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 the orographic effect in the West. A baseline system is currently being implemented at the National Operational Hydrologic Remote Sensing Center (NOHRSC) in Minneapolis, MN and the Colorado Basin River Forecast Center (CBRFC) in Salt Lake City, UT for operational testing over the Colorado River basin above Lake Powell.

The Snow Estimation and Updating System (SEUS) uses a geographic information system (GIS) to store and analyze 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 groudn-based snow water equivalent estimates into a conceptual hydrologic model. This paper reviews the results of the system implementation and 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 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 generated by the system can be analyzed based on the likelihood of the precipitation and temperature time series to produce probabilistic forecasts of streamflow peaks, volumes, etc. Difficulties in estimating precipitation in the mountains, can cause inaccuracies in the estimates of the initial conditions used in the models.

The Soil Conservation Service (SCS) collects point snow water equivalent information at over 2000 SNOTEL and snow course locations. Additionally, the NOHRSC collects airborne snow data at over 1500 locations in the US and Canada. The airborne estimation technique measure the natural gamma radiation emitted by the soil prior to any snowfall. During the snow season, the attenuation of the gamma radiation by the snowpack can be measured and estimates of the snow water equivalent are calculated. The NWS has developed a methodology to use these snow data to improve the estimates of the snowpack conditions.

(Day, 1990). The 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 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.

METHODOLOGY

Historical Data Analysis

Historical point snow water equivalent data were ingested into a database at NOHRSC. Snow course data has an extended historical record often back to water year 1948 but measurements are only made around the first of the 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 wider area than either of the point data types and therefore may be far more representative of snow conditions in the area.

The data were reorganized into daily time series. The data were analyzed to determine the closest surrounding stations. These surrounding stations were used for two purposes. Nearby snow course stations could be used for estimating missing data throughout the historical record and nearby SNOTEL sites were useful for adjusting snow course snow water equivalent values to a common date for further 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 and the date for which the analysis is desired, the snow course snow water equivalent values can be adjusted.

In order to compare SNOTEL and snow course data, the snow observation data must have a consistent period of record. Therefore, estimates of the snow water equivalent value for each SNOTEL 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 means and standard deviations were computed for each station. The number of sites reporting in January and in June were far fewer than during the remaining period. The estimation and adjustment techniques were required to search farther afield for nearby stations and thus the resulting snow water equivalent estimates are far less stable during these months. Other techniques for completing the record in these months will need to be considered.

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 relationship determining how well correlated any two stations as a function of the distance between them was developed for use in the interpolation routine. The relationship between the mean and standard deviation for the stations was developed so that the interpolated field of station data could be transformed into estimates of snow water equivalent.

Mean Snow Water Equivalent

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, 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 capabilities to tailor the GIS to the function which needs to be performed.

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 would be extremely computationally intensive to model snow water equivalent at individual grid points, so grid points are lumped into areas with similar 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 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. 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 grouped into bands of elevation. The elevation bands balance the need to minimize computational requirements and yet adequately represent the melt zones adequately. During this first year of operational testing, elevations bands were generally set for each 1000' of elevation within the basin. preliminary results suggest that a finer band is appropriate in some areas.

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, however, grid points in the same zone may experience significant differences in the amount of precipitation which they receive. The mean area 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 different percentages of the basin's MAP time series are used as input to the conceptual snow model. 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. 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 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 data are transformed into standardized deviates by subtracting the station's mean for the selected data and dividing by the standard deviation for the same date. To interpolate at each grid point, the previously calculated basin-specific correlation function is needed to describe the relationship between an individual grid point and the surrounding snow observation data. 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 points increases. This year, the number of points was set to twenty until sufficient experience is gained to determine the optimal number. However, using this number of points is very computationally intensive and causes this step in the process to take a significant amount of time. The present time requirements are probably not acceptable in an operational environment. What is really desired, however, is a gridded field of snow water equivalent. To transform the standardized deviates back into snow water equivalent, the previous defined basin-specific relationship between mean snow water equivalent and standard deviation is used. The equation to calculate standardized deviate is rewritten to solve for snow water equivalent and the field can be 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 at Durango, Colorado for April 1, 1993.

