# A DIRECTION TOWARD IMPROVED STREAMFLOW FORECASTING IN THE WESTERN MOUNTAINS

by

Gerald N. Day[1], John C. Schaake[1], and J. Hugh Ellis[2]

## INTRODUCTION

In the Western United States, more than 70 percent of the annual water supply results from snowmelt (Barton, 1977). Forecasts of water supply are critical for reservoir operation, agricultural and industrial planning, flood control, irrigation scheduling, hydropower planning, municipal water supply decisions, water quality management, riverine navigation, and wildlife and recreation planning. Accurate forecasts and their associated uncertainties are needed to ensure proper operation of reservoirs and efficient use of the available water. Castruccio et al. (1981) estimated that a 6 percent improvement in forecasting accuracy would produce $36.5 million in annual benefits to agriculture and hydropower in the West. An improvement in the ability to quantify the uncertainty of water supply forecasts would provide a better basis for using water supply forecasts in risk assessment and economic analysis. Improvements in the quantification of the uncertainty of long-term forecasts may provide value to distant forecasts that currently are of little benefit to users.

Uncertainty in water supply forecasts can be attributed to three major components: climate variability, model error, and data error (Schaake and Peck, 1985). Most of this uncertainty is due to climate variability. In the long-term an increase in the skill level of extended weather forecasting provides substantial opportunities for improvements in water supply forecasting. However, model and data errors account for a significant portion of the uncertainty in water supply forecasts. Model error is introduced because of our inability to perfectly represent the physical processes of snowmelt and runoff integrated over a basin. Even with perfect knowledge of the current states of the hydrologic system and its future inputs, our forecasts would contain errors due to our inability to exactly describe how the system evolves in time. Data errors are introduced partially because of measurement errors which include such factors as gage catch efficiencies, sensor inaccuracies, data transmission problems, and human errors. Data errors are also introduced because of our inability to perfectly represent meteorological inputs on an areal basis.

This paper presents a framework for streamflow forecasting in the Western mountains that attempts to better utilize currently available data in National Weather Service (NWS) conceptual hydrologic models, and provides the flexibility to accept new data as they become available. Recent advances in the understanding of ocean-atmosphere interactions provides new hope for improved long-range weather forecasts. The framework presented herein offers the potential to incorporate this new information.

## WATER SUPPLY FORECASTING

Historically, regression models have been used to predict seasonal water supply from snowmelt. This practice dates back to the use of Mt. Rose snow course data to forecast the Lake Tahoe lake level early in this century. Regression procedures in use today may include baseflow, precipitation, and snow-water-equivalent as independent variables. The procedures are used throughout the forecast season, January thru May, to produce forecasts of seasonal water supply. More recently, conceptual models have been used for streamflow forecasting in the mountainous west. These models are typically applied on a lumped area basis. They attempt to model snow accumulation and melt processes and to perform soil moisture accounting. The conceptual models provide detailed streamflow information and have the potential to produce accurate forecasts under a wide range of hydrologic conditions.

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1 Office of Hydrology, National Weather Service, Silver Spring, Maryland
2 The Department of Geography and Environmental Engineering, The Johns Hopkins University, Baltimore, Maryland.

Since the mid-seventies conceptual models have been used within the NWS Extended Streamflow Prediction (ESP) procedure (Twedt et al., 1978; Curtis and Schaake, 1979; Day, 1985) to produce forecasts of water supply. This procedure has the flexibility to produce forecasts for a range of streamflow variables, e.g. volumes, peaks, low flows, number of days flow is above/below a threshold, etc. In addition to providing the expected value of the forecast variable it also estimates the probability density function of the variable. This provides the user a measure of the uncertainty of the forecast. ESP, like the conceptual models on which it is based, has the potential to produce accurate forecasts under extreme hydrologic conditions. The technique depends on reliable parameter estimates for the conceptual models, representative historical time series of mean areal precipitation and temperature, and accurate estimates of the current watershed states, e.g. snow pack and soil moisture.

