UPDATING PMP FOR THE ELBOW RIVER: COMPLEX TERRAIN, UNIQUE SOLUTIONS

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ABSTRACT

The devastating floods during June 2013 raised awareness of the risk to infrastructure. Stantec engaged Applied Weather Associates (AWA) to develop PMP values for the Elbow River basin upstream of Glenmore Reservoir and the City of Calgary to understand the flood hydrology of the Elbow River basin and develop design criteria for the Springbank Off-stream Storage Project. PMP studies have been completed in the region from the 1980's through the early 2000's. However, these included limited storm data, outdated methodologies, and did not include several recent extreme storm events, including June of 2005 and June of 2013. AWA has been completing PMP studies for more than 20 years across North America. The data, knowledge, and methods developed during previous and ongoing PMP studies were applied by AWA to produce reliable, reproducible and scientifically defensible PMP values. This work included important collaboration with flood hydrologists and oversight from an independent review board. The direct involvement with hydrologists and other experts ensured appropriate application of the results in the process of determining reasonable site-specific PMP for the basin. This presentation will detail how the PMP was developed in a region of complex terrain and how appropriate applications were provided for a basin with a unique set of requirements for the hydrologic modeling.

RÉSUMÉ

Les inondations dévastatrices de juin 2013 ont causé une prise de conscience quant au risque pour les infrastructures. Stantec a engagé Applied Weather Associates (AWA) pour développer des valeurs PMP pour le bassin de la rivière Elbow en amont du réservoir Glenmore et de la Ville de Calgary afin de comprendre l'hydrologie des crues du bassin de la rivière Elbow et de développer des critères de conception pour le projet Springbank Off-stream Storage. Des études PMP ont été réalisées dans la région à partir des années 1980 jusqu'au début des années 2000. Cependant, celles-ci comprenaient des données partielles de tempête ainsi que des méthodes obsolètes et elles ne considéraient pas plusieurs événements récents de tempêtes extrêmes, y compris celles de juin 2005 et de juin 2013. La firme AWA a réalisé depuis plus de 20 ans des études PMP en Amérique du Nord. Les données, les connaissances et les méthodes développées au cours des études de PMP antérieures et actuellement en cours ont été appliquées par AWA afin de produire des valeurs de PMP fiables, reproductibles et scientifiquement défendables. Ce travail comprenait une collaboration étroite avec des hydrologues pour les inondations et une supervision par un comité d'experts indépendants. L'implication directe avec les hydrologues et d'autres experts a assuré l'application appropriée des résultats dans le processus de détermination de la PMP appropriée pour ce bassin. Ce document détaillera comment la PMP a été développée dans une région de terrain complexe et comment les applications appropriées ont été fournies pour un bassin avec un ensemble unique d'exigences quant à la modélisation hydrologique.

1 GENERAL

Applied Weather Associates (AWA) has completed a 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 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 AWA has completed, 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 kilometres) or local storms (6-hours or less and less than 500-square kilometres). 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 PMP becomes the maximum TAR for all analyzed storms at each grid cell at each duration.

$$TAR_{xhr} = P_{xhr} * IPMF * MTF * OTF \quad (1)$$

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 kilometres), 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.

2 PMP DEVELOPMENT 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). In addition, generalized PMP studies in the contiguous United States relevant for the location include HMR

55A (1988) for the area between the Continental Divide and the 103rd meridian and HMR 57 (1994) for the Pacific Northwest states west of the Continental Divide.

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., 2008 and Kappel et al., 2012-2016) (Figure 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).

