MONTANA ELECTRONIC PRECIPITATION MAP

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ABSTRACT

An accurate estimate of average annual precipitation (AAP) is a necessity for completing hydrologic analysis, developing stream flow statistics, or doing other related water resource planning. Consequently, tools to develop and complete such analysis are required. Endeavors should be automated, capable of very quickly updating AAP information as it become available, and available for widespread use without proprietary requirements. To meet such a mandate, we developed a free-ware UNIX based tool called PMAP, which allows rapid AAP estimates through universal Kriging. A case study was implemented for the state of Montana using the 1981-2010 water-year averages and a 400 m elevation grid. While there are many geo-statistical techniques to choose from in completing such analysis, the strength in our work is not necessarily the method that we selected, but rather the data supporting it. We compiled AAP estimates for over 1,400 stations across the region including 1,100 stations in Montana, and 300 adjacent to the state, to assure compatibility along the border for the analysis which is the most detailed compilation we are aware of. We then proceeded to evaluate the data using a number of geostatistical analysis techniques. Electronic results were then compared to hand-drawn products to assure appropriate location of AAP isohyets. Isohyetal lines were set at 50 mm (2 inch) increments under 500 mm (20 inches) and 250 mm (10 inch) increments above 500 mm (20 inches). The1981-2010 AAP map (isohyets and grids) will be available through the Montana Natural Resource Information System (NRIS) web site electronically, and software will be made available from the Montana Department of Environmental Quality upon request.
(KEYWORDS: annual precipitation, Kriging, climatological stations, isohyetal, multivariate interpolation)

INTRODUCTION

Estimates of spatial mountain precipitation have been around since the early 1970's (Farnes, 1970). In recent years, electronic applications have become customary. Applications such as PRISM, ANUSPLINE, and MTCLIM are all relevant examples (Hammer et al., 1997). In areas where gage networks are sparse, interpolation methods such as these help spatially distribute precipitation across vast landscapes. Either one or multiple explanatory variables are used to derive such estimates, with elevation being the most frequently used independent variable. Once such estimates are made, the end user is then typically a water resource planner, scientist, or engineer with an interest in water or climate related information. The precipitation-based streamflow statistics compiled by the U.S. Geological Survey (USGS), Total Maximum Daily Load (TMDL) estimates, and large-scale climate-change work are all relevant examples. However, most of the methods detailed previously either require periodic maintenance by research organization, or are not available to the general public (i.e., are proprietary). This is a net disadvantage to end users. Additionally, in some instances, not all available data is used in the analysis. For example, many workers only use easily downloaded data from the National Weather Service (NWS) [through the National Climate Data Center (NCDC)] or Natural Resources Conservation Service (NRCS) SNOTEL (SNOw TELemetry) network, but fail to retrieve less-accessible data such as snow course measurements, estimates from discontinued stations, or stations with large periods of missing record.

We initiated this effort to largely fill these deficiencies in regard to AAP estimates for Montana. We first compiled climatic data and then tested a number of spatial interpolation methods to find the most effective and efficient method. Both the products and associated software can then be used in the future to facilitate widespread use by water resource managers across the state.

STUDY AREA

Our study area comprised the entire state of Montana (Figure 1) which provides a good test case due to the vast differences in AAP and associated climatic variability. Climate of the region is generally dry, although the mountains receive vast amounts of precipitation due to topography. In the mountains, most of the precipitation

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comes as snow during the winter whereas the largest precipitation in the valleys is in the spring (Farnes 1995). Frontal systems are the primary precipitation producing mechanism and generally come from the west, north, or south. Those from the north are predominately cold systems with small amounts of precipitation. Those from the southwest are generally warm systems with limited moisture. Within the state itself, the precipitation gage network is sparse. One gage represents about 342 km^2 (132 mi^2), which lends difficulty in characterizing AAP or associated water yields from point estimates. Consequently, methods are needed to extrapolate these point measurements across large areas of terrain in a suitable fashion.

