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Estimating Snow Water Equivalent Using a GIS

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ABSTRACT

In the Western United States approximately 75 percent of the annual runoff results from snowmelt. Observations of the snow cover provide an important source of information for forecasting seasonal water supply months in advance. Regression models have been used for over 70 years with snow water equivalent as one of the independent variables. More recently, conceptual hydrologic models have been used to forecast water supply using the Extended Streamflow Prediction (ESP) technique, which is the long-range forecasting component of the National Weather Service River Forecast System (NWSRFS). The conceptual models rely on estimates of mean areal precipitation and mean areal temperature to compute estimates of current snow cover conditions. Because of the difficulty in accurately estimating precipitation in the mountains, it is essential that snow water equivalent observations be used to update model simulated snow cover conditions to ensure that ESP forecasts are accurate.

This paper describes a software system that interpolates observations of snow water equivalent to produce gridded estimates of snow water equivalent. The system uses the GRASS Geographical Information System (GIS) to store, analyze, and display point, line and gridded data. The GIS permits the analysis of multiple data layers such as elevation, forest cover, seasonal precipitation, and their derived data layers, e.g. slope, aspect, and melt factor classification. The snow cover estimation system includes a calibration component which assists the user in estimating parametric information, and an operational component which performs the interpolation in real-time. The outputs of the system include gridded estimates of snow water equivalent, as well as estimates of the areal snow cover conditions needed by the snow accumulation and ablation model that is part of NWSRFS. These estimates are weighted with the model simulated conditions based on their relative uncertainties to compute updated snow conditions. Updating the simulated snow conditions has been demonstrated to provide significant improvements in streamflow forecasting in areas with significant snow cover.

INTRODUCTION

Because so much of the west's water supply is influenced by snow and snow melt, it is extremely important to accurately estimate the water equivalent contained in the snowpack. Knowledge of snow cover conditions is essential to producing seasonal water supply forecasts, which are needed for estimating hydropower generation, planning reservoir releases and determining water

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allocations. Regression equations are often used to forecast water supply with snowpack snow water equivalent as one of the independent variables. Regression techniques work well in average years, however in extreme years they sometimes do not provide as accurate an estimate as might be desired. It is often these extreme conditions (flooding and drought) that concern water managers the most.

More recently, conceptual models have also been used to forecast water supply. The Extended Streamflow Prediction (ESP) technique is the long-term forecasting component of the National Weather Service. It uses present day streamflow, soil moisture and snowpack conditions along with historical time series of precipitation and temperature to estimate streamflow weeks or months into the future. The streamflow hydrographs can be analyzed based on the likelihood of the precipitation and temperature time series to produce probabilistic forecasts of streamflow peaks, volumes, etc. Because of the difficulties in estimating precipitation in the mountains, the estimates of the initial conditions provided by the models are often inaccurate.

The Soil Conservation Service (SCS) and others have been collecting snow water equivalent information. Snow course data is available at over 1500 sites and in some places the period of record exceeds 40 years. More recently, they have begun collecting data at SNOTEL sites (approximately 650 locations). The NWS has developed a methodology to use snow data to improve the estimates of the snowpack conditions. (Day, 1990). The analysis of these snow data and its incorporation into the model should result in more reliable estimates of seasonal water supply volumes.

SNOW ESTIMATION AND UPDATING SYSTEM (SEUS)

The National Operational Hydrologic Remote Sensing Center (NOHRSC) will ingest available SNOTEL and snow course data on a weekly basis between January and June of each year. After some preliminary error checking, the SEUS will be used to develop gridded estimates of snow water equivalent. This gridded information will be provided to end users. In addition, NWS River Forecast Centers will be able to either use these estimates or recalculate the gridded estimates with perhaps improved error checking and additional data. The RFC's will compute areal estimates of snow water equivalent over basin subareas and use this information to update the snow states of the conceptual snow model.

The SEUS consists of three components, a calibration component, an operational component and an updating component. The calibration component analyzes historical snow observation data and develops the parameters needed to estimate gridded snow water equivalent. The operational component accesses real-time data and takes advantage of the parameters developed in the calibration phase to determine gridded snow water equivalent operationally. The updating component updates the existing snow water equivalent in the conceptual model based on the relative uncertainties of the simulated model snow states and estimates of the snow states developed using the snow observations. Much of the methodology involves managing and analyzing point, line, and gridded data.

SEUS uses the Geographic Resources Analysis Support System (GRASS) GIS to perform these tasks. GRASS is a raster based public domain GIS developed for UNIX platforms by the U.S.

