GRIDDED SNOWMELT AND METEOROLOGICAL TIMESERIES FOR PROBABLE MAXIMUM FLOOD DEVELOPMENT AND ANALYSIS

Doug Hultstrand, Ph.D. [1]
Geoff Muhlestein [2]
Bill Kappel [3]

ABSTRACT

Extreme flooding often results from a combination of runoff from snowmelt and rainfall. Recent years have seen devastating flooding in locations such as the Red River, Assiniboine River, and the northern Missouri River basins. When determining the Probable Maximum Flood (PMF), antecedent and concurrent snow water equivalent (SWE) amounts combined with the meteorological parameters to melt the snowpack are needed. These are then combined with the Probable Maximum Precipitation (PMP) to produce the total runoff. Applied Weather Associates (AWA) updated PMP for the state of North Dakota, with portions of this study extending into southern Saskatchewan and Manitoba. During that study AWA developed a detailed gridded snowmelt tool combined with meteorological data to perform snowmelt and rain-on-snow calculations.

SWE at the 1% exceedance (100-year) were based on surface stations from Snow Telemetry (SNOTEL) and Global Historical Climatology Network (GHCN) data. AWA utilized the National Operational Hydrologic Remote Sensing Center (NOHRSC) SNOw Data Assimilation System (SNODAS) to aid in the spatial interpolation of the observed SWE data. Gridded daily surface temperature timeseries were utilized as input for the gridded snowmelt calculations. A GIS snowmelt calculation tool, utilizing 1% exceedance gridded SWE and daily gridded temperature data was developed to perform gridded snowmelt simulations (clear day, rain-on-snow) efficiently with a variety of user input parameters (starting date, ending date, daily time series gridded datasets, starting day SWE gridded dataset, degree day coefficients, drainage basin). The results are used for spillway capacity reviews, dam safety assessments and seasonal flood operation planning.

[1] Applied Weather Associates, Senior Hydrometeorologist Monument, CO, dhultstrand@appliedweatherassociates.com
[2] Applied Weather Associates, Senior GIS Analyst Monument, CO, gmuhlestein@appliedweatherassociates.com
[3] Applied Weather Associates, Chief Meteorologist, Monument, CO, billkappel@appliedweatherassociates.com

Applied Weather Associates (AWA) developed gridded 100-year snowpack in conjunction with a developed gridded daily average temperature timeseries. The information was developed to cover a timeframe representing a complete picture of snow accumulation and snowmelt throughout the region. It is important to note that the meteorological conditions associated with the full Probable Maximum Precipitation (PMP) rainfall event are valid from June through September over the North Dakota region. Therefore, no direct snowmelt is expected to occur during the PMP rainfall event. This is consistent with all PMP studies in the region completed by AWA (Tomlinson et al., 2008; Kappel et al., 2014; Kappel et al., 2018) and with Hydrometeorological Reports 51 and 55A (Schreiner and Riedel 1978 and Hansen et al., 1988).

DEVELOPMENT OF METEOROLOGICAL DATA

Snow Data

Snowmelt calculations are dependent on the availability of reliable snowpack and temperature climatologies. For this study, AWA utilized surface observations, remote sensing data, and model reanalysis to develop 100-year snow water equivalent (SWE)gridded data sets for the 1st and the 15th of each month from March 1st through September 15th.

Station Data. AWA calculated the 100-year (1% Exceedance) point value SWE based on 194 surface stations from Snow Telemetry (SNOTEL) and Global Historical Climatology Network (GHCN) data networks within and surrounding the basins. SWE data were extracted for the 1st and the 15th of each month from March 1st through September 15th. For each date, for each station the 100-year SWE was calculated based on station L-moments statistics and the generalized extreme value (GEV) probability distribution (Hosking and Wallis 1997). The GHCN network sometimes provided direct measurements of SWE but always provided direct measurements of snow depth. An average snow density of 25% was applied for each date to convert the GHCN snow depth data to SWE (Pomeroy and Gray 1995).

SNODAS Data. In addition to the point snow water equivalent, AWA utilized the National Operational Hydrologic Remote Sensing Center (NOHRSC) SNOw Data Assimilation System (SNODAS) gridded dataset. SNODAS integrates observed, remotely sensed, and modeled datasets into estimated snowpack variables. SNODAS is a physically-based, near real-time energy and mass balance, spatially-uncoupled, vertically-distributed, multi-layer snow model (Carroll et al., 2001; NOHRSC 2004). The model has high spatial (1-km^2) and temporal (1-hour and daily) resolutions and is run for the conterminous United States. Snowpack products generated by SNODAS include SWE, snow depth, snowpack average temperature, snowmelt, and surface and blowing snow sublimation. The SNODAS data are available starting in 2003 through present, providing 16 years of data to create snowpack climatologies for the lower 48 states. Since portions of the North Dakota domain extend into Canada, the unclipped SNODAS data were needed and available starting in 2013 through present, providing 7 years of data for this study.