## NWS Snow Accumulation and Ablation Model

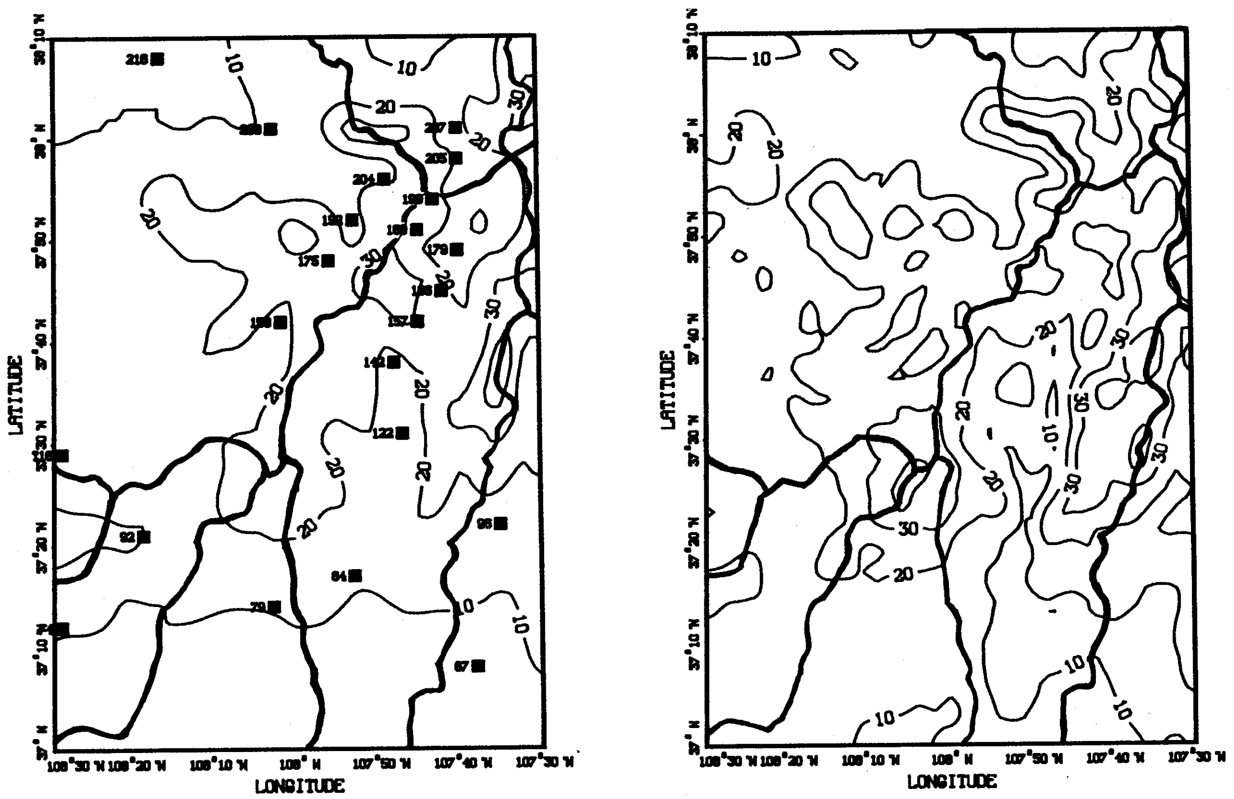
The NWS snow model was developed by Anderson (1973). The model uses air temperature as an index to the energy exchange across the snow-air interface. By making several reasonable assumptions, an energy budget equation is used to approximate melt during rain-on-snow periods. The model uses an empirical temperature driven melt factor relationship to estimate melt during non-rain periods. The model keeps continuous account of the negative heat storage of the pack and requires that any negative heat storage be brought to zero before melt can occur. The model also attempts to simulate the fraction of the basin covered by snow through the use of an areal depletion curve. This curve defines the areal extent of snow cover as a function of the ratio of the mean areal water-equivalent to a maximum mean areal water-equivalent. The model keeps continuous account of the snow pack states given estimates of mean areal precipitation and temperature.

Areal estimates of precipitation and temperature are currently calculated from relatively sparse networks of point observations. The dynamic interactions between storm systems and the topography complicate the estimation of precipitation in the mountains. There is usually a lack of high elevation precipitation data because of the difficulty in locating and servicing gages at high elevations. As well, these data are often a source of error because of the high winds in these areas and the effects of wind on obtaining accurate precipitation measurements (Larson and Peck, 1974). The problem of estimating streamflow is compounded since more of the precipitation falls at high elevations and most of the runoff results from snow which melts at these elevations. In addition, errors in temperature estimates affect the determination of the form of precipitation and the calculation of snowmelt. Temperature lapse rates can exhibit large deviations from normal during individual events. This makes it difficult to extrapolate temperature on an areal basis under some conditions.

The accumulation of snow is further complicated by redistribution of fallen precipitation. The amount of redistribution which occurs is a function of winds and site exposure. Finally, snowmelt is a function of wind, temperature, humidity, and radiation, which in turn are related to aspect, slope, and exposure. These factors complicate the use of a conceptual model in the mountains. Models are limited by both the available data and their ability to properly account for the temporal and spatial variability of the important hydrometeorological processes. However, they also provide a basis for a framework to improve streamflow forecasts as our understanding of these natural variabilities improves.