Army Construction Engineering Research Lab (USACERL). Part of the appeal of using GRASS to develop the SEUS was its compartmentability and the availability of the source code, so that additions and modifications could easily be made to its existing capabilities. GRASS has many low-level commands which when combined with one another, provide the user with the capability to tailor the GIS to the function which needs to be performed. In order to isolate the user from as many of the details of the GIS as possible, all the GRASS commands for a particular function are packaged together in scripts. In addition, a graphical user interface has been developed to further simplify the system for the user.

Calibration Component

The methodology developed involves the interpolation of point snow water equivalent data into gridded estimates of snow water equivalent. The interpolation technique chosen requires that the data are second-order stationary and isotropic. This assumption asserts that each point has the same mean and variance and that the correlation between two points is a function only of distance. To meet these requirements, the point snow water equivalent data is transformed into standardized deviates (z) using the following equation.

$$z = \frac{x - \bar{x}}{\sigma}$$

where z = standardized deviate
x = observation
$\bar{x}$ = mean, for the station
σ = standard deviation for the station

This transformation requires the knowledge of each station's mean and standard deviation for specific dates when the interpolation is performed. Snow course and SNOTEL data were analyzed to estimate long term means and standard deviations for the first of each month from January to June. Weekly station means and standard deviations were estimated using the variation of the snow cover in the vicinity of the observation during the month.

The interpolation method also requires an estimate of the spatial correlation function of the standardized data. A correlation function was developed for each basin using the historical station data and expressing the correlation between each station pair as a function of distance. An equation of the form:

$$\rho = ce^{-dx}$$

where ρ = correlation coefficient
x = distance between points in km
c,d = regression coefficients

was fit to the data. Given a correlation function and a station mean and variance the point snow water equivalent can be transformed and interpolated at each grid point to produce a gridded field of standardized deviates.

What is really desired, however, is a gridded field of snow water equivalent. To transform the standardized deviate values back into snow water equivalent, an estimate of the mean and variance of the snow water equivalent at each grid point is needed. Estimates of the mean snow water equivalent are developed using a modeling approach which is discussed in the next section. The historical station data were analyzed to develop a relationship between the mean snow water equivalent at a point and its standard deviations for the first of each month during the snow season. The form of this relationship was assumed to be:

$$\sigma = a\bar{x}^{b}.$$

where σ = standard deviation
$\bar{x}$ = mean
a & b = regression coefficients

Given an estimate of the mean snow water equivalent at a grid point, this function can be used to transform the grid point deviate into an estimate of the actual snow water equivalent.

Mean Weekly Snow Water Equivalent

The approach taken in estimating the mean snow water equivalent at a particular grid point is to model the snow accumulation and ablation taking into account the precipitation and site characteristics of the grid point. The GIS is used to store, analyze and display spatial information to assist in the estimation of gridded mean snow water equivalent on a weekly basis throughout the snow melt season.

In the adopted approach, the mean snow water equivalent at each grid point is estimated using the conceptual snow model calibrated for the basin in which the grid point is located. It would be extremely computationally intensive to model snow water equivalent at individual grid points, so grid points are lumped into zones based on snow melt characteristics. The first step is to form melt factor classes which are a function of aspect, slope, and forest cover. Aspect and slope are computed from digital elevation data using the GIS, and then combined to form a new surface which represents an index to the available solar radiation. Since east and west-facing slopes receive the same amount of solar radiation over a day as a horizontal surface, the available solar radiation can be represented by three classes: north, south, and horizontal. The GIS is also used to classify vegetation data into forest and open area classifications. The three solar radiation classes and the two vegetation classes are combined to produce six melt factor classes. Given the average melt factors from a model calibration for the basin and the distribution of melt factor classes throughout the basin, melt factors are estimated for the six different melt factor classes.

The melt which occurs at a grid point is a function of temperature, as well as melt factor. Since temperature is well correlated with elevation, the elevation data are reclassed and combined with the melt factor classes to form snow melt zone classes. It is expected that all the grid points in a particular snow melt zone will exhibit similar snow melt characteristics, however, grid points in the same zone may experience significant differences in the amount of precipitation which they receive. The mean areal temperature (MAT) and mean areal precipitation (MAP) time series for the basin are used to simulate the snow cover for each zone. The melt factors for the zone are used in place of the average basin melt factors and the MAT time series is lapsed from the mean basin elevation to the elevation of the zone. In order to account for the different amounts of precipitation which can occur at grid points within the zone, the zone snow cover is simulated for different percentages of the basin's MAP time series. The resulting simulations are used to define a relationship for the zone between the mean seasonal precipitation and the mean snow water equivalent for a particular date, e.g. April 1. An example of one of these relationships is shown in Figure 1.