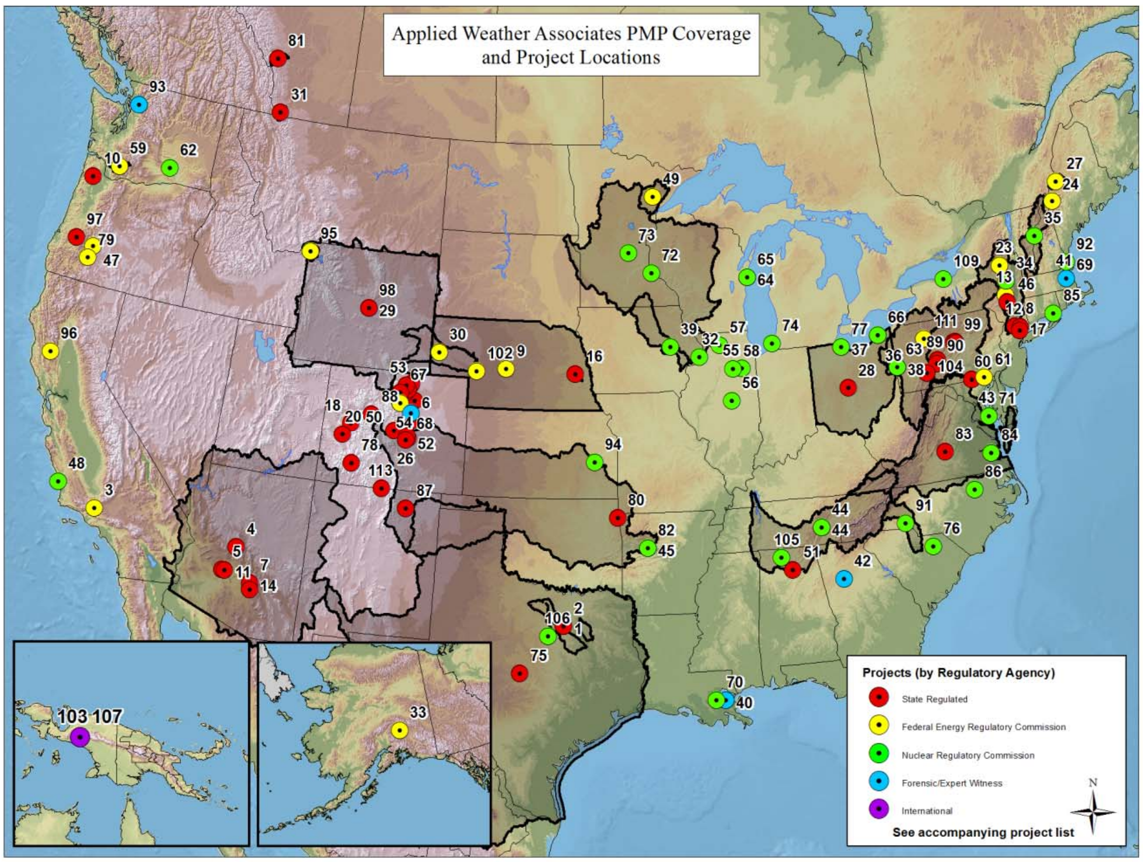

Figure 1: Locations of AWA PMP studies as of June 2016, Springbank is shown as number 83

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). 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

2.2 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.

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. 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. 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 PMP values.

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).

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.

2.3 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 kilometres. 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 2 shows the basin location and surrounding topography.