## Orographic Precipitation Model

The estimation of mean areal precipitation can be improved through the use of an orographic precipitation model. An orographic precipitation model accounts for condensation or evaporation caused by vertical displacements as an air mass moves over the underlying topography. Part of the condensate formed over an area precipitates and part is carried by the air mass to precipitate or evaporate downstream. The orographic precipitation model provides detailed information about the spatial distribution of precipitation that is not available from a sparse network of point observations. Figure 1(a) shows an October through April isohyetal map for part of the San Juan mountains. The map was constructed following the procedures discussed in Peck and Brown (1962). Figure 1(b) shows the same map constructed using an orographic precipitation model. There are strong similarities between the two maps, but the map constructed using the orographic precipitation model shows the effects of the local topography in more detail. The orographic precipitation model provides information useful in defining the climatological mean precipitation and snow-water-equivalent. This information is useful in procedure development, model calibration, and network design. The use of an orographic precipitation model in real-time also provides the potential to better define the spatial distribution of precipitation on an event-by-event basis.




(a) Peck, Brown Procedure (in.)

(b) Orographic Precipitation Model (in.)

Figure 1. October thru April Isohyetal Maps - San Juan Mountains

## Snow Observations

Snow observations are another source of information about the water balance in mountainous areas. The Soil Conservation Service (SCS) has the responsibility for coordinating the Cooperative Snow Survey Program in the Western U.S., excluding California. As part of this program, snow-water-equivalent is estimated at approximately 1800 snow courses during the late winter and early spring (Palmer, 1988). Many state and private agencies are also involved in the collection of snow survey measurements. In 1978 the SCS began collecting snow-water-equivalent data remotely using snow pillows through the SNOTEL (snow telemetry) System (Schaefer and Shafer, 1982). The present SNOTEL system collects snow-water-equivalent, temperature, and precipitation from approximately 550 sites. Estimates of snow-water-equivalent from snow courses and snow pillows are typically considered as point observations. The effect of local conditions on the measurements makes it difficult to treat them as anything more than an index to basin snow-water-equivalent.

The NWS began research in 1969 to develop a technique using natural terrestrial gamma radiation attenuation to measure snow-water-equivalent and soil-moisture from low flying aircraft. (Carroll et al., 1985). The NWS is currently responsible for maintaining a Federal Interagency National Remote Sensing Hydrology Program. The program was established to facilitate the collection, analysis, distribution, and use of remotely sensed hydrologic products. It includes an Airborne Snow Survey Program and a Satellite Snow Cover Mapping Program. The Airborne Snow Survey section currently has a calibrated network of over 1400 flight lines covering portions of 25 states and 7 Canadian provinces. Flight lines are typically 16 kilometers long and 300 meters wide. An integrated snow-water-equivalent value is reported over the flight line area (Carroll and Allen, 1988). The technique was originally applied in the Upper Midwest, but it is now being applied to basins in the West. Flight line data may be more representative of areal snow-water-equivalent than point data because of the inherent measurement errors of the techniques and the larger areal extent of the line data. However, line data can still not account for the variability in water-equivalent over an entire basin, and in fact will not be available in extremely rugged terrain.

The Satellite Hydrology section provides estimates of areal extent of snow cover operationally over large areas of the Western U.S. Data are currently reported by USGS cataloging units and by elevation zones for some basins. There are also plans to provide fields of gridded estimates of snow/no snow operationally in the future.

## SYSTEMS APPROACH

One way to improve snowmelt simulation is to adjust model states based on observations of snow-water-equivalent. The procedure of adjusting a model's states so that the model simulation reflects observations is referred to as updating. Estimation theory provides a logical framework for updating in which an estimate of a state variable from a model simulation can be objectively combined with one from observations, based on the relative uncertainties of the estimates. The Kalman filter is an optimal estimator which provides a linear unbiased minimum variance estimate of a model state. Application of the filter requires a system equation and a measurement equation. The system equation describes how the model states evolve in time as a function of the current states and future inputs. The measurement equation relates the observations to the model states. The filter assumes a linear system, so the equations must be linearized when a non-linear model is used. A derivation of the filter equations is presented in Gelb et al. (1974).

A schematic of the methodology is shown in Figure 2. The approach combines the information offered by the conceptual hydrologic models with the additional information obtained from an orographic precipitation model and a statistical analysis of the available snow data. Currently, meteorological processing consists of weighting the point observations with a set of fixed weights based on a climatological analysis of the precipitation. An orographic precipitation model offers the possibility of adjusting these weights in real-time based on the particular storm direction and type. This analysis should result in improved estimates of areal precipitation and improved simulated snow model states.

The statistical analysis of the snow data consists of a spatial interpolation of the available data to form an estimate of the snow-water-equivalent throughout the basin. An optimal interpolation technique originally presented by Gandin (1965) is used to interpolate the snow observations. The technique estimates the value at a point as a weighted sum of the observations. The weights are computed by minimizing the expected sum of the squared error of the interpolation estimate based on the correlation structure of the random field. Standardized deviates are calculated for each observation:

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

where
- $z$ = standardized deviate,
- $x$ = water-equivalent observation,
- $\bar{x}$ = mean water-equivalent at the site, and
- $s$ = standard deviation of the water-equivalent at the site.