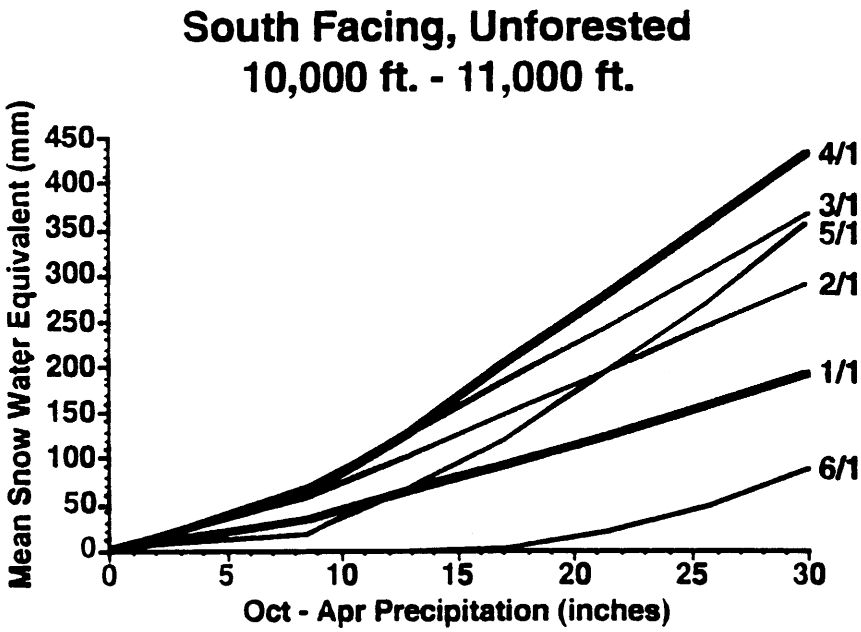

Figure 1.

The GIS is used to derive weekly mean snow water equivalent surfaces from the snow melt zone surface, a surface of the long-term mean October through April precipitation, and the relationships between seasonal precipitation and snow water equivalent. The mean April 1 snow water equivalent surface for a portion of the headwaters of the San Juan Basin in southern Colorado is shown in Figure 2.

Pseudo-Observed Snow Water Equivalent

All of the information needed to estimate snow water equivalent is now available, however, the snow water equivalent estimated using the interpolation procedure may not be consistent with the snow water equivalent states in the conceptual snow model. Historical estimates of the snow water equivalent needed by the model are generated by computing the model states which would have been necessary on a specific date (e.g. April 1, 1960) in order for the model to simulate the seasonal runoff (e.g. April through July, 1960), that was actually observed. These estimates are called pseudo-observed snow water equivalent, and they represent our best estimate of the optimal snow water equivalent model states.

In order to account for biases between the pseudo-observed values and the estimates of snow water equivalent from the interpolation procedure, regression relationships are developed from

