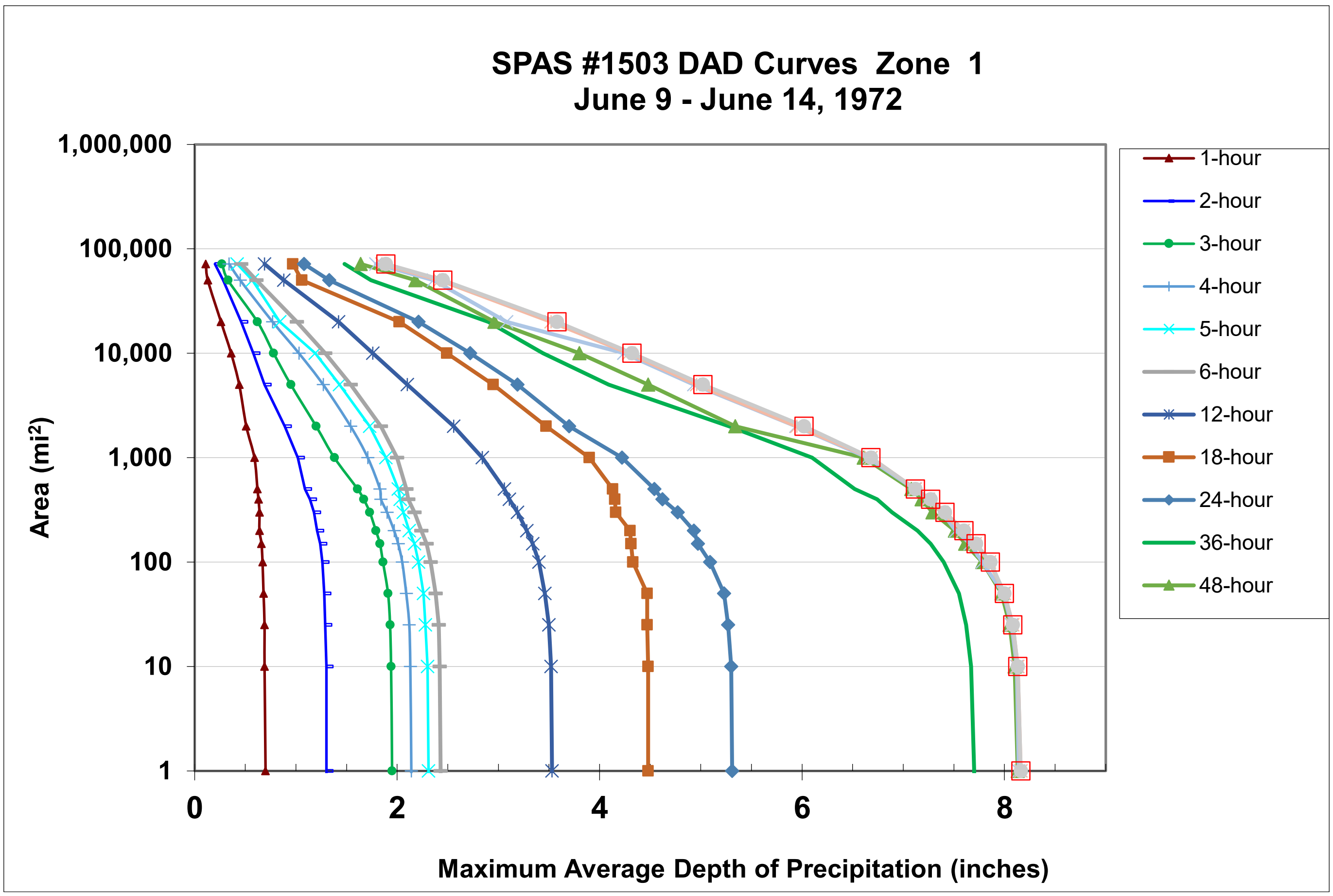


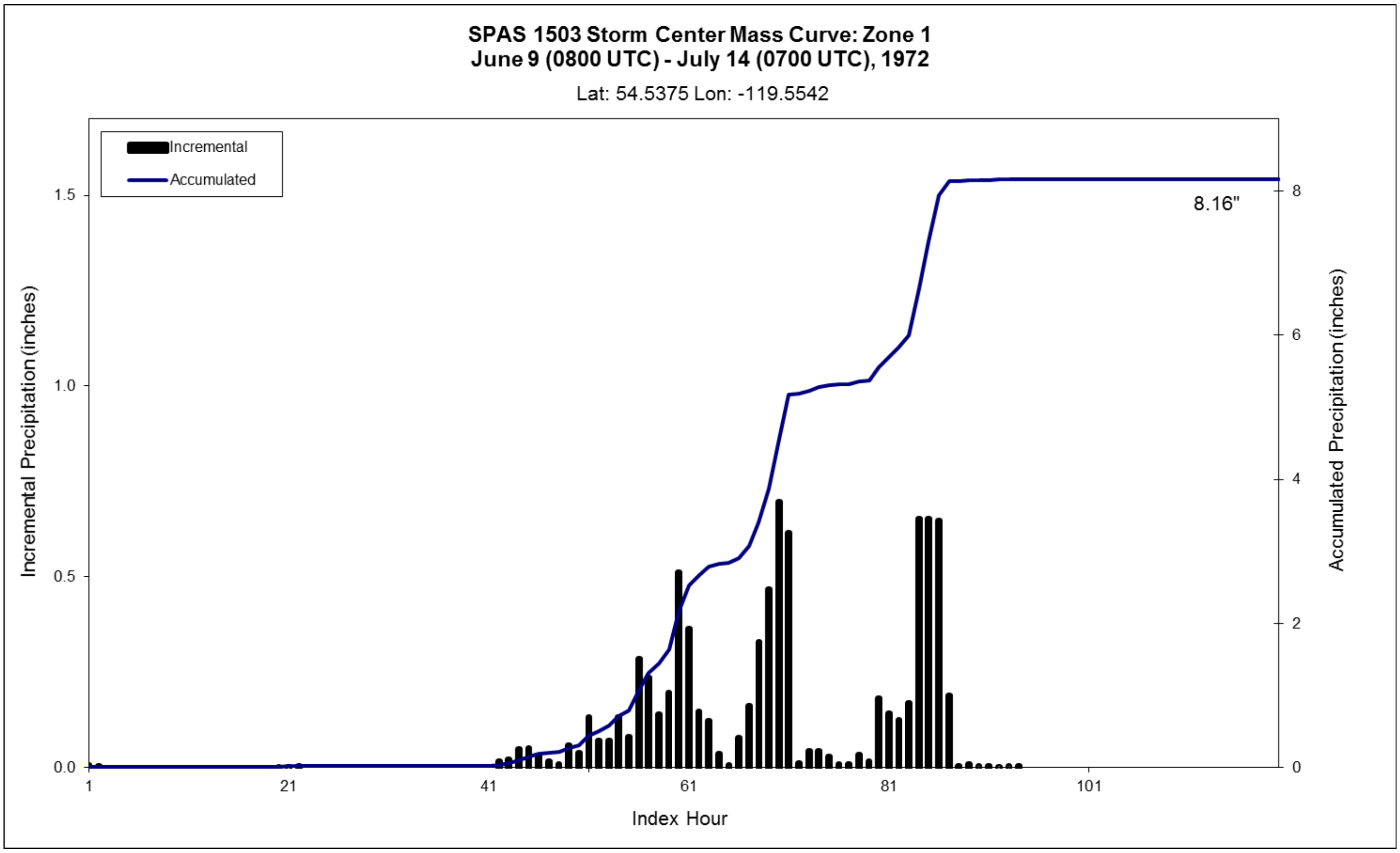

TUESDAY, JUNE 13, 1972
HIGH
LOW
HIGH
HIGH
SURFACE WEATHER MAP
AND STATION WEATHER
AT 7:00 A.M. E.S.T.


NOAA HYSPLIT MODEL
Backward trajectories ending at 0000 UTC 12 Jun 72
CDC1 Meteorological Data
Source ★ at 54.54 N 119.55 W
55
-100
-105
-110
-115
-120
50
45
noaa
hPa
700
849
885
700
750
800
850
900
950
18
12
06
00
06/11
18
12
06
00
06/10
18
12
06
00
06/09
Job ID: 181648 Job Start: Wed May 20 19:32:27 UTC 2015
Source 1 lat.: 54.537500 lon.: -119.554200 hgts: 0, 350, 1930 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jun 2072 - reanalysis

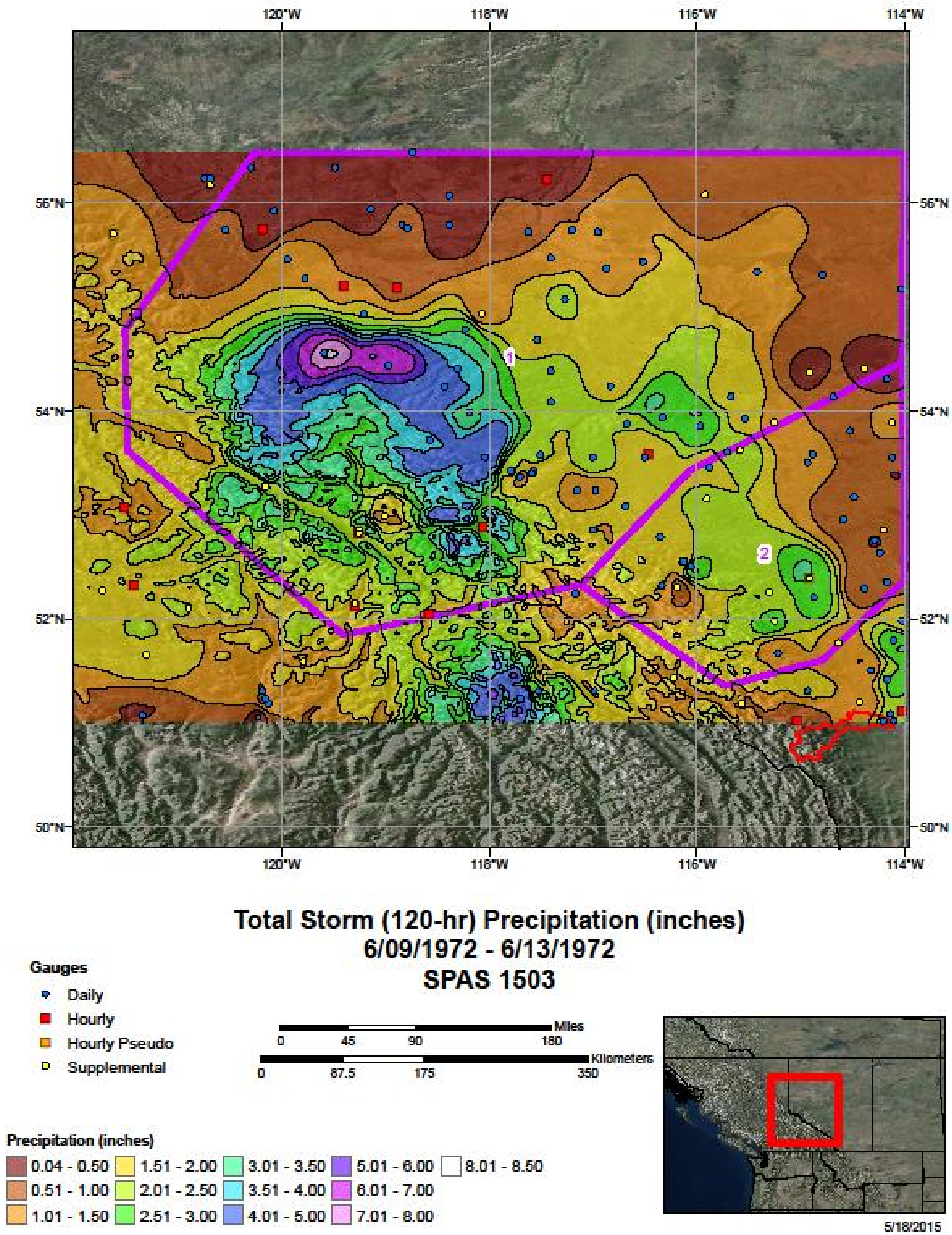

SPAS 1503 Nose Mountain, AB Storm Analysis
June 9 - 12, 1972
Storm Center
54.54 N, 119.55 W
EDS
66.0
RMH
68.5
YQF
67.0
COR
66.0
BNF
66.0
YYC
70.0
YXH
65.0
YXC
65.0
PDH
68.0
YQL
69.5
YCG
65.0
KCTB
65.0
KHVR
66.5
KGGW
70.5
KFCA
62.5
KSKA
63.5
KGFA
66.5
KLWT
69.5
KMSO
63.5
KHLN
64.5
Hysplit
Surface
850mb
700mb
Miles
0
200
400
800

Storm 1503 - June 9 (0800 UTC) - June 14 (0700 UTC), 1972															
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)															
Area (mi^2)	Duration (hours)														
	1	2	3	4	5	6	12	18	24	36	48	72	96	120	Total
0.2	0.70	1.31	1.95	2.14	2.31	2.44	3.53	4.60	5.34	7.70	8.13	8.15	8.16	8.16	8.16
1	0.70	1.30	1.95	2.14	2.31	2.43	3.53	4.48	5.31	7.70	8.13	8.14	8.16	8.16	8.16
10	0.69	1.30	1.94	2.13	2.30	2.42	3.52	4.48	5.30	7.67	8.10	8.12	8.13	8.13	8.13
25	0.69	1.29	1.93	2.12	2.28	2.41	3.50	4.47	5.27	7.62	8.05	8.07	8.08	8.08	8.08
50	0.68	1.28	1.91	2.09	2.26	2.38	3.46	4.47	5.23	7.55	7.97	7.99	8.00	8.00	8.00
100	0.67	1.26	1.86	2.05	2.21	2.33	3.40	4.33	5.09	7.40	7.78	7.78	7.85	7.86	7.86
150	0.66	1.24	1.83	2.01	2.17	2.29	3.34	4.31	4.97	7.27	7.61	7.66	7.71	7.72	7.72
200	0.64	1.21	1.79	1.97	2.12	2.24	3.28	4.30	4.93	7.14	7.51	7.52	7.59	7.60	7.60
300	0.64	1.18	1.73	1.90	2.06	2.17	3.19	4.16	4.77	6.89	7.29	7.38	7.38	7.41	7.41
400	0.63	1.14	1.67	1.84	2.03	2.11	3.11	4.15	4.62	6.74	7.18	7.24	7.25	7.27	7.27
500	0.62	1.09	1.61	1.83	2.01	2.09	3.06	4.13	4.54	6.52	7.08	7.11	7.12	7.12	7.12
1,000	0.59	1.02	1.38	1.71	1.89	2.00	2.84	3.90	4.22	6.10	6.61	6.65	6.68	6.68	6.68
2,000	0.51	0.89	1.20	1.54	1.73	1.84	2.56	3.47	3.70	5.28	5.34	5.94	5.95	6.02	6.02
5,000	0.44	0.69	0.95	1.27	1.43	1.54	2.10	2.95	3.19	4.09	4.48	4.93	4.96	5.02	5.02
10,000	0.36	0.58	0.78	1.03	1.19	1.29	1.76	2.49	2.72	3.44	3.80	4.24	4.29	4.32	4.32
20,000	0.26	0.46	0.62	0.77	0.84	1.01	1.42	2.02	2.21	2.90	2.96	3.08	3.52	3.58	3.58
50,000	0.13	0.28	0.33	0.45	0.57	0.61	0.88	1.06	1.33	1.74	2.18	2.36	2.42	2.45	2.45
71,733	0.11	0.20	0.27	0.34	0.42	0.46	0.69	0.97	1.08	1.48	1.64	1.79	1.85	1.89	1.89





SPAS 1503 Storm Center Mass Curve: Zone 1
June 9 (0800 UTC) - July 14 (0700 UTC), 1972
Lat: 54.5375 Lon: -119.5542
Incremental
Accumulated
8.16"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour
0.0
0.5
1.0
1.5
0
2
4
6
8
1
21
41
61
81
101


120°W
118°W
116°W
114°W
56°N
54°N
52°N
50°N
1
2
Total Storm (120-hr) Precipitation (inches)
6/09/1972 - 6/13/1972
SPAS 1503
Gauges
Daily
Hourly
Hourly Pseudo
Supplemental
Miles
0 45 90 180
Kilometers
0 87.5 175 350
Precipitation (inches)
0.04 - 0.50
0.51 - 1.00
1.01 - 1.50
1.51 - 2.00
2.01 - 2.50
2.51 - 3.00
3.01 - 3.50
3.51 - 4.00
4.01 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
8.01 - 8.50
5/18/2015

Pelican Mountain, AB

June 26 – July 2, 1970

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1504

General Storm Location: Pelican Mtn, Alberta

Storm Dates: June 26 - July 2, 1970

Event: Synoptic/Convective Event

DAD Zone 1

> **Latitude**: 55.5542°
>
> **Longitude**: -113.6625°
>
> **Max. Grid Rainfall Amount**: 286mm
>
> **Max. Observed Rainfall Amount**: 266mm

Number of Stations: 524 (385 Daily, 37 Hourly, 13 Hourly Pseudo, 0 Hourly Estimated Pseudo, and 89 Supplemental)

SPAS Version: 10.0

Basemap: Blended PRISM July 1961-1990 Climatology (Canada) and AL 6-70 Isohyetal

Spatial resolution: 30 second (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and AL 6-70 data. We have a good degree of confidence in the station based storm total results; the spatial pattern is dependent on the station data and a basemap. The timing is based on hourly and hourly pseudo stations.

Storm Name:	**SPAS 1504 - Pelican Mtn., AB**	
Storm Date:	**6/26 - 7/2/1970**	**Storm Adjustment Summary**
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **15-Jul**

	Lat	Long
Storm Center Location	**55.55 N**	**113.66 W**
Storm Rep Dew Point Location	**51.14 N**	**103.08 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**ESE @ 853**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**823**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**19.7 °C**	with total precipitable water above sea level of		**51**	millimeters.
The in-place maximum dew point is	**24.4 °C**	with total precipitable water above sea level of		**76**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**823**	which subtracts	**13**	millimeters of precipitable water at	**19.7 °C**
The in-place storm elevation is	**823**	which subtracts	**17**	millimeters of precipitable water at	**24.4 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.50**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: DAD values taken from SPAS 1504. Storm representative Td value was based on maximum 24-hr average Td values on June 28 - July 1, 1970. IPMF calcualted at 1.53, held to 1.50.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**18**					**85**	**141**	**156**	**181**
26 km^2 (10 mi^2)	**18**					**85**	**141**	**156**	**181**
259 km^2 (100 mi^2)	**17**					**83**	**140**	**153**	**179**
518 km^2 (200 mi^2)	**17**					**82**	**138**	**150**	**176**
1,295 km^2 (500 mi^2)	**17**					**76**	**131**	**141**	**170**
2,590 km^2 (1,00 mi^2)	**16**					**72**	**124**	**131**	**167**
5,180 km^2 (2,000 mi^2)	**14**					**65**	**113**	**123**	**158**
12.950 km^2 (5000 mi^2)	**11**					**54**	**91**	**112**	**137**
25,900 km^2 (10,000 mi^2)	**9**					**45**	**80**	**100**	**120**
51,800 km^2 (20,000 mi^2)	**7**					**36**	**62**	**84**	**99**

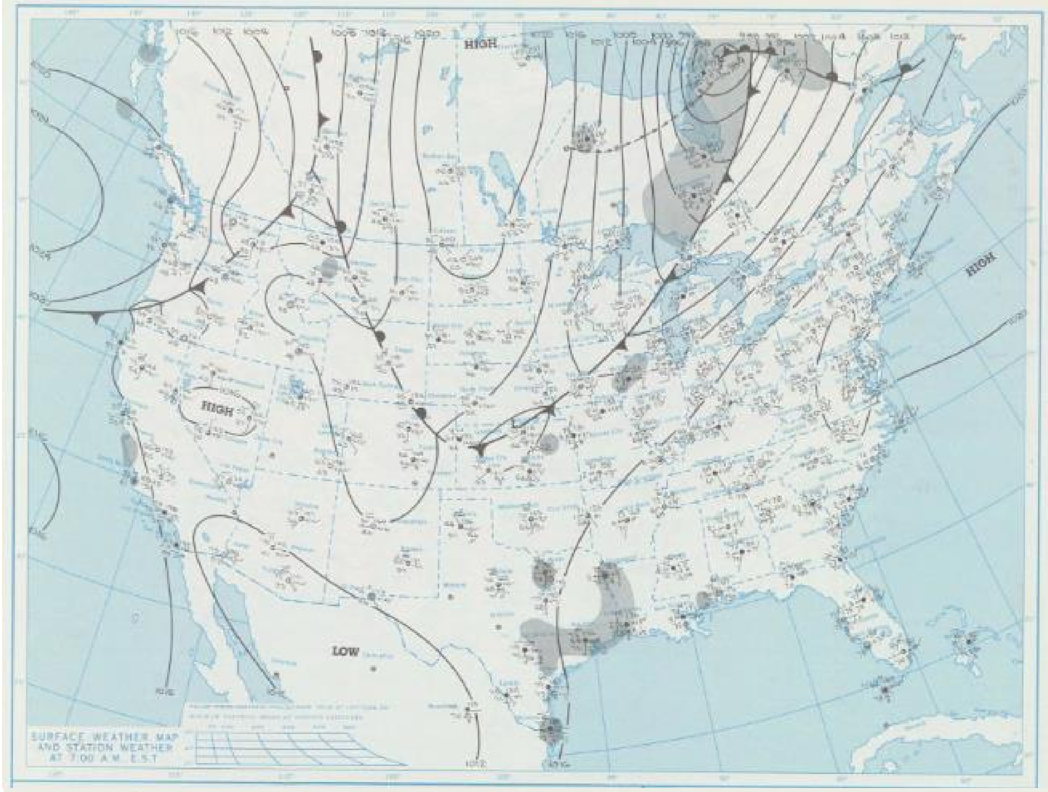
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***

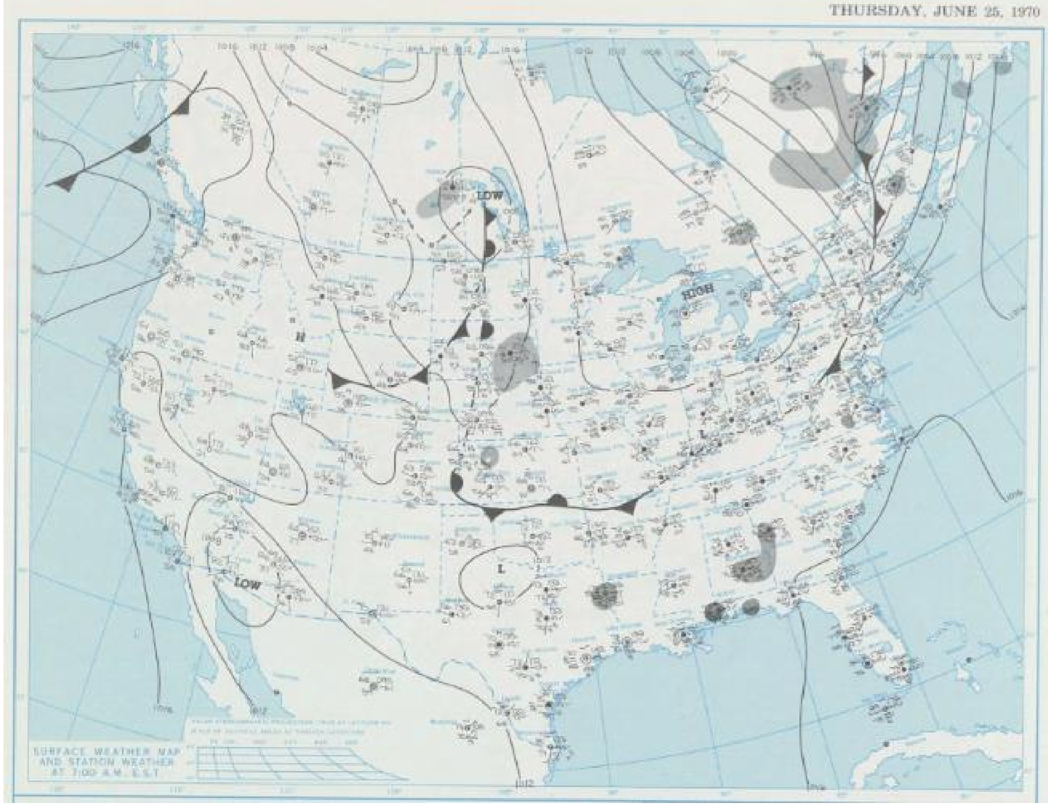
Storm or Storm Center Name	**SPAS 1504 - Pelican Mtn., AB**	
Storm Date(s)	6/26 - 7/2/1970	
Storm Type	Synoptic	
Storm Location	55.55 N	113.66 W
Storm Center Elevation	823	meters
Precipitation Total & Duration	286	millimeters
Storm Representative Dew Point	19.7 °C	24
Storm Representative Dew Point Location	51.14 N	103.08 W
Maximum Dew Point	24.4 °C	
Moisture Inflow Vector	ESE @ 853	kilometers
In-place Maximization Factor	**1.50**	
Temporal Transposition (Date)	15-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

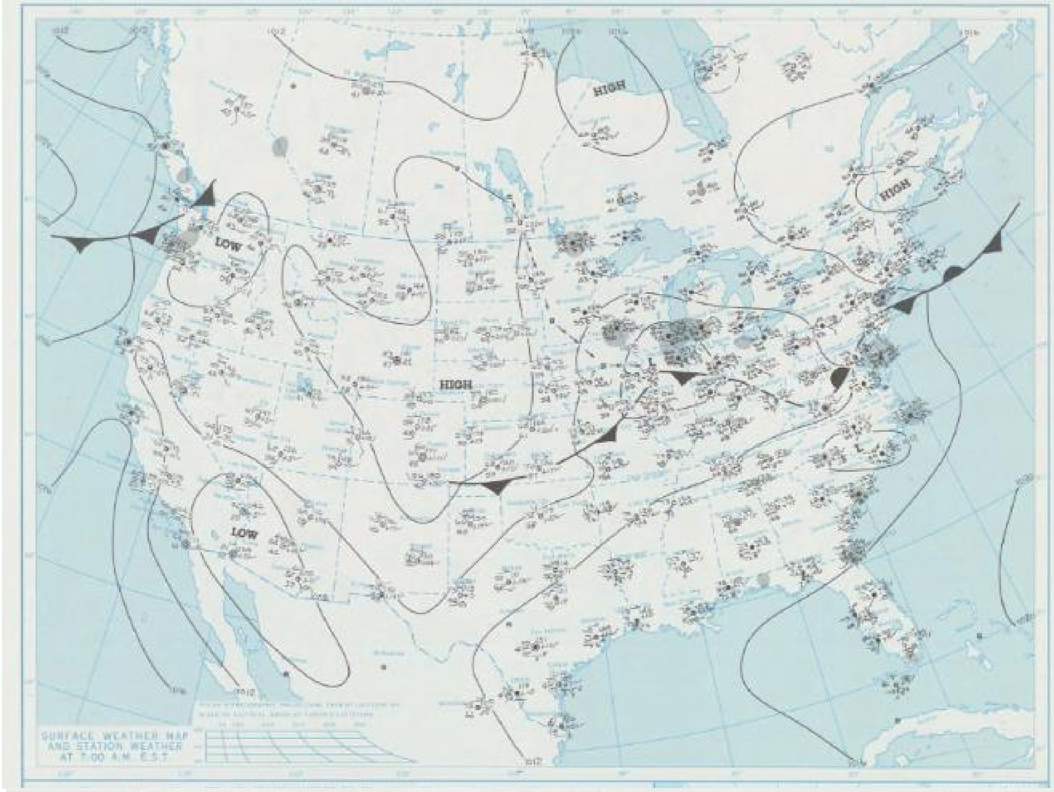
WEDNESDAY, JUNE 24, 1970



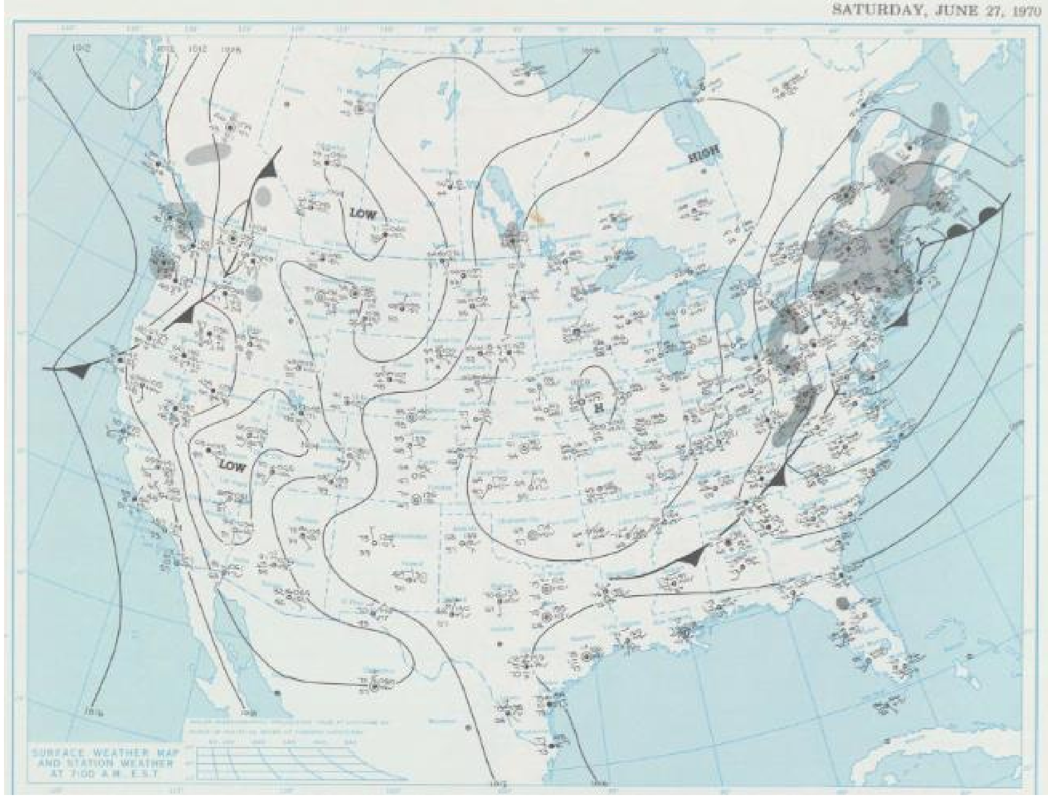
THURSDAY, JUNE 25, 1970



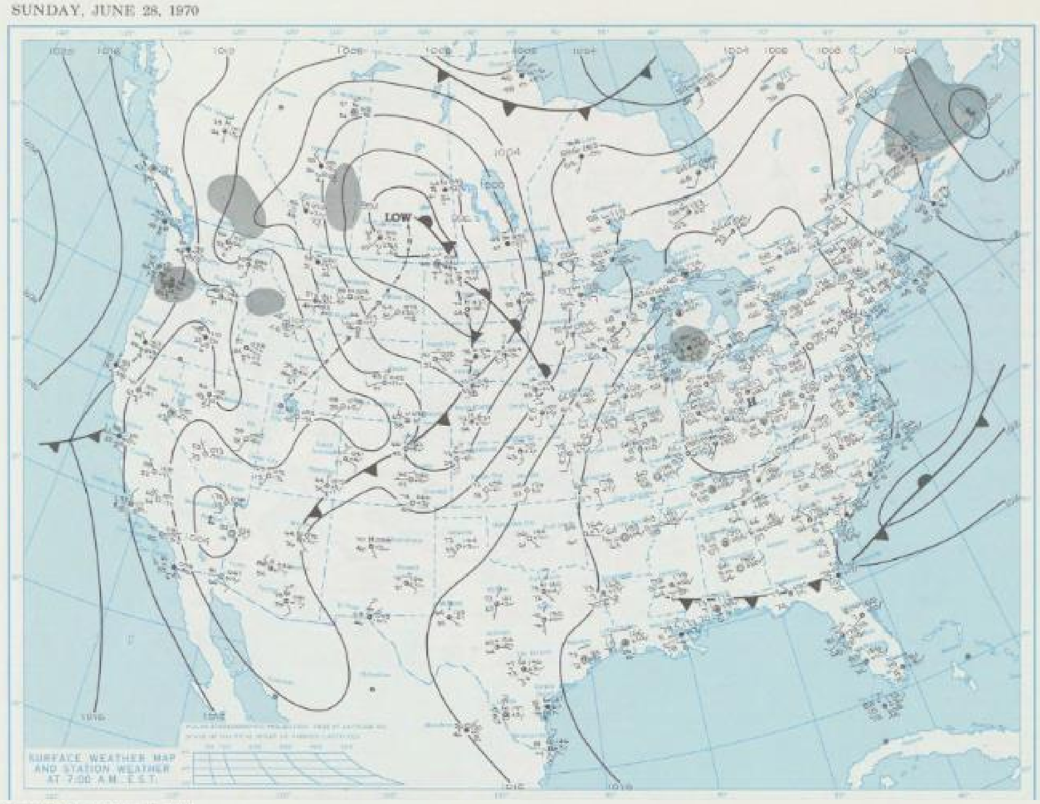
FRIDAY, JUNE 26, 1970



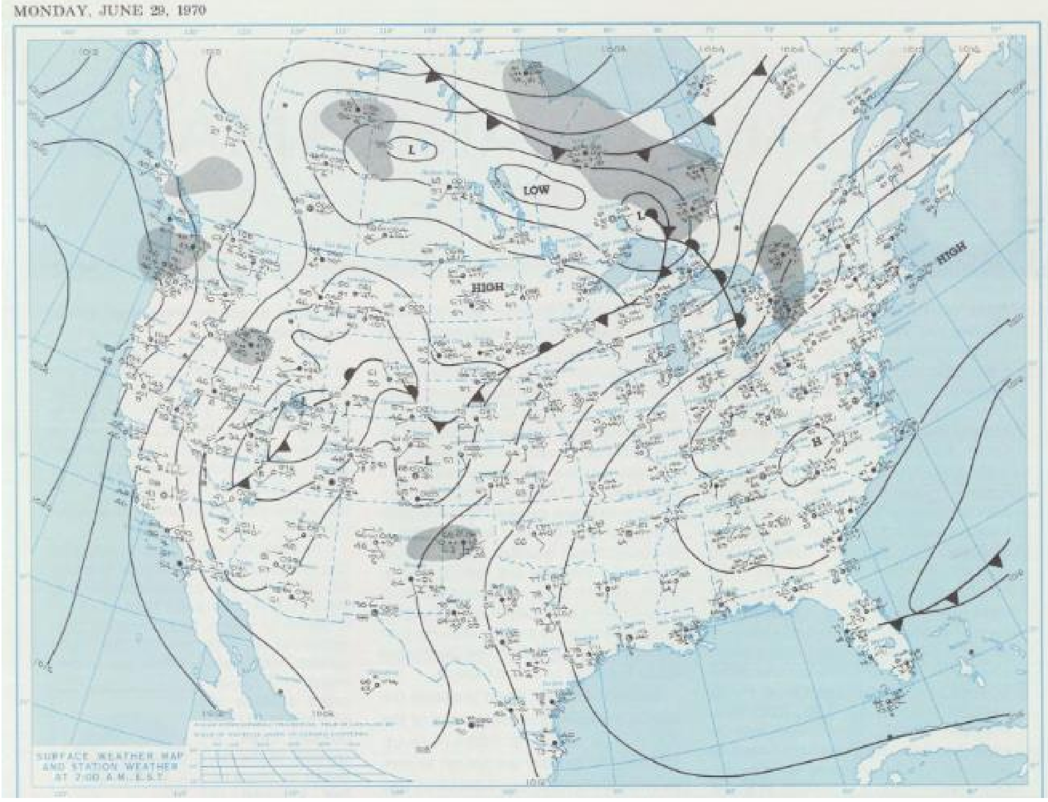
SATURDAY, JUNE 27, 1970



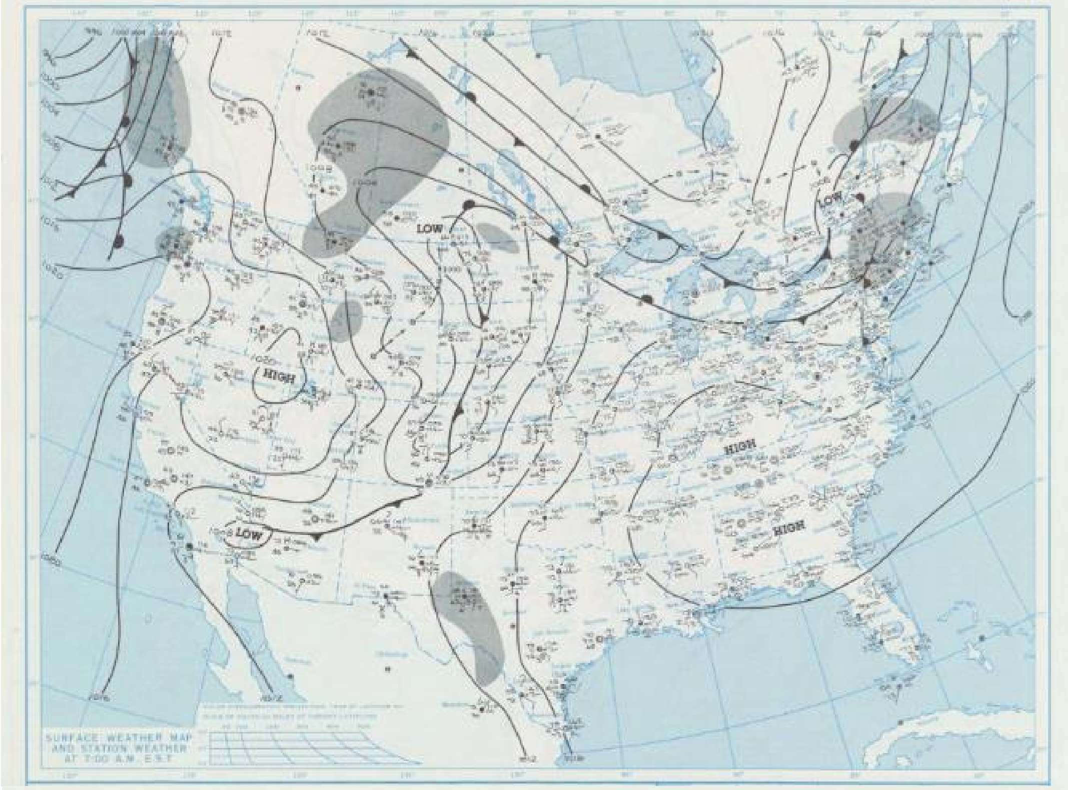
SUNDAY, JUNE 28, 1970



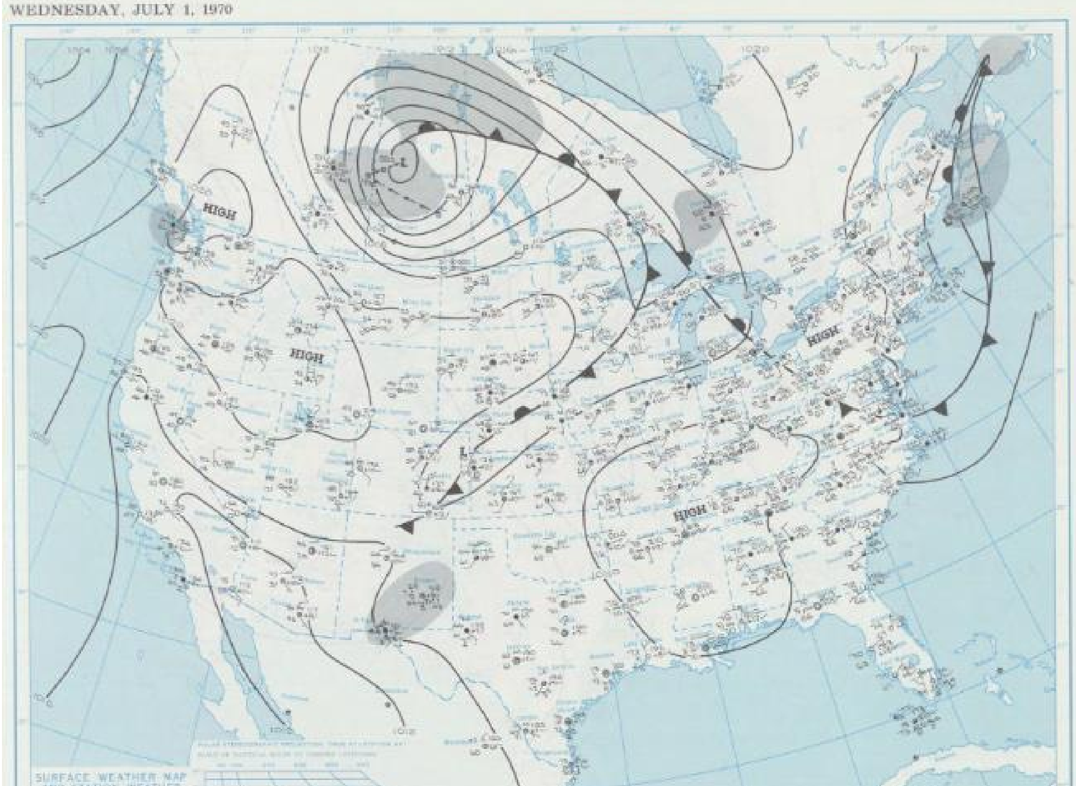
MONDAY, JUNE 29, 1970

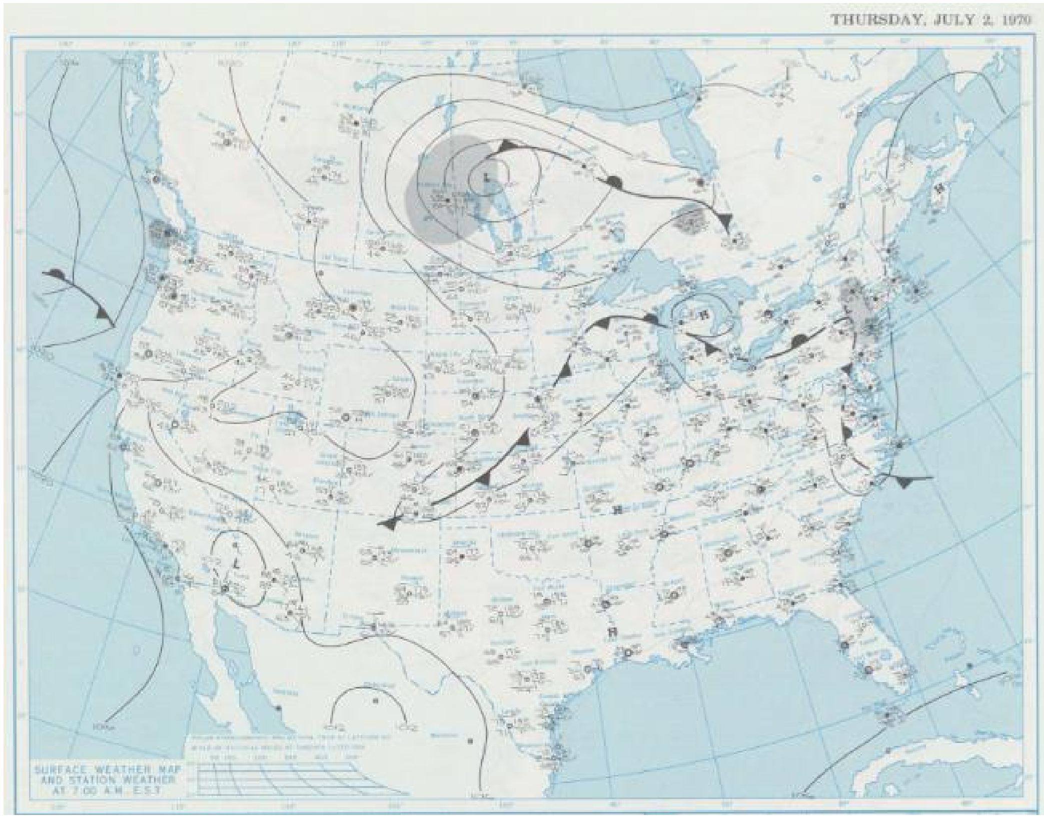


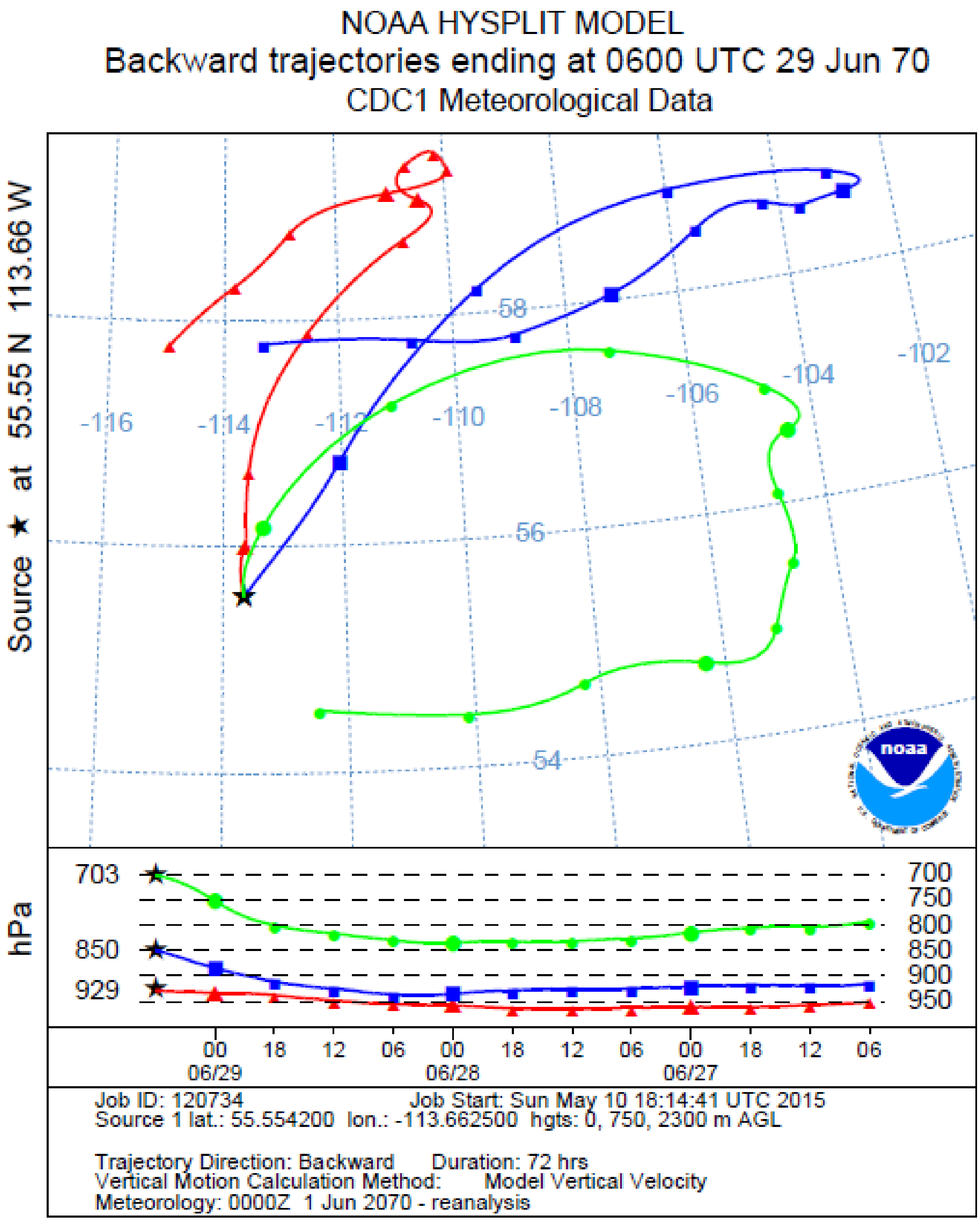
TUESDAY, JUNE 30, 1970



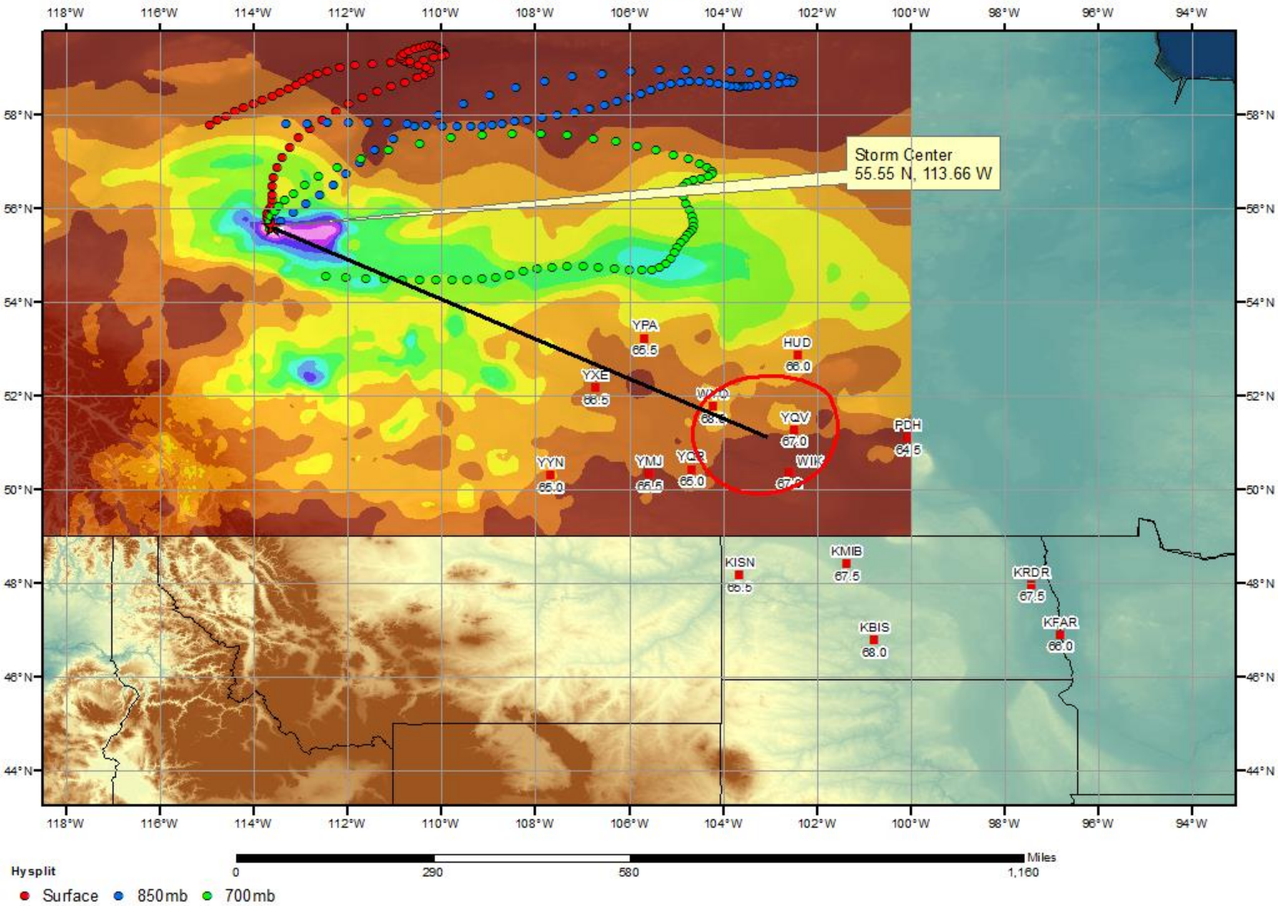
WEDNESDAY, JULY 1, 1970



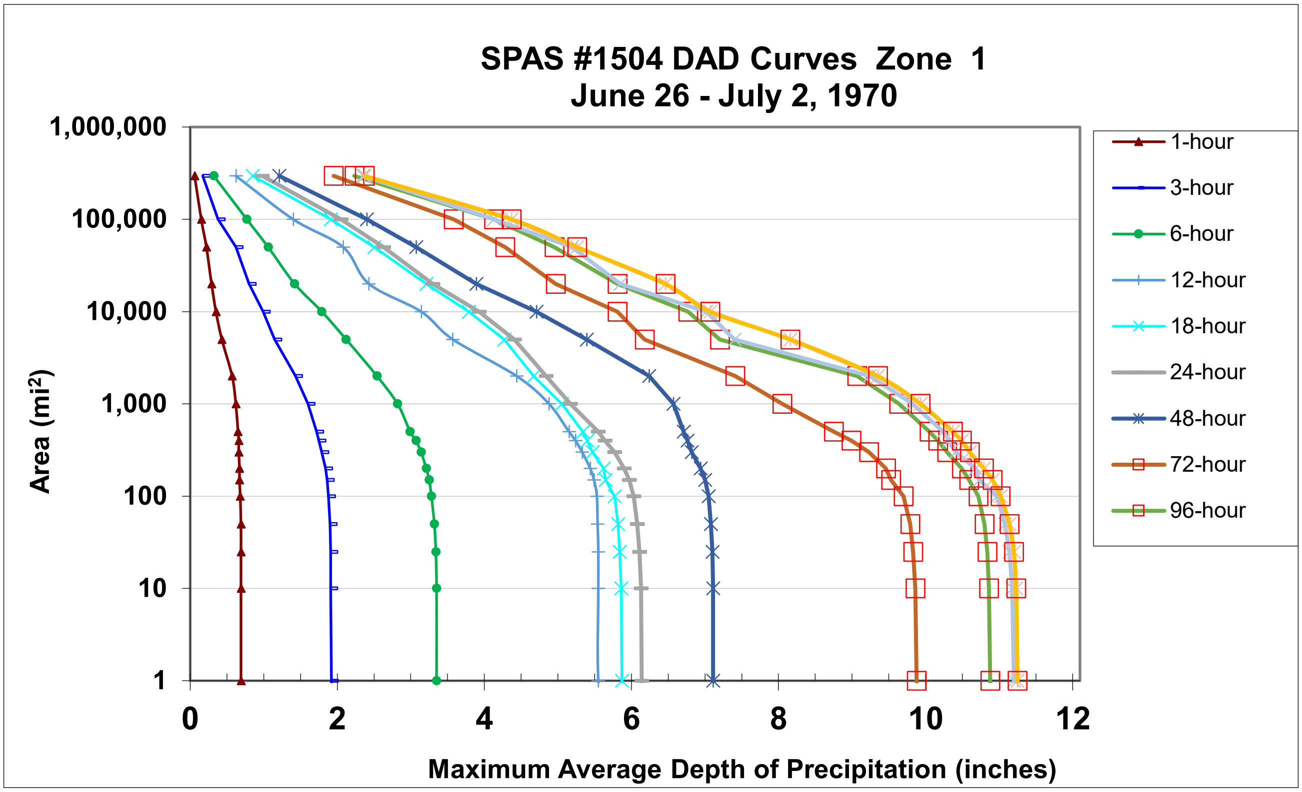

THURSDAY, JULY 2, 1970
SURFACE WEATHER MAP
AND STATION WEATHER
AT 7:00 A.M., E.S.T.

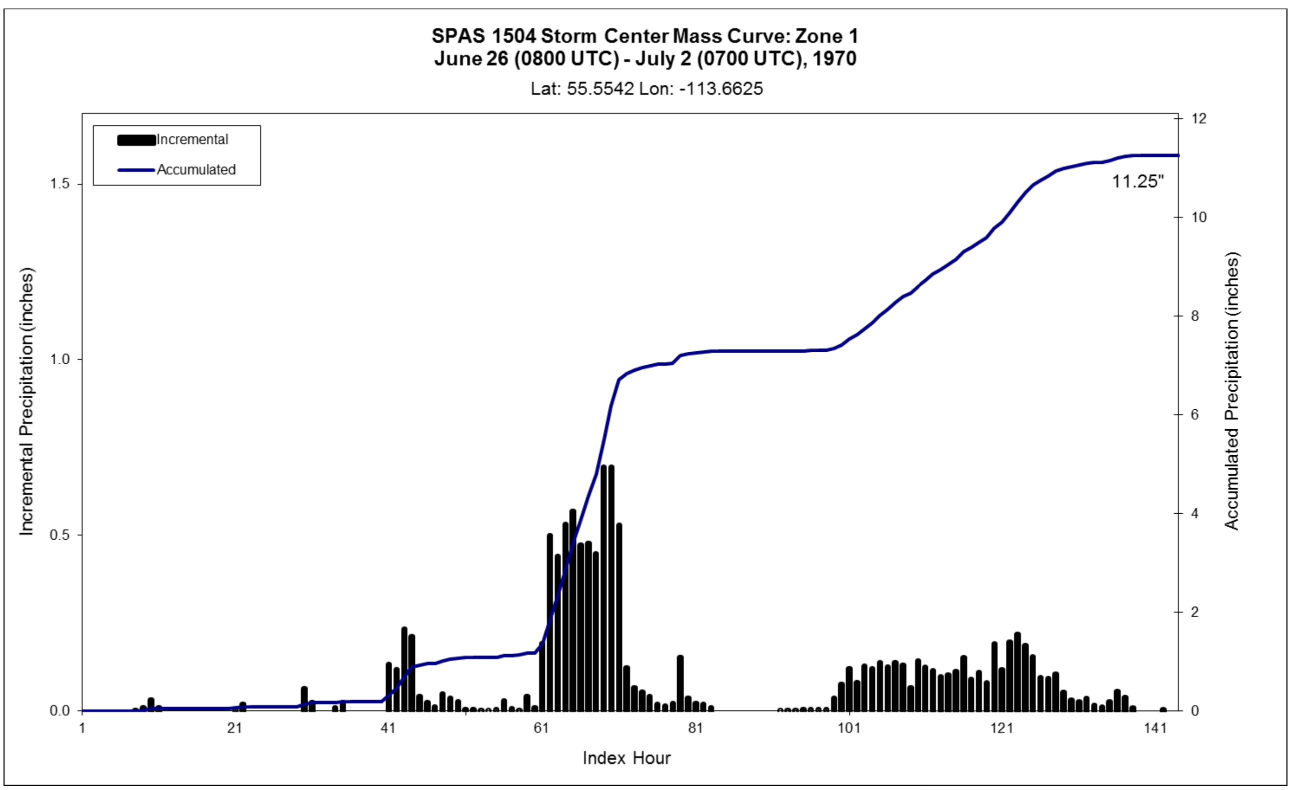

NOAA HYSPLIT MODEL
Backward trajectories ending at 0600 UTC 29 Jun 70
CDC1 Meteorological Data
Source ★ at 55.55 N 113.66 W
-116
-114
-112
-110
-108
-106
-104
-102
58
56
54
noaa
hPa
703
850
929
700
750
800
850
900
950
00 18 12 06 00 18 12 06 00 18 12 06
06/29
06/28
06/27
Job ID: 120734 Job Start: Sun May 10 18:14:41 UTC 2015
Source 1 lat.: 55.554200 lon.: -113.662500 hgts: 0, 750, 2300 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jun 2070 - reanalysis

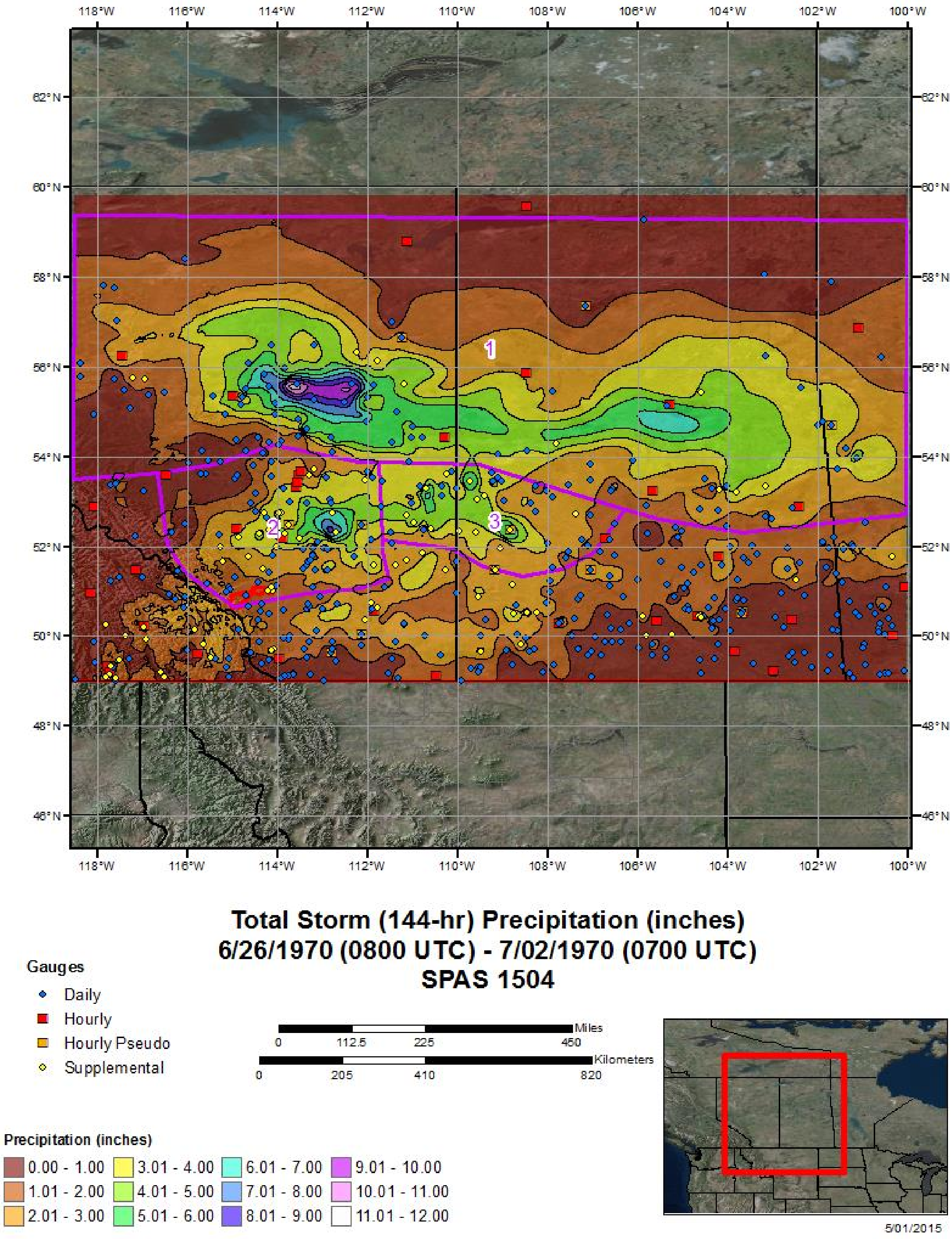
SPAS 1504 Pelican Mtn, AB Storm Analysis
June 28 - July 1, 1970



Storm 1504 - June 26 (0800 UTC) - July 2 (0700 UTC), 1970												
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)												
Area (mi^2)	Duration (hours)											
	1	3	6	12	18	24	48	72	96	120	144	Total
0.2	0.69	1.92	3.35	5.67	5.89	6.16	7.22	9.92	10.95	11.20	11.25	11.25
1	0.69	1.92	3.35	5.55	5.87	6.14	7.11	9.88	10.88	11.20	11.25	11.25
10	0.69	1.91	3.35	5.55	5.86	6.13	7.11	9.86	10.86	11.18	11.23	11.23
25	0.69	1.91	3.34	5.55	5.84	6.11	7.10	9.83	10.84	11.14	11.20	11.20
50	0.69	1.90	3.32	5.54	5.82	6.08	7.08	9.79	10.80	11.08	11.14	11.14
100	0.68	1.88	3.28	5.53	5.77	6.03	7.05	9.70	10.72	10.97	11.02	11.02
150	0.67	1.86	3.25	5.49	5.65	5.97	7.00	9.53	10.59	10.73	10.91	10.91
200	0.67	1.84	3.21	5.44	5.62	5.90	6.94	9.46	10.49	10.68	10.79	10.79
300	0.66	1.79	3.14	5.33	5.47	5.77	6.82	9.23	10.29	10.41	10.60	10.60
400	0.66	1.75	3.07	5.24	5.40	5.64	6.76	8.99	10.17	10.32	10.49	10.49
500	0.65	1.72	2.99	5.15	5.34	5.55	6.71	8.75	10.05	10.24	10.37	10.37
1,000	0.62	1.60	2.82	4.88	5.05	5.17	6.57	8.05	9.64	9.82	9.93	9.93
2,000	0.57	1.43	2.54	4.44	4.67	4.84	6.24	7.41	9.07	9.24	9.35	9.35
5,000	0.43	1.15	2.12	3.57	4.27	4.41	5.39	6.18	7.20	7.40	8.16	8.16
10,000	0.35	0.99	1.79	3.14	3.79	3.93	4.71	5.81	6.77	7.02	7.07	7.07
20,000	0.29	0.80	1.42	2.43	3.21	3.30	3.89	4.97	5.81	5.85	6.46	6.46
50,000	0.22	0.62	1.06	2.08	2.50	2.63	3.07	4.28	4.95	5.19	5.26	5.26
100,000	0.15	0.38	0.77	1.40	1.91	2.05	2.40	3.58	4.13	4.13	4.37	4.37
295,706	0.06	0.17	0.32	0.62	0.85	0.98	1.21	1.95	2.23	2.35	2.37	2.37


SPAS #1504 DAD Curves Zone 1
June 26 - July 2, 1970
Area (mi²)
1,000,000
100,000
10,000
1,000
100
10
1
0
2
4
6
8
10
12
Maximum Average Depth of Precipitation (inches)
1-hour
3-hour
6-hour
12-hour
18-hour
24-hour
48-hour
72-hour
96-hour


SPAS 1504 Storm Center Mass Curve: Zone 1
June 26 (0800 UTC) - July 2 (0700 UTC), 1970
Lat: 55.5542 Lon: -113.6625
Incremental
Accumulated
11.25"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour


118°W
116°W
114°W
112°W
110°W
108°W
106°W
104°W
102°W
100°W
62°N
60°N
58°N
56°N
54°N
52°N
50°N
48°N
46°N
1
2
3
Total Storm (144-hr) Precipitation (inches)
6/26/1970 (0800 UTC) - 7/02/1970 (0700 UTC)
SPAS 1504
Gauges
Daily
Hourly
Hourly Pseudo
Supplemental
Miles
0
112.5
225
450
Kilometers
0
205
410
820
Precipitation (inches)
0.00 - 1.00
1.01 - 2.00
2.01 - 3.00
3.01 - 4.00
4.01 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
8.01 - 9.00
9.01 - 10.00
10.01 - 11.00
11.01 - 12.00
5/01/2015

Pekisko, AB

June 19-30, 1969

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1505

General Storm Location: Pekisko, Alberta

Storm Dates: June 19 - June 30, 1969

Event: Synoptic Event

DAD Zone 1

- **Latitude**: 50.2375°
- **Longitude**: -114.2708°
- **Max. Grid Rainfall Amount**: 257mm
- **Max. Observed Rainfall Amount**: 255mm

DAD Zone 2 (UNRELIABLE TIMING)

- **Latitude**: 49.0958°
- **Longitude**: -115.0125°
- **Max. Grid Rainfall Amount**: 191mm
- **Max. Observed Rainfall Amount**: 165mm

Number of Stations: 272 (187 Daily, 18 Hourly, 18 Hourly Pseudo, 0 Hourly Estimated Pseudo, and 49 Supplemental)

SPAS Version: 10.0

Basemap: Blended PRISM June 1961-1990 Climatology (Canada) and AL 6-69 Isohyetal

Spatial resolution: 30 second (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and AL 6-69 data. We have a good degree of confidence in the station based storm total results, the spatial pattern is dependent on the station data and a basemap. The timing is based on hourly and hourly pseudo stations. *** The timing in DAD Zone 2 is unreliable, do not recommend using DAD 2 for further PMP calculations.

Storm Name:	**SPAS 1505 - Pekisko, AB Zone 1**
Storm Date:	**6/19-30/1969**
AWA Analysis Date:	**7/20/2015**

Storm Adjustment Summary

Temporal Transposition Date **10-Jul**

	Lat	Long
Storm Center Location	**50.24 N**	**114.27 W**
Storm Rep Dew Point Location	**43.50 N**	**107.40 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**SE @ 941**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**1,494**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**16.1 °C**	with total precipitable water above sea level of		**37**	millimeters.
The in-place maximum dew point is	**22.8 °C**	with total precipitable water above sea level of		**66**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**1,494**	which subtracts	**17**	millimeters of precipitable water at	**16.1 °C**
The in-place storm elevation is	**1,494**	which subtracts	**25**	millimeters of precipitable water at	**22.8 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.50**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Storm representative Td was based on the 24hr average Td from KCPR, KLND and KSHR on June 22-23, 1969. The in-place maximization factor is capped at 1.50

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)									
26 km^2 (10 mi^2)	**18**					**43**	**71**	**92**	**107**
259 km^2 (100 mi^2)	**17**					**41**	**68**	**88**	**101**
518 km^2 (200 mi^2)	**17**					**39**	**65**	**84**	**97**
1,295 km^2 (500 mi^2)	**16**					**34**	**55**	**70**	**93**
2,590 km^2 (1,00 mi^2)	**14**					**32**	**46**	**65**	**90**
5,180 km^2 (2,000 mi^2)	**12**					**28**	**43**	**57**	**85**
12.950 km^2 (5000 mi^2)	**8**					**24**	**36**	**48**	**77**
25,900 km^2 (10,000 mi^2)	**6**					**21**	**30**	**42**	**66**
51,800 km^2 (20,000 mi^2)	**4**					**16**	**25**	**37**	**58**

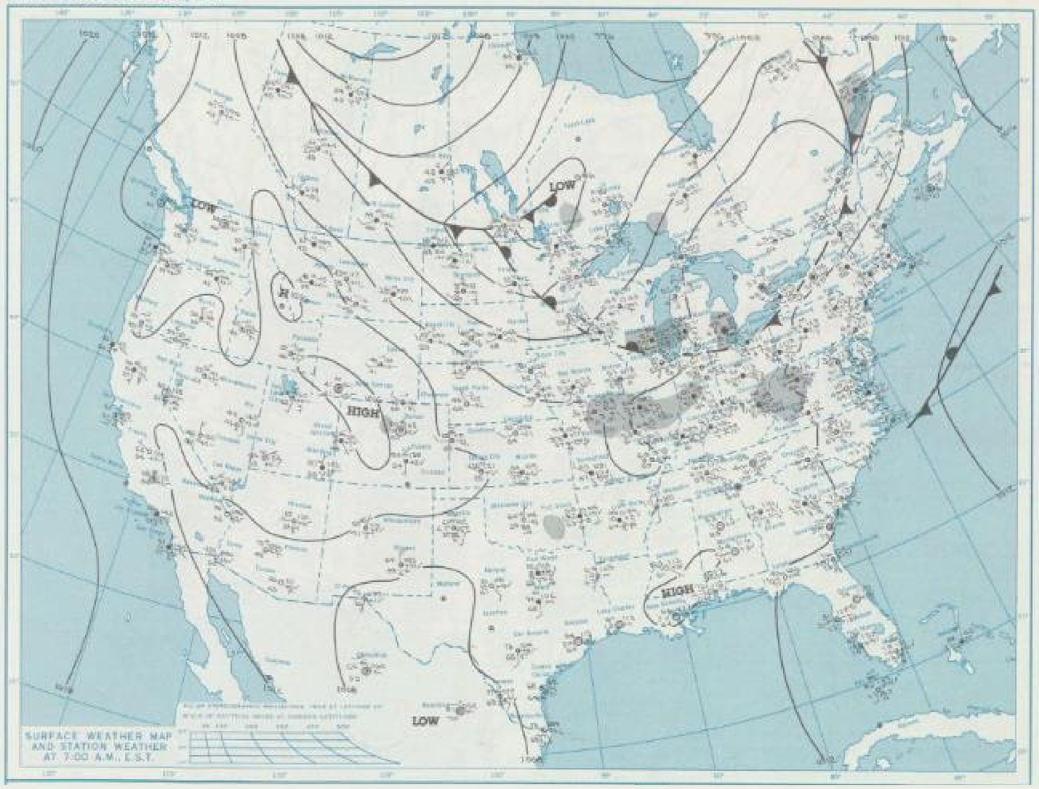
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)									
26 km2 (10 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***					**N/A***	**N/A***	**N/A***	**N/A***

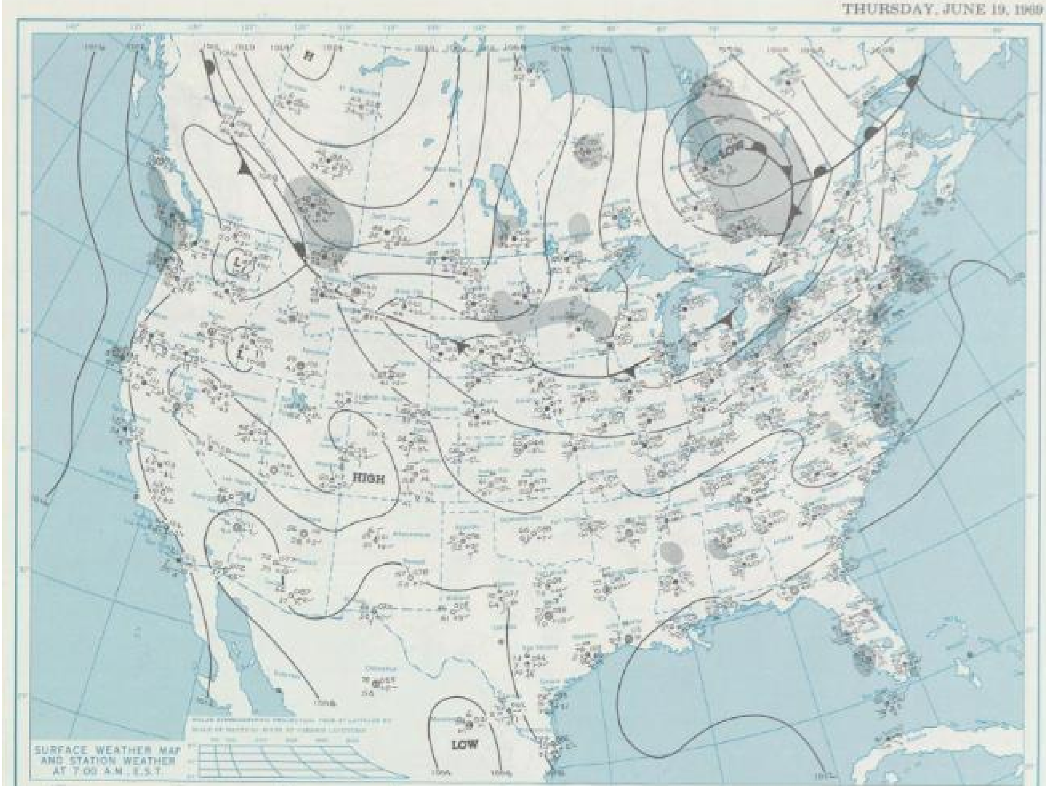
Storm or Storm Center Name	**SPAS 1505 - Pekisko, AB Zone 1**		
Storm Date(s)	6/19-30/1969		
Storm Type	Synoptic		
Storm Location	50.24 N	114.27 W	
Storm Center Elevation	1,494	meters	
Precipitation Total & Duration	257	millimeters	
Storm Representative Dew Point	16.1 °C		24
Storm Representative Dew Point Location	43.50 N	107.40 W	
Maximum Dew Point	22.8 °C		
Moisture Inflow Vector	SE @ 941	kilometers	
In-place Maximization Factor	**1.50**		
Temporal Transposition (Date)	10-Jul		
Transposition Dew Point Location	N/A*	N/A*	
Transposition Maximum Dew Point	N/A*		
Transposition Adjustment Factor	N/A*		
Average Basin Elevation	N/A*		
Barrier Adjustment Factor	N/A*		
Total Adjustment Factor	**N/A***		