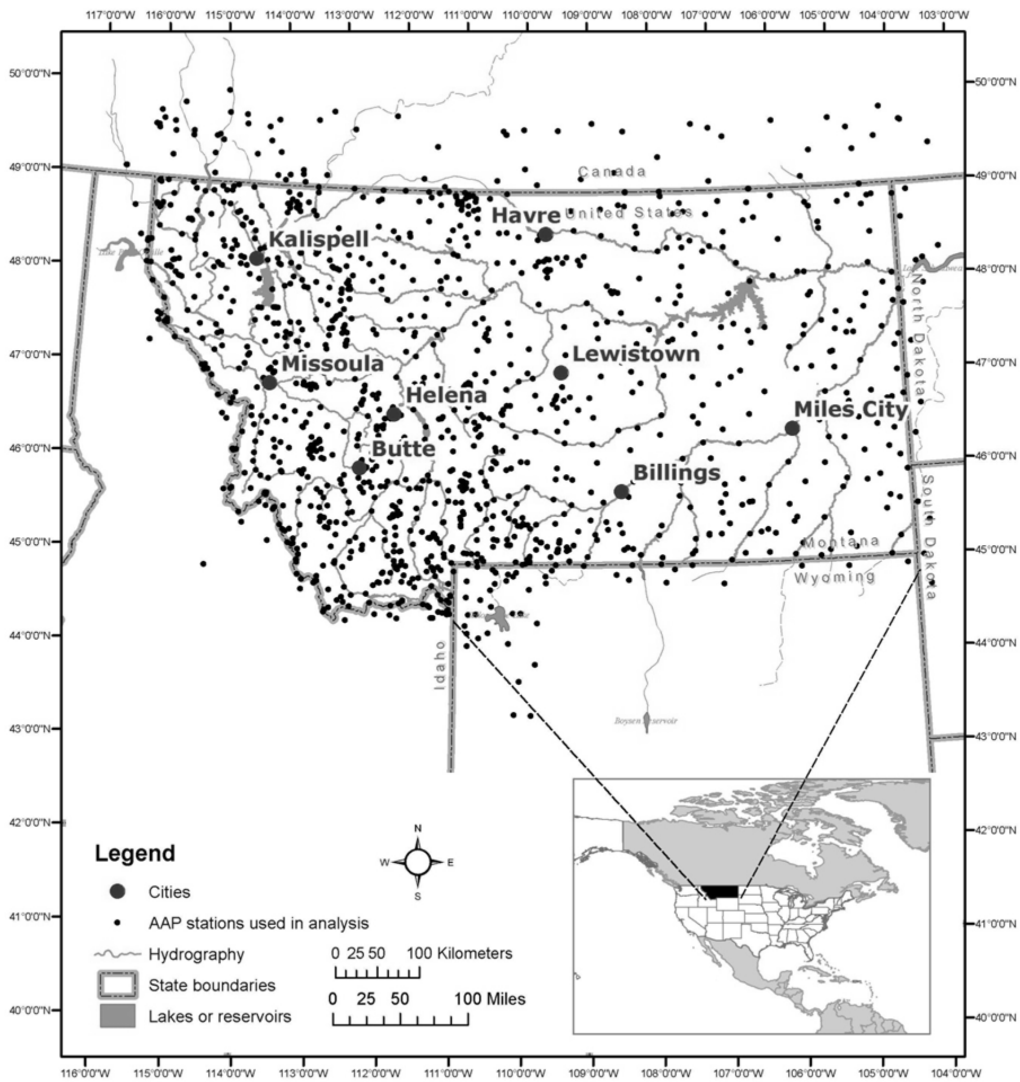

Figure 1. Study area map and locations and distribution of stations used to develop the Montana 1981-2010 average annual water-year precipitation map.