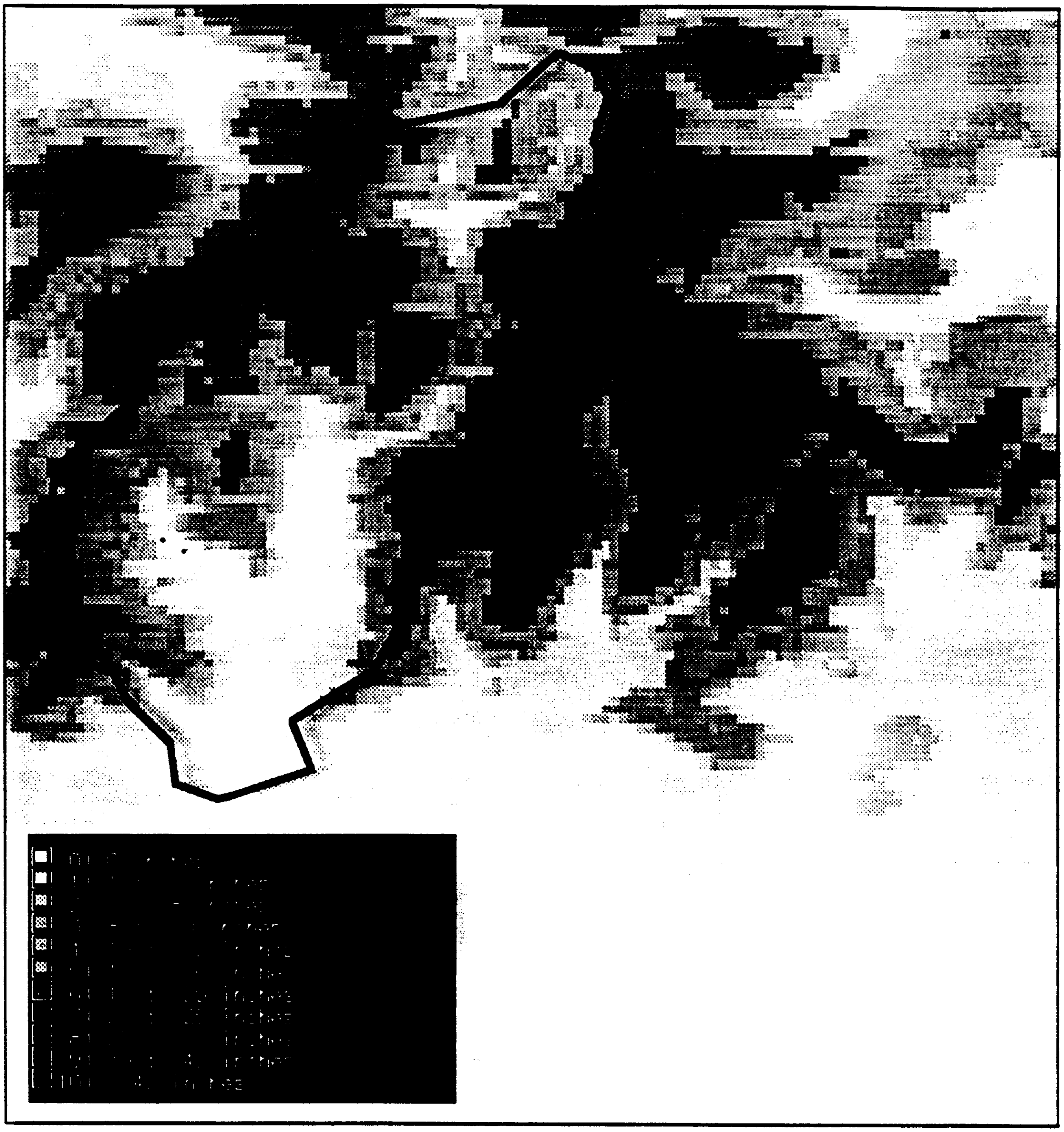

Figure 2. April 1, 1980 Interpolated Snow Water Equivalent Grid, Animas River @ Durango, Colorado

the historical data. Pseudo-observed values are estimated for the first of each month for the entire historical record. Similarly, the interpolation procedure is performed for the first of each month throughout the historical record. The GIS is used to compute basin averages from the gridded estimates of snow water equivalent. Regression relationships, which predict pseudo-observed values from basin average snow water equivalent, are developed for the first of each month. These relationships are used in the operational system to compute estimates of the model snow water equivalent states that can be used for updating.

Operational Component

The Operational Component uses the parametric information defined with the Calibration Component to estimate real-time snow water equivalent each week from January through June. As in the Calibration Component, the GIS is used to store, analyze, and display spatial information. The user interacts with the Operational Component through a GUI, that is structured like the one used for the Calibration Component. Real-time station observations are transformed to standardized deviates, and interpolated using the correlation function estimated for the basin in the calibration step. The GIS is used to transform the standardized deviates developed to estimates of the actual snow water equivalent on a grid point basis.

Updating Component

The GIS was also used to develop basin boundary outlines and to store masks representing the area within each watershed. The estimated snow water equivalent within a basin boundary is summed to determine an areal estimate of snow water equivalent. This basin average snow water equivalent is used with the regression relationships to estimate basin pseudo-observed snow water equivalent. The Updating Component of the methodology combines the pseudo-observed estimates with the current model simulated snow water equivalent states in NWSRFS. The two estimates are weighted based on the relative uncertainty of the estimates, to compute the updated model snow water equivalent states. These updated snow model states are then reflected in any streamflow forecast for the basin. A schematic of the updating step is shown in Figure 3.