*Variable dependent on transposition location

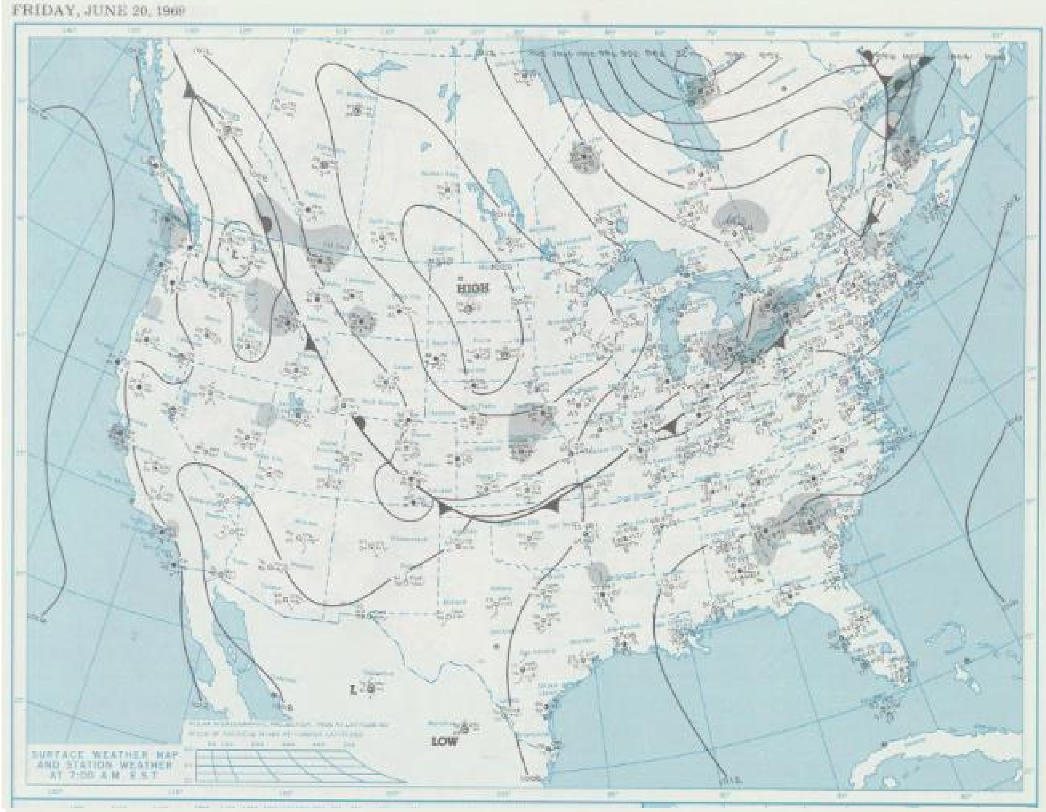
WEDNESDAY, JUNE 18, 1969



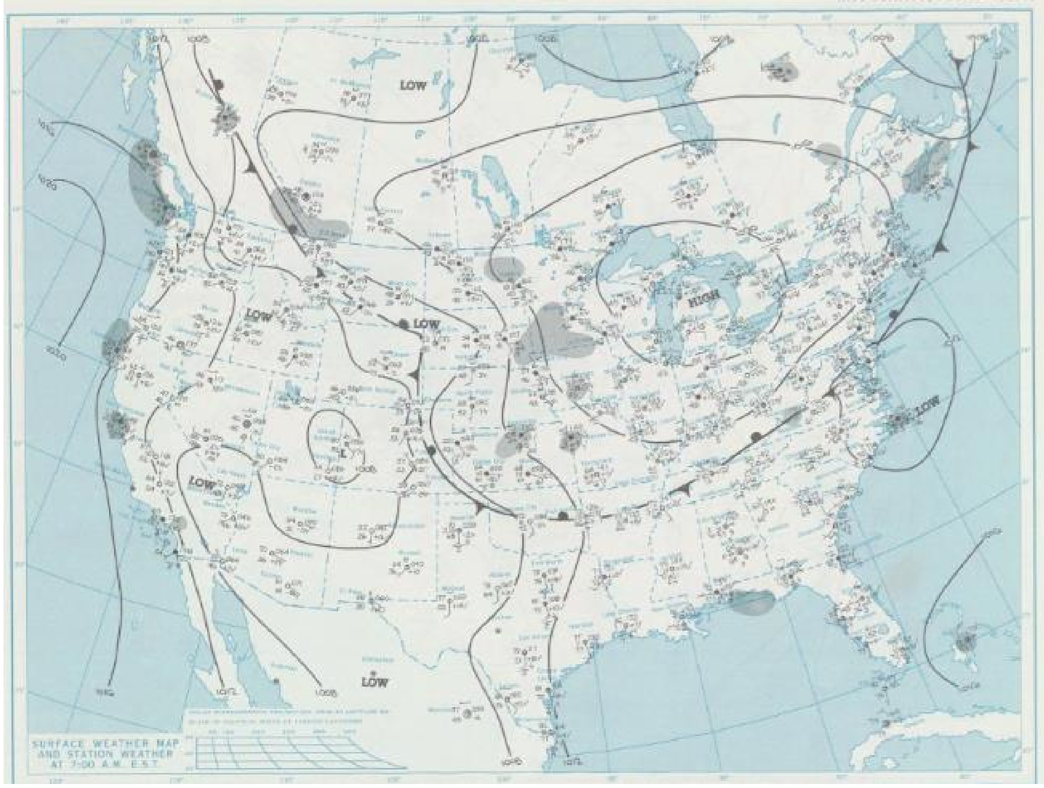
THURSDAY, JUNE 19, 1969



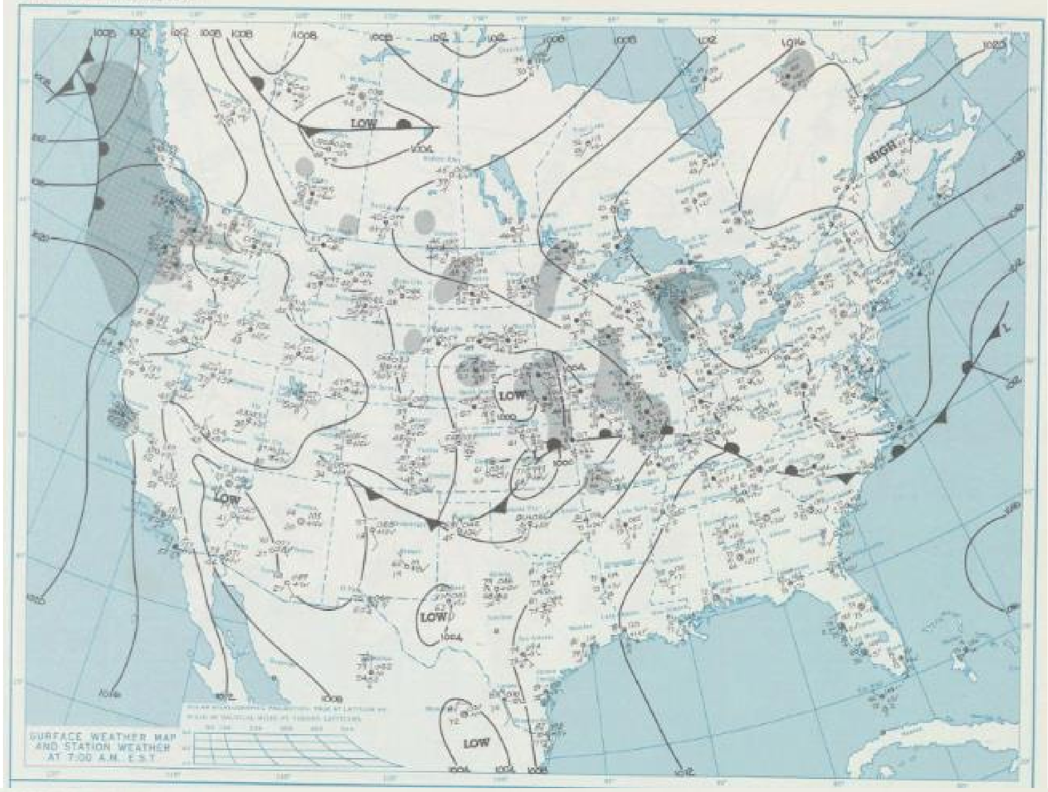
FRIDAY, JUNE 20, 1969



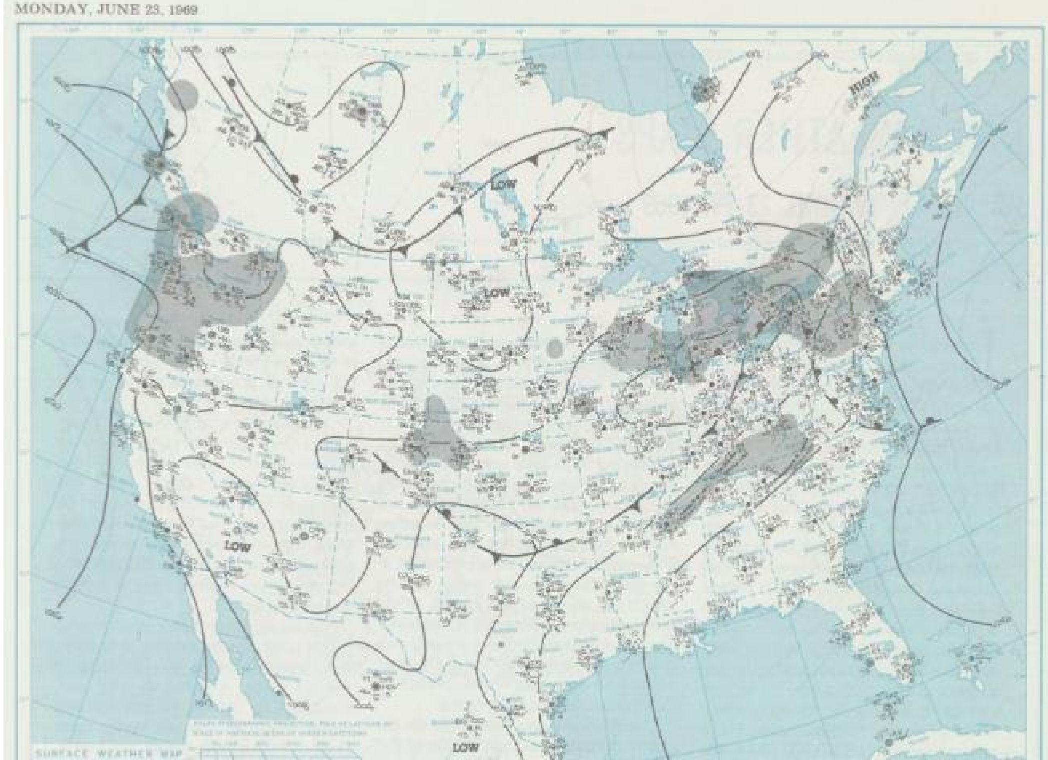
SATURDAY, JUNE 21, 1969



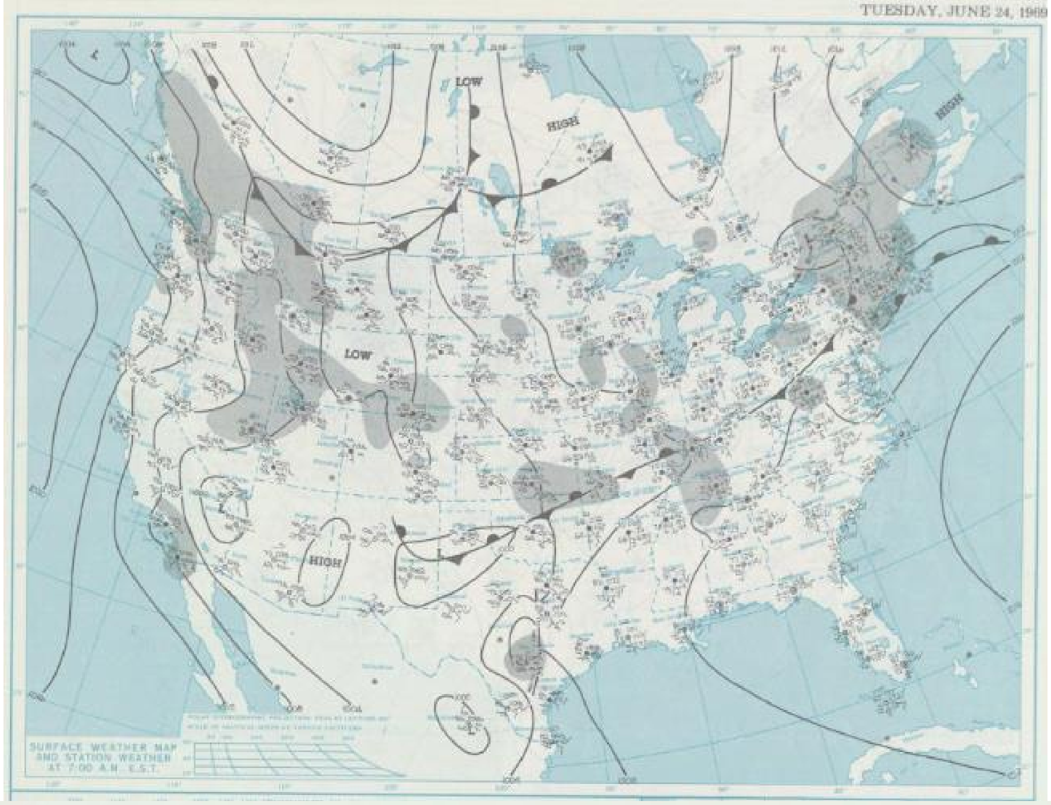
SUNDAY, JUNE 22, 1969



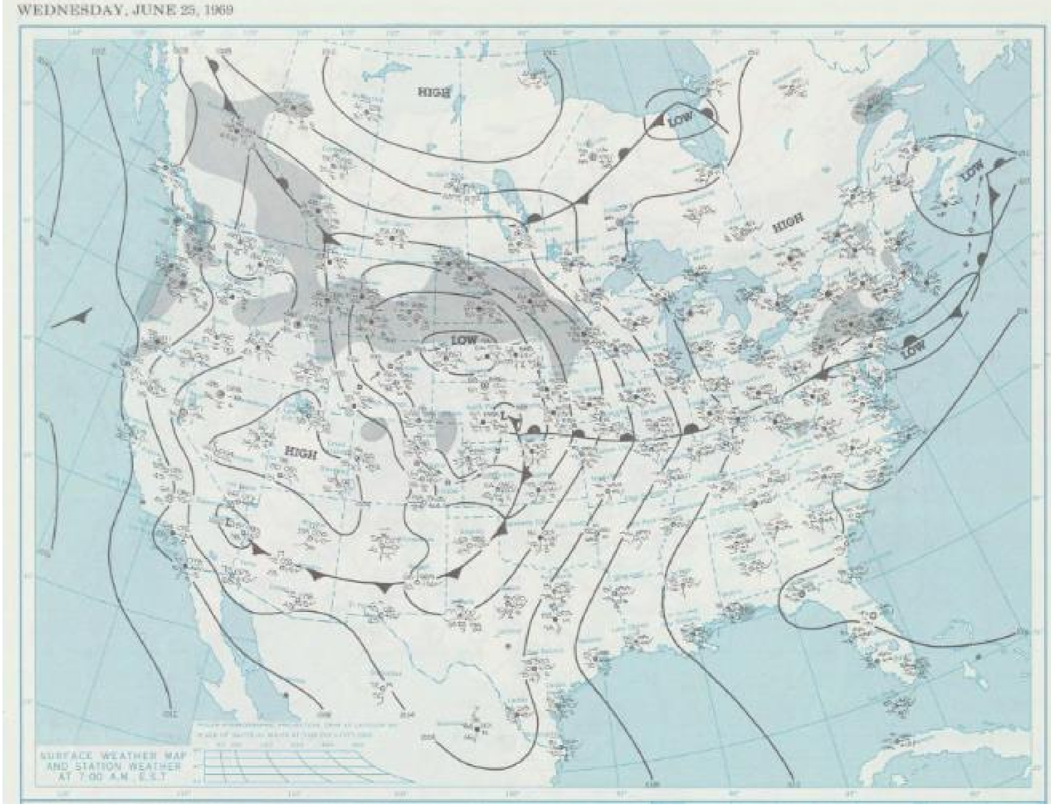
MONDAY, JUNE 23, 1969



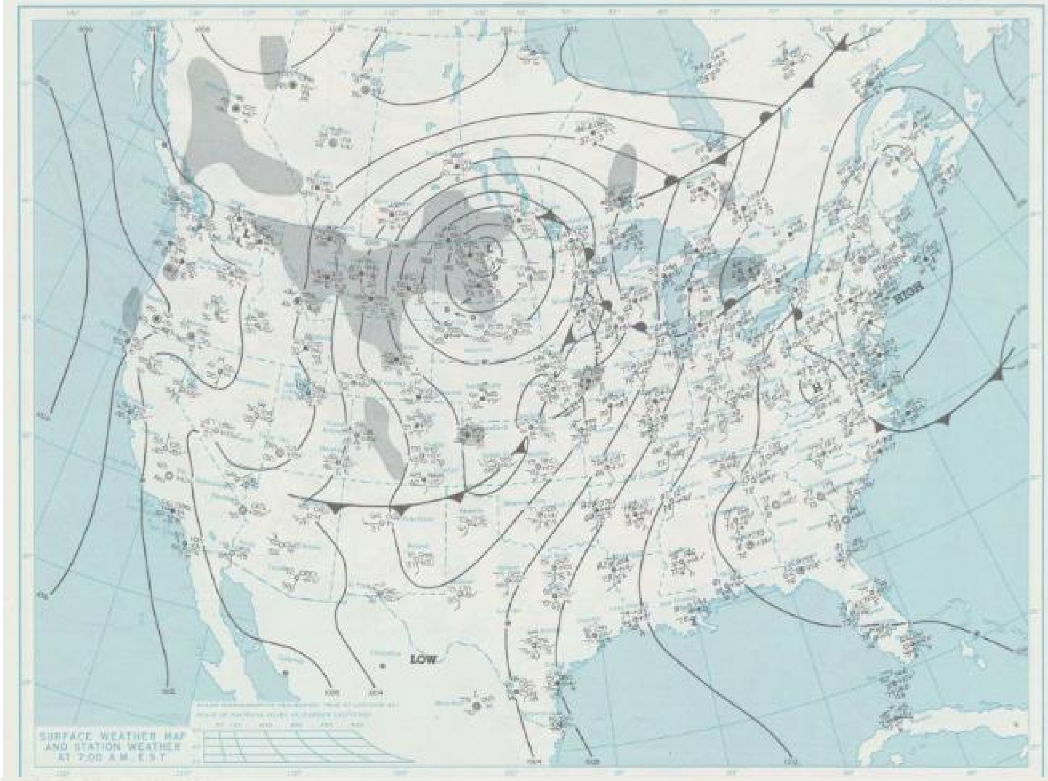
TUESDAY, JUNE 24, 1969



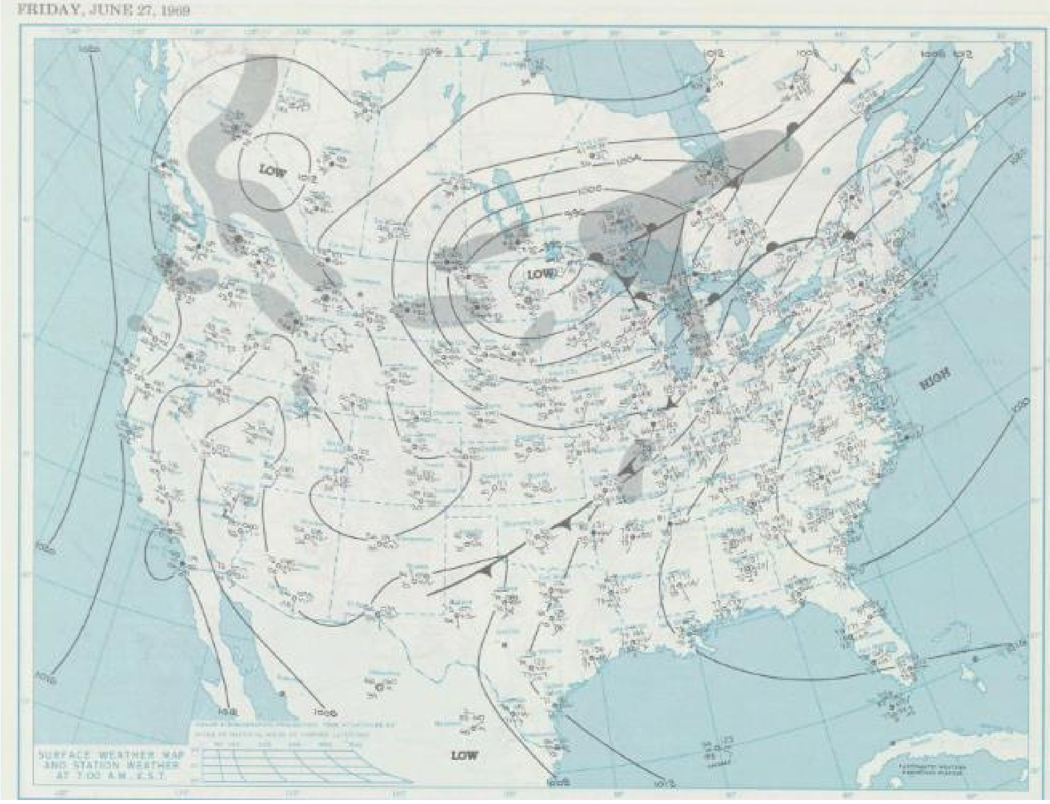
WEDNESDAY, JUNE 25, 1969



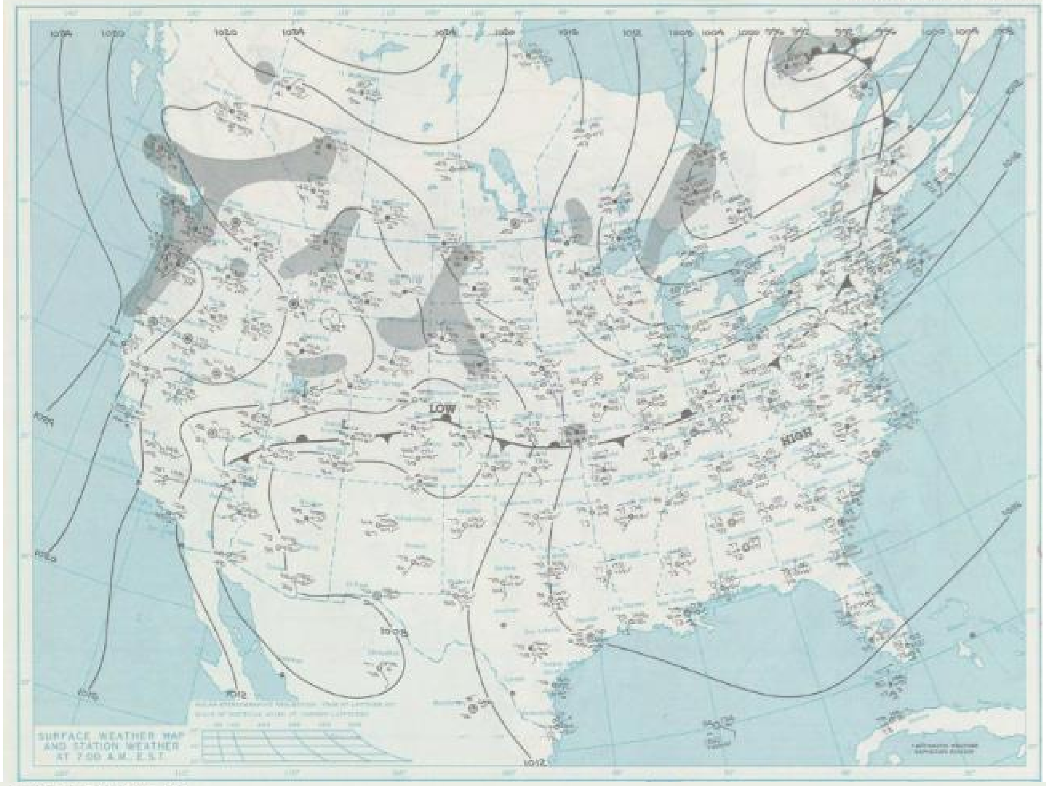
THURSDAY, JUNE 26, 1969



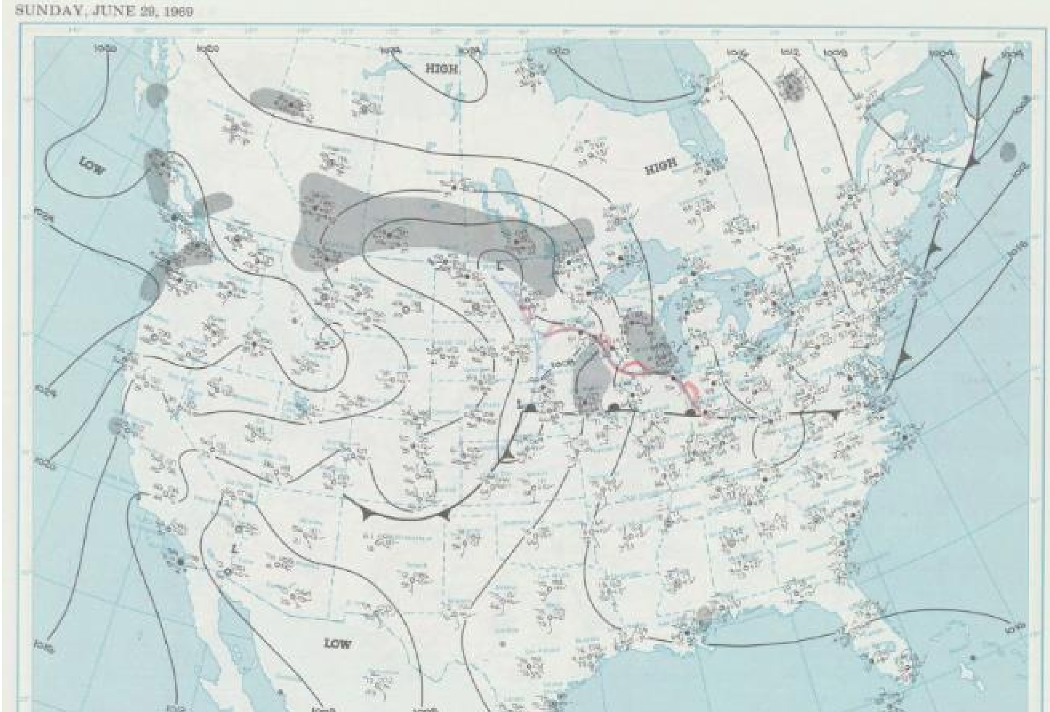
FRIDAY, JUNE 27, 1969



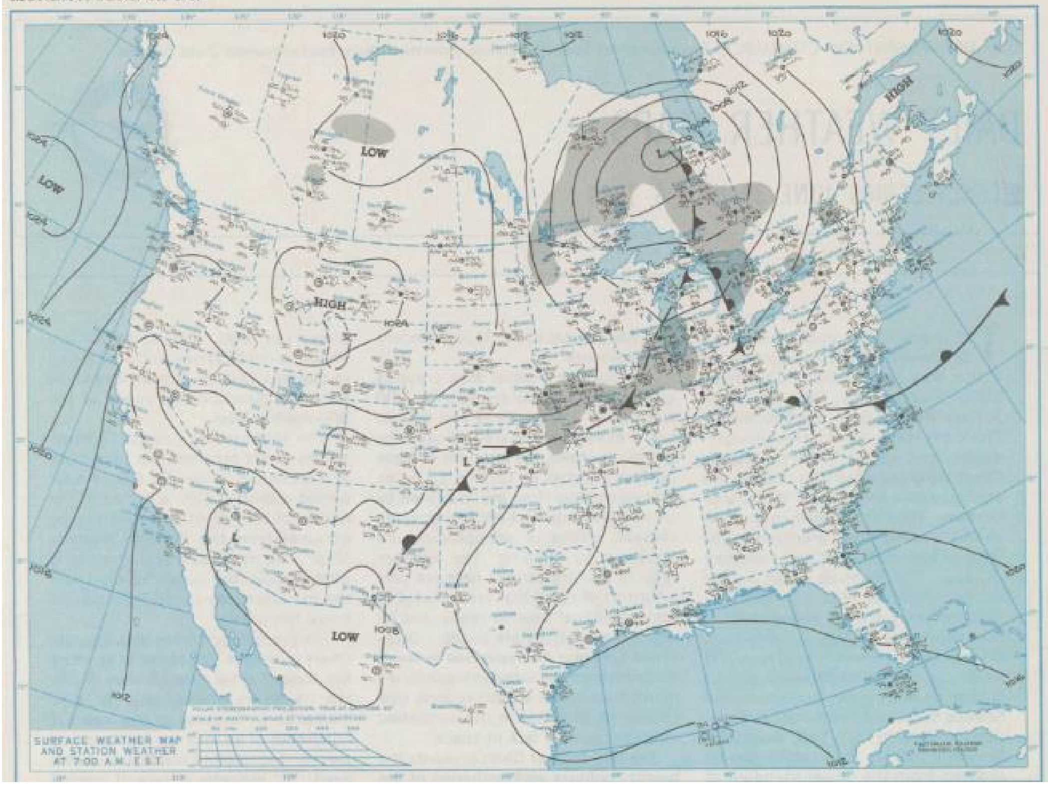
SATURDAY, JUNE 28, 1969

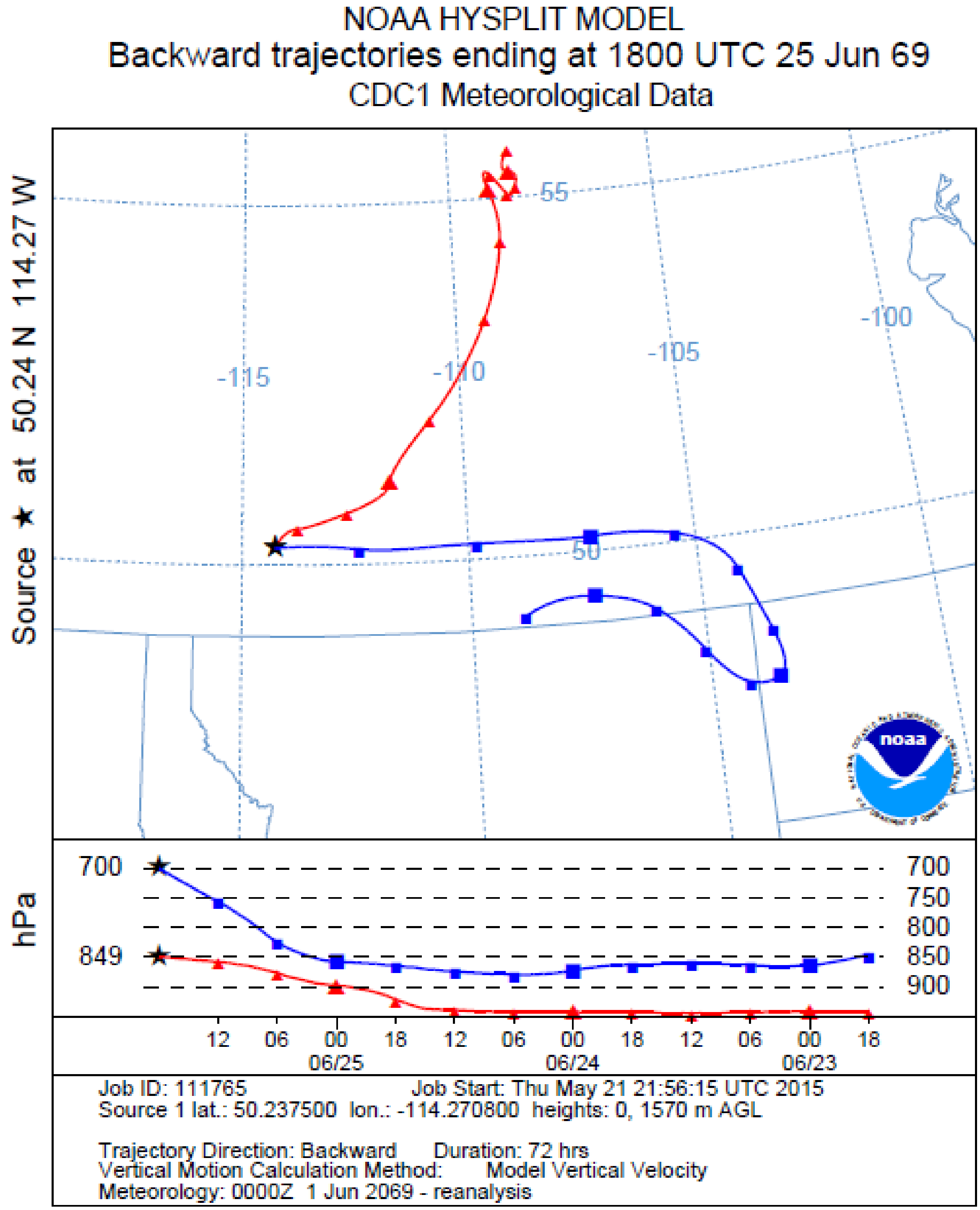


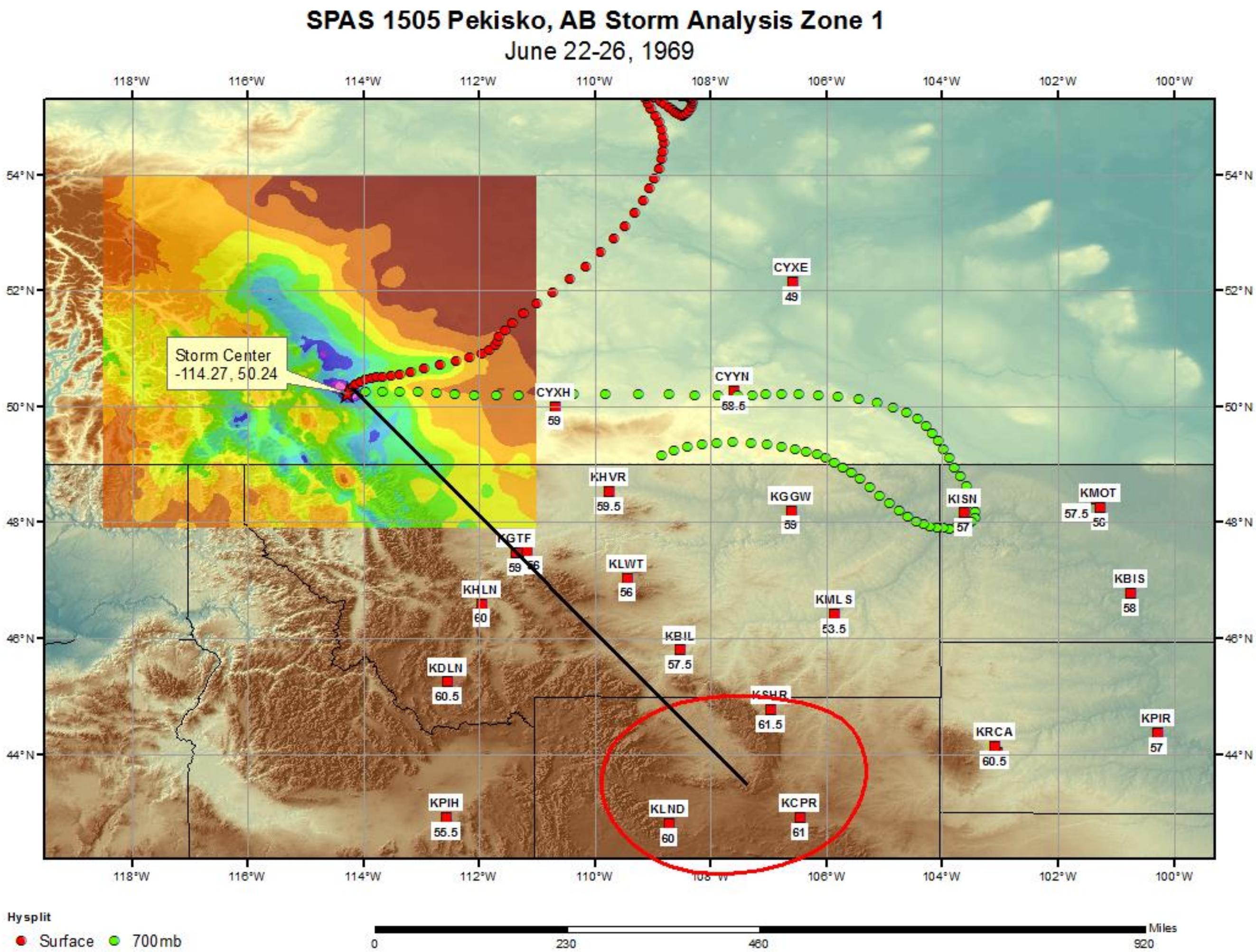
SUNDAY, JUNE 29, 1969



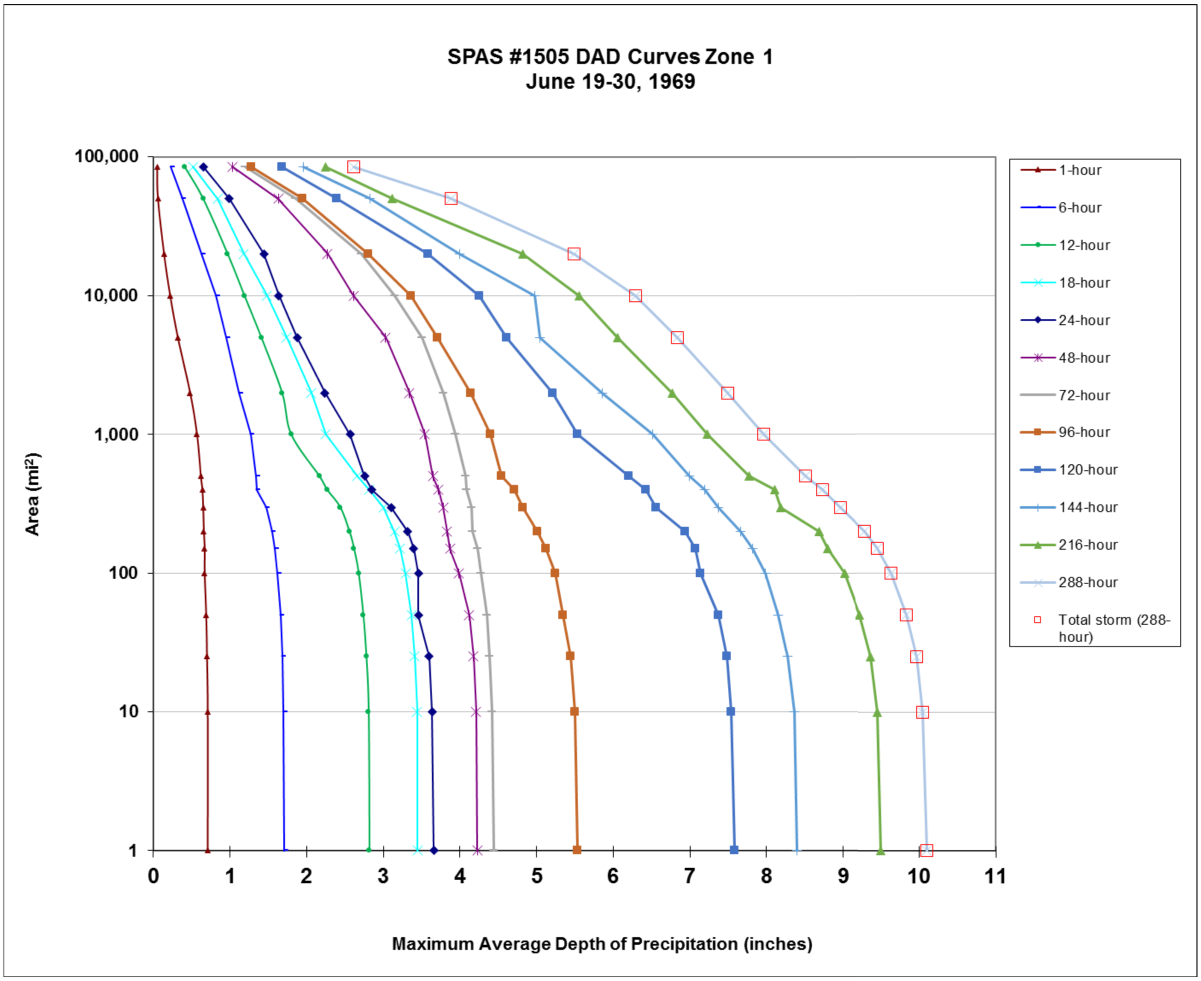
MONDAY, JUNE 30, 1969



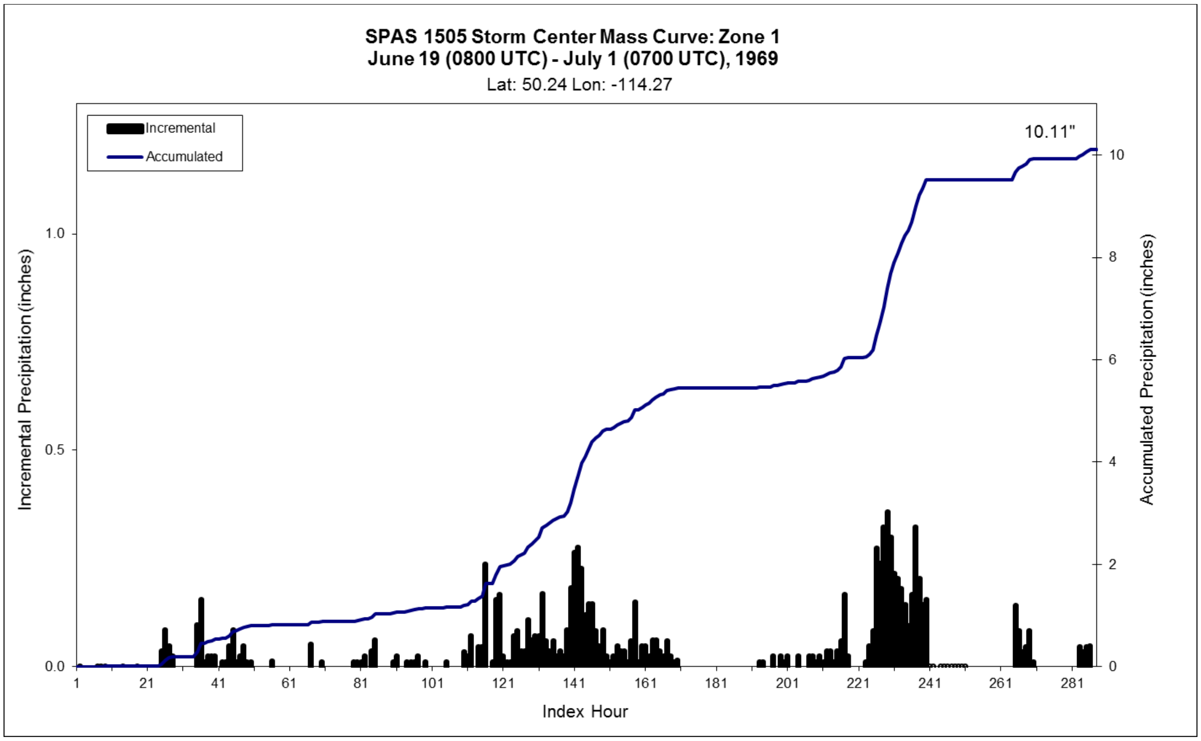

NOAA HYSPLIT MODEL
Backward trajectories ending at 1800 UTC 25 Jun 69
CDC1 Meteorological Data
Source ★ at 50.24 N 114.27 W
55
50
-115
-110
-105
-100
hPa
700
849
700
750
800
850
900
12 06 00 18 12 06 00 18 12 06 00 18
06/25
06/24
06/23
Job ID: 111765 Job Start: Thu May 21 21:56:15 UTC 2015
Source 1 lat.: 50.237500 lon.: -114.270800 heights: 0, 1570 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jun 2069 - reanalysis



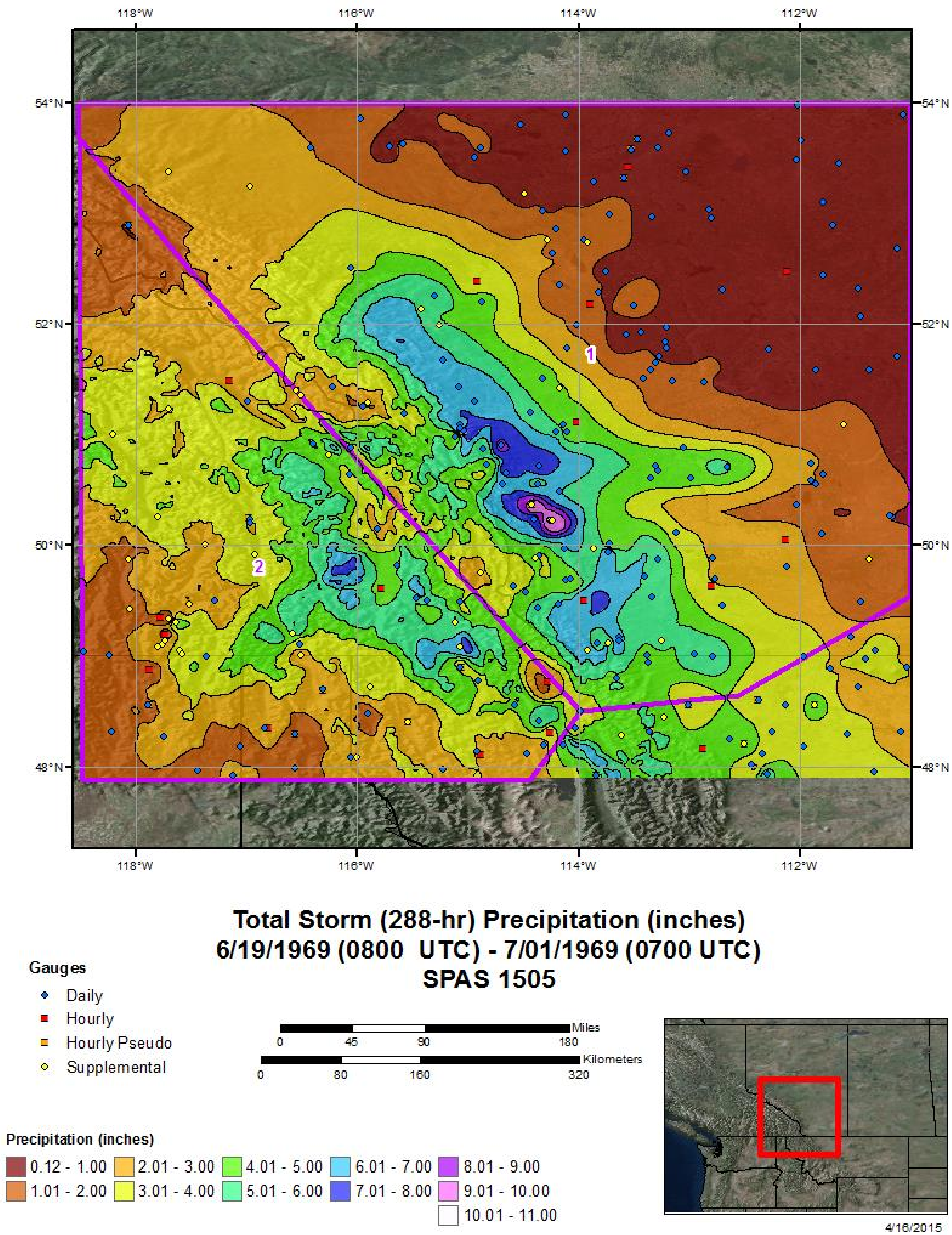
Storm 1505 Zone 1 - June 19 (0800 UTC) - July 1 (0700 UTC), 1969														
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)														
	Duration (hours)													
areasqmi	1	6	12	18	24	48	72	96	120	144	216	288		Total
0.2	0.71	1.71	2.82	3.47	3.66	4.24	4.44	5.53	7.58	8.40	9.51	10.11		10.11
1	0.71	1.71	2.82	3.45	3.66	4.23	4.44	5.53	7.58	8.40	9.50	10.10		10.10
10	0.71	1.70	2.81	3.44	3.64	4.21	4.42	5.50	7.54	8.36	9.45	10.05		10.05
25	0.70	1.68	2.78	3.41	3.60	4.18	4.39	5.45	7.48	8.28	9.37	9.97		9.97
50	0.69	1.66	2.74	3.37	3.46	4.12	4.35	5.35	7.37	8.15	9.22	9.83		9.83
100	0.67	1.62	2.68	3.29	3.46	3.99	4.28	5.25	7.14	7.98	9.02	9.63		9.63
150	0.67	1.59	2.62	3.22	3.40	3.87	4.23	5.12	7.07	7.82	8.80	9.45		9.45
200	0.66	1.55	2.56	3.15	3.32	3.83	4.16	5.01	6.94	7.66	8.69	9.29		9.29
300	0.65	1.47	2.44	3.00	3.10	3.78	4.15	4.82	6.56	7.37	8.18	8.97		8.97
400	0.64	1.35	2.27	2.82	2.85	3.72	4.09	4.71	6.42	7.19	8.11	8.73		8.73
500	0.62	1.34	2.17	2.66	2.76	3.65	4.07	4.54	6.20	6.99	7.77	8.51		8.51
1,000	0.57	1.27	1.80	2.25	2.57	3.54	3.94	4.40	5.53	6.51	7.23	7.96		7.96
2,000	0.48	1.12	1.68	2.06	2.24	3.34	3.79	4.14	5.21	5.86	6.77	7.50		7.50
5,000	0.32	0.95	1.41	1.74	1.88	3.03	3.51	3.71	4.61	5.04	6.06	6.84		6.84
10,000	0.22	0.82	1.19	1.48	1.64	2.61	3.15	3.36	4.25	4.98	5.56	6.29		6.29
20,000	0.14	0.63	0.97	1.18	1.44	2.27	2.72	2.80	3.59	4.00	4.82	5.49		5.49
50,000	0.06	0.38	0.65	0.84	0.99	1.63	1.86	1.95	2.39	2.83	3.12	3.88		3.88
84,788	0.05	0.23	0.41	0.52	0.65	1.03	1.20	1.28	1.68	1.96	2.25	2.61		2.61



SPAS #1505 DAD Curves Zone 1
June 19-30, 1969
Area (mi²)
Maximum Average Depth of Precipitation (inches)
1-hour
6-hour
12-hour
18-hour
24-hour
48-hour
72-hour
96-hour
120-hour
144-hour
216-hour
288-hour
Total storm (288-hour)



SPAS 1505 Storm Center Mass Curve: Zone 1
June 19 (0800 UTC) - July 1 (0700 UTC), 1969
Lat: 50.24 Lon: -114.27
Incremental
Accumulated
10.11"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour



Total Storm (288-hr) Precipitation (inches)
6/19/1969 (0800 UTC) - 7/01/1969 (0700 UTC)
SPAS 1505

Bassano, AB

May 29 – June 2, 1923

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1521

General Storm Location: Bassano, Alberta

Storm Dates: May 29 - June 2, 1923

Event: Synoptic/Convective Event

DAD Zone 1

- **Latitude**: 50.4375°
- **Longitude**: -114.3042°
- **Max. Grid Rainfall Amount**: 167mm
- **Max. Observed Rainfall Amount**: 171mm

DAD Zone 2

- **Latitude**: 50.7792°
- **Longitude**: -112.5708°
- **Max. Grid Rainfall Amount**: 196mm
- **Max. Observed Rainfall Amount**: 191mm

Number of Stations: 90 (65 Daily, 1 Hourly, 2 Hourly Pseudo, 0 Hourly Estimated Pseudo, and 22 Supplemental)

SPAS Version: 10.0

Basemap: Blended PRISM July 1961-1990 Climatology (Canada) and AL 5-23 Isohyetal

Spatial resolution: 30 second (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and AL 5-23 data. We have a good degree of confidence in the station based storm total results; the spatial pattern is dependent on the station data and a basemap. The timing is based on hourly and hourly pseudo stations.

		Storm Adjustment Summary
Storm Name:	SPAS 1521 - Bassano, AB Zone 1	
Storm Date:	5/29- 6/2/1923	
AWA Analysis Date:	7/20/2015	

Temporal Transposition Date **15-Jun**

	Lat	Long
Storm Center Location	**50.44 N**	**114.30 W**
Storm Rep Dew Point Location	**48.50 N**	**107.00 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**ESE @ 571**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**1,372**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**15.0 °C**	with total precipitable water above sea level of	**33**	millimeters.	
The in-place maximum dew point is	**21.9 °C**	with total precipitable water above sea level of	**61**	millimeters.	
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of	**N/A***	millimeters.	
The in-place storm elevation is	**1,372**	which subtracts	**14**	millimeters of precipitable water at	**15.0 °C**
The in-place storm elevation is	**1,372**	which subtracts	**22**	millimeters of precipitable water at	**21.9 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.50**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Unable to find any hourly surface Td data or daily RH observations. IPMF held at 1.50

Observed Storm Depth-Area-Duration (millimeters)

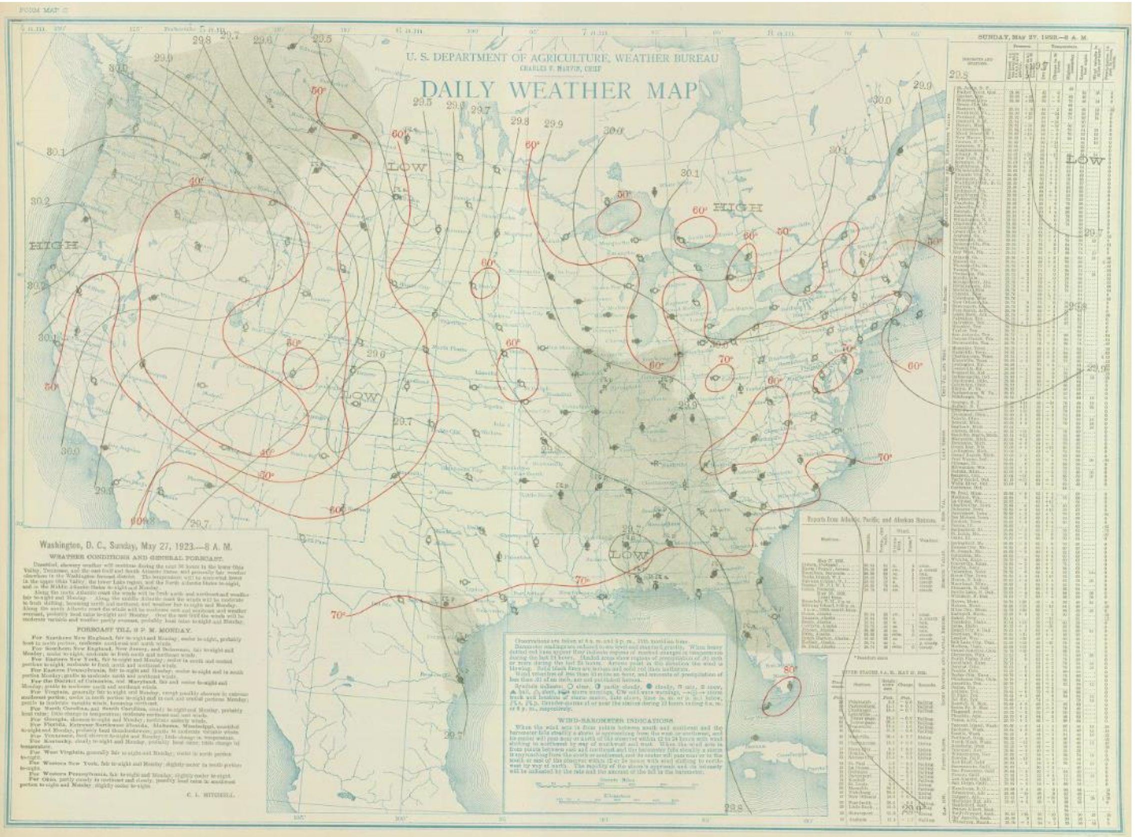
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)									
26 km^2 (10 mi^2)	**14**		**40**			**53**	**82**	**103**	**143**
259 km^2 (100 mi^2)	**14**		**39**			**53**	**81**	**102**	**141**
518 km^2 (200 mi^2)	**14**		**39**			**53**	**77**	**100**	**140**
1,295 km^2 (500 mi^2)	**13**		**38**			**51**	**77**	**97**	**136**
2,590 km^2 (1,00 mi^2)	**13**		**36**			**48**	**73**	**93**	**130**
5,180 km^2 (2,000 mi^2)	**12**		**34**			**45**	**66**	**83**	**120**
12.950 km^2 (5000 mi^2)	**10**		**30**			**40**	**55**	**69**	**105**
25,900 km^2 (10,000 mi^2)	**9**		**26**			**35**	**48**	**58**	**99**
51,800 km^2 (20,000 mi^2)	**7**		**18**			**28**	**40**	**53**	**84**

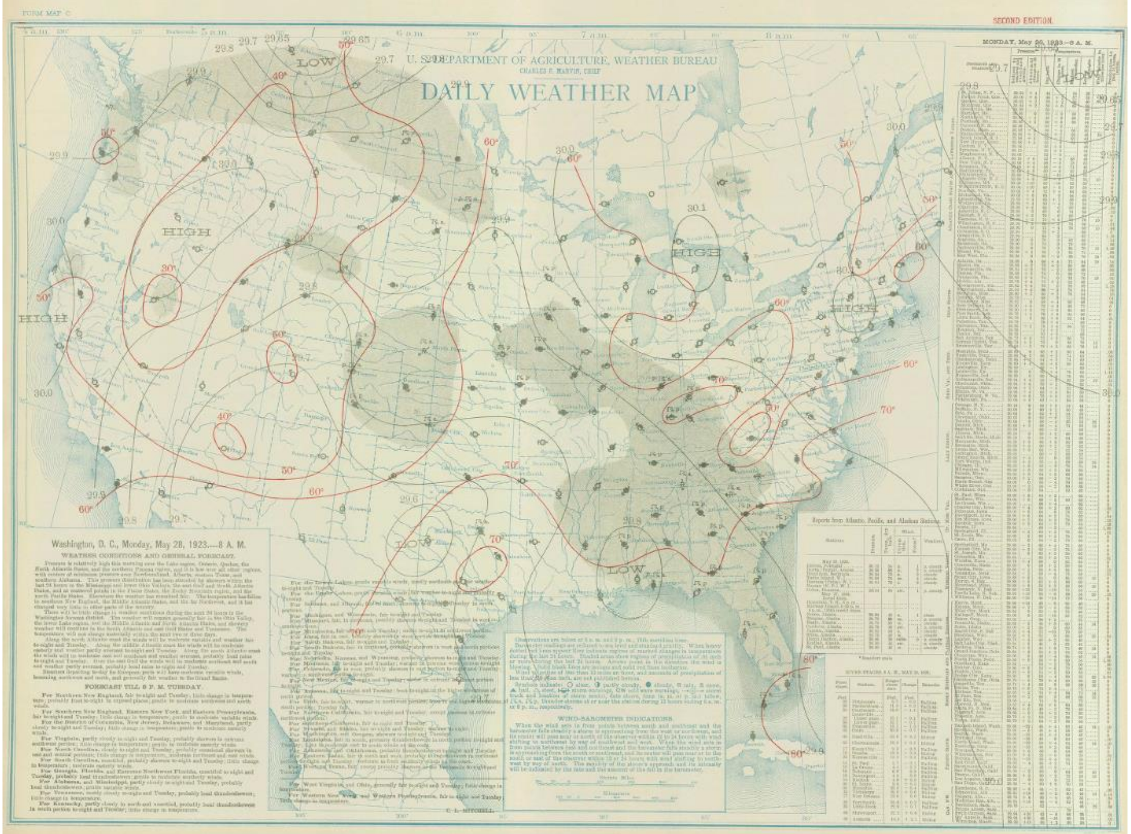
Adjusted Storm Depth-Area-Duration (millimeters)

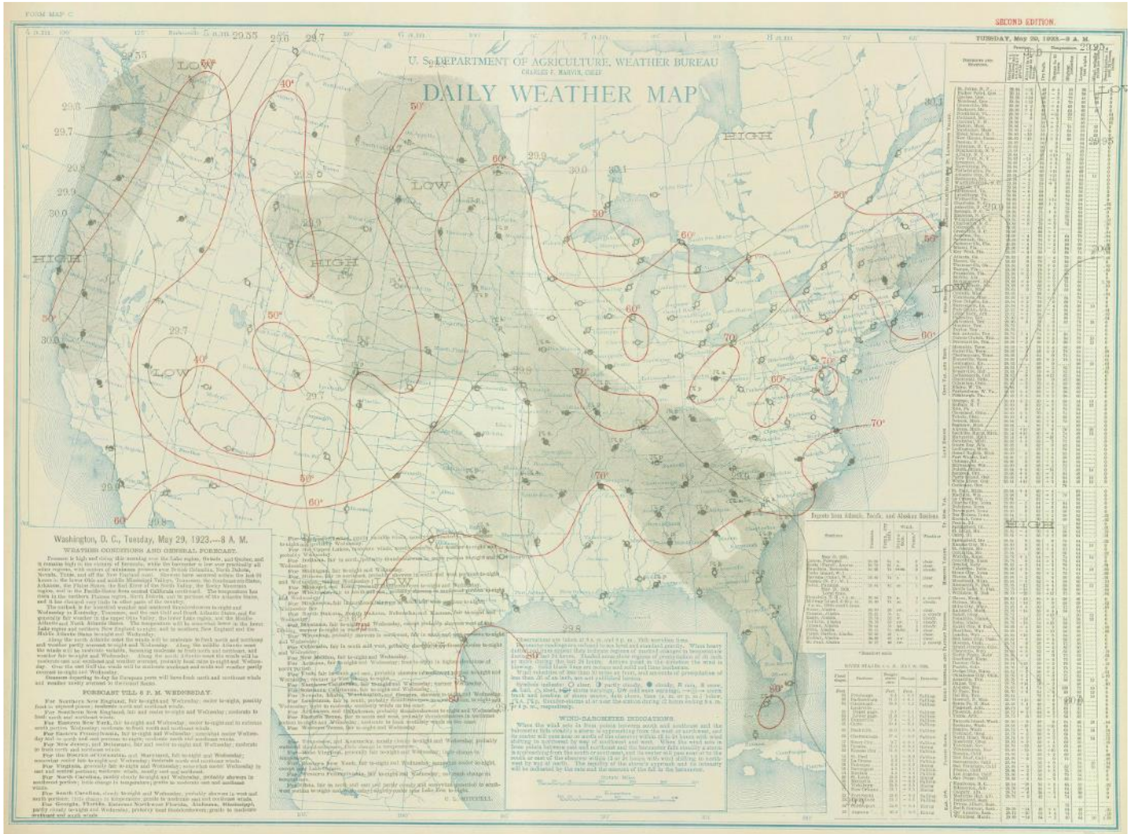
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)									
26 km2 (10 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***		**N/A***			**N/A***	**N/A***	**N/A***	**N/A***

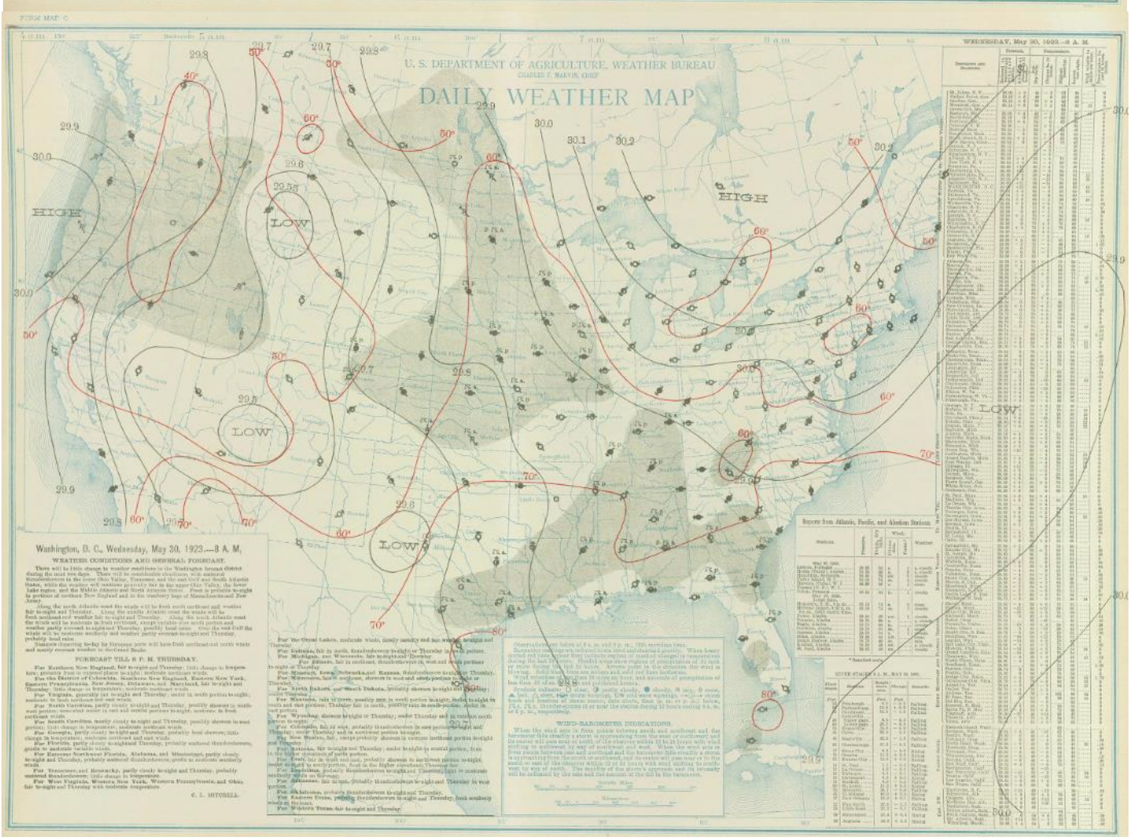
Storm or Storm Center Name	**SPAS 1521 - Bassano, AB Zone 1**	
Storm Date(s)	5/29- 6/2/1923	
Storm Type	Synoptic/ Convective Event	
Storm Location	50.44 N	114.30 W
Storm Center Elevation	1,372	meters
Precipitation Total & Duration	167	millimeters
Storm Representative Dew Point	15.0 °C	24
Storm Representative Dew Point Location	48.50 N	107.00 W
Maximum Dew Point	21.9 °C	
Moisture Inflow Vector	ESE @ 571	kilometers
In-place Maximization Factor	**1.50**	
Temporal Transposition (Date)	15-Jun	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

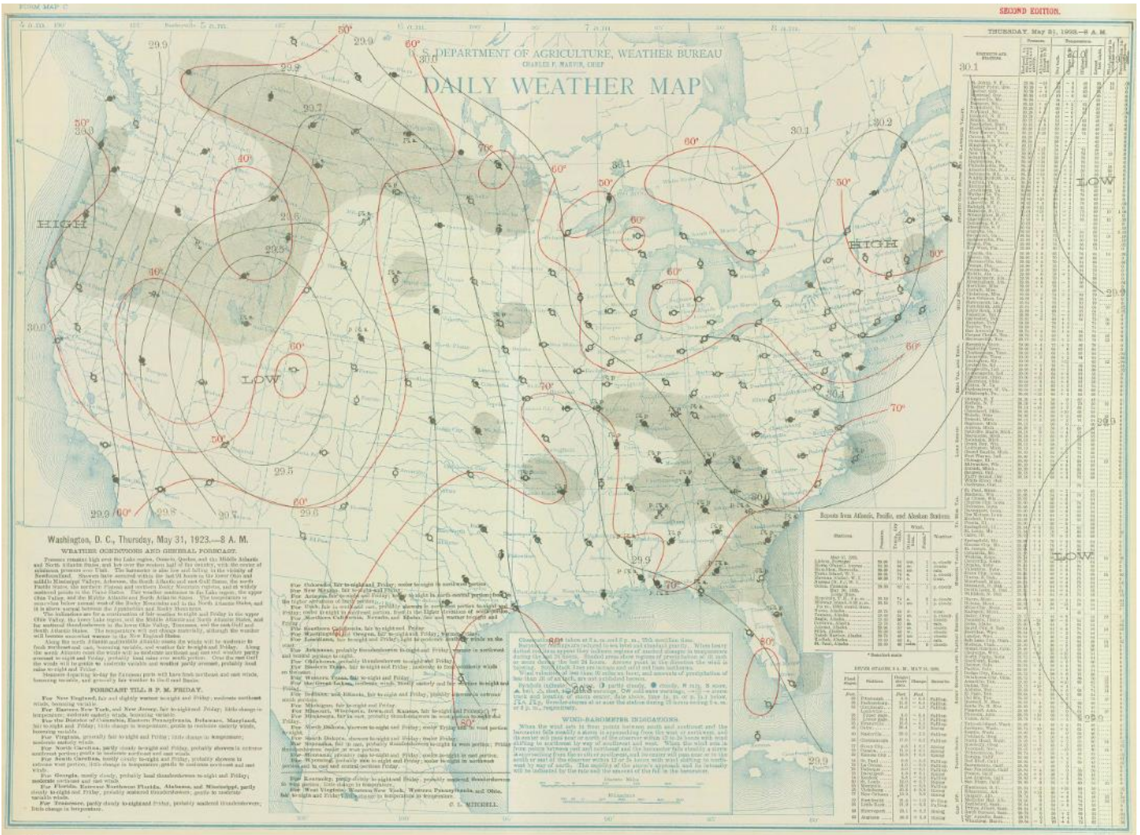
*Variable dependent on transposition location

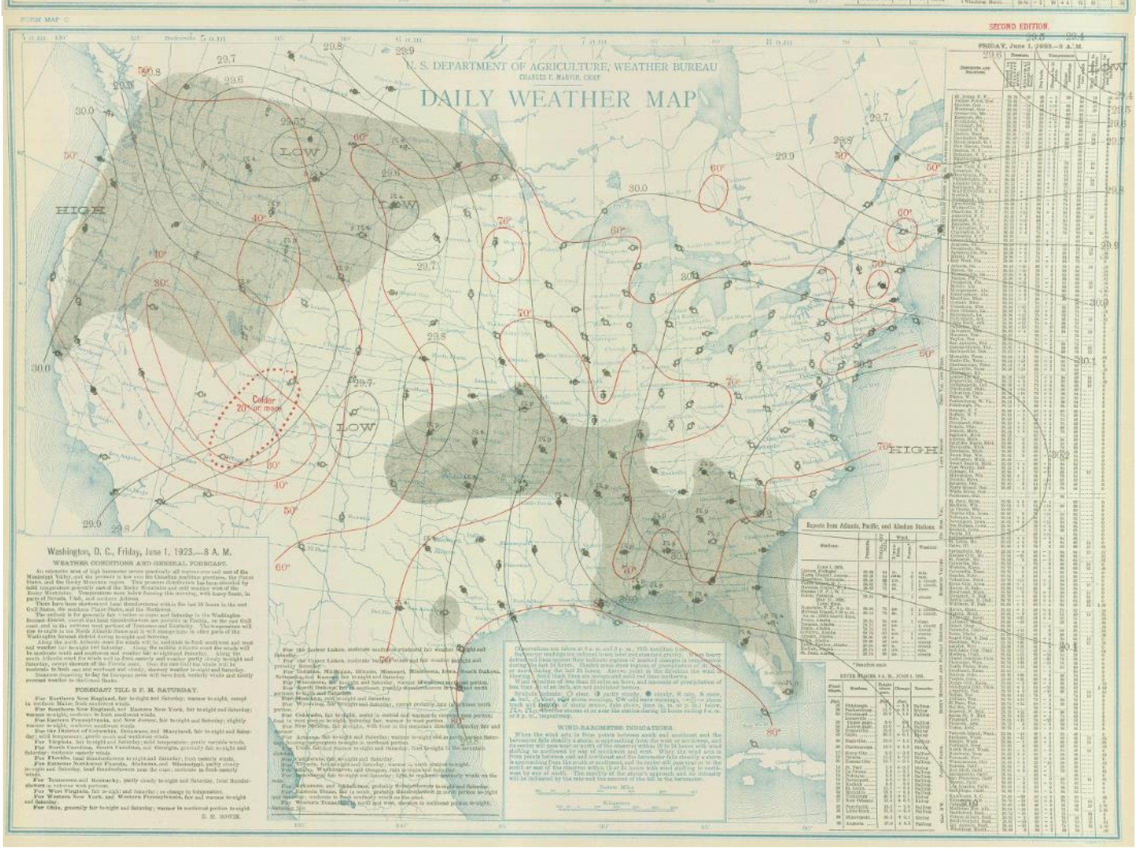

U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
SUNDAY, May 27, 1923.—8 A. M.
HIGH
LOW
Washington, D. C., Sunday, May 27, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. MONDAY.
Reports from Atlantic, Pacific, and Alaskan Stations.
WIND-BAROMETER INDICATIONS.

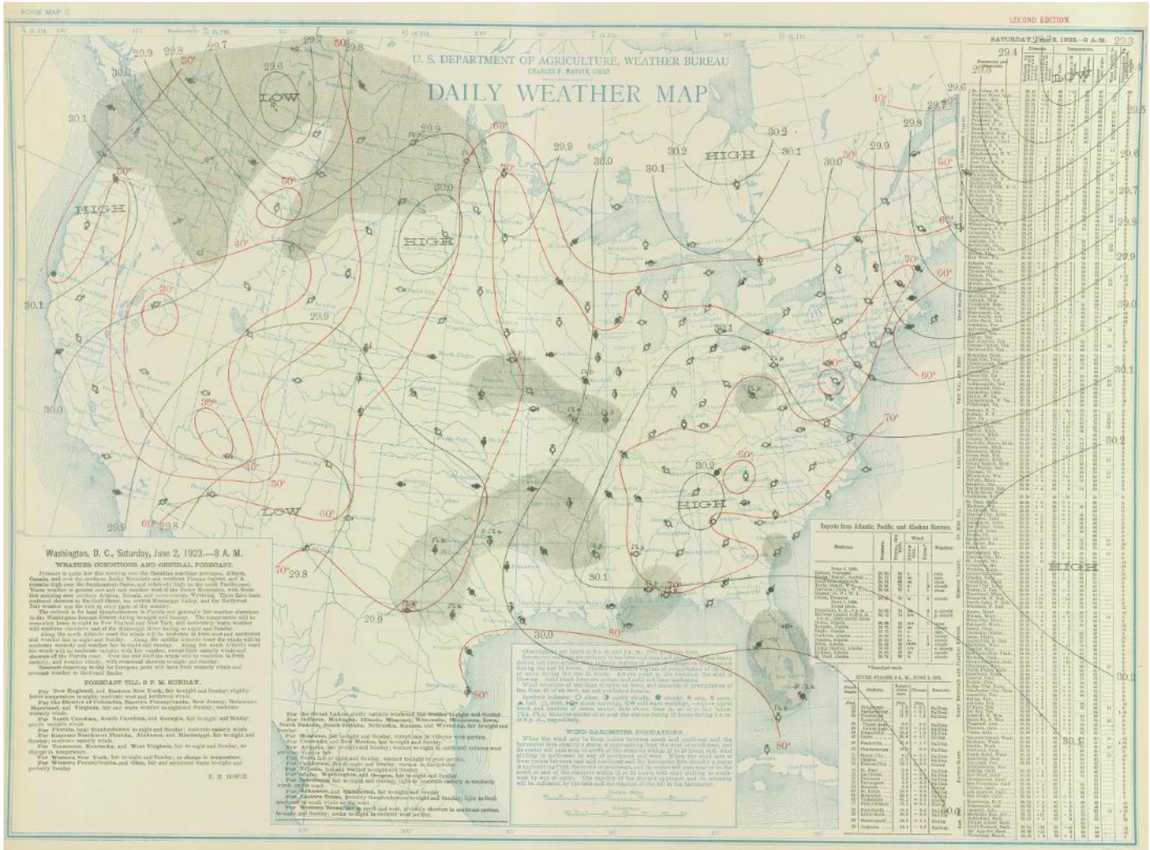

SECOND EDITION.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
MONDAY, May 28, 1923.—8 A. M.
HIGH
LOW
Washington, D. C., Monday, May 28, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. TUESDAY.
Reports from Atlantic, Pacific, and Alaskan Stations.
WIND-BAROMETER INDICATIONS.


SECOND EDITION.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Tuesday, May 29, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations


U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Wednesday, May 30, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. THURSDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations

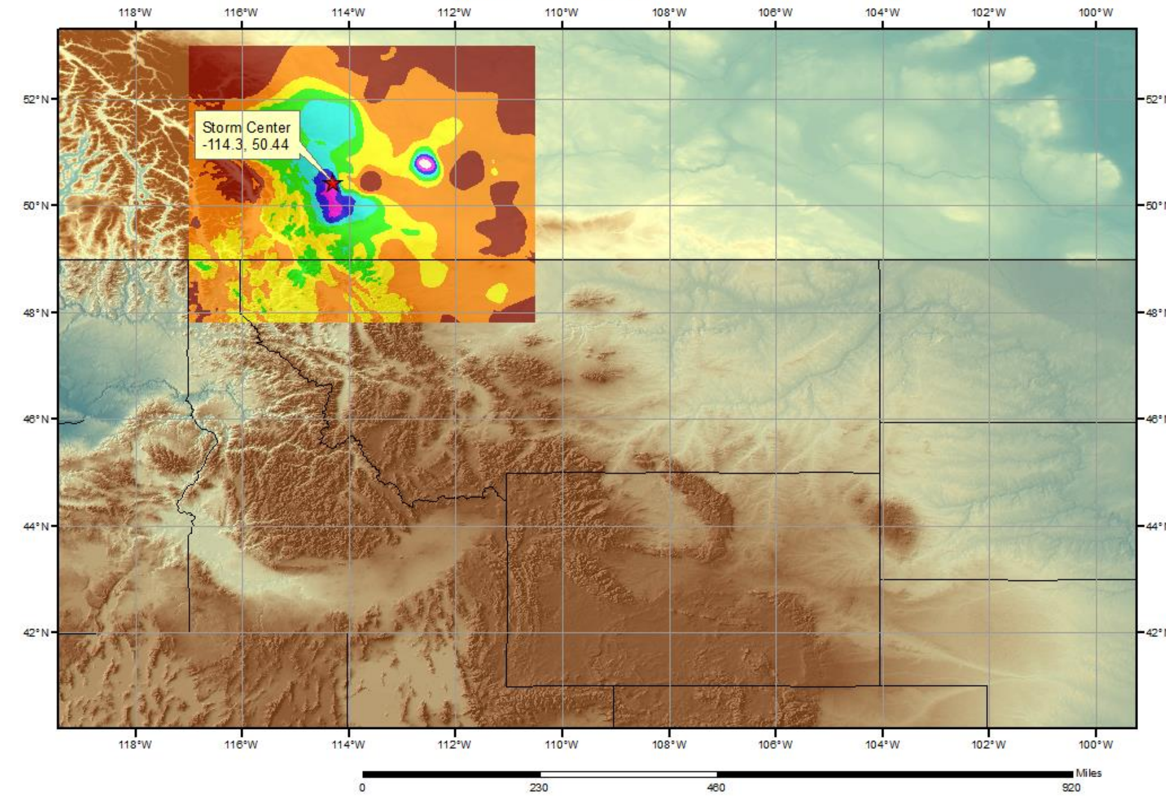

SECOND EDITION.
THURSDAY, May 31, 1923—8 A. M.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Thursday, May 31, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. FRIDAY.
WIND-BAROMETER INDICATIONS.


SECOND EDITION.
FRIDAY, June 1, 1923—8 A. M.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
Colder 20° or more
Washington, D. C., Friday, June 1, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SATURDAY.
WIND-BAROMETER INDICATIONS.

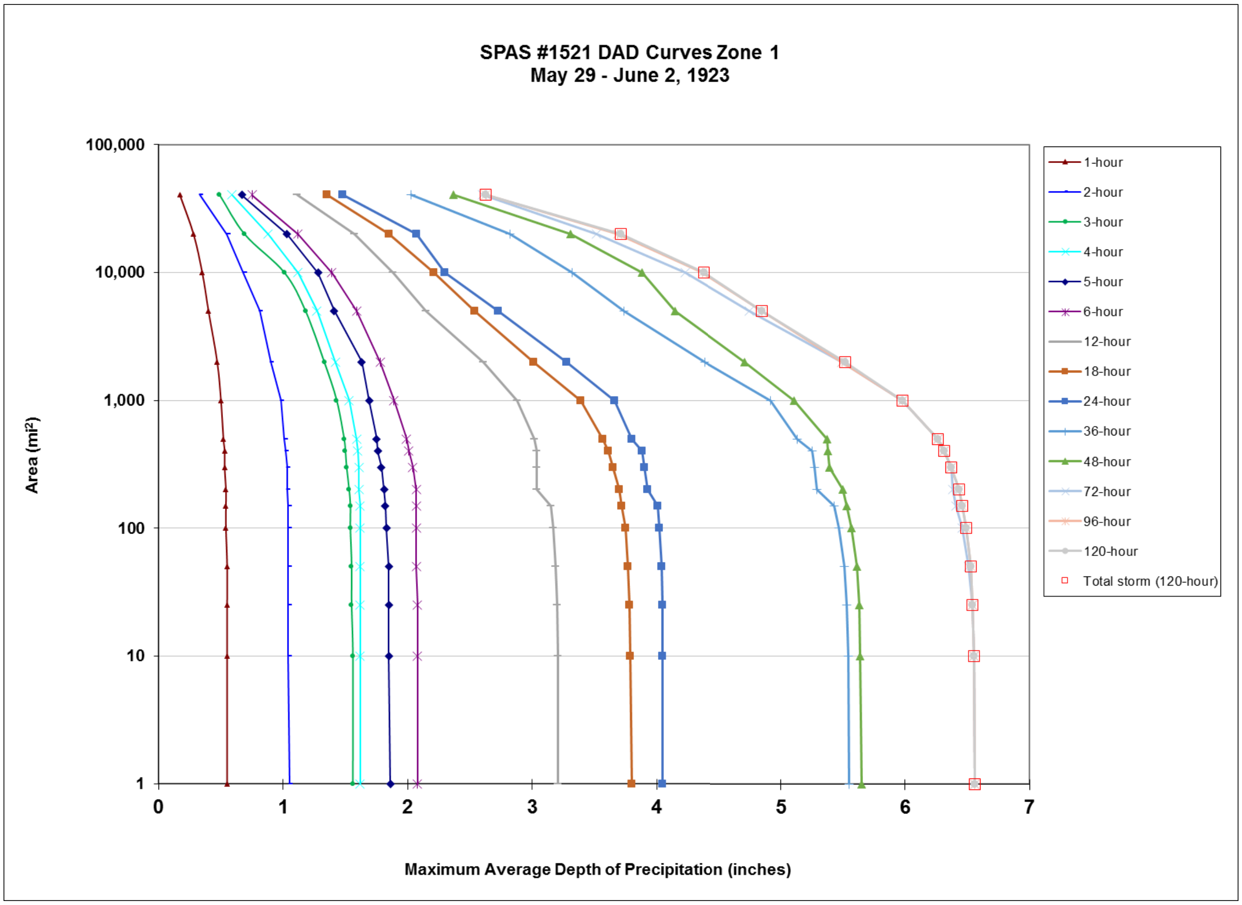

SECOND EDITION
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
LOW
HIGH
HIGH
HIGH
LOW
HIGH
LOW
HIGH
Washington, D. C., Saturday, June 2, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SUNDAY.
WIND-BAROMETER INDICATIONS
Reports from Atlantic, Pacific, and Alaskan Stations

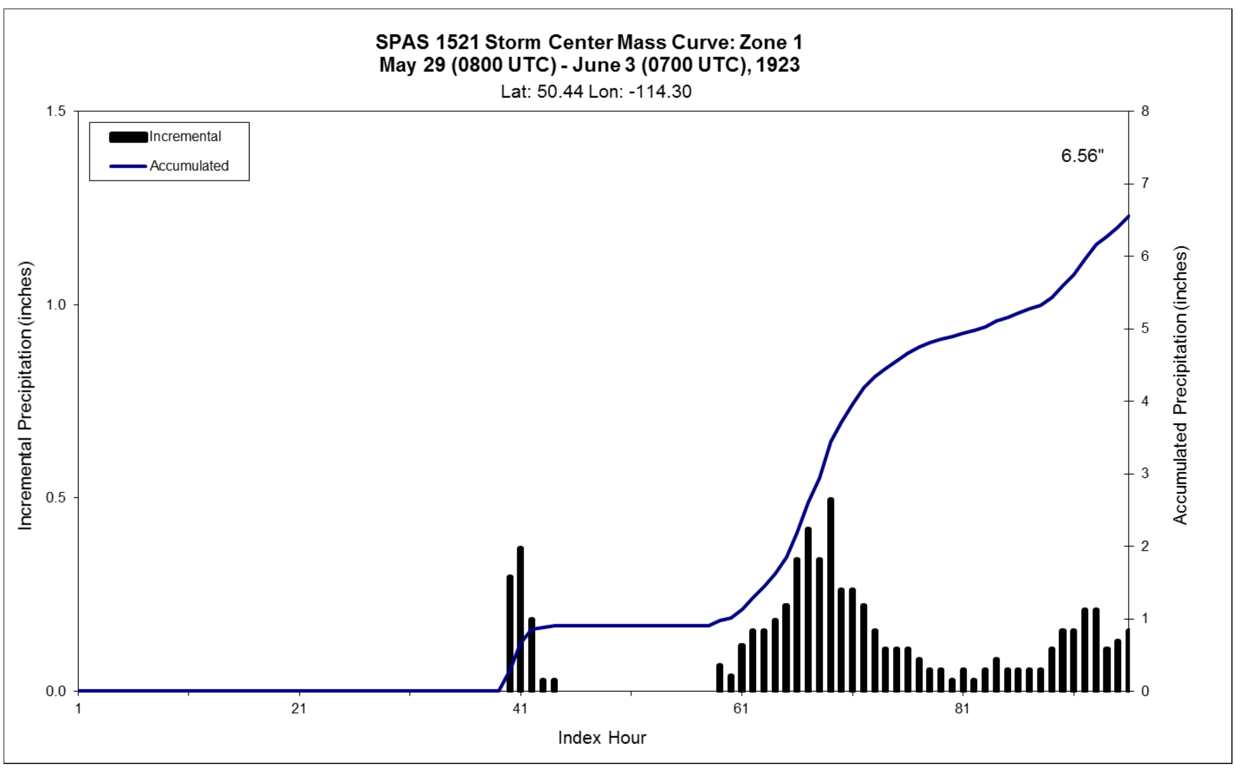
SPAS 1521 Storm Analysis Zone 1

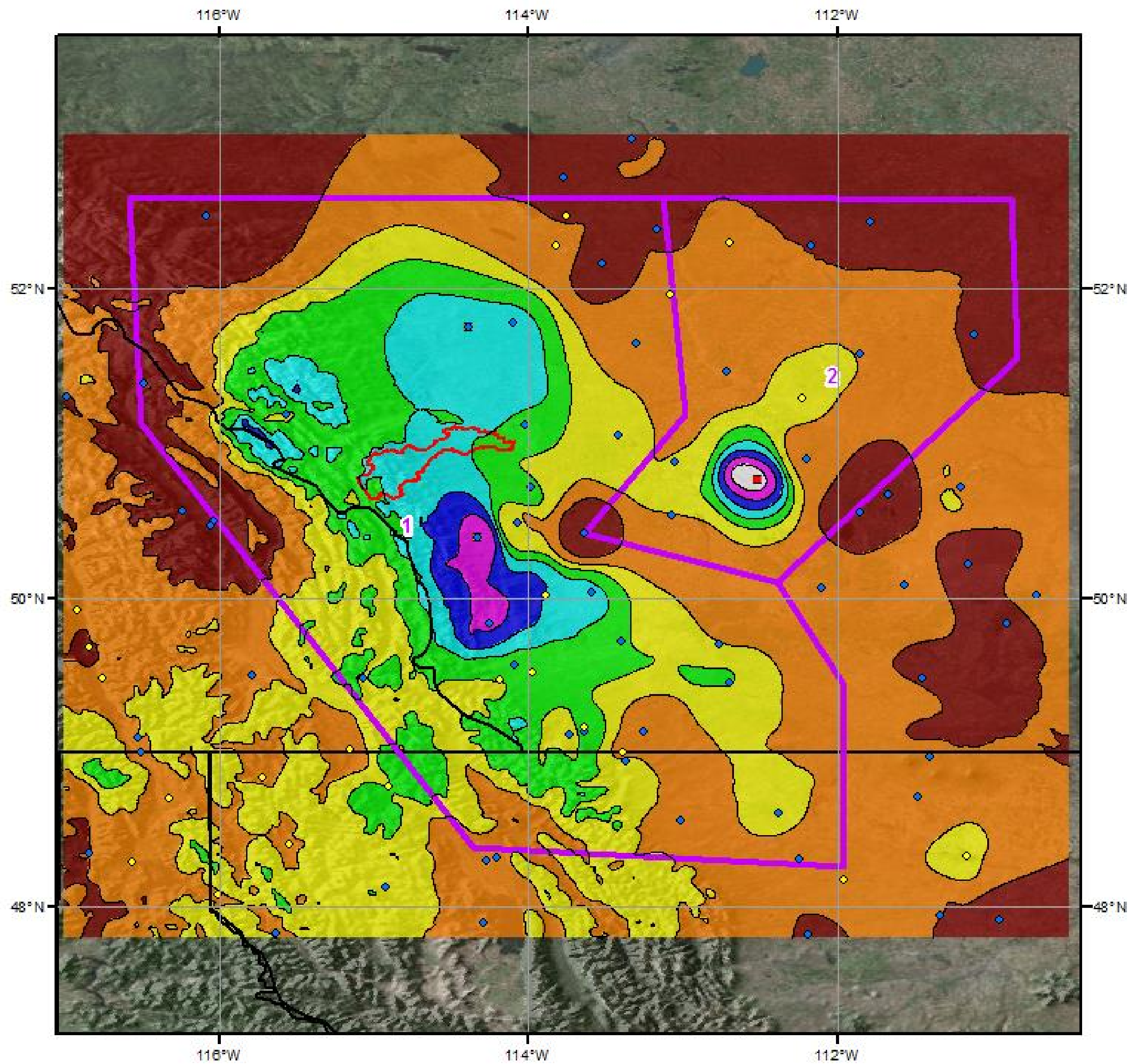
May 31- June 1, 1923



Storm 1521 Zone 1 - May 29 (0800 UTC) - June 3 (0700 UTC), 1923															
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)															
	Duration (hours)														
areasqmi	1	2	3	4	5	6	12	18	24	36	48	72	96	120		Total
0.2	0.55	1.06	1.56	1.66	1.88	2.12	3.21	3.80	4.10	5.55	5.65	6.56	6.56	6.56		6.56
1	0.55	1.05	1.56	1.62	1.86	2.08	3.21	3.80	4.05	5.55	5.65	6.56	6.56	6.56		6.56
10	0.55	1.04	1.56	1.62	1.85	2.08	3.21	3.79	4.05	5.54	5.64	6.55	6.55	6.55		6.55
25	0.55	1.04	1.55	1.62	1.85	2.08	3.20	3.78	4.05	5.53	5.63	6.54	6.54	6.54		6.54
50	0.55	1.04	1.55	1.62	1.85	2.07	3.19	3.77	4.04	5.51	5.61	6.51	6.53	6.53		6.53
100	0.54	1.04	1.54	1.62	1.83	2.07	3.17	3.75	4.02	5.47	5.57	6.46	6.49	6.49		6.49
150	0.54	1.04	1.54	1.62	1.82	2.07	3.15	3.72	4.01	5.43	5.53	6.41	6.46	6.46		6.46
200	0.54	1.03	1.53	1.61	1.81	2.07	3.04	3.70	3.93	5.29	5.50	6.38	6.43	6.43		6.43
300	0.53	1.03	1.51	1.61	1.79	2.04	3.04	3.65	3.90	5.27	5.39	6.37	6.37	6.37		6.37
400	0.53	1.02	1.50	1.60	1.76	2.01	3.04	3.61	3.88	5.25	5.38	6.31	6.31	6.31		6.31
500	0.52	1.01	1.49	1.59	1.75	1.99	3.02	3.57	3.80	5.13	5.37	6.26	6.26	6.26		6.26
1,000	0.50	0.98	1.43	1.53	1.69	1.89	2.88	3.39	3.66	4.92	5.11	5.98	5.98	5.98		5.98
2,000	0.47	0.90	1.33	1.42	1.63	1.78	2.61	3.01	3.28	4.39	4.71	5.49	5.49	5.52		5.52
5,000	0.40	0.81	1.18	1.27	1.41	1.59	2.15	2.54	2.73	3.74	4.15	4.75	4.85	4.85		4.85
10,000	0.35	0.68	1.01	1.12	1.28	1.39	1.88	2.21	2.30	3.32	3.88	4.23	4.37	4.38		4.38
20,000	0.28	0.55	0.69	0.88	1.03	1.12	1.57	1.85	2.07	2.82	3.31	3.52	3.69	3.71		3.71
40,448	0.17	0.33	0.49	0.59	0.67	0.75	1.11	1.35	1.48	2.03	2.37	2.60	2.63	2.63		2.63


SPAS #1521 DAD Curves Zone 1
May 29 - June 2, 1923
Area (mi²)
Maximum Average Depth of Precipitation (inches)
100,000
10,000
1,000
100
10
1
0
1
2
3
4
5
6
7
1-hour
2-hour
3-hour
4-hour
5-hour
6-hour
12-hour
18-hour
24-hour
36-hour
48-hour
72-hour
96-hour
120-hour
Total storm (120-hour)


SPAS 1521 Storm Center Mass Curve: Zone 1
May 29 (0800 UTC) - June 3 (0700 UTC), 1923
Lat: 50.44 Lon: -114.30
Incremental
Accumulated
6.56"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour
1.5
1.0
0.5
0.0
8
7
6
5
4
3
2
1
0
1
21
41
61
81

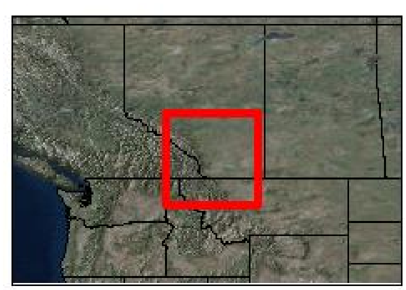


Total Storm (120-hr) Precipitation (inches)
5/29/1923 (0800 UTC) - 6/03/1923 (0700 UTC)
SPAS 1521

Gauges
- Daily
- Hourly
- Hourly Pseudo
- Supplemental

Miles: 0, 37.5, 75, 150
Kilometers: 0, 70, 140, 280

Precipitation (inches)
- 0.38 - 1.00
- 1.01 - 2.00
- 2.01 - 3.00
- 3.01 - 4.00
- 4.01 - 5.00
- 5.01 - 6.00
- 6.01 - 7.00
- 7.01 - 8.00



4/16/2015

Simonette Lo, AB

July 30 – August 2, 1987

Storm Type: General

Storm Precipitation Analysis System (SPAS) For Storm #1522

General Storm Location: Simonette Lo, Alberta

Storm Dates: July 30 - August 2, 1987

Event: Synoptic/Convective Event

DAD Zone 1

- **Latitude**: 54.2375°
- **Longitude**: -118.4042°
- **Max. Grid Rainfall Amount**: 334mm
- **Max. Observed Rainfall Amount**: 318mm

DAD Zone 2

- **Latitude**: 57.6458°
- **Longitude**: -117.4042°
- **Max. Grid Rainfall Amount**: 228mm
- **Max. Observed Rainfall Amount**: 228mm

Number of Stations: 213 (129 Daily, 32 Hourly, 9 Hourly Pseudo, 00 Hourly Estimated Pseudo, and 43 Supplemental)

SPAS Version: 10.0

Basemap: Blended PRISM July 1961-1990 Climatology (Canada) and AL 7-87 Isohyetal

Spatial resolution: 30 second (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and AL 7-87 data. We have a good degree of confidence in the station based storm total results, the spatial pattern is dependent on the station data and a basemap. The timing is based on hourly and hourly pseudo stations.