METHODS

Data Analysis

The most important consideration in any precipitation mapping analysis is the data behind it. A number of data sources were considered for the effort, with varying quality. The largest was the National Weather Service (NWS) and National Climate Data Center (NCDC) which consists of primarily valley-floor locations where it is possible to obtain daily manual observations, and the Natural Resources Conservation Service (NRCS) which operates and maintains high-elevation SNOTEL network in remote mountainous locations. A number of other agencies, companies, and individuals operate smaller networks which were incorporated as well. Climatic AAP is generally averaged over a 30-year base period (i.e., 1961-1990 or 1971-2000) for reporting purposes and is updated every ten years. For the purpose of this analysis, we used the 1981-2010 water year precipitation which was determined as follows:

- If there was a full record for this period, the arithmetic average for the 30 years was used.
- If some months were missing, they were estimated from adjacent stations to compute arithmetic averages.
- If there were not 30 years in the base period, then the annual total was compared to adjacent stations that had 30 years in the base period and the 1981-2010 average estimated.

Figure 1 shows a map of Montana and the surrounding region along with the distribution of stations that were used to complete the analysis. Stations from adjacent states and provinces were used to maintain continuity at the state boundary and overall a total of 1,412 stations were used in the analysis. This included 1,112 stations within Montana, 90 stations in Idaho, 11 in North Dakota, four in South Dakota, 122 in Wyoming, 28 in Alberta, 21 in British Columbia, and 24 in Saskatchewan. Specific stations in Montana included 469 NWS climatological stations, 34 NWS storage gauges, 19 NWS hourly gauges, 158 NRCS SNOTEL and storage gauge stations, 200 NRCS snow courses, 27 RAWS stations, and 205 synthetic stations were used. Synthetic data were developed for higher elevations in the State where accurate measurement of precipitation was not possible. Generally, these areas were above tree-line in mountainous areas where measurement error is too great for station placement. In prairie areas, synthetic points were also placed for the highest elevations of the surrounding area not typically monitored by climatological stations. Synthetic points were established for highest points in each mountain range or areas where measurements were not available which helped control the estimated precipitation in areas where the elevation of points to be estimated was well above the range of measured stations where a slight change in slope could impart large errors in the precipitation estimate.

During the data compilation, we noted several issues with the locational data. First, most latitude and longitude locations in the data base were recorded only to the nearest minute. Additionally, some of the older stations had locations based on NAD 27. The latitude and longitude of all stations were recorded to the nearest second using NAD 83 and then converted to Montana state plane coordinates. Additionally, there was significant amounts of missing data. For example, when an observer did not enter a daily reading or did not send the monthly observation sheet to the correct location, those blanks remained in the data base. If the average was determined with missing data, then it was not accurate. Since the NWS/NCDC does not estimate missing records, it was necessary to estimate any missing data by correlation with adjacent sites. Data from SNOTEL stations were generally complete, and most stations had 30 years of records during the base period. NRCS storage gages have prorated annual precipitation and most have 30 years of record during the base period. For those SNOTEL and storage gage stations not having a full record, the 30-year average was estimated by correlation. There was a very good correlation between April 1 snow water equivalent (SWE) and annual precipitation at SNOTEL stations. The SWE at snow courses was corrected for snow tube over measurement (0.91) (Farnes et al, 1982) and canopy cover (Farnes and Hartman, 1989). Monthly precipitation data from remote automated weather stations (RAWS) was problematic. Only 28 of the 89 stations tabulated had data that was useable and it appeared that many of the stations were located in wind-prone areas where the precipitation gages under-catch precipitation. They also used tipping buckets which do not accurately collect frozen winter precipitation. Even the summer data had problems, again related to wind. Where data did not appear reasonable in comparison to nearby stations, the station was not used. Where summer precipitation appeared reasonable, it was correlated to nearby stations and then prorated to annual precipitation.