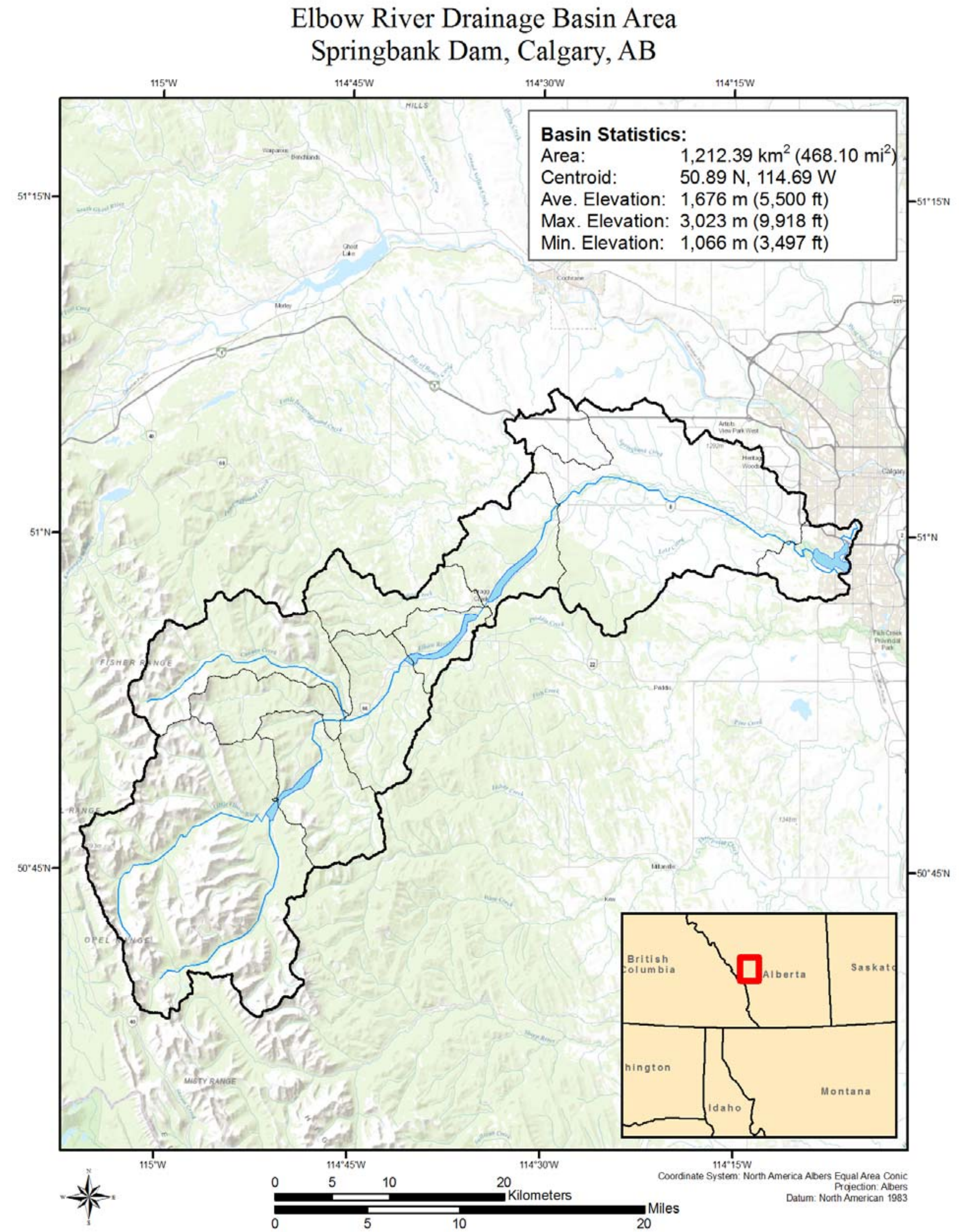

Figure 2: Elbow River basin location and regional setting

3 TOPOGRAPHIC EFFECTS ON PMP RAINFALL

The terrain within the basin varies significantly, often over relatively short distances (Figure 3). 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. 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.