Storm Name:	SPAS 1522 - Simonette Lo, AB Zone 1
Storm Date:	7/30 - 8/2/1987
AWA Analysis Date:	7/20/2015

Storm Adjustment Summary

Temporal Transposition Date 15-Jul

	Lat	Long
Storm Center Location	54.24 N	118.40 W
Storm Rep Dew Point Location	53.70 N	113.50 W
Transposition Dew Point Location	N/A*	N/A*
Basin Location	50.89 N	114.69 W

Moisture Inflow Direction	ESE @ 322	kilometers
Basin Average Elevation	N/A*	meters
Storm Center Elevation	1,280	meters
Storm Analysis Duration	24	hours

The storm representative dew point is	**20.0 °C**	with total precipitable water above sea level of		**52**	millimeters.
The in-place maximum dew point is	**20.8 °C**	with total precipitable water above sea level of		**56**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**1,280**	which subtracts	**19**	millimeters of precipitable water at	**20.0 °C**
The in-place storm elevation is	**1,280**	which subtracts	**20**	millimeters of precipitable water at	**20.8 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.08**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: DAD values taken from SPAS 1522. Storm representative Td value was based on maximum 24-hr average Td values between CYXD and CYED on July 30 - August 2, 1987.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**40**	**51**				**86**	**128**	**164**	**262**
26 km^2 (10 mi^2)	**39**	**51**				**86**	**127**	**164**	**261**
259 km^2 (100 mi^2)	**38**	**49**				**83**	**123**	**159**	**258**
518 km^2 (200 mi^2)	**35**	**46**				**80**	**121**	**159**	**250**
1,295 km^2 (500 mi^2)	**28**	**44**				**76**	**116**	**155**	**241**
2,590 km^2 (1,00 mi^2)	**24**	**43**				**70**	**108**	**151**	**227**
5,180 km^2 (2,000 mi^2)	**21**	**41**				**61**	**96**	**137**	**220**
12.950 km^2 (5000 mi^2)	**15**	**37**				**51**	**73**	**116**	**184**
25,900 km^2 (10,000 mi^2)	**12**	**30**				**45**	**66**	**91**	**152**
51,800 km^2 (20,000 mi^2)	**9**	**25**				**39**	**58**	**84**	**119**

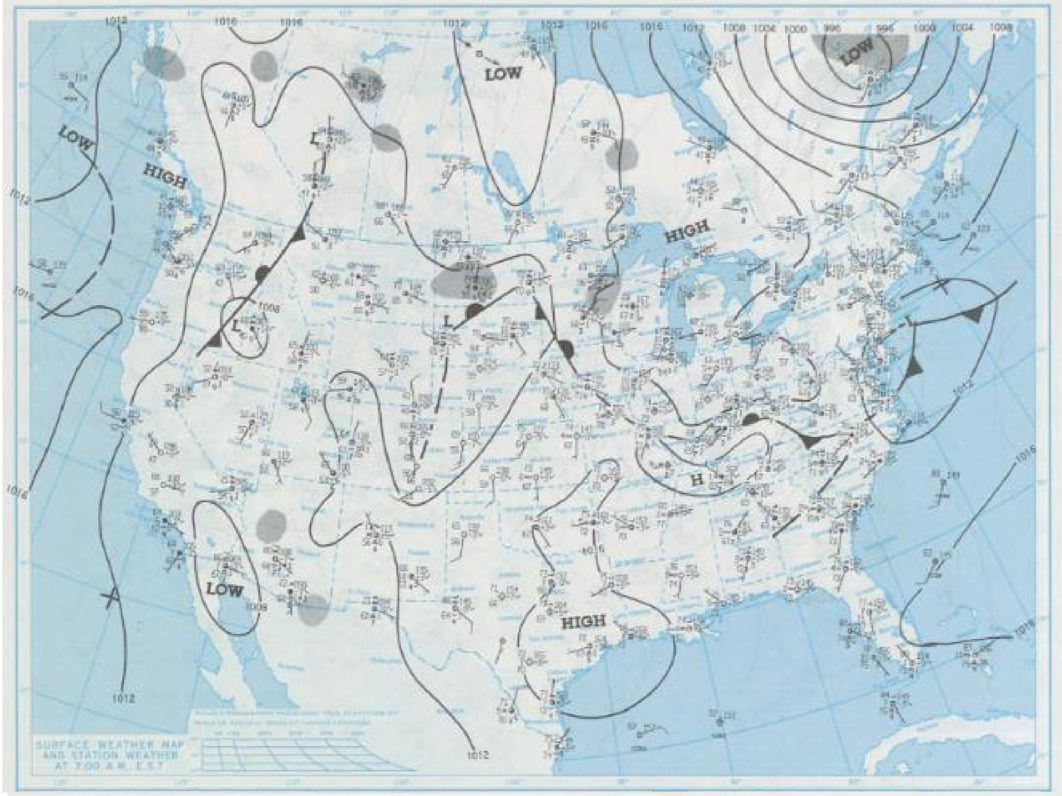
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
26 km2 (10 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
259 km2 (100 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
518 km2 (200 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
1,295 km2 (500 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
2,590 km2 (1,00 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
5,180 km2 (2,000 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
12.950 km2 (5000 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
25,900 km2 (10,000 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***
51,800 km2 (20,000 mi2)	**N/A***	**N/A***				**N/A***	**N/A***	**N/A***	**N/A***

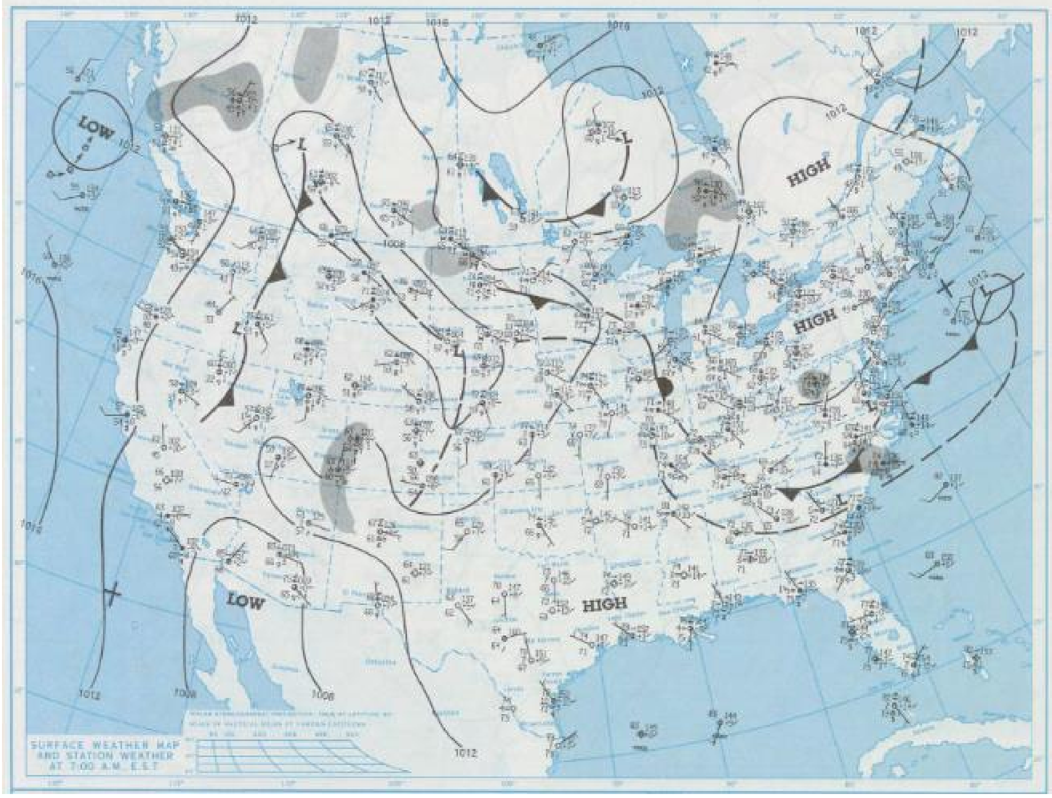
Storm or Storm Center Name	**SPAS 1522 - Simonette Lo, AB Zone 1**	
Storm Date(s)	7/30 - 8/2/1987	
Storm Type	Synoptic	
Storm Location	54.24 N	118.40 W
Storm Center Elevation	1,280	meters
Precipitation Total & Duration	334	millimeters
Storm Representative Dew Point	20.0 °C	24
Storm Representative Dew Point Location	53.70 N	113.50 W
Maximum Dew Point	20.8 °C	
Moisture Inflow Vector	ESE @ 322	kilometers
In-place Maximization Factor	**1.08**	
Temporal Transposition (Date)	15-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

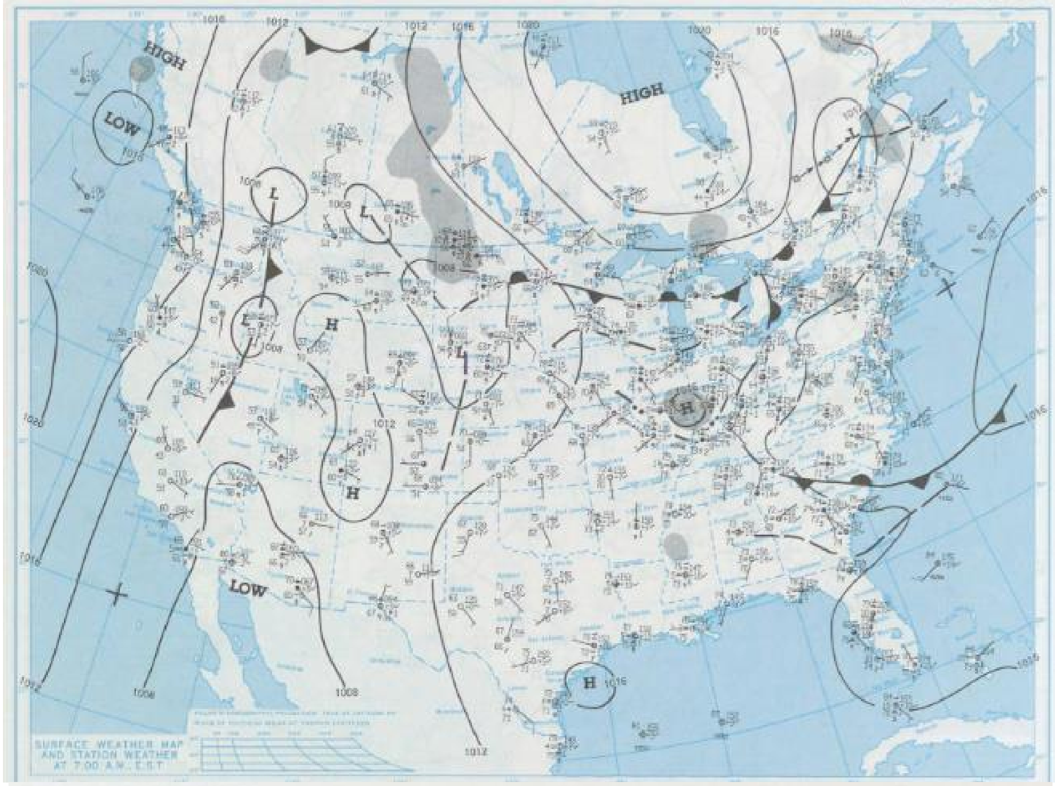
TUESDAY, JULY 28, 1987



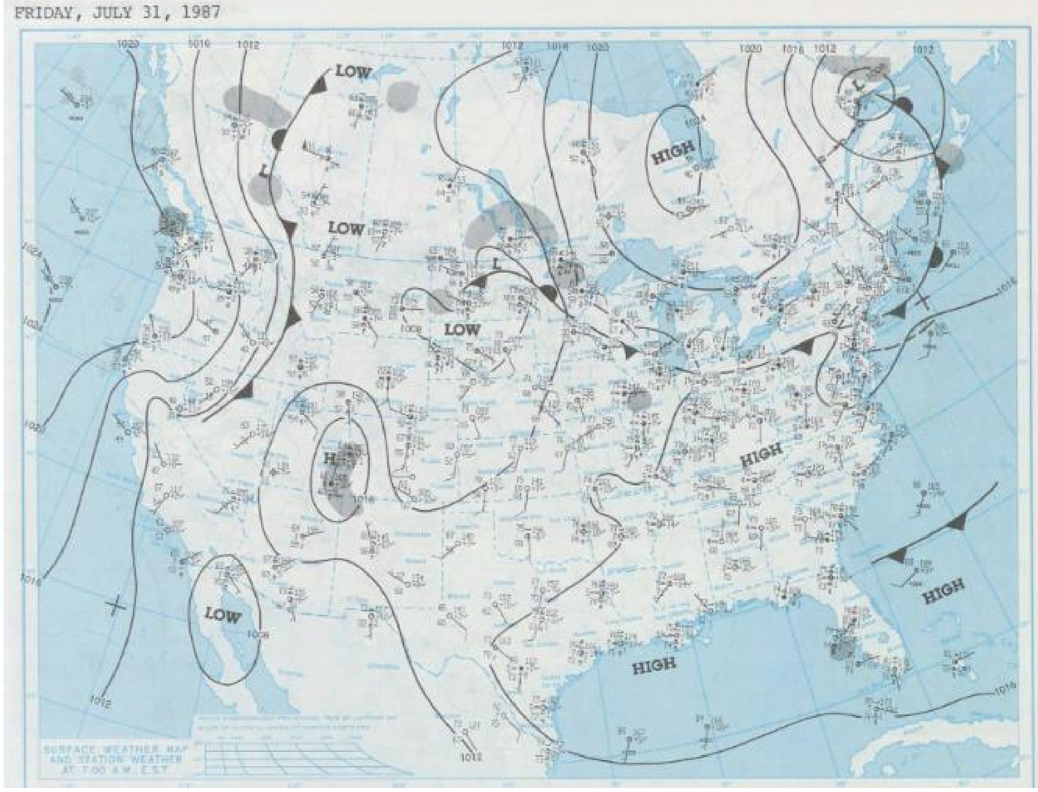
WEDNESDAY, JULY 29, 1987



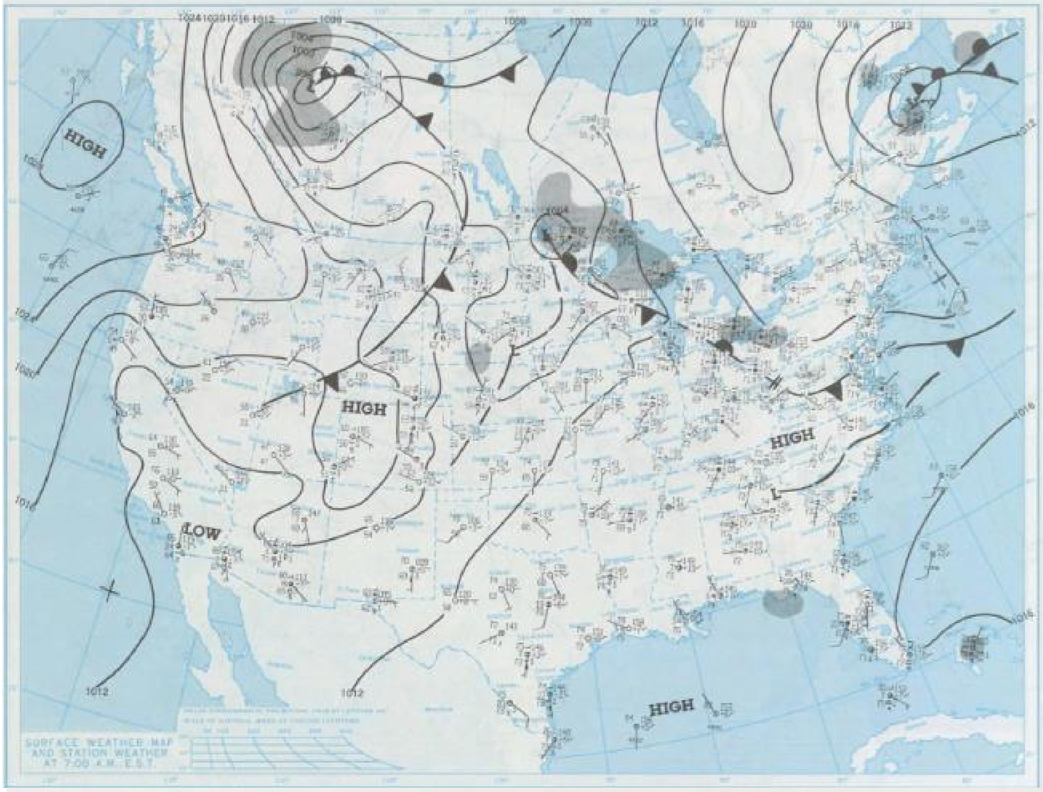
THURSDAY, JULY 30, 1987



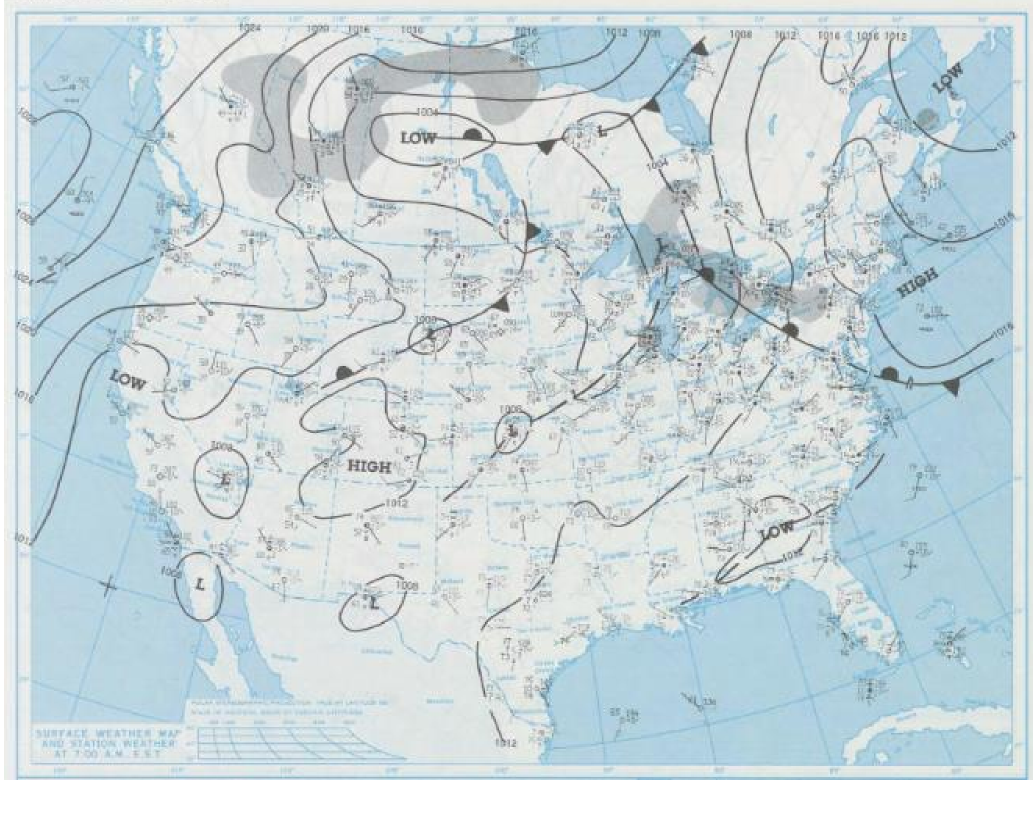
FRIDAY, JULY 31, 1987

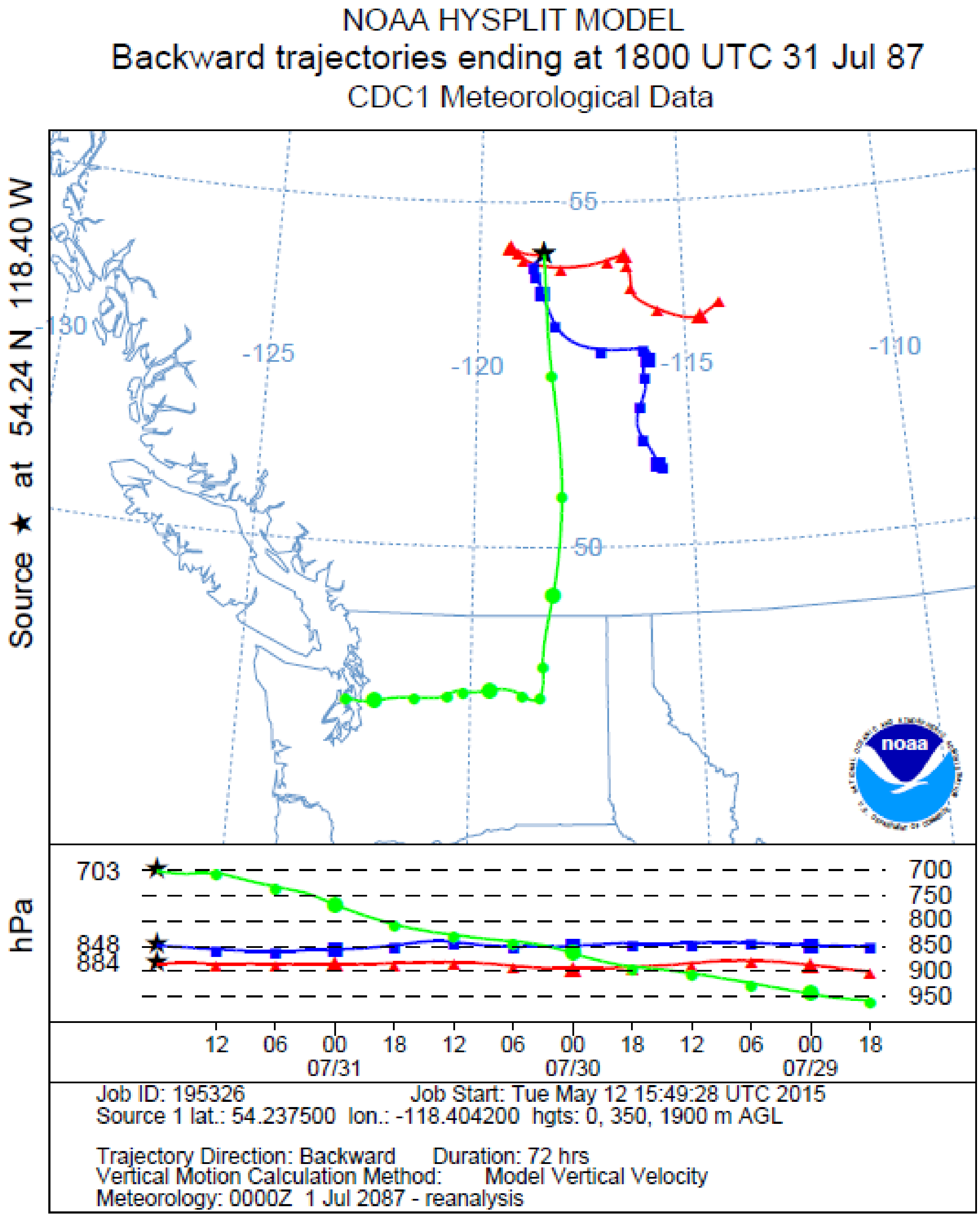


SATURDAY, AUGUST 1, 1987

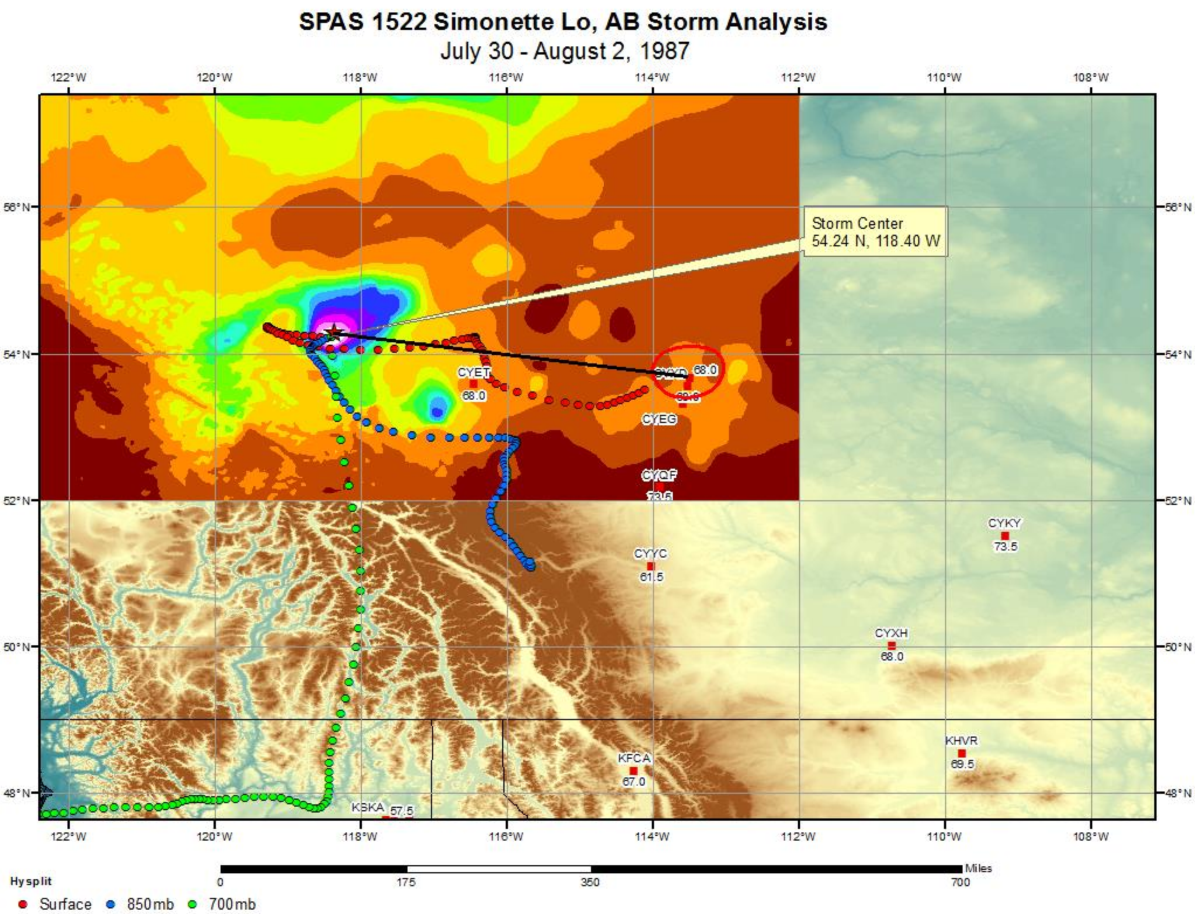


SUNDAY, AUGUST 2, 1987

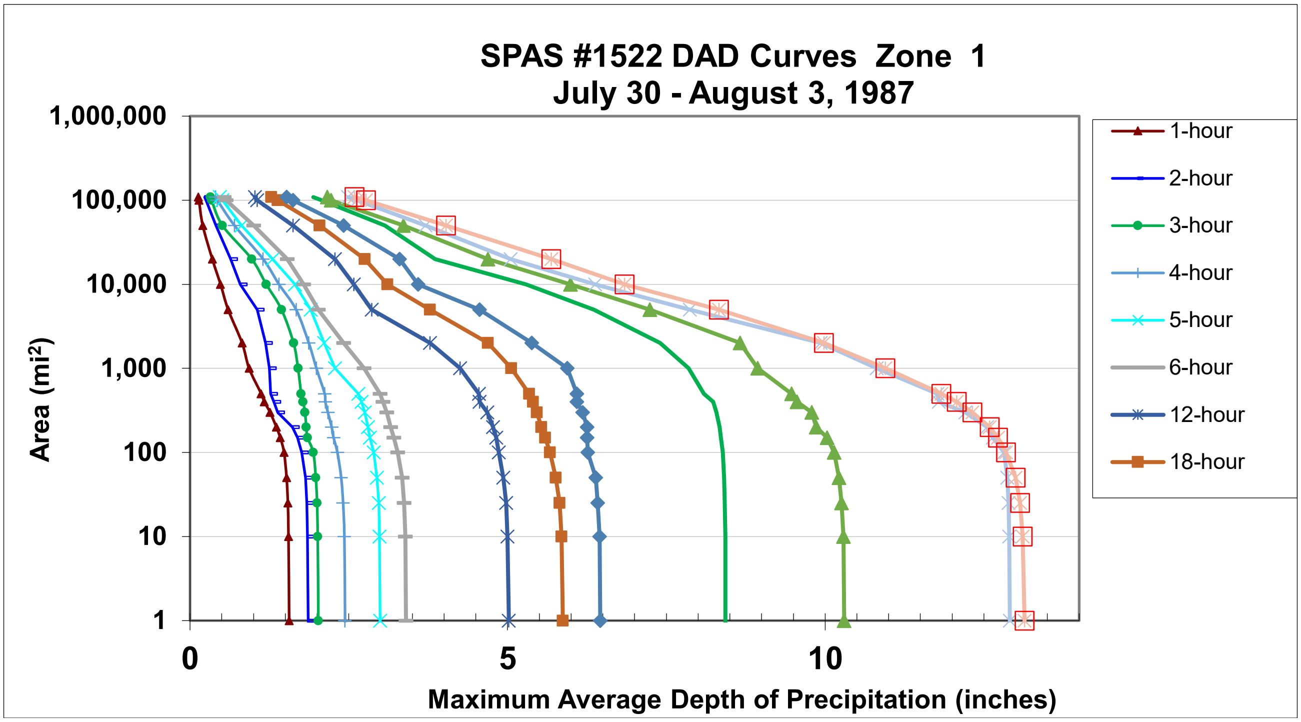


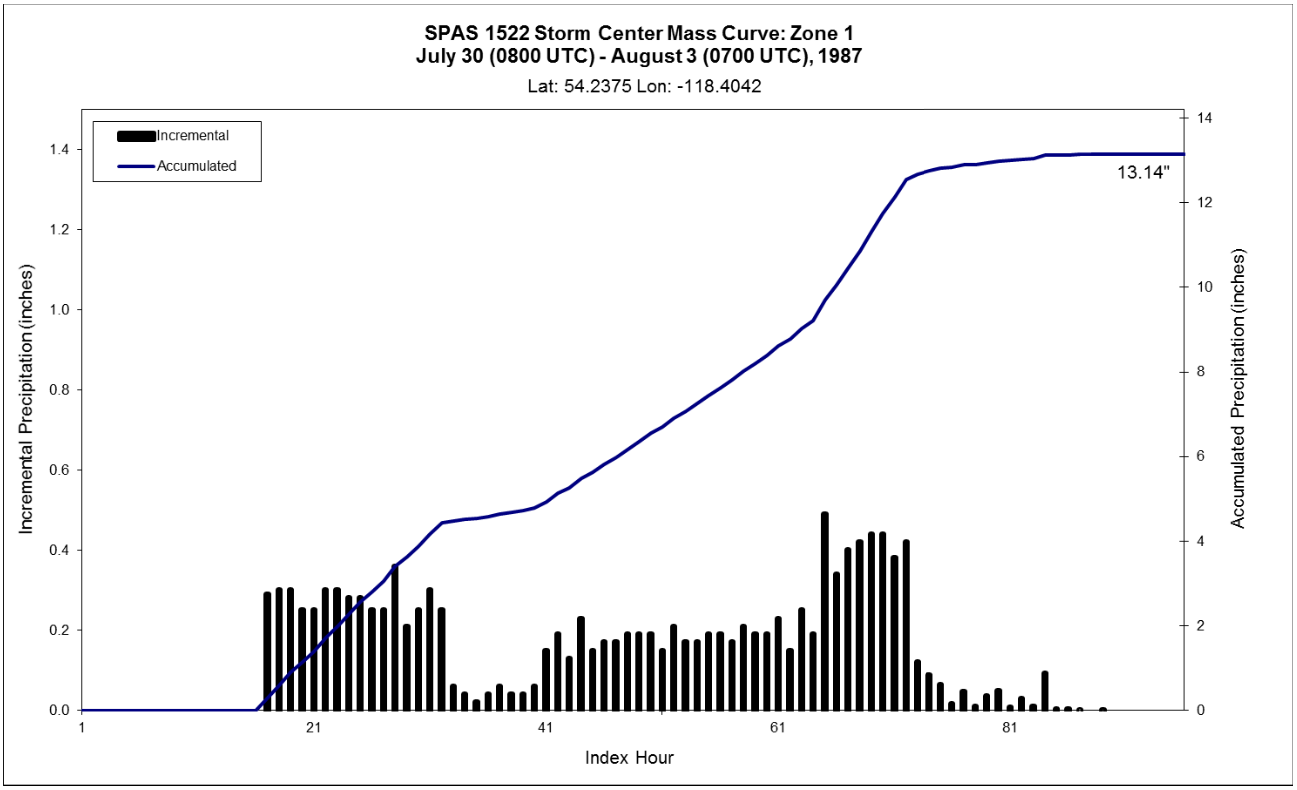


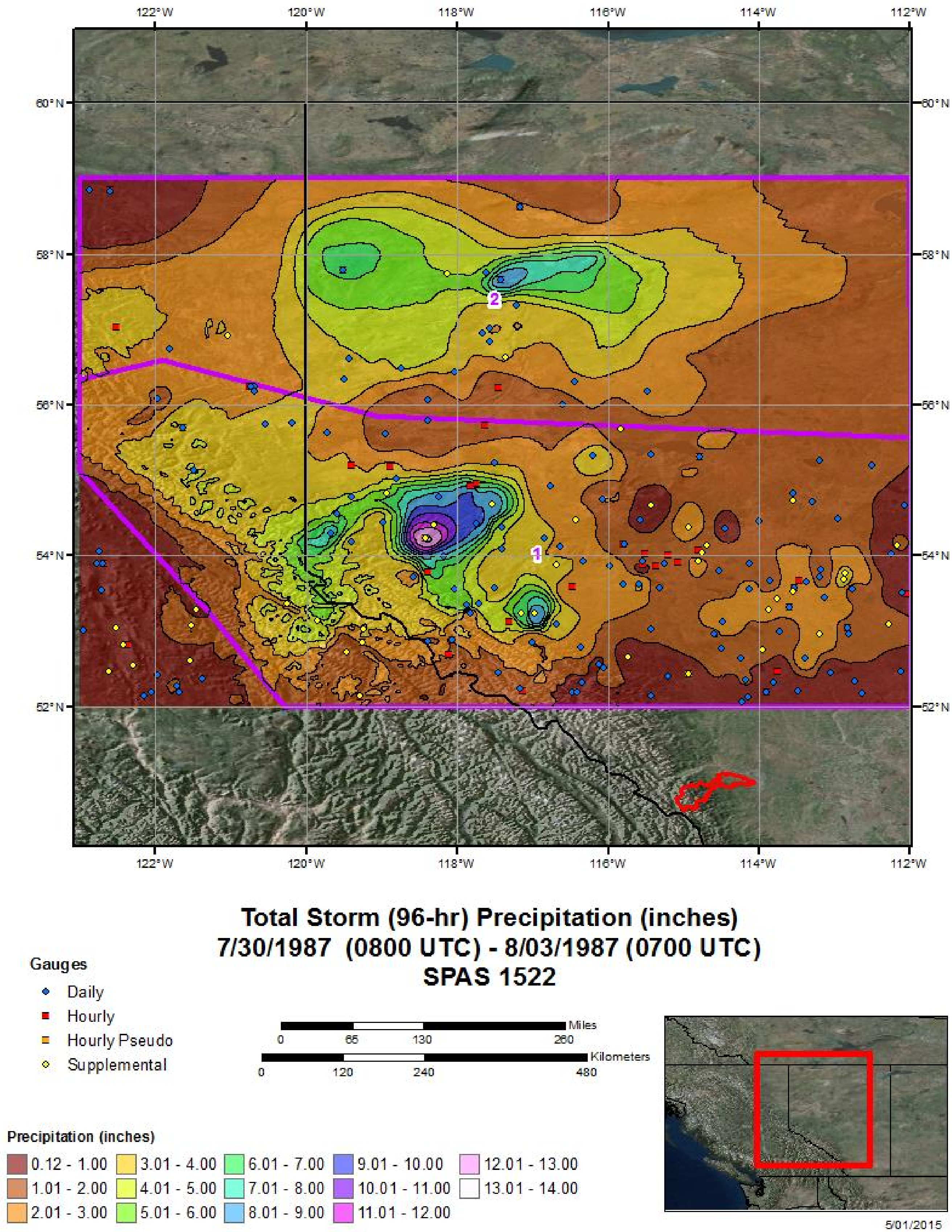
NOAA HYSPLIT MODEL
Backward trajectories ending at 1800 UTC 31 Jul 87
CDC1 Meteorological Data
Source ★ at 54.24 N 118.40 W
55
50
-130
-125
-120
-115
-110
noaa
hPa
703
848
884
700
750
800
850
900
950
12 06 00 18 12 06 00 18 12 06 00 18
07/31
07/30
07/29
Job ID: 195326
Job Start: Tue May 12 15:49:28 UTC 2015
Source 1 lat.: 54.237500 lon.: -118.404200 hgts: 0, 350, 1900 m AGL
Trajectory Direction: Backward
Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jul 2087 - reanalysis



Storm 1522 - July 30 (0800 UTC) - August 3 (0700 UTC), 1987														
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)														
Area (mi^2)	Duration (hours)													
	1	2	3	4	5	6	12	18	24	36	48	72	96	Total
0.2	1.56	1.86	2.02	2.44	3.00	3.40	5.02	5.87	6.53	8.44	10.30	13.14	13.14	13.14
1	1.56	1.86	2.02	2.44	2.99	3.40	5.02	5.87	6.46	8.43	10.30	12.91	13.14	13.14
10	1.55	1.85	2.01	2.43	2.98	3.39	5.00	5.85	6.45	8.43	10.29	12.90	13.11	13.11
25	1.54	1.84	2.00	2.41	2.97	3.37	4.98	5.82	6.42	8.42	10.26	12.89	13.07	13.07
50	1.52	1.82	1.98	2.38	2.94	3.34	4.93	5.76	6.39	8.41	10.22	12.87	13.00	13.00
100	1.48	1.76	1.94	2.32	2.89	3.27	4.86	5.67	6.26	8.39	10.14	12.82	12.85	12.85
150	1.42	1.69	1.85	2.26	2.83	3.21	4.82	5.59	6.25	8.36	10.03	12.64	12.72	12.72
200	1.36	1.61	1.83	2.23	2.80	3.16	4.77	5.53	6.25	8.34	9.86	12.55	12.59	12.59
300	1.26	1.38	1.81	2.17	2.75	3.10	4.68	5.46	6.18	8.29	9.79	12.21	12.32	12.32
400	1.17	1.32	1.78	2.13	2.70	3.04	4.56	5.40	6.09	8.24	9.56	11.79	12.07	12.07
500	1.12	1.27	1.75	2.12	2.65	2.99	4.55	5.34	6.09	8.09	9.47	11.77	11.83	11.83
1,000	0.93	1.25	1.70	1.99	2.28	2.74	4.25	5.06	5.94	7.85	8.94	10.81	10.95	10.95
2,000	0.82	1.19	1.63	1.87	2.11	2.42	3.78	4.69	5.38	7.40	8.66	9.93	9.98	9.98
5,000	0.60	1.06	1.44	1.67	1.90	2.02	2.86	3.78	4.56	6.36	7.24	7.87	8.33	8.33
10,000	0.48	0.79	1.20	1.40	1.65	1.79	2.58	3.11	3.59	5.29	5.99	6.38	6.84	6.84
20,000	0.35	0.64	0.97	1.15	1.30	1.53	2.28	2.75	3.30	3.86	4.69	5.05	5.69	5.69
50,000	0.20	0.41	0.51	0.70	0.81	1.00	1.62	2.04	2.42	3.07	3.36	3.71	4.03	4.03
100,000	0.14	0.25	0.34	0.43	0.51	0.57	1.06	1.38	1.62	2.07	2.22	2.63	2.77	2.77
108,816	0.13	0.23	0.32	0.40	0.47	0.54	1.02	1.28	1.52	1.94	2.16	2.49	2.59	2.59


SPAS #1522 DAD Curves Zone 1
July 30 - August 3, 1987
Area (mi²)
1,000,000
100,000
10,000
1,000
100
10
1
0
5
10
Maximum Average Depth of Precipitation (inches)
1-hour
2-hour
3-hour
4-hour
5-hour
6-hour
12-hour
18-hour


SPAS 1522 Storm Center Mass Curve: Zone 1
July 30 (0800 UTC) - August 3 (0700 UTC), 1987
Lat: 54.2375 Lon: -118.4042
Incremental
Accumulated
13.14"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour



Total Storm (96-hr) Precipitation (inches)
7/30/1987 (0800 UTC) - 8/03/1987 (0700 UTC)
SPAS 1522

Local Storms

Vanguard, SK

July 3-4, 2000

Storm Type: Local

Storm Precipitation Analysis System (SPAS) For Storm #1177

General Storm Location: Vanguard, Saskatchewan, Canada

Storm Dates: July 3-4, 2000 (7/3/2000 1600 UTC – 7/4/2000 0900 UTC)

Event: MCC

DAD Zone 1:

- **Latitude**: 49.9218°
- **Longitude**: -107.2100°
- **Max. Grid Rainfall Amount**: 388mm
- **Max. Observed Rainfall Amount**: 375mm

Number of Stations: 73 (1 Daily, 1 Hourly, 0 Hourly Estimated, 13 Hourly Pseudo, 53 Supplemental, and 5 Supplemental Estimated)

SPAS Version: 8.5

Base Map Used: A blend of an isohyetal from a technical report, the Level III radar-estimated precipitation from the Glasgow, MT radar and the ippt results.

Spatial resolution: 36 seconds (degree: minute: second, WGS84, ~ 0.31 mi^2, 0.80 km^2)

Radar Included: Yes (KGGW)

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: Given the bucket survey in/around the Vanguard storm center, we have a relatively high degree of confidence in the magnitude of precipitation in/around Vanguard; elsewhere we have less confidence. Although this storm had radar data, the storm cells occurred at the outer limits of the radar scan. Level II radar data was only available for the first half of the storm, while coarser Level III data was available for the latter half of the storm. We have moderate confidence in the overall spatial patterns of the storm precipitation. The temporal distribution of precipitation was largely govern by pseudo hourly gauges derived from a default ZR relationship and the radar data. Anecdotal information from the bucket survey however provided some good guidance on rainfall intensities, which the final results are consistent with.

Storm Name:	**SPAS 1177 Vanguard, SK**	**Storm Adjustment Summary**
Storm Date:	**7/3-7/4/2000**	
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **15-Jul**

	Lat	Long
Storm Center Location	**49.92 N**	**107.21 W**
Storm Rep Dew Point Location	**46.00 N**	**104.00 W**
Transposition Dew Point Location	N/A*	N/A*
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**SSE @ 499**	kilometers
Basin Average Elevation	N/A*	meters
Storm Center Elevation	732	meters
Storm Analysis Duration	6	hours

The storm representative dew point is	**24.7 °C**	with total precipitable water above sea level of		**78**	millimeters.
The in-place maximum dew point is	**25.6 °C**	with total precipitable water above sea level of		**84**	millimeters.
The transpositioned maximum dew point is	N/A*	with total precipitable water above sea level of		N/A*	millimeters.
The in-place storm elevation is	**732**	which subtracts	**15**	millimeters of precipitable water at	**24.7 °C**
The in-place storm elevation is	**732**	which subtracts	**16**	millimeters of precipitable water at	**25.6 °C**
The transposition basin elevation at	N/A*	which subtracts	N/A*	millimeters of precipitable water at	N/A*

The in-place storm maximization factor is	**1.08**
The transposition/elevation to basin factor is	N/A*
The barrier adjustment factor is	N/A*
The total adjustment factor is	N/A*

Notes: DAD values taken from SPAS 1177. Storm representative dew point value was based on average 6-hr Td values July 3 at KBHK and K2WX.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**154**		**292**			**366**			
26 km^2 (10 mi^2)	**143**		**277**			**358**			
259 km^2 (100 mi^2)	**109**		**212**			**314**			
518 km^2 (200 mi^2)	**93**		**184**			**283**			
1,295 km^2 (500 mi^2)	**67**		**136**			**218**			
2,590 km^2 (1,00 mi^2)	**48**		**89**			**169**			
5,180 km^2 (2,000 mi^2)	**38**		**72**			**125**			
12.950 km^2 (5000 mi^2)	**25**		**51**			**80**			
25,900 km^2 (10,000 mi^2)	**13**		**35**			**57**			
51,800 km^2 (20,000 mi^2)									

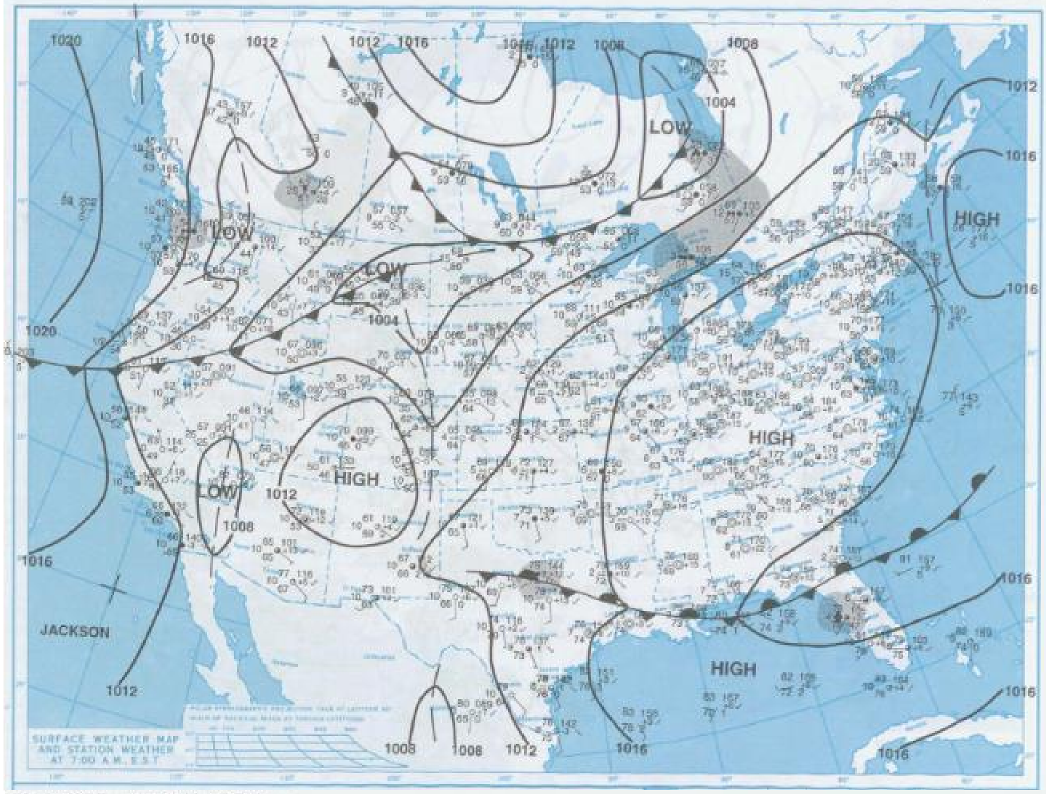
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	N/A*		N/A*			N/A*			
26 km2 (10 mi2)	N/A*		N/A*			N/A*			
259 km2 (100 mi2)	N/A*		N/A*			N/A*			
518 km2 (200 mi2)	N/A*		N/A*			N/A*			
1,295 km2 (500 mi2)	N/A*		N/A*			N/A*			
2,590 km2 (1,00 mi2)	N/A*		N/A*			N/A*			
5,180 km2 (2,000 mi2)	N/A*		N/A*			N/A*			
12.950 km2 (5000 mi2)	N/A*		N/A*			N/A*			
25,900 km2 (10,000 mi2)	N/A*		N/A*			N/A*			
51,800 km2 (20,000 mi2)									

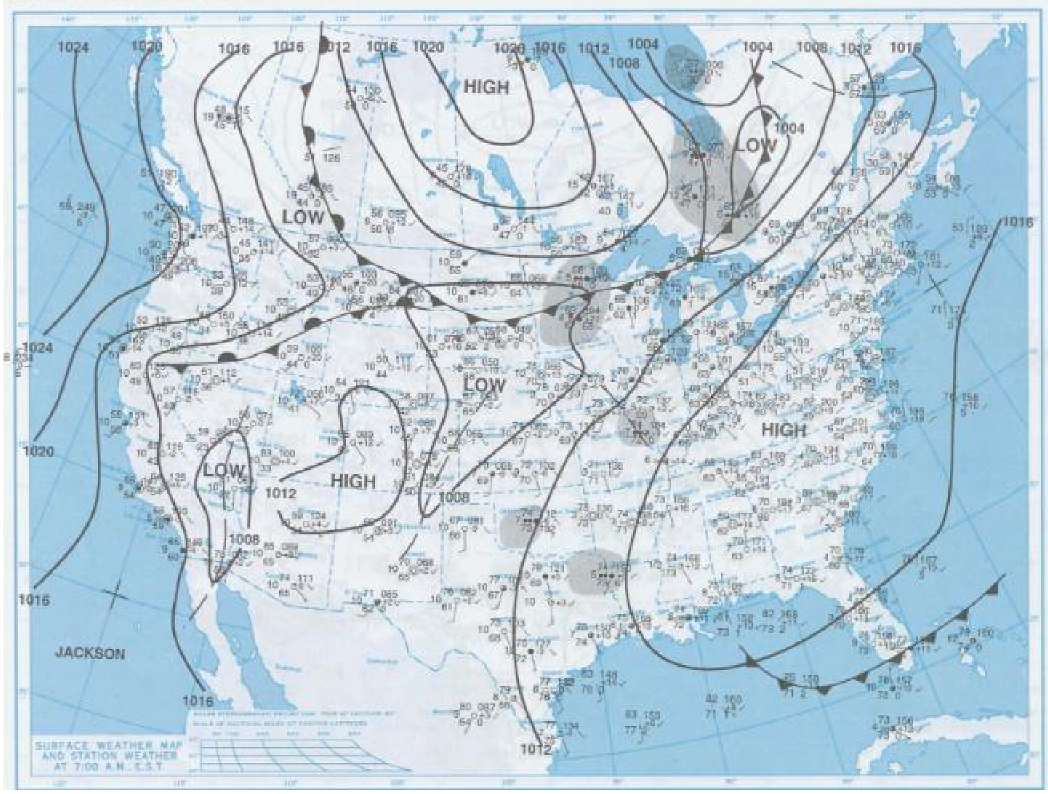
Storm or Storm Center Name	**SPAS 1177 Vanguard, SK**	
Storm Date(s)	7/3-7/4/2000	
Storm Type	MCC	
Storm Location	49.92 N	107.21 W
Storm Center Elevation	732	meters
Precipitation Total & Duration	388	millimeters
Storm Representative Dew Point	24.7 °C	6
Storm Representative Dew Point Location	46.00 N	104.00 W
Maximum Dew Point	25.6 °C	
Moisture Inflow Vector	SSE @ 499	kilometers
In-place Maximization Factor	**1.08**	
Temporal Transposition (Date)	15-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

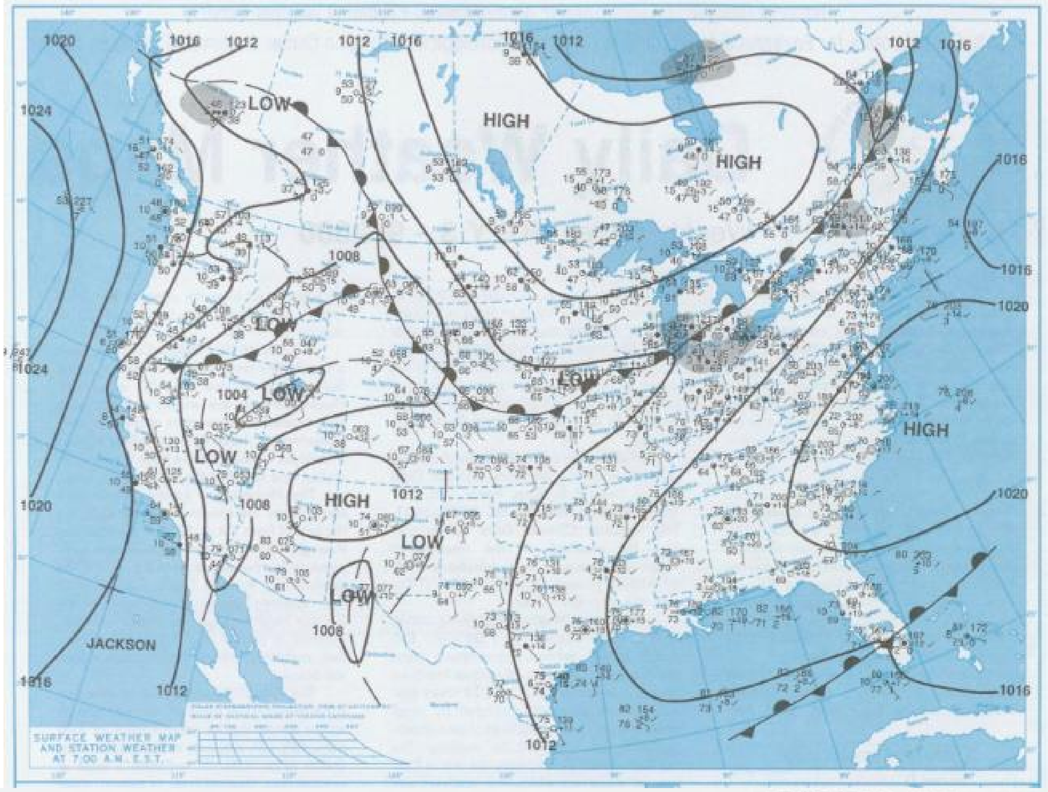
SATURDAY, JULY 1, 2000



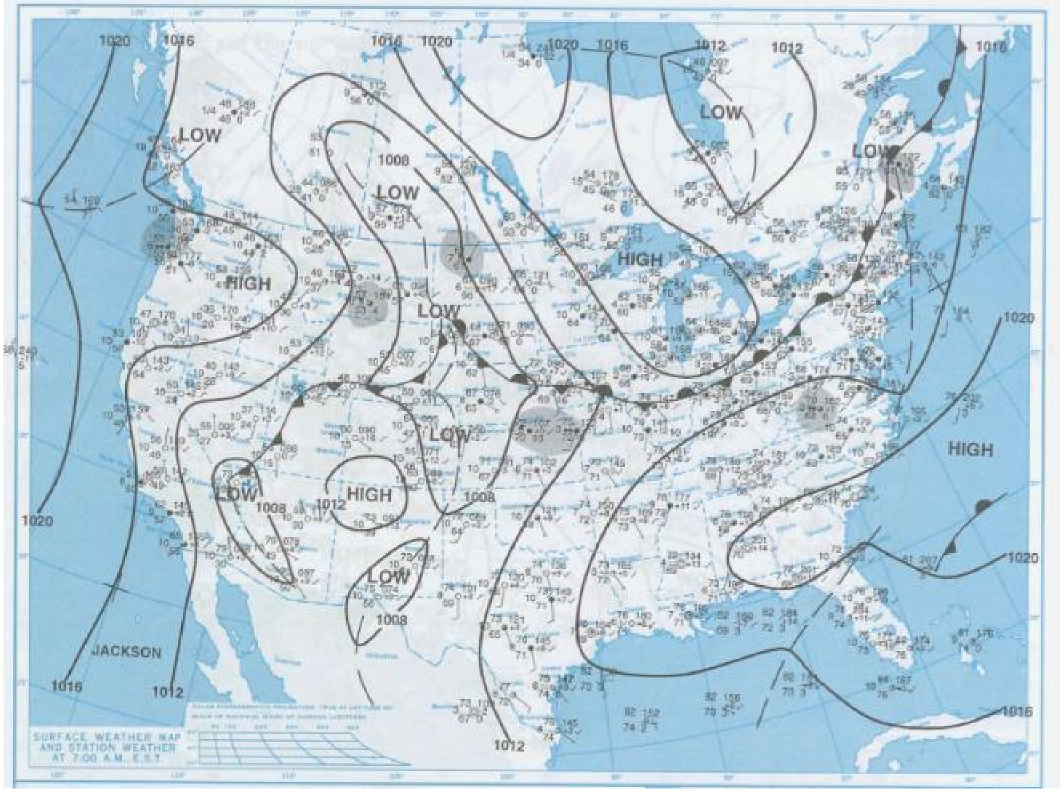
SUNDAY, JULY 2, 2000

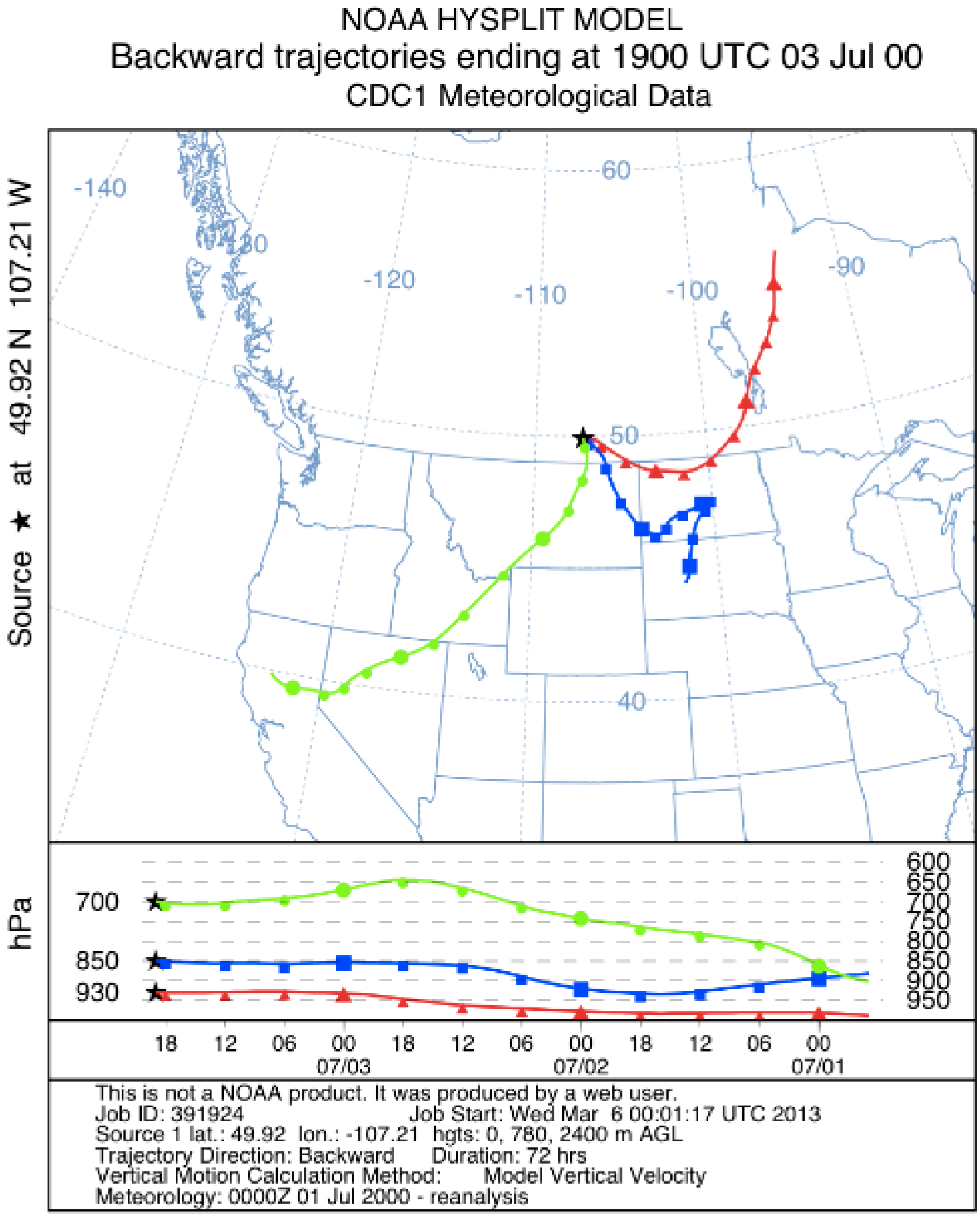


MONDAY, JULY 3, 2000

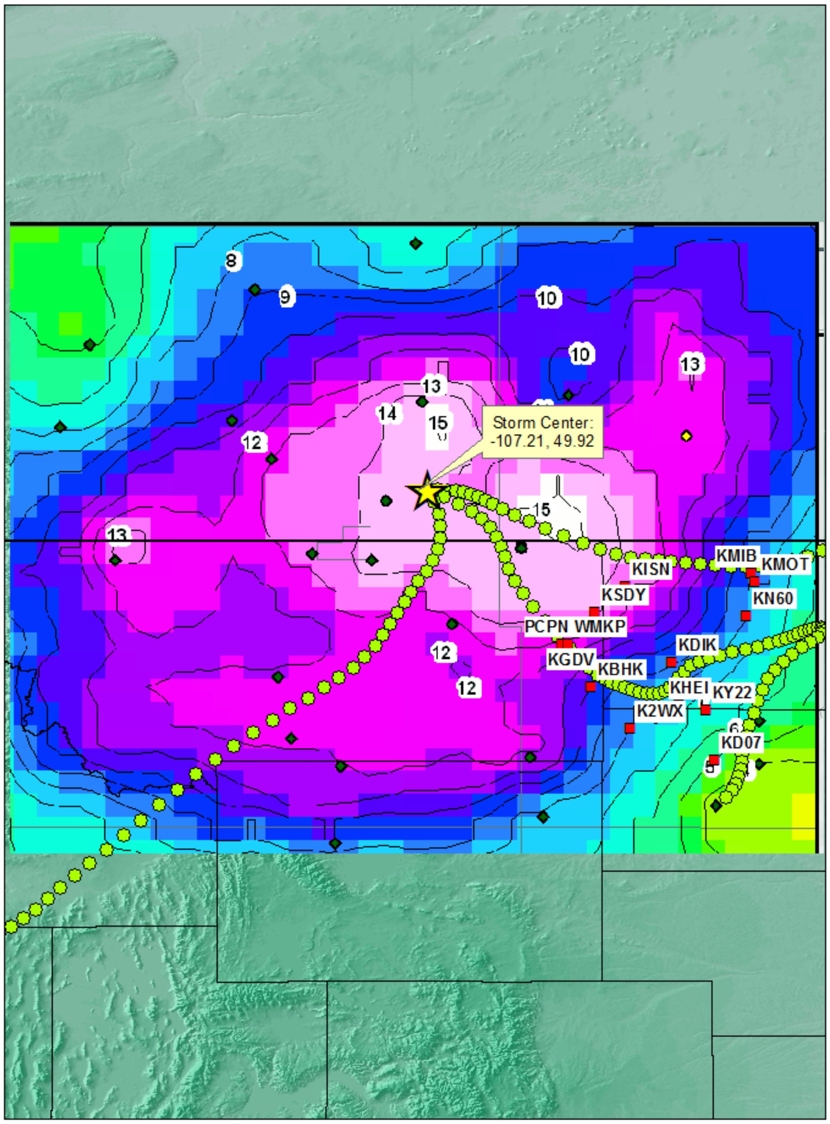


TUESDAY, JULY 4, 2000



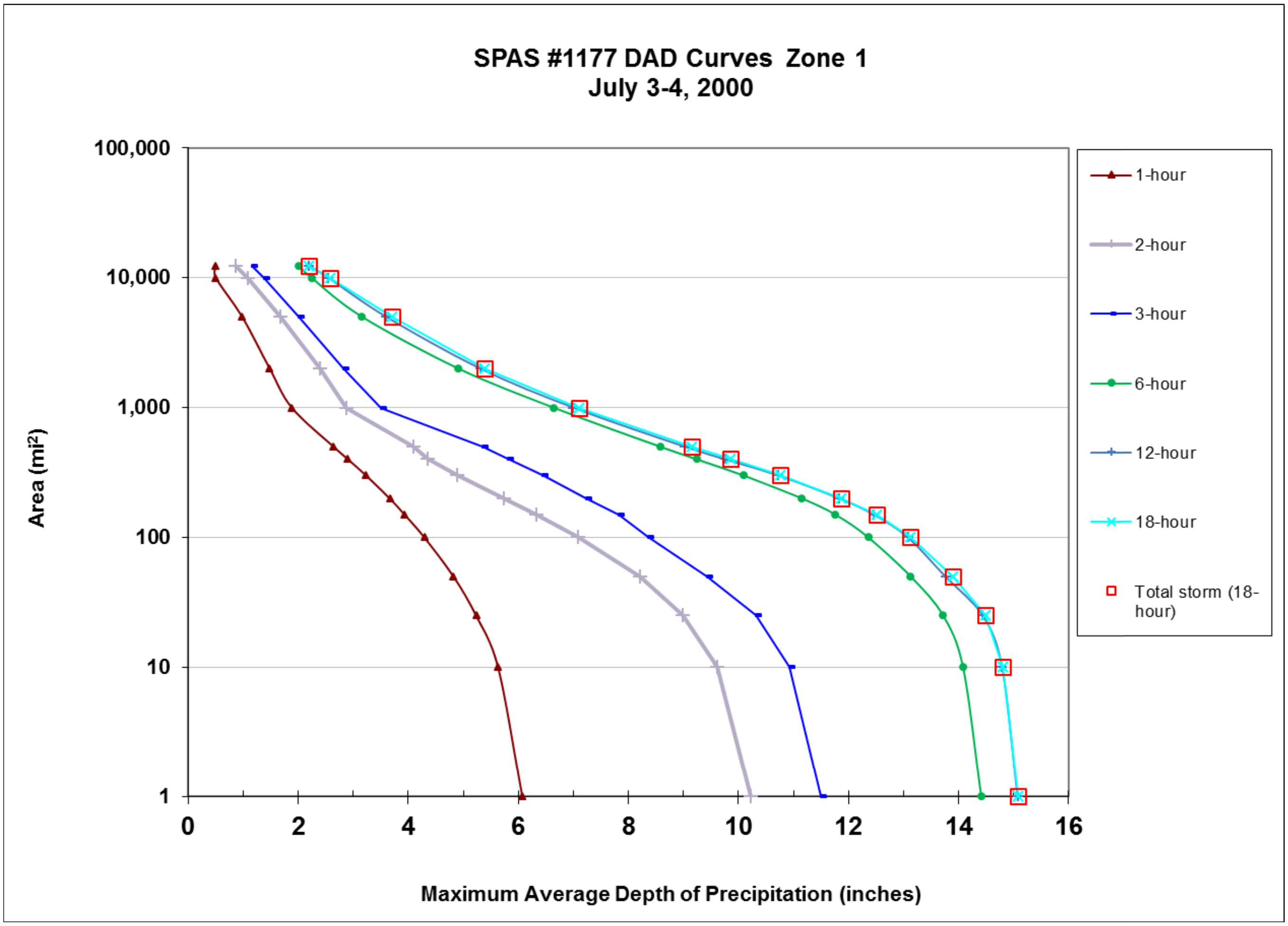


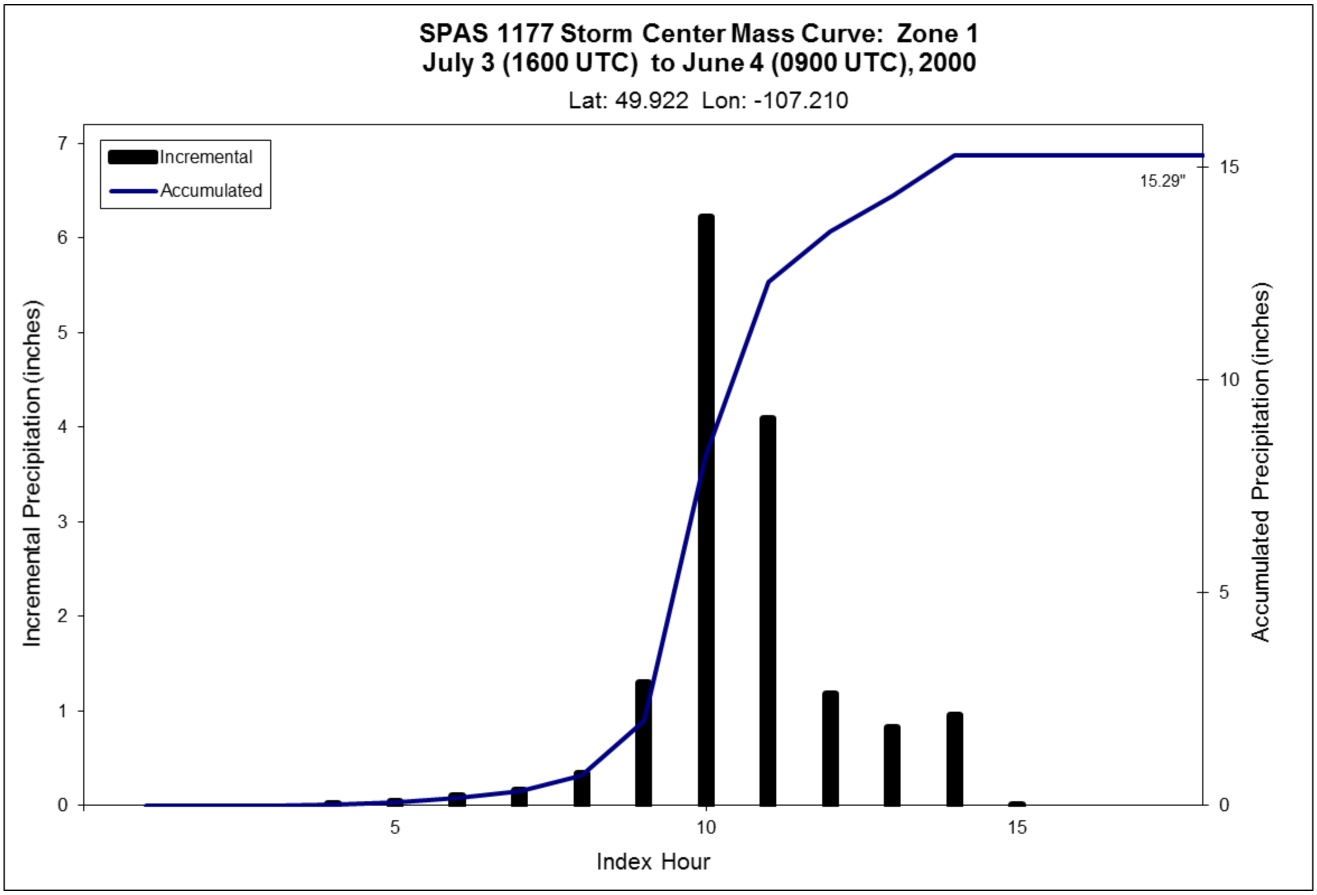
NOAA HYSPLIT MODEL
Backward trajectories ending at 1900 UTC 03 Jul 00
CDC1 Meteorological Data
Source ★ at 49.92 N 107.21 W
-140
-130
-120
-110
-100
-90
60
50
40
hPa
700
850
930
600
650
700
750
800
850
900
950
18 12 06 00 18 12 06 00 18 12 06 00
07/03
07/02
07/01
This is not a NOAA product. It was produced by a web user.
Job ID: 391924 Job Start: Wed Mar 6 00:01:17 UTC 2013
Source 1 lat.: 49.92 lon.: -107.21 hgts: 0, 780, 2400 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 01 Jul 2000 - reanalysis

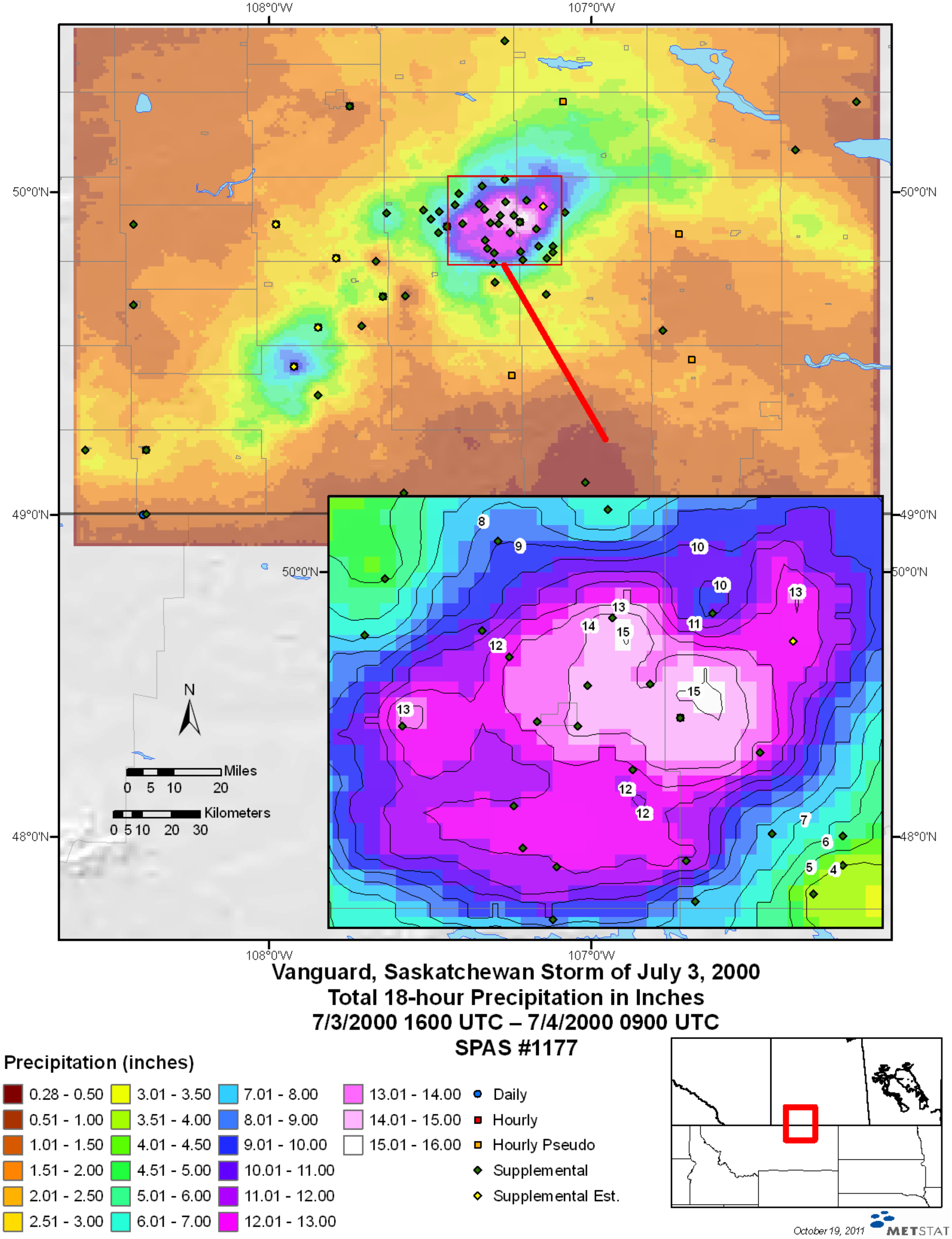


8
9
10
10
13
13
14
15
12
13
Storm Center:
-107.21, 49.92
15
12
12
KISN
KMIB
KMOT
KSDY
KN60
PCPN
WMKP
KDIK
KGDV
KBHK
KHEI
KY22
K2WX
KD07

Storm 1177 - July 3 (1600 UTC) - July 4 (900 UTC), 2000							
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)							
	Duration (hours)						
Area (mi^2)	1	2	3	6	12	18	Total
0.3	6.25	10.37	11.62	14.58	15.29	15.29	15.29
1	6.07	10.22	11.5	14.41	15.07	15.07	15.07
10	5.63	9.61	10.92	14.08	14.79	14.81	14.81
25	5.23	8.99	10.32	13.72	14.44	14.48	14.48
50	4.82	8.21	9.42	13.13	13.76	13.9	13.90
100	4.29	7.09	8.35	12.36	13.08	13.12	13.12
150	3.93	6.32	7.83	11.76	12.46	12.51	12.51
200	3.66	5.74	7.24	11.15	11.83	11.87	11.87
300	3.23	4.89	6.43	10.09	10.73	10.75	10.75
400	2.9	4.36	5.81	9.24	9.76	9.86	9.86
500	2.64	4.1	5.34	8.58	9.03	9.15	9.15
1,000	1.88	2.87	3.51	6.64	7	7.11	7.11
2,000	1.48	2.4	2.82	4.91	5.31	5.39	5.39
5,000	0.98	1.67	2.01	3.16	3.6	3.71	3.71
10,000	0.5	1.08	1.38	2.24	2.55	2.58	2.58
12,353	0.49	0.86	1.16	2	2.2	2.2	2.20




SPAS 1177 Storm Center Mass Curve: Zone 1
July 3 (1600 UTC) to June 4 (0900 UTC), 2000
Lat: 49.922 Lon: -107.210
Incremental
Accumulated
15.29"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour
0
1
2
3
4
5
6
7
0
5
10
15
5
10
15



Vanguard, Saskatchewan Storm of July 3, 2000
Total 18-hour Precipitation in Inches
7/3/2000 1600 UTC – 7/4/2000 0900 UTC
SPAS #1177

Rapid City, SD

June 8-10, 1972

Storm Type: Local

Storm Precipitation Analysis System (SPAS) For Storm #1212

General Storm Location: Black Hills, South Dakota – a.k.a "Rapid City Flood of June 9, 1972"

Storm Dates: June 8-10, 1972

Event: Thunderstorm & stationary front

DAD Zone 1

Latitude: 43.8875°

Longitude: -103.40416°

Max. Grid Rainfall Amount: 401mm

Max. Observed Rainfall Amount: 381+mm

Number of Stations: 310

SPAS Version: 8.5

Base Map: Blend of PRISM and USGS isohyetal.

Spatial resolution: 30 seconds (degree: minute: second, WGS84, ~ 0.25 mi^2, 0.65 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes*

Reliability of results: Although this storm analysis was not based on radar data, abundant supplemental gauge data provided a high degree in confidence in the final magnitudes. Hourly precipitation gauge data was more limited, but available at a few key locations. Given the few hourly reports, storm reports, bucket survey data and other information, enough hourly data was collected to justify a high degree of confidence in the temporal distribution of the results

*Although it's difficult to determine the impact of terrain on the rainfall, in this particular storm the literature suggests (by no surprise) terrain "played a somewhat greater role" in the extreme rains as compared to other extreme storms in the region, we decided to initially create two DAD zones for this reason – a northern and southern zone, split between a relatively low area of precipitation and terrain. However, the literature on this storm also says "There does not appear to be a simple or direct relation between maximum rainfall centers and terrain features at these locations except for the slight indication that east-facing valleys may have contributed to some forced convergence of the prevailing low-level winds."

Storm Name:	**SPAS 1212 Rapid City, SD**	**Storm Adjustment Summary**
Storm Date:	**6/8-11/1972**	
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **15-Jul**

	Lat	Long
Storm Center Location	**43.88 N**	**103.40 W**
Storm Rep Dew Point Location	**44.15 N**	**103.10 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**NE @ 40**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**1,433**	meters
Storm Analysis Duration	**6**	hours

The storm representative dew point is	**25.6 °C**	with total precipitable water above sea level of		**84**	millimeters.
The in-place maximum dew point is	**26.1 °C**	with total precipitable water above sea level of		**87**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**1,433**	which subtracts	**29**	millimeters of precipitable water at	**25.6 °C**
The in-place storm elevation is	**1,433**	which subtracts	**30**	millimeters of precipitable water at	**26.1 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.05**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Used 6hr average Td from KRCA. Temporal trans date to July 15.

Observed Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**119**	**189**	**232**	**270**	**315**	**352**			
26 km^2 (10 mi^2)	**95**	**156**	**194**	**230**	**264**	**291**			
259 km^2 (100 mi^2)	**68**	**106**	**150**	**189**	**216**	**231**			
518 km^2 (200 mi^2)	**60**	**98**	**135**	**171**	**194**	**207**			
1,295 km^2 (500 mi^2)	**47**	**81**	**109**	**137**	**153**	**170**			
2,590 km^2 (1,00 mi^2)	**37**	**62**	**84**	**101**	**114**	**123**			
5,180 km^2 (2,000 mi^2)	**31**	**46**	**63**	**77**	**88**	**96**			
12.950 km^2 (5000 mi^2)	**21**	**32**	**40**	**52**	**60**	**65**			
25,900 km^2 (10,000 mi^2)	**15**	**23**	**28**	**35**	**41**	**49**			
51,800 km^2 (20,000 mi^2)									

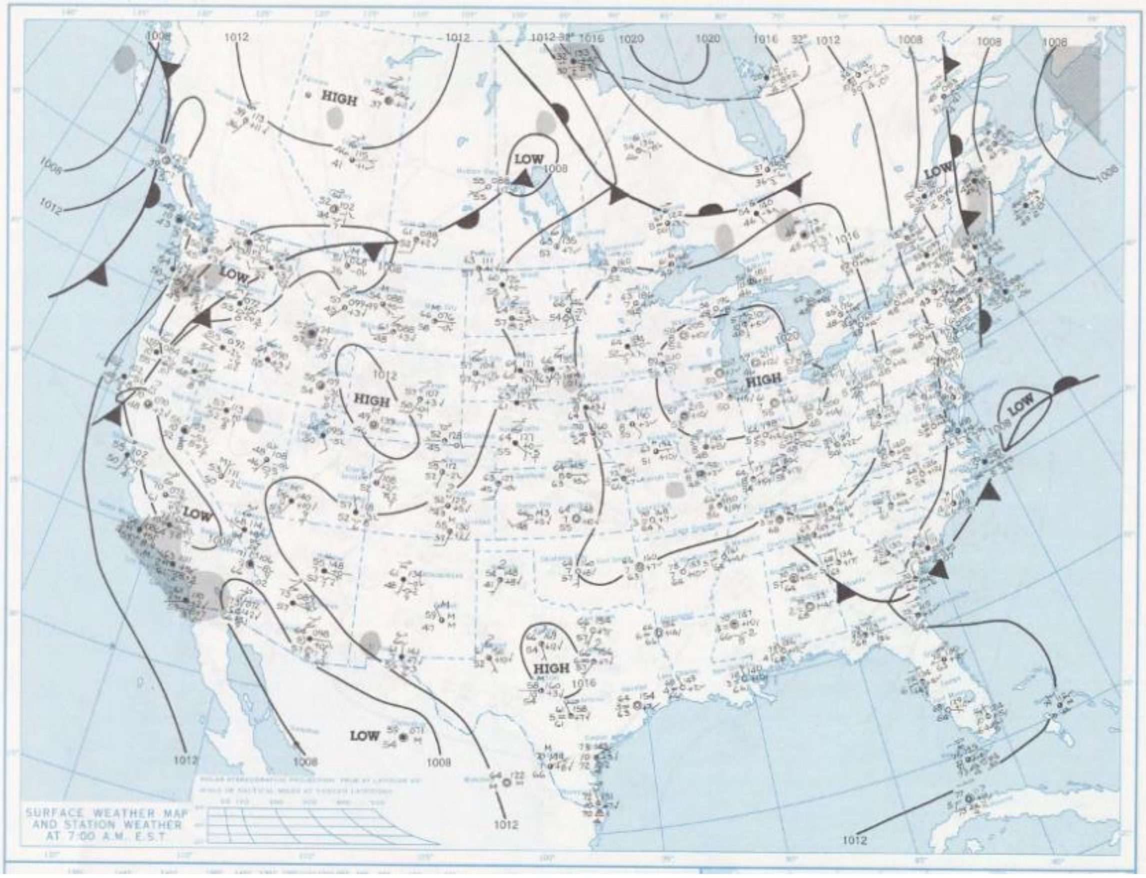
Adjusted Storm Depth-Area-Duration (millimeters)

	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
26 km2 (10 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
259 km2 (100 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
518 km2 (200 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
1,295 km2 (500 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
2,590 km2 (1,00 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
5,180 km2 (2,000 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
12.950 km2 (5000 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
25,900 km2 (10,000 mi2)	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***	**N/A***			
51,800 km2 (20,000 mi2)									

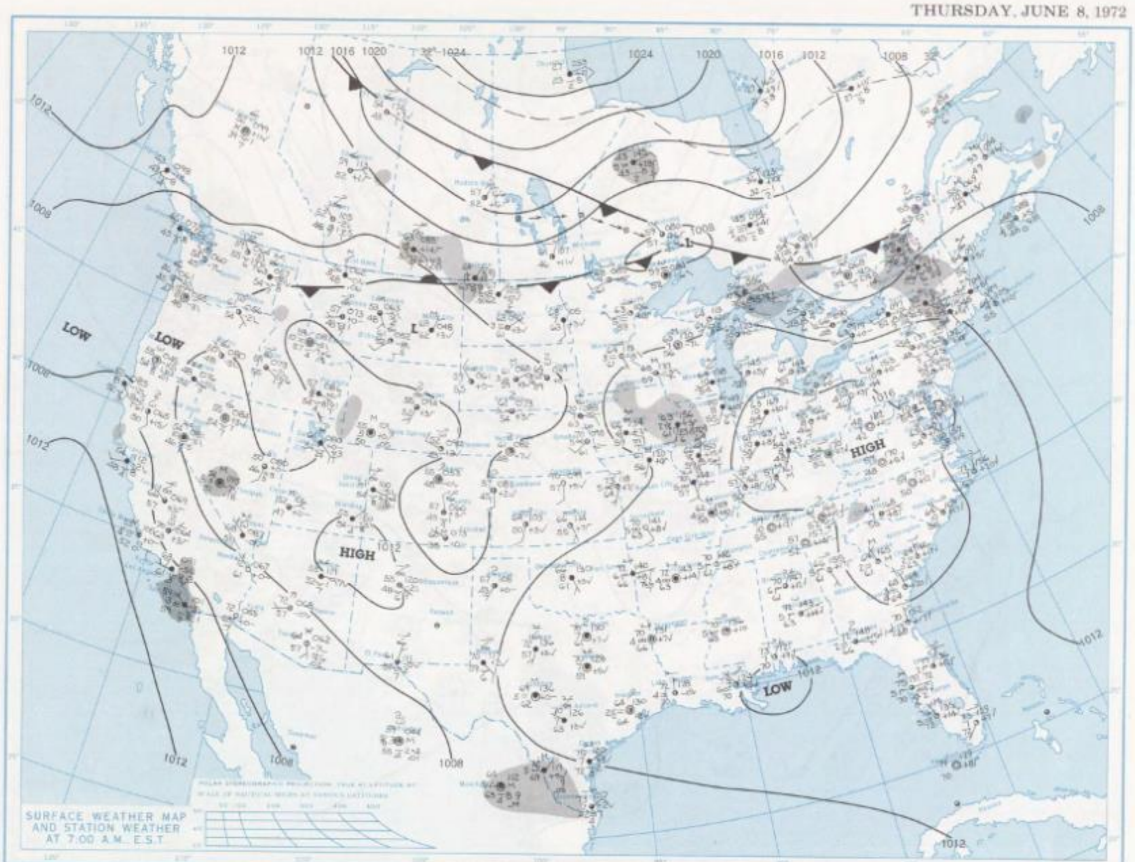
Storm or Storm Center Name	**SPAS 1212 Rapid City, SD**	
Storm Date(s)	6/8-11/1972	
Storm Type	MCC	
Storm Location	43.88 N	103.40 W
Storm Center Elevation	1,433	meters
Precipitation Total & Duration	401	millimeters
Storm Representative Dew Point	25.6 °C	6
Storm Representative Dew Point Location	44.15 N	103.10 W
Maximum Dew Point	26.1 °C	
Moisture Inflow Vector	NE @ 40	kilometers
In-place Maximization Factor	**1.05**	
Temporal Transposition (Date)	15-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location

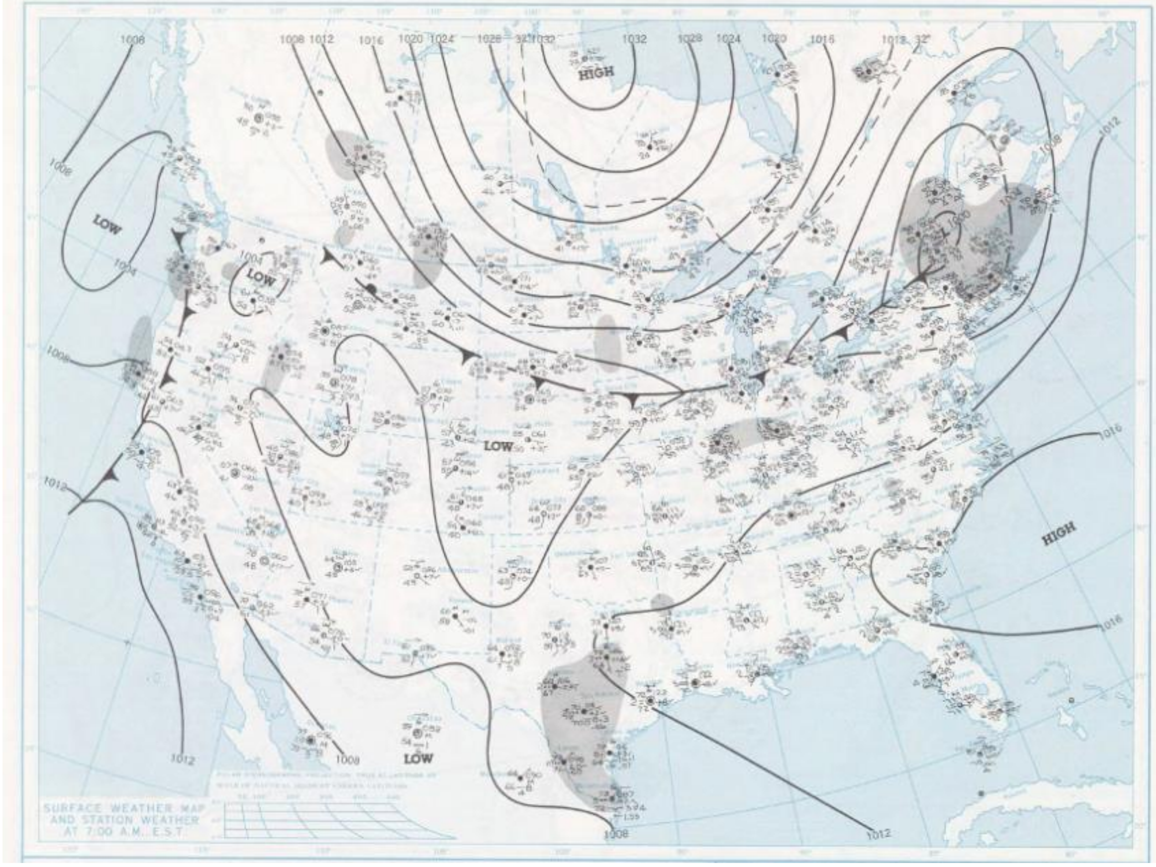
WEDNESDAY, JUNE 7, 1972



THURSDAY, JUNE 8, 1972

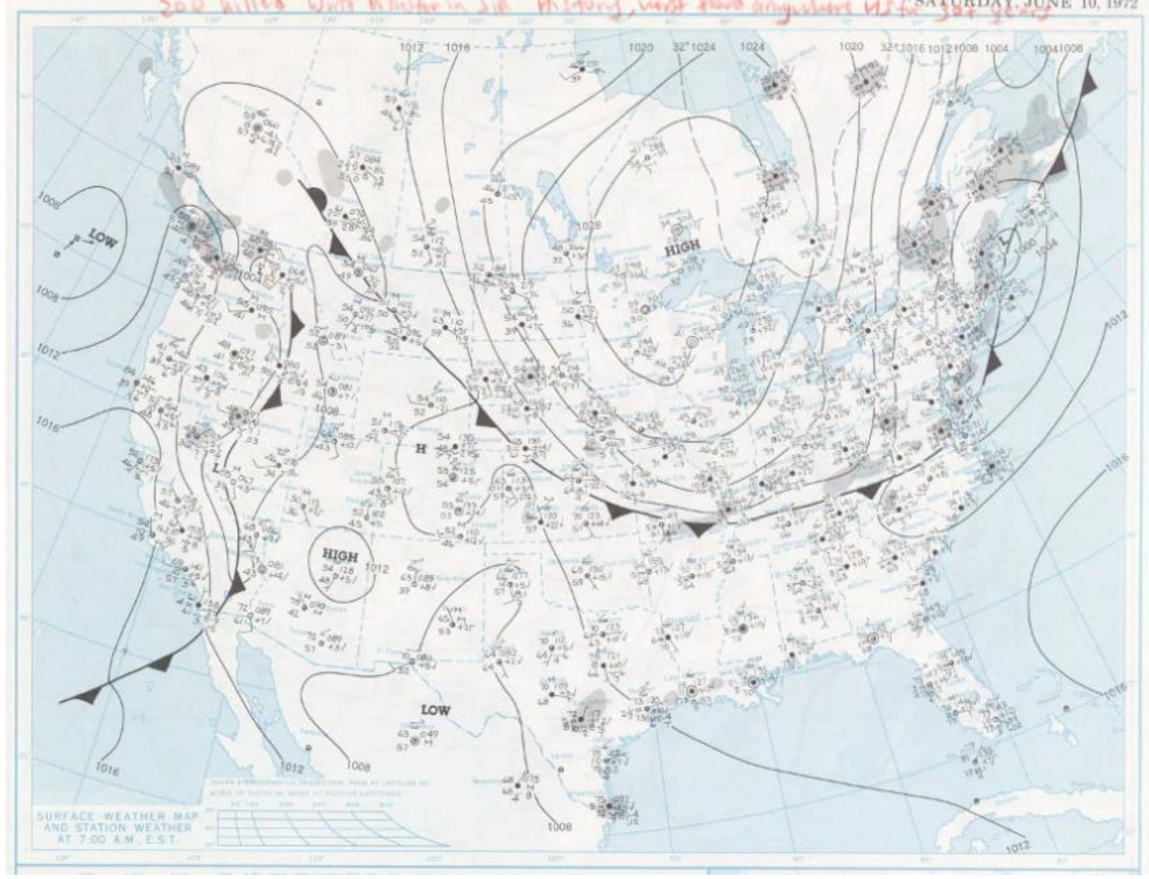


FRIDAY, JUNE 9, 1972

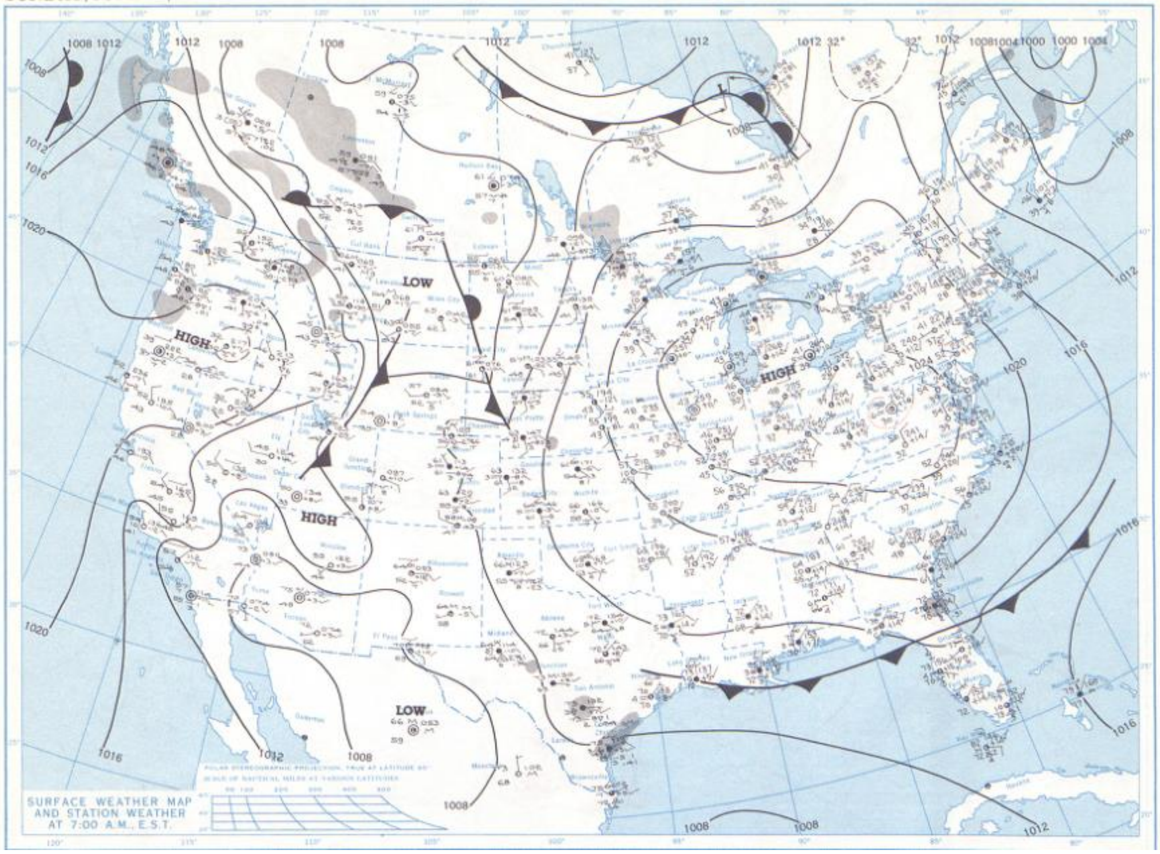


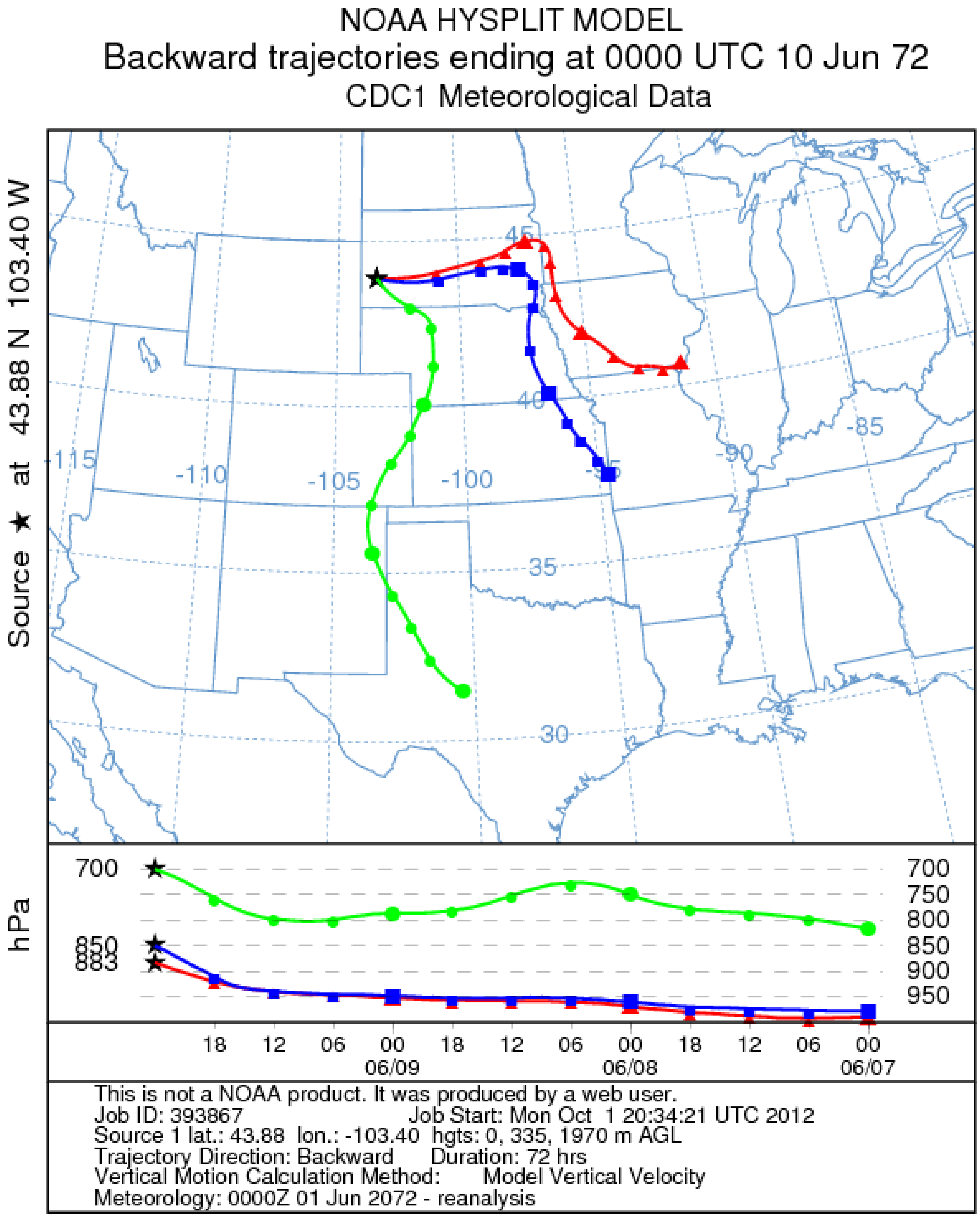
Disastrous Flash Floods Rapid City - Black Hills area, up to 7" rain in 12 hr some spots. 200 killed Worst Disaster in S.D. History, worst flood anywhere US for 38 years