Elevation Data

Since elevation was one of the primary variables used in both universal Kriging and linear regression, it is imperative that it was of suitable quality for the analysis. We used a 30 m digital elevation model (DEM) downloaded from the USDA Geospatial Gateway. The data originated in separate tiles for the three UTMs covering Montana and was projected from UTM to NAD83 in degrees and mosaiced for analysis. The DEM was found to include some missing data. Holes in the elevation map were filled in by using other maps of different scales. The applications were written to use meters and the elevation data was projected from the three UTMs (11, 12, and 13) to Montana state plane. There were two large patches of missing data and many smaller ones and we used an ESRI grid of ten meter elevation data to patch the missing thirty meter data. The elevation data was sorted and written to a binary structure of floats with an index file to allow for quick access.

Geo-statistical Methods

Initially three different schemes (ordinary Kriging, inverse distance weighting, and simple regression) were considered in relating AAP to spatial location. Geo-statistical interpolation applications were developed using C under Linux Ubuntu 10 64 bit OS using level 1 I/O, which allowed the user to change the grid size and rectangular neighborhood of stations and output shapefile isohyets. The applications were written on Linux and then rewritten to run on Windows to use level 2 I/O. However, upon initial examination, the interpolation schemes failed to produce realistic or desirable products as gradients did not follow elevation contours. New applications were therefore written using elevation as the primary trend for universal Kriging, as well as for multivariate inverse distance weighting and simple regression which greatly improved our results. Given the computing requirements of universal Kriging, the LAPACK library was used for matrix inverse operations and was modified to use OpenMP multi-threading for speed. Both regression and Kriging produced reasonable precipitation distributions across the landscape and Kriging was used in the final analysis as this method incorporates both elevation and distance in the weightings procedure.

Multiple runs of grid size, curvilinear coefficient, and number of stations for universal Kriging and regression were then completed but still revealed that isohyets were still not comparable to prior hand drawn maps. Data sites were not located uniformly across the state (due to access and location of observers) and problems were encountered when trying to use a given set of data points to distribute precipitation across the landscape. Thus two additional changes were made to the computational algorithm to resolve the issue. First, the rectangular neighborhood of selected stations was changed so that an optimal number nearest neighboring (NN) stations could be used under the constraint that at least one of these stations must fall above and below the cell being evaluated (i.e., to ensure Kriging weights are appropriate). In other words, if one of the three stations was at a lower elevation and one at a higher elevation, the program then used the three stations to estimate the precipitation. If there was neither one of the three NN at a higher and lower elevation, then it added the fourth NN, or fifth NN until at least one station was at a higher and one at lower elevation up to a total of 8 NN. If the criteria were not met with 8 NN, the precipitation was estimated using the 8 NN. With more than 8 NN, the area of consideration expanded into different climatic regimes for most areas in Montana.

Secondly, the output was changed to create polygon grids based on the user selected grid size. This meant that no additional processing would be required. The data could be imported directly into ArcGIS, clipped with the Montana state polygon, and converted directly to a raster for creating 50 mm (2 inch) contours. A Visual Basic macro was then used to remove the 50 mm (2 inch) contours above 500 mm (20 inches) leaving only 250 mm (10 inch) contours as the mountains replace the plains at around the 500 mm (20 inch) increment, and isohyetal lines became too close to be useful. At increments below 500 mm (20 inches), the 50 mm (2 inch) difference becomes significant to many uses such as agriculture and hydrology. It was also found when generating the isohyets that contours created with ArcGIS were not accurate. Research determined that the “gdal contour” application accurately computes contours from the ESRI gridded data. The applications were rewritten to Regress and Krige the log values of precipitation and elevation and this proved to be the best results. Output was aggregated into a 400 m elevation grid.