(Note: The site mean and standard deviation are for the observation date, e.g., April 1.)

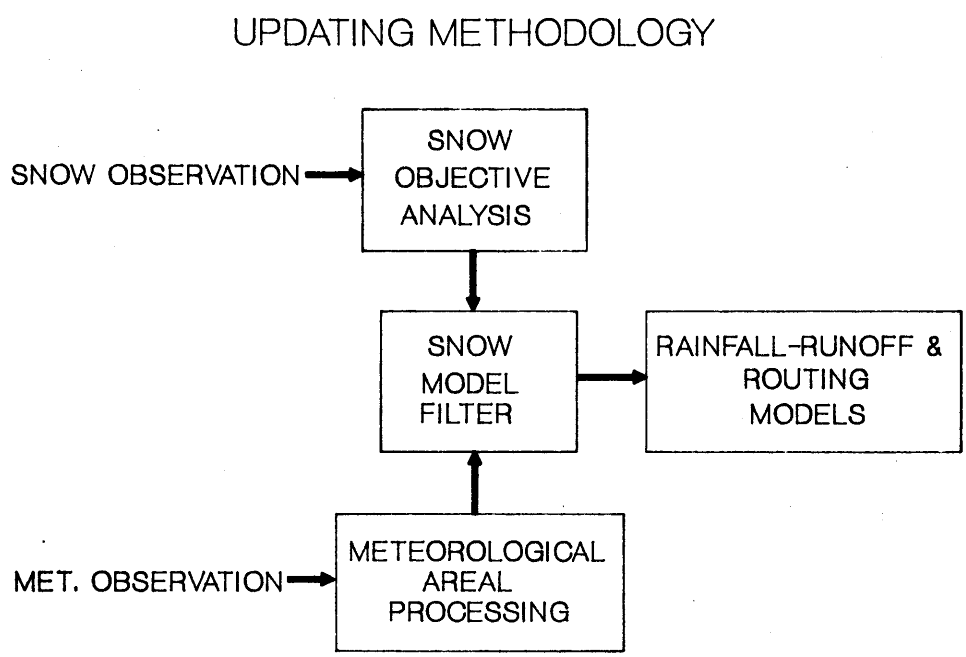



Figure 2. Updating Methodology

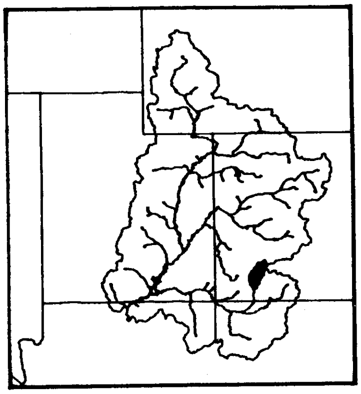
The standardized deviates provide a field that is more easily interpolated since they are stationary in the mean and variance. The standardized deviates are interpolated at grid points throughout the basin. Given the mean and standard deviation at each grid point, an estimate of the current water-equivalent at each point can be made. Estimates of mean areal snow water-equivalent can be made by averaging over the grid points in the subareas. The interpolation procedure can be performed for each historical year to develop a historical record of spatially interpolated estimates of mean areal water-equivalent for a specific date, e.g., April 1. These historical estimates can be used to develop a relationship between the interpolated values and the model states. Minor changes to the observation network should not affect the relationship, but they may affect its uncertainty. In order to use the procedure, estimates must be made of the mean and variance of the snow-water-equivalent at all of the grid points, the mean and variance of the snow-water-equivalent observations, and the correlation structure of the standardized deviates. If a reasonable estimate of the mean and variance at a new observation site can be made, the procedure can incorporate the new site into the estimation procedure. The uncertainty in estimating the mean at the new site is taken into account and reflected in the weight assigned to the site in the estimation procedure.

The orographic precipitation model can provide information on the spatial variability of precipitation at the grid points. The snow model can be used to define the spatial variability of melt. Grid points can be grouped into zones of similar melt characteristics by taking into account elevation, aspect, slope, and forest cover. Assumptions can be made about how the melt factors vary from zone to zone so that snow model calculations can be performed for each zone. This procedure can be calibrated by comparing the results from the grid point analysis to the lumped model results.

