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Gridded Snow Water Equivalent Estimation Using Ground-Based and Airborne Snow Data

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ABSTRACT

The National Weather Service (NWS) has developed a methodology to generate real-time, gridded (1 km) snow water equivalent estimates using ground-based and airborne snow data. The gridded snow water equivalents incorporate the spatial variability of the snowpack induced by orographic effects in the West. A baseline system is currently being implemented by the NWS over the Colorado River basin above Lake Powell.

The Snow Estimation and Updating System (SEUS) uses a geographic information system (GIS) to store, analyze and display gridded, point and line data, such as elevation, basin boundaries and snow observations. The system has a calibration component to define basin-specific parameters, an operational component to ingest real-time data and calculate gridded snow water equivalent estimates, and an updating component to incorporate the ground-based snow water equivalent estimates into a conceptual hydrologic model. This paper reviews the system implementation and the results of operational testing during the 1993 snow season.

INTRODUCTION

In the Western United States approximately 75 percent of the annual runoff results from snow melt. 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 allocations. The National Weather Service River Forecast System (NWSRFS) is a series of continuous hydrologic conceptual models used to predict streamflow. The Extended Streamflow Prediction (ESP) technique is the long-term forecasting component of this system. 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 generated by the system can be analyzed based on the likelihood of the precipitation and temperature time series to produce probabilistic forecasts of such streamflow variables as peaks and volumes. However, difficulties in estimating precipitation in the mountains, can cause inaccuracies in the estimates of the initial conditions provided to the models. SEUS uses airborne and ground-based snow observations to provide a better estimate of these initial snow water equivalent conditions.

The Soil Conservation Service (SCS) collects point snow water equivalent information at over 2000 SNOTEL and snow course locations. Additionally, the National Operational Hydrologic Remote Sensing Center (NOHRSC) collects airborne snow data at over 1500 locations in the United States and Canada. The airborne estimation technique measures the natural gamma radiation emitted by the soil prior to the snow season. During the snow season, the attenuation of the gamma radiation by the snowpack is measured and estimates of the snow water equivalent are calculated. The NWS has developed a methodology to use these snow data to improve the initial estimates of the snowpack conditions (Day, 1990). Analysis of the snow data and incorporation into the conceptual snow model should result in more reliable estimates of seasonal water supply volumes.

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 component to determine gridded snow water equivalent. The updating component modifies the existing snow water equivalent states of the conceptual snow model based on the weighted contributions of the simulated model snow states and the estimates of the snow

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states developed using the snow observations. The weighting for each estimate reflects the relative uncertainty of the estimate due to such factors as model bias and measurement error.

METHODOLOGY

SEUS uses the Geographic Resources Analysis Support System (GRASS) GIS to manage the gridded, line and point data used in the system. 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. Additions and modifications can easily be made to its existing capabilities. Its structure permits the combination of any number of commands to perform the desired function.

SEUS ingests point snow observations and computes estimates of snow water equivalent on a gridded basis (roughly 1 sq. km). A significant number of steps however separate the input from the final product. Several of the critical capabilities are described in the following sections.

Historical Data Analysis

The system analyzes different types of snow observations in a variety of locations with different elevations, slopes, aspects and forest cover. All of these factors affect the snow water equivalent measured by a station. The effects of all these factors are removed by standardizing the data prior to running the interpolation procedure. To compute standardized deviates, the mean snow water equivalent for the site is subtracted from the actual snow water equivalent observation. That value is then divided by the standard deviation of the site. To perform these calculations, it was necessary to examine the historical record of all snow observations to determine the means and standard deviations.

Historical point snow water equivalent data were ingested into a database at NOHRSC. Snow course data have a long period of record but measurements were taken at the beginning of each month and occasionally mid-month. SNOTEL data have a much shorter period of record but are generally reported on a daily basis. Flight line data have a short period of record and are sampled at irregular intervals but provide an areal estimate of snow water equivalent over a much larger area than either of the point data types and therefore may be more representative of snow conditions in the area.

In order to compare SNOTEL, snow course and flight line data, the snow observation data must have a consistent period of record. To fill in missing data and/or extend the period of record for certain stations, the data were analyzed to determine the closest surrounding stations. Nearby snow course stations could be used for estimating missing data throughout the historical record. Estimates of the snow water equivalent value for each SNOTEL and flight line record were calculated for the entire historical record for the first of each month from January through June using the station's relationship to nearby snow course stations.