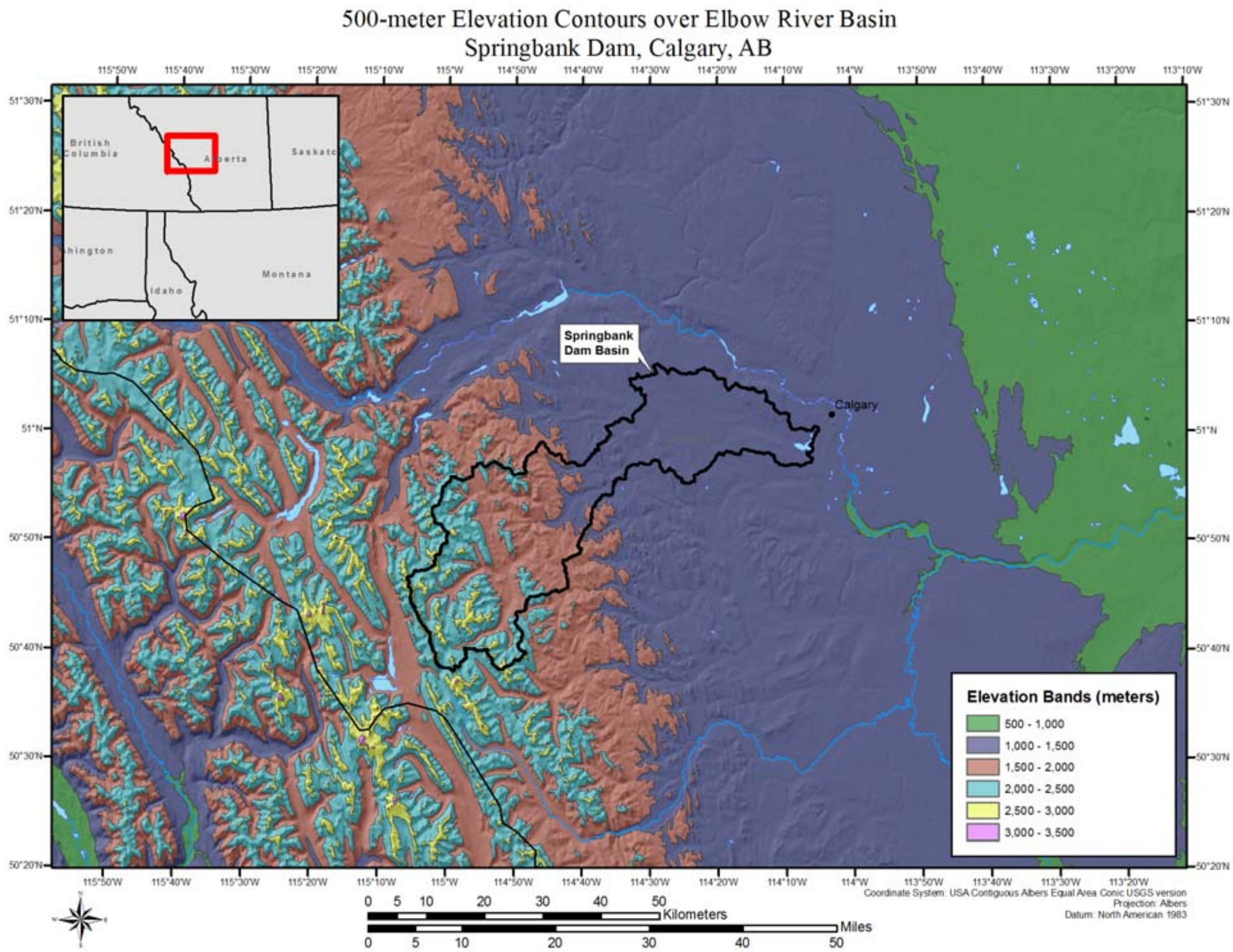

Figure 3: Elevation contours at 1,000 foot intervals over Elbow River Basin

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).

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.

4 PMP STORM IDENTIFICIATION

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 4). This ensured a large enough area was searched to capture all significant storms that could potentially influence PMP values for the basin.

Figure 4: Elbow River storm search domain

4.1 *Final Storm Selections Used for PMP*

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.

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 (Figures 5 and 6). 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