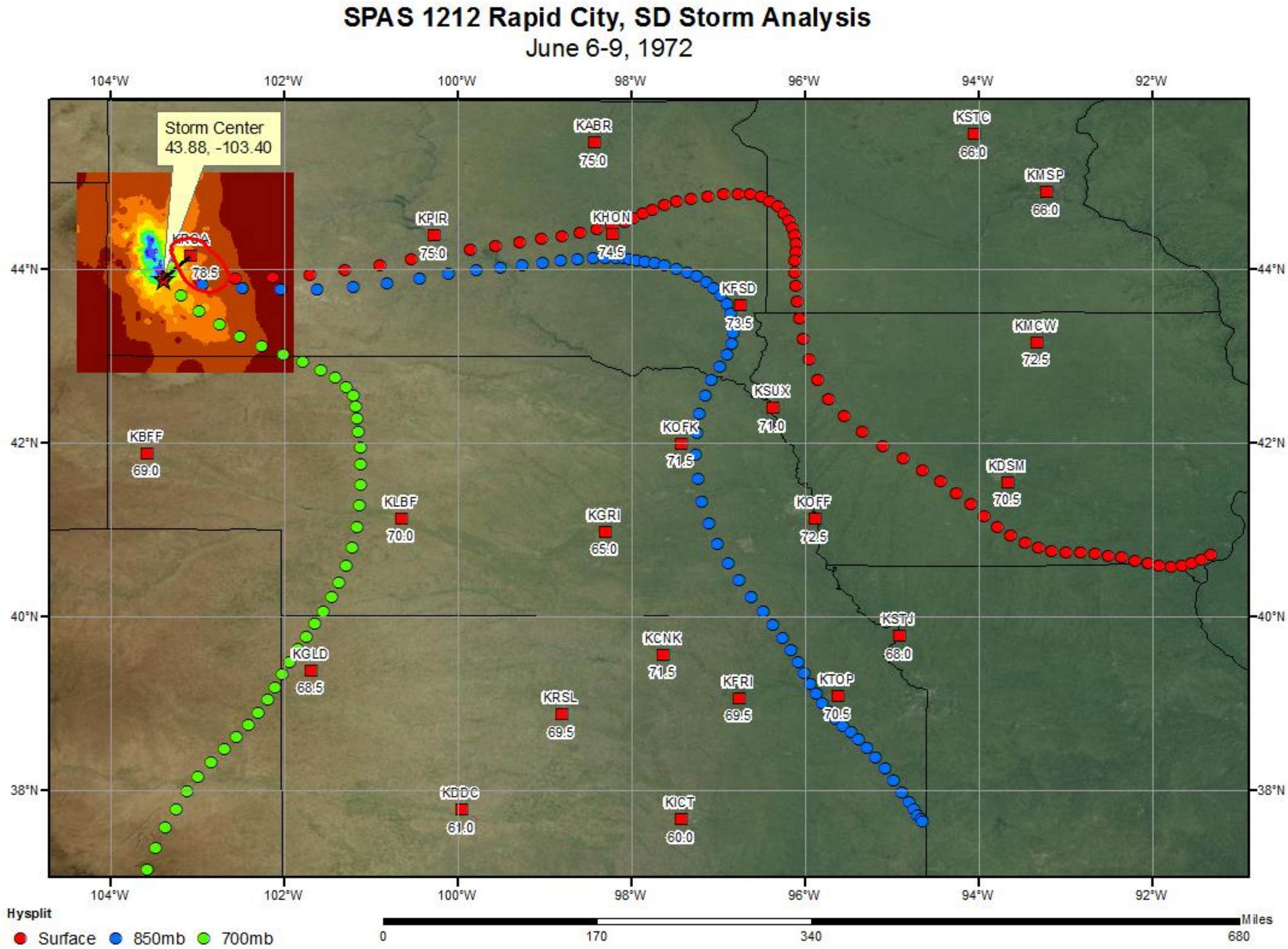
SATURDAY, JUNE 10, 1972



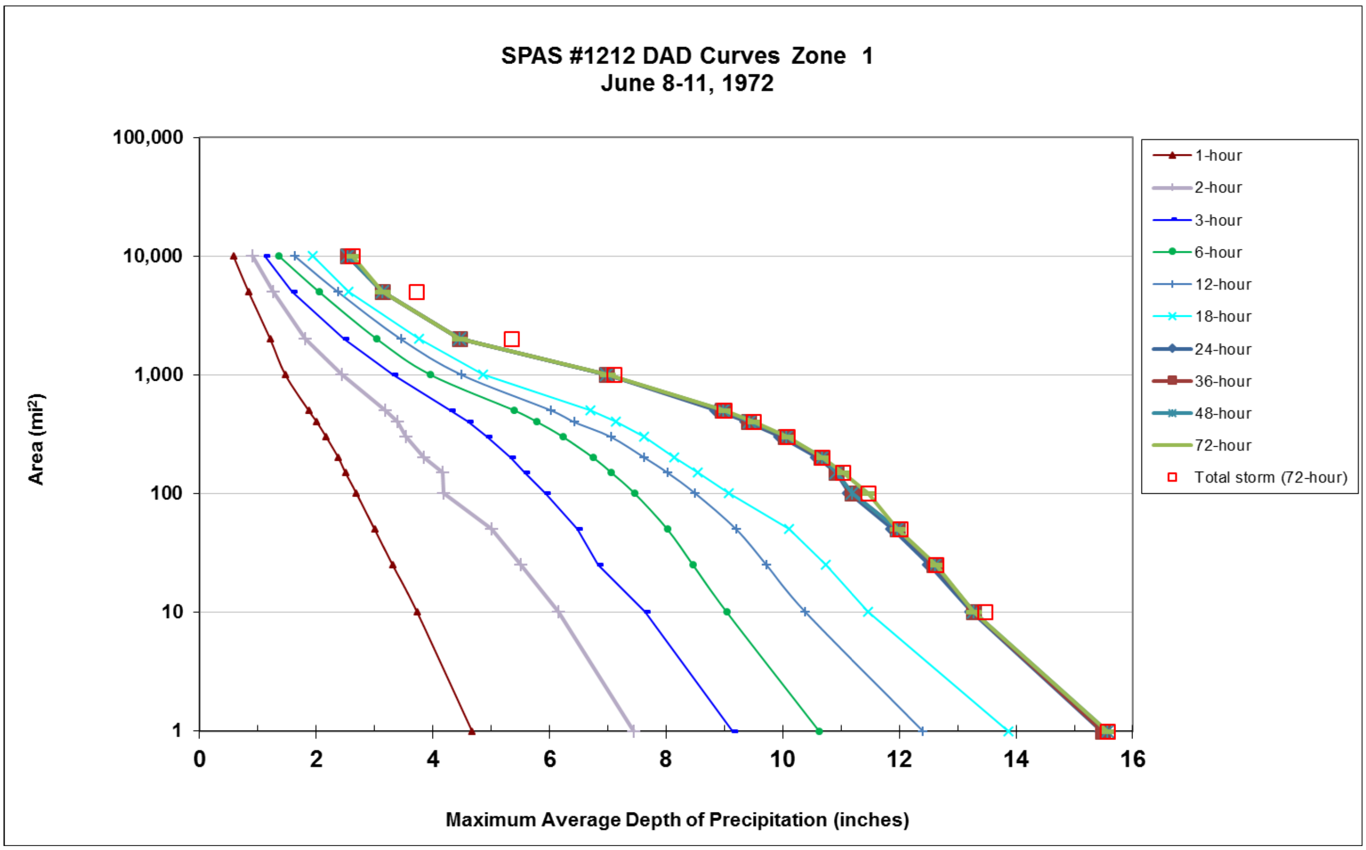
SUNDAY, JUNE 11, 1972

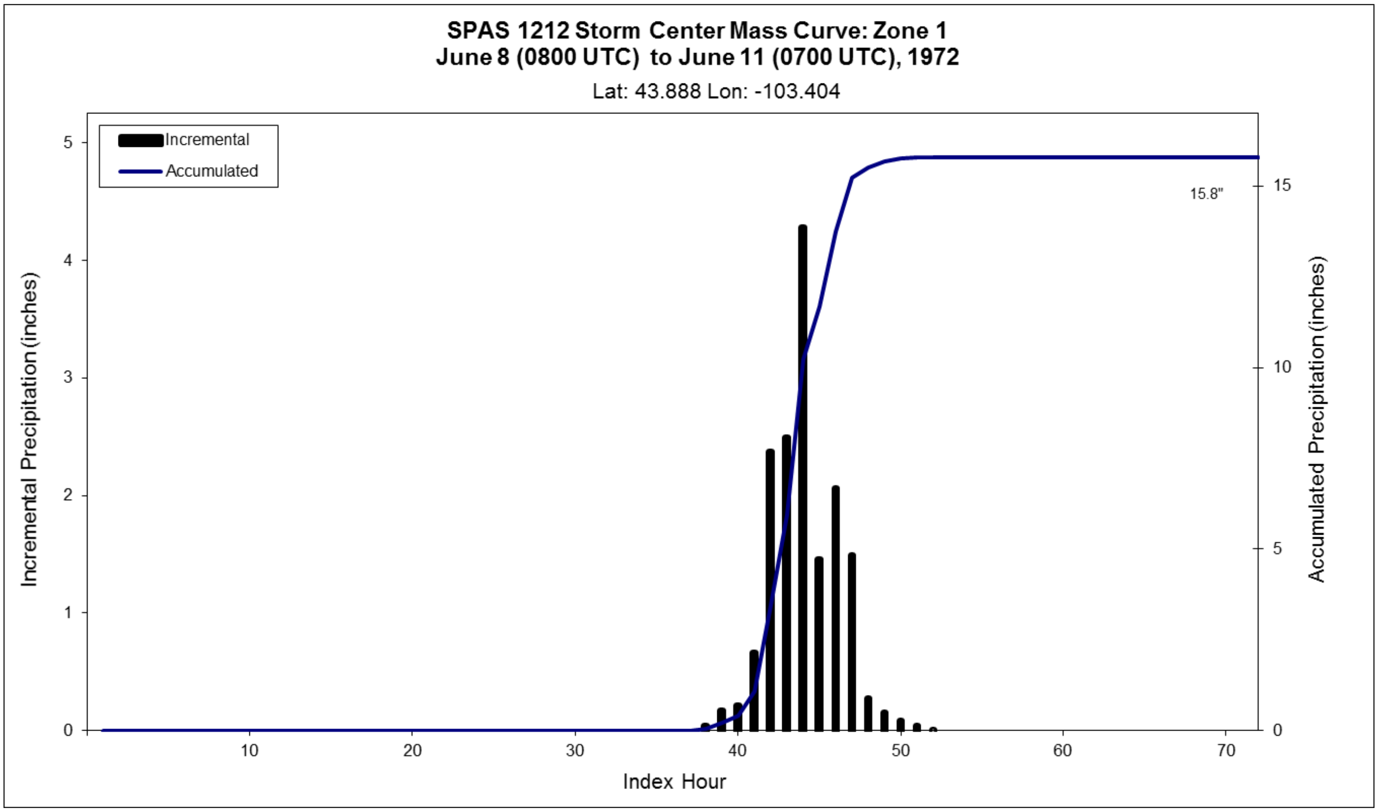


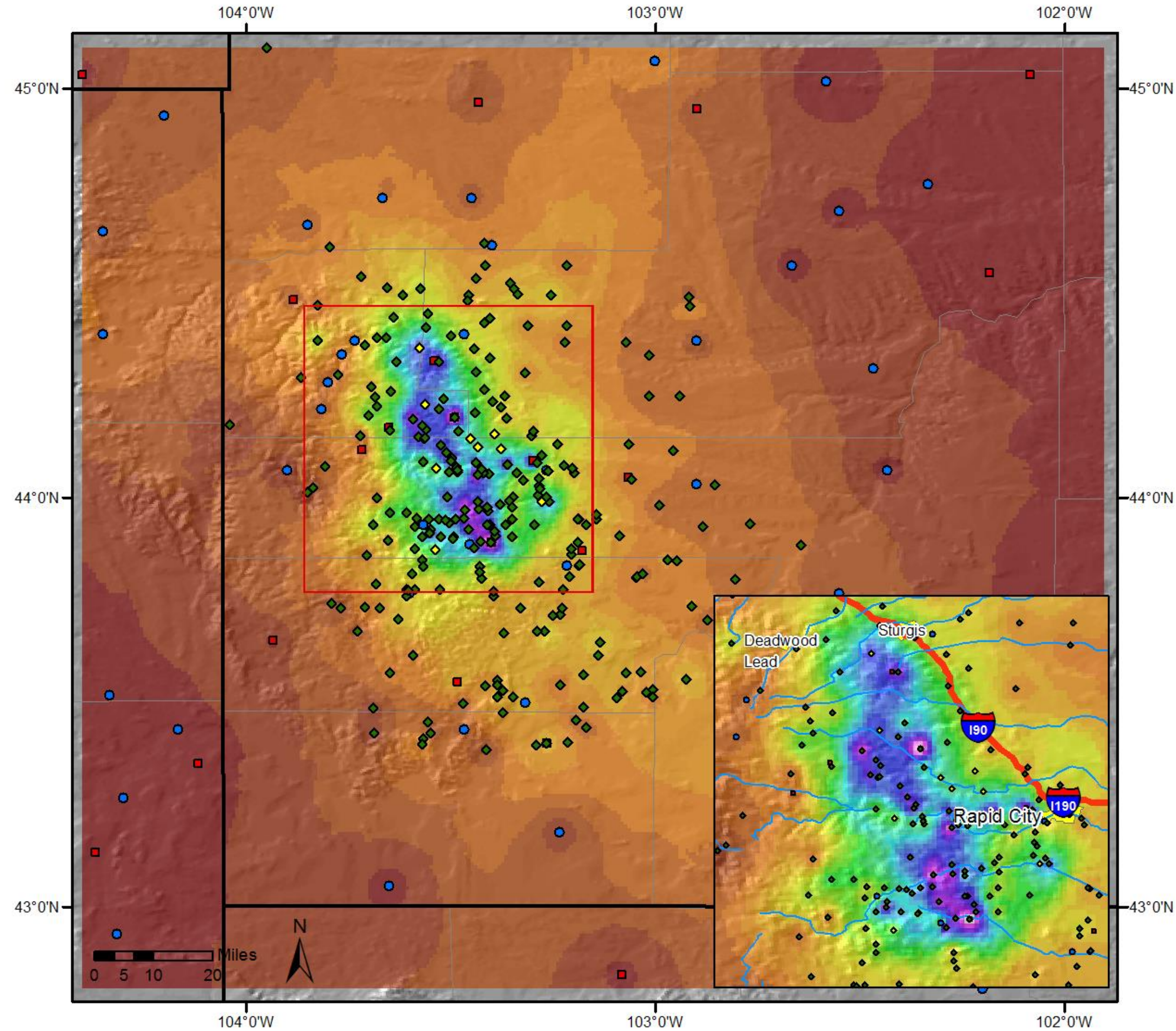

NOAA HYSPLIT MODEL
Backward trajectories ending at 0000 UTC 10 Jun 72
CDC1 Meteorological Data
Source ★ at 43.88 N 103.40 W
-115
-110
-105
-100
-95
-90
-85
45
40
35
30
hPa
700
750
800
850
900
950
850
883
18 12 06 00 18 12 06 00 18 12 06 00
06/09
06/08
06/07
This is not a NOAA product. It was produced by a web user.
Job ID: 393867 Job Start: Mon Oct 1 20:34:21 UTC 2012
Source 1 lat.: 43.88 lon.: -103.40 hgts: 0, 335, 1970 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 01 Jun 2072 - reanalysis


SPAS 1212 Rapid City, SD Storm Analysis
June 6-9, 1972
Storm Center
43.88, -103.40
KRCA
78.5
KABR
75.0
KSTC
66.0
KMSP
66.0
KPIR
75.0
KHON
74.5
KFSD
73.5
KMCW
72.5
KSUX
71.0
KOFK
71.5
KBFF
69.0
KDSM
70.5
KLBF
70.0
KGRI
65.0
KOFF
72.5
KSTJ
68.0
KCNK
71.5
KGLD
68.5
KFRI
69.5
KTOP
70.5
KRSL
69.5
KDDC
61.0
KICT
60.0
104°W
102°W
100°W
98°W
96°W
94°W
92°W
44°N
42°N
40°N
38°N
Hysplit
Surface
850mb
700mb
Miles
0
170
340
680

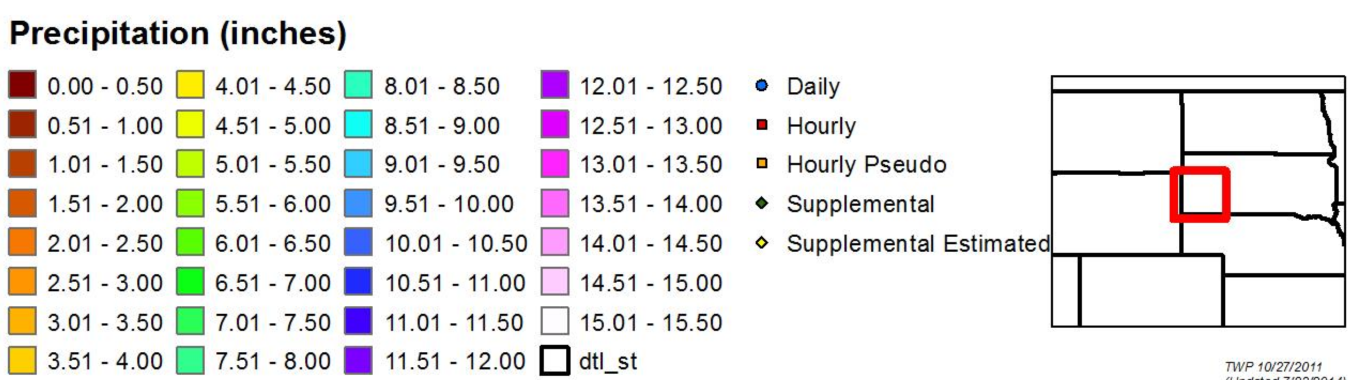
Storm 1212 - June 8 (800 UTC) - June 11 (900 UTC), 1972											
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)											
	Duration (hours)										
Area (mi^2)	1	2	3	4	5	6	12	18	24	36	Total
0.2	5.06	7.74	9.56	11.53	12.80	14.89	15.71	15.80	15.80	15.80	15.80
1	4.67	7.44	9.14	10.62	12.40	13.87	15.47	15.48	15.56	15.57	15.57
10	3.73	6.15	7.64	9.04	10.39	11.46	13.24	13.27	13.27	13.27	13.46
25	3.31	5.50	6.83	8.46	9.72	10.73	12.51	12.60	12.61	12.62	12.62
50	3.00	5.00	6.48	8.02	9.20	10.11	11.89	11.96	11.96	11.97	12.02
100	2.69	4.18	5.92	7.46	8.50	9.08	11.14	11.19	11.19	11.47	11.47
150	2.50	4.16	5.57	7.06	8.02	8.55	10.92	10.92	10.92	11.03	11.03
200	2.38	3.85	5.33	6.75	7.63	8.14	10.59	10.65	10.67	10.68	10.68
300	2.17	3.54	4.93	6.23	7.05	7.62	9.96	10.04	10.06	10.07	10.07
400	2.01	3.40	4.60	5.79	6.42	7.14	9.38	9.42	9.43	9.50	9.50
500	1.87	3.19	4.30	5.40	6.03	6.71	8.86	8.96	8.98	8.99	8.99
1,000	1.47	2.44	3.31	3.96	4.49	4.86	6.97	6.98	6.98	6.99	7.10
2,000	1.21	1.81	2.48	3.04	3.45	3.76	4.46	4.46	4.46	4.46	5.34
5,000	0.84	1.27	1.59	2.05	2.37	2.56	3.13	3.13	3.13	3.13	3.72
10,000	0.58	0.91	1.11	1.36	1.63	1.94	2.53	2.53	2.53	2.62	2.62




SPAS 1212 Storm Center Mass Curve: Zone 1
June 8 (0800 UTC) to June 11 (0700 UTC), 1972
Lat: 43.888 Lon: -103.404
Incremental
Accumulated
15.8"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour
0
1
2
3
4
5
10
20
30
40
50
60
70
0
5
10
15



TOTAL 72-HOUR PRECIPITATION
June 9-10, 1972 - "Rapid City Flood of 1972"
SPAS #1212



TWP 10/27/2011
(Updated 7/23/2014)

Glen Ullin, ND

June 24, 1966

Storm Type: Local

Storm Precipitation Analysis System (SPAS) For Storm #1324

General Storm Location: Near Glen Ullin, ND (Stanton, ND)

Storm Dates: June 24, 1966

Event: Thunderstorm cloud-burst

DAD Zone 1

- **Latitude**: 47.3041°
- **Longitude**: -101.3875°
- **Max. grid rainfall amount**: 327mm
- **Max. observed rainfall amount**: 158mm (Glen Ullin, ND)
- **Number of Stations**: 58

SPAS Version: 9.5

Base Map Used: Modified Digitized USGS Isohyetal Map

Spatial resolution: 30 seconds (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of Results: Given the analysis had 18 hourly stations, 39 daily stations and a detailed USGS total isohyetal map, the overall confidence in the results are higher than average. Three hourly stations resided at locations in/near the storm center, therefore increasing confidence amongst the heaviest precipitation. Heavy amounts of hail accompanied this storm, which may have influenced the timing at tipping bucket gauges. Unofficial, newspaper reports of up to "10 inches of rain in a half hour" could not be verified and therefore the analysis does not represent rainfall intensities that high. The maximum storm center precipitation is based on the fact the USGS report noted up to 13" of rain fell.

NOTE: This storm was included in NOAA Technical Report NWS 25 (Comparison of Generalized Estimates of Probable Maximum Precipitation With Greatest Observed Rainfalls, Washington, D.C., March 1980). This storms' observed rainfall was >= 50% of the all-season PMP for 6-hr/10mi^2, 12-hr/10mi^2 and 6-hr/200mi^2.

Storm Name:	SPAS 1324 Glen Ullin, ND	**Storm Adjustment Summary**
Storm Date:	6/24/1966	
AWA Analysis Date:	7/20/2015	

Temporal Transposition Date **8-Jul**

	Lat	Long
Storm Center Location	**47.30 N**	**101.38 W**
Storm Rep Dew Point Location	**42.00 N**	**102.00 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**S @ 595**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**518**	meters
Storm Analysis Duration	**6**	hours

The storm representative dew point is	**22.2 °C**	with total precipitable water above sea level of		**63**	millimeters.
The in-place maximum dew point is	**26.4 °C**	with total precipitable water above sea level of		**89**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**518**	which subtracts	**10**	millimeters of precipitable water at	**22.2 °C**
The in-place storm elevation is	**518**	which subtracts	**12**	millimeters of precipitable water at	**26.4 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.46**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: DAD values taken from SPAS 1324. Storm representative dew point value was based on maximum 6-hr Td values on June 23-24, 1966 at KHON, KPIR, and KABR. Values were selected in region where temperature did not vary more than a 1-degree over a large area.

Observed Storm Depth-Area-Duration (millimeters)

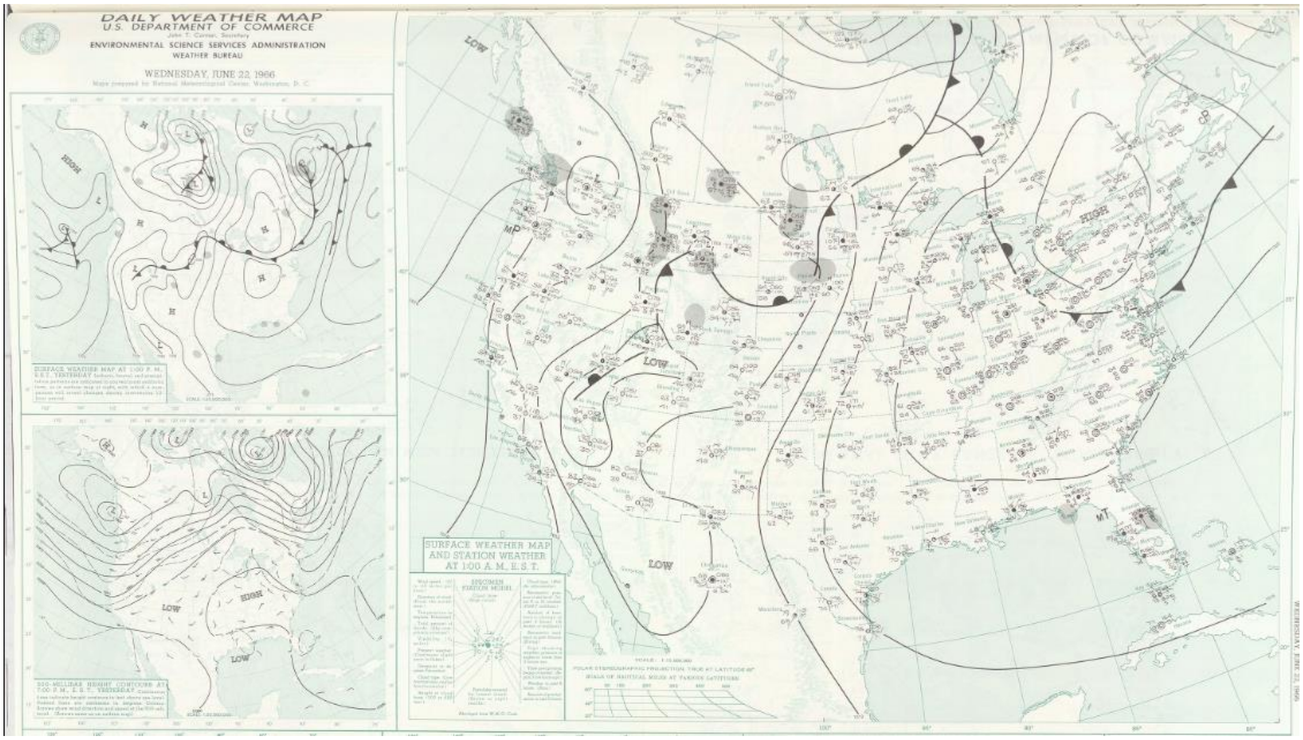
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**203**		**303**			**315**			
26 km^2 (10 mi^2)	**190**		**285**			**296**			
259 km^2 (100 mi^2)	**151**		**232**			**245**			
518 km^2 (200 mi^2)	**122**		**192**			**212**			
1,295 km^2 (500 mi^2)	**81**		**145**			**172**			
2,590 km^2 (1,00 mi^2)	**53**		**108**			**126**			
5,180 km^2 (2,000 mi^2)	**37**		**68**			**102**			
12.950 km^2 (5000 mi^2)	**23**		**45**			**56**			
25,900 km^2 (10,000 mi^2)	**11**		**34**			**39**			
51,800 km^2 (20,000 mi^2)									

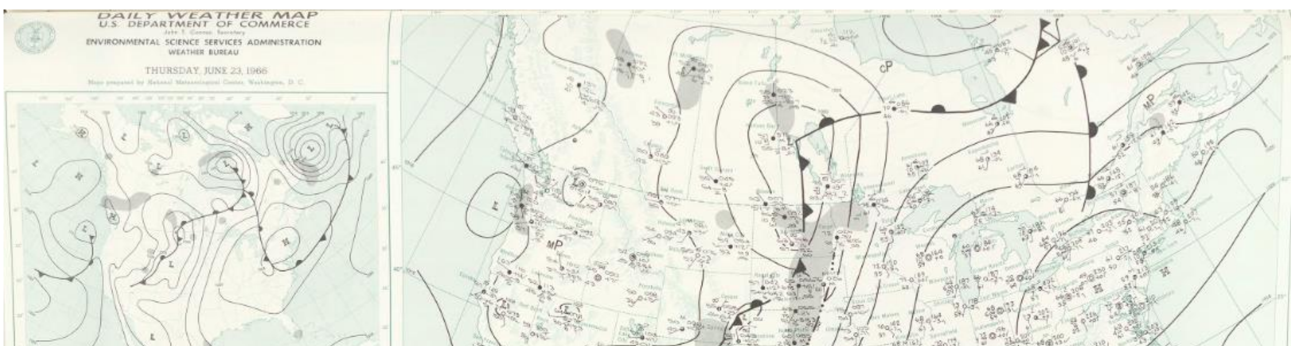
Adjusted Storm Depth-Area-Duration (millimeters)

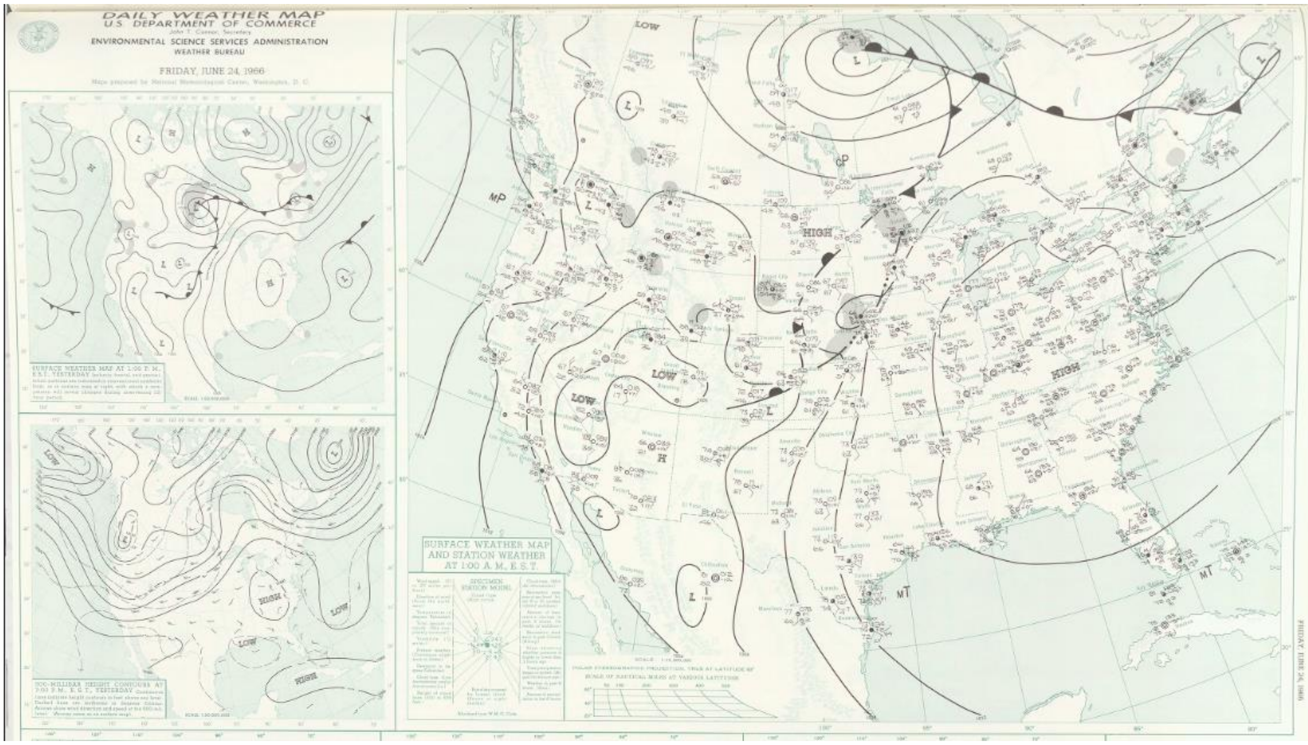
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***		**N/A***			**N/A***			
26 km2 (10 mi2)	**N/A***		**N/A***			**N/A***			
259 km2 (100 mi2)	**N/A***		**N/A***			**N/A***			
518 km2 (200 mi2)	**N/A***		**N/A***			**N/A***			
1,295 km2 (500 mi2)	**N/A***		**N/A***			**N/A***			
2,590 km2 (1,00 mi2)	**N/A***		**N/A***			**N/A***			
5,180 km2 (2,000 mi2)	**N/A***		**N/A***			**N/A***			
12.950 km2 (5000 mi2)	**N/A***		**N/A***			**N/A***			
25,900 km2 (10,000 mi2)	**N/A***		**N/A***			**N/A***			
51,800 km2 (20,000 mi2)									

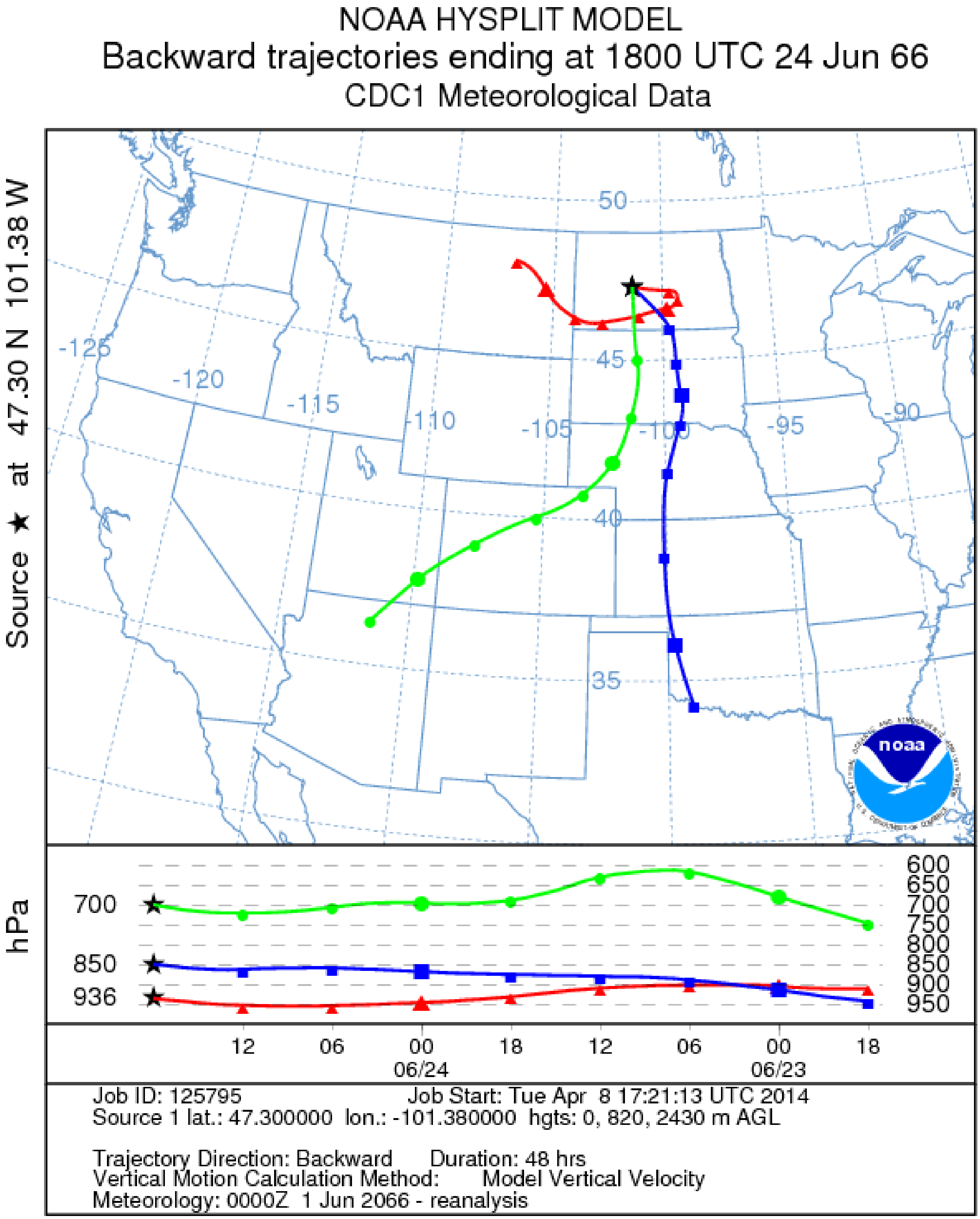
Storm or Storm Center Name	**SPAS 1324 Glen Ullin, ND**	
Storm Date(s)	6/24/1966	
Storm Type	Convective	
Storm Location	47.30 N	101.38 W
Storm Center Elevation	518	meters
Precipitation Total & Duration	327	millimeters
Storm Representative Dew Point	22.2 °C	6
Storm Representative Dew Point Location	42.00 N	102.00 W
Maximum Dew Point	26.4 °C	
Moisture Inflow Vector	S @ 595	kilometers
In-place Maximization Factor	**1.46**	
Temporal Transposition (Date)	8-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

*Variable dependent on transposition location


DAILY WEATHER MAP
U.S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
WEATHER BUREAU
WEDNESDAY, JUNE 22, 1966
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.
LOW
HIGH
LOW
LOW
HIGH
LOW

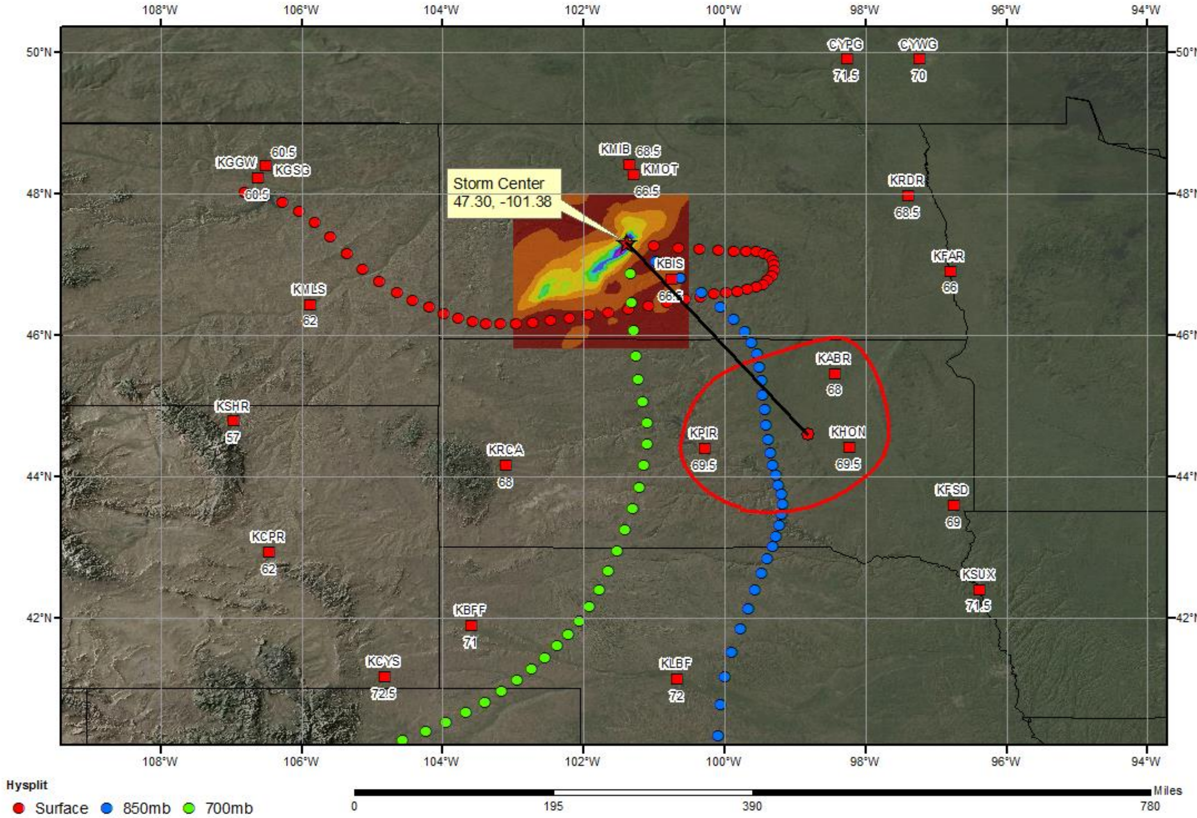

DAILY WEATHER MAP
U.S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
WEATHER BUREAU
THURSDAY, JUNE 23, 1966
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.
HIGH
HIGH


DAILY WEATHER MAP
U.S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
WEATHER BUREAU
FRIDAY, JUNE 24, 1966
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.
HIGH
LOW

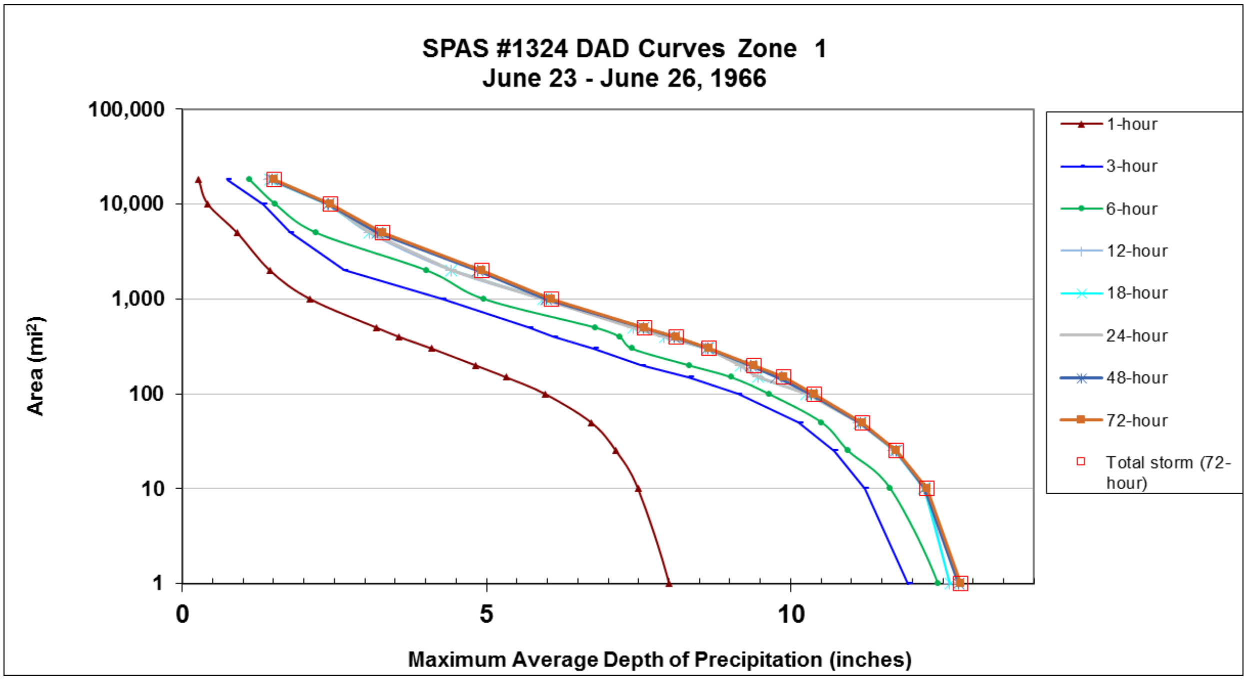

NOAA HYSPLIT MODEL
Backward trajectories ending at 1800 UTC 24 Jun 66
CDC1 Meteorological Data
Source ★ at 47.30 N 101.38 W
50
45
40
35
-125
-120
-115
-110
-105
-100
-95
-90
noaa
hPa
700
850
936
600
650
700
750
800
850
900
950
12
06
00
18
12
06
00
18
06/24
06/23
Job ID: 125795
Job Start: Tue Apr 8 17:21:13 UTC 2014
Source 1 lat.: 47.300000 lon.: -101.380000 hgts: 0, 820, 2430 m AGL
Trajectory Direction: Backward
Duration: 48 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Jun 2066 - reanalysis

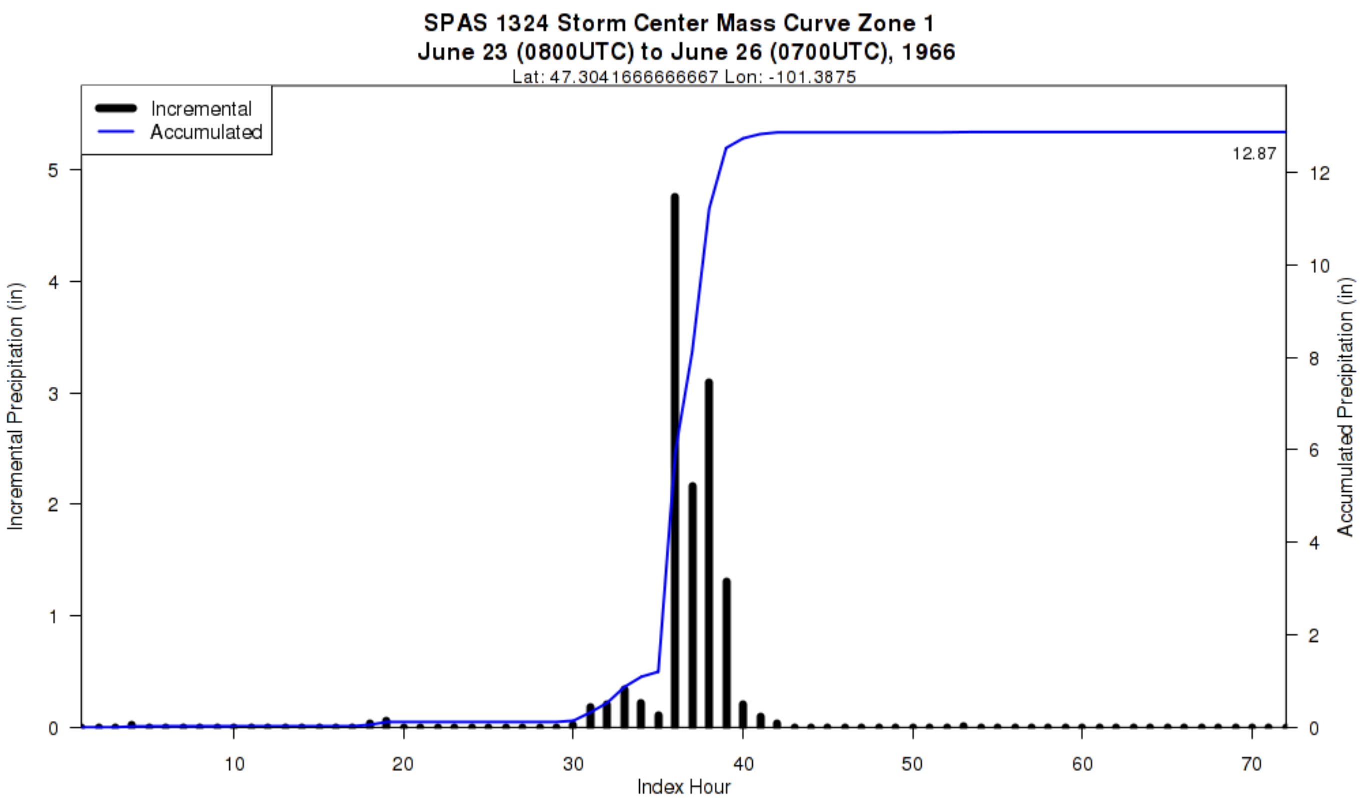
SPAS 1324 Glen Ullin, ND Storm Analysis

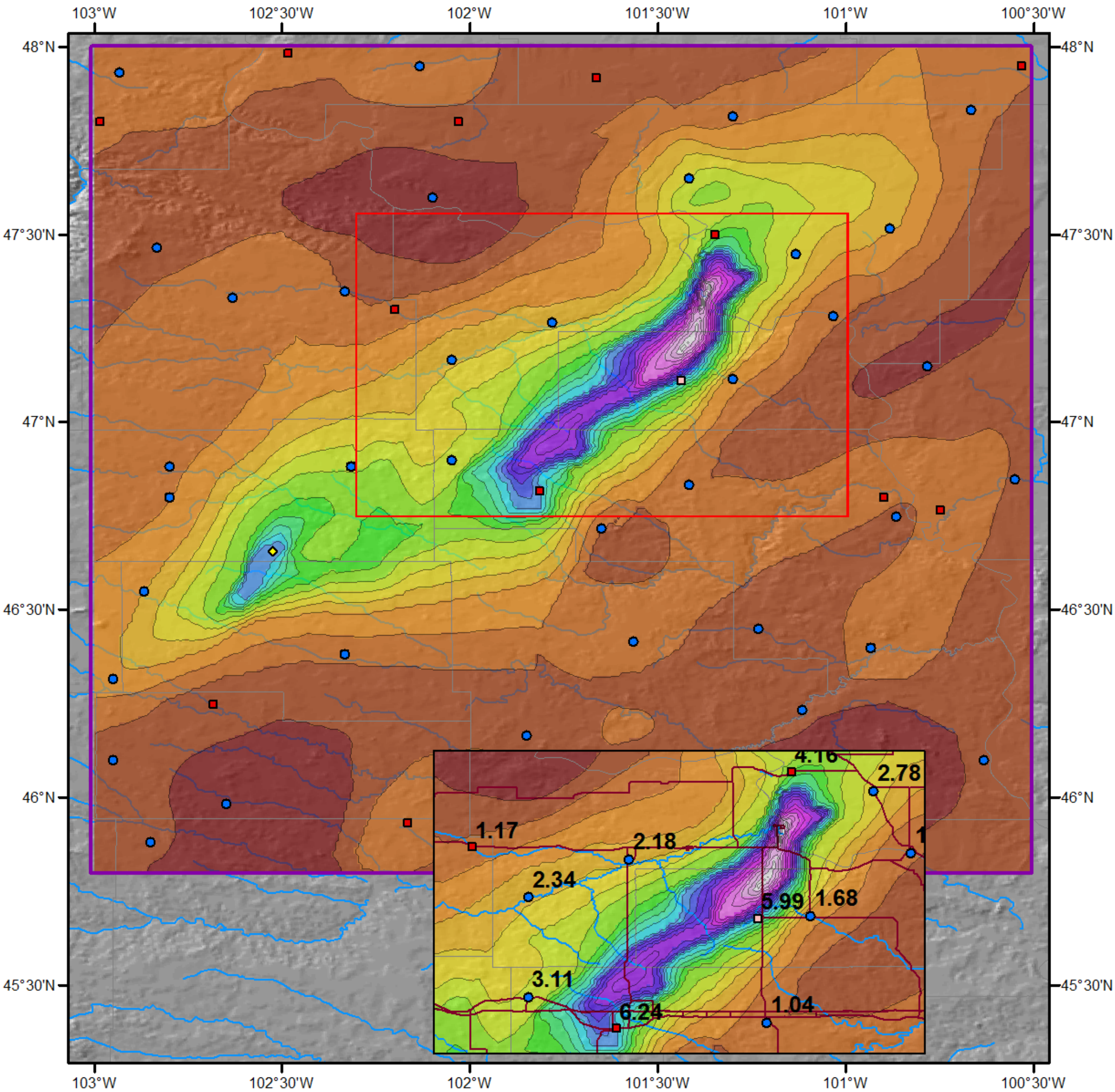
June 23-24, 1966



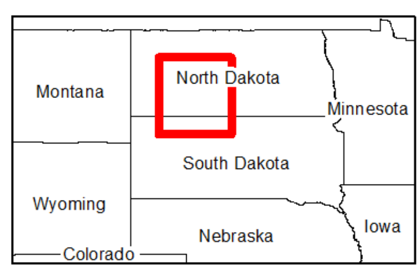
Storm 1324 - June 23 (0800 UTC) - June 26 (0700 UTC), 1966									
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)									
Area (mi^2)	Duration (hours)								
	1	3	6	12	18	24	48	72	Total
0.2	8.14	12.10	12.59	12.82	12.82	12.82	12.86	12.87	12.87
1	8.00	11.93	12.42	12.61	12.62	12.76	12.76	12.80	12.80
10	7.49	11.22	11.64	12.18	12.19	12.20	12.21	12.23	12.23
25	7.13	10.71	10.95	11.69	11.70	11.72	11.73	11.74	11.74
50	6.72	10.13	10.51	11.11	11.12	11.13	11.14	11.17	11.17
100	5.96	9.13	9.64	10.25	10.26	10.29	10.34	10.38	10.38
150	5.32	8.33	9.02	9.46	9.46	9.46	9.77	9.88	9.88
200	4.82	7.54	8.33	9.18	9.18	9.18	9.35	9.39	9.39
300	4.10	6.77	7.39	8.61	8.62	8.63	8.64	8.65	8.65
400	3.56	6.10	7.19	7.92	7.93	7.93	8.09	8.11	8.11
500	3.19	5.69	6.79	7.42	7.42	7.42	7.58	7.60	7.60
1,000	2.10	4.26	4.96	5.92	5.93	5.93	5.98	6.07	6.07
2,000	1.44	2.66	4.02	4.42	4.42	4.43	4.86	4.92	4.92
5,000	0.90	1.77	2.20	3.07	3.07	3.09	3.21	3.30	3.30
10,000	0.42	1.33	1.53	2.39	2.40	2.40	2.40	2.43	2.43
17,987	0.27	0.74	1.11	1.42	1.44	1.45	1.48	1.51	1.51


SPAS #1324 DAD Curves Zone 1
June 23 - June 26, 1966
Area (mi²)
Maximum Average Depth of Precipitation (inches)
1-hour
3-hour
6-hour
12-hour
18-hour
24-hour
48-hour
72-hour
Total storm (72-hour)
100,000
10,000
1,000
100
10
1
0
5
10


SPAS 1324 Storm Center Mass Curve Zone 1
June 23 (0800UTC) to June 26 (0700UTC), 1966
Lat: 47.3041666666667 Lon: -101.3875
Incremental
Accumulated
12.87
Incremental Precipitation (in)
Accumulated Precipitation (in)
Index Hour



Total 72-hr Precipitation (inches)
June 23, 1966 0700 UTC - June 25,1966 0700 UTC
SPAS #1324



TWP 04/03/2014

Buffalo Gap, SK

May 30, 1961

Storm Type: Local

Storm Precipitation Analysis System (SPAS) For Storm #1334

General Storm Location: Buffalo Gap, Saskatchewan, Canada (just north of Montana

Storm Dates: May 30, 1961

Event: Severe convective thunderstorm

DAD Zone 1

Latitude: 49.1146°

Longitude: -105.2896°

Max. grid rainfall amount: 267mm

Max. observed rainfall amount: 267mm (near BUFFALO GAP, SK, CANADA)

Number of Stations: 22

SPAS Version: 9.5

Base Map Used: Based on digitized Canadian Climate Centre of Environment Canada Isohyetal Map (storm total)

Spatial resolution: 15 seconds (degree: minute: second, WGS84, ~ 0.1 mi^2, 0.26 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of Results: There were no recording gauges and a great deal of estimation was employed at all stations which ranged from standard size gauges, small orifice gauges, bucket measurements and straight estimation. The storm also consisted of high winds and heavy hail that could have impacted the rainfall measurements. During the analysis one bucket measurement was removed to improve the spatial pattern in an area with a steep isohyetal gradient but the resulting amount at that location is consistent with observed. This was a very small storm that occurred over only 3 hours. Resulting DADs are consistent with the Environment Canada analysis.

Storm Name:	SPAS 1334 Buffalo Gap, SK
Storm Date:	5/30 - 6/1/1961
AWA Analysis Date:	7/20/2015

Storm Adjustment Summary

Temporal Transposition Date **15-Jun**

	Lat	Long
Storm Center Location	**49.11 N**	**105.29 W**
Storm Rep Dew Point Location	**41.50 N**	**104.00 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**SSE @ 853**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**792**	meters
Storm Analysis Duration	**6**	hours

The storm representative dew point is	**19.7 °C**	with total precipitable water above sea level of		**51**	millimeters.
The in-place maximum dew point is	**24.4 °C**	with total precipitable water above sea level of		**76**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**792**	which subtracts	**12**	millimeters of precipitable water at	**19.7 °C**
The in-place storm elevation is	**792**	which subtracts	**16**	millimeters of precipitable water at	**24.4 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.50**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Storm rep dew point taken from the 6hr average values at KCYS and KBFF on afternoon of the 29th. Calculated value held to 1.50.

Observed Storm Depth-Area-Duration (millimeters)

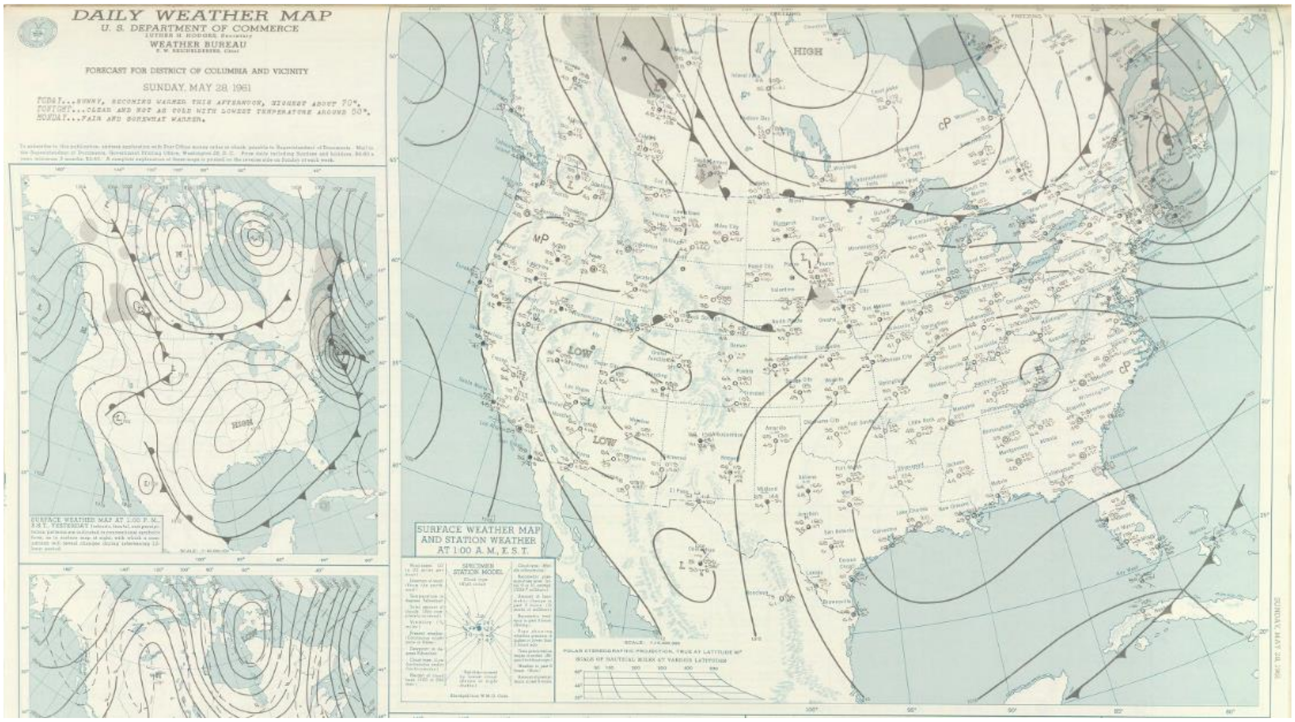
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**260**	**260**	**260**			**260**			
26 km^2 (10 mi^2)	**196**	**197**	**197**			**197**			
259 km^2 (100 mi^2)	**76**	**94**	**97**			**97**			
518 km^2 (200 mi^2)	**61**	**75**	**80**			**80**			
1,295 km^2 (500 mi^2)	**29**	**40**	**43**			**43**			
2,590 km^2 (1,00 mi^2)									
5,180 km^2 (2,000 mi^2)									
12.950 km^2 (5000 mi^2)									
25,900 km^2 (10,000 mi^2)									
51,800 km^2 (20,000 mi^2)									

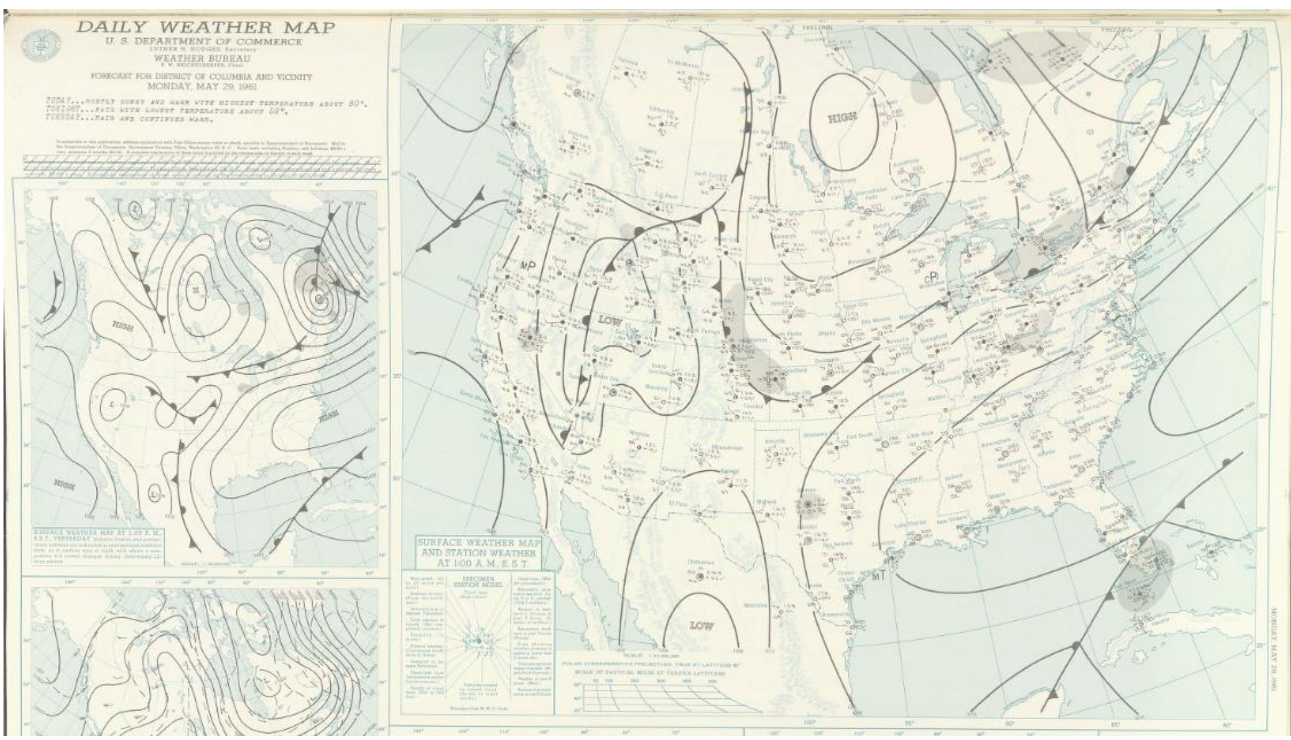
Adjusted Storm Depth-Area-Duration (millimeters)

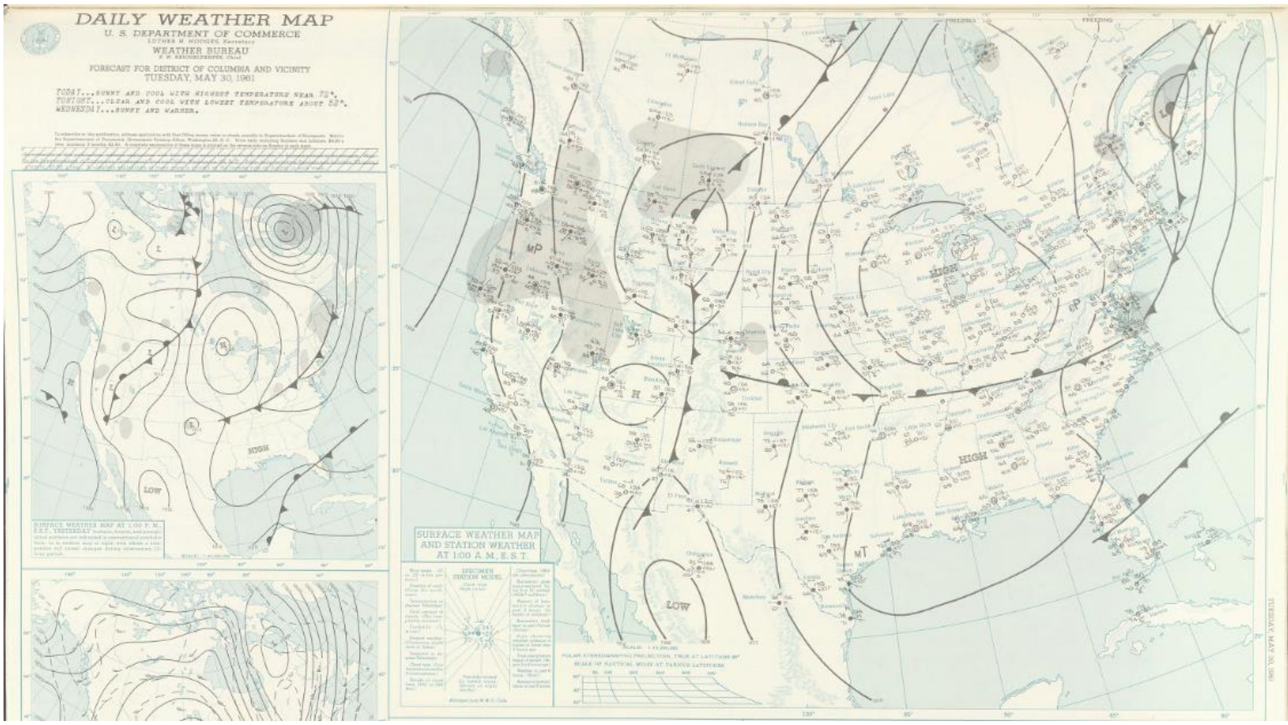
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***	**N/A***	**N/A***			**N/A***			
26 km2 (10 mi2)	**N/A***	**N/A***	**N/A***			**N/A***			
259 km2 (100 mi2)	**N/A***	**N/A***	**N/A***			**N/A***			
518 km2 (200 mi2)	**N/A***	**N/A***	**N/A***			**N/A***			
1,295 km2 (500 mi2)	**N/A***	**N/A***	**N/A***			**N/A***			
2,590 km2 (1,00 mi2)									
5,180 km2 (2,000 mi2)									
12.950 km2 (5000 mi2)									
25,900 km2 (10,000 mi2)									
51,800 km2 (20,000 mi2)									

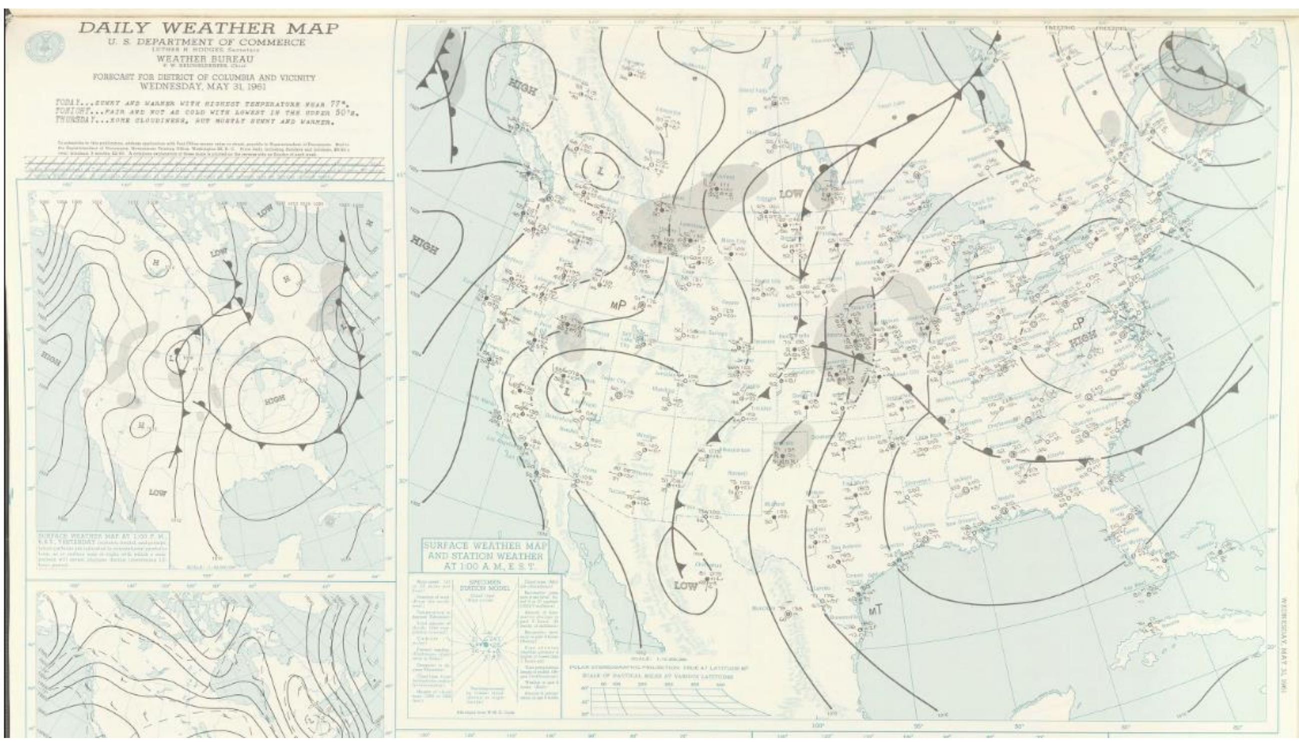
Storm or Storm Center Name	**SPAS 1334 Buffalo Gap, SK**	
Storm Date(s)	5/30 - 6/1/1961	
Storm Type	Convective	
Storm Location	49.11 N	105.29 W
Storm Center Elevation	792	meters
Precipitation Total & Duration	267	millimeters
Storm Representative Dew Point	19.7 °C	6
Storm Representative Dew Point Location	41.50 N	104.00 W
Maximum Dew Point	24.4 °C	
Moisture Inflow Vector	SSE @ 853	kilometers
In-place Maximization Factor	**1.50**	
Temporal Transposition (Date)	15-Jun	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

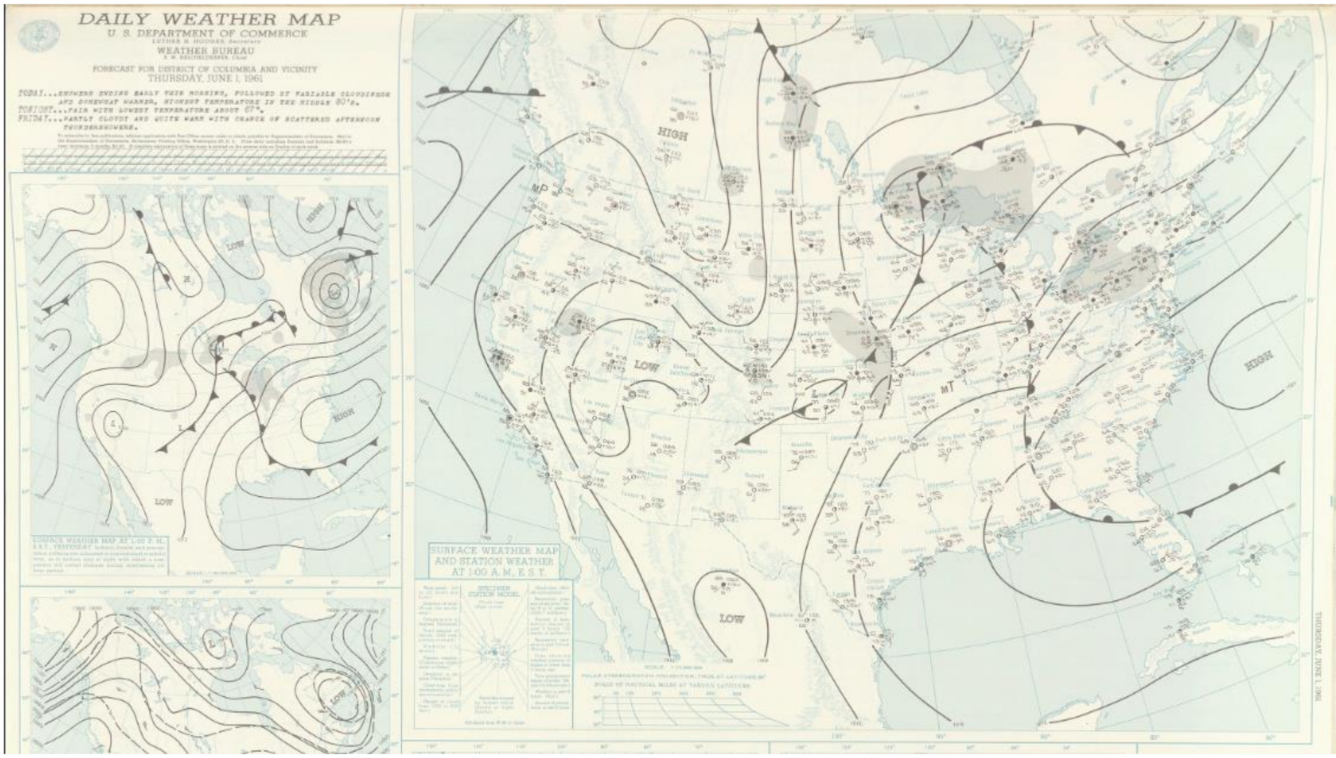
*Variable dependent on transposition location

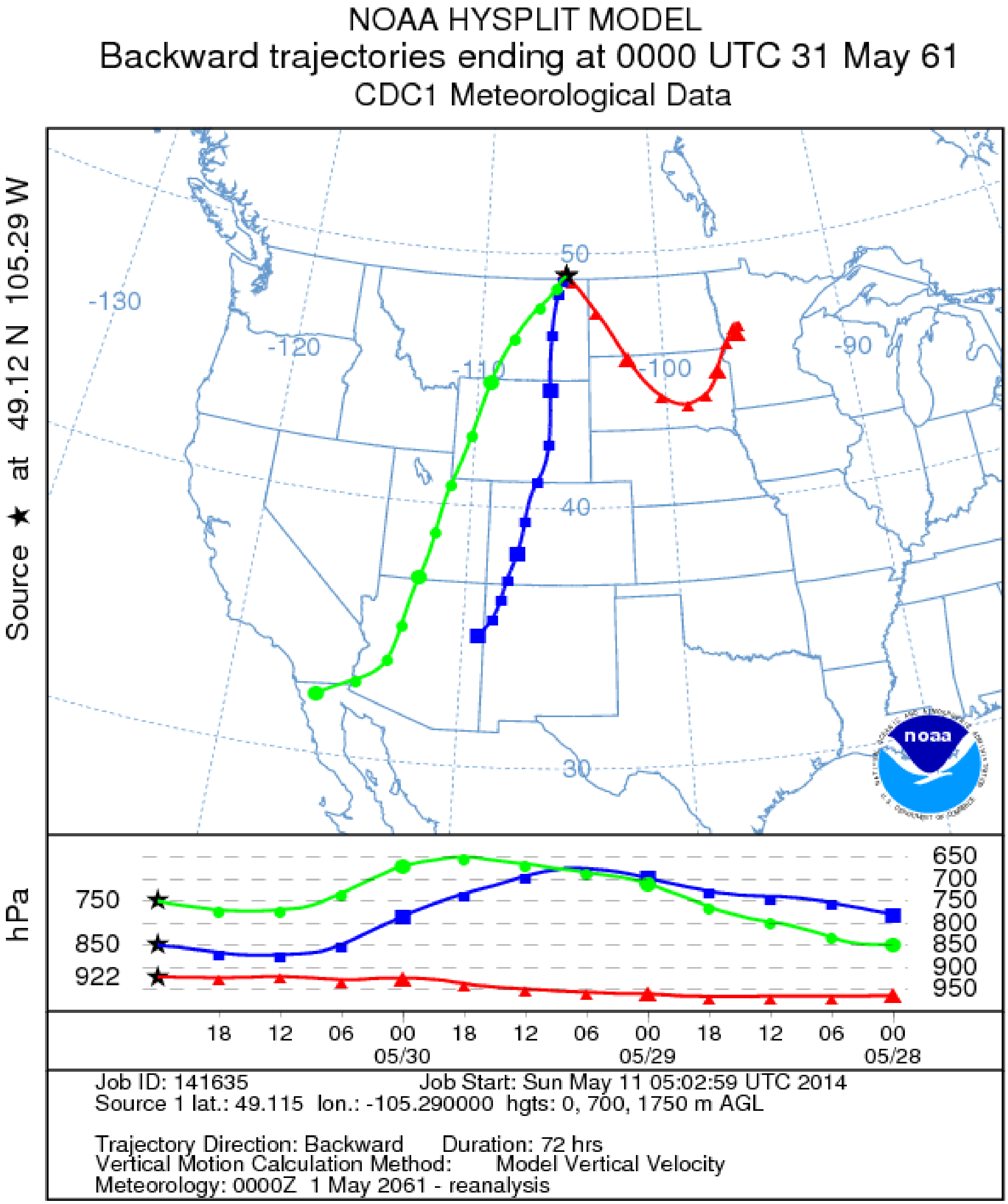

DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
FORECAST FOR DISTRICT OF COLUMBIA AND VICINITY
SUNDAY, MAY 28, 1961
TODAY...SUNNY, BECOMING WARMER THIS AFTERNOON, HIGHEST ABOUT 70°.
TONIGHT...CLEAR AND NOT AS COLD WITH LOWEST TEMPERATURE AROUND 50°.
MONDAY...FAIR AND SOMEWHAT WARMER.
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.


DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
FORECAST FOR DISTRICT OF COLUMBIA AND VICINITY
MONDAY, MAY 29, 1961
TODAY...MOSTLY SUNNY AND WARM WITH HIGHEST TEMPERATURE ABOUT 80°.
TONIGHT...FAIR WITH LOWEST TEMPERATURE ABOUT 58°.
TUESDAY...FAIR AND CONTINUED WARM.
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.


DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
FORECAST FOR DISTRICT OF COLUMBIA AND VICINITY
TUESDAY, MAY 30, 1961
TODAY...SUNNY AND COOL WITH HIGHEST TEMPERATURE NEAR 72°.
TONIGHT...CLEAR AND COOL WITH LOWEST TEMPERATURE ABOUT 52°.
WEDNESDAY...SUNNY AND WARMER.
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.
HIGH
LOW

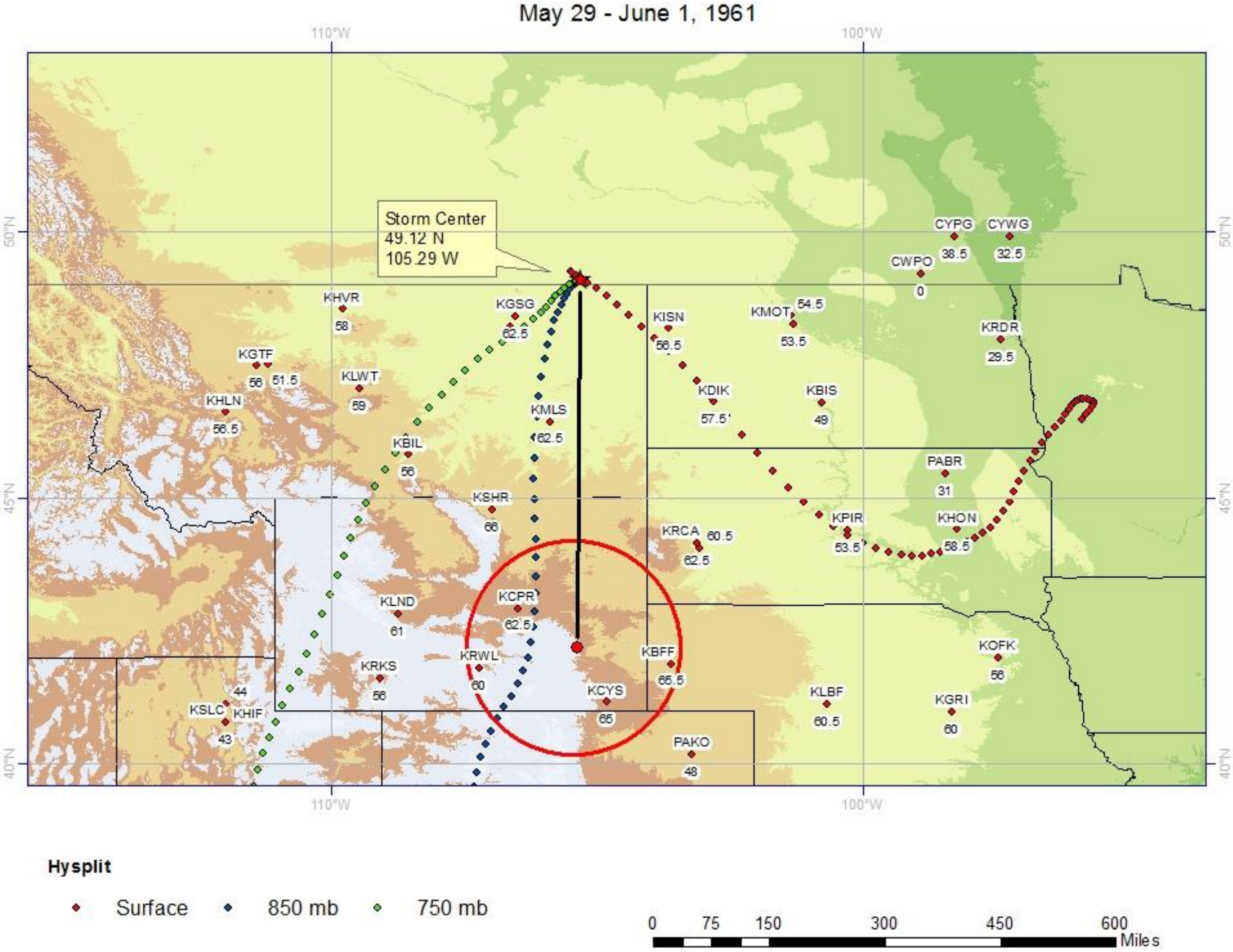

DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
FORECAST FOR DISTRICT OF COLUMBIA AND VICINITY
WEDNESDAY, MAY 31, 1961
TODAY...SUNNY AND WARMER WITH HIGHEST TEMPERATURE NEAR 77°.
TONIGHT...FAIR AND NOT AS COLD WITH LOWEST IN THE UPPER 50'S.
THURSDAY...SOME CLOUDINESS, BUT MOSTLY SUNNY AND WARMER.
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.
HIGH
LOW


DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
FORECAST FOR DISTRICT OF COLUMBIA AND VICINITY
THURSDAY, JUNE 1, 1961
TODAY...SHOWERS ENDING EARLY THIS MORNING, FOLLOWED BY VARIABLE CLOUDINESS AND SOMEWHAT WARMER, HIGHEST TEMPERATURE IN THE MIDDLE 80's.
TONIGHT...FAIR WITH LOWEST TEMPERATURE ABOUT 67°.
FRIDAY...PARTLY CLOUDY AND QUITE WARM WITH CHANCE OF SCATTERED AFTERNOON THUNDERSHOWERS.
HIGH
LOW
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.
SPECIMEN STATION MODEL
THURSDAY, JUNE 1, 1961

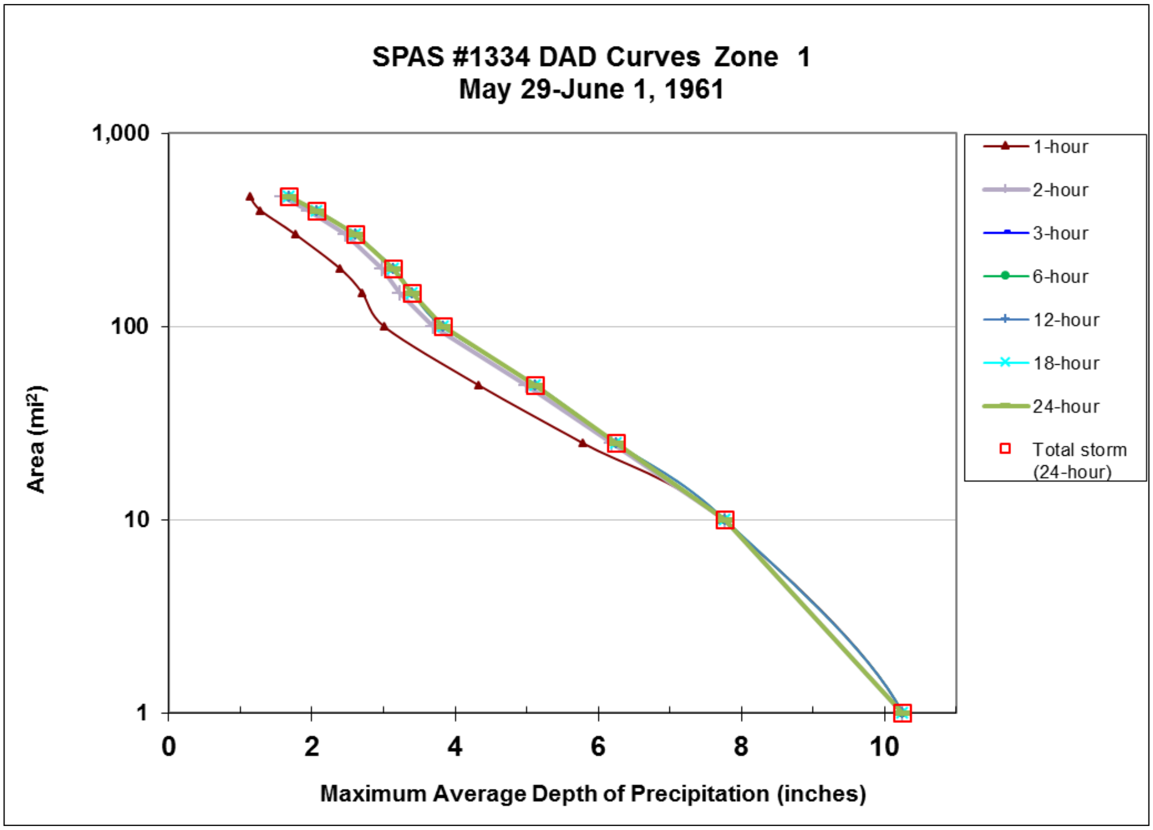

NOAA HYSPLIT MODEL
Backward trajectories ending at 0000 UTC 31 May 61
CDC1 Meteorological Data
Source ★ at 49.12 N 105.29 W
-130
-120
-110
-100
-90
50
40
30
hPa
750
850
922
650
700
750
800
850
900
950
18 12 06 00 18 12 06 00 18 12 06 00
05/30
05/29
05/28
Job ID: 141635 Job Start: Sun May 11 05:02:59 UTC 2014
Source 1 lat.: 49.115 lon.: -105.290000 hgts: 0, 700, 1750 m AGL
Trajectory Direction: Backward Duration: 72 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 May 2061 - reanalysis

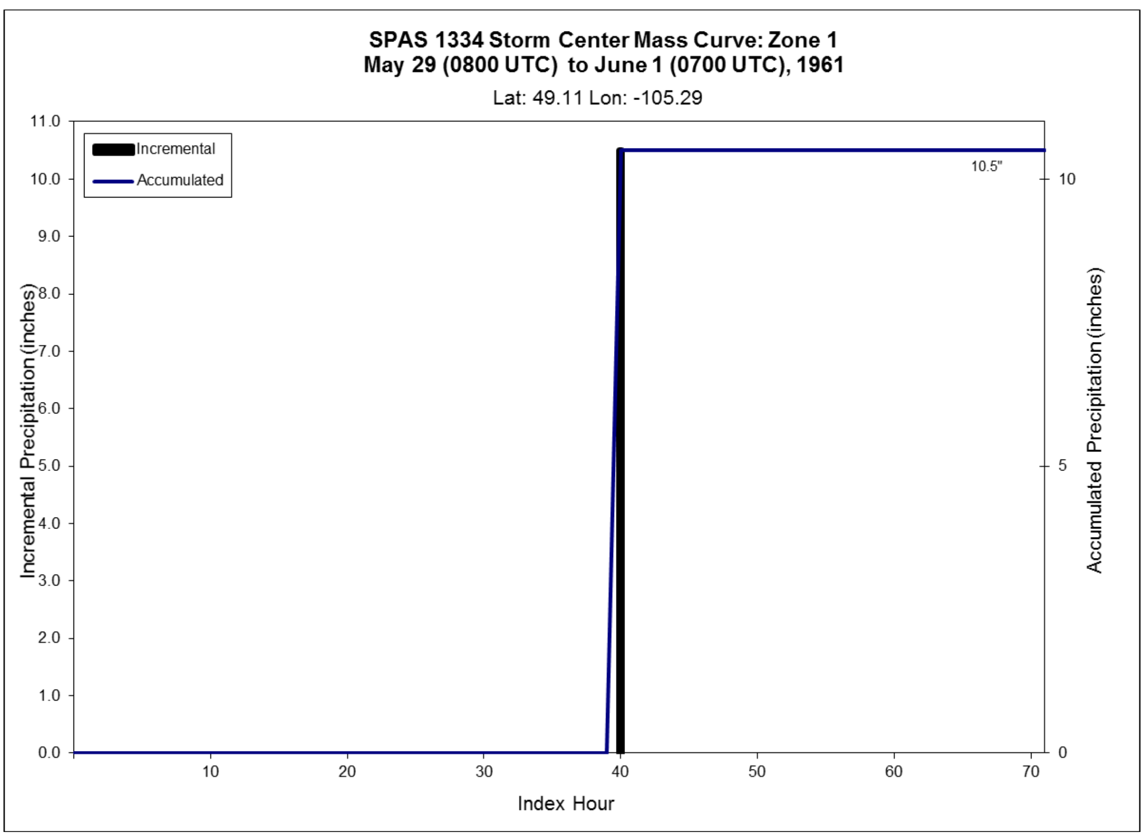
SPAS 1334

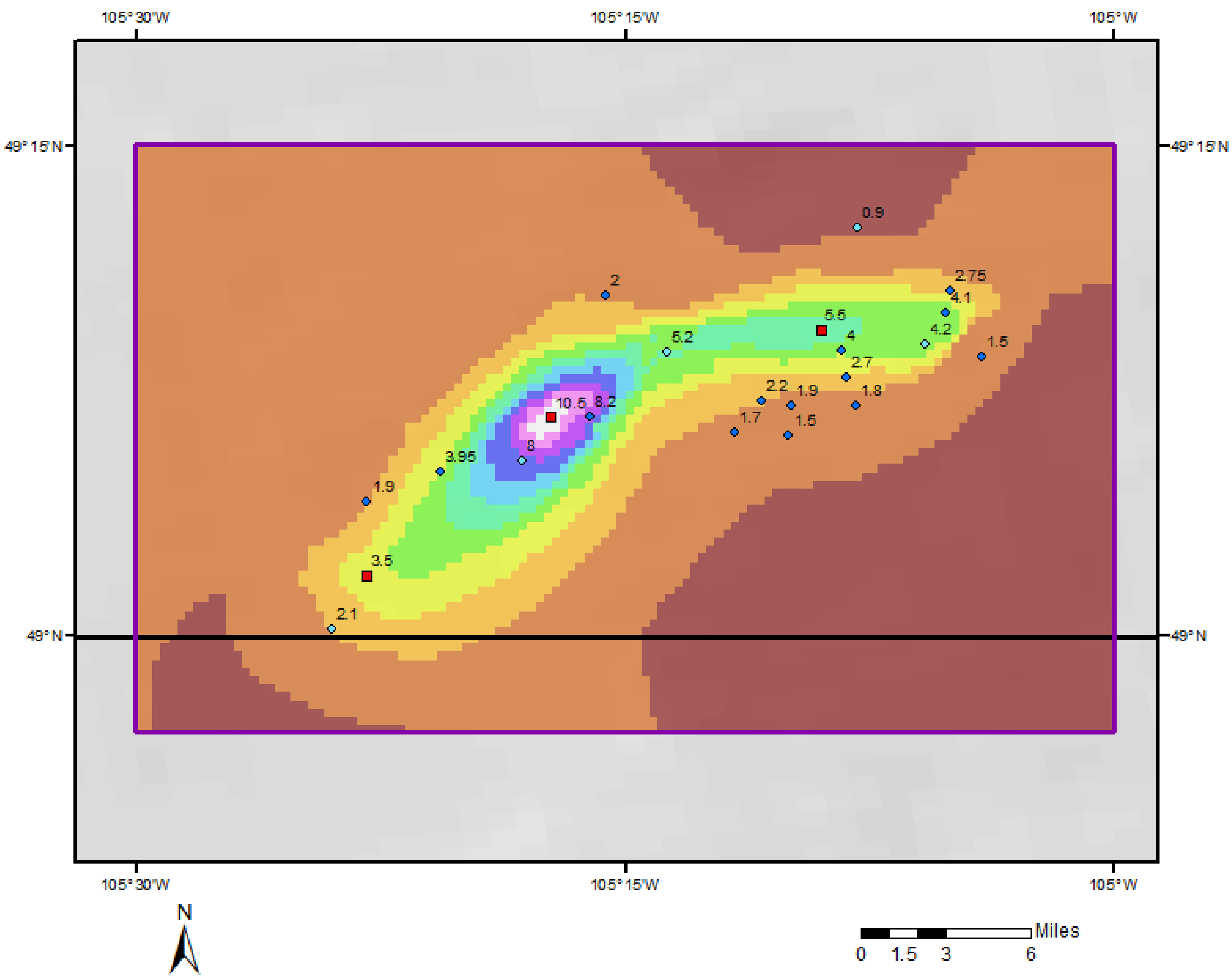
May 29 - June 1, 1961



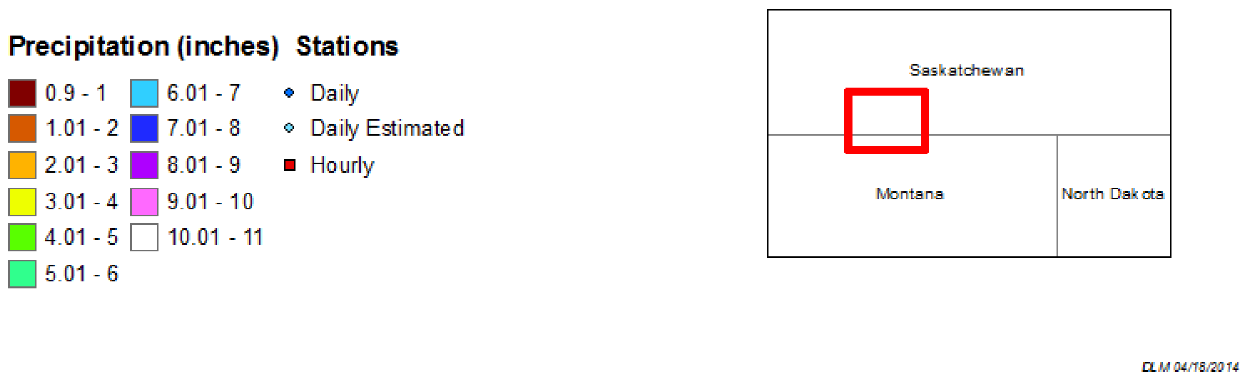
Storm 1334 - May 29 (0900 UTC) - June 1 (0700 UTC), 1961								
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)								
	Duration (hours)							
Area (mi^2)	**1**	**2**	**3**	**6**	**12**	**18**	**24**	**Total**
0.1	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50
1	10.25	10.25	10.25	10.25	10.25	10.25	10.25	10.25
10	7.73	7.77	7.77	7.77	7.77	7.77	7.77	7.77
25	5.78	6.19	6.25	6.25	6.25	6.25	6.25	6.25
50	4.32	4.99	5.11	5.12	5.12	5.12	5.12	5.12
100	3.01	3.69	3.83	3.83	3.83	3.83	3.83	3.83
150	2.70	3.23	3.40	3.40	3.40	3.40	3.40	3.40
200	2.39	2.97	3.13	3.14	3.14	3.14	3.14	3.14
300	1.77	2.46	2.60	2.60	2.60	2.60	2.60	2.60
400	1.28	1.95	2.06	2.06	2.06	2.06	2.06	2.06
470	1.13	1.59	1.68	1.68	1.68	1.68	1.68	1.68


SPAS #1334 DAD Curves Zone 1
May 29-June 1, 1961
Area (mi²)
1,000
100
10
1
0
2
4
6
8
10
Maximum Average Depth of Precipitation (inches)
1-hour
2-hour
3-hour
6-hour
12-hour
18-hour
24-hour
Total storm (24-hour)


SPAS 1334 Storm Center Mass Curve: Zone 1
May 29 (0800 UTC) to June 1 (0700 UTC), 1961
Lat: 49.11 Lon: -105.29
Incremental
Accumulated
10.5"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour



Total 24-hr Precipitation (inches)
May 30,1961 0800 UTC
SPAS #1334



Springbrook, MT

June 17-21, 1921

Storm Type: Local

Storm Precipitation Analysis System (SPAS) For Storm #1336

General Storm Location: Springbrook, Montana

Storm Dates: June 17-21, 1921

Event: Mid-latitude cyclone

DAD Zone 1

- **Latitude**: 47.3642°
- **Longitude**: -105.7778°
- **Max. grid rainfall amount**: 386mm
- **Max. observed rainfall amount**: 383mm (SPRINGBROOK MT)

Number of Stations: 98

SPAS Version: 9.5

Base Map Used: Based on digitized HMR 55A Isohyetal Map (storm total)

Spatial resolution: 30 seconds (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of Results: There were no digitized hourly data available, so hourly data for the five stations used in the analysis were derived from mass curves in the USACE report. Because of the nature of the data, DAD results for shorter than 6-hours may be less reliable (previous studies do not provide results for less than 6 hours). That said, the DAD results for 6 hour and longer are consistent with those from HMR55A and USACE. Because there are very few stations located near the center of the storm, confidence is low regarding the spatial pattern near the center but storm magnitudes are reliable.

Storm Name:	**SPAS 1336 Springbrook, MT**	**Storm Adjustment Summary**
Storm Date:	**6/17 - 21/1921**	
AWA Analysis Date:	**7/20/2015**	

Temporal Transposition Date **5-Jul**

	Lat	Long
Storm Center Location	**47.36 N**	**105.78 W**
Storm Rep Dew Point Location	**45.30 N**	**98.55 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**ESE @ 595**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**823**	meters
Storm Analysis Duration	**24**	hours

The storm representative dew point is	**23.3 °C**	with total precipitable water above sea level of		**69**	millimeters.
The in-place maximum dew point is	**25.6 °C**	with total precipitable water above sea level of		**84**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**823**	which subtracts	**16**	millimeters of precipitable water at	**23.3 °C**
The in-place storm elevation is	**823**	which subtracts	**18**	millimeters of precipitable water at	**25.6 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.22**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Storm rep Td taken from USACE/NWS analysis and added 2°F to convert 12-hr persisting to 24-hr average value.