Monthly mean snow water equivalent and the associated standard deviation were computed for each station. The number of sites reporting in January and June were far fewer than during the intervening months. The estimation and adjustment techniques were required to search farther afield for nearby stations and thus there is less confidence in snow water equivalent estimates during these months. Other techniques for completing the records in these months will need to be investigated.

Operationally, nearby SNOTEL sites are useful for adjusting snow course and flight line snow water equivalent values to a common date before analysis. SNOTEL daily records provide an indication of snow pack conditions in the general area. Depending upon whether the snow pack has been accumulating or ablating during the period between the actual measurement at the snow course or flight line and the date for which the analysis is desired, the snow course and flight line snow water equivalent values can be adjusted.

A daily time series was created for each snow observation. The time series included all observed data and estimates of the adjusted snow water equivalent when an observation had to be "moved" to the first of the month. Snow water equivalent values that were estimated for determining means and standard deviations were not included in these time series.

As individual basins were calibrated, the snow observations which represent the area were identified and these data were analyzed to develop basin-specific parameters. A linear relationship describing the correlation between any two stations as a function of distance was developed for use in the interpolation routine. The relationship between the mean and standard deviation for these same stations was also developed so that the interpolated field of station data could be transformed into estimates of snow water equivalent.

Mean Snow Water Equivalent

The mean snow water equivalent is estimated at any particular grid point using NWSRFS to model the snow accumulation and ablation taking into account the precipitation and site characteristics at the grid point. It is computationally prohibitive to model snow water equivalent at individual grid points, so grid points are lumped into classes with similar snow melt characteristics. Melt factor classes which are a function of aspect, slope and forest cover are created. Aspect and slope are computed from digital elevation data stored at a grid spacing of 30-arc seconds (roughly 1 km), and then combined to form a new surface which represents an index to the available solar radiation. East and west-facing slopes were assumed to receive the same amount of solar radiation over a day as a horizontal surface. A grid was considered to be horizontal if the slope was less than 10 percent. Thus, the available solar radiation can be represented by three classes: north, south, and horizontal. The GIS is also used to classify vegetation data into forested 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.

Within the NWSRFS snow model, the melt which occurs is a function of temperature as well as melt factor. Since temperature is well correlated with elevation, the elevation data are grouped into bands of elevation. The elevation bands balance the need to minimize computational requirements and yet represent the melt zones adequately. During this first year of operational testing, elevations bands were generally set for each 300 meters of elevation within the basin.

The reclassed elevation layer is 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. 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. To represent the different amounts of precipitation which can occur within a given zone, the basin's MAP time series is multiplied by factors ranging from 0.5 to 1.75. The resulting simulations are used to define a relationship for the zone between the mean October through April precipitation and the mean snow water equivalent for a particular date, e.g., April 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 relationship between seasonal precipitation and snow water equivalent.

Snow Water Equivalent Estimates

The methodology developed involves the interpolation of point snow water equivalent data into gridded estimates of snow water equivalent. The interpolation procedure is beyond the scope of this paper and therefore is not discussed. Interested parties may wish to review Day (1990) and Carroll and Carroll (this proceedings) for detailed discussions of the interpolation procedure.

The interpolation routine permits the specification of the number of snow observations to use to compute each grid point. The interpolated field of standardized deviates is smoother as the number of stations used increases. This year the number of stations was set to twenty until sufficient experience is gained to determine the optimal number. However, using this number of stations is very computationally intensive and causes this step in the process to take a significant amount of time. The present time requirements are not acceptable in an operational environment and both the interpolation routine and the system design are being reviewed.

What is really desired, however, is a gridded field of snow water equivalent. To transform the standardized deviates into snow water equivalent, the previously defined basin-specific relationship between mean snow water equivalent and standard deviation is used. The equation to calculate standardized deviates is rewritten to solve for snow water equivalent and the field is calculated. This gridded field of snow water equivalent can be used for many purposes. Figures 1a & 1b depict gridded fields of standardized deviates and snow water equivalents respectively for the Animas River basin at Durango, Colorado for April 1, 1993.

To update the snow conditions of the NWSRFS, the GIS is used to compute the average snow water equivalent over an area. Most basins calibrated in NWSRFS are split into two or more subareas which are representative of the snow cover which the area can expect to accumulate during an average year. An areal average of each subarea is made to update the initial estimates for the snow model.