RESULTS

Results indicated that both universal Kriging and linear regression create good representations of AAP in Montana (i.e., by examining the results against previous hand-drawn maps in the state). We ultimately selected universal Kriging (which belongs to the family of linear least squares estimation algorithms) as this seemed to provide the best representation across the state. This required a variable number of nearest neighbors from 3 to 8, with programming rules that required that at least two of the neighbors bound the cell being evaluated in elevation. The computed range of precipitation using the method is about 3560 mm (140 inches), which overall reflects the distribution believed to occur within the state. The lowest AAP station for Montana was in south central part of the State near the Wyoming border at 150 mm (5.9 inches). The highest was in Glacier National Park in northwestern Montana at 3708 mm (146 inches) annually for the 1981-2010 base period. The state-wide map based on universal Kriging is shown in Figure 2. A sample of the results for Meagher County, which is located in central Montana, is shown in Figure 3.

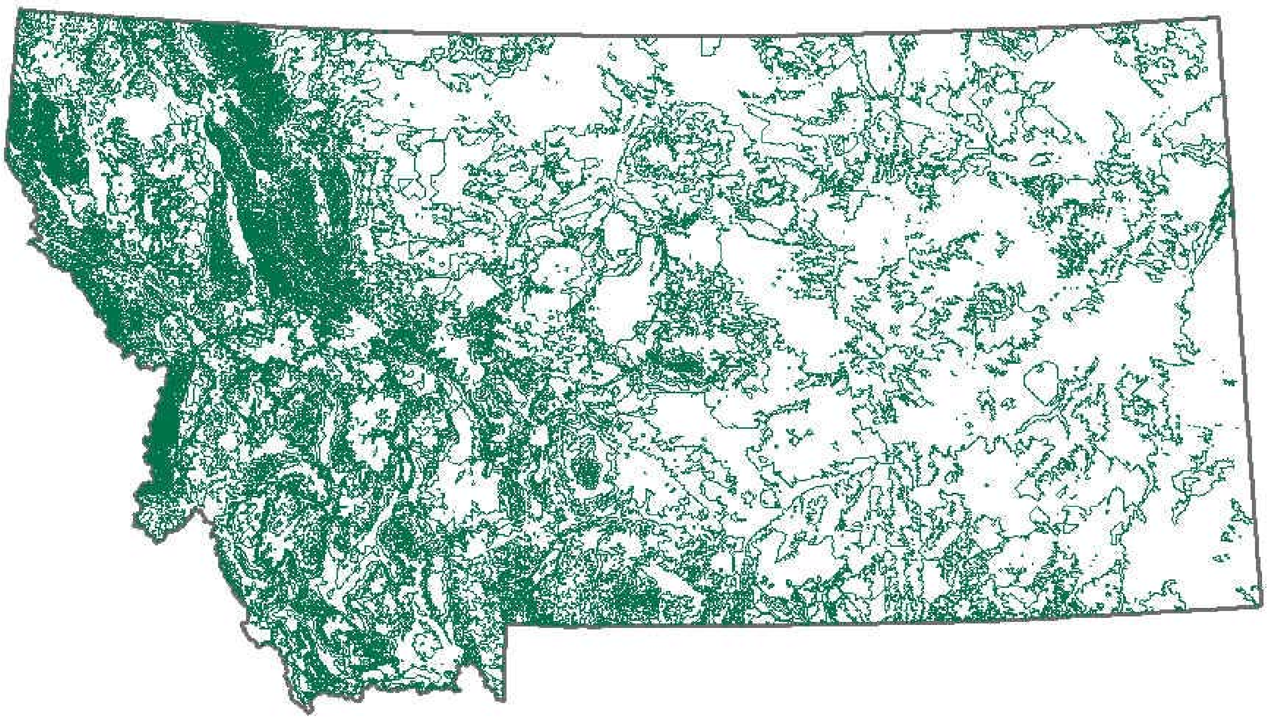

Figure 2. Isohyetal lines generated for the Montana precipitation map for 1981-2010 average annual water-year period generated with 3 to 8 nearest neighbors and 400 m elevation grid.