Observed Storm Depth-Area-Duration (millimeters)

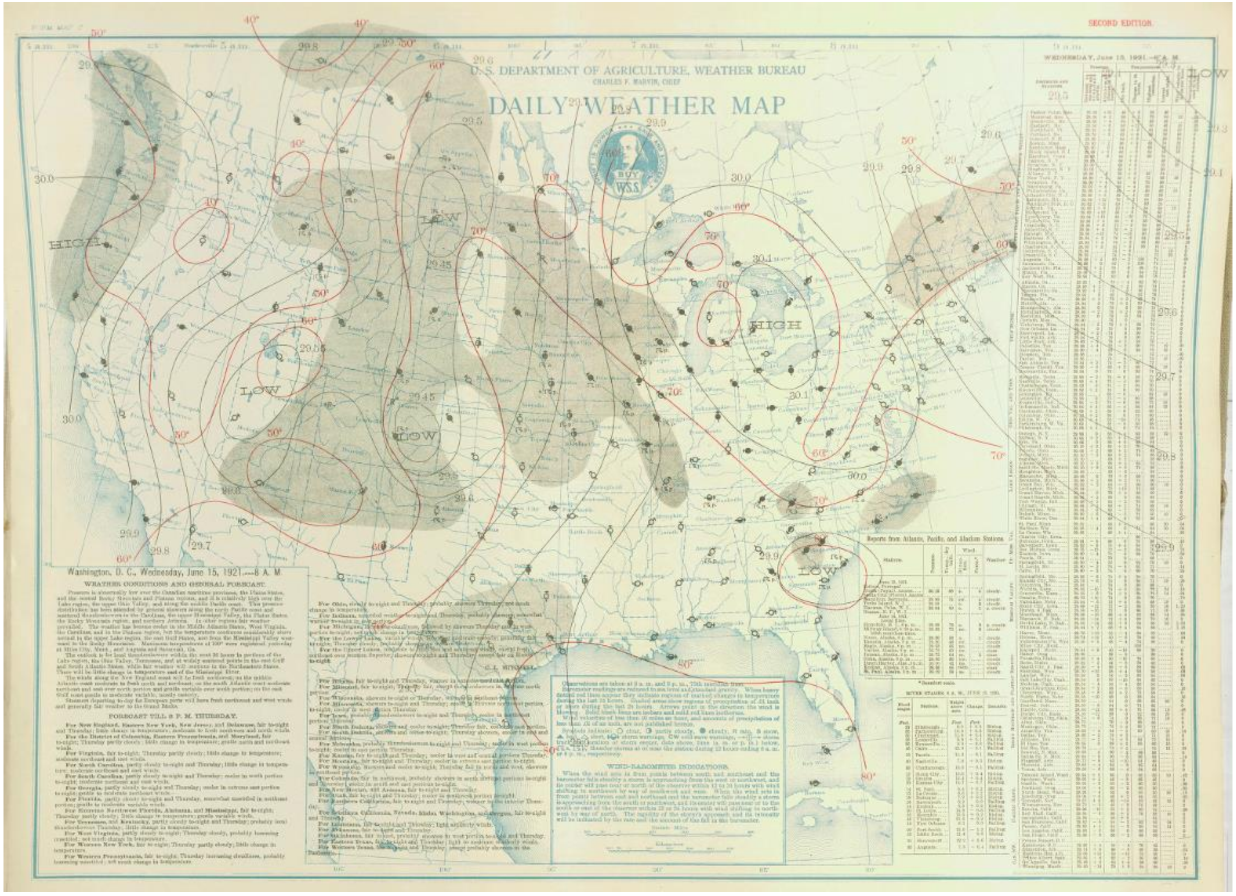
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)	**67**		**192**			**276**			
26 km^2 (10 mi^2)	**67**		**192**			**275**			
259 km^2 (100 mi^2)	**65**		**187**			**268**			
518 km^2 (200 mi^2)	**63**		**182**			**262**			
1,295 km^2 (500 mi^2)	**60**		**172**			**247**			
2,590 km^2 (1,00 mi^2)	**54**		**156**			**226**			
5,180 km^2 (2,000 mi^2)	**45**		**128**			**187**			
12.950 km^2 (5000 mi^2)	**31**		**73**			**114**			
25,900 km^2 (10,000 mi^2)	**19**		**51**			**78**			
51,800 km^2 (20,000 mi^2)	**13**		**26**			**33**			

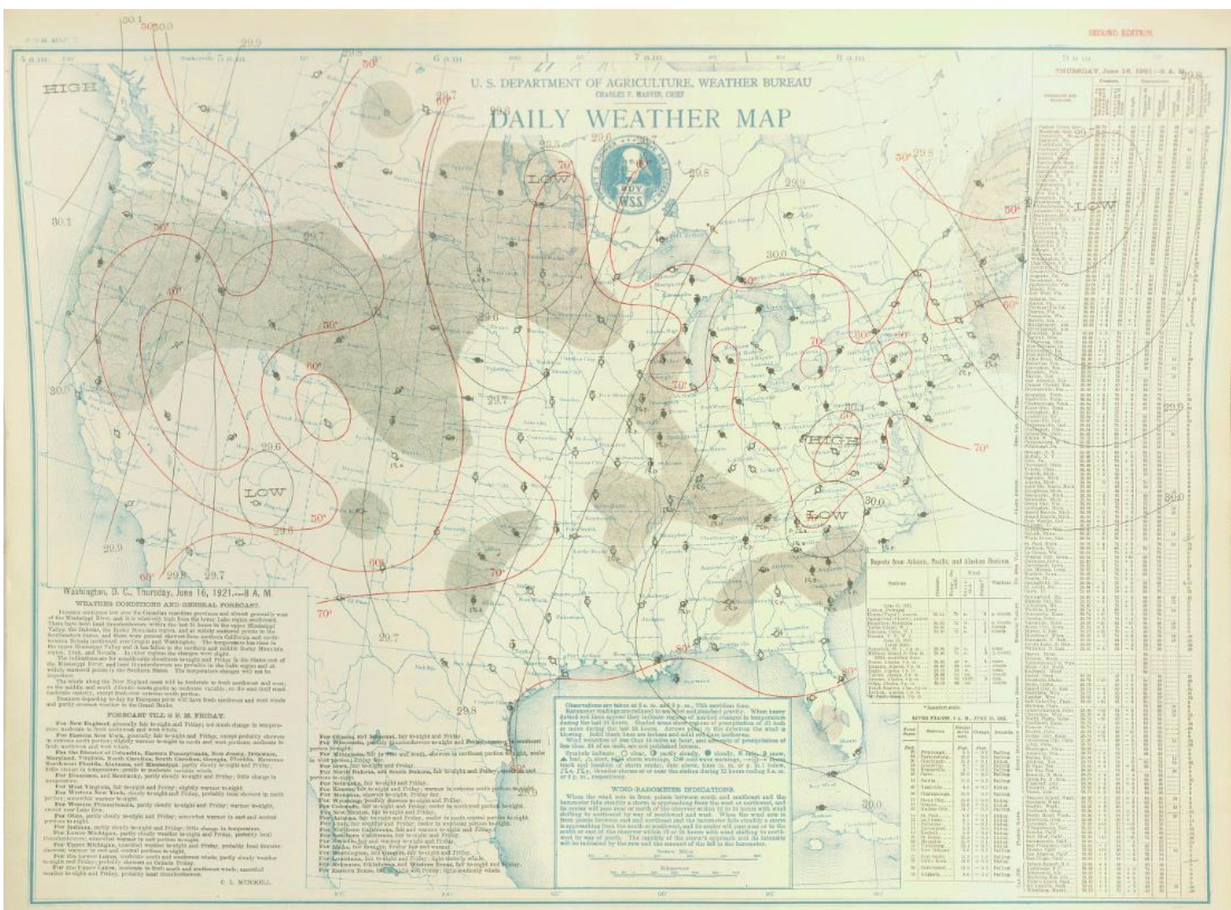
Adjusted Storm Depth-Area-Duration (millimeters)

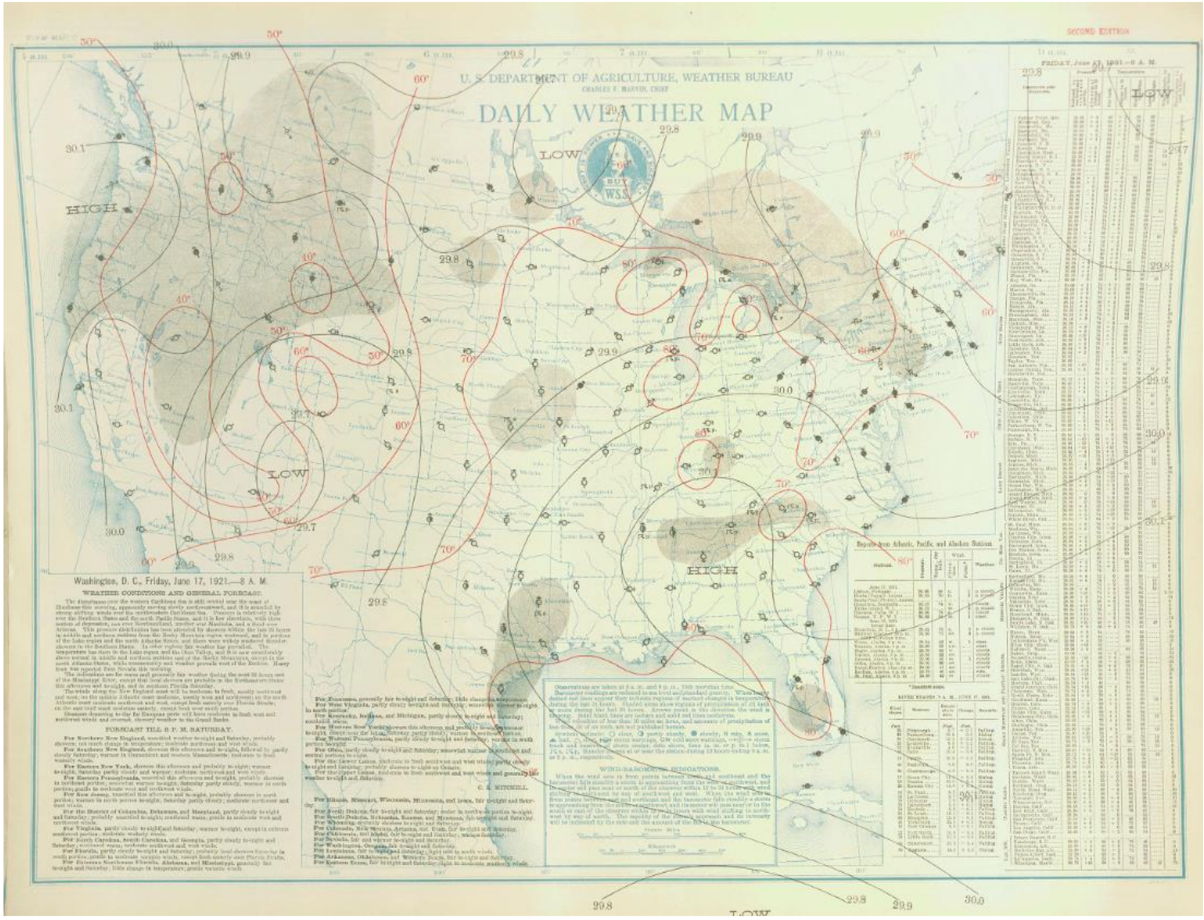
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)	**N/A***		**N/A***			**N/A***			
26 km2 (10 mi2)	**N/A***		**N/A***			**N/A***			
259 km2 (100 mi2)	**N/A***		**N/A***			**N/A***			
518 km2 (200 mi2)	**N/A***		**N/A***			**N/A***			
1,295 km2 (500 mi2)	**N/A***		**N/A***			**N/A***			
2,590 km2 (1,00 mi2)	**N/A***		**N/A***			**N/A***			
5,180 km2 (2,000 mi2)	**N/A***		**N/A***			**N/A***			
12.950 km2 (5000 mi2)	**N/A***		**N/A***			**N/A***			
25,900 km2 (10,000 mi2)	**N/A***		**N/A***			**N/A***			
51,800 km2 (20,000 mi2)	**N/A***		**N/A***			**N/A***			

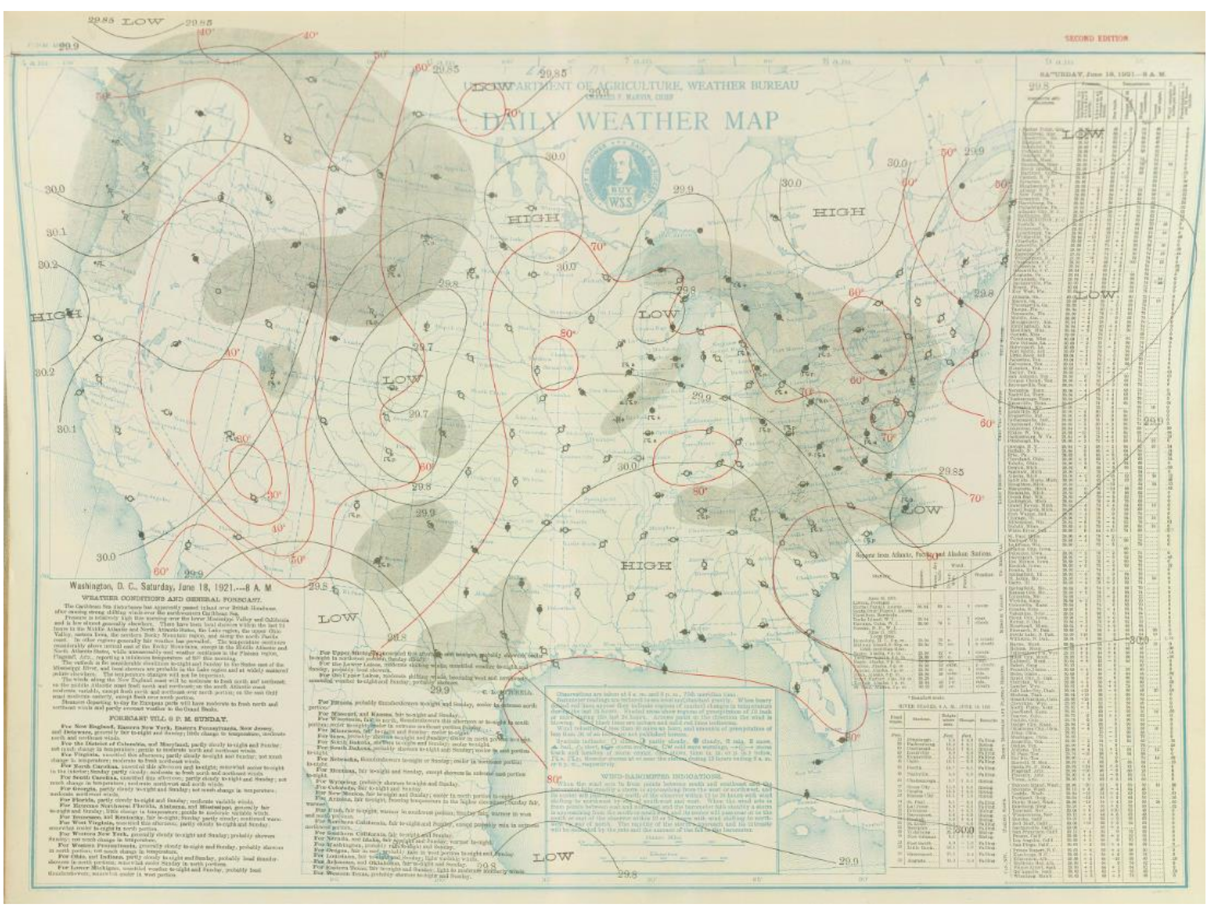
Storm or Storm Center Name	**SPAS 1336 Springbrook, MT**	
Storm Date(s)	6/17 - 21/1921	
Storm Type	Synoptic	
Storm Location	47.36 N	105.78 W
Storm Center Elevation	823	meters
Precipitation Total & Duration	386	millimeters
Storm Representative Dew Point	23.3 °C	24
Storm Representative Dew Point Location	45.30 N	98.55 W
Maximum Dew Point	25.6 °C	
Moisture Inflow Vector	ESE @ 595 kilometers	
In-place Maximization Factor	**1.22**	
Temporal Transposition (Date)	5-Jul	
Transposition Dew Point Location	N/A*	N/A*
Transposition Maximum Dew Point	N/A*	
Transposition Adjustment Factor	N/A*	
Average Basin Elevation	N/A*	
Barrier Adjustment Factor	N/A*	
Total Adjustment Factor	**N/A***	

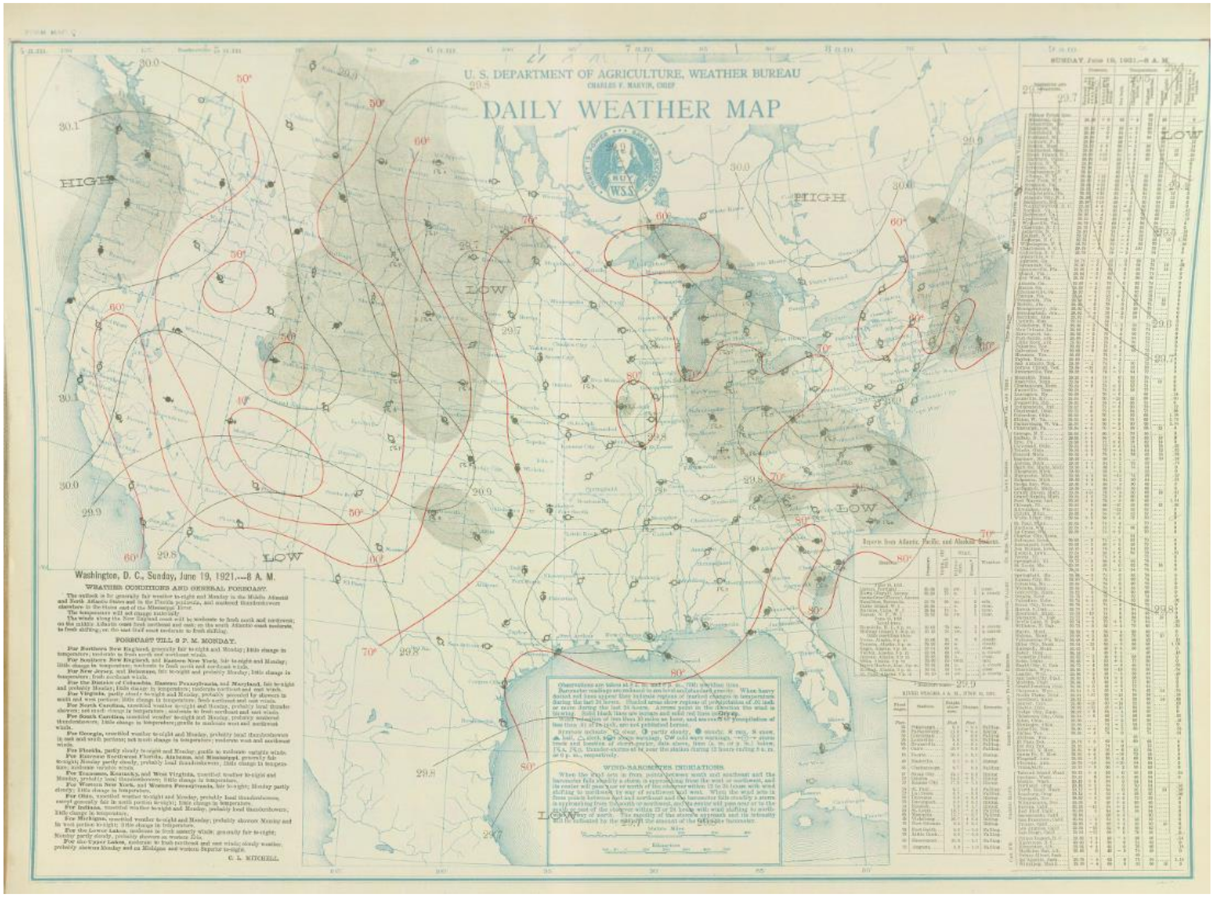
*Variable dependent on transposition location

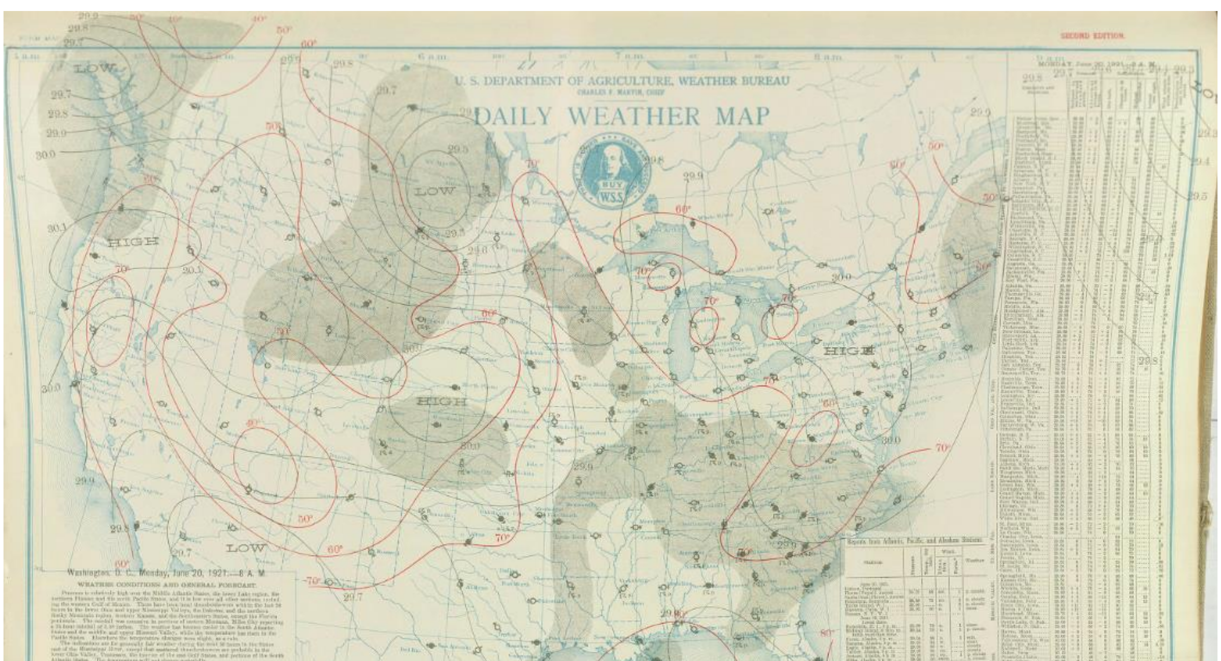

SECOND EDITION
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
HIGH
LOW
HIGH
LOW
LOW
LOW
Washington, D. C., Wednesday, June 15, 1921—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. THURSDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations


SECOND EDITION
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
HIGH
LOW
LOW
HIGH
LOW
LOW
Washington, D. C., Thursday, June 16, 1921—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. FRIDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations


SECOND EDITION
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
LOW
HIGH
LOW
Washington, D. C., Friday, June 17, 1921.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SATURDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations.
RIVER STAGES
FRIDAY, June 17, 1921—8 A. M.


SECOND EDITION
LOW
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
HIGH
HIGH
LOW
LOW
LOW
HIGH
LOW
LOW
LOW
Washington, D. C., Saturday, June 18, 1921.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SUNDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations.
RIVER STAGES
SATURDAY, June 18, 1921—8 A. M.


U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Sunday, June 19, 1921.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. MONDAY.
WIND-BAROMETER INDICATIONS.


SECOND EDITION
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Monday, June 20, 1921.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. TUESDAY.
WIND-BAROMETER INDICATIONS.

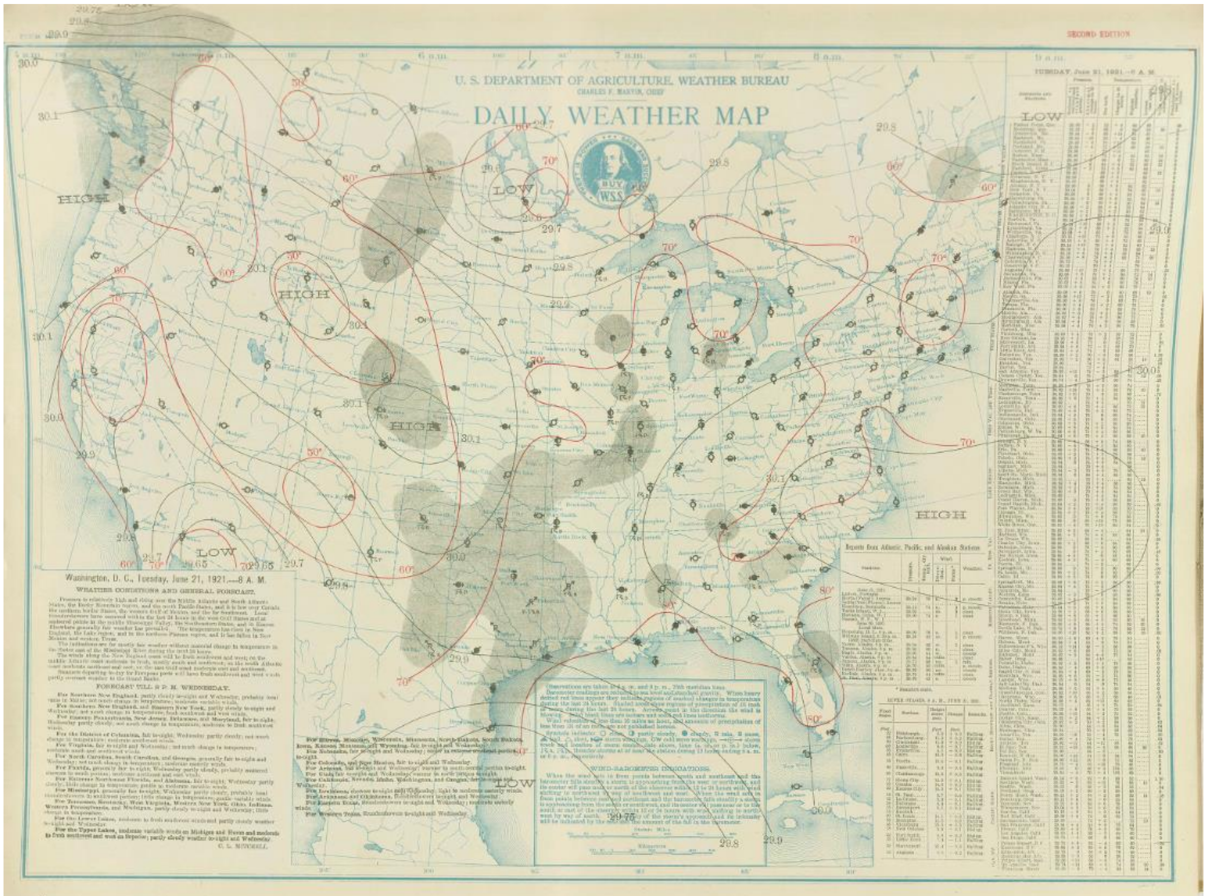
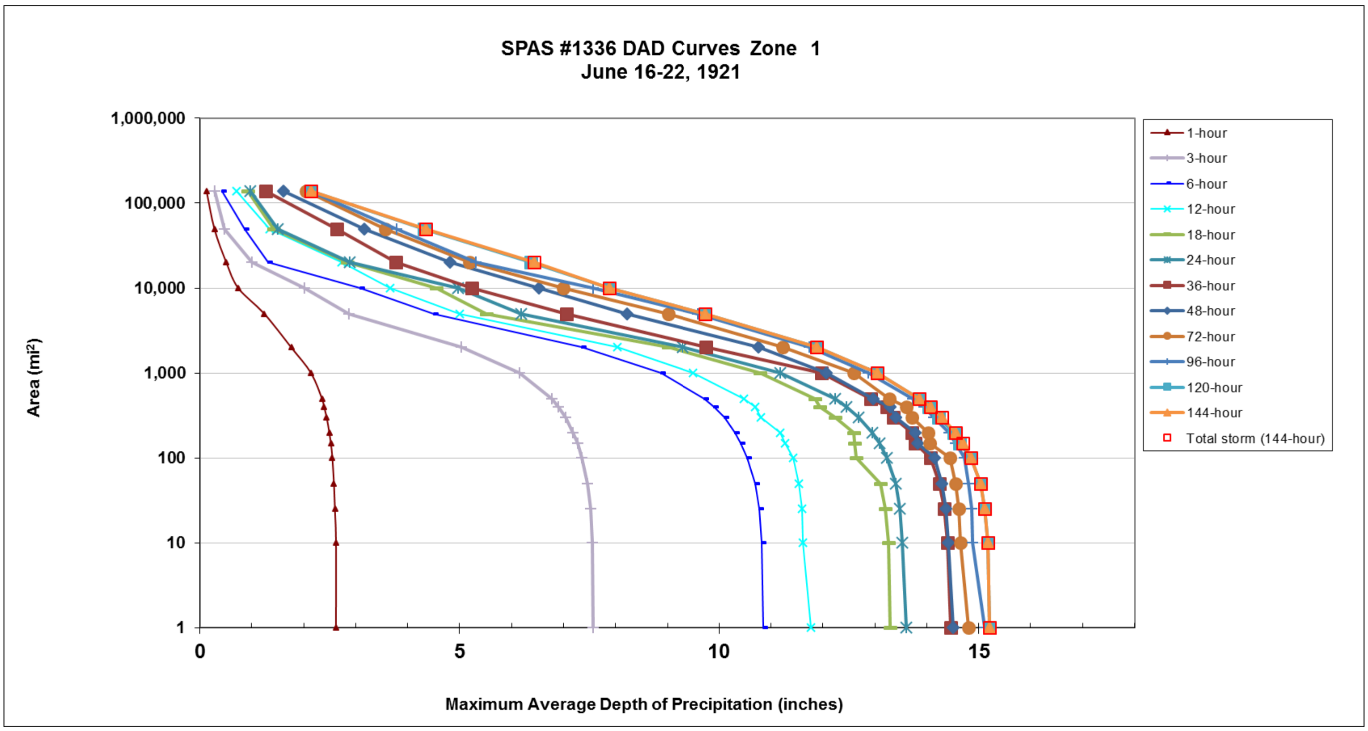

U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Tuesday, June 21, 1921.—8 A. M.

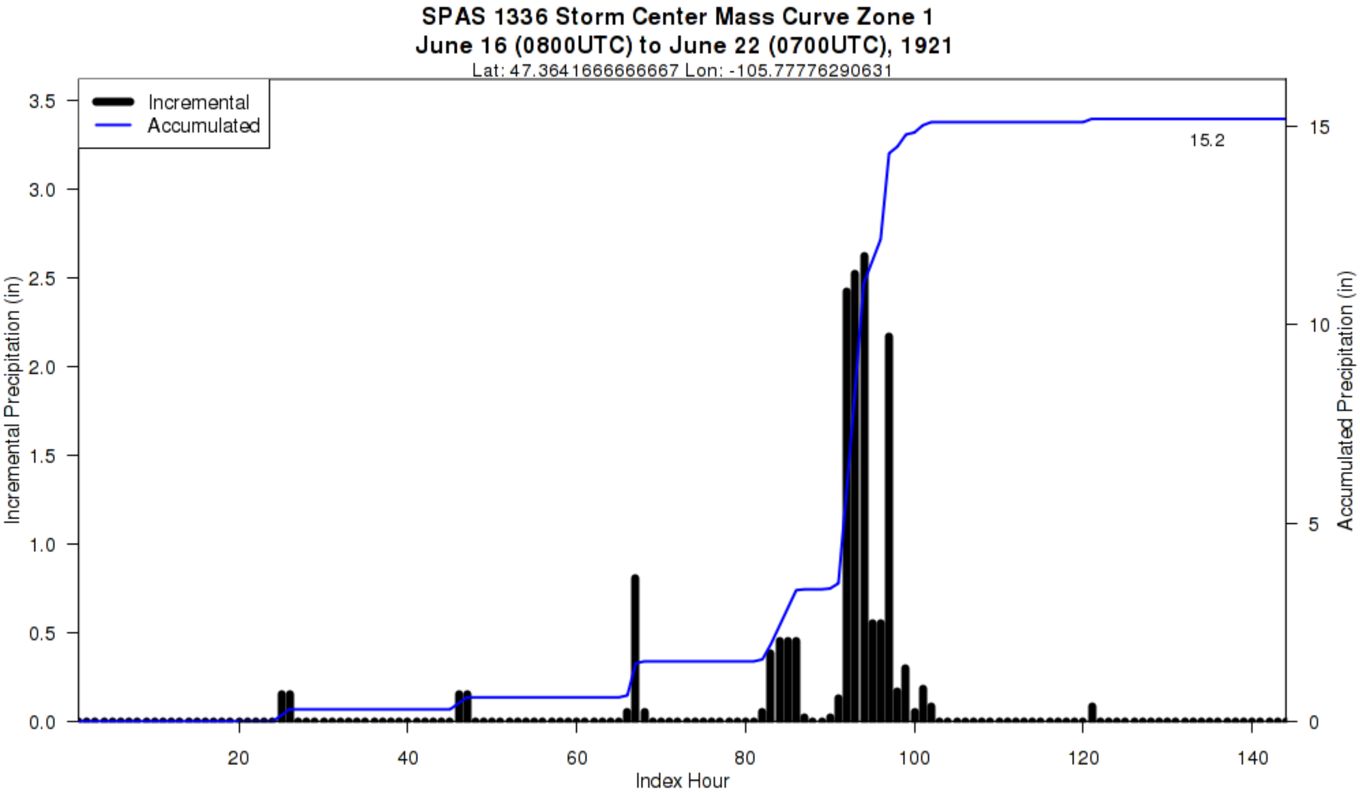
Table 5.1.--Representative persisting 12-hr 1000-mb storm and maximum dew points for important storms in and near study region

Storm No.	Name	Storm T_d Old	Storm T_d New	Date+	Ref. Old	Loc. New	Max. T_d Old	Max. T_d New	Stations
1.	Ward District, CO	62	64	30	325SE	350SE	75	77	AMA, DDC
6.	Boxelder, CO	60	60	4	350SE	320SE	72	74	DEN, PUB, DDC, OKC, ICT
8.	Rociada, NM	72	72	28	170SSE	300ESE	76	77	ABI, AMA
10.	Warrick, MT	64	64	6	380ESE	380ESE	73	75	ISN, PIR
13.	Evans, MT	65	65	4	510ESE	510ESE	75	76	BIS, RAP, PIR, VTN, HON
86.	May Valley, CO	67	67	18	450SSE	450SSE	76	76	AMA, ABI, FTW, SAT
20.	Clayton, NM	68	69	1	550SE	560SSE	76	77	SAT, DRT, CRP
23.	Tajique, NM	69	69	21	80SE	160SSE	77	78	ELP, ROW
25.	Lakewood, NM	-	76	7	-	350SE	-	79	DRT, SAT
27.	Meek, NM	72	72	15	390ESE	400ESE	78	79	AMA, ABI, FTW, OKC, SAT, GBK
30.	Fry's Ranch, CO	56	63	15	550ESE	700SE	71	74	FWH, DAL
31.	Penrose, CO	67	70	4	400SE	350SE	77	77	AMA, OKC
32.	Springbrook, MT	71	72	18	500ESE	370ESE	76	77	PIR, HON, FAR
35.	Virsylvia, NM (Cerro)	-	66	17	-	120SW	-	77	ABQ
38.	Savageton, WY	68	72	28	550SE	530SE	75	76	FRI, CNK
44.	Porter, NM	70	71	11	540SE	380SE	78	77	DRT, AUS, FTW, ABI
46.	Kassler, CO	71	66	10	440SE	420SE	77	77	OKC, DDC
47.	Cherry Creek, CO	72	71	30	540SE	560SE	76	79	ABI, ACT, FTW, SPS
101.	Hale, CO	72	71	30	540SE	560SE	76	79	ABI, ACT, FTW, SPS
48.	Las Cruces, NM*	-	71	30	-	-	-	78	ELP
105.	Broome, TX	77	77	14	350SSE	350SSE	78	80	CRP, BRO
53.	Loveland, CO	71	71	1	180SE	210SE	76	76	PUB, GLD
55.	Masonville, CO*	-	65	10	-	-	-	74	AKO
108.	Snyder, TX	73	75	19	100SE	340SSE	78	79	SAT, CRP
56.	Prairieview, NM	70	73	20	390SE	370SE	77	78	SAT, AUS
58.	McColleum Ranch, NM	72	72	21	50SE	300SE	77	79	ELP, DRT, SAT, CRP
60.	Rancho Grande, NM	74	75	31	250SE	250SE	77	78	LBB, BGS, ABI
66.	Ft. Collins, CO	66	67	30	570SE	600SE	78	78	GAG, TUL
67.	Golden, CO*	65	65	7	-	-	76	75	AMA

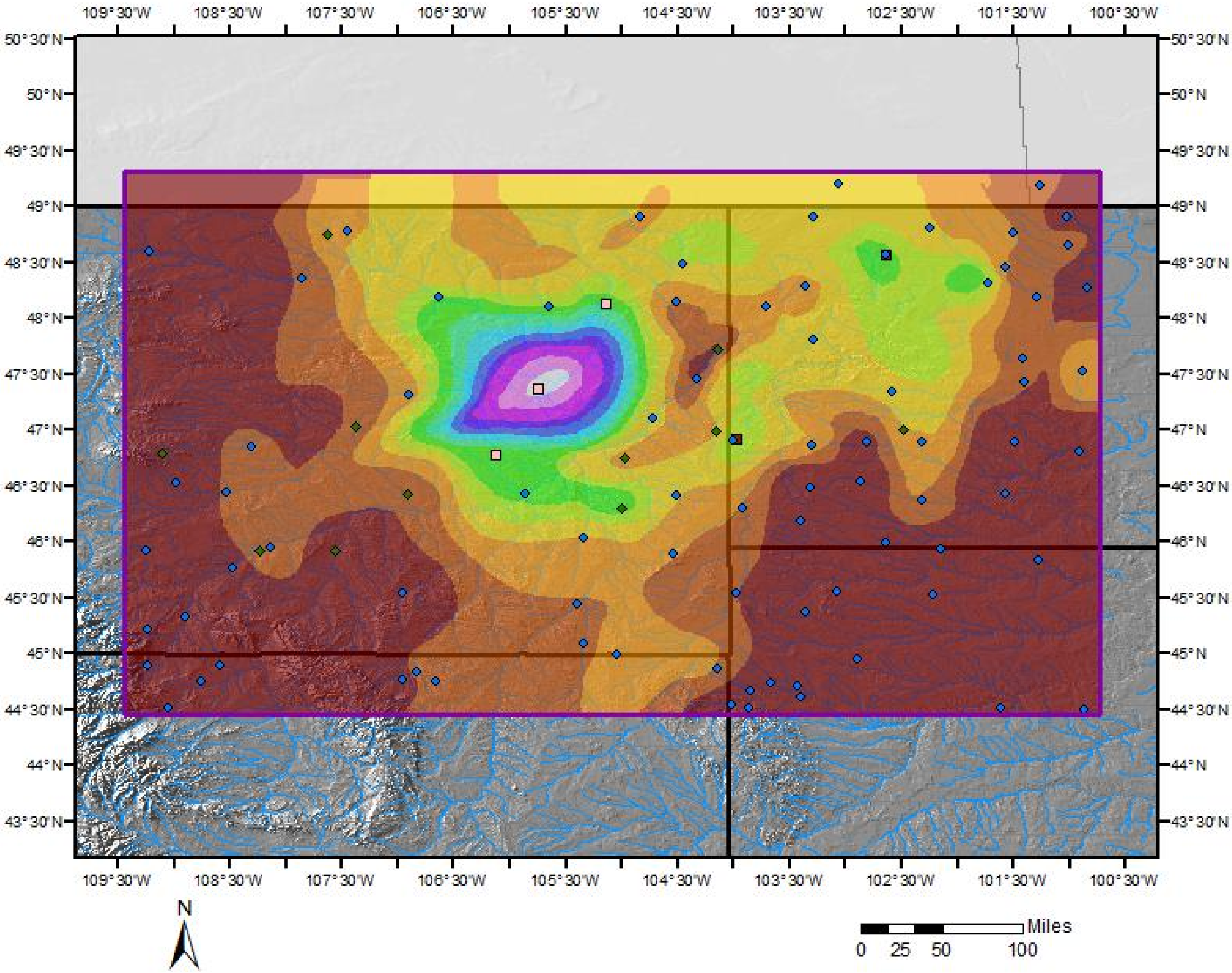
Note, this table is copied from HMR 55A and therefore units are in °F and miles.

SPAS 1336 - June 16 (0800 UTC) - June 22 (0700 UTC), 1921													
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)													
	Duration (hours)												
Area (mi^2)	1	3	6	12	18	24	36	48	72	96	120	144	Total
0.2	2.62	7.57	10.85	11.77	13.29	13.60	14.46	14.51	14.81	15.11	15.20	15.20	15.20
1	2.62	7.57	10.85	11.77	13.29	13.60	14.46	14.51	14.81	15.11	15.20	15.20	15.20
10	2.62	7.55	10.82	11.62	13.26	13.52	14.40	14.41	14.64	14.88	15.17	15.17	15.17
25	2.60	7.52	10.77	11.59	13.20	13.48	14.34	14.36	14.61	14.86	15.12	15.12	15.12
50	2.58	7.46	10.69	11.54	13.11	13.40	14.25	14.29	14.55	14.81	15.03	15.03	15.03
100	2.55	7.35	10.54	11.42	12.64	13.23	14.07	14.15	14.44	14.73	14.85	14.85	14.85
150	2.52	7.27	10.42	11.27	12.61	13.09	13.78	13.82	14.06	14.55	14.63	14.70	14.70
200	2.49	7.18	10.30	11.17	12.59	12.95	13.71	13.77	14.02	14.43	14.52	14.55	14.55
300	2.44	7.04	10.10	10.80	12.24	12.69	13.36	13.40	13.72	14.14	14.22	14.29	14.29
400	2.39	6.90	9.90	10.70	11.94	12.46	13.23	13.30	13.60	13.94	14.04	14.07	14.07
500	2.35	6.77	9.72	10.47	11.85	12.24	12.92	12.97	13.28	13.73	13.86	13.86	13.86
1,000	2.14	6.16	8.88	9.49	10.79	11.18	11.97	12.07	12.59	12.88	13.04	13.04	13.04
2,000	1.76	5.03	7.35	8.03	9.01	9.29	9.74	10.75	11.23	11.74	11.88	11.88	11.88
5,000	1.24	2.87	4.50	5.00	5.52	6.19	7.06	8.22	9.02	9.59	9.73	9.73	9.73
10,000	0.74	2.01	3.09	3.67	4.55	4.97	5.24	6.52	7.00	7.57	7.88	7.88	7.88
20,000	0.51	1.01	1.31	2.73	2.84	2.89	3.77	4.81	5.18	5.31	6.37	6.44	6.44
50,000	0.28	0.47	0.87	1.34	1.42	1.50	2.63	3.17	3.57	3.79	4.31	4.35	4.35
138,316	0.13	0.28	0.42	0.71	0.92	0.97	1.26	1.61	2.04	2.12	2.14	2.14	2.14

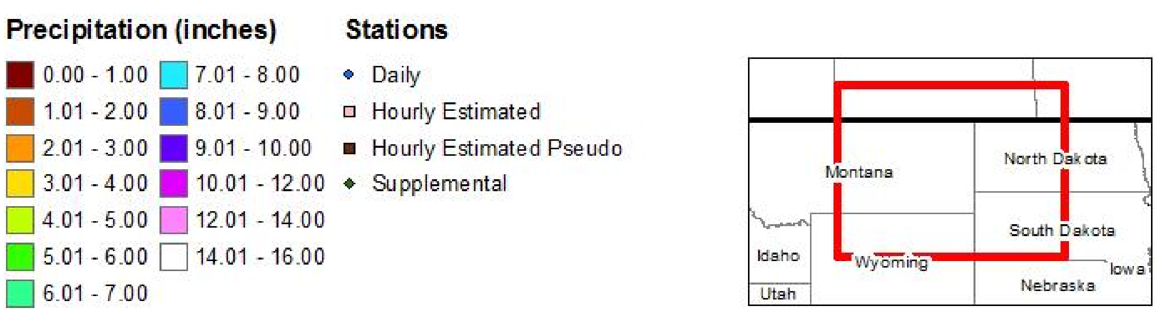




SPAS 1336 Storm Center Mass Curve Zone 1
June 16 (0800UTC) to June 22 (0700UTC), 1921
Lat: 47.3641666666667 Lon: -105.77776290631
Incremental
Accumulated
15.2
Incremental Precipitation (in)
Accumulated Precipitation (in)
Index Hour



Total 96-hr Precipitation (inches)
June 16, 1921 0800 UTC - June 21,1921 0800 UTC
SPAS #1336



DLM 05/05/2014

Pekisko, AB

May 29 – June 2, 1923

Storm Type: Local

Storm Precipitation Analysis System (SPAS) For Storm #1521 Zone 2

General Storm Location: Bassano, Alberta

Storm Dates: May 29 - June 2, 1923

Event: Synoptic/Convective Event

DAD Zone 1

Latitude: 50.4375°

Longitude: -114.3042°

Max. Grid Rainfall Amount: 167mm

Max. Observed Rainfall Amount: 171mm

DAD Zone 2

Latitude: 50.7792°

Longitude: -112.5708°

Max. Grid Rainfall Amount: 196mm

Max. Observed Rainfall Amount: 191mm

Number of Stations: 90 (65 Daily, 1 Hourly, 2 Hourly Pseudo, 0 Hourly Estimated Pseudo, and 22 Supplemental)

SPAS Version: 10.0

Basemap: Blended PRISM July 1961-1990 Climatology (Canada) and AL 5-23 Isohyetal

Spatial resolution: 30 second (degree: minute: second, WGS84, ~ 0.3 mi^2, 0.78 km^2)

Radar Included: No

Depth-Area-Duration (DAD) analysis: Yes

Reliability of results: This analysis was based on hourly data, daily data, supplemental station data and AL 5-23 data. We have a good degree of confidence in the station based storm total results, the spatial pattern is dependent on the station data and a basemap. The timing is based on hourly and hourly pseudo stations.

Storm Name:	SPAS 1521 Pekisko, AB Zone 2
Storm Date:	5/29 - 6/2/1923
AWA Analysis Date:	7/20/2015

Storm Adjustment Summary

Temporal Transposition Date **15-Jun**

	Lat	Long
Storm Center Location	**50.78 N**	**112.57 W**
Storm Rep Dew Point Location	**48.50 N**	**107.00 W**
Transposition Dew Point Location	**N/A***	**N/A***
Basin Location	**50.89 N**	**114.69 W**

Moisture Inflow Direction	**ESE @ 475**	kilometers
Basin Average Elevation	**N/A***	meters
Storm Center Elevation	**823**	meters
Storm Analysis Duration	**6**	hours

The storm representative dew point is	**15.0 °C**	with total precipitable water above sea level of		**33**	millimeters.
The in-place maximum dew point is	**22.5 °C**	with total precipitable water above sea level of		**64**	millimeters.
The transpositioned maximum dew point is	**N/A***	with total precipitable water above sea level of		**N/A***	millimeters.
The in-place storm elevation is	**823**	which subtracts	**9**	millimeters of precipitable water at	**15.0 °C**
The in-place storm elevation is	**823**	which subtracts	**15**	millimeters of precipitable water at	**22.5 °C**
The transposition basin elevation at	**N/A***	which subtracts	**N/A***	millimeters of precipitable water at	**N/A***

The in-place storm maximization factor is	**1.50**
The transposition/elevation to basin factor is	**N/A***
The barrier adjustment factor is	**N/A***
The total adjustment factor is	**N/A***

Notes: Unable to find any hourly surface Td data or daily RH observations. IPMF held to 1.50.

Observed Storm Depth-Area-Duration (millimeters)

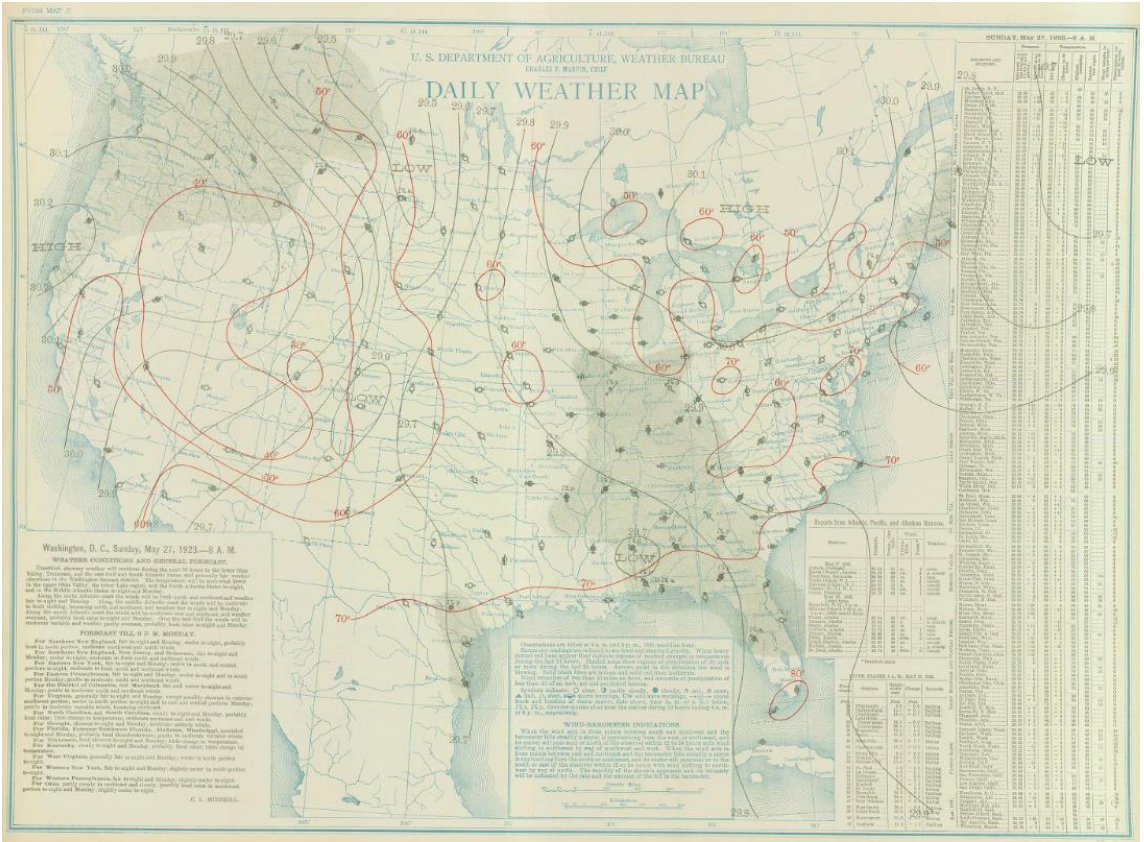
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km^2 (1 mi^2)									
26 km^2 (10 mi^2)	**51**		**145**			**157**			
259 km^2 (100 mi^2)	**48**		**137**			**149**			
518 km^2 (200 mi^2)	**45**		**129**			**141**			
1,295 km^2 (500 mi^2)	**38**		**107**			**117**			
2,590 km^2 (1,00 mi^2)	**28**		**61**			**86**			
5,180 km^2 (2,000 mi^2)	**19**		**41**			**61**			
12.950 km^2 (5000 mi^2)	**11**		**25**			**37**			
25,900 km^2 (10,000 mi^2)	**7**		**21**			**21**			
51,800 km^2 (20,000 mi^2)									

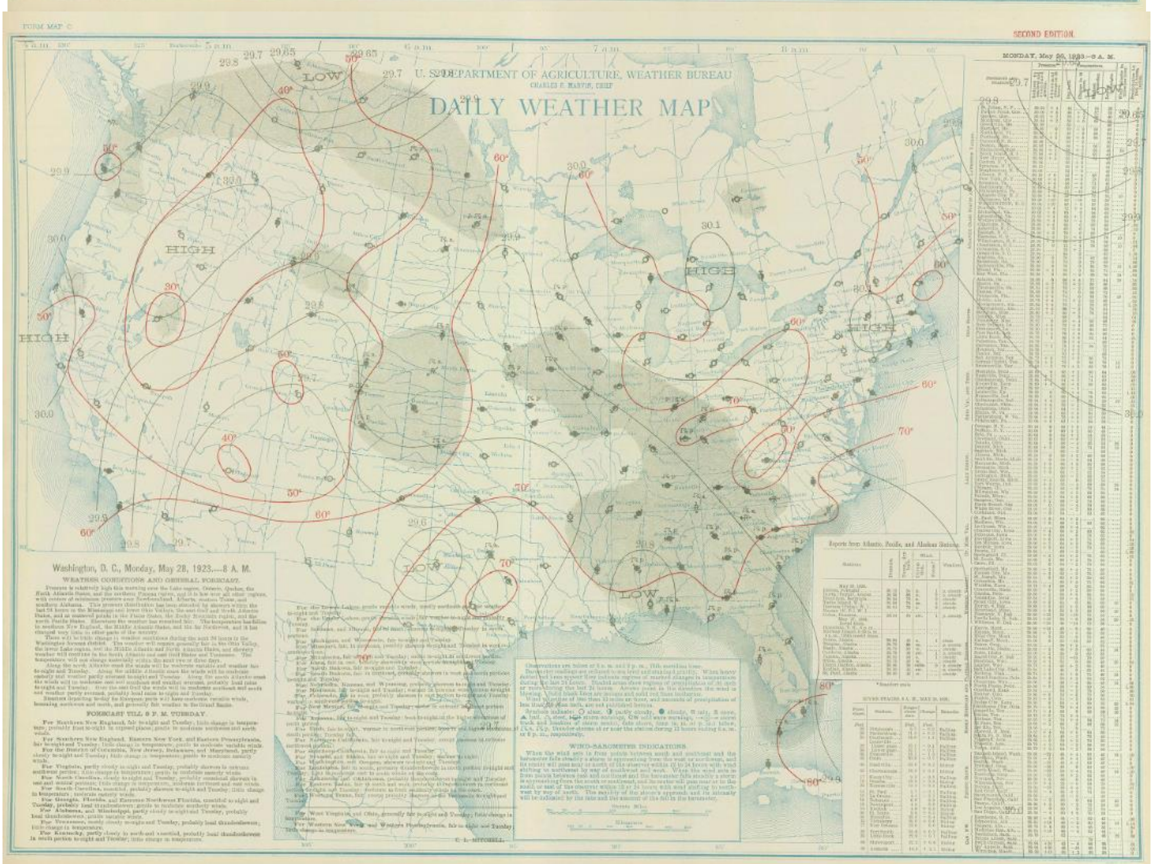
Adjusted Storm Depth-Area-Duration (millimeters)

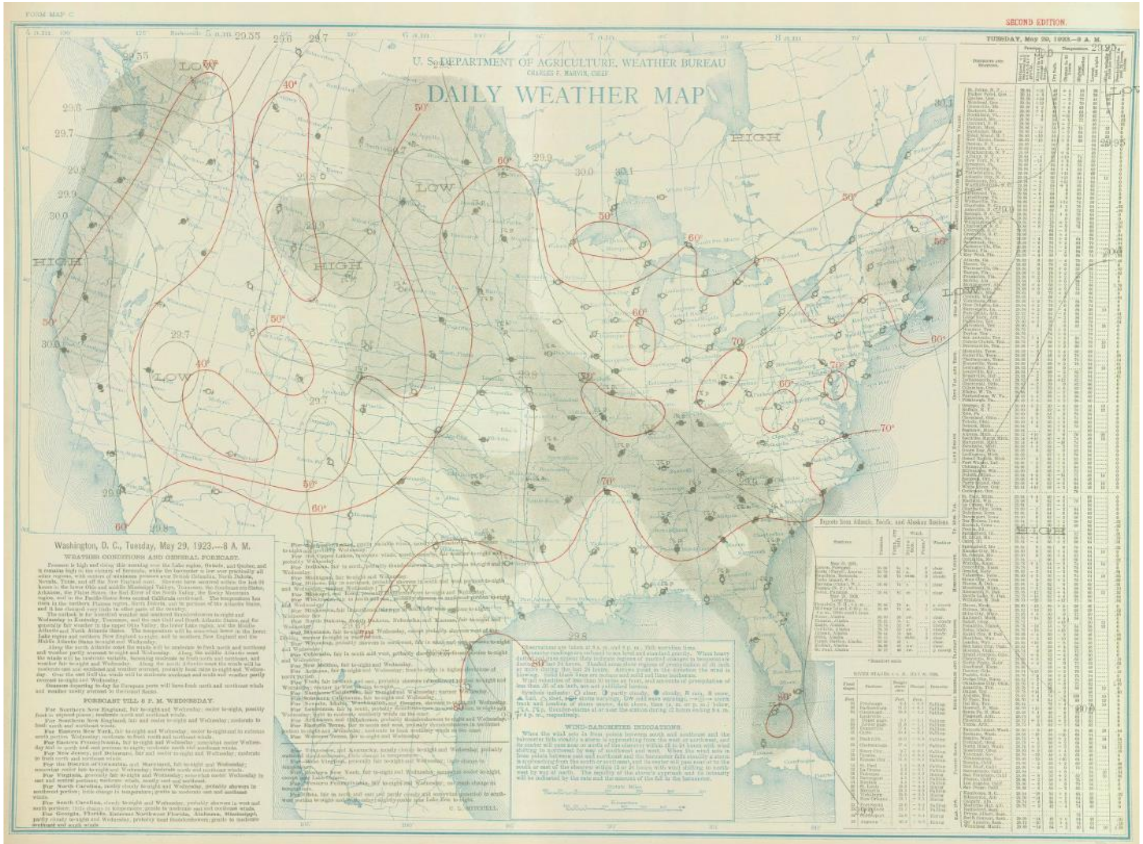
	1 Hours	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours	12 Hours	24 Hours	48 Hours
3 km2 (1 mi2)									
26 km2 (10 mi2)	**N/A***		**N/A***			**N/A***			
259 km2 (100 mi2)	**N/A***		**N/A***			**N/A***			
518 km2 (200 mi2)	**N/A***		**N/A***			**N/A***			
1,295 km2 (500 mi2)	**N/A***		**N/A***			**N/A***			
2,590 km2 (1,00 mi2)	**N/A***		**N/A***			**N/A***			
5,180 km2 (2,000 mi2)	**N/A***		**N/A***			**N/A***			
12.950 km2 (5000 mi2)	**N/A***		**N/A***			**N/A***			
25,900 km2 (10,000 mi2)	**N/A***		**N/A***			**N/A***			
51,800 km2 (20,000 mi2)									

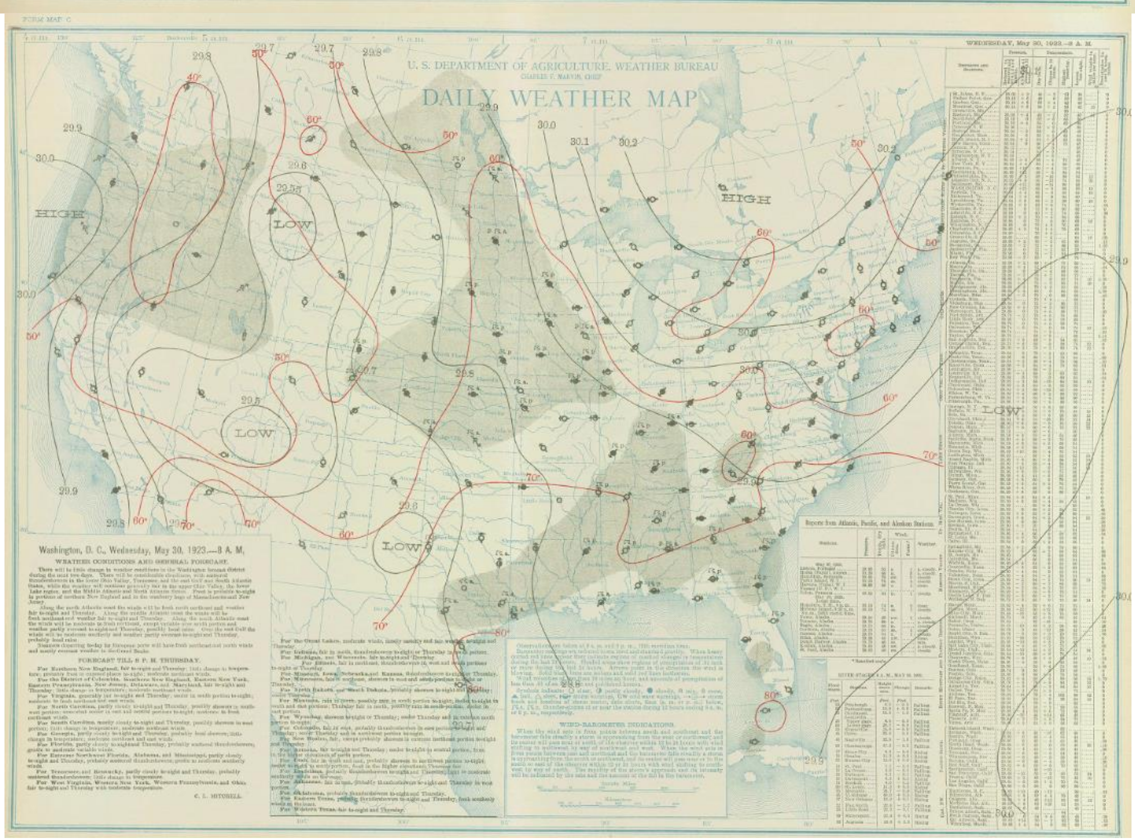
Storm or Storm Center Name	**SPAS 1521 Pekisko, AB Zone 2**		
Storm Date(s)	5/29 - 6/2/1923		
Storm Type	Synoptic/ Convective Event		
Storm Location	50.78 N	112.57 W	
Storm Center Elevation	823	meters	
Precipitation Total & Duration	196	millimeters	
Storm Representative Dew Point	15.0 °C		6
Storm Representative Dew Point Location	48.50 N	107.00 W	
Maximum Dew Point	22.5 °C		
Moisture Inflow Vector	ESE @ 475 kilometers		
In-place Maximization Factor	**1.50**		
Temporal Transposition (Date)	15-Jun		
Transposition Dew Point Location	N/A*	N/A*	
Transposition Maximum Dew Point	N/A*		
Transposition Adjustment Factor	N/A*		
Average Basin Elevation	N/A*		
Barrier Adjustment Factor	N/A*		
Total Adjustment Factor	**N/A***		

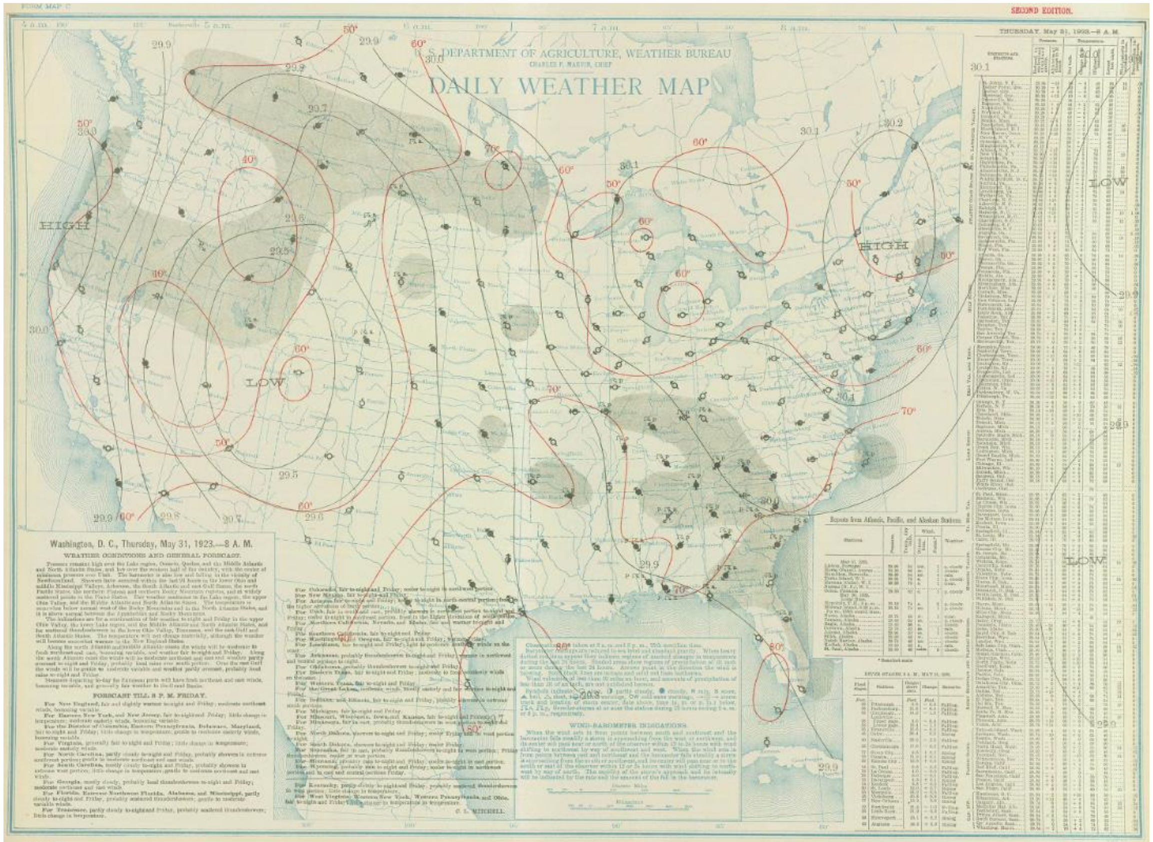
*Variable dependent on transposition location

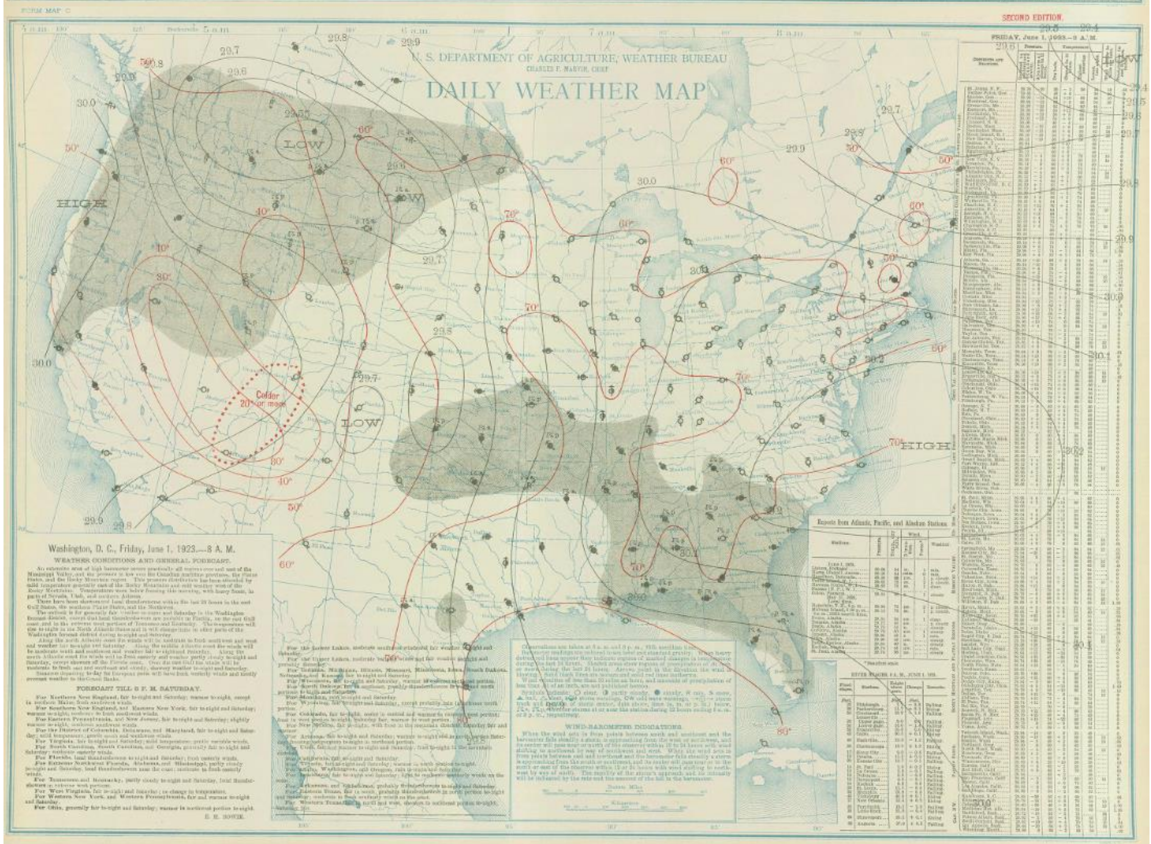

U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
Washington, D. C., Sunday, May 27, 1923.—8 A. M.
HIGH
LOW

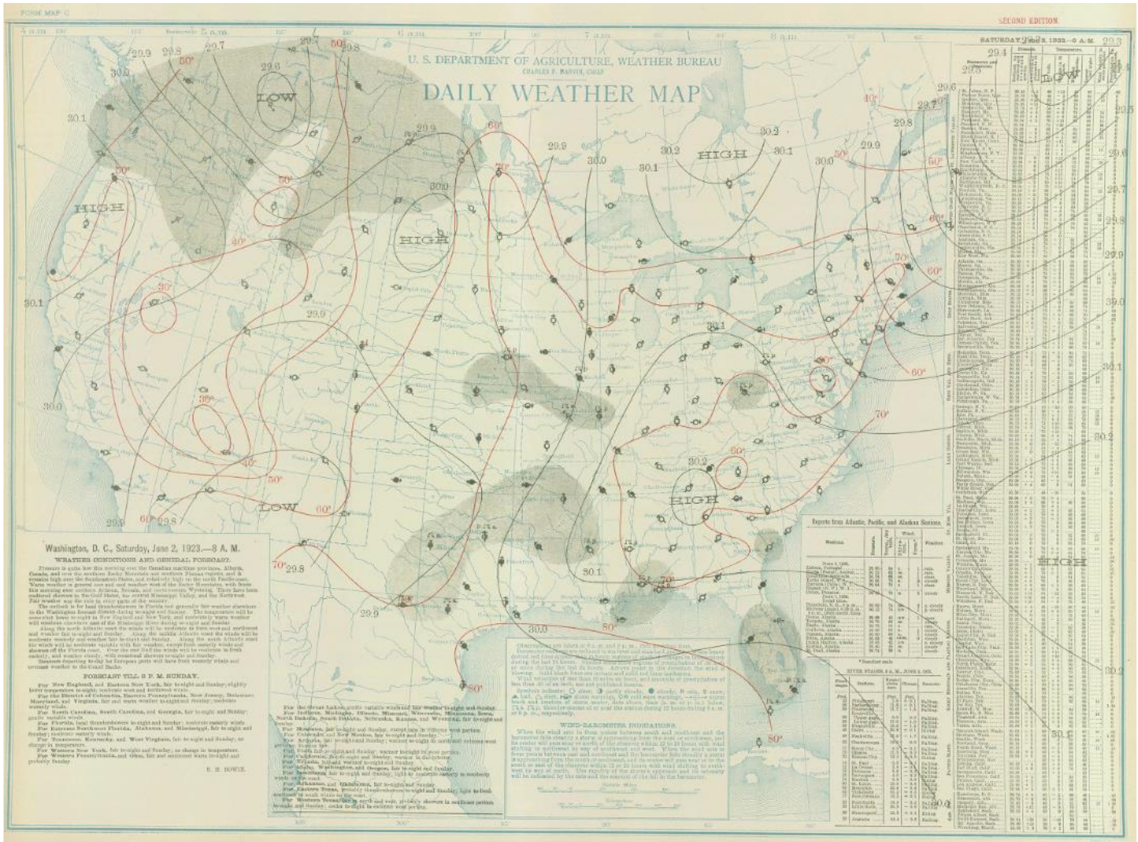

SECOND EDITION
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
Washington, D. C., Monday, May 28, 1923.—8 A. M.
HIGH
LOW


SECOND EDITION.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Tuesday, May 29, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. WEDNESDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations

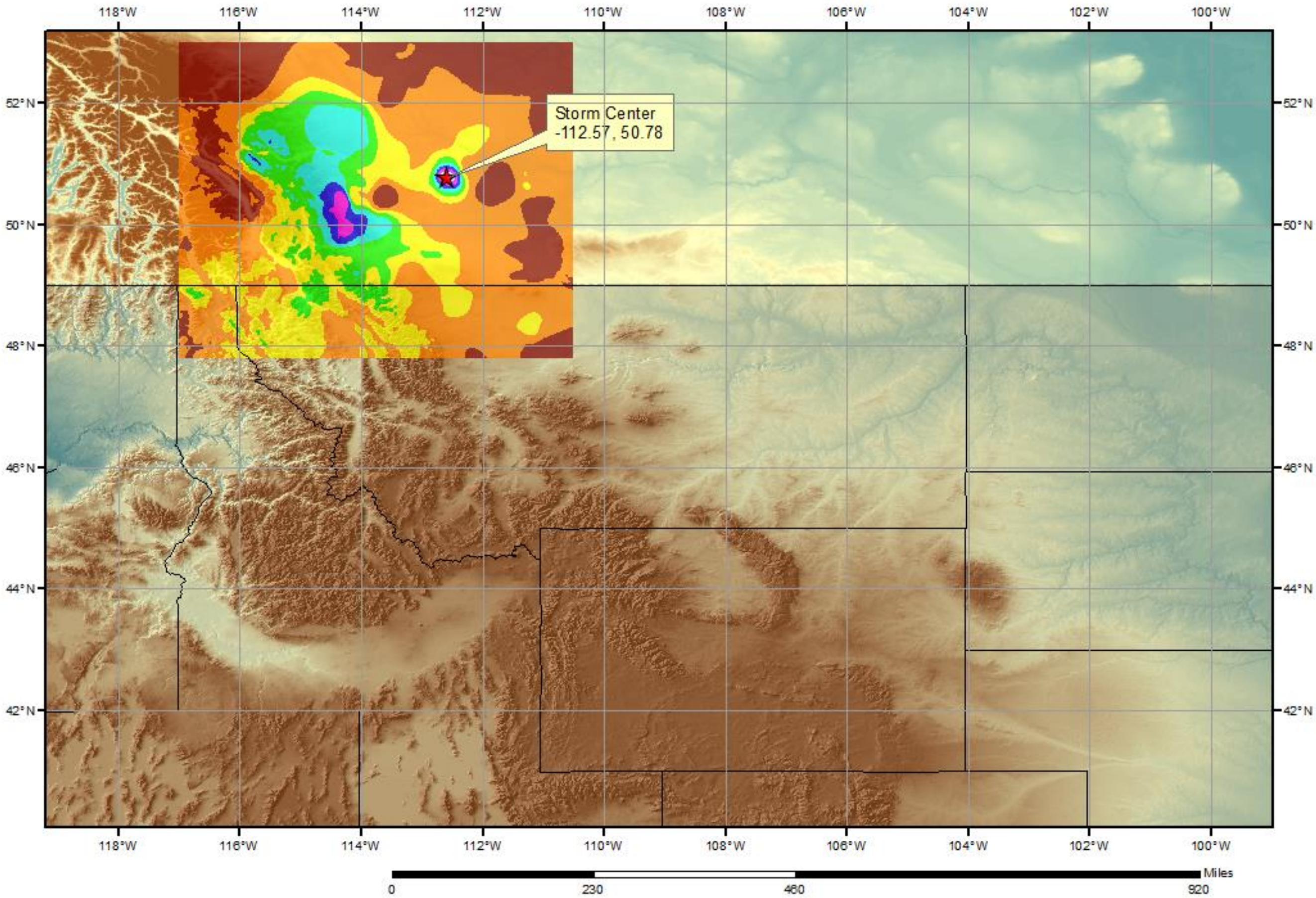

U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
Washington, D. C., Wednesday, May 30, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. THURSDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations


SECOND EDITION.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
THURSDAY, May 31, 1923.—8 A. M.
HIGH
LOW
Washington, D. C., Thursday, May 31, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. FRIDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations

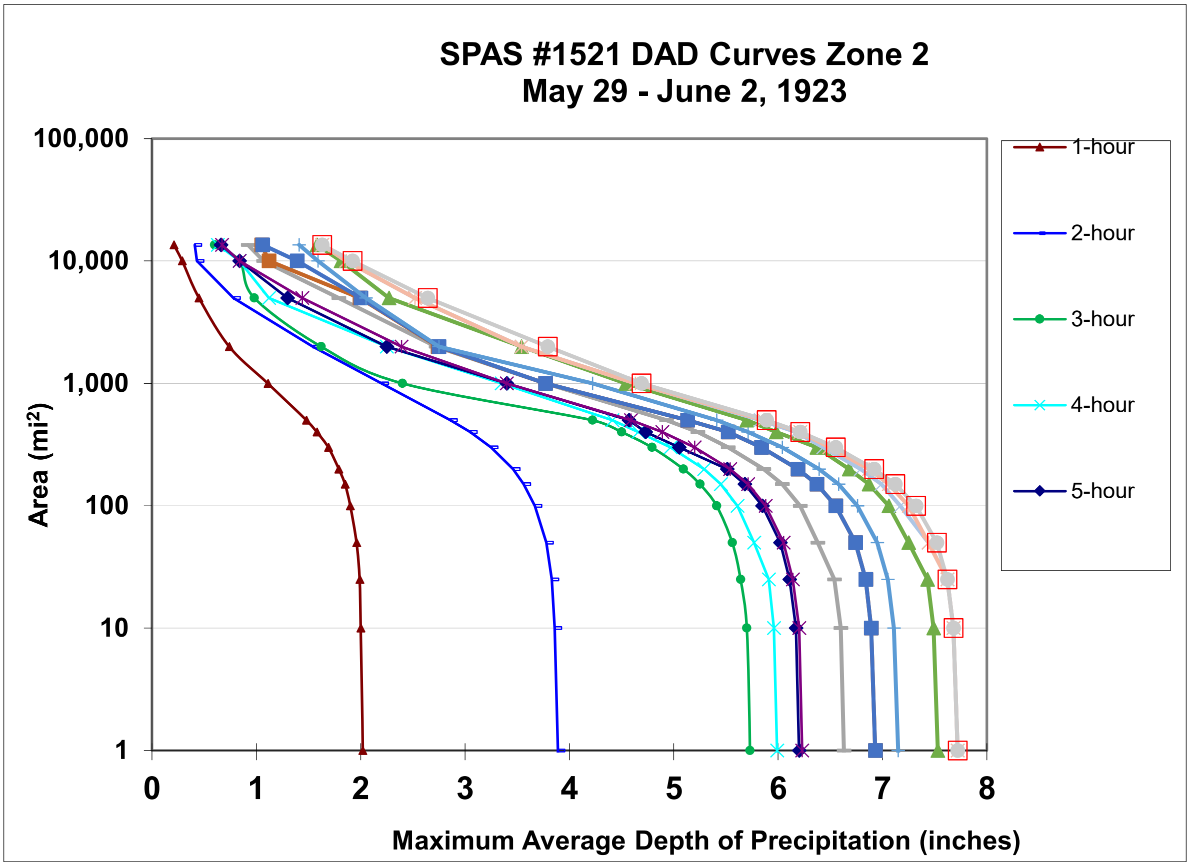

SECOND EDITION.
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
FRIDAY, June 1, 1923.—8 A. M.
HIGH
LOW
Colder
Washington, D. C., Friday, June 1, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SATURDAY.
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations

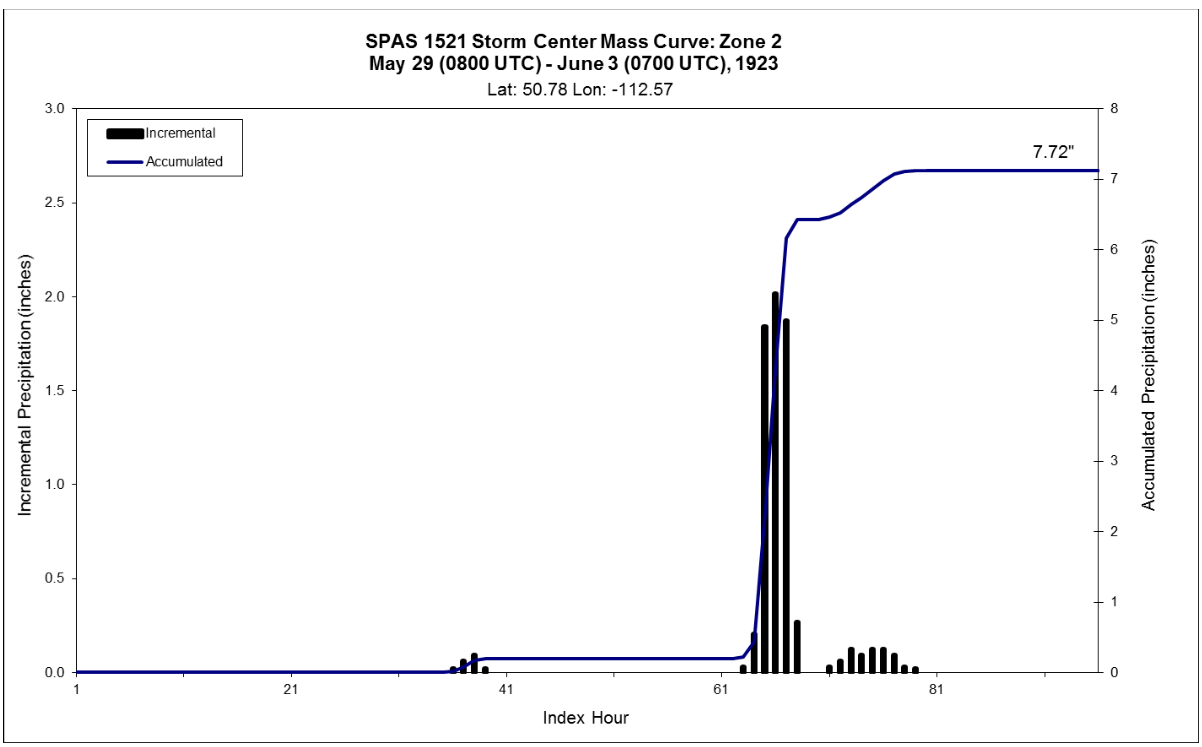

SECOND EDITION
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
LOW
HIGH
Washington, D. C., Saturday, June 2, 1923.—8 A. M.

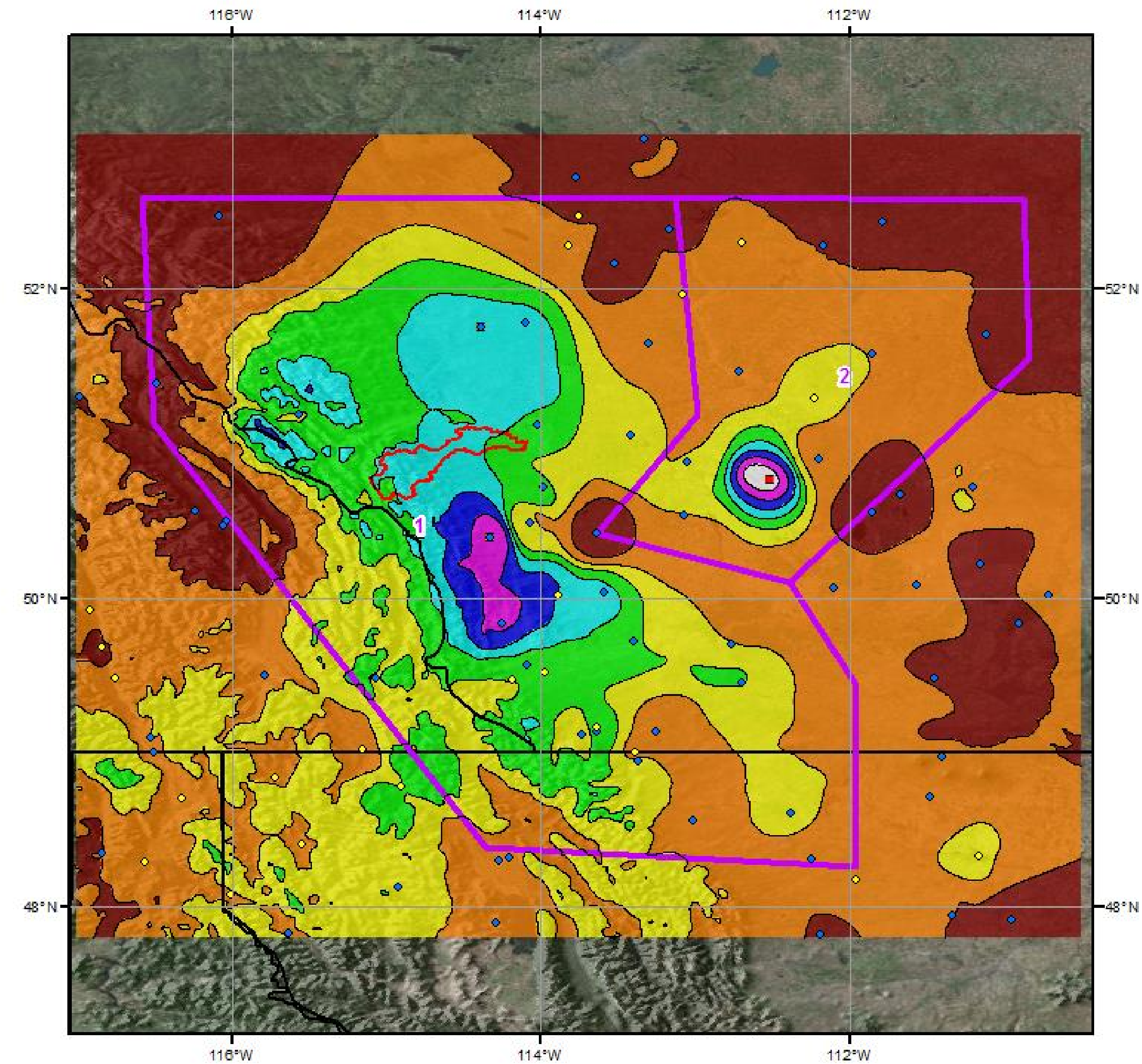
SPAS 1521 Storm Analysis Zone 2
May 31- June 1, 1923



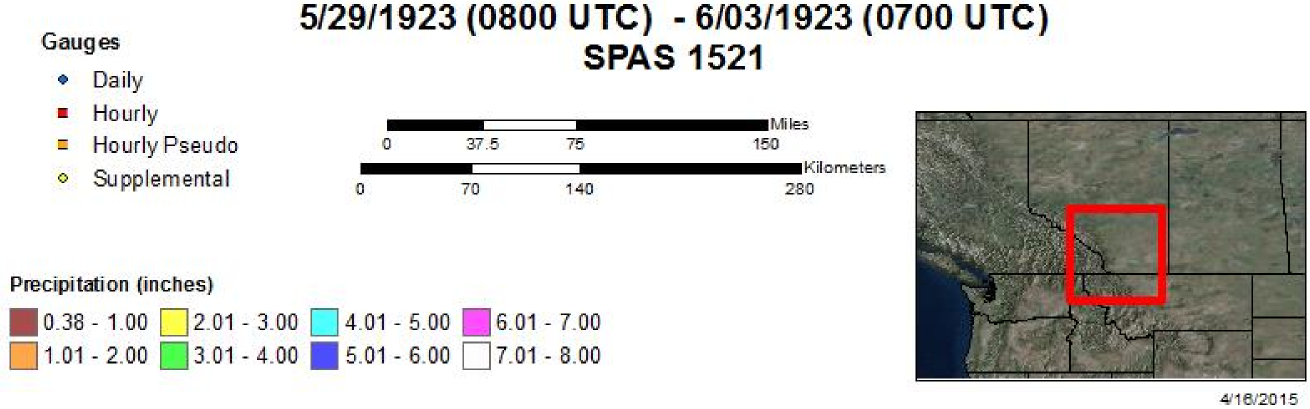
Storm 1521 Zone 2 - May 29 (0800 UTC) - June 3 (0700 UTC), 1923																
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)																
	Duration (hours)															
areasqmi	1	2	3	4	5	6	12	18	24	36	48	72	96	120		Total
0.2	2.02	3.89	5.73	6.00	6.20	6.23	6.63	6.93	6.93	7.15	7.53	7.72	7.72	7.72		7.72
1	2.02	3.89	5.73	5.99	6.20	6.23	6.63	6.93	6.93	7.15	7.53	7.72	7.72	7.72		7.72
10	2.00	3.86	5.70	5.96	6.17	6.20	6.60	6.89	6.89	7.11	7.49	7.68	7.68	7.68		7.68
25	1.99	3.83	5.64	5.91	6.11	6.14	6.54	6.84	6.84	7.05	7.43	7.62	7.62	7.62		7.62
50	1.96	3.78	5.56	5.77	6.02	6.05	6.38	6.74	6.74	6.95	7.25	7.44	7.44	7.52		7.52
100	1.90	3.67	5.41	5.61	5.85	5.88	6.21	6.55	6.55	6.76	7.06	7.17	7.25	7.32		7.32
150	1.85	3.56	5.25	5.45	5.68	5.71	6.04	6.37	6.37	6.58	6.87	6.99	7.06	7.12		7.12
200	1.79	3.46	5.09	5.29	5.51	5.54	5.86	6.19	6.19	6.39	6.68	6.79	6.87	6.92		6.92
300	1.69	3.25	4.79	4.97	5.05	5.20	5.52	5.84	5.84	6.04	6.37	6.43	6.49	6.55		6.55
400	1.58	3.05	4.50	4.66	4.73	4.89	5.23	5.52	5.52	5.71	5.98	6.17	6.21	6.21		6.21
500	1.48	2.86	4.22	4.41	4.57	4.59	4.93	5.13	5.13	5.41	5.70	5.83	5.86	5.89		5.89
1,000	1.11	2.20	2.40	3.35	3.40	3.40	3.77	3.77	3.77	4.22	4.54	4.63	4.63	4.69		4.69
2,000	0.74	1.54	1.62	2.25	2.25	2.39	2.72	2.74	2.75	2.75	3.54	3.54	3.54	3.79		3.79
5,000	0.45	0.78	0.98	1.12	1.30	1.44	1.79	1.99	2.00	2.05	2.27	2.52	2.52	2.64		2.64
10,000	0.29	0.43	0.84	0.84	0.84	0.84	1.07	1.12	1.39	1.59	1.81	1.86	1.86	1.92		1.92
13,567	0.21	0.41	0.60	0.63	0.66	0.67	0.92	1.05	1.06	1.41	1.58	1.63	1.63	1.63		1.63


SPAS #1521 DAD Curves Zone 2
May 29 - June 2, 1923
100,000
10,000
1,000
100
10
1
Area (mi²)
0
1
2
3
4
5
6
7
8
Maximum Average Depth of Precipitation (inches)
1-hour
2-hour
3-hour
4-hour
5-hour


SPAS 1521 Storm Center Mass Curve: Zone 2
May 29 (0800 UTC) - June 3 (0700 UTC), 1923
Lat: 50.78 Lon: -112.57
Incremental
Accumulated
7.72"
Incremental Precipitation (inches)
Accumulated Precipitation (inches)
Index Hour
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
21
41
61
81
8
7
6
5
4
3
2
1
0



Total Storm (120-hr) Precipitation (inches)
5/29/1923 (0800 UTC) - 6/03/1923 (0700 UTC)
SPAS 1521



Appendix G

Elbow River Basin Temporal Analysis

Elbow River Basin Standardized Timing Distributions by Storm Type

Twenty-two SPAS storms were used for temporal distribution analysis: seventeen General Storms and five Local Storms (Table G.1). The location of the storm center, for each storm analysis, was used for the temporal distribution calculations. Hourly gridded rainfall data were used for all SPAS analyzed storms (General and Local).