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

Pseudo-observed Snow Water Equivalent

The estimated snow water equivalent from the snow observation data should provide a better 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. 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 the historical data. Pseudo-observed values are estimated for the first of each month for the entire historical record. Similarly, the interpolation precedure is performed for the first of each month throughout the historical record. The GIS is used to compute subareal averages from the gridded estimates of snow water equivalent. Regression relationships, which predict pseudo-observed values from subareal 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.

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. These basins were used to represent larger regional areas until all the basins within the region have been recalibrated and can be brought in to the SEUS.

The 1993 snow season brought record snowfalls to some areas in the West. Within the study area of the SEUS, snowfall was greater than expected 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. With the exception of the Green River at Warren Bridge, all the basins were experiencing greater than average snow water equivalent. However, in the other areas, the trend that can be seen, the lower subarea is contributing a much greater percentage than during average years. The lower subarea is generally defined as that area which only receives an appreciable amount of snow during "big" years.

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Table 1

	Lower Subarea		Upper Subarea		Total	
	SWE (mm)	% of avg.	SWE (mm)	% of avg.	SWE (mm)	% of avg.
Green River at Warren Bridge, WY	237[1]	84	476	82	354	83
Blue River at Dillon Reservoir	171[2]	112	405	108	357	109
William's Fork River at William's Fork Reservoir	146[2]	132	419	115	254	125
Blue River local area above Green Mountain Reservoir	144[2]	123	545	111	344	117
Animas River at Durango, CO	188[3]	280	601	130	405	200

[1] area below 2900 m (9500 feet)

[2] area below 3050 m (10,000 feet)

[3] area below 3385 m (11,100 feet)

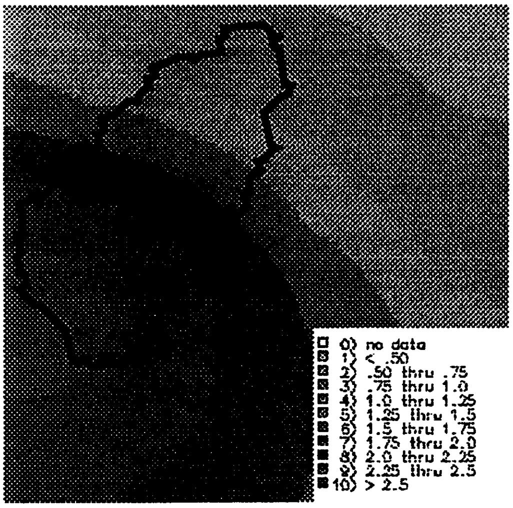

Figure 1a. April 1, 1993 standardized deviate grided surface.

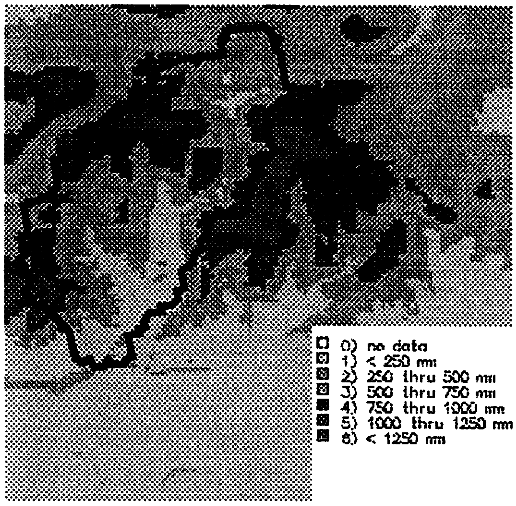

Figure 1b. April 1, 1993 estimated snow water equivalent gridded surface.