Pseudo-observed Snow Water Equivalent

The estimated snow water equivalent from the

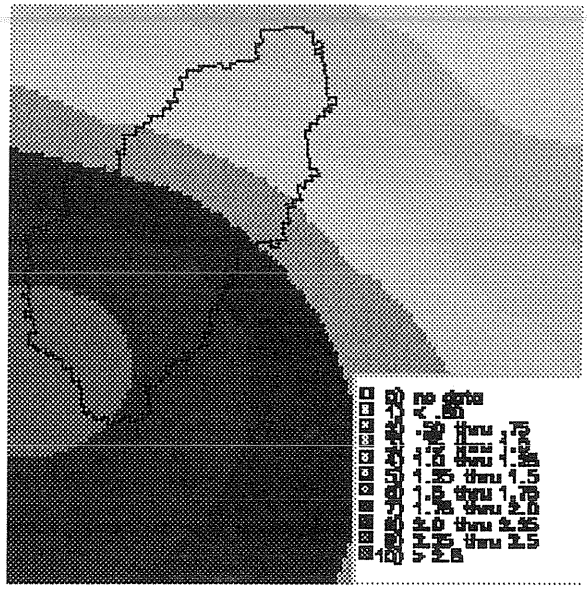

Figure 1a. April 1, 1993 standardized deviate gridded surface.

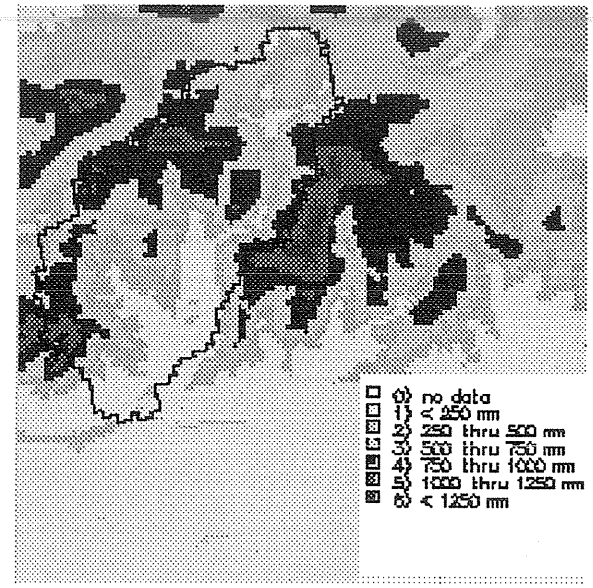

Figure 1b. April 1, 1993 estimated snow water equivalent gridded surface.

snow observation data should provide a good estimate of the initial snow conditions needed in the conceptual snow model. The estimates could be used to update the conceptual model. 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 due to model bias.

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 represent our best estimate of the optimal snow water equivalent model states. Pseudo-observed snow water equivalents are developed for each basin subarea which has been calibrated for NWSRFS.

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 the historical data. Pseudo-observed values are estimated for the first of each month for the entire historical record. SEUS is run for the first of each month throughout the historical record to develop gridded snow water equivalent estimates. The GIS is then used to compute subareal averages from the gridded estimates of snow water equivalent. Regression relationships, which predict pseudo-observed values from these subareal average snow water equivalents, are developed for the first of each month. These relationships are used in the operational system to calculate estimates of the model snow water equivalent states to be used for updating.

RESULTS

This is the first year that the system has been implemented operationally. The initial focus has been on the Colorado River basin above Lake Powell. Within this area a few basins have been selected which have recently been calibrated to develop parameters needed to run NWSRFS (Figure 2). Each basin's parameters were used to represent larger regional areas until all the basins within the region can be recalibrated and parameters necessary for SEUS can be determined.

The Animas River basin drains 1850 km^2 above Durango, Colorado. Within the basin, the elevation ranges from 2000 meters to 3960 meters above msl. This basin was used to represent the San Juan River basin. The Green River basin above Warren Bridge, Wyoming is slightly smaller comprising 1200 km^2, with an elevation range from 2300 meters to 3960 meters. It was used to represent the Green River above it's confluence with the Colorado River.