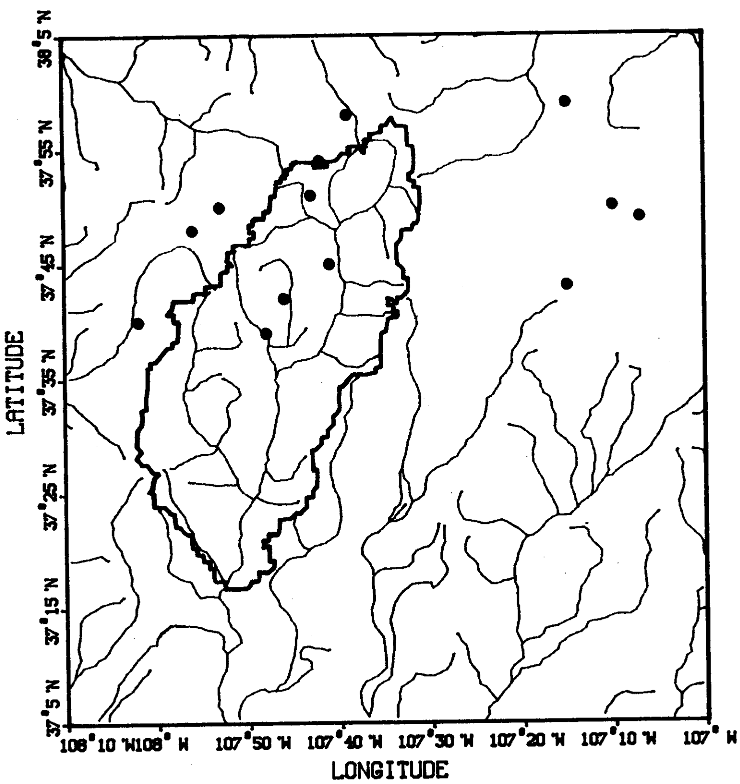
The interpolation methodology can be extended to handle additional sampling geometries, such as the flight line data from the Airborne Snow Survey Program. The Kalman filter formulation for the snow model will allow other observations, e.g. areal extent of snow cover, to be used for updating the snow model states provided a relationship between the observation and the model states can be defined. In general, as improvements are made in our ability to account for the spatial variability of the snow accumulation and ablation processes, these improvements will be reflected in the estimates of the snow states and their uncertainties. This approach allows us to combine estimates of the snow states from the model simulation with estimates from the snow observations based on their relative uncertainties.

RESULTS

Some parts of the approach have been tested on the Animas Basin at Durango, Colorado. The drainage area of the Animas is about 1792 square kilometers. The location of the Animas, within the Upper Colorado, is shown in Figure 3(a). Figure 3(b) is a larger map of the Animas showing the basin drainage network and the location of the point snow-water-equivalent observations used in the analysis. The test consisted of using April 1 observations to update the simulated April 1 states of the snow model each year of the historical record. The success of the updating is judged by its effect on the seasonal streamflow volume simulation (April thru September).



(a) Location in Upper Colorado Basin




(b) Animas Drainage Network and Point Snow Water-Equivalent Sites

Figure 3. Animas River Basin at Durango, Colorado

Snow model calculations were done on a zonal basis to estimate the mean snow-water-equivalent field for the first of March, April, May, and June. These results were compared qualitatively with satellite derived areal snow cover maps for 1985 and 1986. There appeared to be reasonable agreement in the way snow cover retreated, except along the ridge on the southwest edge of the basin. The modeling results show that the snow cover is not depleted in this area as quickly as the maps indicate. This could be due to an overestimate of the precipitation in this area or an underestimate of the melt rates. The mean snow-water-equivalent field for April 1 is shown in Figure 4.

The interpolation procedure was used to interpolate the April 1 standardized deviates for each historical year. Figure 5 shows the interpolated deviates for April 1, 1980. The resulting estimated April 1, 1980 snow-water-equivalent field is shown in Figure 6. The estimated field was summed over each subarea to produce mean areal snow-water-equivalent estimates. These values were converted into observations of the model states and used for updating. Updates were made each April 1 and the resulting April thru

September volumes were calculated. The observed seasonal volumes are shown plotted against the simulated seasonal volumes in Figure 7 and against the updated seasonal volumes in Figure 8. The updating decreased the unexplained variance of the observed volumes from 10 percent to 5 percent. Additional statistics are shown in Table 1. The updating improved the seasonal, monthly, and daily statistics. The effects of the updating on hydrograph simulation are shown in Figure 9 for 1980. The updating did not affect the shape of the hydrograph, but it improved the volume simulation.