Locations of Short List Storms
Elbow River-Springbank Dam PMP Study, Calgary, AB

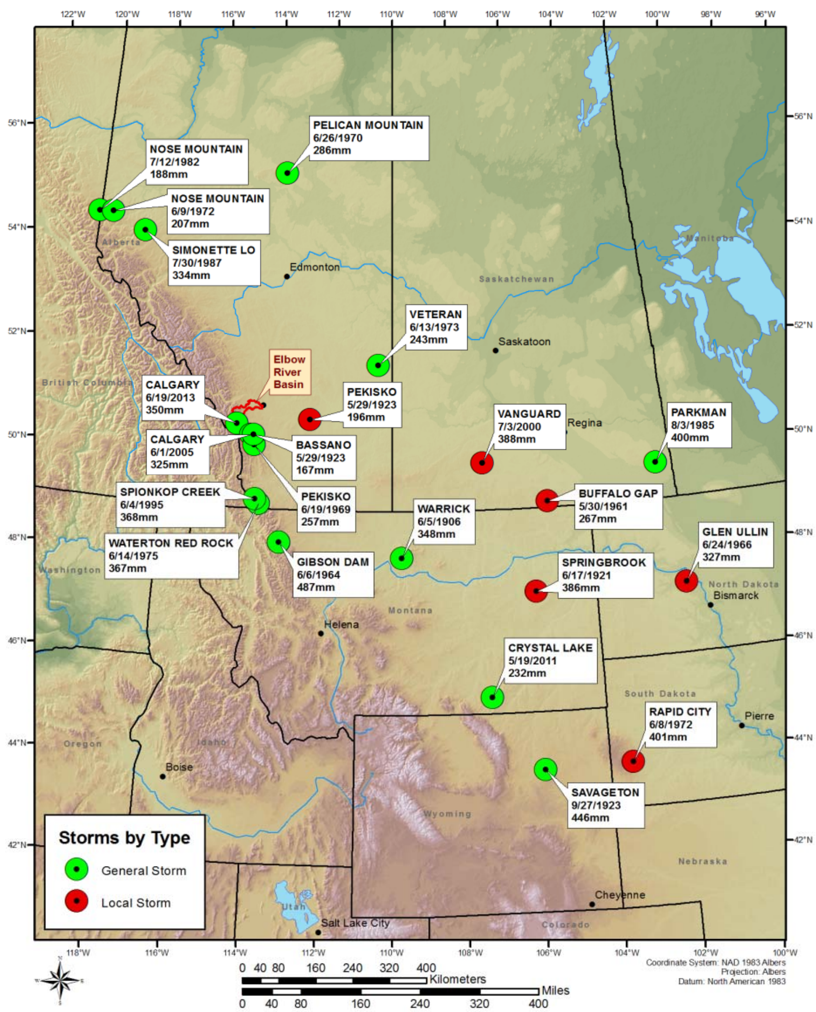

Figure 5: Final short storm list storm locations

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

Figure 6: Short storm list used in the development of the PMP values, sorted by storm type, chronologically

5 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). 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.

6 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) (Figure 7). The gridded PMP was spatially redistributed utilizes various methods, including precipitation frequency climatology and past storm patterns over the basins. For each of these scenarios, PMP was summarized by the gridded average over the sub-basins that comprise the drainage area

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

Figure 7: Drainage basin PMP scenarios. PF in this table refers to Precipitation Frequency

The following figures summarize the sub-basin average PMP values for each dam scenario. Scenario 1 (Figure 9) includes general storm PMP for the 11 sub-basins upstream of the Glenmore Dam (shown in Figure 8).

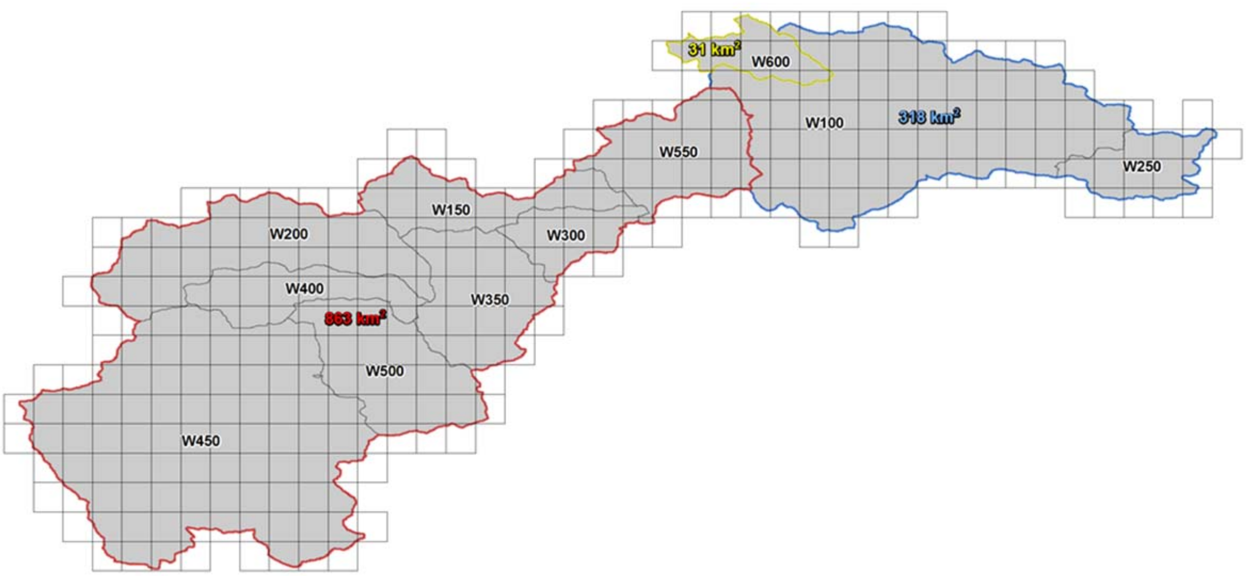

Figure 8: The 11 sub-basins included in the PMP analysis for Scenario 1 – upstream of Glenmore Dam (1,212 km^2)

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

Figure 9: Sub-basin average 1,212 km² general storm PMP

Scenario 2 includes the 8 sub-basins upstream of the SR1 Diversion (shown in Figure 10). Figure 11 provides the general storm PMP values for the drainage above the SR1 diversion. Figure 12 provides the local storm PMP using the 1-hour Glen Ullin, ND, June 1966 spatial redistribution. Table Figure 14 provides the local storm PMP for the 31 square kilometre drainage upstream from the SR1 dam