Three contiguous basins within the Colorado River mainstem basin were also included in the baseline system. The Blue River basin at Dillon Reservoir is the largest and highest of the three

Figure 2 Location map of the Upper Colorado basin showing study sites.

comprising 870 km² and ranging in elevation from 2680 meters to 4100 meters. Also on the Blue River, the local contributing area above Green Mountain Reservoir is 645 km² in area with elevation ranges from 2440 meters to 4085 meters. William's Fork River above William's Fork Reservoir is the smallest of the three basins comprising only 557 km² and the lowest with an elevation range of 2380 meters to 3990 meters.

The 1993 snow season brought diverse snowfall to the West. Within the study area of the SEUS, snowfall was greater than average in the southern and mid sections of the Upper Colorado basin. However, areas in the Green River basin indicated lower than average snow water equivalent. Table 1 details the estimated snow water equivalent for each of the test basins, for April 1, 1993. Looking at the totals for each basin, it can be seen that, with the exception of the Green River at Warren Bridge, all the basins were experiencing greater than average snow water equivalent.

As mentioned previously, for modelling purposes, basins within NWSRFS are often split into subareas representing areas with common snow accumulation properties. The "upper" area is considered to accumulate snow every year which contributes to the seasonal streamflow hydrograph. The "lower" subarea generally only receives significant snow

Table 1 - April 1, 1993 Snow Water Equivalent (SWE) Estimates

	Lower Subarea		Upper Subarea		Total	
	SWE (mm)	% of avg.	SWE (mm)	% of avg.	SWE (mm)	% of avg.
Green River at Warren Bridge, WY	240[1]	84	475	82	350	83
Blue River at Dillon Reservoir	170[2]	112	400	108	360	109
William's Fork River at William's Fork Reservoir	150[2]	132	420	115	250	125
Blue River local area above Green Mountain Reservoir	140[2]	123	550	111	340	117
Animas River at Durango, CO	190[3]	280	600	130	400	200

[1] area below 2740 m (9000 feet)
[2] area below 3050 m (10,000 feet)
[3] area below 3080 m (10,100 feet)

during years with large snowfalls. Examining the subarea columns in Table 1, it can be seen that although the upper subarea values for all the basins except the Green River at Warren Bridge show greater than 100 percent of average snow water equivalent, the lower subarea shows an even greater positive deviation from the average. Again, these results would be expected in years with large snowfalls. More importantly, these results suggest that both the upper and lower subareas in all but the Green River at Warren Bridge will be contributing significant amounts of water to the streamflow for the 1993 season.

To improve streamflow forecasting, the snow water equivalent estimates generated using SEUS were used to update the snow model states in NWSRFS. Forecasts of April through July streamflow volumes for water supply purposes were made and the results tabulated in Table 2. When reviewing the table, several factors should be kept in mind:

1. The observed runoff for the 1993 water year is as yet unknown. In general, an update that improves agreement with the coordinated volume is desirable. However, the coordinated volume may not be the most accurate forecast.

2. The results achieved in a single year do not validate or invalidate the SEUS methodology.

3. The five basin models used in the demonstration were 'cold started' during the fall and winter of water year 1993. As a result, unknown errors in initial parameter states may affect the quality of the extended forecasts.

These caveats aside, using the snow water equivalent values generated by SEUS to update the NWSRFS models produced very encouraging results. In general, the forecast volumes were very close to those provided by regression and coordinated with the SCS. Some of the pre-updating differences may be attributable to the 'cold starting' error.

Although one year of data on five basins is not sufficient to validate a methodology, the preliminary results suggest the method provides comparable estimates to regression techniques. The spatial nature of the methodology and its products permit additional uses of the output and provide more information on the distribution of snow water equivalent over an area. In coming years, additional basins in different hydrologic settings will be examined.

Table 2 - April-July Streamflow Volume Forecasts as of April 1, 1993

	April - July Streamflow Volumes		
	Without Updating (acre-ft)	With Updating (acre-ft)	Coordinated Forecast (acre-ft)
Green River at Warren Bridge, WY	356 (439)[1]	239 (295)	220 (271)
Blue River at Dillon Reservoir	133 (164)	155 (190)	150 (184)
William's Fork River at William's Fork Reservoir	108 (133)	87 (107)	84 (104)
Blue River local area above Green Mountain Reservoir	122 (151)	110 (136)	125 (154)
Animas River at Durango, CO	—[2]	483 (596)	590 (728)

[1] units in parentheses are thousands of cubic meters.
[2] data not available

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