SNODAS daily gridded data were utilized on the 1st and the 15th of each month, starting March 1st through September 15th. These data were utilized to calculate the 1% exceedance (100-year), mean, maximum, and minimum snowpack spatial variation. The SNODAS dataset were used to derive snowpack 1% Exceedance (1% Exceedance = average + (2.3263 * St. Dev)) spatial snowpack climatologies; 2.3263 is the z-score (standard deviation) of the 99th percentile from the normal distribution (R example qnorm (0.99) = 2.326348). The daily gridded SNODAS climatologies were used to aid in the spatial interpolation of the station 100-year SWE (i.e., scaling the gridded spatial pattern to the observed station 100-year SWE). The final adjusted 100-year SWE grids were derived using the estimated SNODAS 100-year climatologies, and station data 100-year SWE estimates, as input into a climatologically aided spatial interpolation process following Daly et al., (1994); Schaake et al., (2004); Hultstrand and Kappel (2017); Hultstrand and Fassnacht (2020).

<u>Daymet Data.</u> In addition to the SNODAS and station data, AWA utilized NASA's Oak Ridge National Laboratory Daymet gridded dataset. Daymet is a collection of gridded estimates of daily weather parameters generated by interpolation and extrapolation from daily meteorological observations (Thornton et al., 2016). The model has high spatial (1-km^2) and temporal (daily) resolutions and is run for all of North America. Daymet products include SWE and are available starting in 1980 through present, providing 40 years of data to help create snowpack climatologies.

Like the other data sets, AWA utilized daily gridded Daymet data for the 1st and the 15th of each month, starting March 1st and continuing through September 15th. These data were used to calculate the 1% Exceedance (100-year), mean, maximum, and minimum snowpack spatial variation. The Daymet dataset was used to derive snowpack 1% Exceedance (1% Exceedance = average + (2.3263 * St. Dev)) spatial snowpack climatologies. The daily gridded Daymet climatologies were used to aid in the spatial interpolation of the station 100-year SWE (i.e., scaling the gridded spatial pattern to the observed station 100-year SWE). The final adjusted 100-year SWE grids were derived using the estimated SNODAS 100-year climatologies and station data 100-year SWE estimates as input into a climatologically aided spatial interpolation process following Daly et al., (1994); Schaake et al., (2004); Hultstrand and Kappel (2017); Hultstrand and Fassnacht (2020).

<u>Final 100-year SWE Climatologies.</u> Comparison of the station observed 100-year SWE estimates to the gridded 1% exceedance estimates for SNODAS and Daymet were made for the 1st and the 15th of each month from March 1st through September 15th. The SNODAS and Daymet 1% exceedance estimates had similar goodness-of-fit measurements (mean error (ME), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (r)). Based on the goodness-of-fit measurements, and available period of record (POR) the Daymet grids were adjusted to the surface station

100-year estimates and the SNODAS data were not used in the final grid development due to the short POR.

The final adjusted 100-year gridded SWE climatologies were produced from a combination of station data and Daymet for the 1st and the 15th of each month from March 1st through September 15th. The gridded SWE values utilized for snowmelt calculations over the drainage basins are illustrated below for April 15th (Figure 1).

Temperature Timeseries Information

Gridded daily surface average temperature timeseries (T_a) were compiled and utilized as input for the gridded snowmelt calculations as described in the following snowmelt methodology section (Section 2). Daily gridded temperature data was obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM 2004). The Daymet temperature products were also obtained and considered as an alternative option for snowmelt and sensitivity analysis of the snowmelt model but were not used in the final snowmelt tool calculations. The daily minimum ($T_{a\ min}$), daily maximum ($T_{a\ max}$), and daily average ($T_{a\ avg}$) parameters were each evaluated. These data sets covered the same time period as the SWE 100-year climatology but were developed on a daily timestep. The gridded $T_{a\ avg}$ Daymet values utilized for snowmelt calculations over the drainage basins are illustrated below for April 15th (Figure 2).