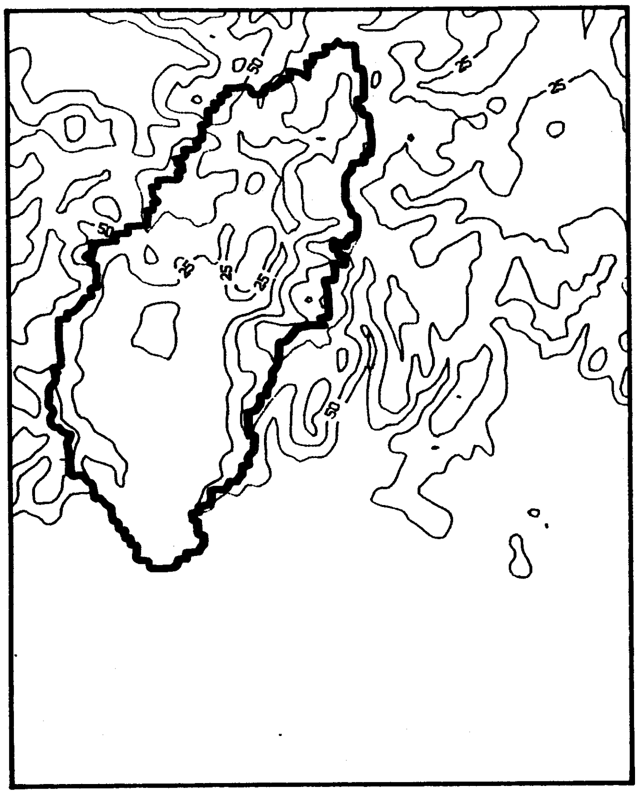



Figure 4. Mean April 1 Snow-Water-Equivalent (cm.)

Table 1. Streamflow Statistics for the Animas Basin

| | Simulated | Updated (April 1) |
|---|---|---|
| Seasonal (Apr.-Sep.) | | |
| Avg. Absolute Error ($10^6 m^3$) | 62.3 | 36.9 |
| RMS Error ($10^6 m^3$) | 80.2 | 48.5 |
| Bias (%) | -.004 | .000 |
| Correlation Coefficient | .951 | .977 |
| Monthly | | |
| Avg. Absolute Error (mm) | 5.4 | 4.5 |
| RMS Error (mm) | 9.8 | 7.4 |
| Daily | | |
| Avg. Absolute Error (CMSD) | 5.0 | 4.5 |
| RMS Error (CMSD) | 9.8 | 8.5 |
| Correlation Coefficient | .946 | .958 |

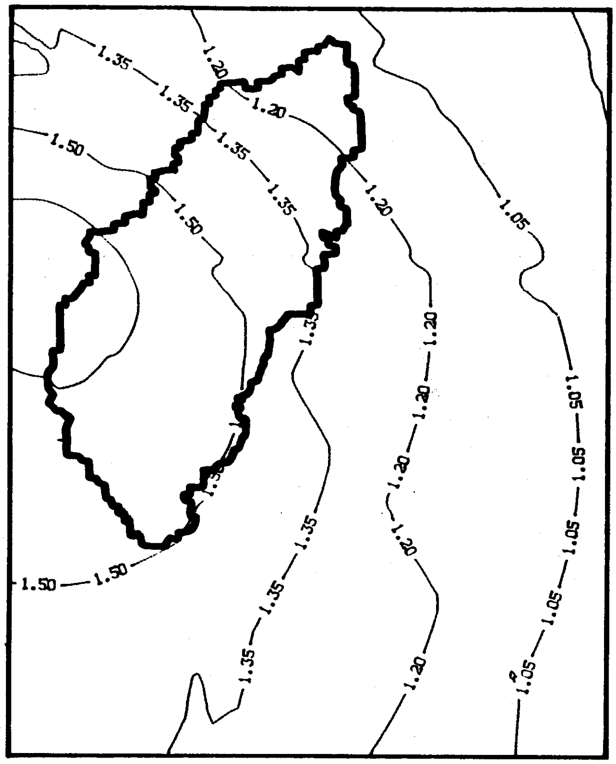



Figure 5. Interpolated Standardized Deviates - April 1, 1980

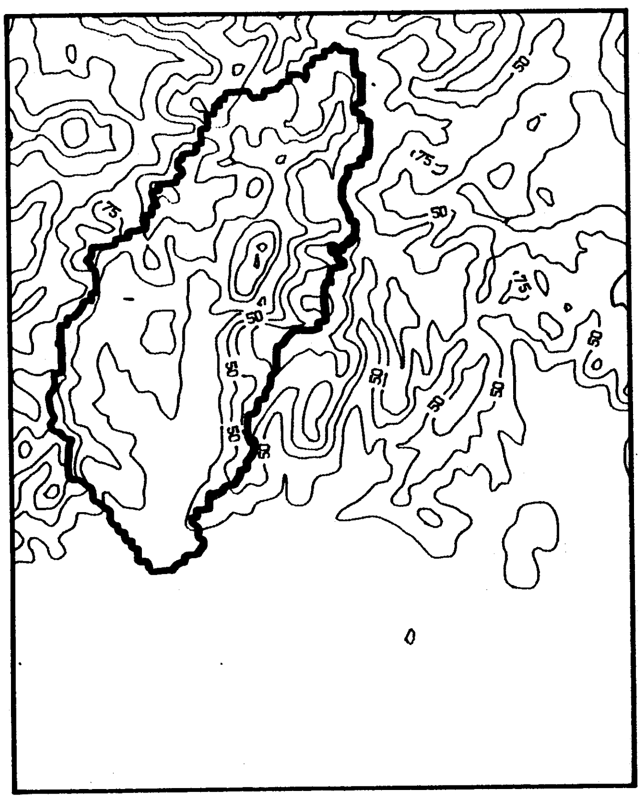



Figure 6. April 1, 1980 Snow-Water-Equivalent (cm.)