Table G.1 SPAS storm events used in PMP temporal distribution

SPAS #	Storm Name	State	Lat.	Lon.	Year	Month	Day	Max Rainfall (mm)	Elevation (m)
General Storms									
1211_1	GIBSON DAM	MT	48.3542	-113.3708	1964	6	6	486.7	2438
1252_1	WATERTON RED ROCK	AB	49.0875	-114.0458	1975	6	18	367.3	2391
1320_1	CALGARY	AB	50.6350	-114.8550	2013	6	19	350.0	2591
1325_1	SAVAGETON	WY	43.8458	-105.8042	1923	9	27	446.0	1455
1335_1	WARRICK	MT	48.0791	-109.7041	1906	6	6	347.7	1257
1336_1	SPRINGBROOK	MT	47.3642	-105.7778	1921	6	18	386.1	819
1337_1	PARKMAN	SK	49.7020	-101.8958	1985	8	3	400.1	634
1338_1	SPIONKOP CREEK	AB	49.1708	-114.1625	1995	6	5	367.8	1631
1404_1	CRYSTAL LAKE	MT	45.3150	-107.1750	2011	5	19	232.4	1524
1492_1	CALGARY	AB	50.4350	-114.3850	2005	6	1	325.4	1478
1501_1	NOSE MOUNTAIN	AB	54.5125	-120.0292	1982	7	15	187.7	1372
1502_1	VETERAN	AB	51.8625	-110.4292	1973	6	15	242.8	666
1503_1	NOSE MOUNTAIN	AB	54.5375	-119.5542	1972	6	10	207.3	1489
1504_1	PELICAN MOUNTAIN	AB	55.5542	-113.6625	1970	6	28	285.8	833
1505_1	PEKISKO	AB	50.2375	-114.2708	1969	6	19	256.8	1484
1521_1	BASSANO	AB	50.4375	-114.3042	1923	5	30	166.6	1341
1522_1	SIMONETTE LO	AB	54.2375	-118.4042	1987	7	30	333.8	1276
Local Storms									
1177_1	VANGUARD	SK	49.9218	-107.2100	2000	7	3	388.4	758
1212_1	RAPID CITY	SD	43.8875	-103.4042	1972	6	9	401.3	1439
1324_1	GLEN ULLIN	ND	47.3041	-101.3875	1966	6	24	326.9	525
1334_1	BUFALLO GAP	SK	49.1146	-105.2896	1961	5	30	266.7	792
1521_2	PEKISKO	AB	50.7792	-112.5708	1923	5	30	196.1	820

The rainfall mass curve at the storm center was used for the temporal distribution calculations. Rainfall data for the twenty-two storm centers were used in this analysis. The Significant Precipitation Period (SPP) for each storm was selected by excluding relatively small rainfall accumulations at the beginning and end of the rainfall duration. Accumulated rainfall (R) amounts during the SPP were used in the analysis for the hourly storm rainfall. The total rainfall during the SSP was used to normalize the hourly rainfall amounts. The time scale (TS) was computed to describe the time duration when half of the accumulated rainfall (R) had fallen. The basic procedure used to calculate these parameters are listed below.

Parameters:

SPP – Significant Precipitation Period when the majority of the rainfall occurred
R - Accumulated Rainfall at the storm center during the SSP
R_n - Normalized R
T - Time when R occurred
T_{50} - Time when $R_n = 0.5$
T_s - Shifted Time

max24hr - maximum 24-hour point rainfall at storm center location
max6hr - maximum 6-hour point rainfall at storm center location

Procedure to calculate parameters:

1. Determine the SPP. Inspect each storm's rainfall data for "inconsequential" rainfall at either the beginning and/or the end of the records. Remove these "tails" from calculations. Generally use a criteria of less than 0.1 inches/hour intensity. No internal rainfall data are deleted.
2. Recalculate the accumulated rainfall records for R.
3. Plot the SPAS rainfall and R mass curves and inspect for reasonableness (Figure G.1).
4. Normalize the R record by dividing all values by the total R to produce R_n for each hour, R_n ranges from 0.0 to 1.0.
5. Determine T_{50} using the time when $R_n = 0.5$.
6. Calculate T_s by subtracting T_{50} from each value of T. Negative time values precede the time to 50% rainfall, and positive values follow.
7. Determine max24hr and max6hr precipitation, convert accumulations into a ratio of the cumulative rainfall to the total accumulated rainfall for that duration.
8. Prepared graphs of a) T vs R, b) T vs R_n, and c) T_s vs R_n d) maximum point precipitation for General (24-hour) and Local (6-hour) storm events.

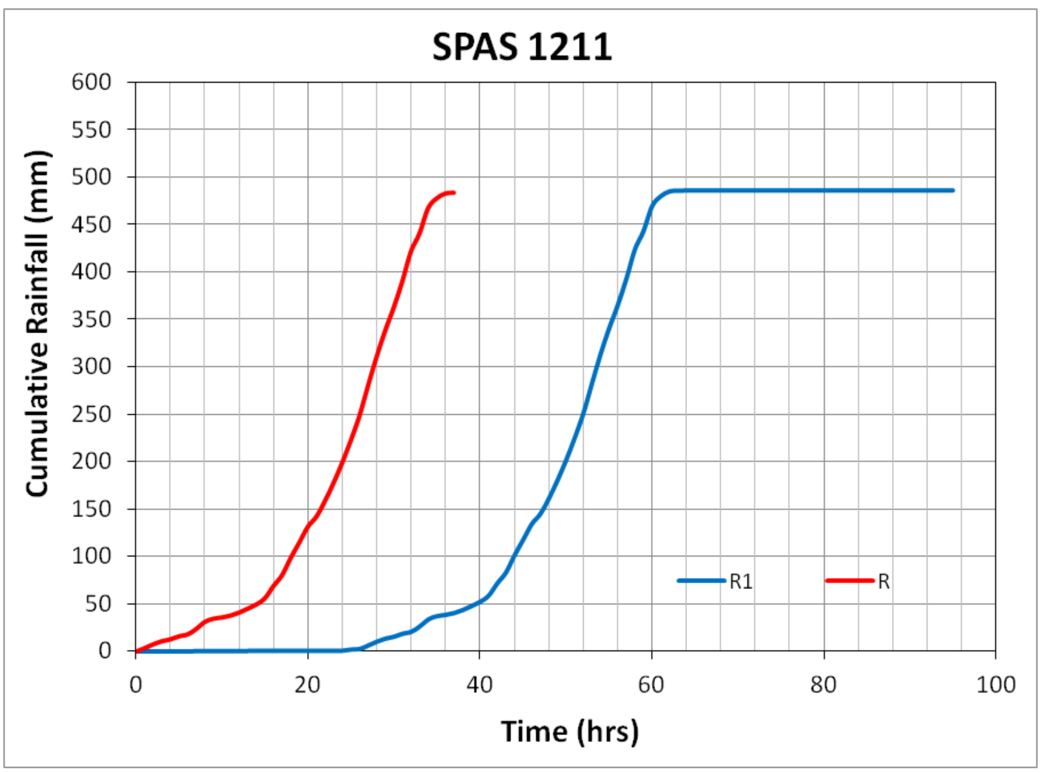


Figure G.1 R and SPAS rainfall for Flathead National Forest, MT June 1964,

Results of the Analysis

Following the procedures and description from the previous section, results are presented as three graphs. The graphs are a) T vs R, b) T vs R_n, and c) T_s vs R_n for General and Local storm events. Figures G.2 - G.5 show graphs for General SPAS storm events comparing T vs R, T vs R_n, and T_s vs R_n. Figures G.6 - G.9 show graphs for the Local SPAS storm events comparing T vs R, T vs R_n, and T_s vs R_n.

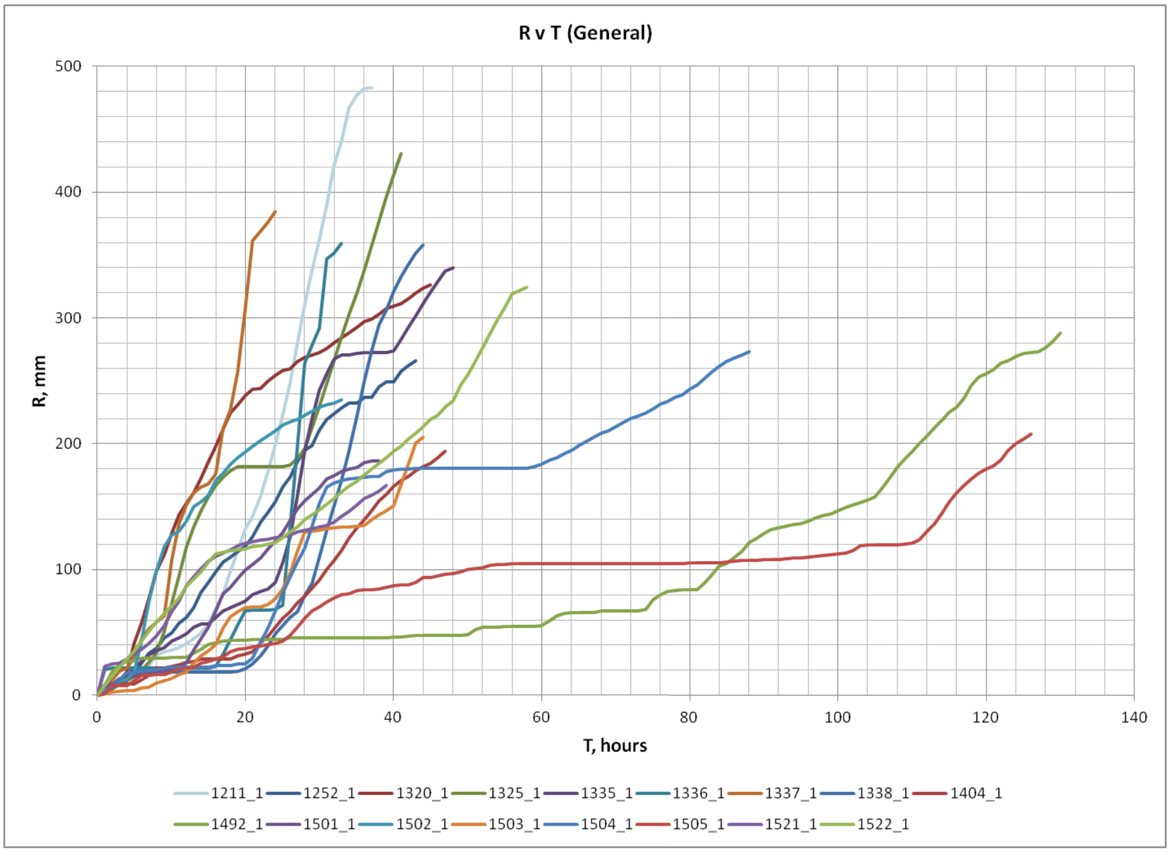


Figure G.2 Rainfall R versus Time for SPAS General storms

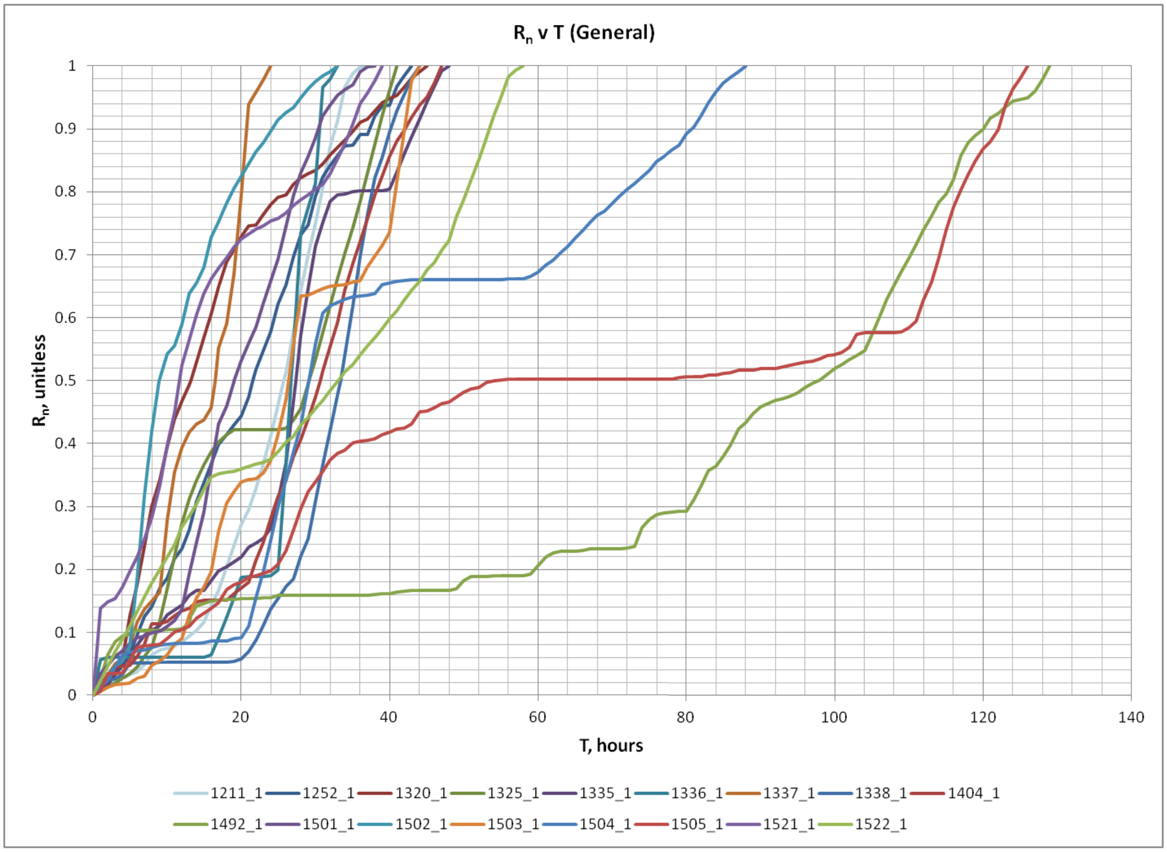


Figure G.3 Normalized R versus Time for SPAS General storms

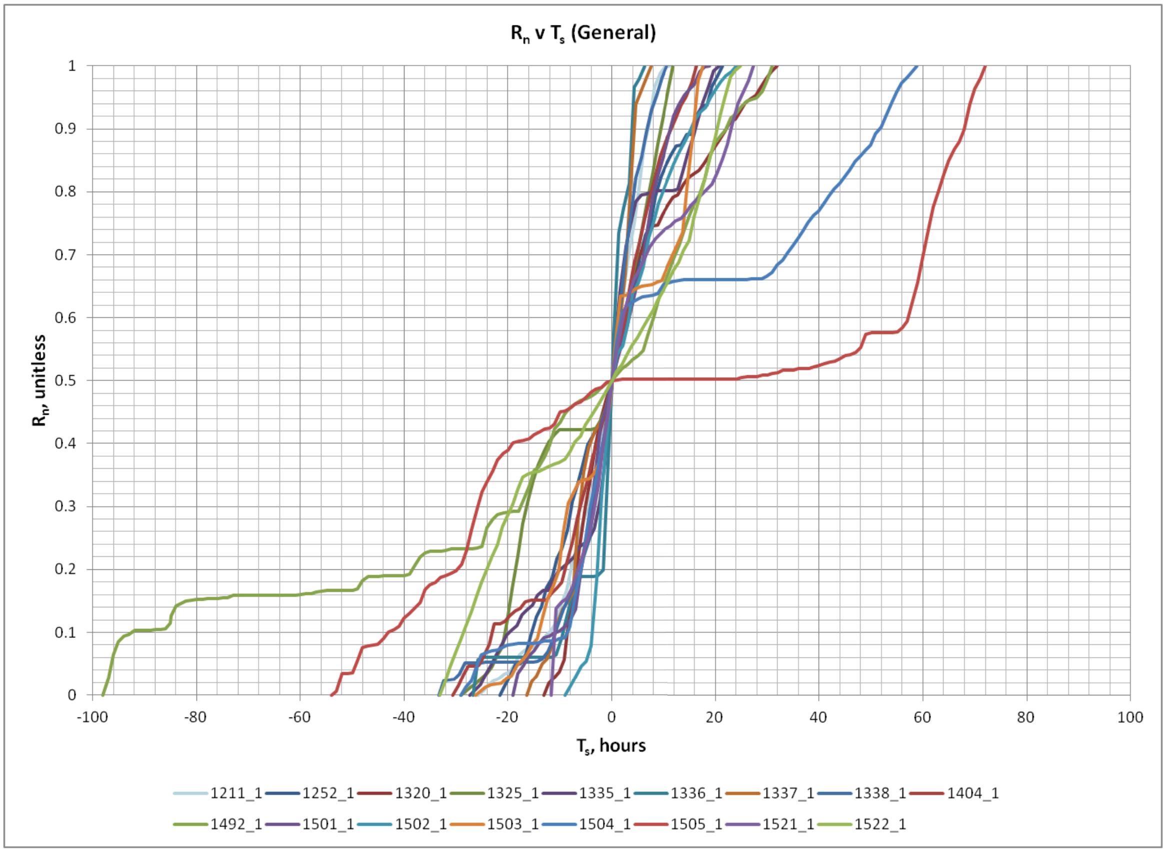


Figure G.4 Normalized R versus shifted time for SPAS General storms

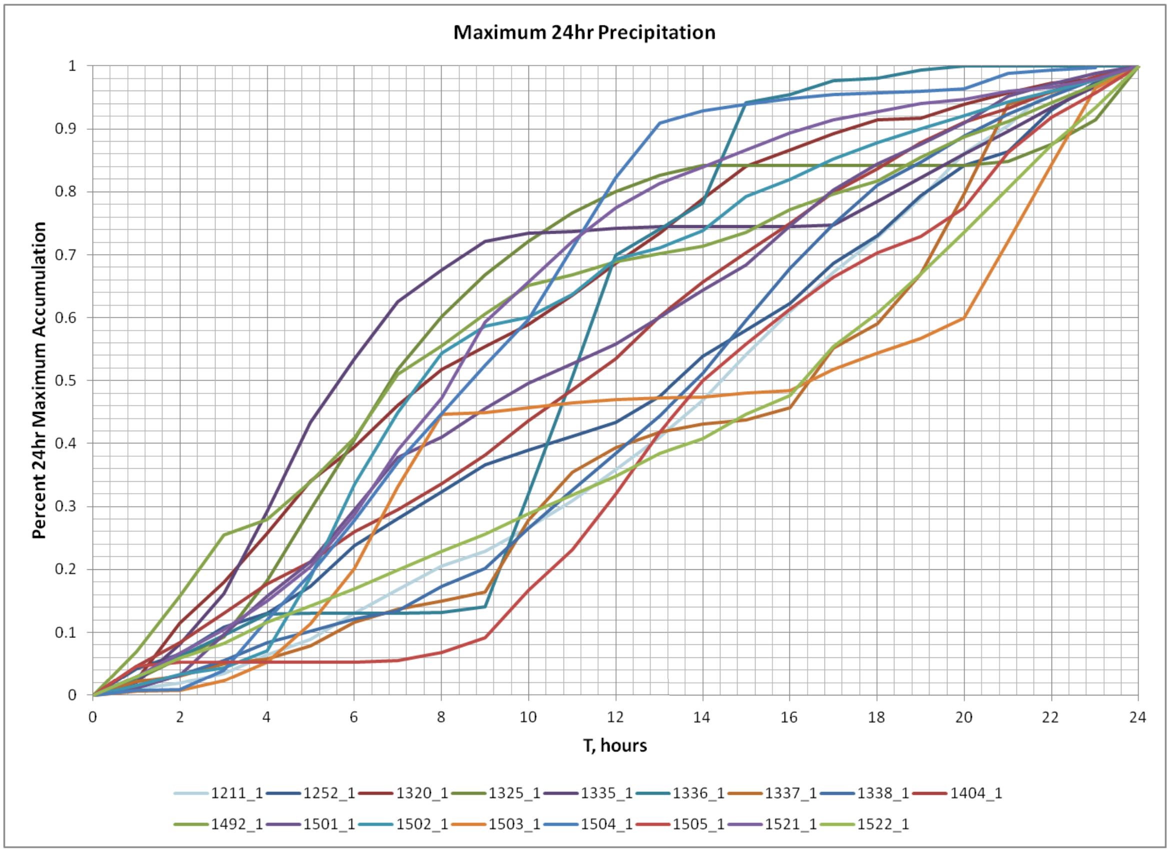


Figure G.5 Maximum 24-hour point rainfall versus Time for SPAS General storms

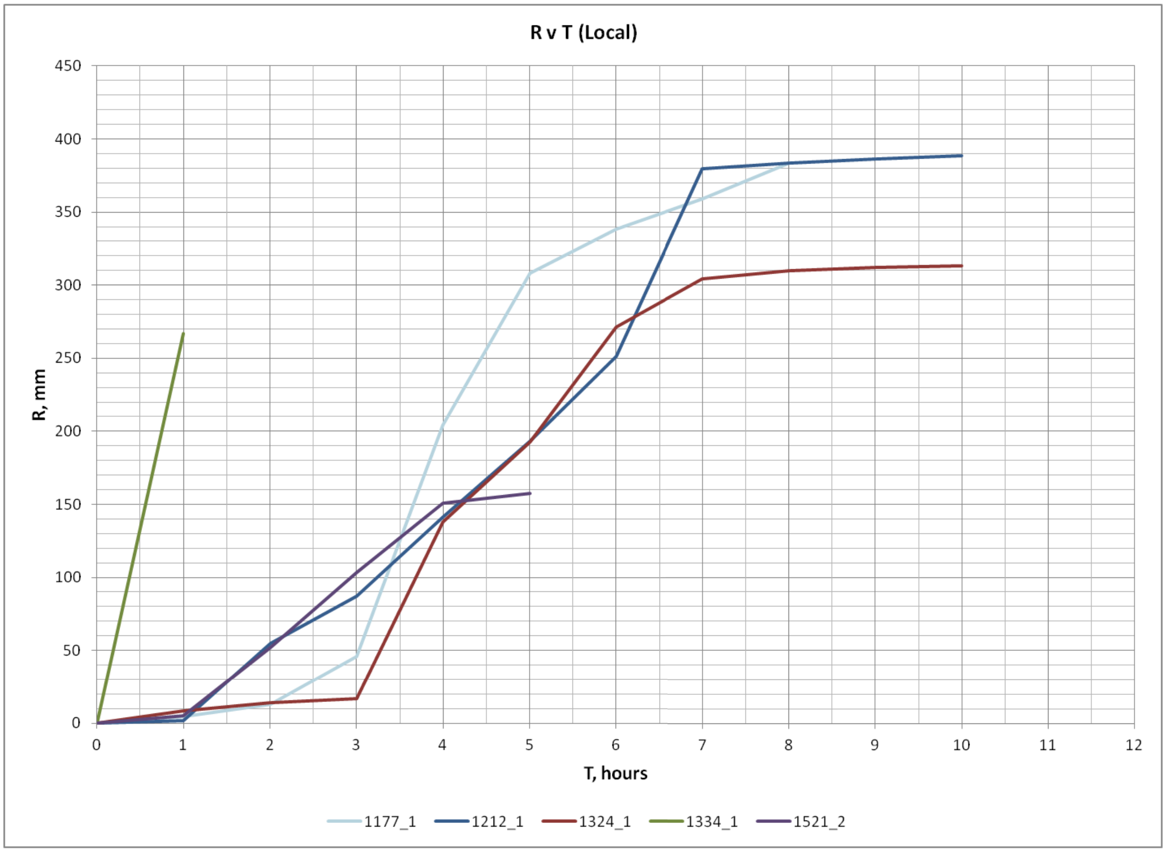


Figure G.6 Rainfall R versus Time for SPAS Local storms

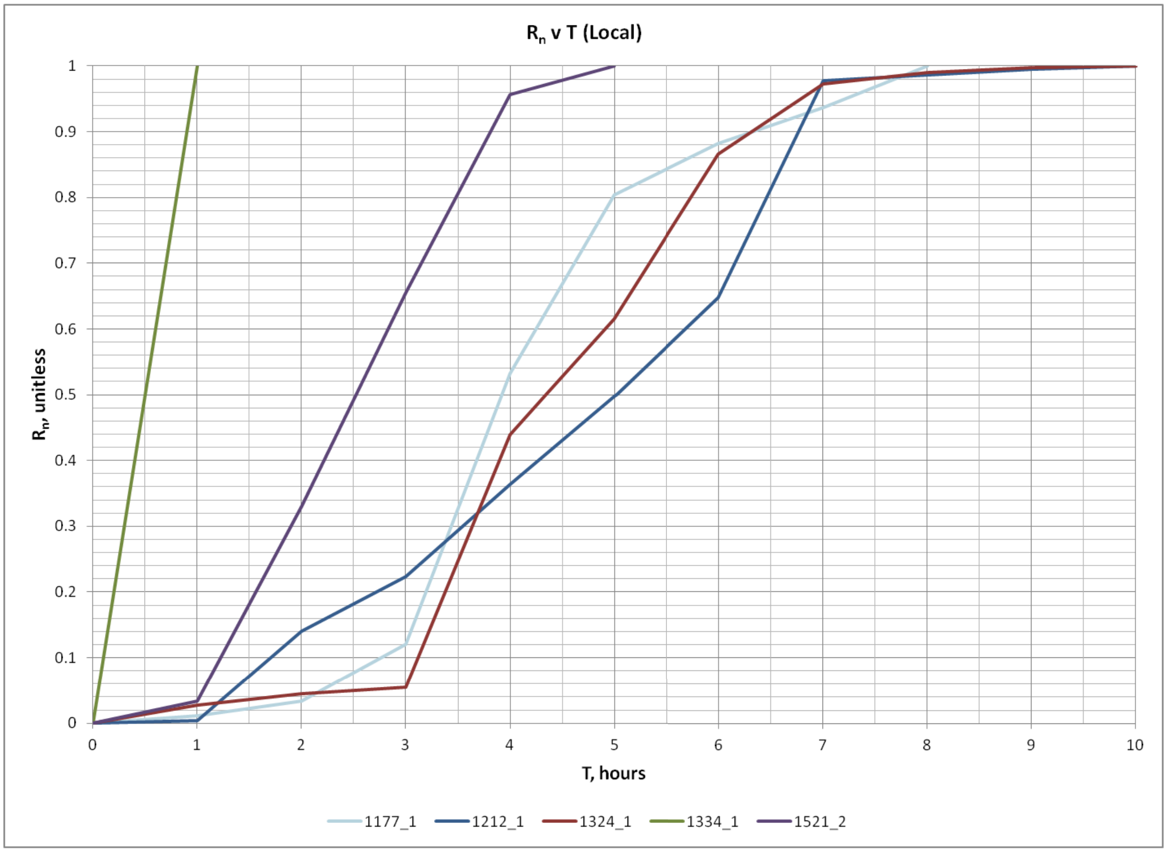


Figure G.7 Normalized R versus Time for SPAS Local storms

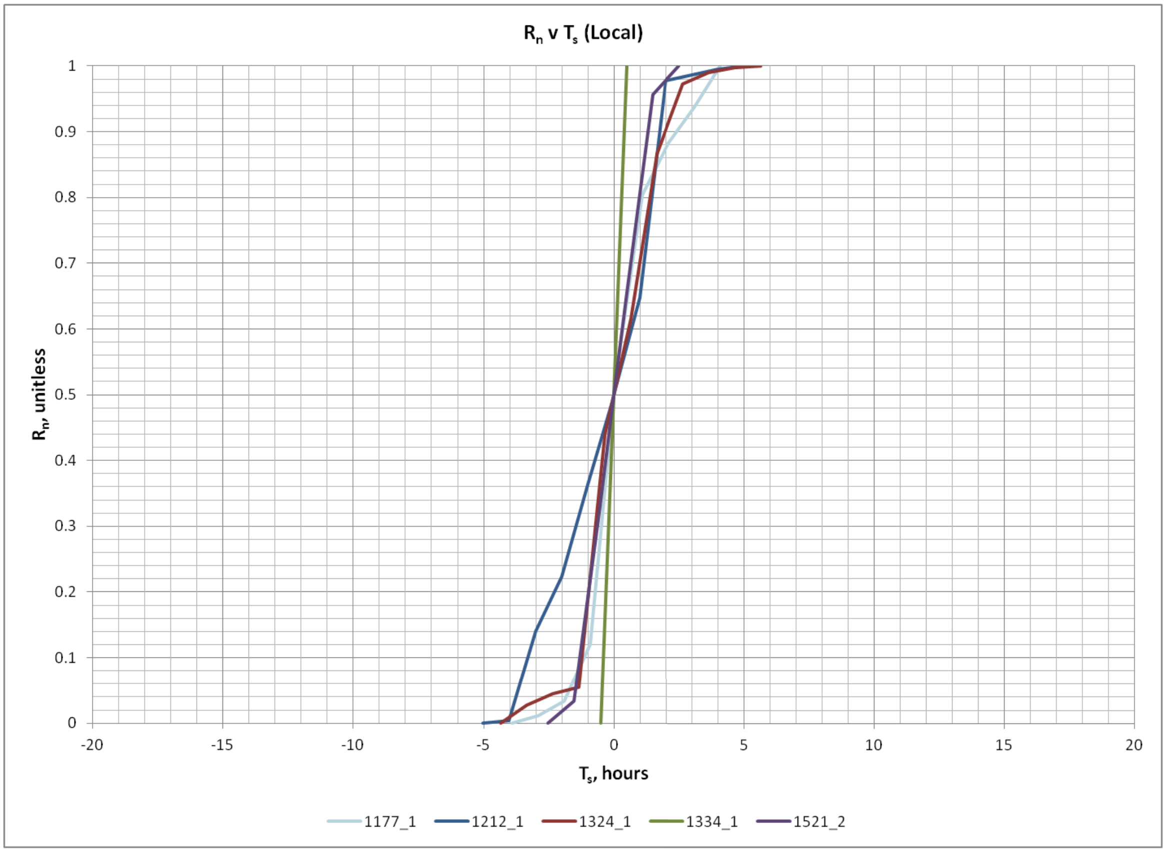


Figure G.8 Normalized R versus shifted time for SPAS Local storms

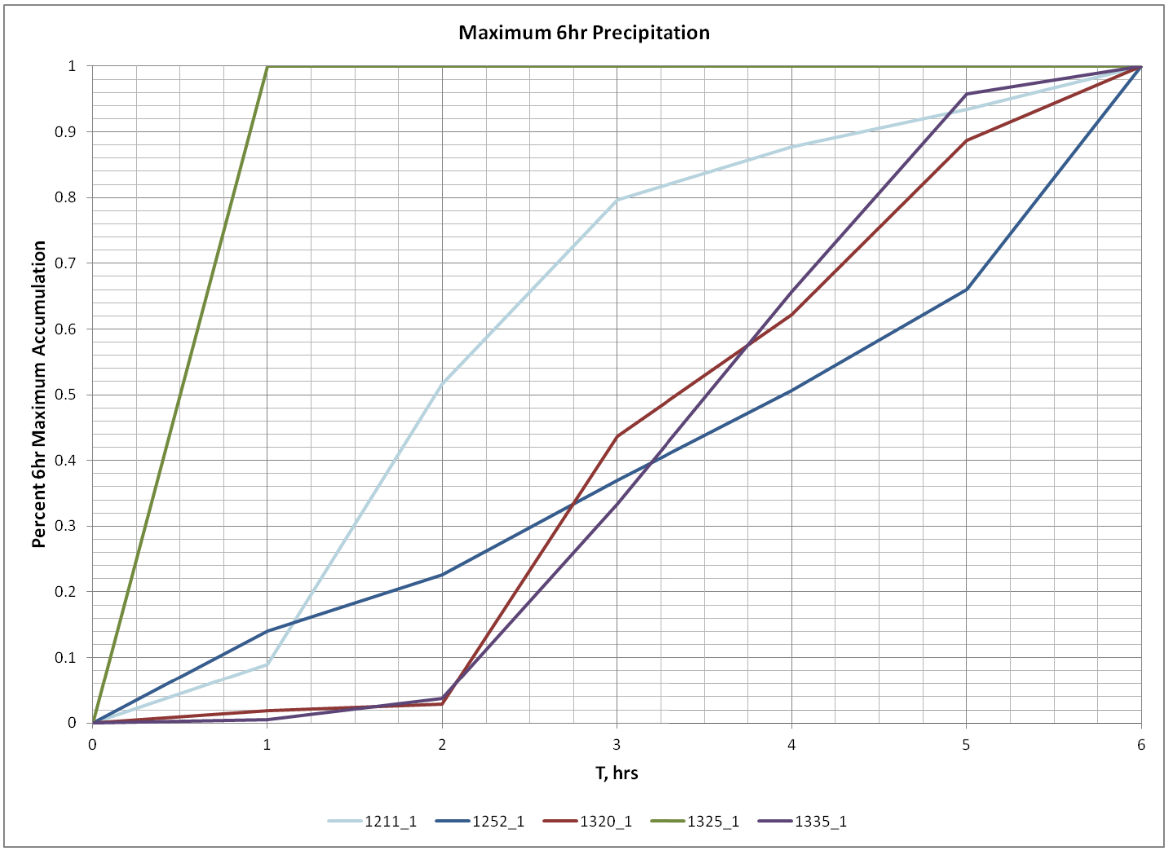


Figure G.9 Maximum 6-hour point rainfall versus Time for SPAS Local storms

Results of this investigations show consistent results for each of the two storm types analyzed. The General events have 100% of their precipitation occur within durations of 24 and 130 hours, and the Local events have 100% of their precipitation occur within durations of 1 and 6 hours. The General events have 50% of their precipitation occur within durations between 9 and 99 hours (9 and 33hours if SPAS 1492 and 1505 not included), and the Local events have 50% of their precipitation occur within durations between 0.5 and 5 hours.

APPENDIX B.4 – PMF ANALYSIS

APPENDIX B.4-1 – PMF ANALYSIS REPORT

Springbank Off-Stream Reservoir Project

Probable Maximum Flood Analysis

REPORT

Prepared for:
Alberta Transportation

Prepared by:
Stantec Consulting Ltd.

110773396

August 7, 2015

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

APPENDIX E PROBABLE MAXIMUM FLOOD WATER BALANCE FIGURES PER SUB-BASIN

1.0 INTRODUCTION

1.1 SCOPE

This report presents the analyses and results for the estimation of the Probable Maximum Flood (PMF) for the Springbank Off-Stream Reservoir (SR1); specifically, the PMF for the design of the Elbow River Diversion Dam and the SR1 Off-Stream Flood Storage Dam. The PMF was estimated by development and calibration of a Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) model. The model development included a comprehensive evaluation of appropriate methodologies and relevant recorded data pertaining to the meteorological, hydrometric, and physical characteristics of the Elbow River Basin. The initial calibration determined model parameters to simulate the 2005 and 2013 floods. The model was further refined based on flood frequency simulation. The calibrated model was applied to estimate the PMF by using Probable Maximum Precipitation (PMP) data. PMP data was developed for four scenarios: general storm (48-hour) and local storm (6-hour) for the 863 km^2 watershed upstream of the SR1 Diversion Site; general storm for the 1,212 km^2 watershed upstream of Glenmore Reservoir; and local storm for the 31 km^2 watershed upstream of the SR1 Off-Stream Dam.

2.0 HYDROLOGIC MODEL SETUP

A basin wide watershed model for the Elbow River Basin upstream of Glenmore Reservoir was developed using HEC-HMS. The drainage area was systematically partitioned based on a sub-basin approach where each sub-basin is represented by hydrologic parameters.

HEC-HMS was selected for the development of the Elbow River Basin hydrologic model. The model is available in the public domain and is widely applied to different hydrological studies in Canada and the United States.

2.1 SUB-BASIN DELINEATION

Topographic data for the study area are derived from a 1:50,000 (approximately 20 m x 20 m grid cells) digital elevation model (DEM) that covers the entire Elbow River Basin (GeoGratis 2015). The outer boundary of the basin consists of elevations varying between 1,058 m and 3,164 m and was delineated using the DEM. A map showing the variation in topography across the Elbow River Basin is included in Appendix A.

The Elbow River Basin was partitioned into eleven sub-basins based primarily on the topographic characteristics of the area with consideration of vegetation, surficial geology, and land use. Several hydrologic parameters were derived for each sub-basin including length and slope of watercourses, area, elevation at centroid of the sub-basins, and upstream and downstream elevations. Individual sub-basins ranged in size from 3,120 ha to 35,300 ha. Some of the basic model parameters generated for each sub-basin are shown in Table 1. See Figure 1 for a map of the delineated sub-basins and the boundary of the Elbow River Basin.

Table 1: Main Attributes of Sub-Basins

Sub-Basin Name	Area (ha)	Watercourse Name	Sub-basin Length (m)	Sub-basin Slope (m/m)
W100	27,800	-	-	-
W150	5,830	R240	7,050	0.0070
W200	12,100	R190	3,480	0.013
W250	3,360	R160	2,680	0.015
W300	8,150	R180	8,900	0.0090
W350	5,040	R130	10,300	0.0076
W400	35,300	R750	12,300	0.0073
W450	8,900	R100	7,400	0.0065
W500	7,690	R10	1,930	0.012
W550	3,120	R20	19,800	0.0045
W600	3,980	R120	8,140	0.00010

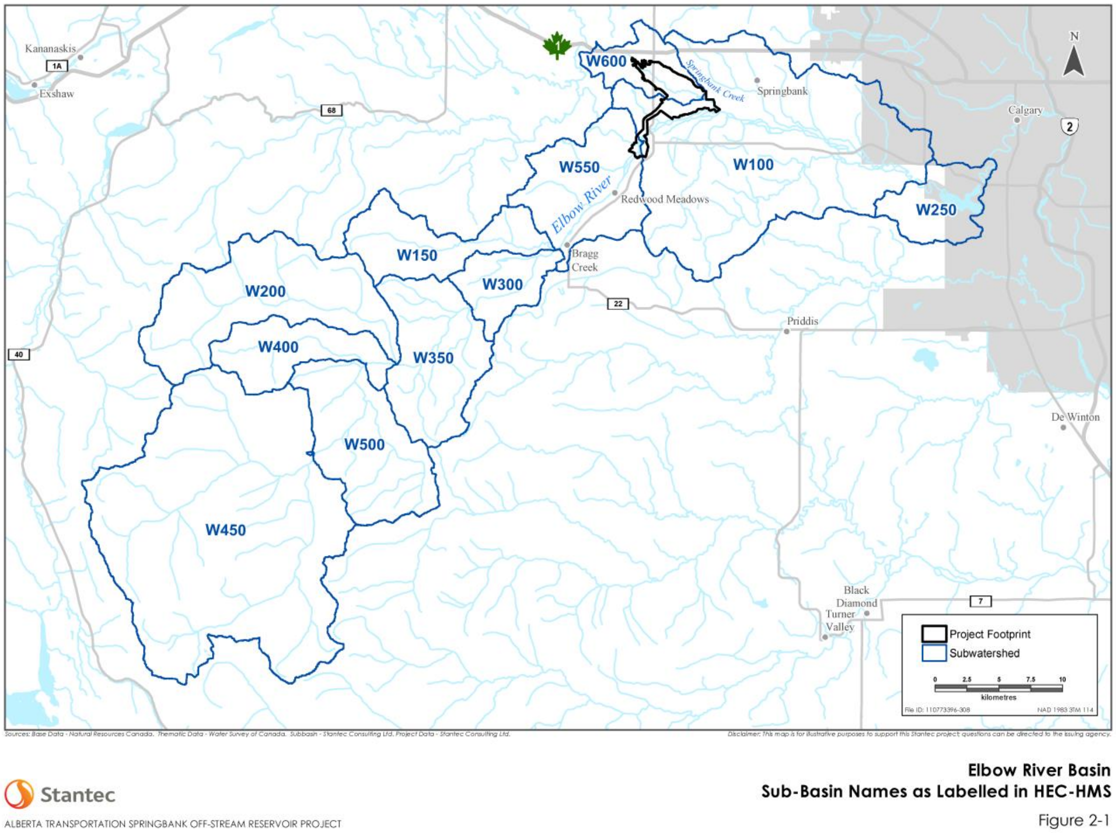


Figure 1: Sub-Basin Names as Labelled in HEC-HMS

2.2 RAINFALL LOSS PARAMETERS

HEC-HMS computes runoff volume by estimating the depth of rainfall loss and subtracting it from precipitation. It is computed using an initial and constant loss rate method. Initial loss represents interception, depression storage, and some portion of the initial soil infiltration. The constant loss rate represents the saturated soil hydraulic conductivity. Soils throughout the watershed are comprised primarily of loam. Using typical values from Tables 8 and 10 of the State of Colorado *Hydrologic Basin Response Parameter Estimation Guidelines* (Sabol 2008), an initial loss of 20 mm was assigned to all sub-basins. Using typical values from Table 12 of the same State of Colorado guidance document, a constant loss rate of 6 mm/hour was assigned to each sub-basin. The initial estimate for the rainfall loss parameters of each sub-basin is presented in Table 2.

The surficial geology of the Elbow River Basin was obtained from Alberta Geological Survey's digital data for the surficial geology of Alberta un-generalized digital mosaic. This GIS dataset is an organization of existing surficial map information for Alberta tiled into one layer (AGS 2013). A map of the different types of surficial geology within the Elbow River Basin is included in Appendix A.

Surficial geology data together with land use data was used to estimate the impervious area of each sub-basin by calculating the area of exposed bedrock and assuming it to be effectively impervious. The estimate of the impervious percent of each sub-basin is presented in Table 2.

Table 2: Summary of Initial Rainfall Loss Parameters

Sub-Basin	Drainage Area (ha)	Initial Loss (mm)	Constant Loss Rate (mm/hour)	Percent Impervious (%)
W100	27,800	20	6	0
W150	5,830	20	6	5
W200	12,100	20	6	33
W250	3,360	20	6	13
W300	8,150	20	6	0
W350	5,040	20	6	13
W400	35,300	20	6	23
W450	8,900	20	6	53
W500	7,690	20	6	19
W550	3,120	20	6	0
W600	3,980	20	6	0

2.3 RUNOFF TRANSFORMATION (UNIT HYDROGRAPH METHOD)

Runoff transformation is a process by which precipitation excess is converted into a volumetric time sequence of surface runoff or hydrograph. The unit hydrograph is one such transformation method whereby precipitation excess is converted into runoff hydrographs based on physiographic characteristics. In this work, unit hydrographs were developed for each sub-basin using the method described in the State of Colorado, *Hydrologic Basin Response Parameter Estimation Guidelines* (Sabol 2008). Based on this method, the US Bureau of Reclamation (USBR) synthetic unit hydrograph for the Rocky Mountain general storm was used for all sub-basins during initial model development.

The coordinates of each unit hydrograph are a function of the basin lag time (L_g) parameter. Lag time is estimated from topographic characteristics of each sub-basin. A lumped parameter representing resistance to overland flow (K_n) was estimated for each sub-basin in order to estimate lag time. The length of the longest watercourse (L), basin slope (S), and distance to the sub-basin centroid (L_{ca}) were estimated in HEC-GeoHMS using the 20 m resolution topographic data. A K_n value of 0.15 was initially selected for all sub-basins based on Table 7 from the State of Colorado guidance document. Parameters used to develop the unit hydrographs are presented in Table 3. These input parameters are presented in Imperial Units as used in the guidance document. The resulting unit hydrographs were converted to SI units after calculations were completed. Full unit hydrographs for each sub-basin are presented in Figure 2.

Table 3: Summary of Initial Sub-Basin Unit Hydrograph Input Parameters

Sub-Basin	Drainage Area (mi²)	Basin Slope (ft/mi)	L (mi)	L_{ca} (mi)	K_n	Computed L_g (hr)	Unit Duration, D (min)
W100	107	51.7	21.7	9.37	0.15	11.8	60
W150	22.5	168	13.3	7.48	0.15	7.65	60
W200	46.7	205	18.1	9.35	0.15	8.81	60
W250	15.4	47.0	9.81	6.65	0.15	8.20	60
W300	13.0	161	7.76	4.27	0.15	5.35	60
W350	31.5	125	9.23	3.52	0.15	5.54	60
W400	19.4	300	11.2	6.40	0.15	6.22	60
W450	136	229	19.1	5.74	0.15	7.50	60
W500	34.4	206	12.9	4.40	0.15	6.14	60
W550	29.7	83.4	10.4	5.90	0.15	7.32	60
W600	12.0	34.9	8.04	3.64	0.15	6.61	60

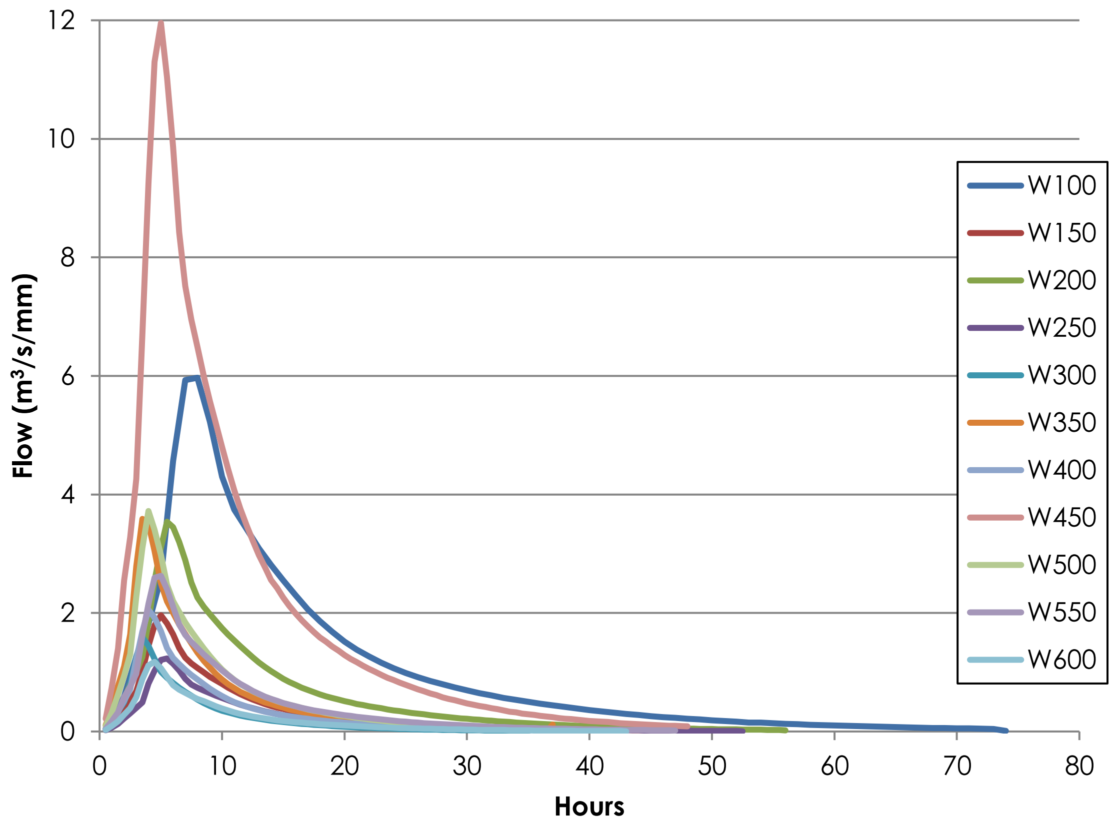


Figure 2: Sub-Basin Unit Hydrographs Used in the Initial Modeling

2.4 CHANNEL ROUTING

River routing within the model represents the travel time and attenuation that occurs within the Elbow River and its tributaries between modeling concentration points. Two methods were employed in the model to represent channel routing. For small tributaries and the upstream reaches of the Elbow River, the kinematic wave routing method was used. The river length, slope, and approximate width were estimated from the 20 m by 20 m topographic data and aerial imagery. The Muskingum routing method was used for the portion of Elbow River between Bragg Creek and the Glenmore Reservoir. This routing method requires the specification of travel time, K, and a parameter defining attenuation, X. The travel times were selected based on observed historic flood peaks at Bragg Creek and Sarcee Bridge hydrometric stations. An X value of 0.4 was initially assumed for all Muskingum routing reaches which results in low attenuation. Table 4 summarizes routing parameters used in the model.

Table 4: Summary of Initial Reach Routing Parameters

Kinematic Wave Reach Routing Methodology						
Sub-Basin	**Length (m)**	**Slope (m/m)**	**Manning's n**	**Sub-Reaches**	**Shape**	**Width (m)**
R160	2,680	0.015	0.02	2	Rectangular	75
R240	7,050	0.0071	0.02	2	Rectangular	40
R190	3,480	0.013	0.02	2	Rectangular	40
R180	8,900	0.0091	0.03	2	Rectangular	100
R10	1,930	0.012	0.03	2	Rectangular	20
***Muskingum* Reach Routing Methodology**						
Sub-Basin	**K (hour)**			**X**		
R750	4.0			0.4		
R130	1.2			0.4		
R100	2.0			0.4		
R20	6.0			0.4		
R120	2.0			0.4		

2.5 BASEFLOW

2.5.1 Baseflow Method

Baseflow was initially assumed to be a constant value. As such, all sub-basins were assigned a fixed baseflow of 1 m^3/s, except for the largest upstream sub-basin, W450, which was adjusted so that the flow at the beginning of the simulation matched the observed flow. The initial estimate for the baseflow for each sub-basin is presented in Table 5.

Table 5: Summary of Initial Sub-Basin Baseflow

Sub-Basin	Baseflow Methodology	2005 Event Baseflow (m^3/s)	2013 Event Baseflow (m^3/s)
W100	Constant	1	1
W150	Constant	1	1
W200	Constant	1	1
W250	Constant	1	1
W300	Constant	1	1
W350	Constant	1	1
W400	Constant	1	1
W450	Constant	27	21
W500	Constant	1	1
W550	Constant	1	1
W600	Constant	1	1

3.0 HYDROLOGIC MODEL CALIBRATION

3.1 CALIBRATION EVENTS

The HEC-HMS model was calibrated for two flood events: June 4, 2005 to June 16, 2005 and June 19, 2013 to June 28, 2013.

3.1.1 Precipitation Data

Gridded precipitation data was developed by Applied Weather Associates (AWA); a sub-consultant to Stantec for this project (see Table 6). Appendix B provides cumulative precipitation maps for the 2005 and 2013 flood events.

Table 6: Summary of Precipitation Data Provided by AWA

Precipitation Data	Time Period
2005 Flood Event	June 1, 2005 at 8:00 to June 9, 2005 at 7:00
2013 Flood Event	June 19, 2013 at 8:00 to June 22, 2013 at 7:00

3.1.2 Hydrometric Data

Available hydrometric data was obtained and analyzed from four sources: City of Calgary; Alberta Environment and Sustainable Resource Development (ESRD); Alberta Environment Monitoring Branch, now part of Alberta Environmental Monitoring and Reporting Agency (AEMERA); and Water Survey of Canada (WSC). ESRD takes raw gauged data and develops real-time flow rates for use in flood forecasting and real time water management. Since data from ESRD is intended for real-time use and as ESRD generally does not back correct data after the event has passed, their data can be prone to some data errors. AEMERA reviews and adjusts data from their own gauges prior to submission to WSC. WSC does not issue preliminary hydrograph data until it has undergone an extensive review process which can take months or years prior to the releasing official streamflow data. It is generally accepted that WSC data is preferred when available for calibration. Therefore, WSC was taken as a reference for comparison because it is generally known to be the "official" and most reliable source for streamflow data.

The gauging stations used in model calibration were Elbow River at Bragg Creek (05BJ004) and Elbow River at Sarcee Bridge (05BJ010). The Bragg Creek Station is located upstream of the proposed SR1 Diversion Structure, while the Sarcee Bridge Station is situated downstream of the Diversion Structure, upstream of Glenmore Reservoir.

The contributing drainage area to the Bragg Creek Station is 790.8 km^2 and includes the mountainous portions of the basin where both the 2005 and 2013 rainfalls were the heaviest. The contributing drainage area to the Sarcee Bridge Station is 1189.3 km^2 and represents nearly the full study area. To the end of 2005, the Sarcee Bridge station was operated by AEMERA. The station was taken over by WSC in 2006.

See Table 7 for a summary and refer to Appendix A for a map of the relevant hydrometric stations.

Table 7: Relevant Hydrometric Station Summary

Station ID	Station Name	Drainage Area (km^2)	Period of Record		Type of Flow	Operation Schedule
			From	To		
05BJ004	Elbow River at Bragg Creek	790.8	1934	2012	Natural	Continuous
05BJ010	Elbow River at Sarcee Bridge	1189.3	1979	2012	Natural	Continuous

3.1.2.1 2005 Hydrometric Data for Model Calibration

There were three closely spaced storms in June of 2005 resulting in flood discharges. The first of the three storms and floods took place between June 1, 2005 and June 16, 2005 and was selected for model calibration. Hydrograph data was obtained from WSC for the Bragg Creek station and is presented in Figure 3.

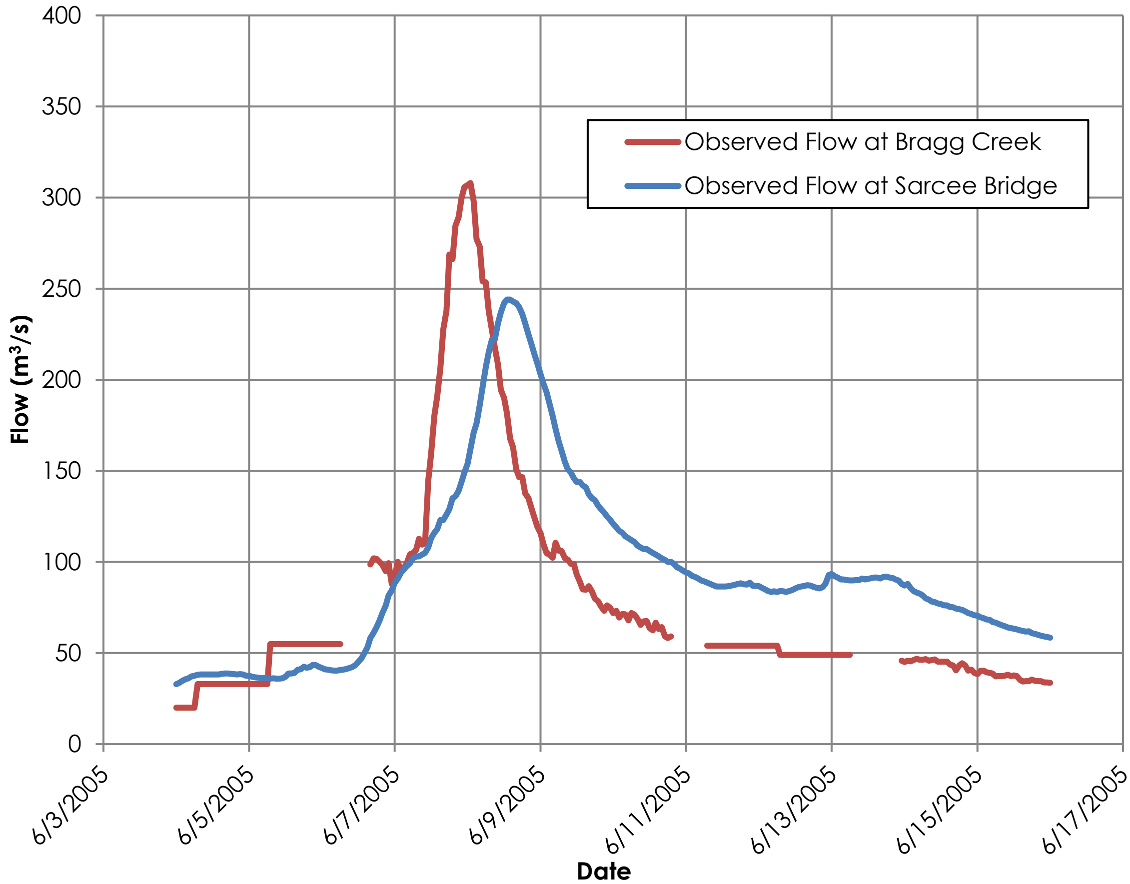


Figure 3: Observed Flood Hydrographs for the 2005 Flood Event

Hydrograph data was obtained from AEMERA for the Sarcee Bridge station and is also presented in Figure 3. This is hourly data which was not previously submitted to WSC. The peak is significantly lower than the peak flow at Bragg Creek and according to the field notes of Jay Parsons, a field technician for the Alberta Environment – Water Survey Branch (AE-WSB) responsible for this site in 2005, the peak of the hydrograph at Sarcee Bridge is likely underestimated (Mahler pers. comm. 2015).

3.1.2.2 2013 Hydrometric Data for Model Calibration

The SR1 hydrological model was also calibrated to the 2013 flood event, which took place between June 19, 2013 and June 24, 2013. WSC has not yet issued an official hydrograph for the 2013 event at Bragg Creek but has estimated a peak instantaneous flow for the site of 1150 m^3/s (Lazowski pers. comm. 2015). Stantec developed an estimated hydrograph at this location using

WSC's estimated peak flow and WSC real time preliminary water level data together with stage-discharge rating curves (See the separate Springbank Off-Stream Reservoir Project Hydrology Flood Frequency Analysis Report). The hydrograph developed by Stantec was used for calibration purposes and is presented in Figure 4.

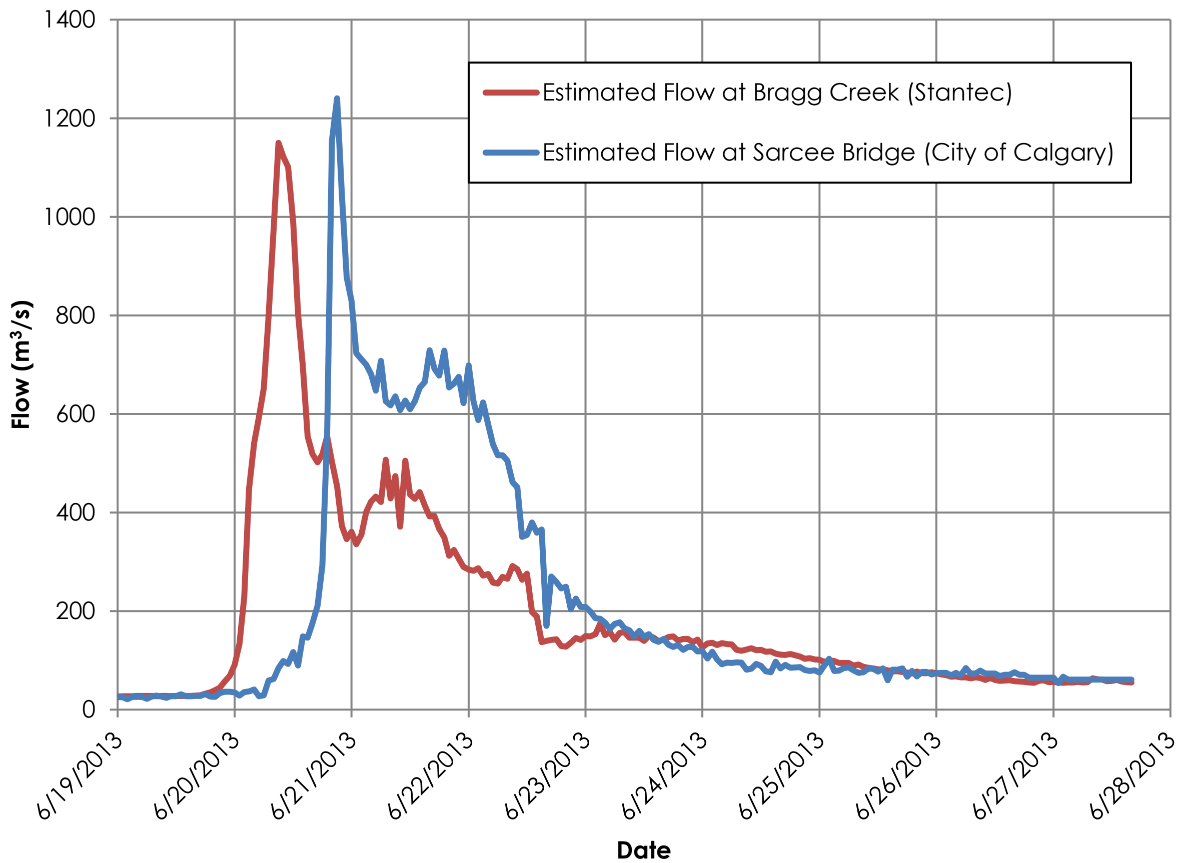


Figure 4: Flood Hydrographs for 2013 Event

The City of Calgary provided an estimated inflow hydrograph into the Glenmore Reservoir for the June 2013 event. This estimate was based on back calculations using reservoir level (change in storage) and outflow. That hydrograph is referred to herein as the estimated flow at Sarcee Bridge as shown in Figure 4. No official WSC streamflow data is available for the 2013 flood at Sarcee Bridge or into Glenmore Reservoir. However, WSC did supply a preliminary 2013 peak instantaneous flow of 1240 m^3/s (Lazowski pers. comm. 2015). Because there is no official hydrograph as of yet for 2013 from WSC, the City of Calgary 2013 estimate represents the best information available for calibration at this time.

3.2 GENERAL APPROACH

Calibration was carried out by attempting to match model simulation to the 2005 and 2013 flood hydrographs in terms of peak flow, hydrograph shape, and runoff volume. The 2005 flood hydrograph at Bragg Creek is considered to be generally reliable. Therefore emphasis was placed on matching the model result to the peak flow, hydrograph shape, and runoff volume of this event. Since the 2005 hydrograph at Sarcee Bridge has an unreliable peak, emphasis was placed on matching the rising and falling limbs of this hydrograph rather than matching the magnitude of the peak. As the entire 2013 flood hydrograph at Bragg Creek and Sarcee Bridge are estimated based on preliminary peak values from WSC, emphasis was placed on matching the magnitude of the peak.

The primary parameters used for calibration include impervious area and constant loss rate of each sub-basin, as well as baseflow methodology. Attenuation in river reaches and surface storage were used for additional fine tuning of the HEC-HMS model. Calibration of parameters was performed manually in an attempt to match the simulated flow with the observed flow.

3.3 CALIBRATED PARAMETERS

The initial parameters presented in Section 2.0, were adjusted to produce the calibrated model. The calibrated parameters are presented in Table 8 through Table 10.

Notable changes from the initial parameter estimates include:

- Reduction of impervious areas by 25% for all sub-basins.
- Additional impervious area to the downstream sub-basins to account for urbanization.
- Reduction of the constant loss rate to 2.5 mm/hour upstream of Bragg Creek and to 3 mm/hour downstream of Bragg Creek.
- Incorporation of 10 mm surface storage in the sub-basins upstream of Bragg Creek.
- Reduction of attenuation in the Muskingum routing reaches by an increase of the Muskingum *X* value to 0.5.
- Alteration of the baseflow methodology for the mountainous sub-basins upstream of Bragg Creek from the constant baseflow to linear reservoir routing method (the linear reservoir routing method generates baseflow based on previous rainfall infiltration within each respective sub-basin).

Table 8: Summary of Calibrated Sub-Basin Loss Parameters

Sub-Basin	Drainage Area (ha)	Initial Loss (mm)	Constant Loss Rate (mm/hour)	Percent Impervious (%)
W100	27,800	20	3	4.0
W150	5,830	20	2.5	4.0
W200	12,100	20	2.5	24.0
W250	3,980	20	3	25.0
W300	3,360	20	3	1.0
W350	8,150	20	2.5	10.0
W400	5,040	20	2.5	17.0
W450	35,300	20	2.5	39.0
W500	8,900	20	2.5	14.0
W550	7,690	20	3	1.0
W600	3,120	20	3	1.0

Table 9: Summary of Calibrated Reach Routing Parameters

Calibrated Parameters for *Kinematic Wave* Reach Routing Method						
Reach	Length (m)	Slope (m/m)	Manning's *n*	Sub-reaches	Shape	Width (m)
R160	2,680	0.015	0.02	2	Rectangular	75
R240	7,050	0.007	0.02	2	Rectangular	40
R190	3,480	0.013	0.02	2	Rectangular	40
R180	8,900	0.009	0.03	2	Rectangular	100
R10	1932.9	0.012	0.03	2	Rectangular	20

Calibrated Parameters for *Muskingum* Reach Routing Method		
Reach	K (hour)	Muskingum *X*
R750	4	0.5
R130	2	0.5
R100	2	0.5
R20	6	0.5
R120	2	0.5

Table 10: Summary of Calibrated Sub-Basin Baseflow Parameters

Sub-Basin	Baseflow Methodology	2005 Event Initial / Constant Baseflow (m^3/s)	2013 Event Initial / Constant Baseflow (m^3/s)	GW 1 Coefficient	GW 1 Reservoirs
W100	Constant	3	1	-	-
W150	Linear Reservoir	2	1	200	1
W200	Linear Reservoir	3	5	75	2
W250	Constant	3	1	-	-
W300	Constant	2	1	-	-
W350	Linear Reservoir	2	1	200	1
W400	Linear Reservoir	2	2	75	2
W450	Linear Reservoir	9	14	75	2
W500	Linear Reservoir	2	4	75	2
W550	Constant	3	1	-	-
W600	Constant	3	1	-	-

3.3.1 Snowmelt

The contribution of snowmelt to the 2005 and 2013 floods was considered in regard to model calibration. For that purpose the volume of snowmelt for each of those floods was estimated. The data available for evaluating snowmelt contribution in 2013 is based on remotely sensed data. The satellite data for snow water equivalent maps was obtained from the National Operational Hydrologic Remote Sensing Center (NOHRSC) under the National Oceanic and Atmospheric Administration (NOAA) (NOAA 2015).

Remote sensing data is not available for the 2005 flood. However, a map showing spatial extent of snow cover on June 4, 2005 was obtained from NOHRSC (NOAA 2015). At that time, snow cover was only present on a small fraction of sub-basin W450. Therefore it is assumed that snowmelt contribution to the 2005 flood is negligible in regard to both flood peak and runoff volume.

Remote sensing data showing the spatial distribution and depth of snowpack were extracted before and after the 2013 flood on June 19, 2013 and June 24, 2013. These figures are provided in Appendix A.

In 2013, snowpack was observed only in the mountainous portion of the watershed within the extent of four model sub-basins. The data was processed to estimate the snowpack before and after the storm to determine the volume that would have contributed during the 2013 flood. A summary of the snowmelt contribution by sub-basin is presented in Table 11.

Table 11: Summary of 2013 Snowpack Volume by Sub-Basin

	June 19, 2013		June 24, 2013	
Sub-Basin	SWE (mm)	SWE (dam^3)	SWE (mm)	SWE (dam^3)
W200	29	3,557	18	2,216
W400	52	2,606	24	1,188
W450	188	66,312	148	52,055
W500	10	885	5	343
Total	-	73,360	-	55,802

Based on the remote sensing data for June 2013, snowmelt contributed approximately 17,558 dam^3 to the total flood volume of 157,308 dam^3, or approximately 12% of the total flood hydrograph. This is an estimated snowmelt moisture input and may not translate into flow. However, considering the accuracy and uncertainty of the 2013 flood hydrographs, any attempt to calibrate to those hydrographs exceeds the reliability of the available data. Therefore, snowmelt was not incorporated in the 2013 model calibration effort. Furthermore, snowmelt for the PMF model was calculated external from the HEC-HMS and entered as a baseflow hydrograph. No calibration of snowmelt processes was required.

3.4 CALIBRATION RESULTS

3.4.1 2005 Flood Calibration Results

Comparisons of the simulated and observed hydrographs at Bragg Creek and Sarcee Bridge for the 2005 flood are presented in Figure 5 and Figure 6. Table 12 summarizes the accuracy of the match in terms of hydrograph peak, timing, and flood volume at Bragg Creek. Similarly, Table 13 summarizes the accuracy of the match in terms of hydrograph peak, timing, and flood volume at Sarcee Bridge.

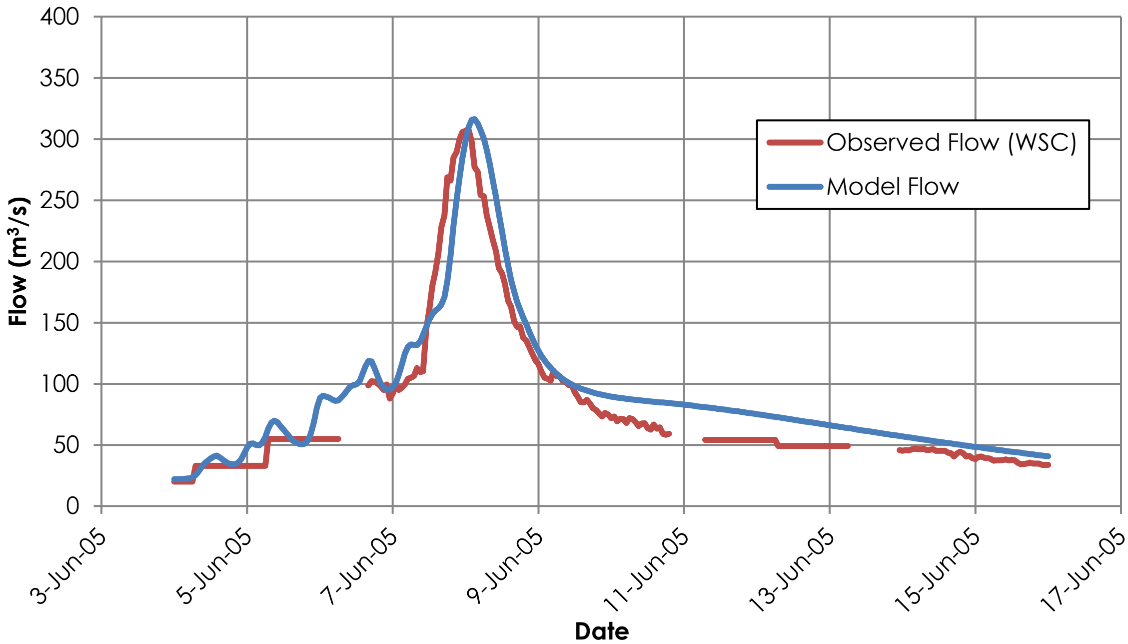


Figure 5: Observed and Calibrated Hydrographs at Bragg Creek for the 2005 Flood

Table 12: Calibration Accuracy for the 2005 Flood at Bragg Creek

Name	Peak Discharge (m^3/s)	Time of Peak	Volume (dam^3)[1]
Observed (WSC)	308.0	June 8, 2005 at 1:00	79,905
Calibrated Model	316.3	June 8, 2005 at 3:00	93,070
Percent Difference	+2.7%	-	+16.5%

[1] - Volume was calculated for the duration of simulation (June 4, 2005 at 00:00 to June 16, 2005 at 00:00).

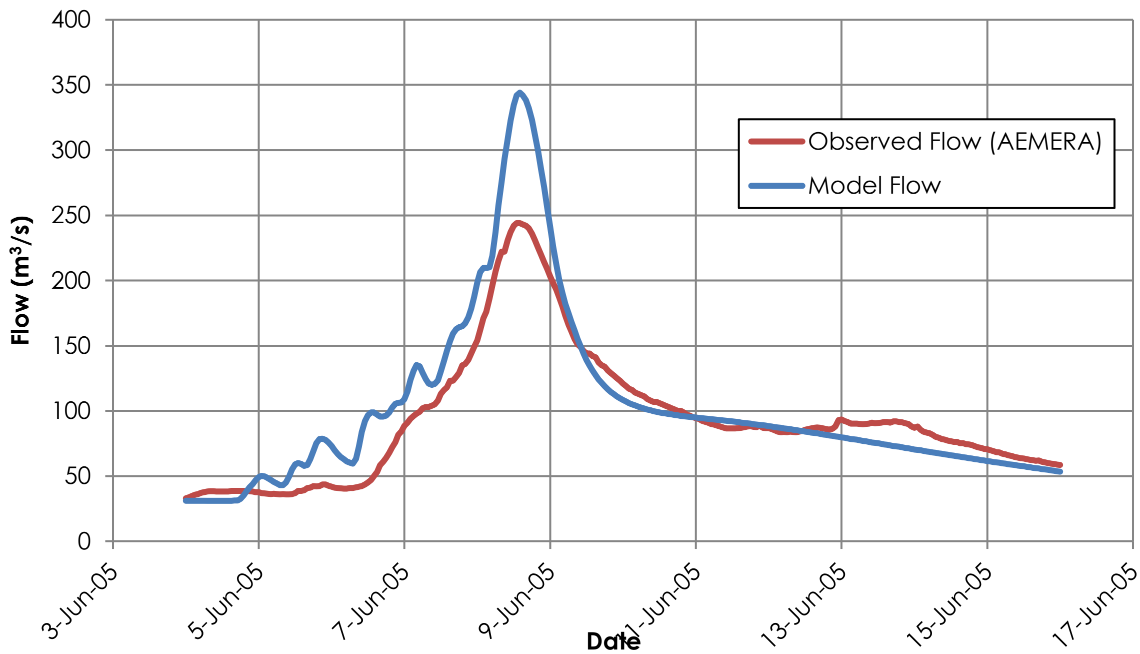


Figure 6: Observed and Calibrated Hydrographs at Sarcee Bridge for the 2005 Flood

Table 13: Calibration Accuracy for 2005 Flood at Sarcee Bridge

Name	Peak Discharge (m^3/s)	Time of Peak (UTC)	Volume (dam^3)[1]
Observed (AEMERA)	244.0	June 8, 2005 at 13:00	97,260
Calibrated Model	344.1	June 8, 2005 at 14:00	105,929
Percent Difference	+41.0%	-	+8.9%

[1] - Volume was calculated for the duration of simulation (June 4, 2005 at 00:00 to June 16, 2005 at 00:00).

3.4.1.1 Calibration Results per Sub-Basin

For each sub-basin, a graph is provided in Appendix C that illustrates the hourly temporal distribution of rainfall, the corresponding amount of rainfall loss and rainfall excess, and the resulting sub-basin runoff hydrograph. Those figures illustrate well the modeled hydrologic process and model results at the sub-basin level. See Table 14 for a summary of the 2005 model calibration outputs.

Table 14: Water Balance Summary for the 2005 Flood Calibration (June 4 to 16, 2005)

Sub-Basin	Rainfall (dam^3)	Baseflow (dam^3)	Direct Runoff (dam^3)	Total Inflow (dam^3)	Total Inflow-Rainfall Ratio	Direct Runoff-Rainfall Ratio	Baseflow-Total Inflow Ratio
W100	29,091	3,110	2,920	6,031	0.21	0.10	0.52
W150	10,296	6,633	1,557	8,189	0.80	0.15	0.81
W200	20,379	10,405	5,553	15,959	0.78	0.27	0.65
W250	4,384	3,110	1,217	4,327	0.99	0.28	0.72
W300	6,033	2,074	694	2,767	0.46	0.11	0.75
W350	14,922	8,026	3,272	11,298	0.76	0.22	0.71
W400	8,740	5,553	1,808	7,361	0.84	0.21	0.75
W450	46,908	18,221	18,280	36,500	0.78	0.39	0.50
W500	14,056	9,223	1,972	11,195	0.80	0.14	0.82
W550	10,785	3,110	1,274	4,384	0.41	0.12	0.71
W600	3,097	3,110	223	3,333	1.08	0.07	0.93
Sum[1]	164,306	69,466	37,552	107,017	0.65	0.23	0.65

[1] - Represents the sum at Sarcee Bridge i.e. not including W250.

As can be seen in Table 14, most of the 2005 runoff in the Elbow River Basin was generated from the mountainous part of the watershed (W200, W350, W400, W450 and W500) upstream of Bragg Creek. The sub-basins downstream of Bragg Creek contributed less runoff in comparison. This is attributed to two factors; first, the heaviest rainfall in 2005 occurred in the upper watershed and second, the rainfall losses are less in that portion of the watershed due to the high percent of rock outcrop.

3.4.2 2013 Flood Calibration Results

Comparisons of the modeled and estimated hydrographs at Bragg Creek and Sarcee Bridge for the 2013 flood are presented in Figure 7 and Figure 8. Table 15 summarizes the accuracy of the match in terms of hydrograph peak, timing, and flood volume at Bragg Creek. Similarly, Table 16 summarizes the accuracy of the match in terms of hydrograph peak, timing, and flood volume at Sarcee Bridge.

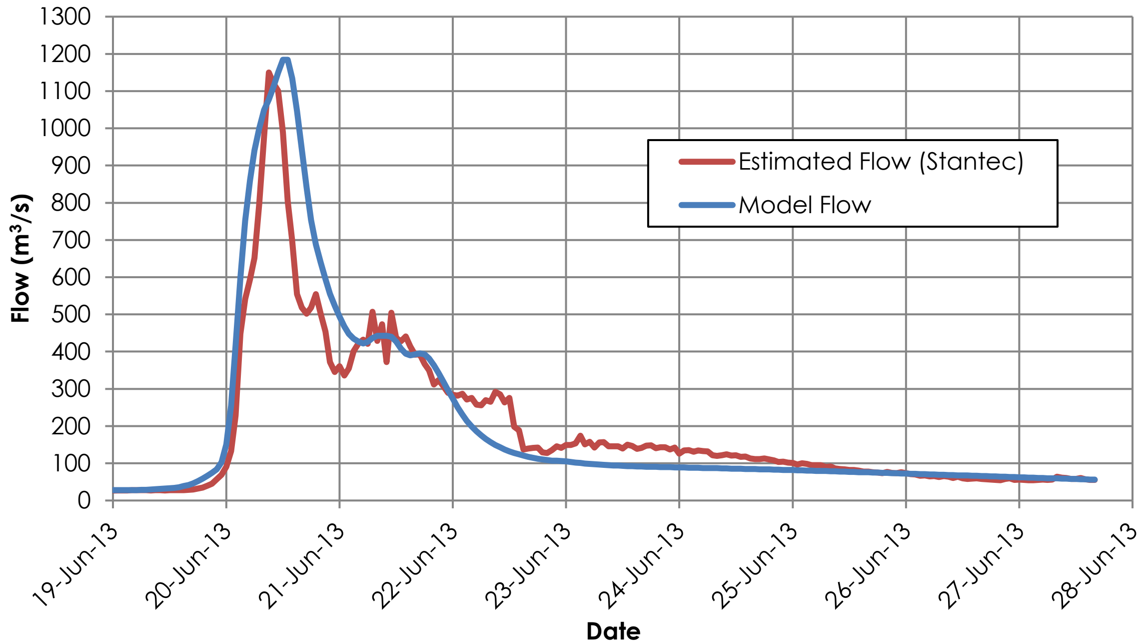


Figure 7: Estimated and Calibrated Hydrographs at Bragg Creek for the 2013 Flood

Table 15: Calibration Accuracy for the 2013 Flood at Bragg Creek

Name	Peak Discharge (m^3/s)	Time of Peak	Volume (dam^3)[1]
Estimated (Stantec)	1150	June 20, 2013 at 17:00	147,446
Calibrated Model	1184	June 20, 2013 at 21:00	153,827
Percent Difference	+3.0%	-	+4.3%

[1] - Volume was calculated for the duration of simulation (June 19, 2013 at 08:00 to June 28, 2013 at 00:00).

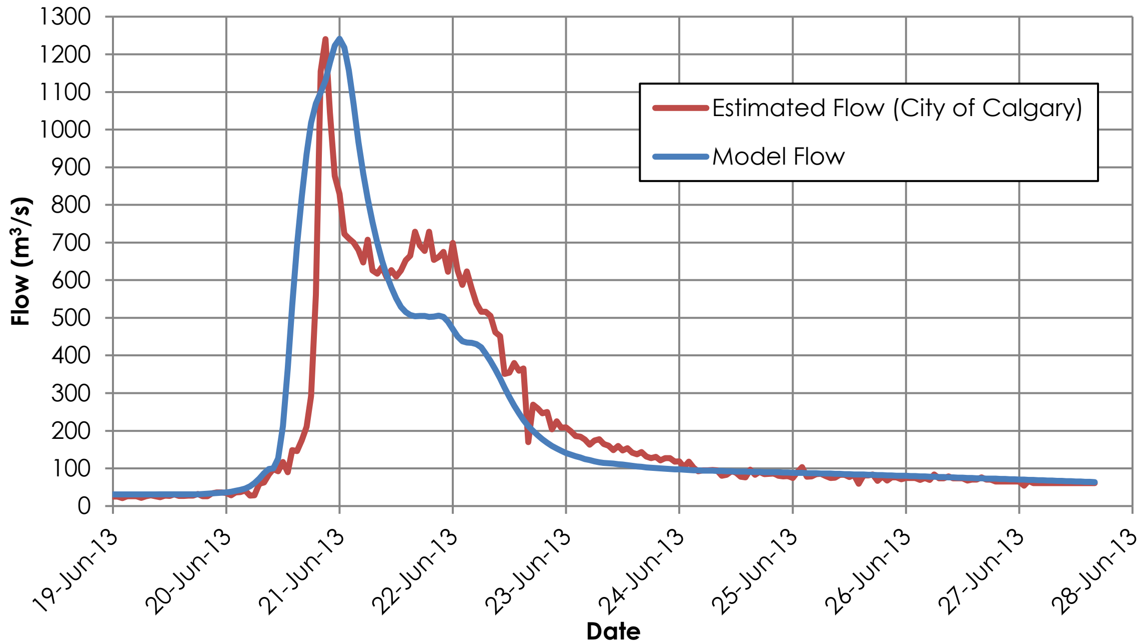


Figure 8: Estimated and Calibrated Hydrographs at Sarcee Bridge for the 2013 Flood

Table 16: Calibration Accuracy for the 2013 Flood Event at Sarcee Bridge

Name	Peak Discharge (m^3/s)	Time of Peak (UTC)	Volume (dam^3)[1]
Estimated (City of Calgary)	1240.4	June 21, 2013 at 5:00	157,308
Calibrated Model	1241.3	June 21, 2013 at 8:00	164,896
Percent Difference	+0.1%	-	+4.8%

[1] - Volume was calculated for the duration of simulation (June 19, 2013 at 08:00 to June 28, 2013 at 00:00).

3.4.2.1 Calibration Results per Sub-Basin

For each sub-basin, a graph is provided in Appendix C that illustrates the hourly temporal distribution of rainfall, the corresponding amount of rainfall loss and rainfall excess, and the resulting sub-basin runoff hydrograph. Those are very instructive in illustrating the modeled hydrologic process and model results at the sub-basin level. See Table 17 for a breakdown of the 2013 model calibration outputs on a sub-basin level.

Table 17: Water Balance Summary for the 2013 Flood Event (June 19, 2013 at 8:00 to June 28, 2013 at 00:00)

Sub-Basin	Rainfall (dam^3)	Baseflow (dam^3)	Direct Runoff (dam^3)	Total Inflow (dam^3)	Total Inflow-Rainfall Ratio	Direct Runoff-Rainfall Ratio	Baseflow-Total Inflow Ratio
W100	25,662	749	6,186	6,934	0.27	0.24	0.11
W150	10,629	4,630	3,014	7,644	0.72	0.28	0.61
W200	28,446	8,920	15,255	24,175	0.85	0.54	0.37
W250	3,509	749	1,478	2,227	0.63	0.42	0.34
W300	5,896	749	1,144	1,893	0.32	0.19	0.40
W350	15,187	5,686	5,025	10,710	0.71	0.33	0.53
W400	11,632	4,208	5,623	9,831	0.85	0.48	0.43
W450	93,997	19,083	62,738	81,820	0.87	0.67	0.23
W500	20,815	8,003	9,998	18,000	0.86	0.48	0.44
W550	11,611	749	3,275	4,024	0.35	0.28	0.19
W600	3,376	749	678	1,427	0.42	0.20	0.52
Sum[1]	227,250	53,524	112,933	166,457	0.73	0.50	0.32

[1] - Represents the sum at Sarcee Bridge i.e. not including W250.

As can be seen in Table 17, most of the 2013 runoff in the Elbow River Basin was generated from the mountainous part of the watershed (W200, W350, W400, W450 and W500) upstream of Bragg Creek. The sub-basins downstream of Bragg Creek contributed less runoff in comparison. As with the 2005 calibration, this is attributed to two factors; first, the heaviest rainfall in 2013 occurred in the upper watershed, and, second, the rainfall losses are less in that portion of the watershed due to the high percent of rock outcrop. As opposed to the 2005 storm, the 2013 storm was centered further to the west and sub-basin W450 provided an even greater portion of the watershed runoff.

3.5 CALIBRATION SUMMARY

Calibration of the HEC-HMS model had limited success, which was due to the uncertainty of the hydrometric data at the Bragg Creek and Sarcee Bridge gauging stations. The partial areal coverage and non-uniformity of rainfall used in calibration also played a role in the calibration process. Calibration was successful in adequately establishing the sub-basin rainfall loss parameters, in refining the channel routing parameters, and in developing reasonable baseflow simulation methodology. However, actual rainfall for the 2005 and 2013 storms were highly variable in spatial distribution resulting in some sub-basins receiving little rainfall and other sub-basins receiving highly non-uniform rainfall. The consequences are that calibration of the unit hydrograph for the sub-basins was tenuous since the basic unit hydrograph requirement of uniform rainfall over the sub-basins is not achieved. Therefore, the model was recalibrated during the PMF simulation. That calibration was performed by adjusting the unit hydrograph parameters so that the simulated 100-year peak discharge and runoff volume for the input of the 100-year rainfall represented the calculated 100-year frequency flood peak and 7-day flood volume (see Section 4.5).

4.0 PROBABLE MAXIMUM FLOOD (PMF) ESTIMATION

The PMF can be defined as theoretically the largest flood resulting from a combination of the most severe meteorological and hydrologic conditions that could reasonably be expected to occur in a given area. The PMF is generally viewed as the flood resulting from a PMP, plus snowmelt where appropriate, applied to reasonable severe antecedent watershed conditions.

4.1 GENERAL APPROACH

The calibrated hydrologic model was applied to estimate the PMF for several viable PMP scenarios. A 100-year frequency rainfall as an antecedent condition and, in some cases, snowmelt were applied in the PMF simulations.

4.2 PROBABLE MAXIMUM PRECIPITATION (PMP) SCENARIOS

PMP is defined by the World Meteorological Organization (WMO 1986) as "*theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year.*" The PMP data was developed by sub-consultant AWA for multiple spatial distributions in the Elbow River Basin. AWA provided Stantec with average sub-basin and gridded PMP data for general and local storms, centered on various spatial distributions. Gridded local storm PMP values were calculated for 6-hour durations, while general storm PMP values were calculated for 48-hour durations. The local storms were assessed for the area upstream of the SR1 Diversion (863 km^2) and sub-basin W600, which is the drainage area for the SR1 Off-Stream Dam (31 km^2). The general storms were assessed for the entire watershed upstream of Glenmore Dam (1,212 km^2), as well as the area upstream of the SR1 Diversion (863 km^2).

In regards to spatial distribution, the local storm PMP for the SR1 Off-Stream Dam was centered over the W600 sub-basin. The PMP for the local storm upstream of the proposed SR1 Diversion was spatially distributed using a representative severe local storm from the PMP database. The general storm PMP spatial pattern is based on orographic and moisture transposition factors of controlling storms (hereafter referred to as the orographic distribution). Therefore, a total of four different PMP scenarios were developed by AWA (see Table 18).

Table 18: Summary of PMP Scenarios

Scenario	Description
1	General storm PMP (48 hour) with orographic pattern over watershed upstream of proposed SR1 Diversion (863 km^2)
2	General storm PMP (48 hour) with orographic pattern over watershed upstream of Glenmore Dam (1,212 km^2)
3	Local storm PMP (6 hour) with maximum 1 hour spatial distribution centered over the watershed upstream of the proposed SR1 Diversion (863 km^2)
4	Local storm PMP (6 hour) centered over sub-basin W600 upstream of proposed SR1 Dam (31 km^2)

For the local storm, the cumulative 1- to 6-hour basin average PMP values were provided for each sub-basin for the various spatial scenarios. For the general storms, the cumulative 1-, 6-, 12-, 24-, and 48-hour basin average PMP values were provided for each sub-basin for the various spatial scenarios. For the general storm, the basin average PMP for durations other than 1-, 6- 12-, 24-, and 48-hour were estimated by interpolating from the durations for which PMP was provided. See Appendix D for the storm PMP averaged by sub-basin for each scenario.

4.2.1 Summary of Spatial Distribution of Gridded PMP

The PMP spatial distribution for the general storm was shaped by the orographic factors while the spatial distribution of the local storm was shaped by a representative severe local storm. However, both the general and local storms showed the highest values to be concentrated in the mountainous region of the watershed. The PMP values then decreased to the east or the low lying reaches of the Elbow River Basin. See Table 19 for a summary of the spatial distribution of each PMP scenario.

Table 19: Summary of Spatial Distribution of Gridded PMP Scenarios

Scenario	Average PMP Grid Value (mm)	Highest Average PMP Value by Sub-Basin	Grid Value Range
1	402	442 mm in W450	333 mm in W150 to 465 mm in W450
2	378	427 mm in W450	322 mm in W150 to 449 mm in W450
3	201	307 mm in W400	53 mm in W450 to 502 mm in W450
4	N/A	286 mm in W600	N/A

4.2.2 Summary of Temporal Distribution of Gridded PMP

The temporal distribution of the PMP for the local storms was determined by first calculating the incremental hourly rainfall depths from the cumulative PMP's provided by AWA (i.e. 2-hr PMP minus 1-hour PMP, 3-hour PMP minus 2-hour PMP, etc.) and by then distributing the hourly values according to the "alternating block" method (i.e. the highest 1-hour rainfall was placed in the 3rd hour, the second highest hourly rainfall was placed in the 4th hour, the third highest was placed in the 2nd hour, etc.). This was done for each sub-basin and spatial distribution.

The temporally distributed hourly incremental values for the local storm were calculated as a percentage of the 6-hour PMP and plotted against time. See Figure 9 for the average temporal distribution, as a percentage of 6-hour PMP, for the area upstream of the SR1 Diversion. See Figure 10 for the temporal distribution, represented as a percentage of 6-hour PMP, for the area of the SR1 Off-Stream Dam.

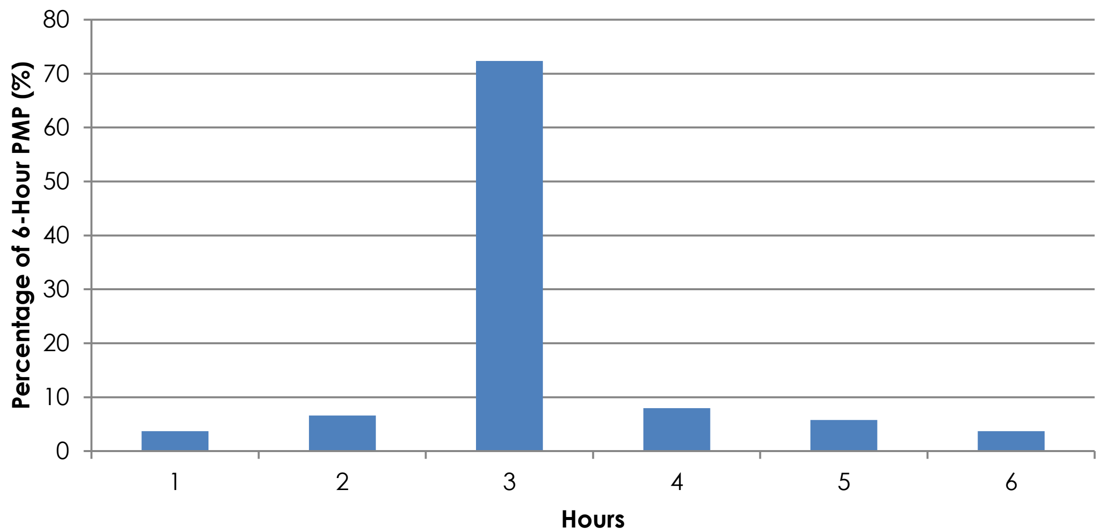


Figure 9: Average Temporal Distribution of Local Storm as a Percentage of 6-hour PMP for the Area Upstream of the SR1 Diversion (863 km²)

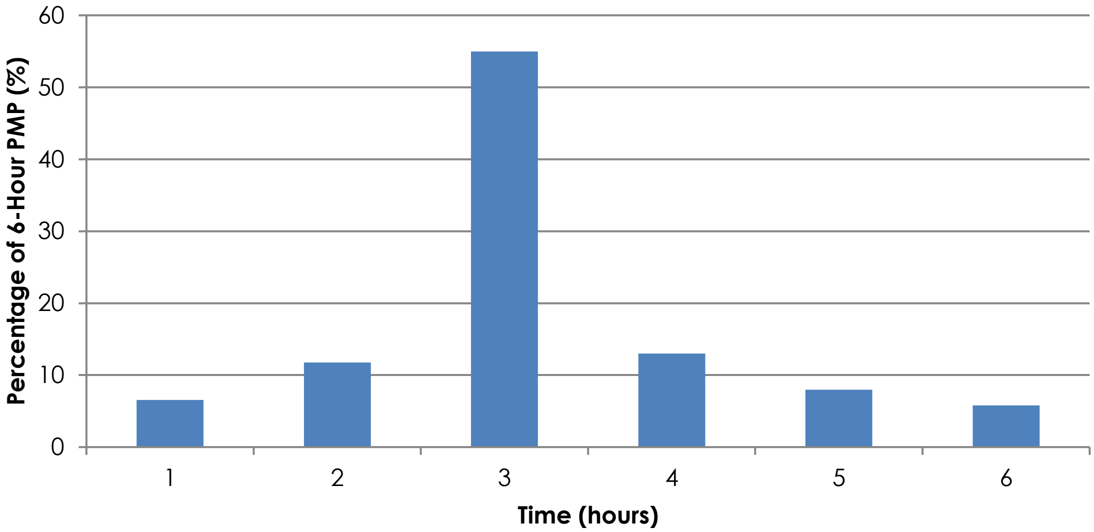


Figure 10: Temporal Distribution of Local Storm as Percentage of 6-hour PMP for the Area of the SR1 Off-Stream Dam (31 km²)

Temporal distribution of the PMP for the general storm was determined by first plotting the 1-, 6-, 12-, 24-, and 48-hour PMP values as a percentage of the 48-hour PMP against time. A third order polynomial relationship was fitted to this data to determine the PMP for all hours in the 48-hour duration. The incremental difference in rainfall depth between subsequent hours was determined throughout the entire storm duration. The hourly incremental values were then temporally distributed using the “alternating block” method. The center of the storm occurred 24-hours into the PMP.