METHODOLOGY

Snowmelt Equation

The U.S. Army Corps of Engineers (USACE) has conducted numerous snowmelt studies, which were aimed primarily at providing procedures for deriving maximum snow melt design floods. The USACE summarized two approaches to compute snowmelt. The first is the energy budget method, which allows the snowmelt solution to be as physically based as practicable by incorporating into snowmelt equations factors such as solar radiation, wind, and long-wave radiation exchange. The second method, temperature index equation, is a more simplified approach in which air temperature is assumed to be a representative index of all energy sources so that it can be used as the sole independent variable in calculating snowmelt. The energy budget equation for a rain-free situation with a forested area of 60-80% coverage is defined as:

$$M = k(0.0084v)(0.22T_a + 0.78T_d) + 0.029T_a \quad (1)$$

where M is snowmelt (inches/day), T_a is air temperature (°F), T_d is dew point temperature (°F), and v is the wind speed (mph).

The Temperature Index equation is defined as:

$$M = C_m (T_a - T_b) \quad (2)$$

where M is snowmelt (inches/day), C_m is melt rate coefficient, T_a is the air temperature (°F), and T_b is the base air temperature of 32.0°F (0°C). The range of the C_m factor is typically between 1mm and 2mm/°C for rain-free situations and up to 4.5mm for rain-on-snow situations. A C_m of 1.5mm is a common factor used when other calibration and/or snowmelt information is limited and for generally rain free snowmelt scenarios (USACE 1998). For this study, four C_m are available (Table 1).

Table 1. Temperature index model melt rate coefficient used in PMP tool.

Melt Rate Coefficient(C_m)	General Description
1.5	Clear sky, limited wind, the melt factor for clear day can range between 1 and 2
4.5	Heavy Rain, 10 mph (16 km/h) Wind, 10-in per 24-hr period
6.8	Heavy Rain, 20 mph (32 km/h) Wind, 10-in per 24-hr period
9	Heavy Rain, 30 mph (48 km/h) Wind, 10-in per 24-hr period

GIS Data Preparation and Snowmelt Tool

Geographic Information Systems (GIS) were utilized to facilitate spatial data management, spatial analysis, and mapping. Temperature and SWE gridded datasets were obtained and processed in the Network Common Data Form (netCDF) multidimensional file format. Climate Data Operators (CDO) (Schulzweida 2019) were used to process gridded files in netCDF format. Processing gridded files involved calculating daily ensemble means for the available period of record for the T_a datasets, resampling the T_a and SWE gridded datasets to the 90 arc-second spatial resolution grid format, using the WGS 1984 coordinate system, and converting the gridded datasets from netCDF format to ESRI geodatabase raster format. The 90 arc-second grid network matches the grid network utilized in the North Dakota Statewide PMP Study and provides full coverage over the analysis domain at a spatial resolution sufficient to capture variations over the spatial field.

A basin snowmelt calculation tool, utilizing SWE and daily temperature derived during this study, was developed within the ArcGIS environment which allowed snowmelt calculations to be made efficiently with a variety of input parameters. Starting date, ending date, daily T_a time series gridded datasets, starting day SWE gridded dataset, degree day coefficient, and the drainage basin are all variable input parameters.

Based on the input parameters, the GIS snowmelt tool calculates the basin average snowmelt, using the Temperature Index method along with the basin average values for daily T_a, degree days, and SWE. The GIS snowmelt tool contains several temperature profiles to simulate rain-on-snow scenarios for the 1-, 3-, 5-, and 7-day durations for use in probable maximum flood analysis. The tool also can provide the output for a discrete point location. The output is provided in a table in both ArcGIS geodatabase and Excel format. Figure 1 displays the 100-year SWE coverage of the North Dakota study domain on April 15.

RESULTS AND DISCUSSION

Figure 1 shows the April 15th 100-year SWE and Figure 2 shows the gridded temperature patterns over the same domain. The grids serve as input into the GIS snowmelt tool to derive the snowmelt on a gridded basis. Figure 3 provides example showing the basin average SWE versus temperatures starting March 15 and ending in June.

The climatological average and maximized daily temperature and SWE gridded timeseries were developed for this study to be used to estimate snowmelt during noral conditions and during cool-season rain-on-snow PMP events. In addition, the Snowmelt Tool was developed to produce gridded snowmelt timeseries to be utilized in conjunction with hydrologic models for snowmelt runoff scenarios and cool-season PMP scenarios.

Development of this data set and the gridded process from which to derive daily snowmelt is a significant improvement over previous data sets and process, including HMR 48. This information allows for an explicit calculation of total runoff from cool-season PMP and snowmelt to be derived on a grided basis for any day during the cool-season period. The database and calculation procedures allow for detailed investigation regarding snowmelt parameters and combinations that were not available previously and provide the opportunity to efferently determine the worst-case combination of factors.