SUMMARY

Both regression methods and universal Kriging were investigated to estimate the spatial distribution across the landscape using elevation as the primary variable. Kriging was selected for the final analysis as this method incorporates both elevation and distance in the weightings procedure. This produced a very reasonable approximation of AAP based on the sparse gage network within the state and the interdependence of AAP on elevation. It is planned to utilize the same procedure to develop maps for monthly and seasonal precipitation and similar maps could be generated for temperature, growing degree days, growing seasons, snowfall, and snow water equivalents. Currently, we are developing snow load maps based on 50-year frequency ground loadings in cooperation with Montana State University.

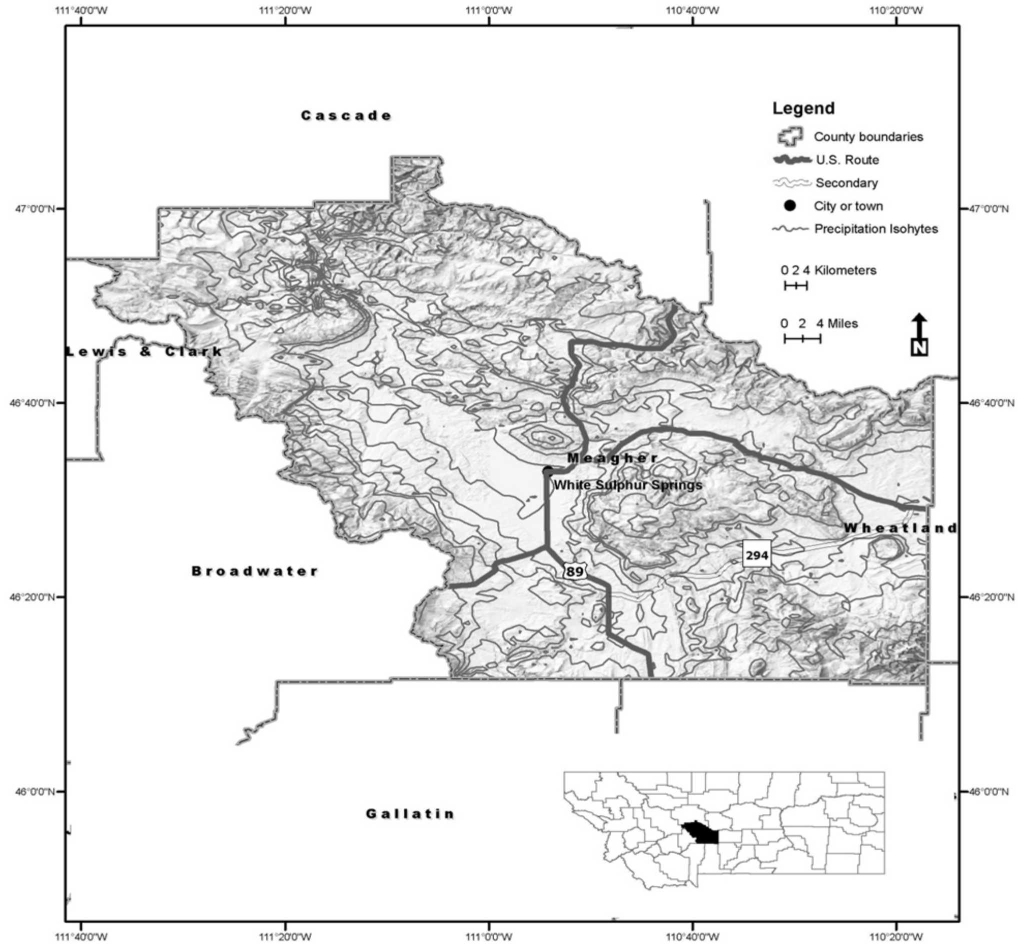

Figure 3. The 1981-2010 average annual water-year precipitation for Meagher County in central Montana generated with the Kriging procedure and 3 to 8 nearest neighbors and 400 m grid scale. Isohyets are shown in inches.

ACKNOWLEDGMENTS

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