See Figure 11 for the average temporal distribution of the general storm represented as a percentage of 48-hour PMP for the watershed upstream of Glenmore Dam. See Figure 12 for the average temporal distribution of the general storm represented as a percentage of 48-hour PMP for the area upstream of the SR1 Diversion.

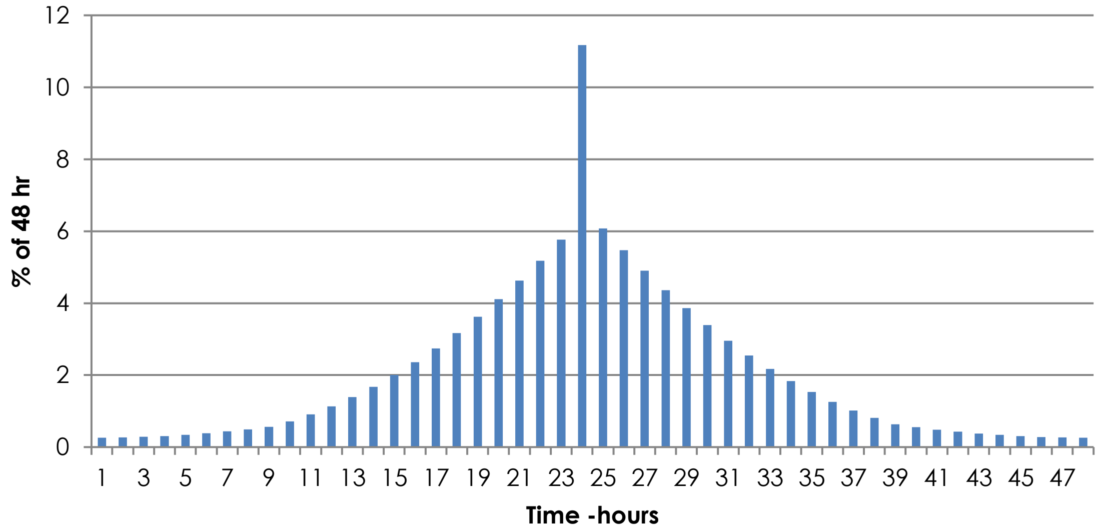


Figure 11: Average Temporal Distribution of General Storm as Percentage of 48-hour PMP for the Full Basin (1,212 km²)

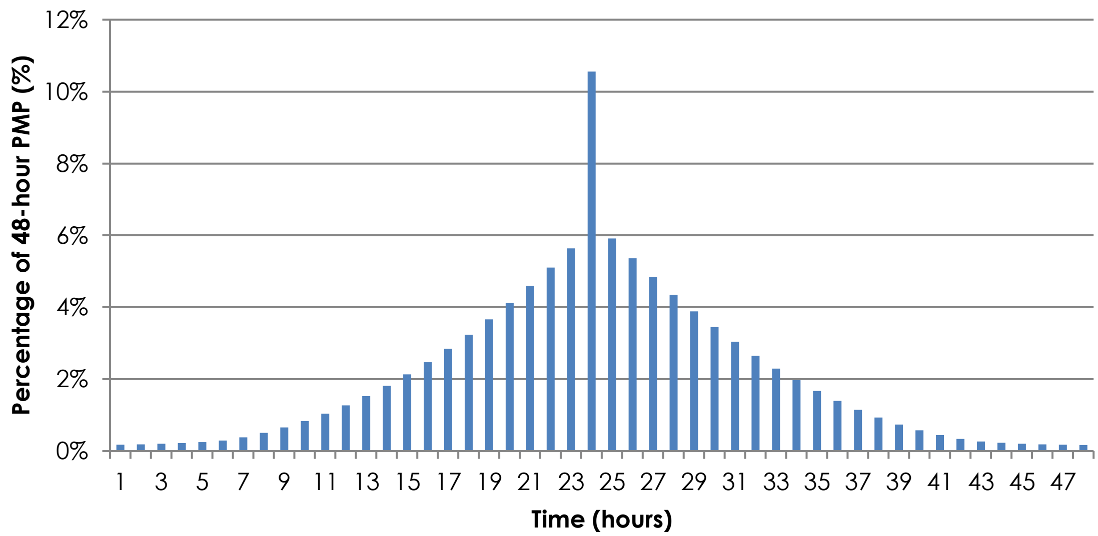


Figure 12: Average Temporal Distribution of General Storm Distribution as Percentage of 48-hour PMP for the Area Upstream of the SR1 Diversion (863 km²)

4.3 ANTECEDENT RAINFALL

4.3.1 Estimation of 100-Year, 24-Hour Antecedent Rainfall

The procedures for selecting antecedent basin conditions vary among different agencies and hydrologists. A common practice in British Columbia (BC) and Alberta is "… *to precede the PMP with a 100-year 24-hour rainfall leaving a period of three days between the storms*"(Alberta Transportation 2004). While the shortest observed time interval between two severe rainfall events in the mountain and foothill areas of Alberta is on the order of 5-7 days, studies suggest that a time interval as short as three days is possible (Gerhard 2000). Based on the aforementioned, a decision was made to establish the basin antecedent conditions for the Elbow River prior to the PMP by introducing an antecedent storm, having a 100-year 24-hour rainfall, three days prior to the start of PMP, as has been the common practice in BC and Alberta.

Short duration (up to 24-hours) "point" (single station) rainfall amounts for various return periods are computed and published by Environment Canada, Meteorological Services Canada (MSC) for most airports and key meteorological sites across Canada. Currently there are no estimates of the 100-year, 24-hour rainfall amounts for larger area sizes. As such, it was decided that the estimation of the 100-year, 24-hour rainfall for the Elbow River Basin would be carried out by applying an area reduction factor (ARF) to the 100-year point rainfall values. For this project the ARF was based on the ratio of the 1,000 km^2 (approximately the drainage area of the Elbow River Basin) rainfall to 10 km^2 rainfall observed for major storms in Alberta. Point rainfalls are generally considered as representative of rainfall for a 10 km^2 area. It was further decided that the 100-year, short-duration point rainfall amounts to be used would be based on the rainfall amounts for Pincher Creek Airport. This Environment Canada meteorological station is the closest in proximity and physiographic characteristics to the Elbow River Basin. It also has a relatively long period of record.

The "*n*"-year, including 100-year, rainfall amounts for durations of 1-, 2-, 6-, 12-, and 24-hour at Pincher Creek Airport were computed and published by MSC in 2014. The 100-year rainfall amounts for other durations were computed by plotting the 1-, 2-, 6-, 12-, and 24-hr accumulations against time and fitting a curve through the values published by MSC (Figure 13).

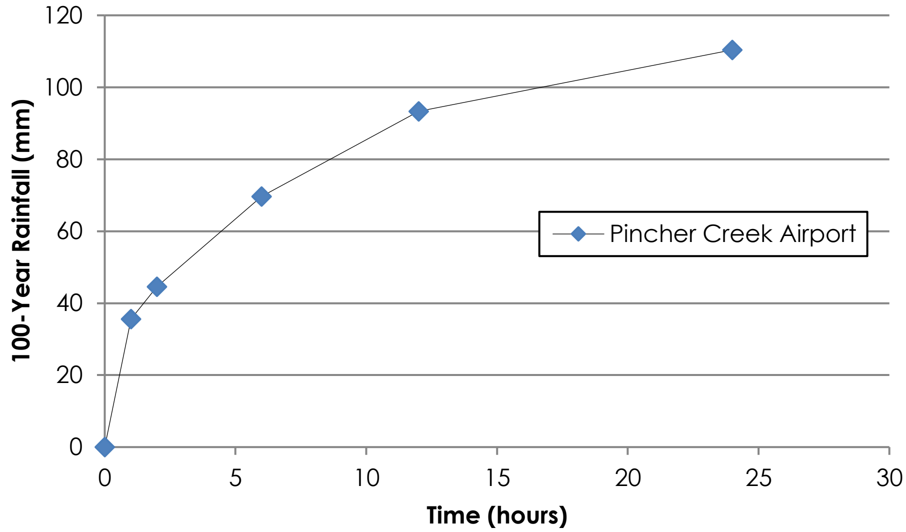


Figure 13: Pincher Creek Airport Station 100-Year Rainfall as a Function of Time

The incremental rainfall values were subsequently computed by disaggregating the cumulative "n"-hour 100-year rainfall into hourly values. These hourly values were divided by the 100-year, 24-hour rainfall total to determine the percentage of incremental rainfall per 100-year, 24-hour rainfall. These percentages were then temporally distributed according to the "alternating block" method, with maximum intensity at the center of the storm period (Alberta Transportation 2004). This method is commonly termed the "Chicago" or "Theoretical" hyetograph method. In this method the highest hourly value is placed at the center of the storm (in this case, at 12 hours), the second highest hourly value is placed after and next to the highest value (in this case at 13 hours), the third highest value is placed next to and in front of the highest hourly value (in this case at 11 hours), the fourth highest hourly value is placed next to and after the second highest hourly value etc. See Figure 14 and the last column of Table 20 for the temporal distribution of the antecedent rainfall as a percentage of the 24-hour rainfall.

Table 20: Computation of Antecedent 100-Year, 24-hour Rainfall to Precede PMP

Duration (hours)	100-Year Short Duration Point Rainfall Amounts (mm)	Incremental Point Rainfall (mm)	Incremental Rainfall as a Percentage of 24-Hour Rainfall (%)	Temporal Distribution of 100-Year, 24-Hour Rainfall as Antecedent Rainfall (%)
1	***35.6***	35.6	32.25	1.11
2	***44.6***	9.0	8.15	1.17
3	52.6	8.0	7.23	1.25
4	59.1	6.5	5.91	1.33
5	64.7	5.6	5.09	1.44
6	***69.7***	5.0	4.52	1.57
7	74.4	4.7	4.24	3.20
8	78.7	4.3	3.90	3.62
9	82.7	4.0	3.62	4.24
10	86.4	3.7	3.39	5.09
11	90.0	3.5	3.20	7.23
12	***93.3***	3.3	3.03	32.25
13	95.0	1.7	1.57	8.15
14	96.7	1.7	1.50	5.91
15	98.3	1.6	1.44	4.52
16	99.8	1.5	1.38	3.90
17	101.3	1.5	1.33	3.39
18	102.7	1.4	1.29	3.03
19	104.1	1.4	1.25	1.50
20	105.4	1.3	1.21	1.38
21	106.7	1.3	1.17	1.29
22	108.0	1.3	1.14	1.21
23	109.2	1.2	1.11	1.14
24	***110.4***	1.2	1.08	1.08

Bold and italicized *rainfall values obtained from Environment Canada's IDF curve for Pincher Creek Airport.*

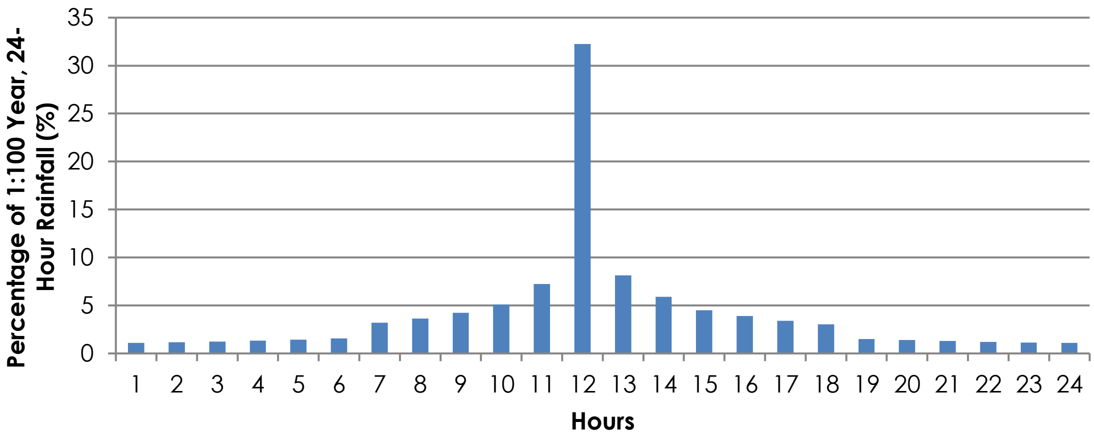


Figure 14: Temporal Distribution of Antecedent Rainfall as Percentage of 100-Year Rainfall

AWA provided the gridded precipitation data for the 100-year, 24-hour rainfall. Stantec used that data to calculate the average 100-year, 24-hour rainfall per sub-basin using ArcGIS. The hourly values as a percentage of the 100-year, 24-hour rainfall calculated from the Pincher Creek Airport station were then multiplied by the average 100-year, 24-hour rainfall volume for each sub-basin. This was chosen as the antecedent rainstorm for the local storm of the SR1 Off-Stream Dam area. For all other PMP scenarios studied, the previously computed antecedent point rainfall was multiplied by an ARF.

Alberta Transportation has analyzed depth-area-duration (DAD) curves of large storms in Alberta and has computed the mean DAD curve for the top 10, 20, and 50 storms (Figure 15). The ARF applied to adjust the previously computed antecedent point rainfall to a 100-year, 24-hour rainfall was estimated at 0.85 based on the ratio of the 1,000 km^2 to 10 km^2 rainfall for the top 20 large storms (195 mm/225 mm = 0.85). This antecedent storm was applied three days prior to the local and general PMP for the full basin and area upstream of the SR1 Diversion scenarios.

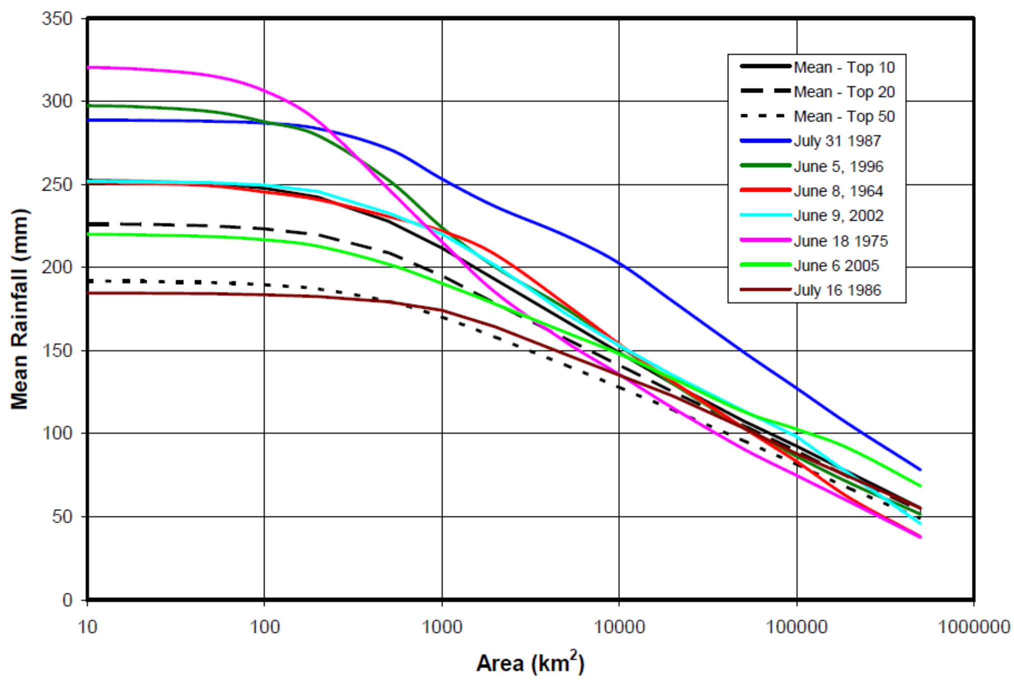


Figure 15: Depth-area-duration curves for large storms in Alberta (Alberta Transportation 2007)

4.4 SNOWMELT HYDROGRAPH

4.4.1 Antecedent Snow Water Equivalent

The moisture input from snowmelt during PMP is governed primarily by two factors: the snow-covered-area and the rate of melt. The snowmelt contribution to PMF then becomes simply the product of the snowmelt volume times the runoff coefficient. Snowmelt was applied to the general storms, not the local storms since severe convective storms cannot develop over large snowpack areas.

The procedures for computing snowmelt contribution to PMF for mountain and foothill areas where floods are dominated by rain on snow vary significantly among different agencies and hydrologists. Two of the three specifications used by BC Hydro for areas in the interior are (Alberta Transportation 2004):

- To apply "*a 100-year snowpack followed by a 100-year high temperature melt sequence then the PMP (the return period of the melt sequence can be reduced or the melt sequence can be eliminated entirely if it [the melt sequence] results in a worse flood [than applying PMP]*".

- To apply "*average snowpack and average melt conditions followed by a pre-storm and then PMP*".

In their report "Guidelines on Extreme Flood Analysis", Alberta Transportation (2004) recommends:

> "*For a PMP on snowpack ... the initial snow water equivalent and snow-covered area at the start of the antecedent rainfall event should be representative of 10-year conditions. Estimates of snow water equivalent should be based on analysis of historic snowpack or snow-on-ground data over a period extending two weeks either side of the date of the PMP*."

However, the above noted recommendation appears to be driven primarily by the concern that combining too many extreme conditions may lead to over maximization of PMF rather than any scientific reasoning.

Since 1978, AEMERA has operated five snow pillow stations, and eight snow courses that are within or in close proximity of the Elbow River Basin (see Figure 16). The snow pillows have hourly readings of SWE for most years and the snow courses have SWE observations on the first (plus or minus 3 days) of each month during the December to June period. Therefore, it was felt that a more reliable estimate of snowmelt moisture input to PMP (the product of snow covered area and melt rates) and contribution to PMF could be obtained based on the maximum observed snow covered area and melt rates during the four largest rainfall events in this period. This decision was supported by a review of June 1 SWE for snow pillow and snow course sites in the vicinity of the Elbow River Basin which indicate that the June 1, 1995 SWE (shortly prior to one of the four largest rainfall events that occurred during the 1978 to 2015 period) had a return period of about 5-years; relatively similar to the 10-year SWE recommended by Alberta Transportation.

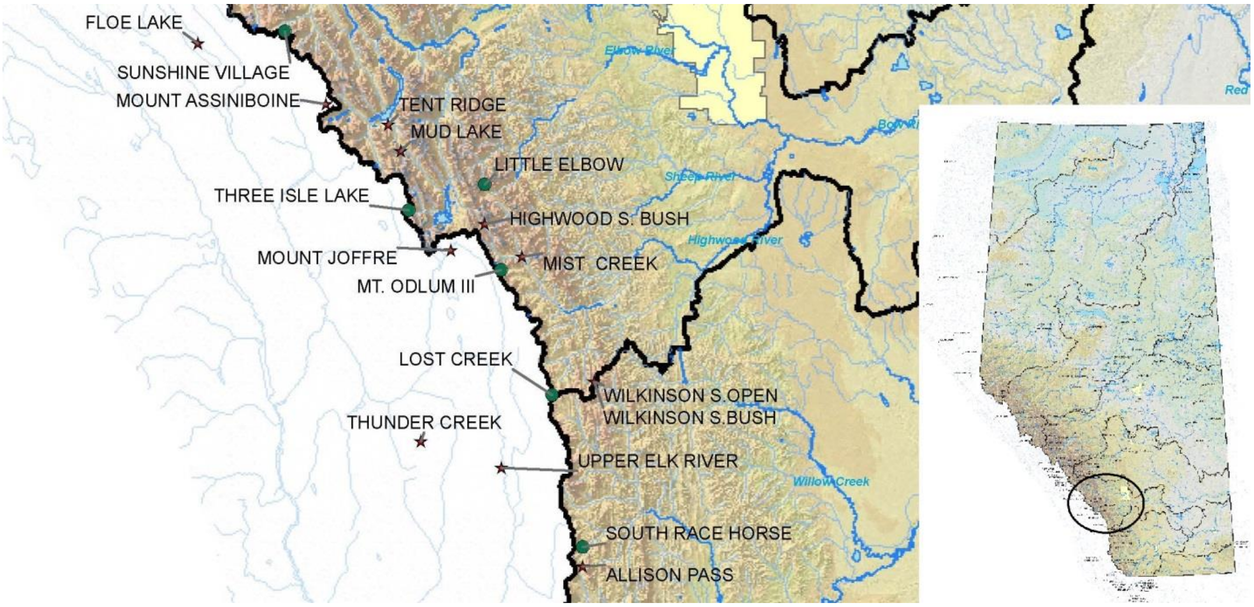


Figure 16: Location of Snow Pillow and Snow Course Sites within the Bow/Elbow Basins (Government of Alberta 2011)

4.4.1.1 Estimation of Maximum Snowmelt Rates during Antecedent Storm and PMP

Table 21 shows the observed SWE at five snow pillow sites within, or in close proximity to the Elbow River Basin for the day prior to and during the four largest rainfall events during the 1978 to 2014 period (June 6 – 7, 1995; June 5 – 7, 2005; June 17 – 18, 2005; and June 19 – 21, 2013). This data was obtained from Alberta Environment and Parks WISKI database.

Table 21: Snow Water Equivalent (SWE) during Large Rainfalls in the Elbow River Basin

Snow Pillow Location	Lost Creek South	Sunshine Village	Three Isle Lake	Little Elbow Summit	Mount Odlum
Elevation (m)	**2130**	**2230**	**2160**	**2120**	**2060**
Date	**Snow Water Equivalents (mm)**				
June 6-7, 1995 Event					
5-Jun-95	507	445	446	367	279
6-Jun-95	478	431	439	246	258
7-Jun-95	460	411	422	332	243
8-Jun-95	458	395	409	329	227
June 5-7, 2005 Event					
4-Jun-05	48	157	243	17	-

Snow Pillow Location	Lost Creek South	Sunshine Village	Three Isle Lake	Little Elbow Summit	Mount Odlum
5-Jun-05	34	132	223	8	-
6-Jun-05	41	130	227	30	-
7-Jun-05	124	127	246	88	-
8-Jun-05	160	114	250	94	-
June 17-18, 2005 Event					
16-Jun-05	87	12	160	20	-
17-Jun-05	64	20	149	35	-
18-Jun-05	52	64	149	34	-
19-Jun-05	38	50	130	16	-
June 19-21, 2013 Event					
18-Jun-13	256	182	274	199	53
19-Jun-13	229	151	266	178	38
20-Jun-13	204	105	233	148	10
21-Jun-13	192	75	252	186	0
22-Jun-13	167	43	246	179	0

Note: 1995 and Lost Creek SWE were based on daily average, all other values were based on 12:00 AM values

The maximum snowmelt during the 100-year, 24-hour antecedent storm and PMP was estimated by calculating the daily change in SWE (snow accumulation or depletion), during the four largest rainfall events (see Table 22).

Table 22: Daily Accumulation and Depletion in SWE during Large Rainfalls

Snow Pillow Location	Lost Creek South	Sunshine Village	Three Isle Lake	Little Elbow Summit	Mount Odlum	Average daily accumulation and depletion for pillows not limited by low SWE
Elevation (m)	**2130**	**2230**	**2160**	**2120**	**2060**	
Date	**Snow Water Equivalents (mm)**					
June 6-7, 1995 Event						
5-Jun-95	-	-	-	-	-	-
6-Jun-95	-29	-14	-7	-21	-21	-18
7-Jun-95	-18	-20	-17	-14	-15	-17
8-Jun-95	-2	-16	-13	-3	-16	-10
Total	-49	-50	-37	-38	-52	-45

Snow Pillow Location	Lost Creek South	Sunshine Village	Three Isle Lake	Little Elbow Summit	Mount Odlum	Average daily accumulation and depletion for pillows not limited by low SWE
Elevation (m)	**2130**	**2230**	**2160**	**2120**	**2060**	
June 5-7, 2005 Event						
4-Jun-05	-	-	-	-	-	-
5-Jun-05	-14	-25	-20	-9	-	-17
6-Jun-05	7	-2	4	22	-	8
7-Jun-05	83	-3	19	58	-	39
8-Jun-05	36	-13	4	6	-	8
Total	112	-43	7	77	0	38
June 17-18, 2005 Event						
16-Jun-05	-	-	-	-	-	-
17-Jun-05	-23	8	-11	5	-	-5
18-Jun-05	-12	44	0	5	-	9
19-Jun-05	-14	-14	-19	-18		-16
Total	-49	38	-30	-8	0	-12
June 19-21, 2013 Event						
18-Jun-13	-	-	-	-	-	-
19-Jun-13	-27	-31	-8	-21	-15	-20
20-Jun-13	-25	-46	-33	-30	-28	-32
21-Jun-13	-12	-30	19	38	-10	1
22-Jun-13	-25	-32	-6	-7	-	-18
Total	-89	-139	-28	-20	-53	-69

Notes:
- Highlighted dates indicate period when snowmelt would have been influenced by heavy rainfall.
- Positive values indicated accumulation and negative values indicate depletion of SWE.

Table 22 shows the largest observed snow depletion or melt was 69 mm and occurred during the four days surrounding the June 19 – 21, 2013 rainfall event. The largest single day melt was 32 mm on June 20th, 2013. In general, the rate of melt, or results in snow accumulations, seems to be greatly reduced during the latter part of rainfall event as the cold front begins to move into the area. Based on these assessments, and in consideration of the temporal distribution of the PMP, it was felt that the snowmelt rates given in Table 23 were appropriate for use in the estimation of snowmelt during the antecedent rainfall, PMP, and for days following the two.

Table 23: Snowmelt Rates for Entire PMP Duration

Time Period of Entire PMP	SWE (mm)
1:100-year, 24-hr antecedent rainfall event	30
Day 1 following antecedent rainfall event	20
Day 2 following antecedent rainfall event	15
Day 3 following antecedent rainfall event	10
First 24-hrs of PMP	30
Second 24-hrs of PMP	30
Day 1 following PMP	20
Day 2 following PMP	15
Day 3 following PMP	10

Further, as a review of hourly snow accumulations and depletions during the June 19 – 21, 2013 event do not show any significant degree of diurnal variability (see Table 24); the daily melt rates were assumed to be uniformly distributed throughout each day.

Table 24: Hourly Distribution of Daily Melt Rates

Time (hour)	Hourly Snowmelt Rate (mm)			Average Melt (mm)
	18-Jun-15	19-Jun-15	20-Jun-15	
1:00	0.5	0.8	2.3	1.2
2:00	0.8	1.3	2	1.4
3:00	0.5	0.5	1.8	0.9
4:00	0.3	0.8	1.8	1.0
5:00	0	0.5	1.3	0.6
6:00	0	0.3	1.5	0.6
7:00	0	0	1.8	0.6
8:00	0.3	-0.5	1.5	0.4
9:00	-0.5	0.5	2	0.7
10:00	-0.5	0.8	2.3	0.9
11:00	0.5	1.3	2.3	1.4
12:00	1.3	1.5	2.8	1.9
13:00	1	1.3	1.8	1.4
14:00	1.8	1.3	1.3	1.5
15:00	2	1	1.5	1.5
16:00	1.8	1.5	1.8	1.7

Time (hour)	Hourly Snowmelt Rate (mm)			Average Melt (mm)
	18-Jun-15	19-Jun-15	20-Jun-15	
17:00	1.8	0.5	1.8	1.4
18:00	1.5	0.8	1	1.1
19:00	1.5	0.5	0.8	0.9
20:00	1.5	0	1	0.8
21:00	1.5	1.3	0.5	1.1
22:00	1.8	1	-0.3	0.8
23:00	1	0.8	0.3	0.7
24:00	0.8	1.5	0	0.8

4.4.1.2 Estimation of Snow Covered Area during Antecedent Storm and PMP

Table 25 shows the observed SWE at five snow pillow sites within or in close proximity to the Elbow River Basin on the day prior to and during the four largest rainfall events that occurred during the 1978 to 2014 period, as well as the June 1 (+/- 3 days) snow surveys for the two large storm events that occurred within one week of June 1 (June 6 – 7, 1995 storm and June 5 – 7, 2005 storm).

Table 25: SWE for Snow Pillow and Survey Locations near Elbow River Basin prior to Large Rainfall Events

Snow Pillows/Survey Sites		Elevation (m)	June 5, 1995 SWE (mm)	June 4, 2005 SWE (mm)	June 16, 2005 SWE (mm)	June 18, 2013 SWE (mm)
Snow Pillow Site	Lost Creek South	2130	507	48	87	256
	Sunshine Village	2230	445	157	12	182
	Three Isle Lake	2160	446	243	160	274
	Little Elbow Summit	2120	367	17	20	199
	Mount Odlum	2060	279	-	-	53
Snow Survey Site (based on measurements between May 27 and June 3)	Highwood Summit - Bush	2210	478	140	-	-
	Little Elbow Summit	2120	419	50	-	-
	Lost Creek South	2130	658	215	-	-
	Mount Odlum	2060	328	0	-	-
	Mud Lake	1910	213	0	-	-
	Tent Ridge	2025	257	0	-	-
	Three Isle Lake	2160	511	345	-	-
	Wilkinson Summit - Open	1980	-	0	-	-

The snowline elevation and the associated snow covered area for each sub-basin of the Elbow River was calculated by plotting the SWE's prior to each large rainfall event (Table 25) against the snow pillow and snow course elevations (Figure 17) so as to determine the lowest snowline elevation prior to each of the four large rainfall events.

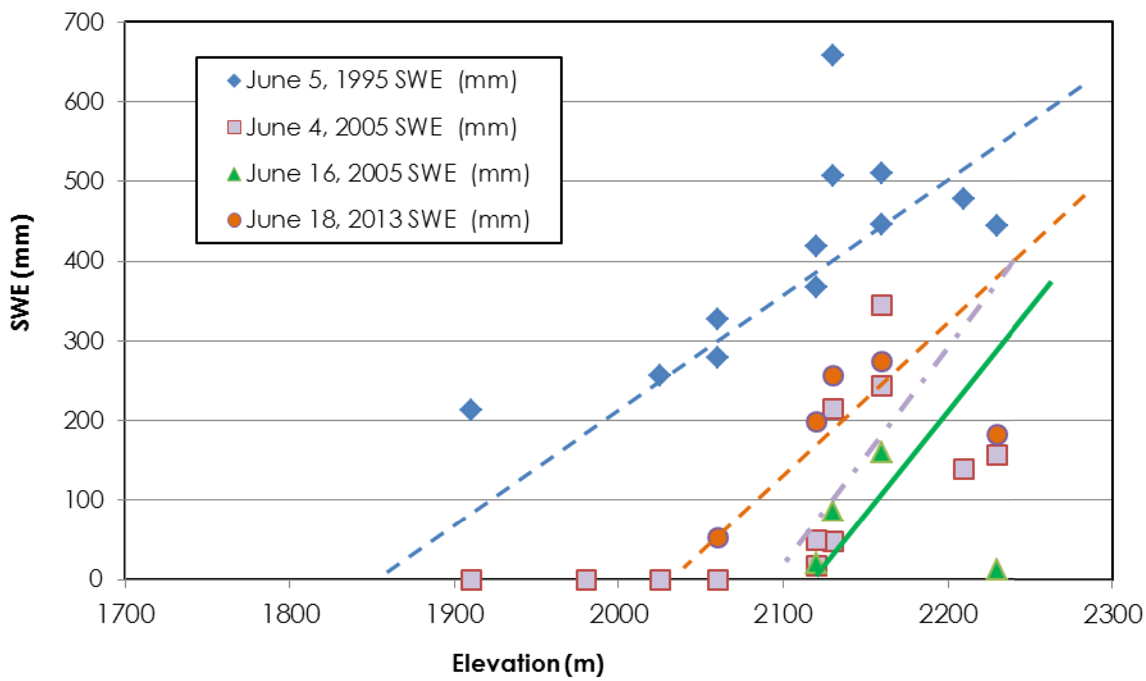


Figure 17: Relationship between SWE and Elevation Prior to Large Storms

Figure 17 shows that the lowest snowline elevation prior to the four largest rainfall events was approximately 1,800 m (5,900 ft). The maximum snow covered area during the antecedent storm and PMP was computed for each of the sub-basins based on the snowline elevation of 1,800 m, determined from the Figure 17 (see Table 26).

Table 26: Area above 1,800 m per Sub-Basin

Sub-Basin	Area above 1,800 m (km^2)
W150	4.50
W200	93.60
W350	2.40
W400	30.80
W450	320.30
W500	31.20
TOTAL (Area upstream of Bragg Creek above 1,800 m)	482.80

4.4.1.3 Estimation of Snowmelt Moisture Input during the Antecedent Storm and PMP, and Flow Contribution to PMF

The snowmelt moisture input for each day of the antecedent storm and PMP were computed by multiplying the snow covered area of each sub-basin (area above 1,800 m) by the melt rates computed in Section 4.4.1.1. The resulting snowmelt moisture input was subsequently converted to a snowmelt runoff contribution to PMF by applying a runoff coefficient of 0.7 to the previously computed snowmelt moisture inputs. Detailed computations of the snowmelt contribution to PMF are presented in Table 27.

Table 27: Snowmelt Moisture Input to Antecedent Storm, PMP, and Flow Contribution to PMF

Sub-Basin	Area Above 1,800 m (km^2)	Ant. Storm	Day 1 after Ant. Storm	Day 2 after Ant. Storm	Day 3 after Ant. Storm	PMP	PMP	Day 1 after PMP	Day 2 after PMP	Day 3 after PMP	Totals
		Snow Melt Rate (mm/day)									
		30	20	15	10	30	30	20	15	10	180
		Moisture Input due to Snowmelt (dam^3)									
W150	4.5	135	90	68	45	135	135	90	68	45	811
W200	93.6	2,808	1,872	1,404	936	2,808	2,808	1,872	1,404	936	16,848
W350	2.4	72	48	36	24	72	72	48	36	24	432
W400	30.8	924	616	462	308	924	924	616	462	308	5,544
W450	320.3	9,609	6,406	4,805	3,203	9,609	9,609	6,406	4,805	3,203	57,655
W500	31.2	936	624	468	312	936	936	624	468	312	5,616

Calculated Values	Ant. Storm	Day 1 after Ant. Storm	Day 2 after Ant. Storm	Day 3 after Ant. Storm	PMP	PMP	Day 1 after PMP	Day 2 after PMP	Day 3 after PMP	Totals
Total snow moisture input upstream of Bragg Creek during antecedent storm and PMP (dam^3)	14,484	9,656	7,242	4,828	14,484	14,484	9,656	7,242	4,828	86,904
Runoff Coefficient	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Snowmelt Runoff Contribution to PMF (dam^3)	10,139	6,759	5,069	3,380	10,139	10,139	6,759	5,069	3,380	60,833
Snowmelt Runoff Contribution to PMF (m^3/sec)	117	78	59	39	117	117	78	59	39	

Note: Ant. refers to Antecedent

4.5 REFINEMENT OF HYDROLOGIC MODEL TO 100-YEAR FLOOD FOR PMF ANALYSIS

The initial model run for PMF analysis was carried out using the hydrologic model calibrated to the 2005 and 2013 floods. That model produced a peak flow of 1,215 m^3/s at the SR1 Diversion Site for the 100-year 24-hour antecedent rainfall. However, the flood frequency analysis performed by Stantec as part of the SR1 Project showed the estimated peak flow for a 100-year event at the proposed SR1 Diversion to be 760 m^3/s (Stantec 2015). Therefore, the model calibrated for the 2005 and 2013 floods overestimated the 100-year flood event by approximately 60%.

In order to match the modeled peak flow using the 100-year, 24-hour antecedent rainfall with the flood peak derived for the 100-year flood frequency value, the model was refined to simulate the 100-year flood peak. This was performed by adjusting the K_n value within the recommended parameter range of 0.15 to 0.3. A K_n value of 0.3 resulted in a peak flow of 813 m^3/s. The 7-day flood volume for the simulation using a K_n value of 0.3 was estimated at 108,000 dam^3, which is approximately equal to the 100-year 7-day volume estimated by the flood frequency analysis. Results are summarized in Table 28 below.

Table 28: Peak Discharge and 7-Day Volumes at Proposed SR1 Diversion for the 100-Year Flood

Scenario	K_n	Peak Discharge (m^3/s)	7-Day Volume (dam^3)
100-year flood by flood frequency analysis	N/A	760	97,600
100-year 24-hour antecedent rainfall	0.30	813	108,000

4.6 UNIT HYDROGRAPHS

The Rocky Mountain general storm unit hydrograph was used for sub-basins upstream of Bragg Creek (W150, W200, W300, W350, W400, W450, and W500) for the general and local storm PMF simulations (Scenarios 1, 2, and 3). The Great Plains unit hydrograph was used in all PMF simulations for sub-basins downstream of Bragg Creek (W100, W250, W550, and W600). In general the Great Plains unit hydrograph has a lower peak and a milder receding limb than the Rocky Mountain unit hydrograph (see Figure 18).

A K_n of 0.07 was used for the Great Plains unit hydrograph for sub-basins W100 and W550. A K_n of 0.045 was used for sub-basin W250 due to partial urbanization and W600 due to its physiographic characteristics.

Figure 18 shows the shape of the Rocky Mountain general storm unit hydrograph applied in Scenarios 1, 2, and 3 using sub-basin W450 as an example; the Great Plains unit hydrograph applied in Scenarios 1, 2, and 3 using sub-basin W100 as an example; and the Great Plains unit hydrograph applied in Scenarios 1 to 4 at sub-basin W600.

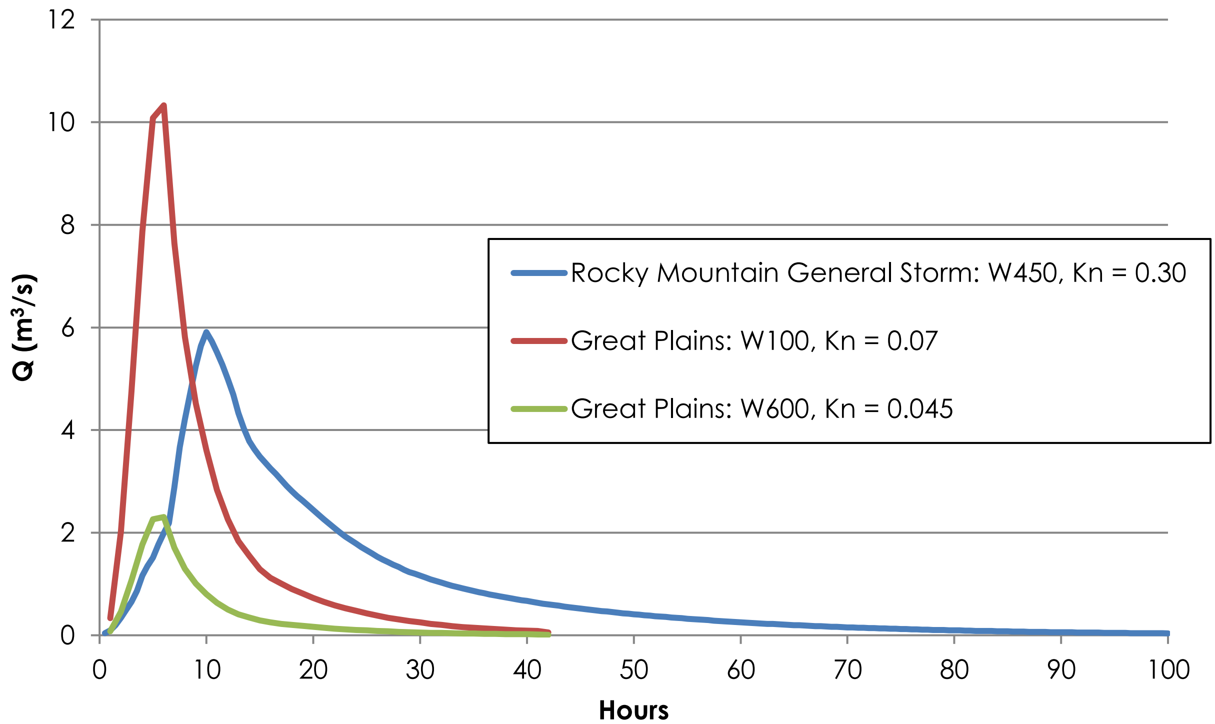


Figure 18: Unit Hydrograph Comparison

4.7 PMF SIMULATION RESULTS

PMF simulations were run for all four scenarios described in the previous sections. The four scenarios differed primarily based on the PMP data but also on the antecedent rainfall, snowmelt, and unit hydrographs used in the models. See Table 29 for a detailed outline of each PMF simulation. See Appendix E for figures representing the model output per sub-basin for each PMF scenario.

Table 29: Summary of Input Data for PMF Simulations

Scenario	Antecedent Rainfall	PMP	Unit Hydrograph	Snowmelt
1	100-year 24-hour precipitation with ARF	General storm PMP with orographic pattern over watershed upstream of proposed SR1 Diversion (863 km^2)	Rocky Mountain (applied to sub-basins upstream of Bragg Creek) and Great Plains (applied to sub-basins downstream of Bragg Creek)	Snowmelt contribution (Table 27) applied at Bragg Creek
2	100-year 24-hour precipitation with ARF	General storm PMP with orographic pattern over watershed upstream of Glenmore Dam (1,212 km^2)	Rocky Mountain (applied to sub-basins upstream of Bragg Creek) and Great Plains (applied to sub-basins downstream of Bragg Creek)	Snowmelt contribution (Table 27) applied at Bragg Creek
3	100-year 24-hour precipitation with ARF	Local storm PMP with a representative severe local storm spatial distribution centered over watershed upstream of proposed SR1 Diversion (863 km^2)	Rocky Mountain (applied to sub-basins upstream of Bragg Creek) and Great Plains (applied to sub-basins downstream of Bragg Creek)	N/A
4	100-year 24-hour precipitation	Local storm PMP centered over sub-basin upstream of proposed SR1 dam (W600) (31 km^2)	Great Plains	N/A

For Scenarios 1, 2, and 3 peak flood and 7-day volume PMF results were reported at the proposed SR1 Diversion Site as well as at the Glenmore Dam. For Scenario 4, PMF results are reported at the proposed SR1Off-Stream Dam.

4.7.1 General Storm PMF Scenarios (Scenarios 1 and 2)

Hydrographs representing the PMF for Scenarios 1 and 2 were generated at the proposed SR1 Diversion Site and Glenmore Dam (see Figure 19 and Figure 20). A detailed summary of the peak flow and 7-day volume for the PMF scenarios is given in Table 30.

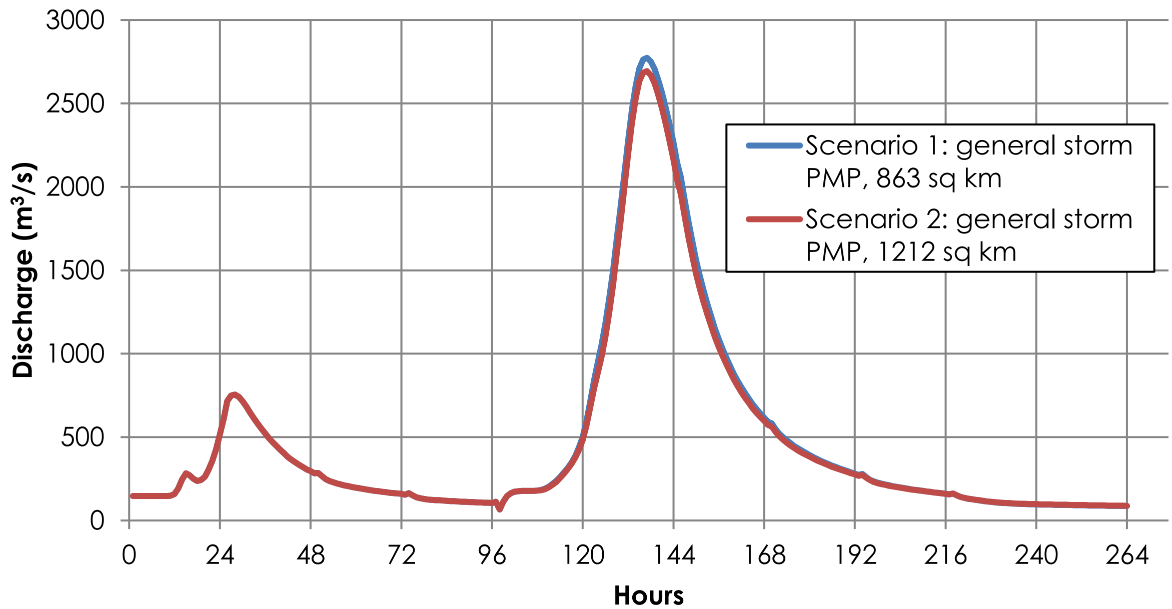


Figure 19: General Strom PMF Simulation Hydrographs for Scenarios 1 and 2 at the Proposed SR1 Diversion Site

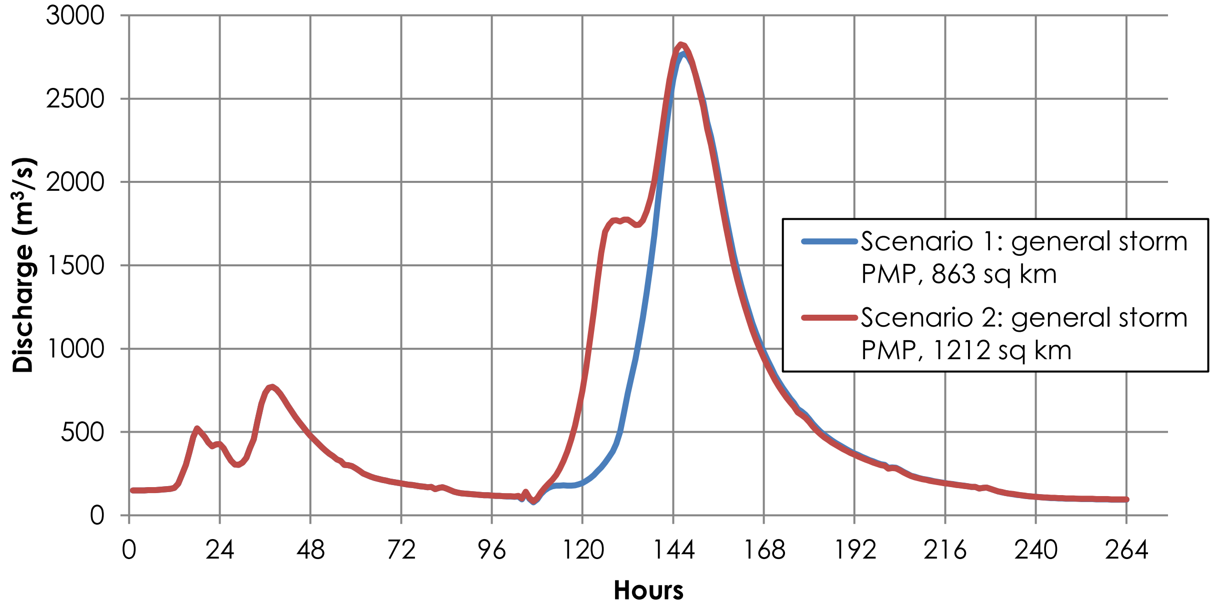


Figure 20: General Storm PMF Simulation Hydrographs for Scenarios 1 and 2 at Glenmore Dam

Table 30: General Strom PMF Results for Scenarios 1 and 2

Scenario	SR1 Diversion Site		Glenmore Dam	
	Peak Flow (m^3/s)	7-Day Volume (dam^3)	Peak Flow (m^3/s)	7-Day Volume (dam^3)
1	2,770	362,000	2,770	364,000
2	2,690	349,000	2,830	437,000

4.7.2 Local Storm PMF Scenario for area upstream of SR1 Diversion (Scenario 3)

A hydrograph representing the local storm PMF was generated at the proposed SR1 Diversion Site and Glenmore Dam (see Figure 21 and Figure 22). A detailed summary of the peak flow and 7-day volume for the local storm PMF Scenario 3 is given in Table 31.

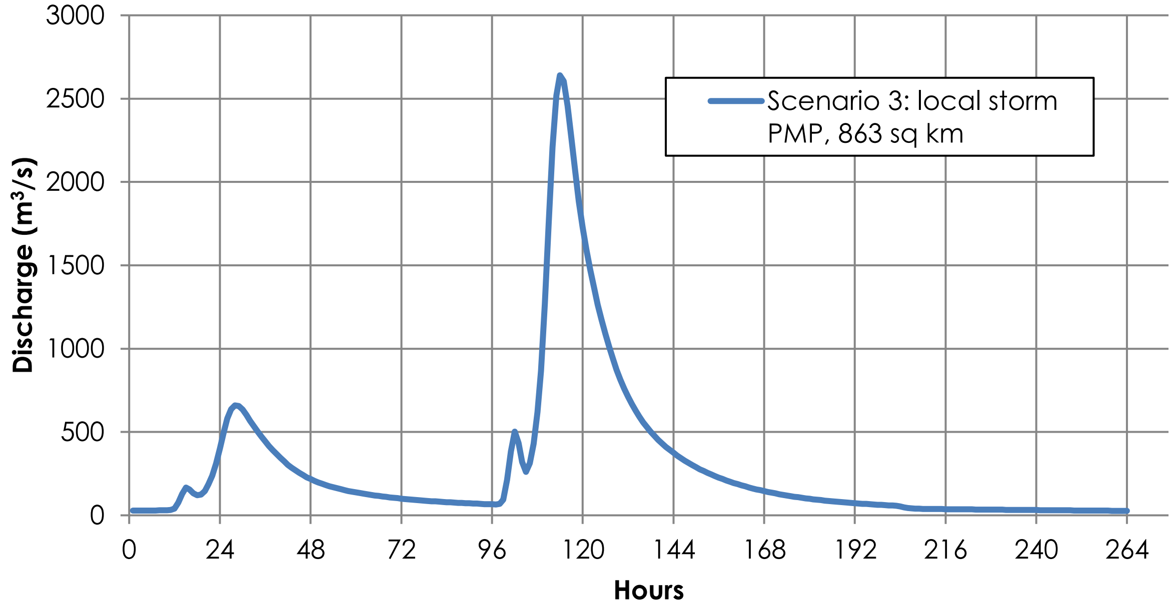


Figure 21: Local Storm PMF Simulation Hydrographs for Scenarios 3 at the Proposed SR1 Diversion Site

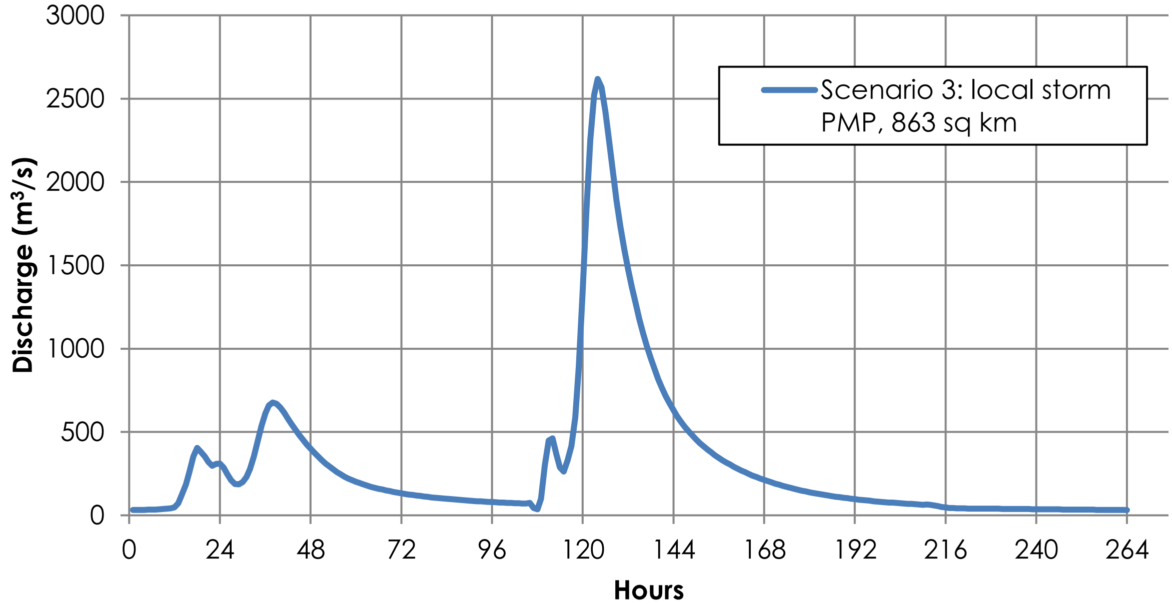


Figure 22: Local Storm PMF Simulation Hydrographs for Scenarios 3 at Glenmore Dam

Table 31: Local Storm PMF Results for Scenario 3

Scenario	SR1 Diversion		Glenmore Dam	
	Peak Flow (m^3/s)	7-Day Volume (dam^3)	Peak Flow (m^3/s)	7-Day Volume (dam^3)
3	2,640	208,000	2,620	211,000

4.7.3 Local Storm PMF Scenario for Area Upstream of Proposed SR1 Dam (Scenario 4)

Figure 23 shows the generated PMF hydrograph for Scenario 4 at the proposed SR1 Off-Stream Dam. The results are summarized in Table 32.

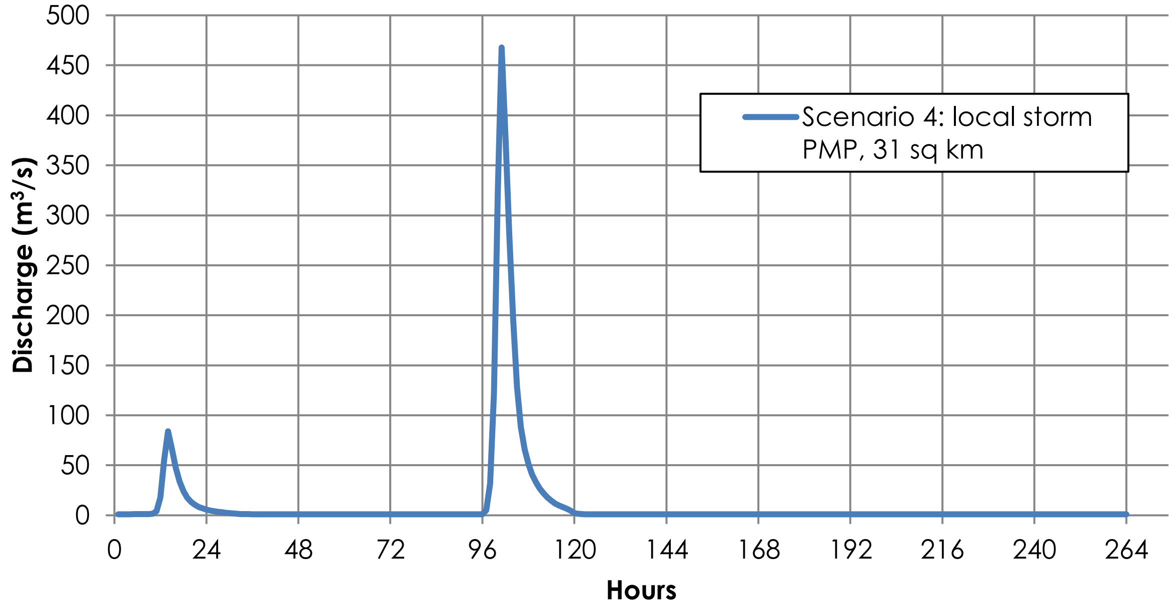


Figure 23: Local Storm PMF Simulation Hydrograph for Scenario 4 at Proposed SR1 Off-Stream Dam

Table 32: Local Storm PMF Results for Scenario 4

Scenario	SR1 Dam	
	Peak Flow (m^3/s)	7-Day Volume (dam^3)
4	468	8,930

5.0 PMF SUMMARY AND CONCLUSION

The PMF for the Elbow River Basin was estimated for design purposes of the proposed SR1 Diversion Structure on the Elbow River and the proposed SR1 Off-Stream Dam. A major component of the PMF estimation was the development of the PMP. The PMP analysis and delivery of the PMP values were provided by AWA of Monument, Colorado, a sub consultant to Stantec. Four PMP scenarios were deemed necessary to assess the possible design floods of interest for the project (see Table 18). The PMF analyses were performed by setting up and calibrating HEC-HMS models of the watershed forced by various PMP data. The HEC-HMS models incorporate:

- 11 sub-basins each representing hydrologically homogeneous characteristics.
- Rainfall loss estimation using the Initial Loss plus Uniform Loss Rate method. Input parameters include the initial loss represented by a rainfall depth, the saturated soil hydraulic conductivity, and the effective impervious area as a percent.
- Unit hydrograph method based on published guidelines for similar Rocky Mountain watershed physiography.
- Channel routing methodology to translate runoff hydrographs at concentration points internal to the model to downstream concentration points.
- Baseflow estimates based on return flow from watershed infiltration to the receiving watercourses.
- Snowmelt contribution to represent seasonal snowmelt that could reasonably be expected to occur with each PMF scenario.
- An antecedent storm was included in the model to represent the 100-year, 24-hour rainfall occurring three days prior to the onset of the PMP storm.

The HEC-HMS model was initially calibrated to the June 2005 and the June 2013 floods. For that purpose, AWA analyzed those storms and provided digital data for each sub-basin that is representative of the actual temporal and spatial distributions of each of those storms. Due to limitations of the aerial extent of those storms and uncertainties in the streamflow data, the model calibration yielded preliminary conclusions. That calibration process was successful in developing appropriate rainfall loss parameter values, and in the development of appropriate watershed channel routing and baseflow methodologies. However, the calibration of the unit hydrograph methodology and parameter estimation could not be relied upon because the historic rainfalls did not fully cover all of the model sub-basins and rainfall intensities were not sufficiently uniform over the watershed and sub-basins to meet the requirements of unit hydrograph theory.

When the initially calibrated HEC-HMS model was used with the PMP scenarios including the antecedent 100-year storm, the runoff for the 100-year rainfall resulted in peak discharges greatly in excess of the 100-year peak discharge that was previously estimated by flood frequency analysis. Inspection of the HEC-HMS model indicated that the unit hydrographs were producing too rapid response for such a uniformly applied PMP rainfall. Subsequently, the unit hydrograph parameters for the sub-basins were adjusted such that the HEC-HMS model satisfactorily reproduced 100-year flood runoff response to a simulated 100-year rainfall over the watershed.

A snowmelt hydrograph was developed based on snowpack and snowmelt data during severe rainstorms on the watershed. That snowmelt hydrograph was applied at the start of the 100-year storm for Scenario 1 and 2 with subsequent recession followed by a rise in snowmelt contribution during the PMP.

The final calibrated HEC-HMS model with PMP input for each of the four scenarios resulted in design PMF estimates at the SR1 Diversion Structure on the Elbow River and the SR1 Off-Stream Dam. Although not a design requirement for the SR1 Project, the PMF for Glenmore Dam was estimated as well.

A summary of the PMF results for each scenario are provided in Table 33 below. The recommended PMF hydrographs are based on the PMF scenario with the largest peak flow and 7-day volume. PMF Scenarios 1, 2, and 4 represent the maximum discharge and volume at the SR1 Diversion Structure, Glenmore Dam, and SR1 Off-Stream Dam, respectively. A summary of the recommended PMF hydrographs at the SR1 Diversion Structure, Glenmore Dam, and SR1 Off-Stream Dam are shown in Table 34.

Table 33: Summary of PMF Results per Scenario

Scenario	Peak Flow (m^3/s)			7-Day Volume (dam^3)		
	SR1 Diversion Structure	Glenmore Dam	SR1 Off-Stream Dam	SR1 Diversion Structure	Glenmore Dam	SR1 Off-Stream Dam
1	2,770	2,770	-	362,000	364,000	-
2	2,690	2,830	-	349,000	437,000	-
3	2,640	2,620	-	208,000	211,000	-
4	-	-	470	-	-	9,000

Table 34: Summary of PMF Results

	SR1 Diversion Structure	Glenmore Dam	SR1 Off-Stream Dam
Peak discharge (m^3/s)	2,770	2,830	470
7-Day Volume (dam^3)	362,000	437,000	9,000
Reference	Figure 19	Figure 20	Figure 23

6.0 REFERENCES

Alberta Biodiversity Monitoring Institute (ABMI). 2012. *ABMI Wall-to-wall Land Cover Map circa 2000, Version 2.1: Metadata*.

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APPENDIX B.4-2 – PMF HYDROGRAPH

Stantec Developed PMF Hydrograph at SR1 Diversion Structure

Date / Time	Discharge (m^3/s)
6/5/00 0:00	105.00
6/5/00 1:00	112.80
6/5/00 2:00	65.70
6/5/00 3:00	111.20
6/5/00 4:00	146.40
6/5/00 5:00	164.50
6/5/00 6:00	172.50
6/5/00 7:00	175.50
6/5/00 8:00	176.40
6/5/00 9:00	176.60
6/5/00 10:00	176.60
6/5/00 11:00	176.90
6/5/00 12:00	178.40
6/5/00 13:00	182.60
6/5/00 14:00	190.80
6/5/00 15:00	202.90
6/5/00 16:00	218.90
6/5/00 17:00	238.00
6/5/00 18:00	260.30
6/5/00 19:00	285.80
6/5/00 20:00	313.90
6/5/00 21:00	346.50
6/5/00 22:00	386.30
6/5/00 23:00	435.60
6/6/00 0:00	500.30
6/6/00 1:00	595.70
6/6/00 2:00	716.70
6/6/00 3:00	842.30
6/6/00 4:00	944.00
6/6/00 5:00	1052.20
6/6/00 6:00	1180.80
6/6/00 7:00	1331.80
6/6/00 8:00	1497.80
6/6/00 9:00	1679.50
6/6/00 10:00	1869.70
6/6/00 11:00	2073.40
6/6/00 12:00	2276.30
6/6/00 13:00	2461.70
6/6/00 14:00	2609.60
6/6/00 15:00	2710.20
6/6/00 16:00	2763.00
6/6/00 17:00	2773.60
6/6/00 18:00	2751.80
6/6/00 19:00	2706.10
6/6/00 20:00	2642.20
6/6/00 21:00	2563.30
6/6/00 22:00	2472.40
6/6/00 23:00	2372.00
6/7/00 0:00	2264.60
6/7/00 1:00	2148.10
6/7/00 2:00	2056.80
6/7/00 3:00	1919.30
6/7/00 4:00	1789.30

Date / Time	Discharge (m^3/s)
6/7/00 5:00	1671.70
6/7/00 6:00	1564.80
6/7/00 7:00	1467.20
6/7/00 8:00	1377.60
6/7/00 9:00	1295.50
6/7/00 10:00	1220.40
6/7/00 11:00	1151.50
6/7/00 12:00	1088.30
6/7/00 13:00	1030.00
6/7/00 14:00	976.10
6/7/00 15:00	926.30
6/7/00 16:00	880.20
6/7/00 17:00	837.60
6/7/00 18:00	798.40
6/7/00 19:00	762.20
6/7/00 20:00	728.80
6/7/00 21:00	697.90
6/7/00 22:00	669.20
6/7/00 23:00	642.40
6/8/00 0:00	617.50
6/8/00 1:00	592.10
6/8/00 2:00	581.50
6/8/00 3:00	549.70
6/8/00 4:00	521.60
6/8/00 5:00	498.80
6/8/00 6:00	479.60
6/8/00 7:00	462.40
6/8/00 8:00	446.70
6/8/00 9:00	432.00
6/8/00 10:00	418.10
6/8/00 11:00	405.00
6/8/00 12:00	392.50
6/8/00 13:00	380.60
6/8/00 14:00	369.30
6/8/00 15:00	358.50
6/8/00 16:00	348.30
6/8/00 17:00	338.50
6/8/00 18:00	329.20
6/8/00 19:00	320.30
6/8/00 20:00	311.80
6/8/00 21:00	303.80
6/8/00 22:00	296.10
6/8/00 23:00	288.70
6/9/00 0:00	281.70
6/9/00 1:00	272.80
6/9/00 2:00	278.20
6/9/00 3:00	260.30
6/9/00 4:00	245.20
6/9/00 5:00	234.90
6/9/00 6:00	227.30
6/9/00 7:00	221.30
6/9/00 8:00	216.10
6/9/00 9:00	211.30

Date / Time	Discharge (m^3/s)
6/9/00 10:00	206.80
6/9/00 11:00	202.50
6/9/00 12:00	198.50
6/9/00 13:00	194.50
6/9/00 14:00	190.80
6/9/00 15:00	187.20
6/9/00 16:00	183.80
6/9/00 17:00	180.50
6/9/00 18:00	177.30
6/9/00 19:00	174.30
6/9/00 20:00	171.30
6/9/00 21:00	168.50
6/9/00 22:00	165.80
6/9/00 23:00	163.00
6/10/00 0:00	160.20
6/10/00 1:00	155.80
6/10/00 2:00	161.30
6/10/00 3:00	150.20
6/10/00 4:00	141.00
6/10/00 5:00	134.70
6/10/00 6:00	130.30
6/10/00 7:00	127.00
6/10/00 8:00	123.50
6/10/00 9:00	120.00
6/10/00 10:00	116.80
6/10/00 11:00	113.90
6/10/00 12:00	111.30
6/10/00 13:00	109.00
6/10/00 14:00	107.00
6/10/00 15:00	105.20
6/10/00 16:00	103.60
6/10/00 17:00	102.20
6/10/00 18:00	100.90
6/10/00 19:00	99.80
6/10/00 20:00	98.90
6/10/00 21:00	98.00
6/10/00 22:00	97.20
6/10/00 23:00	96.60
6/11/00 0:00	96.00
6/11/00 1:00	95.40
6/11/00 2:00	95.00
6/11/00 3:00	94.50
6/11/00 4:00	94.10
6/11/00 5:00	93.70
6/11/00 6:00	93.20
6/11/00 7:00	92.80
6/11/00 8:00	92.40
6/11/00 9:00	92.00
6/11/00 10:00	91.60
6/11/00 11:00	91.20
6/11/00 12:00	90.80
6/11/00 13:00	90.40
6/11/00 14:00	90.00

Date / Time	Discharge (m^3/s)
6/11/00 15:00	89.70
6/11/00 16:00	89.30
6/11/00 17:00	88.90
6/11/00 18:00	88.50
6/11/00 19:00	88.10
6/11/00 20:00	87.70
6/11/00 21:00	87.30
6/11/00 22:00	87.00
6/11/00 23:00	86.60
6/12/00 0:00	86.20

APPENDIX B.5 – RESERVOIR DRAWDOWN SWMM MODEL

APPENDIX B.5 – RESERVOIR DRAWDOWN SWMM MODEL

Springbank Off-Stream Reservoir Project Drawdown SWMM Model

Prepared for:
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3rd Floor – Twin Atria Building
4999 – 98 Avenue
Edmonton, AB T6B 2X3

Prepared by:
Stantec Consulting Services Ltd
Calgary, AB

Project 110773396

September 19, 2019

Sign-off Sheet

This document entitled Springbank Off-Stream Reservoir Project Drawdown SWMM Model was prepared by Stantec Consulting Ltd. (“Stantec”) for the account of Alberta Transportation (the “Client”). Any reliance on this document by any third party is strictly prohibited. The material in it reflects Stantec’s professional judgment in light of the scope, schedule and other limitations stated in the document and in the contract between Stantec and the Client. The opinions in the document are based on conditions and information existing at the time the document was published and do not take into account any subsequent changes. In preparing the document, Stantec did not verify information supplied to it by others. Any use which a third party makes of this document is the responsibility of such third party. Such third party agrees that Stantec shall not be responsible for costs or damages of any kind, if any, suffered by it or any other third party as a result of decisions made or actions taken based on this document.

Prepared by ____

(signature)

Daniel Hoffman, Senior Project Engineer

Approved by ____

(signature)

John Menninger P.Eng., Senior Principal

Table of Contents

September 19, 2019

1.0 INTRODUCTION

The US EPA SWMM 5, version 5.1.012, software package (Reference 1) was used to simulate drawdown of the SR1 Reservoir after a diversion event. For design, this model was used to determine the necessary SR1 Dam Low Level Outlet capacity to achieve design drawdown rates. This memo documents the development and results of the SWMM model. This memo is part of Appendix B.5 to the preliminary Design Report.

2.0 MODEL GEOMETRY

The model is comprised of an upstream storage node representing the SR1 Reservoir, an outlet with a user defined rating curve representing the SR1 Low Level Outlet Works (LLOW) intake structure, pressure pipe and gates, and a length of pipe representing the LLOW gravity conduit downstream of the gates.

The stage-storage curve for the storage node was developed based on the geometry of the preliminary design.

The 180 m length of pipe was simulated as a 2.4 m by 2.4 m basket handle cross section at a slope of 1.8%. The pipe was assumed to have a Manning's roughness of 0.013. The upstream invert elevation of the pipe was set at an elevation of 1186.36 m.

The outlet was assigned a rating curve developed as part of the LLOW hydraulic design calculations. A tabular copy of the Low Level Outlet rating curve is attached.

3.0 BOUNDARY CONDITIONS

The upstream boundary condition was set as a specified pool elevation in the storage unit of 1210.75 m representing the full service level (FSL). The downstream boundary condition was set to normal depth.

4.0 RESULTS

The SWMM model demonstrates the ability of the preliminary design to fully empty the water level in the SR1 Reservoir in approximately 45 days from the maximum design pool elevation. Figure 1 below presents the drawdown hydrograph of this scenario.

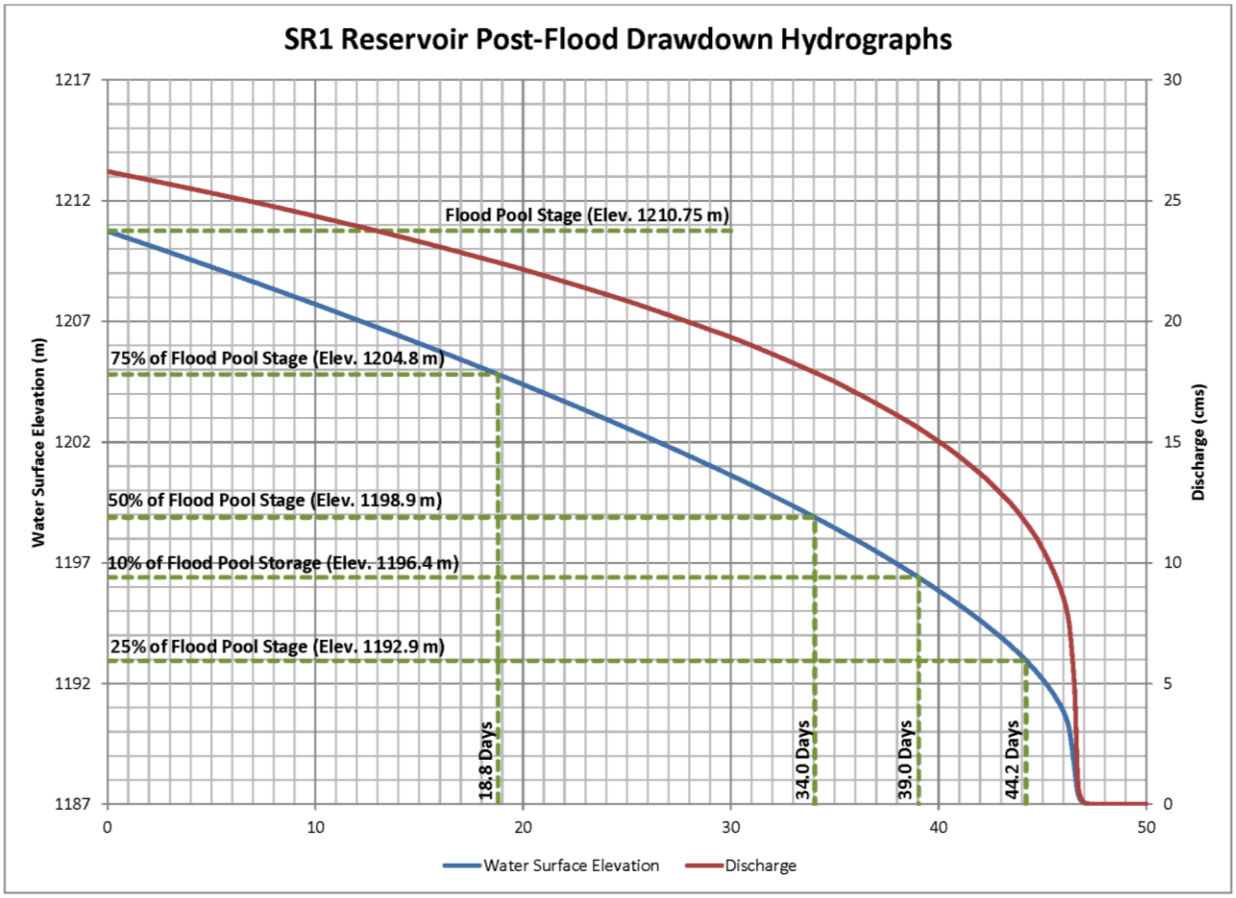


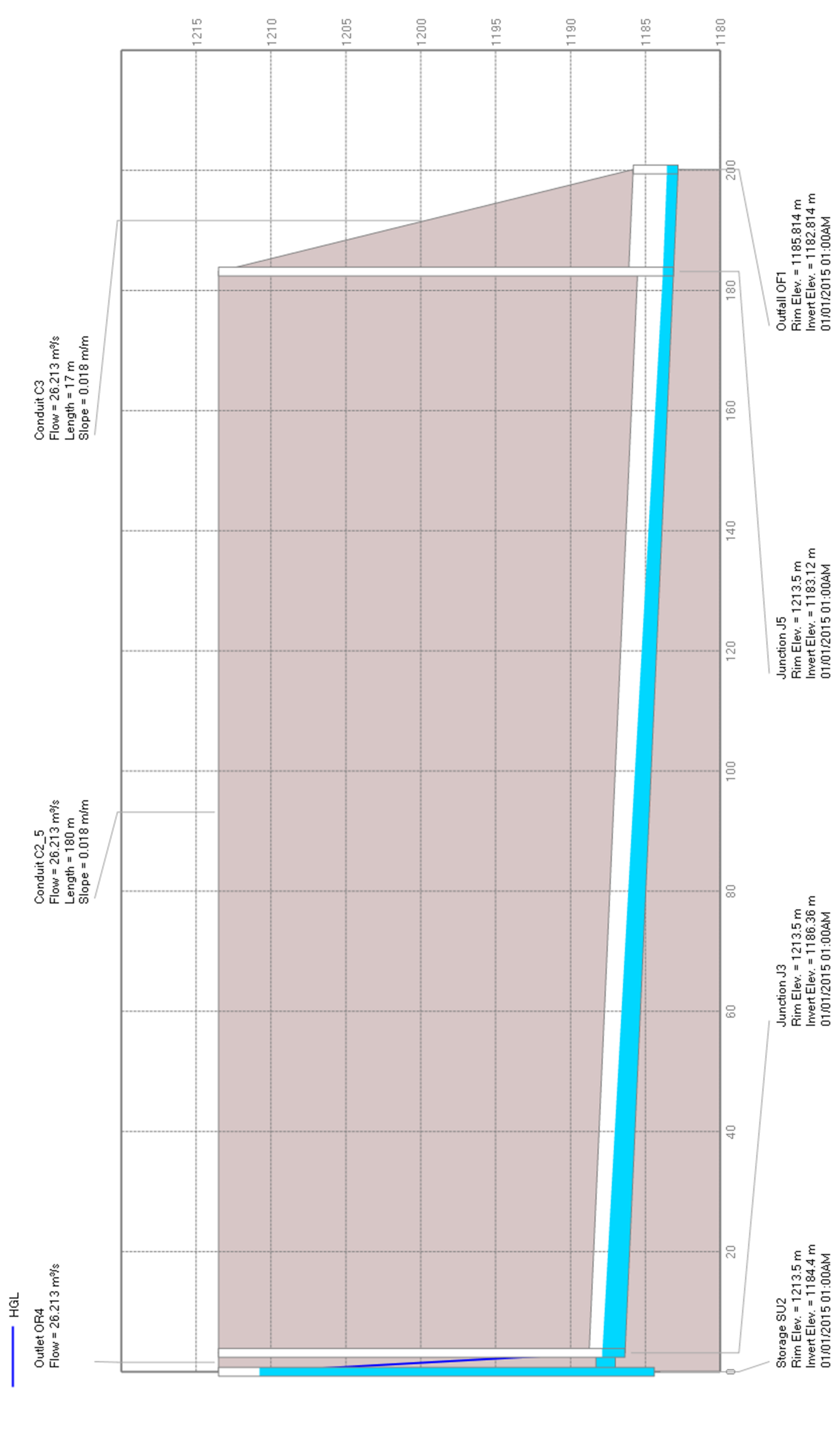
Figure 1. Low Level Outlet Works Drawdown Hydrograph

5.0 REFERENCES

U.S. Environmental Protection Agency (EPA). (2017). Storm Water Management Model, Version 5.1.012. USEPA National Risk Management Research laboratory, Cincinnati, Ohio.

APPENDIX B.5-1 – MODEL LAYOUT

SWMM LLO Drawdown Model Layout



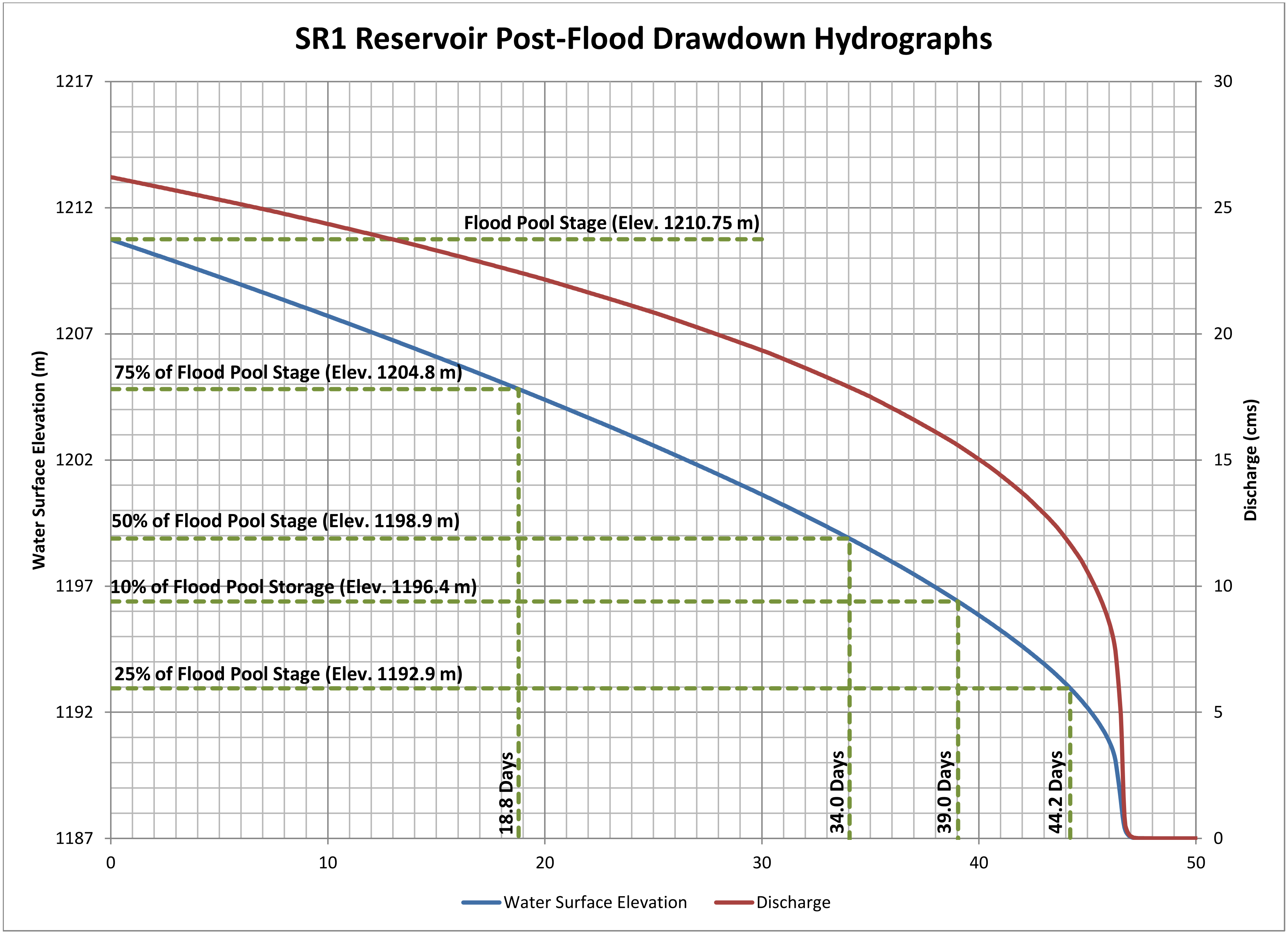
SR1 Reservoir Low Level Outlet Discharge Rating Curve Developed by Stantec for Preliminary Design

Elevation (m)	Low Level Outlet Discharge (m^3/s)	
1187.00	0.0	
1187.32	0.5	
1187.47	1.0	
1187.59	1.5	
1187.70	2.0	
1187.82	2.5	
1187.93	3.0	
1188.05	3.5	
1188.18	4.0	
1188.30	4.5	
1188.55	5.0	
1188.87	5.5	
1189.16	6.0	
1189.50	6.5	
1190.48	8.0	
1191.48	9.5	
1192.48	11.0	
1193.48	12.4	
1194.48	13.6	
1195.48	14.7	
1196.48	15.7	
1198.48	17.5	
1200.48	19.2	
1202.48	20.8	
1204.48	22.2	
1206.48	23.6	
1208.48	24.9	
1211.23	26.5	
1212.00	27.0	<-- Discharge Linearly Extrapolated

SR1 Reservoir Stage-Storage-Area Curve Developed by Stantec for Preliminary Design

Elevation (m)	Cumulative Volume (dam^3)	Area (m^2)
1185.00	0.0	334
1187.50	11.2	22,227
1190.00	103.7	107,317
1192.50	777.6	966,118
1195.00	3,994.3	1,929,575
1197.50	9,514.8	2,842,616
1200.00	17,336.8	3,837,079
1201.00	21,174.8	4,242,801
1202.00	25,410.7	4,594,878
1203.00	30,008.1	4,948,447
1204.00	34,956.7	5,316,475
1205.00	40,271.4	5,683,523
1206.00	45,952.7	6,049,249
1207.00	51,999.0	6,395,499
1208.00	58,396.7	6,768,923
1209.00	65,163.6	7,125,028
1210.00	72,291.7	7,507,534
1211.00	79,798.8	7,885,480
1212.00	87,683.9	8,268,497
1213.00	95,952.1	8,640,302
1214.00	104,596.0	8,990,748
1215.00	113,585.5	9,303,905

APPENDIX B.5-2 – RESULTS



SR1 Reservoir Post-Flood Drawdown Hydrographs
Water Surface Elevation (m)
Discharge (cms)
Flood Pool Stage (Elev. 1210.75 m)
75% of Flood Pool Stage (Elev. 1204.8 m)
50% of Flood Pool Stage (Elev. 1198.9 m)
10% of Flood Pool Storage (Elev. 1196.4 m)
25% of Flood Pool Stage (Elev. 1192.9 m)
18.8 Days
34.0 Days
39.0 Days
44.2 Days
1217
1212
1207
1202
1197
1192
1187
30
25
20
15
10
5
0
0
10
20
30
40
50
Water Surface Elevation
Discharge

APPENDIX B.6 – HEC-RESSIM MODEL

APPENDIX B.6 – HEC-RESSIM MODEL

Springbank Off-Stream Reservoir Project

HEC-ResSim Model

Prepared for:
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Edmonton, AB T6B 2X3

Prepared by:
Stantec Consulting Services Ltd
Calgary, AB

Project 110773396

September 26, 2019

Sign-off Sheet

This document entitled Springbank Off-Stream Reservoir Project HEC-ResSim Model was prepared by Stantec Consulting Ltd. (“Stantec”) for the account of Alberta Transportation (the “Client”). Any reliance on this document by any third party is strictly prohibited. The material in it reflects Stantec’s professional judgment in light of the scope, schedule and other limitations stated in the document and in the contract between Stantec and the Client. The opinions in the document are based on conditions and information existing at the time the document was published and do not take into account any subsequent changes. In preparing the document, Stantec did not verify information supplied to it by others. Any use which a third party makes of this document is the responsibility of such third party. Such third party agrees that Stantec shall not be responsible for costs or damages of any kind, if any, suffered by it or any other third party as a result of decisions made or actions taken based on this document.

Prepared by ____

(signature)

Daniel Hoffman, Senior Project Engineer

Approved by ____

(signature)

John Menninger P.Eng., Senior Principal

Table of Contents

LIST OF TABLES

1.0 INTRODUCTION

The USACE HEC-ResSim, version 3.1, software package (Reference 1) was used to simulate operation of the SR1 Diversion Structure during multiple inflow hydrographs. For design, this model is used to simulate the PMF hydrograph into the Diversion Channel in the event of normal operation or mis-operation or failure of the Diversion Inlet gates. This model was also used to simulate a range of historic events, including the design event, to evaluate the recommended operation scheme. This memo documents the development and results of the HEC-ResSim model. This memo is part of Appendix B.6 to the preliminary design report.

2.0 MODEL GEOMETRY

The HEC-ResSim model is comprised of three dam structures representing the SR1 Diversion Structure, the SR1 Dam and Glenmore Dam. The dams are connected via reaches representing the Elbow River between the SR1 Dam outlet and Glenmore Reservoir, between the SR1 Diversion Structure and SR1 Dam outlet and the SR1 Diversion Channel.

The stage-storage curve for Glenmore Reservoir was provided by the City of Calgary based on 2013 baythmetric data (Reference 2). The same document provides data regarding operation of Glenmore Dam, including a drawdown elevation of 1072.35 m prior to flood events. The outflow rating curve for Glenmore Dam was also provided by the City of Calgary and incorporates both pumped and uncontrolled discharge from the dam (Reference 3). Both the stage-storage and discharge rating curve are included as attachments to this memo.

The stage-storage curve for the SR1 Dam was developed based on the geometry of the preliminary design. The SR1 dam has an Emergency Spillway and a Low Level Outlet Works. The rating curves for the Emergency Spillway and Low Level Outlet Works were developed as part of hydraulic design calculations and documented in Section 10 of the preliminary design report. Both the stage-storage and discharge rating curves are attached.

The SR1 Diversion Structure was setup within the model to ignore storage upstream of the Diversion Structure. The inflow-discharge rating curve for the SR1 Diversion Structure represents desired diversion rates for a specific inflow for most scenarios. For the PMF scenario representing mis-operation or failure of the Diversion Inlet gates, an inflow-discharge rating curve was based on results of the 2D hydraulic model of the Diversion Structure described in Section 4.1 of the Preliminary Design Report in which operation begins as normal, and the Diversion Inlet gates fail to close allowing a portion of the PMF hydrograph to be routed down the Diversion Channel. The inflow-discharge rating curve for the SR1 Diversion Structure is included as an attachment.

The various routing reaches were simulated using the Muskingum-Cunge method with either a prismatic or 8-point channel cross section. Dimensions and slopes of the cross sections were estimated based on measurements of existing or designed topographic information. Reach routing parameters used in the model are provided as attachments to this memo.

3.0 BOUNDARY CONDITIONS AND OPERATIONS

The upstream boundary of the HEC-ResSim model is a user defined hydrograph. The Flood of Record – June 2013 hydrograph and the PMF hydrograph discussed in Section 3.2 and 3.4 of the Preliminary Design Report were both used in the model for design purposes. The downstream boundary is the discharge from Glenmore Dam, which is based on the City of Calgary provided stage-discharge rating curve discussed Section 2.0.

Normal operations in the HEC-ResSim model is based on the following assumptions:

- The SR1 Dam is empty at the start of the simulation
- Glenmore Dam pool elevation is at 1072.35 m due to pre-flood drawdown.
- The SR1 Diversion Structure begins diverting when the inflow exceeds 160 m3/s and will attempt to maintain discharge in the river downstream at 160 m3/s up to a maximum diversion rate of 480 m3/s.
- The SR1 Dam Low Level Outlet Works closes at the start of diversion operations and does not re-open until Glenmore Reservoir returns to a pool elevation of 1072.35 m and discharge in the Elbow River is below 160 m3/s.
- The SR1 Diversion Inlet gates close when the pool level in the SR1 Reservoir reaches or exceeds 1210.75 m.
- Alternative operating scenarios were also evaluated for various design purposes including design of the SR1 Emergency Spillway and evaluation of scour protection and freeboard in the SR1 Diversion Channel. Modifications for each of these scenarios are as follows:
- To support design of the SR1 Emergency Spillway, the normal operations were modified such that the Diversion Inlet gates fail to close during the PMF event and the ability of the crest gates to modulate discharge is exceeded. The starting storage of the SR1 Reservoir was also set to 7,561 dam^3 fully to account for potential sedimentation over time and tributary inflow.
- To support verification of the Diversion Channel freeboard, the normal operations were modified such that the maximum allowable diversion rate is 600 m3/s.

4.0 RESULTS

Table 1 below summarizes the results from each scenario simulated in the HEC-ResSim model. The model demonstrates that the normal 480 m^3/s diversion operation scheme and the maximum 600 m^3/s diversion operation scheme both achieve the level of diversion and storage necessary to limit discharge from Glenmore Dam to 170 m^3/s for the design event. Relevant discharge and stage hydrographs are provided for the HEC-ResSim simulations as attachments to this memo.

Table 1. Summary HEC-ResSim Simulation Results

Scenario	Peak Inflow (m^3/s)	Peak Diversion (m^3/s)	Diversion Volume (dam^3)	Peak Inflow at Glenmore (m3/s)	Peak Flood Storage at Glenmore (dam^3)	Peak Outflow from Glenmore (m^3/s)
Design Event, Normal Operation	1,240	480	70,662	673	9,269	170
Design Event, 600 m^3/s Diversion	1,240	600	75,629	572	4,733	160
PMF Event, Diversion Inlet Gate Failure	2,770	872	110,477	1,898	26,346	1,796
PMF Event, Normal Operation	2,770	480	71,361	2,290	29,184	2,171

5.0 REFERENCES

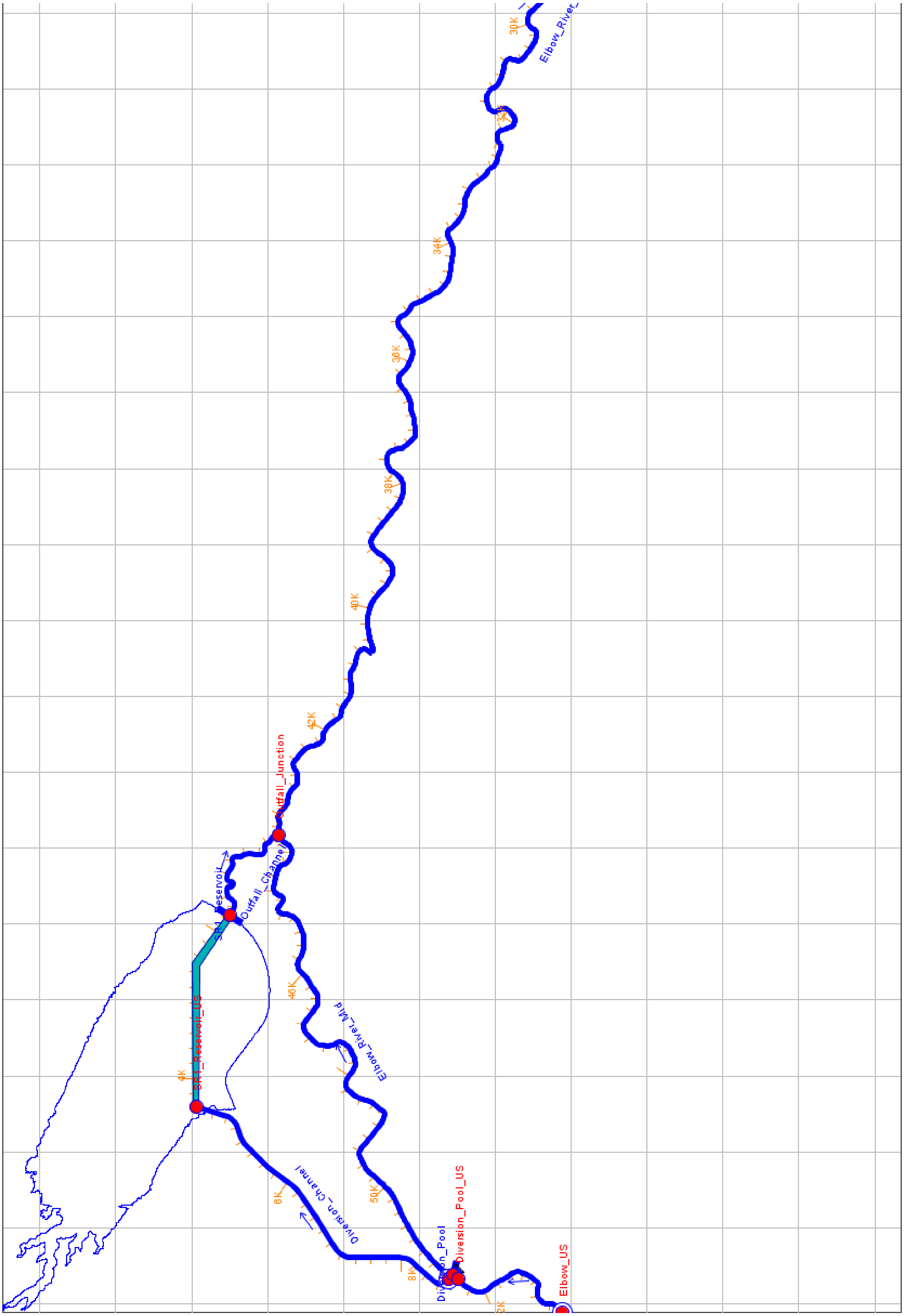
U.S. Army Corps of Engineers. (2013). HEC-ResSim, Version 3.1. Hydrologic Engineering Center, Davis, CA.