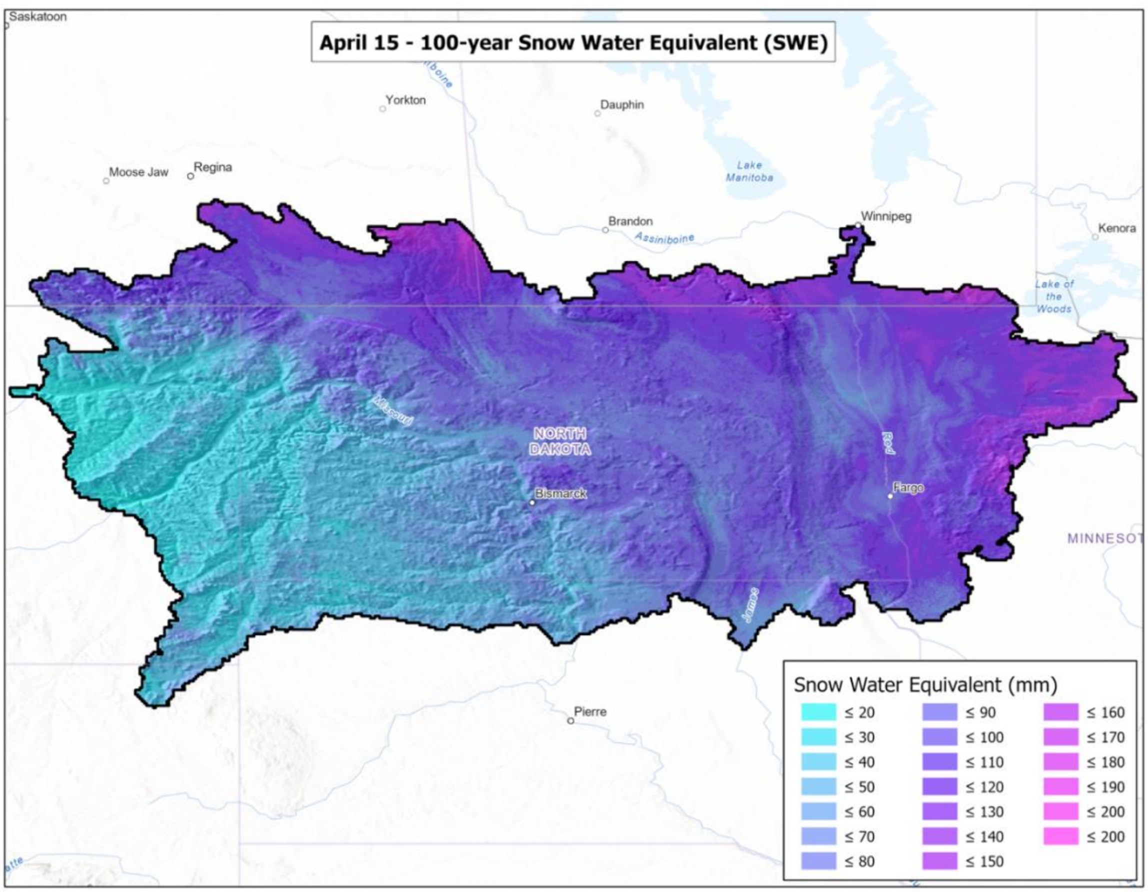

Figure 1. Final 100-year SWE for April 15.