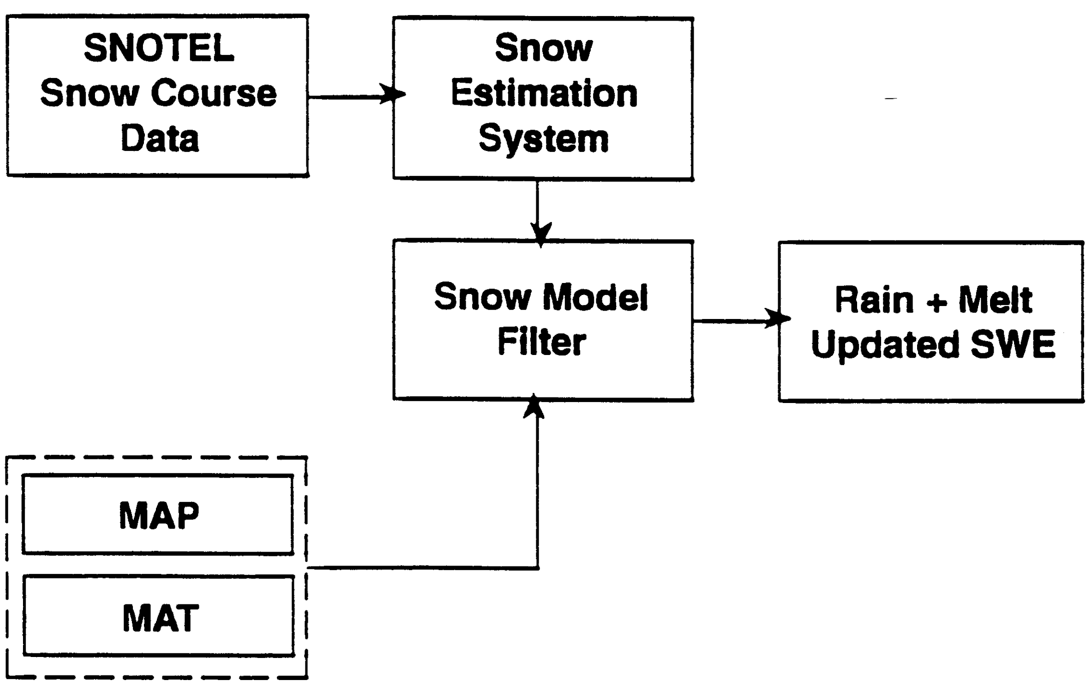

Figure 3.

SUMMARY

The National Weather Service is implementing a snow estimation system which interpolates point snow observations to produce gridded estimates of snow water equivalent. The system uses a GIS to store, analyze, and display point, line and gridded data. The SEUS consists of three components, a calibration component which is used to estimate parametric information and develop derived data planes, an operational component which performs the interpolation of the snow observations in real-time and an updating component which combines the estimated snow water equivalent developed using the system with the model simulated snow water equivalent. Results from several basins have indicated that the updating process improves streamflow forecasting.

This is the first year that the system has been implemented operationally. The baseline system focuses on the Colorado River above Lake Powell. Snow water equivalent grids have been estimated weekly over this area at the NOHRSC. The gridded information was provided to the Colorado Basin River Forecast Center, where it was used to determine areal estimates of snow water equivalent over selected basins within the upper Colorado River drainage basin. The areal estimates were used to update the model computed estimates of snow water equivalent for these selected basins. Additional basins will be included in the updating step in subsequent years.

REFERENCES

Carroll, Thomas R., Day, Gerald N., and McManamon, Ann, "Multistage - Multilevel Snow Estimation in the National Weather Service, A Plan for Development and Implementation", November 25, 1991, Silver Spring, MD

Codd, A.R., and R.A. Work, "Establishing Snow Survey Networks and Snow Courses for Water Supply Forecasting," Proceedings of Western Snow Conference," Portland, Oregon, pp. 6-13, 1955.

Day, Gerald N., McManamon, Ann and McCarthy, Cara S., "Colorado River Forecasting Service Snow Model Updating Project", Status Report, March 1991

Day, Gerald N., "A Methodology for Updating a Conceptual Snow Model With Snow Measurements", NOAA Technical Report NWS 43, Department of Commerce, Silver Spring, MD, March 1990.

Day, Gerald N., "Extended Streamflow Forecasting Using NWSRFS", Journal of Water Resources Planning and Management, ASCE Vol. 111 No. 2 April 1985.

Geographic Resources Analysis Support System (GRASS) User's Reference Manual, Version 4, U. S. Army Corps of Engineers Construction Engineering Research Laboratory, Champaign, IL, July 1991

Shafer, B.A., "SNOTEL, U.S. Department of Agriculture," Soil Conservation Service, Portland, Oregon, pp. 6-13, 1955.