Challenger Geomatics Ltd. (2013). Calgary Glenmore Reservoir Bathymetric Survey, September, 2013. Prepared for Klohn Cirppen Berger Ltd, October, 2013.

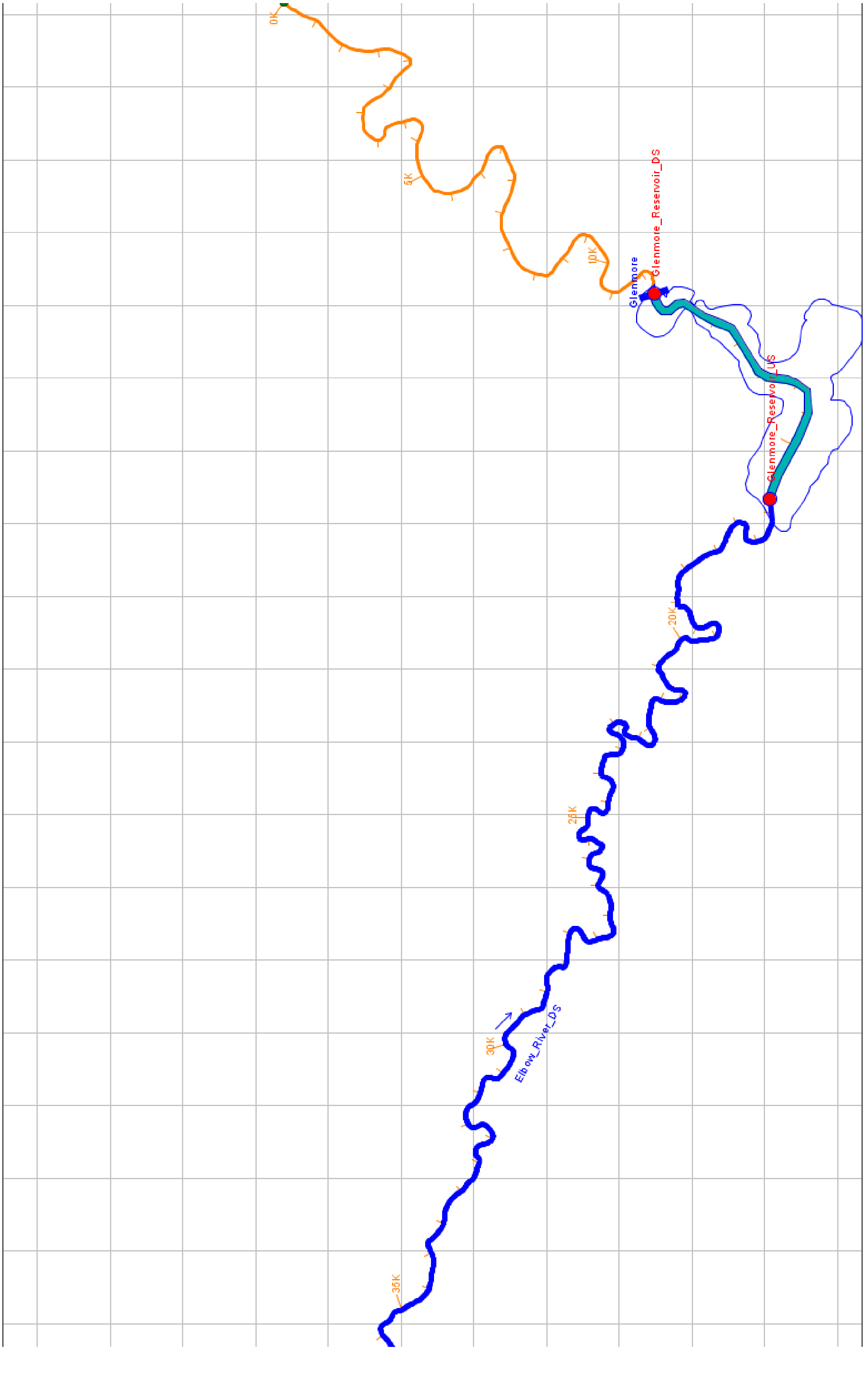
City of Calgary. Glenmore Spillway Curves (Microsoft Excel format). Provided to Stantec by City of Calgary in October 2014.

APPENDIX B.6-1 – MODEL LAYOUT

HEC-ResSim Model Layout (Upstream)



HEC-ResSim Model Layout (Downstream)



HEC-ResSim Reach Routing Parameters

Reach Name	Method	Length (m)	Slope (m/m)	Geometry	Manning's Roughness (Left, Channel, Right)
Elbow_River_US	null routing (no travel time or attenuation)	n/a	n/a	n/a	n/a
Elbow_River_Mid	Muskingum-Cunge 8-pt Channel	7,800	0.0055	8-Point Cross Section (see below)	0.070, 0.038, 0.070
Elbow_River_DS	Muskingum-Cunge 8-pt Channel	27,500	0.0035	8-Point Cross Section (see below)	0.045, 0.045, 0.045
Diversion_Channel	Muskingum-Cunge Prismatic Channel	4,250	0.001	Trapezoid (22 m wide bottom, 4:1 slopes)	0.038
Outlfall_Channel	null routing (no travel time or attenuation)	n/a	n/a	n/a	n/a

Elbow_River_Mid 8-Point Cross Section

Station (m)	Elevation (m)
0	1115
200	1095
710	1094
735	1093
765	1093
790	1094
1300	1095
1500	1115

Elbow_River_DS 8-Point Cross Section

Station (m)	Elevation (m)
0	1115
200	1095
710	1094
735	1093
765	1093
790	1094
1300	1095
1500	1115

Glenmore Reservoir Discharge Rating Curves Provided by City of Calgary

Elevation (m)	Dam Crest Discharge (m^3/s)	Low Level Pump Discharge (m^3/s)	Combined Discharge (m^3/s)
1070.33	0.0	160.0	160.0
1071.43	0.0	160.0	160.0
1071.53	0.0	160.0	160.0
1071.63	0.0	160.0	160.0
1071.73	0.0	160.0	160.0
1071.83	0.0	160.0	160.0
1071.93	0.0	160.0	160.0
1072.03	0.0	160.0	160.0
1072.13	0.0	160.0	160.0
1072.23	0.0	160.0	160.0
1072.33	0.0	160.0	160.0
1072.43	0.0	160.0	160.0
1072.53	0.0	160.0	160.0
1072.63	0.0	160.0	160.0
1072.73	0.0	160.0	160.0
1072.83	0.0	160.0	160.0
1072.93	0.0	160.0	160.0
1073.03	0.0	160.0	160.0
1073.13	0.0	160.0	160.0
1073.23	0.0	160.0	160.0
1073.33	0.0	160.0	160.0
1073.43	0.0	160.0	160.0
1073.53	0.0	160.0	160.0
1073.63	0.0	160.0	160.0
1073.73	0.0	160.0	160.0
1073.83	0.0	160.0	160.0
1073.93	0.0	160.0	160.0
1074.03	0.0	160.0	160.0
1074.13	0.0	160.0	160.0
1074.23	0.0	160.0	160.0
1074.33	0.0	160.0	160.0
1074.43	0.0	160.0	160.0
1074.53	0.0	160.0	160.0
1074.63	0.0	160.0	160.0
1074.73	0.0	160.0	160.0
1074.83	0.0	160.0	160.0
1074.93	0.0	160.0	160.0
1075.03	0.0	160.0	160.0
1075.13	0.0	160.0	160.0
1075.23	0.0	160.0	160.0
1075.33	0.0	165.0	165.0
1075.43	4.0	166.0	170.0
1075.53	11.1	158.9	170.0
1075.63	21.1	148.9	170.0
1075.73	34.0	136.0	170.0
1075.83	49.7	120.3	170.0
1075.93	68.2	101.8	170.0
1076.03	89.5	80.5	170.0
1076.13	113.5	56.5	170.0
1076.23	140.2	29.8	170.0
1076.33	169.4	1.0	170.4
1076.43	201.2	0.0	201.2
1076.53	235.5	0.0	235.5
1076.63	272.3	0.0	272.3
1076.73	311.4	0.0	311.4
1076.83	353.0	0.0	353.0
1076.93	396.8	0.0	396.8
1077.03	442.8	0.0	442.8
1077.13	491.1	0.0	491.1
1077.23	541.5	0.0	541.5
1077.33	594.0	0.0	594.0
1077.43	648.5	0.0	648.5
1077.53	705.1	0.0	705.1
1077.63	763.6	0.0	763.6
1077.73	824.0	0.0	824.0
1077.83	886.3	0.0	886.3

SR1 Diversion Inlet Discharge Rating Curves Developed by Stantec for Preliminary Design

Elbow River Discharge (m^3/s)	Normal Operation Diversion Inlet Discharge (m^3/s)	600 m^3/s Operation Diversion Inlet Discharge (m^3/s)	Uncontrolled Rising Limb (Auxiliary Spillway Fuse Plug not Eroded) Diversion Inlet Discharge (m^3/s)	Uncontrolled Falling Limb (Auxiliary Spillway Fuse Plug Eroded) Diversion Inlet Discharge (m^3/s)
0	0.0	0.0	0.0	0.0
100			0.0	0.0
150				
160	0.0	0.0	0.0	18.0
200	40.0	40.0	0.0	28.6
300	140.0	140.0		
320	160.0	160.0		
330			73.2	73.2
400	240.0	240.0		
500	340.0	340.0		
530			138.3	138.3
600	440.0	440.0		
640	480.0	480.0		
700	480.0	540.0		
760	480.0	600.0		
765			219.4	219.4
1000			310.5	310.5
1240	480.0	600.0	408.0	408.0
1500			522.1	522.1
1850			681.0	643.8
1930				667.5
2210				742.3
2400	480.0	600.0		
2490				807.9
2770				872.3

SR1 Reservoir Discharge Rating Curves Developed by Stantec for Preliminary Design

Elevation (m)	Low Level Outlet Discharge (m^3/s)
1187.00	0.0
1187.32	0.5
1187.47	1.0
1187.59	1.5
1187.70	2.0
1187.82	2.5
1187.93	3.0
1188.05	3.5
1188.18	4.0
1188.30	4.5
1188.55	5.0
1188.87	5.5
1189.16	6.0
1189.50	6.5
1190.48	8.0
1191.48	9.5
1192.48	11.0
1193.48	12.4
1194.48	13.6
1195.48	14.7
1196.48	15.7
1198.48	17.5
1200.48	19.2
1202.48	20.8
1204.48	22.2
1206.48	23.6
1208.48	24.9
1211.23	26.5
1212.00	27.0

<-- Discharge Linearly Extrapolated

Elevation (m)	Emergency Spillway Discharge (m^3/s)
1210.75	0.0
1211.00	22.1
1211.25	79.4
1211.50	156.6
1211.75	249.0
1212.00	353.9

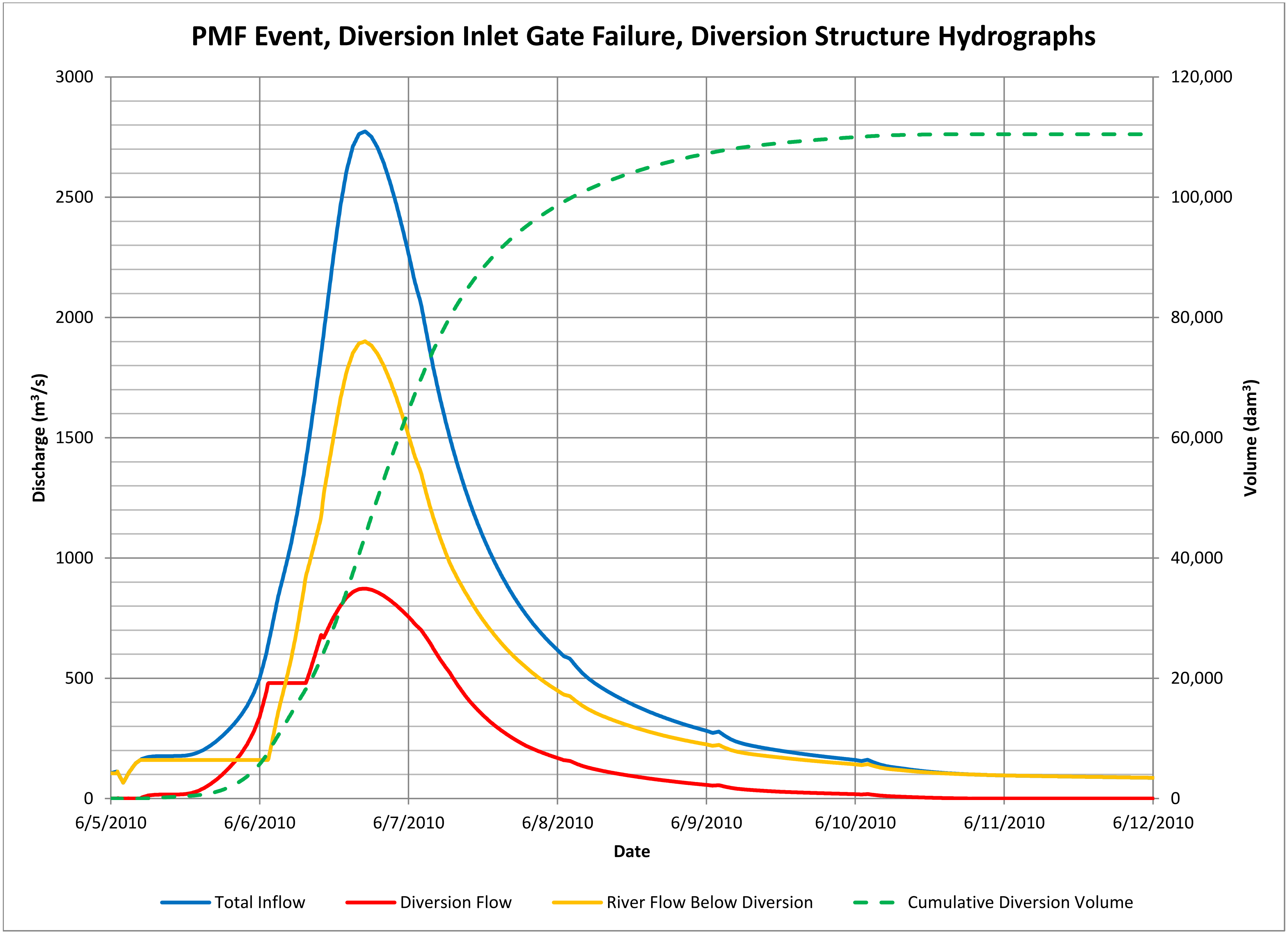
Glenmore Reservoir Stage-Storage Curve Provided by City of Calgary (2013 Bathymetry)

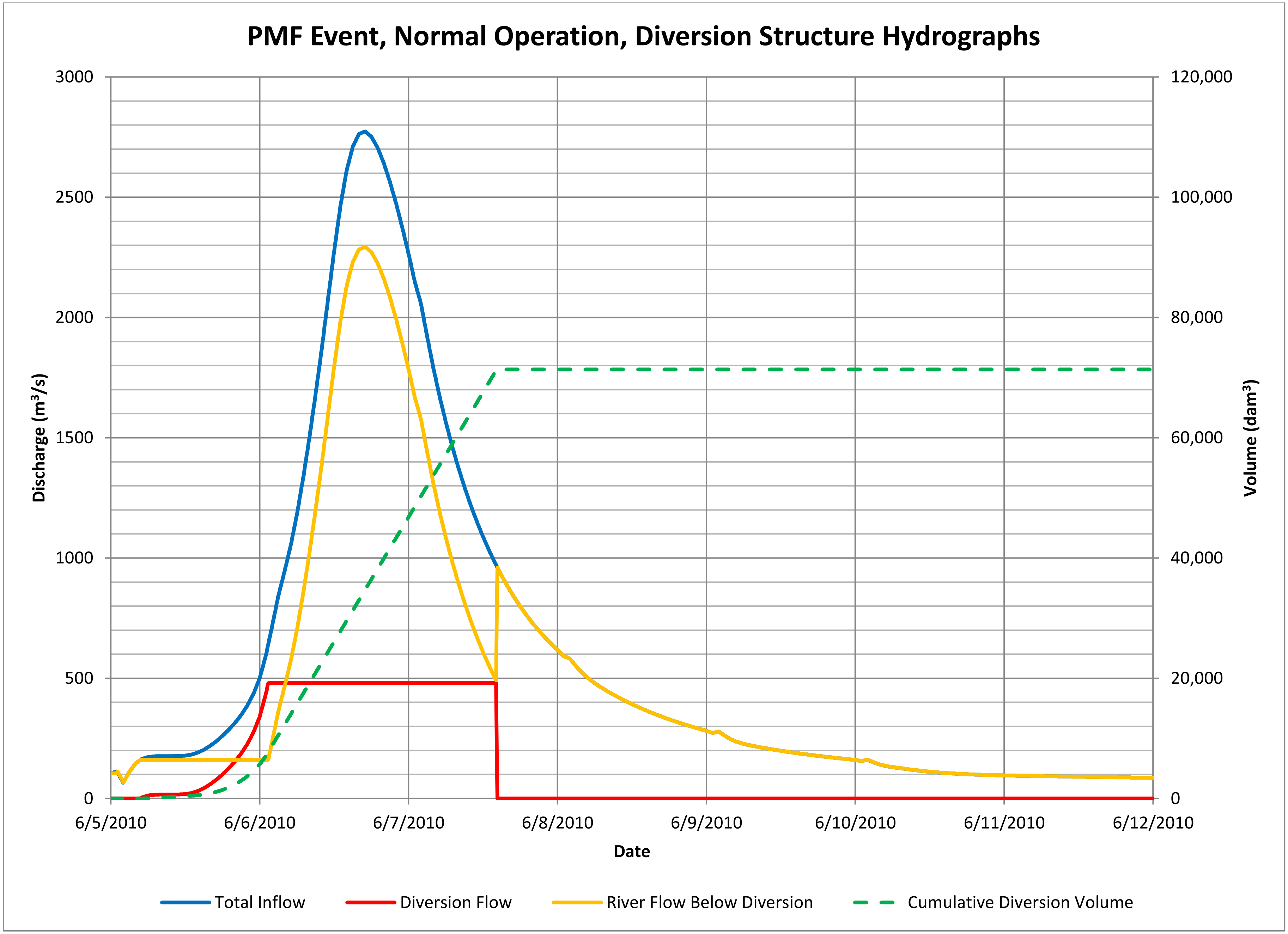
Elevation (m)	Cumulative Volume (m^3)	Cumulative Volume (dam^3)
1057.60	0	0.0
1059.00	2,712	2.7
1060.00	22,699	22.7
1061.00	76,229	76.2
1062.00	163,520	163.5
1063.00	298,581	298.6
1064.00	511,213	511.2
1065.00	836,166	836.2
1066.00	1,288,697	1,288.7
1067.00	1,874,545	1,874.5
1068.00	2,607,596	2,607.6
1069.00	3,520,779	3,520.8
1070.00	4,724,814	4,724.8
1071.00	6,252,266	6,252.3
1072.00	8,039,846	8,039.8
1072.50	9,041,273	9,041.3
1073.00	10,131,590	10,131.6
1073.50	11,319,402	11,319.4
1074.00	12,611,731	12,611.7
1074.50	14,091,706	14,091.7
1075.00	15,805,148	15,805.1
1075.35	17,086,142	17,086.1
1075.50	17,645,172	17,645.2
1076.00	19,595,467	19,595.5
1076.50	21,663,805	21,663.8
1076.85	23,167,079	23,167.1
1077.00	23,827,258	23,827.3
1077.50	26,094,786	26,094.8
1078.00	28,461,157	28,461.2
1079.00	33,475,512	33,475.5
1080.00	38,883,471	38,883.5
1080.44	41,385,937	41,385.9

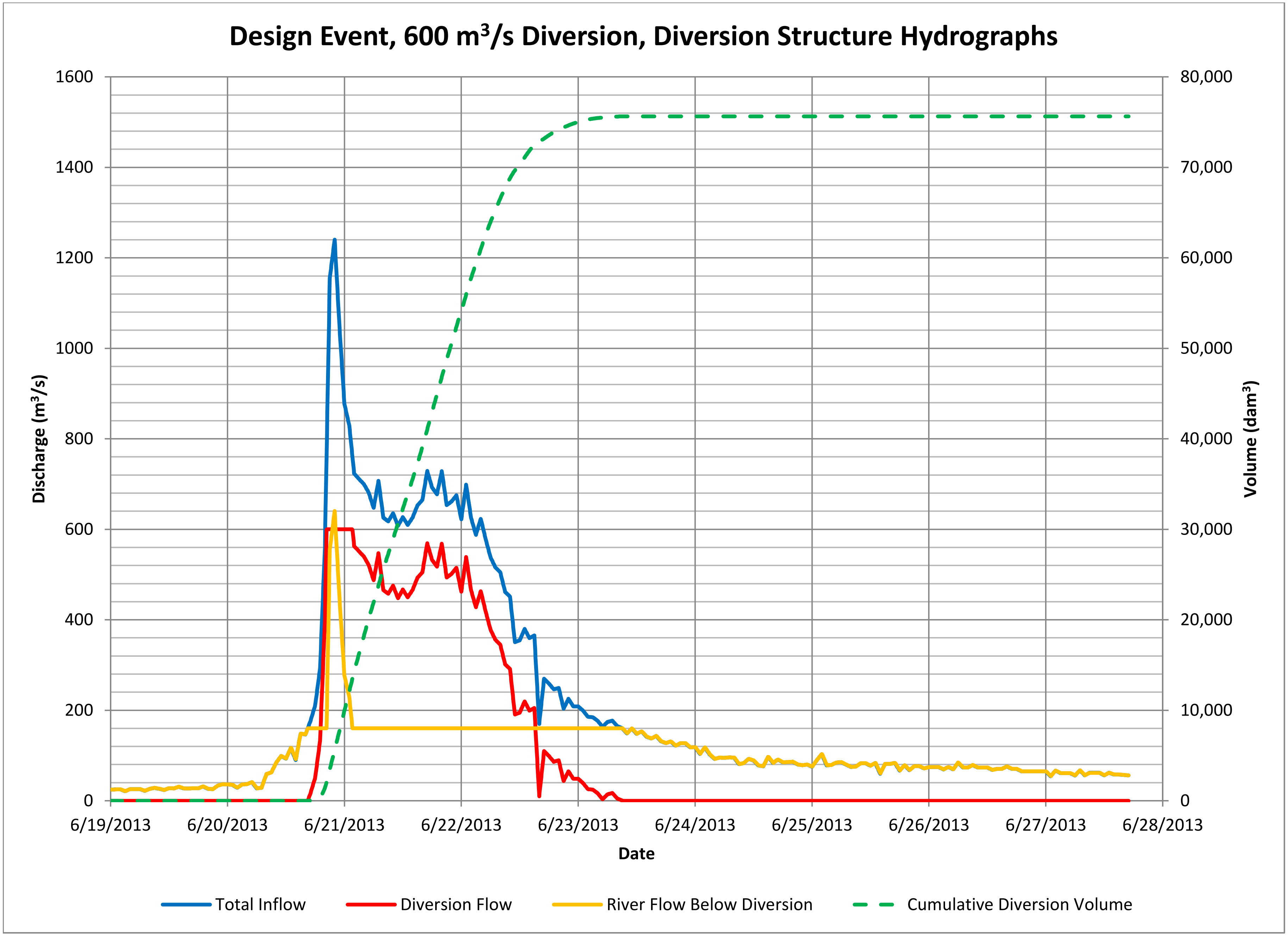
SR1 Reservoir Stage-Storage Curve Developed by Stantec for Preliminary Design

Elevation (m)	Cumulative Volume (m^3)	Cumulative Volume (dam^3)
1185.00	0	0.0
1187.50	11,172	11.2
1190.00	103,666	103.7
1192.50	777,616	777.6
1195.00	3,994,270	3,994.3
1197.50	9,514,791	9,514.8
1200.00	17,336,794	17,336.8
1201.00	21,174,761	21,174.8
1202.00	25,410,700	25,410.7
1203.00	30,008,129	30,008.1
1204.00	34,956,733	34,956.7
1205.00	40,271,381	40,271.4
1206.00	45,952,704	45,952.7
1207.00	51,998,954	51,999.0
1208.00	58,396,731	58,396.7
1209.00	65,163,646	65,163.6
1210.00	72,291,738	72,291.7
1211.00	79,798,750	79,798.8
1212.00	87,683,872	87,683.9
1213.00	95,952,123	95,952.1
1214.00	104,595,976	104,596.0
1215.00	113,585,508	113,585.5

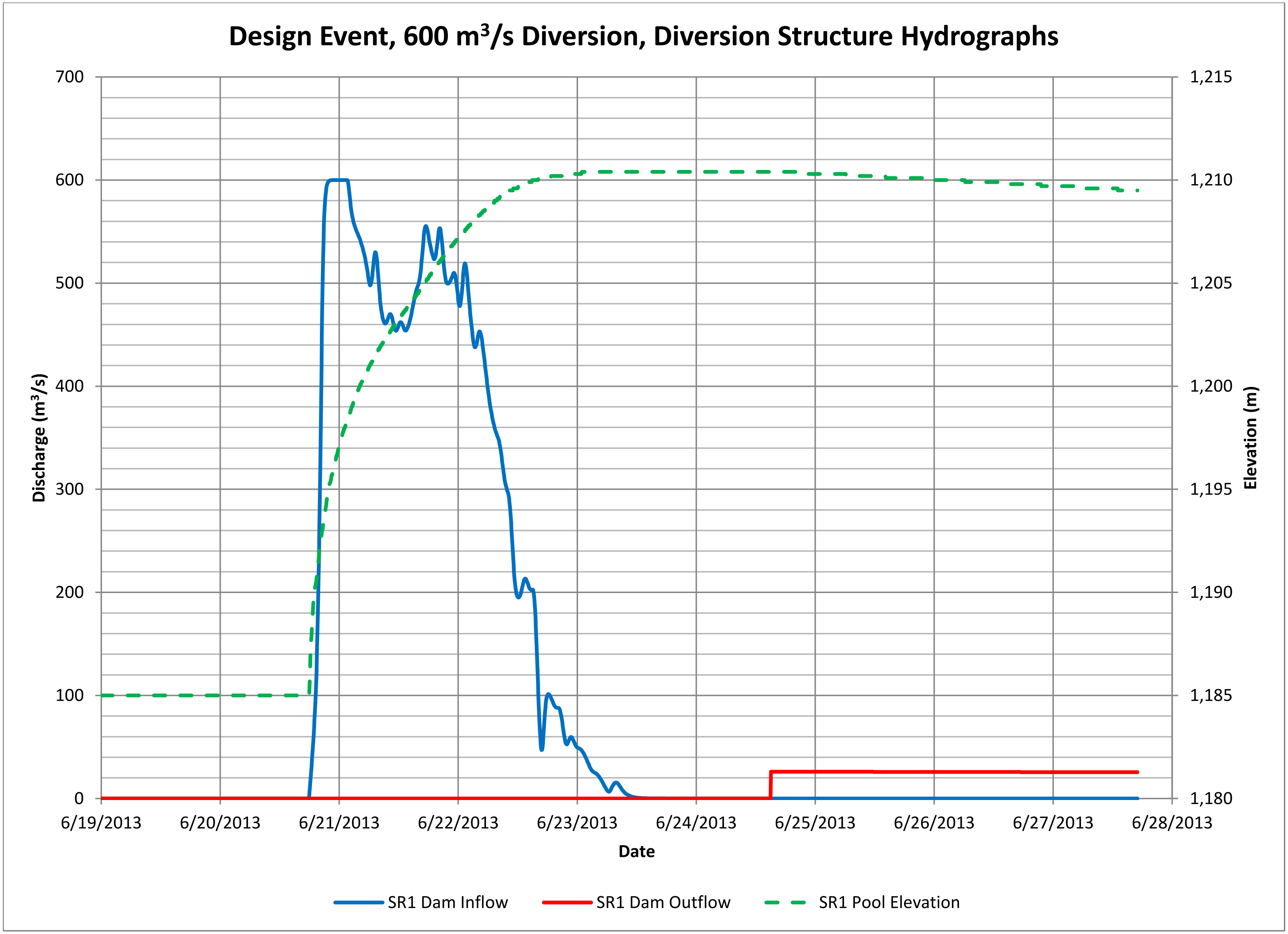
APPENDIX B.6-2 – RESULTS


PMF Event, Diversion Inlet Gate Failure, Diversion Structure Hydrographs
Discharge (m³/s)
Volume (dam³)
3000
2500
2000
1500
1000
500
0
120,000
100,000
80,000
60,000
40,000
20,000
0
6/5/2010
6/6/2010
6/7/2010
6/8/2010
6/9/2010
6/10/2010
6/11/2010
6/12/2010
Date
Total Inflow
Diversion Flow
River Flow Below Diversion
Cumulative Diversion Volume

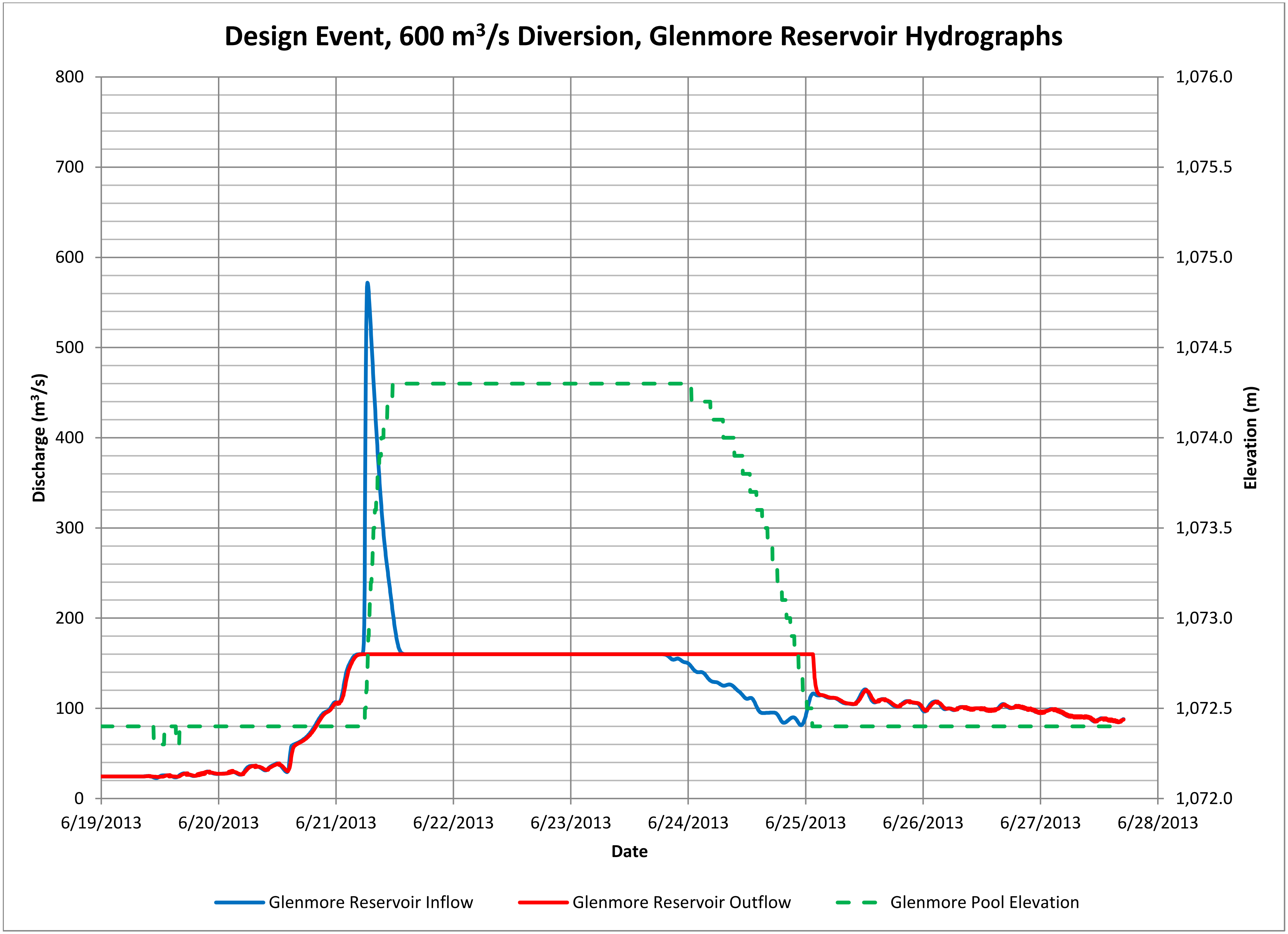

PMF Event, Normal Operation, Diversion Structure Hydrographs
3000
2500
2000
1500
1000
500
0
120,000
100,000
80,000
60,000
40,000
20,000
0
Discharge (m³/s)
Volume (dam³)
6/5/2010
6/6/2010
6/7/2010
6/8/2010
6/9/2010
6/10/2010
6/11/2010
6/12/2010
Date
Total Inflow
Diversion Flow
River Flow Below Diversion
Cumulative Diversion Volume

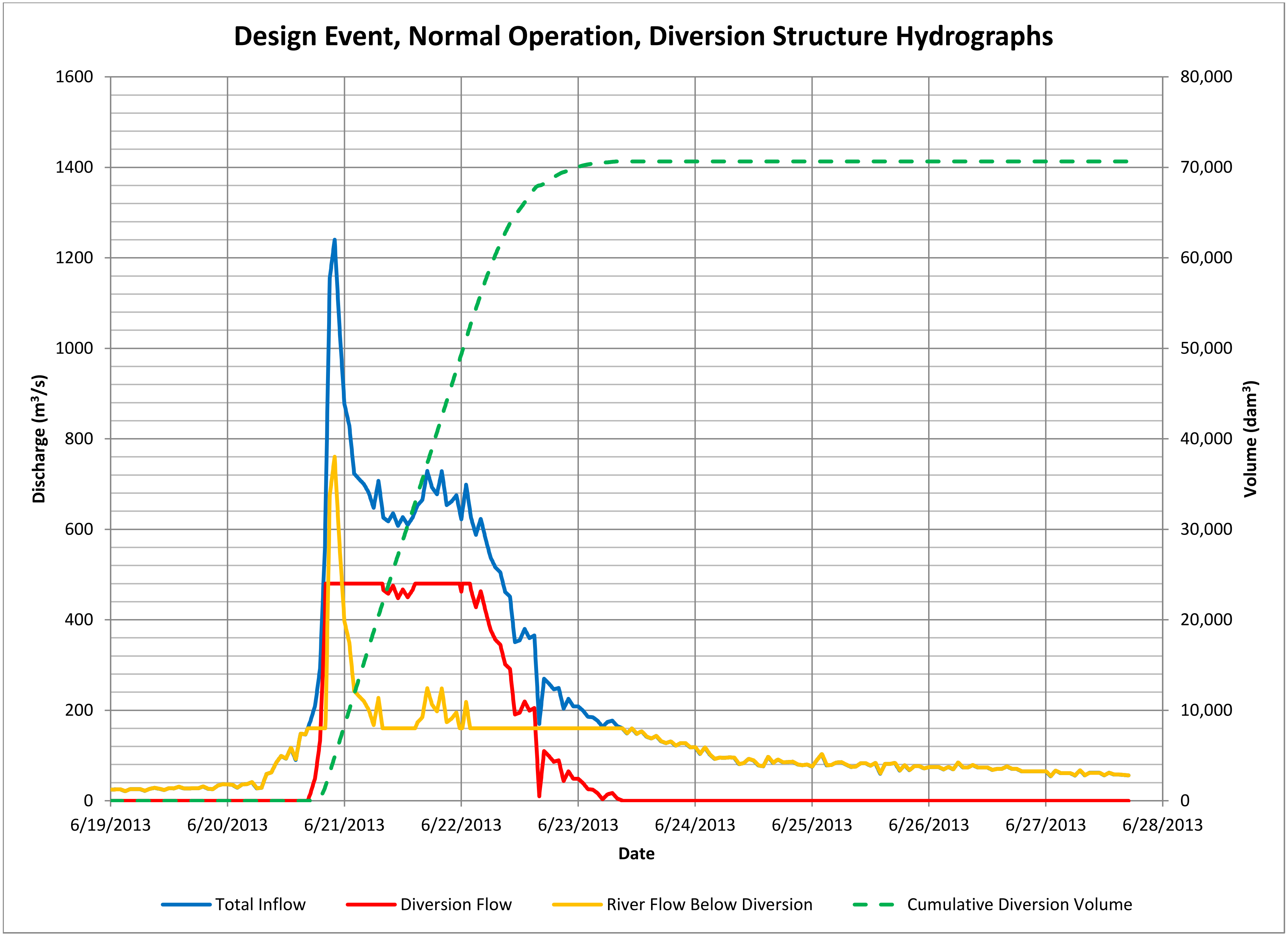


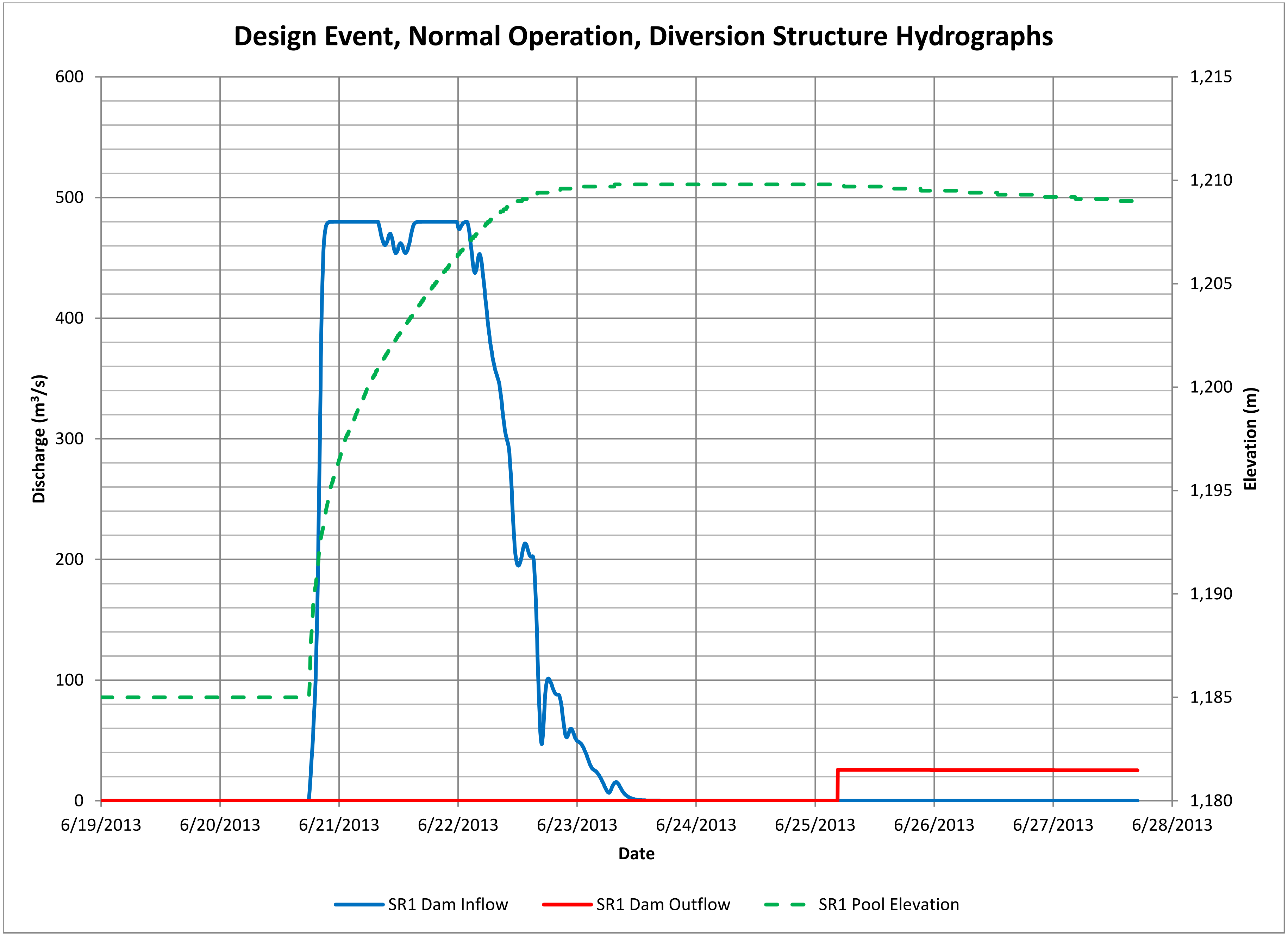
Design Event, 600 m³/s Diversion, Diversion Structure Hydrographs
Discharge (m³/s)
Volume (dam³)
Date
0
200
400
600
800
1000
1200
1400
1600
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
6/19/2013
6/20/2013
6/21/2013
6/22/2013
6/23/2013
6/24/2013
6/25/2013
6/26/2013
6/27/2013
6/28/2013
Total Inflow
Diversion Flow
River Flow Below Diversion
Cumulative Diversion Volume



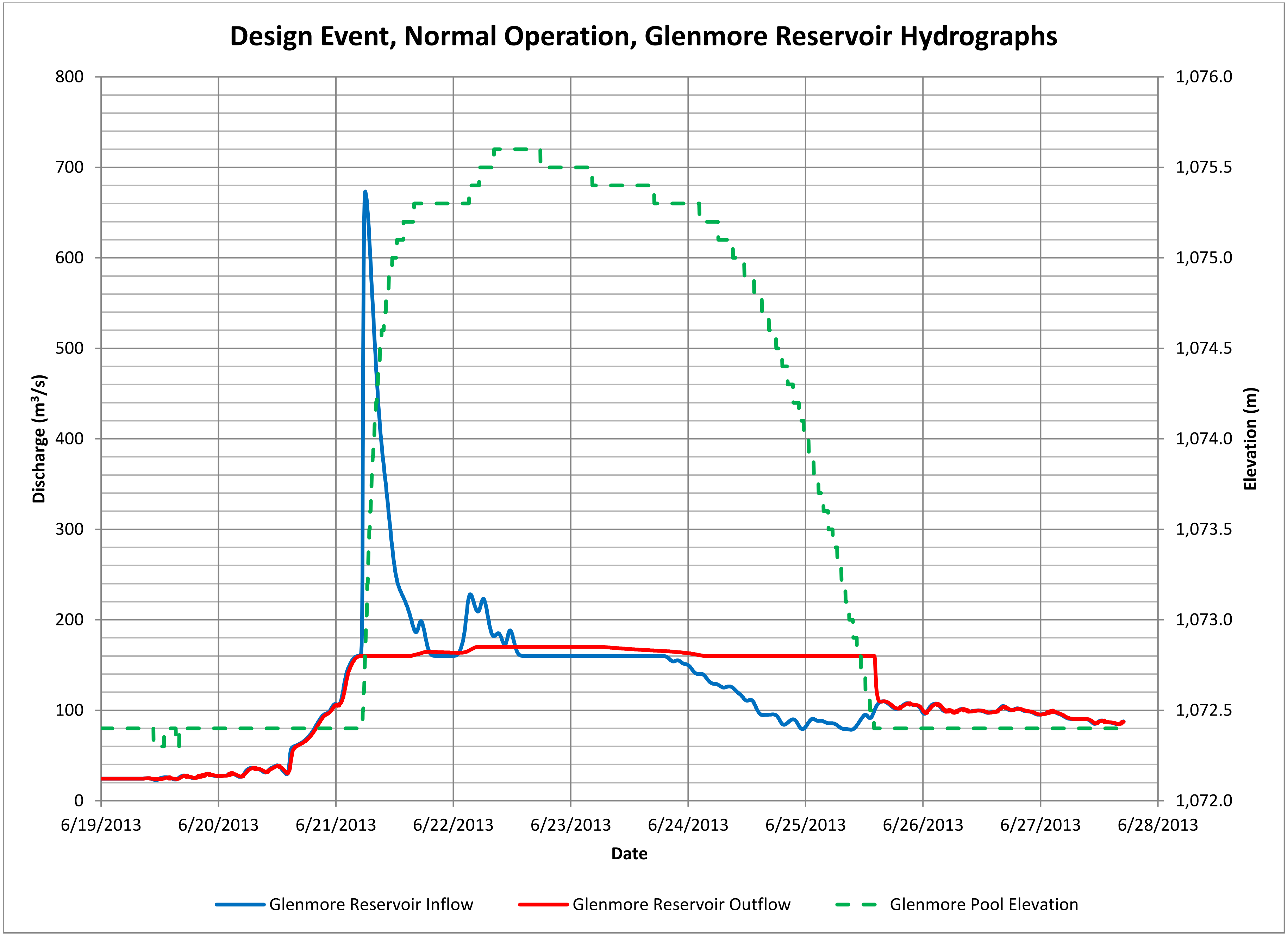
Design Event, 600 m³/s Diversion, Diversion Structure Hydrographs
700
600
500
400
300
200
100
0
1,215
1,210
1,205
1,200
1,195
1,190
1,185
1,180
Discharge (m³/s)
Elevation (m)
6/19/2013
6/20/2013
6/21/2013
6/22/2013
6/23/2013
6/24/2013
6/25/2013
6/26/2013
6/27/2013
6/28/2013
Date
SR1 Dam Inflow
SR1 Dam Outflow
SR1 Pool Elevation


Design Event, 600 m³/s Diversion, Glenmore Reservoir Hydrographs
Discharge (m³/s)
800
700
600
500
400
300
200
100
0
Elevation (m)
1,076.0
1,075.5
1,075.0
1,074.5
1,074.0
1,073.5
1,073.0
1,072.5
1,072.0
6/19/2013
6/20/2013
6/21/2013
6/22/2013
6/23/2013
6/24/2013
6/25/2013
6/26/2013
6/27/2013
6/28/2013
Date
Glenmore Reservoir Inflow
Glenmore Reservoir Outflow
Glenmore Pool Elevation


Design Event, Normal Operation, Diversion Structure Hydrographs
Discharge (m³/s)
Volume (dam³)
1600
1400
1200
1000
800
600
400
200
0
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
6/19/2013
6/20/2013
6/21/2013
6/22/2013
6/23/2013
6/24/2013
6/25/2013
6/26/2013
6/27/2013
6/28/2013
Date
Total Inflow
Diversion Flow
River Flow Below Diversion
Cumulative Diversion Volume



Design Event, Normal Operation, Diversion Structure Hydrographs
Discharge (m³/s)
Elevation (m)
Date
0
100
200
300
400
500
600
1,180
1,185
1,190
1,195
1,200
1,205
1,210
1,215
6/19/2013
6/20/2013
6/21/2013
6/22/2013
6/23/2013
6/24/2013
6/25/2013
6/26/2013
6/27/2013
6/28/2013
SR1 Dam Inflow
SR1 Dam Outflow
SR1 Pool Elevation



Design Event, Normal Operation, Glenmore Reservoir Hydrographs
Discharge (m³/s)
Elevation (m)
800
700
600
500
400
300
200
100
0
1,076.0
1,075.5
1,075.0
1,074.5
1,074.0
1,073.5
1,073.0
1,072.5
1,072.0
6/19/2013
6/20/2013
6/21/2013
6/22/2013
6/23/2013
6/24/2013
6/25/2013
6/26/2013
6/27/2013
6/28/2013
Date
Glenmore Reservoir Inflow
Glenmore Reservoir Outflow
Glenmore Pool Elevation

APPENDIX B.7 – RESERVOIR LOCAL RUNOFF HEC-HMS MODEL

Springbank Off-Stream Reservoir Project
Local Runoff HEC-HMS Model

Prepared for:
Alberta Transportation
3rd Floor – Twin Atria Building
4999 – 98 Avenue
Edmonton, AB T6B 2X3

Prepared by:
Stantec Consulting Services Ltd
Calgary, AB

Project 110773396

September 19, 2019

Sign-off Sheet

This document entitled Springbank Off-Stream Reservoir Project Local Runoff HEC-HMS Model was prepared by Stantec Consulting Ltd. (“Stantec”) for the account of Alberta Transportation (the “Client”). Any reliance on this document by any third party is strictly prohibited. The material in it reflects Stantec’s professional judgment in light of the scope, schedule and other limitations stated in the document and in the contract between Stantec and the Client. The opinions in the document are based on conditions and information existing at the time the document was published and do not take into account any subsequent changes. In preparing the document, Stantec did not verify information supplied to it by others. Any use which a third party makes of this document is the responsibility of such third party. Such third party agrees that Stantec shall not be responsible for costs or damages of any kind, if any, suffered by it or any other third party as a result of decisions made or actions taken based on this document.

Prepared by ______________________________

(signature)

Daniel Hoffman, Senior Project Engineer

Approved by ______________________________

(signature)

John Menninger P.Eng., Senior Principal

Table of Contents

September 19, 2019

1.0 INTRODUCTION

The USACE HEC-HMS, version 4.2, software package (Reference 1) was used to compute local runoff contributing to the SR1 Reservoir and Diversion Channel without diversion operations. For design, this model is used to provide load case information for design of the SR1 Dam Low Level Outlet Works. This memo documents the development and results of the HEC-HMS model. This memo is part of Appendix B.7 to the preliminary design report.

2.0 MODEL GEOMETRY

The HEC-HMS model is comprised of six subbasins, six junctions, six reaches and one reservoir to simulate and route runoff from the contributing drainage areas to the Low Level Outlet Works (LLOW). A model schematic and detailed input data is included as an attachment to this memo.

Subbasins were delineated based on available existing conditions topographic data and the preliminary design CAD surfaces. Four subbasins were located along the Diversion Channel representing intercepted tributary streams. The Reservoir drainage area was divided into two subbasins representing runoff from upstream of the Diversion Channel outlet and runoff to the LLOW. The total contributing drainage area to the LLOW was delineated as approximately 40.7 km2. Runoff was computed based on methodology outlined in the US Soil Conservation Service (SCS) Technical Release 55: Urban Hydrology for Small Watersheds (Reference 2). The predominant soil group in the study area is Type D and the predominant land use is pasture, grassland or range. From SCS guidance for the soil group and land use, all subbasins were assumed to have a Curve Number of 80. Lag times were computed according to SCS guidance and calculations are attached at the end of this memo.

Reach routing between junctions in HEC-HMS was computed using the Kinematic Wave methodology. Each reach was approximated as a trapezoidal channel with cross sectional dimensions estimated from the preliminary design or existing topography. Slopes and lengths for each reach were measured based on topographic data and all were assumed to have a Manning's roughness of 0.038.

The stage-storage curve for the reservoir node was based on the geometry of the preliminary design. The rating curve for the LLOW was developed as part of hydraulic design calculations. The stage-storage curve and outlet rating curve are provided as attachments.

3.0 BOUNDARY CONDITIONS

Runoff simulations were computed for the 10-year, 24-hour event and the 2-year 24-hour event. According to rainfall intensity data developed at the Calgary International Airport, the 10-year, 24-hour precipitation depth is 65 mm and the 2-year 24-hour precipitation depth is 38 mm (Reference 3). An SCS Type II hyetograph shape was applied to the storm (Reference 2).

The downstream boundary was the orifice outlet with free outfall from reservoir representing the SR1 dam and LLOW.

4.0 RESULTS

Results from the HEC-HMS model are used as a structure design case for the LLOW. Based on the HEC-HMS model, the peak inflow to the LLOW during the 10-year, 24-hour event is 62.3 m^3/s, the maximum storage elevation upstream of the LLOW is 1191.8 m and the maximum discharge is 10.1 m^3/s. Inflow to the LLOW during the 2-year, 24-hour event is 15.1 m^3/s, the maximum storage elevation upstream of the LLOW is 1189.8 m and the maximum discharge is 7.0 m^3/s. Flow and stage hydrograph results are presented for the 10-year, 24-hour and 2-year, 24-hour simulations as attachments to this memo.

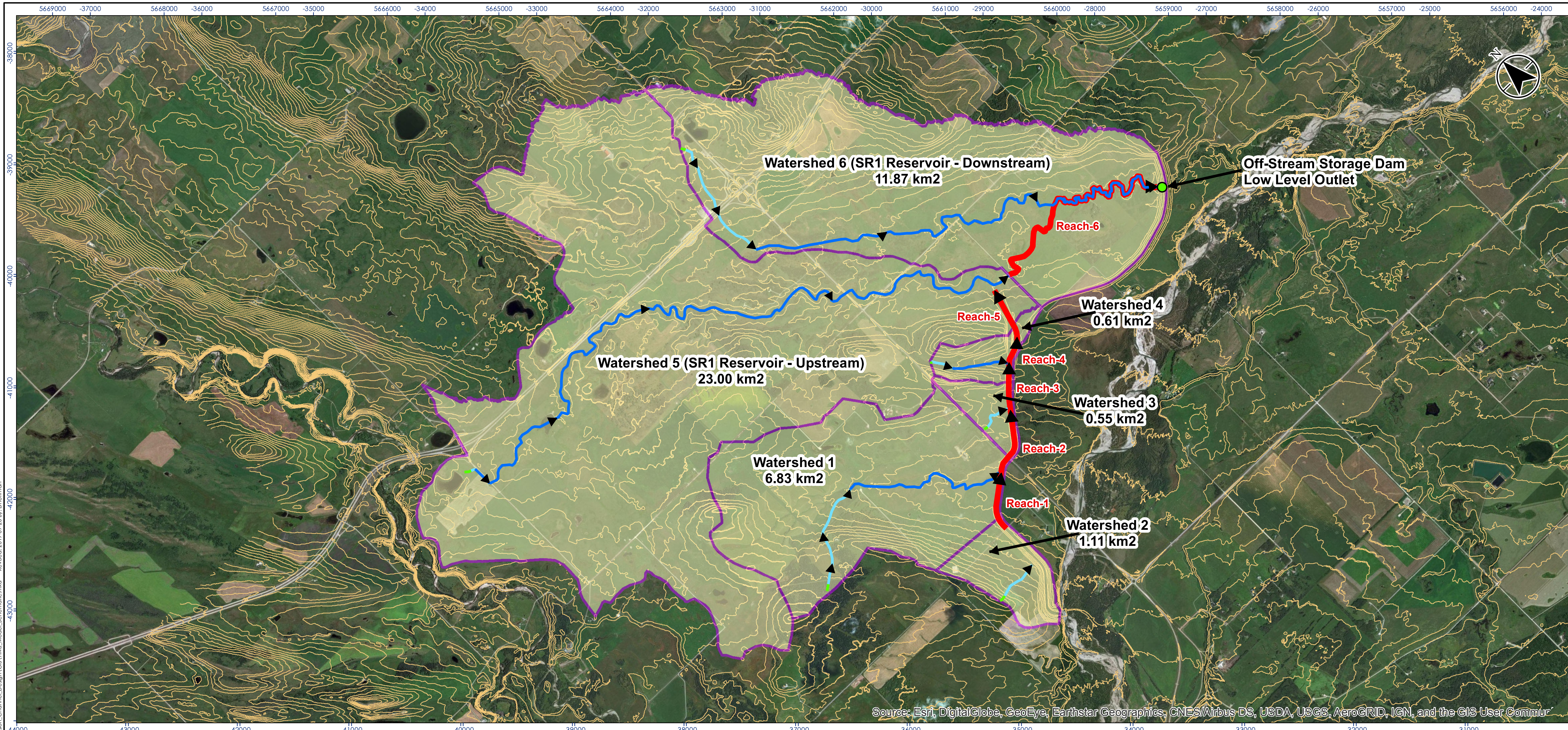
5.0 REFERENCES

U.S. Army Corps of Engineers. (2016). Hydrologic Modeling System (HEC-HMS), Version 4.2. Hydrologic Engineering Center, Davis, CA.

U.S. Soil Conservation Service. (1986). Technical Release 55: Urban Hydrology for Small Watersheds. U.S. Department of Agriculture.

Environment Canada. (2012). Environment Canada Depth-Duration-Frequency data for Calgary International Airport (WMO Station #3031093).

APPENDIX B.7-1 – MODEL LAYOUT



Legend

- Routing Reach Centerlines
- Subbasins
- Elevation Contours (5 m Interval)

Flow Paths for Lag Time Calculation

- Open Channel Flow
- Overland Flow
- Shallow Concentrated Flow

0 300 600
Meters

1:50,000 (At original document size of 11x17)

Stantec

Project Location
City of Calgary
Alberta

110773396
Prepared by DEH on 2017-02-27
Technical Review by DTH on 2017-02-27

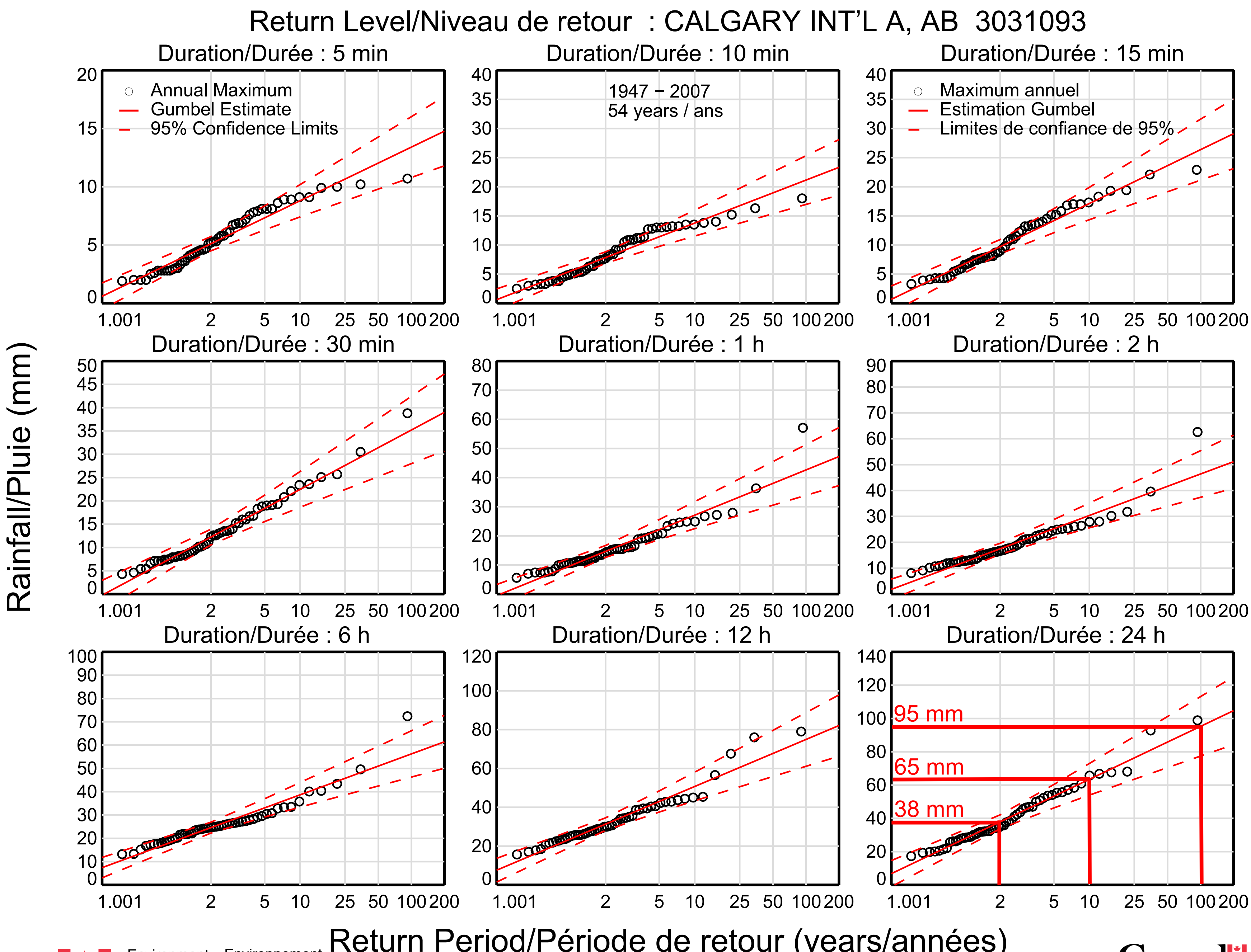
Client/Project
Alberta Transportation
Springbank Off-Stream Reservoir (SR1)

Figure No.
1 of 1

Title
Off-Stream Storage Dam Local Runoff HEC-HMS Model Layout

Notes

1. Coordinate System: NAD 1983 3TM 114



Environment Canada Environnement Canada

2012/02/09

Canada

Reservoir Runoff - Lag Time Calculations

Springbank Off-Stream Reservoir Project
Alberta, Canada
Alberta Transportation Department

1. OBJECTIVE/PURPOSE

The objective of this calculation package is to document the lag time calculations for the reservoir runoff model in order to find a peak discharge at the Low Level Outlet Works for the Springbank Off-Stream Diversion project.

2. CRITERIA

1. Precipitation depth based on 2-year, 24-hour rainfall event.

2. Time of concentration values based on longest flow path within each watershed.

3. Manning's roughness coefficients, n, from TR-55 document.

3. REFERENCES

1. USDA (June 1986). Urban Hydrology for Small Watersheds, Technical Release 55 (TR-55). United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), Conservation Engineering Division.

Low Flow Diversion Channel - Reservoir Runoff

Calculations based on TR-55 document.

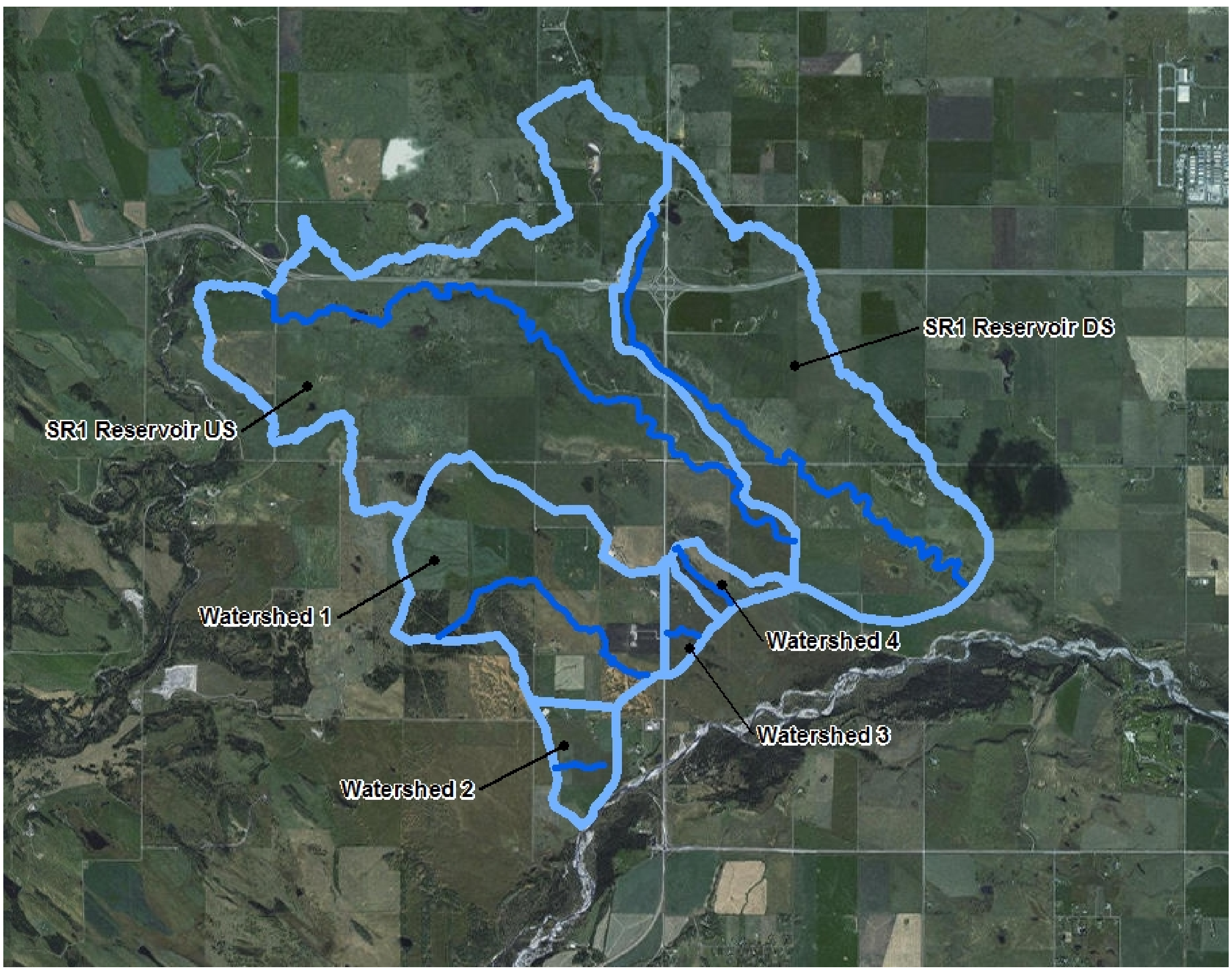
Assumptions:

Precipitation data obtained from the average line on IDF curves for 2-year, 24-hour duration storm.

Units converted from SI to US in order to be used in the equations.

4. DATA PROVIDED

Watersheds shown in configuration below:



5. CALCULATIONS

Watershed 1

Sheet Flow		Segment ID	17
1. Surface description			Woods, light underbrush
2. Manning's roughness coef., n			0.4
3. Flow length, L (Total L less than 300/		ft	278.48
4. Two-year, 24-hour Rainfall, P2		in	1.50
5a. Upstream elevation		ft	4160.11
5b. Downstream elevation		ft	4157.81
5. Land slope, S		ft / ft	0.008
6. Tt = $[0.007(nL)^{0.8}]/[\text{sqrt}(P2)\ S^{0.4}]$		hr	1.69

TOTAL T_C = 1.69 HR

Shallow Concentrated Flow	Segment ID	15	14	13
7. Surface description (paved or unpaved)		Unpaved	Unpaved	Unpaved
8. Flow length, L	ft	885.11	1372.61	2209.51
9a. Upstream elevation	ft	4157.81	4146.98	4084.65
9b. Downstream elevation	ft	4146.98	4084.65	4014.76
9. Watercourse slope, S	ft / ft	0.012	0.045	0.032
10. Average velocity, V	ft / s	1.8	3.4	2.9
11. Tt = L / 3600V	hr	0.14	0.11	0.21

TOTAL T_C = 0.46 HR

Open Channel Flow	Segment ID	10
12. Pipe or Open Channel		Open-channel
13. Diam (pipe) or depth (open)	ft	2.30
14. Base width (open)	ft	6.56
15. Channel side slope	XH:1V	3
16. Cross sectional flow area, a	ft2	30.89
17. Wetted perimeter, Pw	ft	21.09
18. Hydraulic radius, r = a/Pw	ft	1.47
19a. Upstream elevation	ft	4014.76
19b. Downstream elevation	ft	3968.50
19. Channel slope, S	ft / ft	0.006
20. Runoff surface / pipe material		earth, winding, grass weeds
21. Manning's roughness coef., n		0.03
22. V= $(1.49\ r^{2/3}\ S^{1/2} / n)$	ft / s	5.05
23. Flow length, L	ft	7434.74
24. Tt = L / 3600V	hr	0.41

TOTAL T_C = 0.41 HR

25. Watershed Tc (sum Tt from 6, 11, 24) **2.56** **HR**

26. Watershed lag time, TL (=0.6 x Tc) **1.54** **HR**

Watershed 2

Sheet Flow	Segment ID	8	9
1. Surface description		Grass, short prairi	Grass, short prairie
2. Manning's roughness coef., n		0.15	0.15
3. Flow length, L (Total L less than 300/	ft	96.69	188.88
4. Two-year, 24-hour Rainfall, P2	in	1.50	1.50
5a. Upstream elevation	ft	4163.39	4160.11
5b. Downstream elevation	ft	4160.11	4130.58
5. Land slope, S	ft / ft	0.034	0.156
6. Tt = $[0.007(nL)^{0.8}]/[sqrt(P2)\ S^{0.4}]$	hr	0.19	0.17

TOTAL T_C = 0.36 HR

Shallow Concentrated Flow	Segment ID	7
7. Surface description (paved or unpaved)		Unpaved
8. Flow length, L	ft	1754.89
9a. Upstream elevation	ft	4130.58
9b. Downstream elevation	ft	4032.15
9. Watercourse slope, S	ft / ft	0.056
10. Average velocity, V	ft / s	3.8
11. Tt = L / 3600V	hr	0.13

TOTAL T_C = 0.13 HR

Open Channel Flow (none)

25. Watershed Tc (sum Tt from 6, 11, 24) **0.49** **HR**

26. Watershed lag time, TL (=0.6 x Tc) **0.29** **HR**

Watershed 3

Sheet Flow	Segment ID	18
1. Surface description		Grass, short prairie
2. Manning's roughness coef., n		0.15
3. Flow length, L (Total L less than 300/	ft	170.51
4. Two-year, 24-hour Rainfall, P2	in	1.50
5a. Upstream elevation	ft	4005.91
5b. Downstream elevation	ft	4002.62
5. Land slope, S	ft / ft	0.019
6. Tt = $[0.007(nL)^{0.8}]/[\text{sqrt}(P2)\ S^{0.4}]$	hr	0.37

TOTAL T_C = 0.37 HR

Shallow Concentrated Flow	Segment ID	12
7. Surface description (paved or unpaved)		Unpaved
8. Flow length, L	ft	1303.38
9a. Upstream elevation	ft	4002.62
9b. Downstream elevation	ft	3971.46
9. Watercourse slope, S	ft / ft	0.024
10. Average velocity, V	ft / s	2.5
11. Tt = L / 3600V	hr	0.15

TOTAL T_C = 0.15 HR

Open Channel Flow (none)

25. Watershed Tc (sum Tt from 6, 11, 24) **0.52 HR**

26. Watershed lag time, TL (=0.6 x Tc) **0.31 HR**

Watershed 4

Sheet Flow	Segment ID	19
1. Surface description		Woods, light underbrush
2. Manning's roughness coef., n		0.4
3. Flow length, L (Total L less than 300/	ft	97.38
4. Two-year, 24-hour Rainfall, P2	in	1.50
5a. Upstream elevation	ft	4006.23
5b. Downstream elevation	ft	4003.28
5. Land slope, S	ft / ft	0.030
6. Tt = $[0.007(nL)^{0.8}]/[\text{sqrt}(P2)\ S^{0.4}]$	hr	0.43

TOTAL T_C = 0.43 HR

Shallow Concentrated Flow	Segment ID	16
7. Surface description (paved or unpaved)		Unpaved
8. Flow length, L	ft	932.05
9a. Upstream elevation	ft	4003.28
9b. Downstream elevation	ft	4002.62
9. Watercourse slope, S	ft / ft	0.001
10. Average velocity, V	ft / s	0.4
11. Tt = L / 3600V	hr	0.60

TOTAL T_C = 0.60 HR

Open Channel Flow	Segment ID	11
12. Pipe or Open Channel		Open-channel
13. Diam (pipe) or depth (open)	ft	0.66
14. Base width (open)	ft	6.56
15. Channel side slope	XH:1V	3
16. Cross sectional flow area, a	ft2	5.60
17. Wetted perimeter, Pw	ft	10.71
18. Hydraulic radius, r = a/Pw	ft	0.52
19a. Upstream elevation	ft	4002.62
19b. Downstream elevation	ft	3952.43
19. Channel slope, S	ft / ft	0.021
20. Runoff surface / pipe material		earth, winding, grass weeds
21. Manning's roughness coef., n		0.03
22. V= $(1.49\ r^{2/3}\ S^{1/2}\ /\ n)$	ft / s	4.70
23. Flow length, L	ft	2356.59
24. Tt = L / 3600V	hr	0.14

TOTAL T_C = 0.14 HR

25. Watershed Tc (sum Tt from 6, 11, 24) **1.18** **HR**

26. Watershed lag time, TL (=0.6 x Tc) **0.71** **HR**

Watershed 5 (SR1 Reservoir - Upstream)

Sheet Flow	Units	Segment ID 1
1. Surface description		Grass, short prairie
2. Manning's roughness coef., n		0.15
3. Flow length, L (Total L less than 300/	ft	292.62
4. Two-year, 24-hour Rainfall, P2	in	1.50
5a. Upstream elevation	ft	4065.95
5b. Downstream elevation	ft	4064.63
5. Land slope, S	ft / ft	0.004
6. Tt = $[0.007(nL)^{0.8}]/[\text{sqrt}(P2)\ S^{0.4}]$	hr	1.03

TOTAL T_C = 1.03 HR

Shallow Concentrated Flow	Units	Segment ID 2
7. Surface description (paved or unpaved)		Unpaved
8. Flow length, L	ft	187.66
9a. Upstream elevation	ft	4064.63
9b. Downstream elevation	ft	4061.02
9. Watercourse slope, S	ft / ft	0.019
10. Average velocity, V	ft / s	2.2
11. Tt = L / 3600V	hr	0.02

TOTAL T_C = 0.02 HR

Open Channel Flow	Segment ID	3	4	5	0	6
12. Pipe or Open Channel		Open-channel	Open-channel	Open-channel	Open-channel	Open-channel
13. Diam (pipe) or depth (open)	ft	2.95	2.95	3.28	2.95	2.95
14. Base width (open)	ft	9.84	9.84	9.84	9.84	11.48
15. Channel side slope	XH:1V	3	4	5	6	7
16. Cross sectional flow area, a	ft2	55.22	63.94	86.11	81.38	94.94
17. Wetted perimeter, Pw	ft	28.52	34.19	43.30	45.76	53.24
18. Hydraulic radius, r = a/Pw	ft	1.94	1.87	1.99	1.78	1.78
19a. Upstream elevation	ft	4061.02	4054.79	4019.36	3992.78	3942.59
19b. Downstream elevation	ft	4054.79	4019.36	3992.78	3942.59	3918.64
19. Channel slope, S	ft / ft	0.007	0.008	0.003	0.005	0.003
20. Runoff surface / pipe material		earth, winding, grass w	, winding, grass w	, winding, grass w	, winding, grass w	, winding, grass w
21. Manning's roughness coef., n		0.03	0.03	0.03	0.03	0.03
22. V= $(1.49\ r^{2/3}\ S^{1/2} / n)$	ft / s	6.58	6.64	4.45	5.14	3.69
23. Flow length, L	ft	856.33	4560.50	8277.66	10114.17	9360.63
24. Tt = L / 3600V	hr	0.04	0.19	0.52	0.55	0.70

TOTAL T_C = 1.99 HR

25. Watershed Tc (sum Tt from 6, 11, 24) **3.04** **HR**

26. Watershed lag time, TL (=0.6 x Tc) **1.83** **HR**

Watershed 6 (SR1 Reservoir - Downstream)

Sheet Flow		Segment ID	21
1. Surface description			Grass, short prairie
2. Manning's roughness coef., n			0.15
3. Flow length, L (Total L less than 300/	ft		208.66
4. Two-year, 24-hour Rainfall, P2	in		1.50
5a. Upstream elevation	ft		4120.74
5b. Downstream elevation	ft		4117.45
5. Land slope, S	ft / ft		0.016
6. Tt = $[0.007(nL)^{0.8}]/[sqrt(P2)\ S^{0.4}]$	hr		0.47

TOTAL T_C = 0.47 HR

Shallow Concentrated Flow	Segment ID	22	23	24
7. Surface description (paved or unpaved)		Unpaved	Unpaved	Unpaved
8. Flow length, L	ft	994.09	2202.10	2139.76
9a. Upstream elevation	ft	4117.45	4080.05	4030.84
9b. Downstream elevation	ft	4080.05	4030.84	3986.88
9. Watercourse slope, S	ft / ft	0.038	0.022	0.021
10. Average velocity, V	ft / s	3.1	2.4	2.3
11. Tt = L / 3600V	hr	0.09	0.25	0.26

TOTAL T_C = 0.60 HR

Open Channel Flow	Segment ID	25	26	20
12. Pipe or Open Channel		Open-channel	Open-channel	Open-channel
13. Diam (pipe) or depth (open)	ft	2.62	3.28	3.28
14. Base width (open)	ft	6.56	6.56	11.48
15. Channel side slope	XH:1V	3	3	3
16. Cross sectional flow area, a	ft2	37.89	53.82	69.97
17. Wetted perimeter, Pw	ft	23.16	27.31	32.23
18. Hydraulic radius, r = a/Pw	ft	1.64	1.97	2.17
19a. Upstream elevation	ft	3986.88	3946.19	3910.76
19b. Downstream elevation	ft	3946.19	3910.76	3897.31
19. Channel slope, S	ft / ft	0.007	0.004	0.002
20. Runoff surface / pipe material		earth, winding, grass w	, winding, grass w	, winding, grass w
21. Manning's roughness coef., n		0.03	0.03	0.03
22. V= $(1.49\ r^{2/3}\ S^{1/2} / n)$	ft / s	5.83	4.99	3.27
23. Flow length, L	ft	5681.43	8677.82	8712.60
24. Tt = L / 3600V	hr	0.27	0.48	0.74

TOTAL T_C = 1.49 HR

25. Watershed Tc (sum Tt from 6, 11, 24) **2.57** HR

26. Watershed lag time, TL (=0.6 x Tc) **1.54** HR

Table 2-2c Runoff curve numbers for other agricultural lands [1]

Cover description: Cover type	Hydrologic condition	Curve numbers for hydrologic soil group: A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.
2 *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.
3 *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.
4 Actual curve number is less than 30; use CN = 30 for runoff computations.
5 CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.
6 *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

SR1 Reservoir Low Level Outlet Discharge Rating Curve Developed by Stantec for Preliminary Design

Elevation (m)	Low Level Outlet Discharge (m^3/s)	
1187.00	0.0	
1187.32	0.5	
1187.47	1.0	
1187.59	1.5	
1187.70	2.0	
1187.82	2.5	
1187.93	3.0	
1188.05	3.5	
1188.18	4.0	
1188.30	4.5	
1188.55	5.0	
1188.87	5.5	
1189.16	6.0	
1189.50	6.5	
1190.48	8.0	
1191.48	9.5	
1192.48	11.0	
1193.48	12.4	
1194.48	13.6	
1195.48	14.7	
1196.48	15.7	
1198.48	17.5	
1200.48	19.2	
1202.48	20.8	
1204.48	22.2	
1206.48	23.6	
1208.48	24.9	
1211.23	26.5	
1212.00	27.0	<-- Discharge Linearly Extrapolated

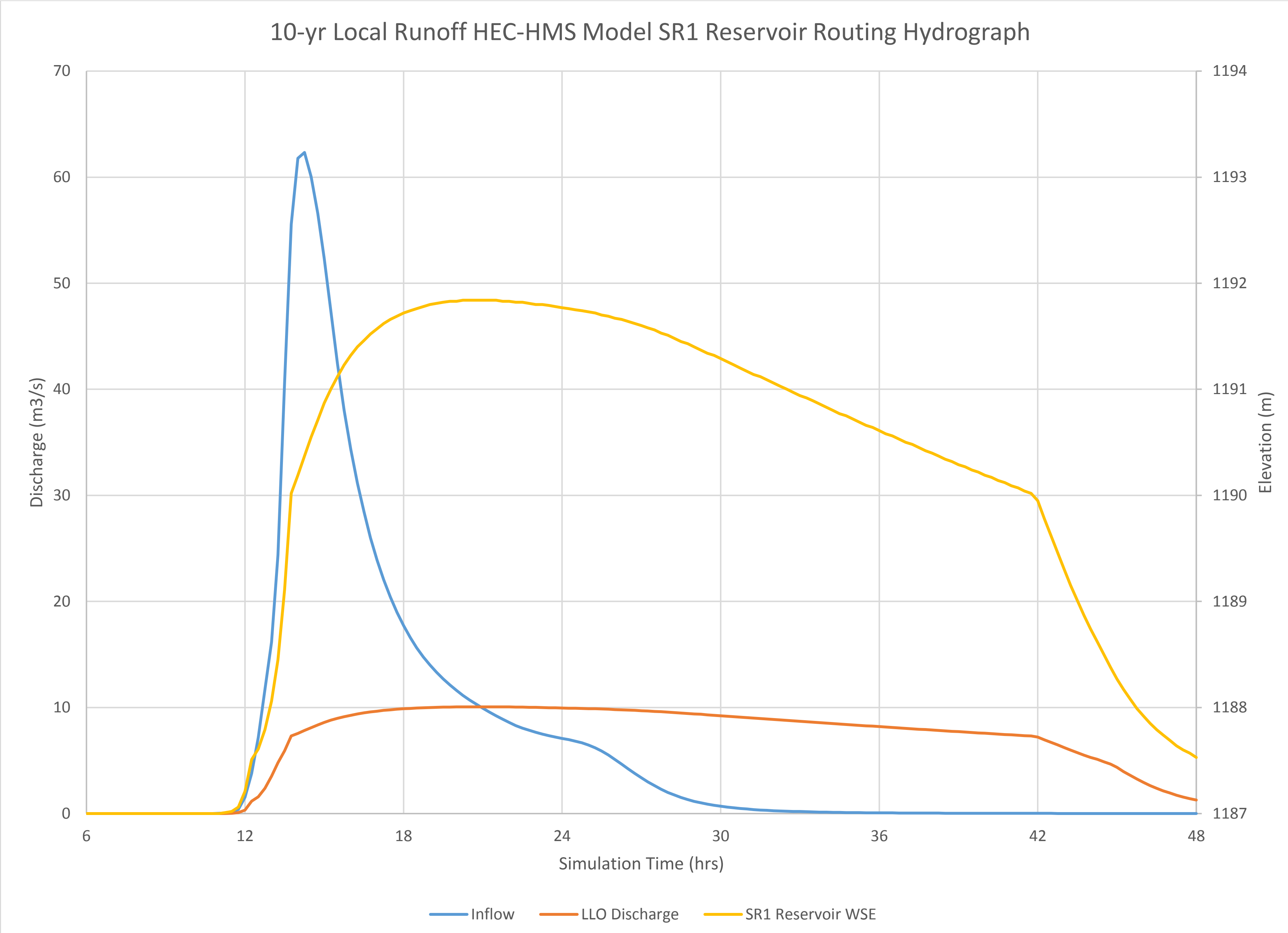
SR1 Off-Stream Storage Dam Local Runoff HEC-HMS Model Reach Routing Parameters

Name	Routing Method	Length (m)	Slope (m/m)	Manning's n	Subreaches	Shape	Bottom Width (m)	Side Slope H:V
Reach-1	Kinematic Wave	754	0.001	0.038	2	Trapezoid	22	4
Reach-2	Kinematic Wave	850	0.0013	0.038	2	Trapezoid	22	4
Reach-3	Kinematic Wave	608	0.002	0.038	2	Trapezoid	22	4
Reach-4	Kinematic Wave	339	0.002	0.038	2	Trapezoid	22	4
Reach-5	Kinematic Wave	658	0.012	0.038	2	Trapezoid	86	4
Reach-6	Kinematic Wave	3,803	0.0024	0.038	2	Trapezoid	10	3

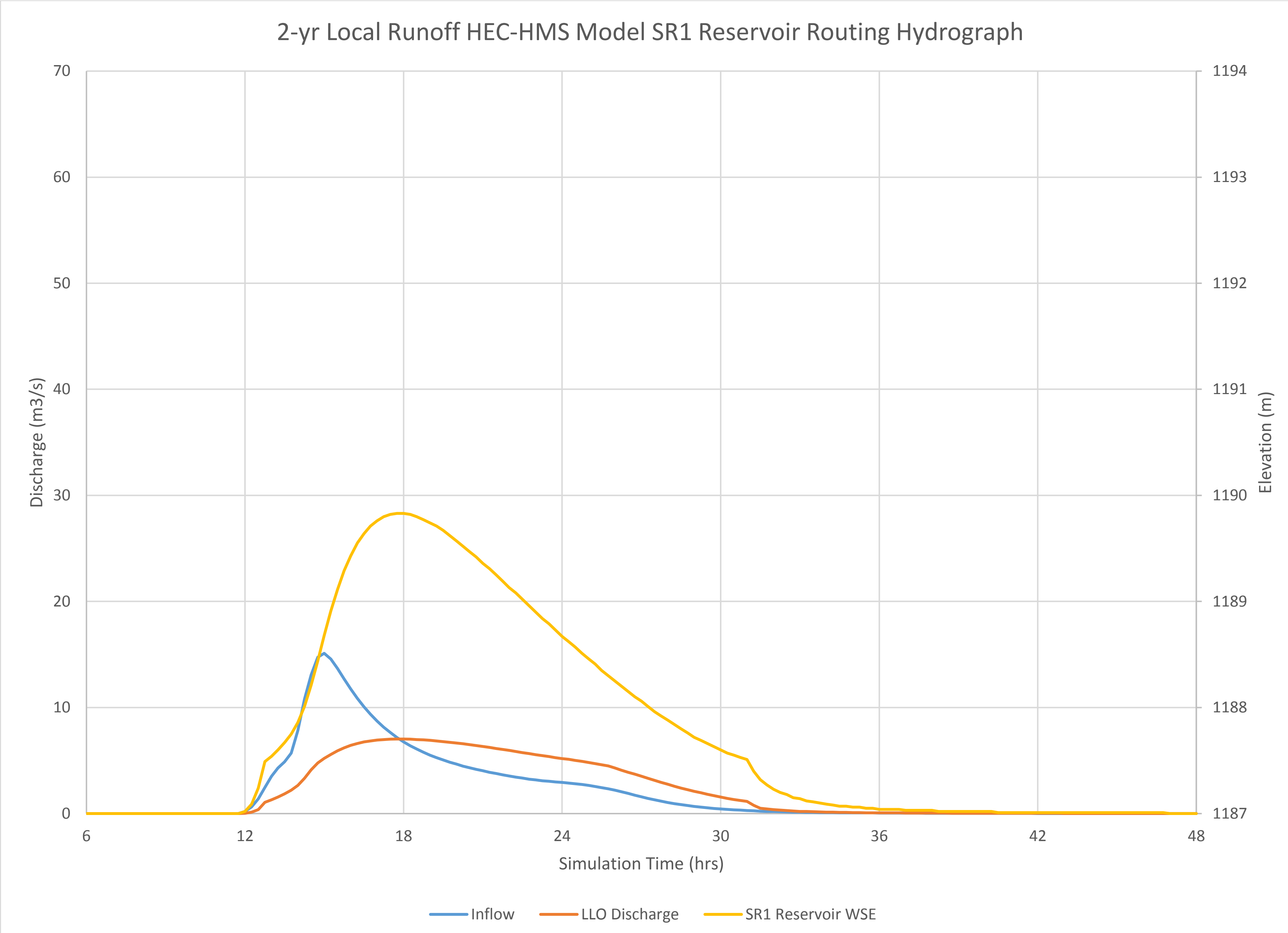
SR1 Reservoir Stage-Storage Curve Developed by Stantec for Preliminary Design

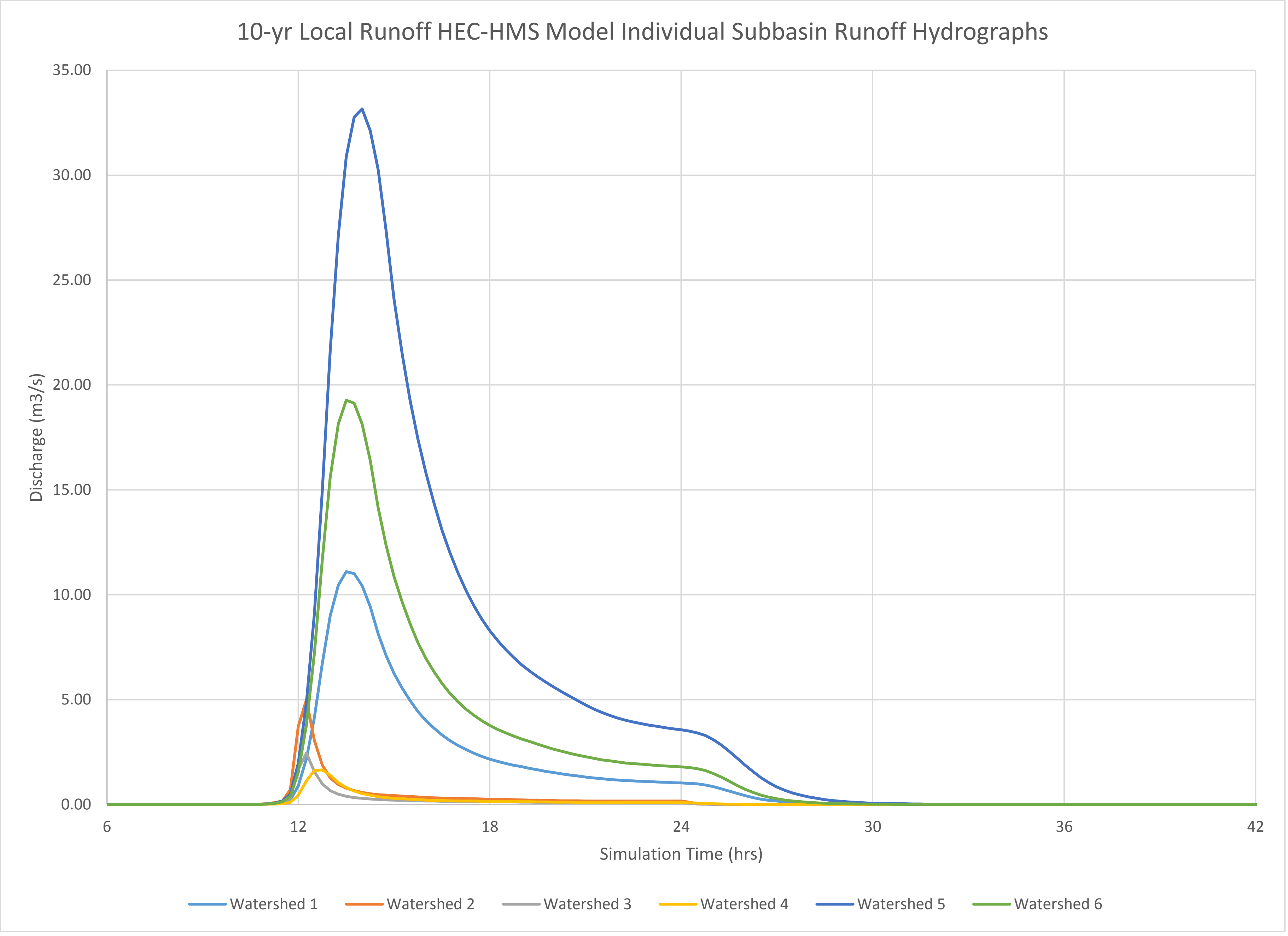
Elevation (m)	Cumulative Volume (m^3)	Cumulative Volume (dam^3)
1185.00	0	0.0
1187.50	11,172	11.2
1190.00	103,666	103.7
1192.50	777,616	777.6
1195.00	3,994,270	3,994.3
1197.50	9,514,791	9,514.8
1200.00	17,336,794	17,336.8
1201.00	21,174,761	21,174.8
1202.00	25,410,700	25,410.7
1203.00	30,008,129	30,008.1
1204.00	34,956,733	34,956.7
1205.00	40,271,381	40,271.4
1206.00	45,952,704	45,952.7
1207.00	51,998,954	51,999.0
1208.00	58,396,731	58,396.7
1209.00	65,163,646	65,163.6
1210.00	72,291,738	72,291.7
1211.00	79,798,750	79,798.8
1212.00	87,683,872	87,683.9
1213.00	95,952,123	95,952.1
1214.00	104,595,976	104,596.0
1215.00	113,585,508	113,585.5

APPENDIX B.7-2 – RESULTS



10-yr Local Runoff HEC-HMS Model SR1 Reservoir Routing Hydrograph
Discharge (m3/s)
70
60
50
40
30
20
10
0
Elevation (m)
1194
1193
1192
1191
1190
1189
1188
1187
6
12
18
24
30
36
42
48
Simulation Time (hrs)
Inflow
LLO Discharge
SR1 Reservoir WSE


2-yr Local Runoff HEC-HMS Model SR1 Reservoir Routing Hydrograph
Discharge (m3/s)
Elevation (m)
Simulation Time (hrs)
70
60
50
40
30
20
10
0
1194
1193
1192
1191
1190
1189
1188
1187
6
12
18
24
30
36
42
48
Inflow
LLO Discharge
SR1 Reservoir WSE



10-yr Local Runoff HEC-HMS Model Individual Subbasin Runoff Hydrographs
Discharge (m3/s)
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
6
12
18
24
30
36
42
Simulation Time (hrs)
Watershed 1
Watershed 2
Watershed 3
Watershed 4
Watershed 5
Watershed 6