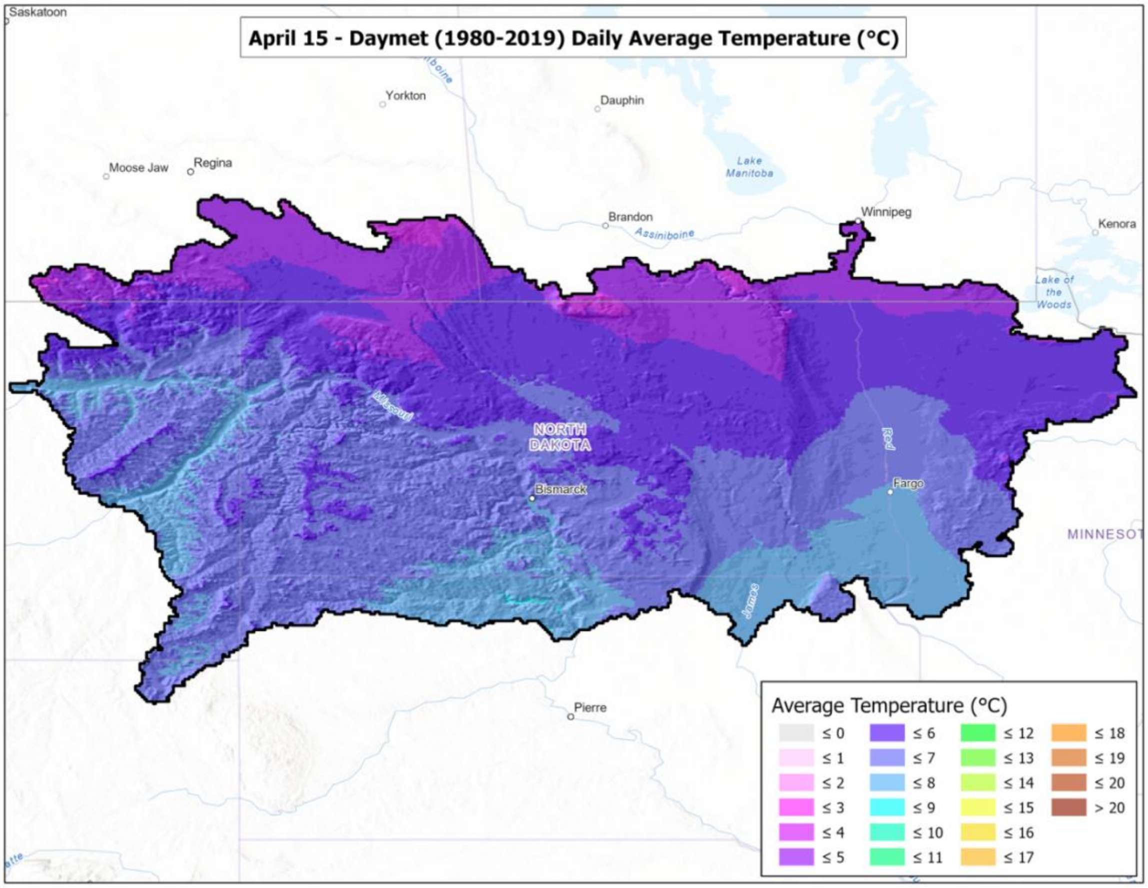

Figure 2. Daily Average Temperature for April 15.

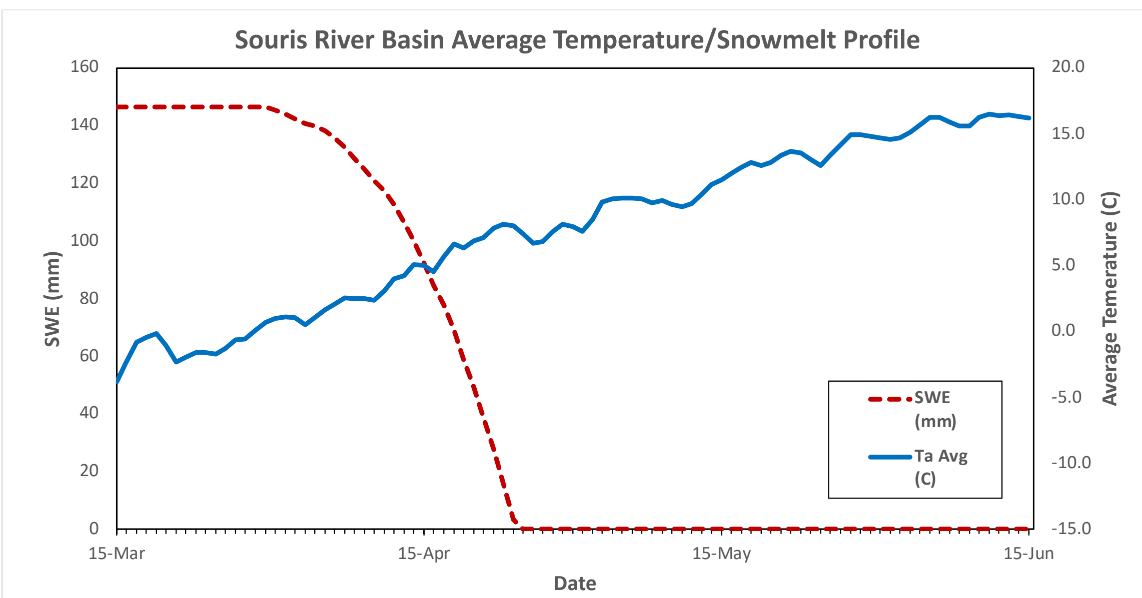

Figure 3. Example out of the GIS tool showing SWE (red dashed line) and temperature (blue line) through time.

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