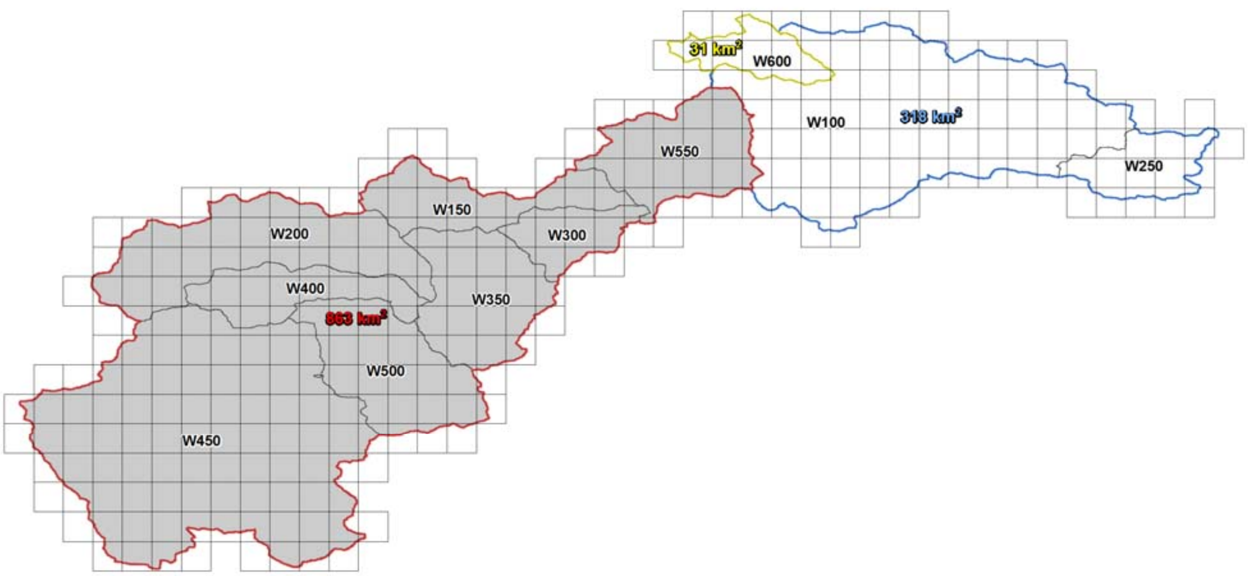

Figure 10: The 8 sub-basins included in the PMP analysis for Scenario 2 – upstream of SR1 Diversion (863 km^2)

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

Figure 11: 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)	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

Figure 12: Sub-basin average local storm PMP using the Glen Ullin, ND June 1966 1-hour rainfall pattern

Scenario 3 is the 31 km² sub-basin average local storm PMP (Figure 14) upstream of the SR1 Dam (shown in Figure 13).

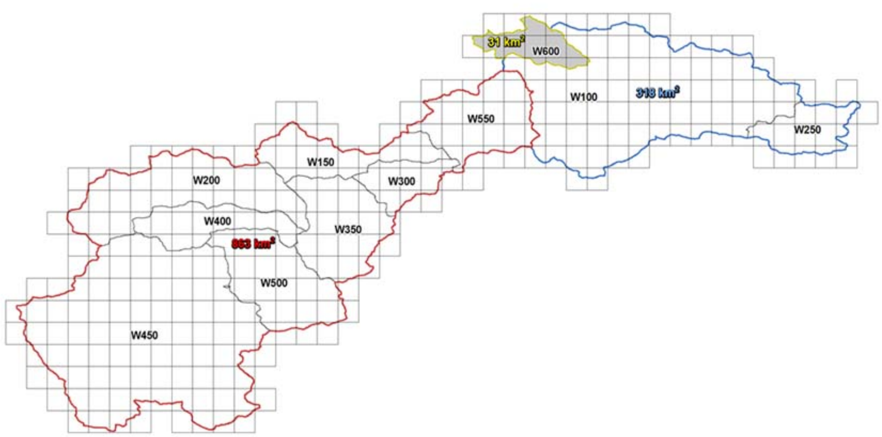

Figure 13: The sub-basin included in the PMP analysis for Scenario 3 – upstream of SR1 dam (31 km^2)

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

Figure 14: Comparison of the PMP Values with the 24-hour 100-Year Precipitation Frequency

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