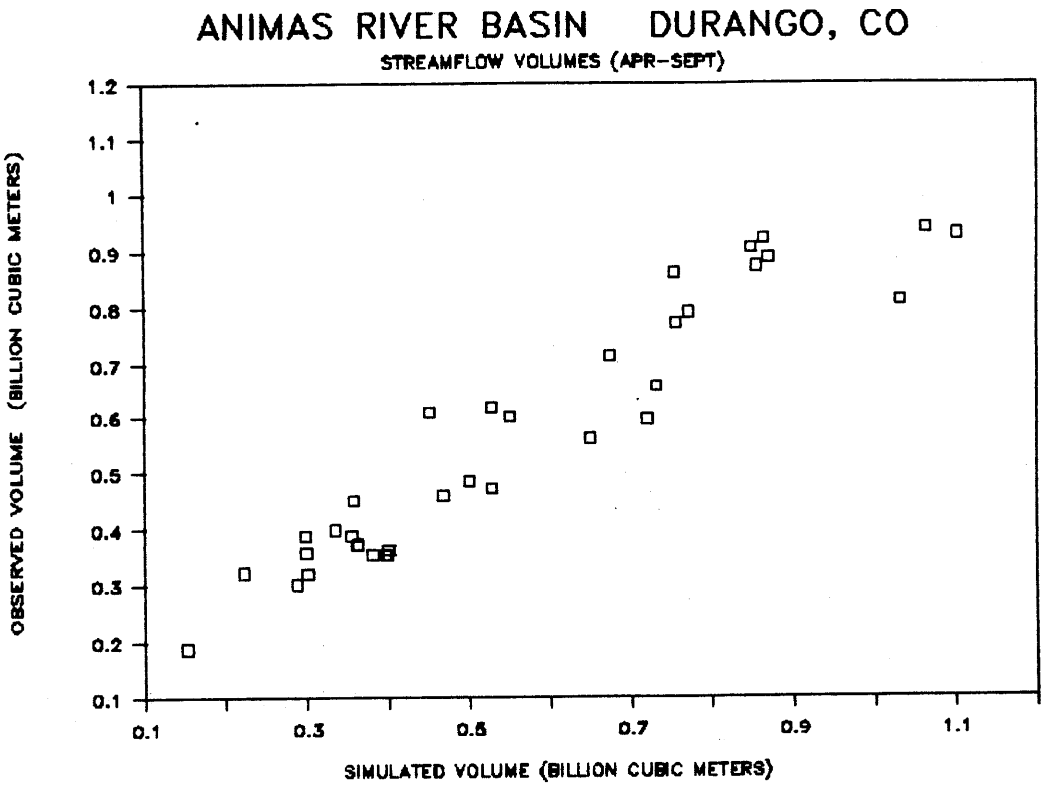



Figure 7. Simulated Seasonal Volumes

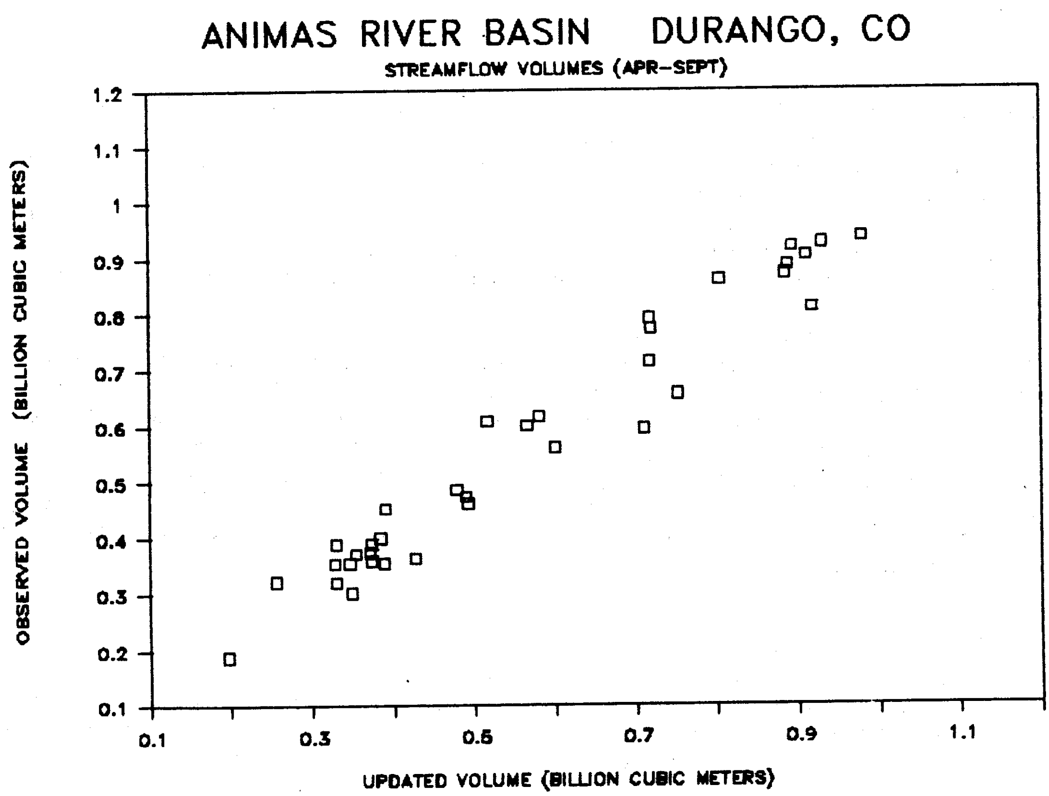



Figure 8. Updated Seasonal Volumes

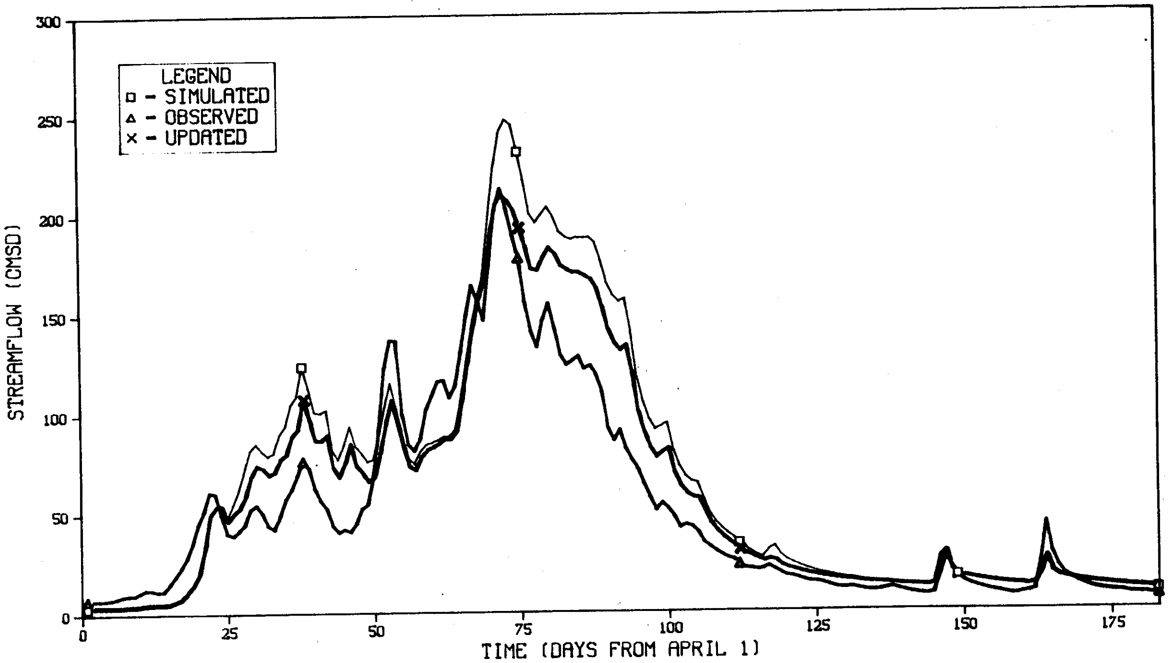



Figure 9. April thru September, 1980 Streamflow

SUMMARY

Conceptual models have the potential to provide detailed streamflow information; however, their performance is often limited by inaccurate estimates of precipitation over a basin. An orographic precipitation model can be used to provide detailed information about the spatial variability of precipitation and snow-water-equivalent in a basin. This information can be used as part of a climatological analysis or to improve estimates of precipitation on an event-by-event basis. Improved estimates of precipitation should produce improved estimates of the model states and better streamflow forecasts.

Snow observations are another source of information for improving estimates of the model states. Kalman filtering provides a framework for combining estimates of states from a model simulation with estimates of states from observations based on the relative uncertainties of the two estimates. Application of the methodology on the Animas River using snow-water-equivalent observations produced significant improvements in the streamflow simulation. The approach can be extended to handle additional observations, e.g. areal extent of snow cover, and provides a framework that can take advantage of an improved understanding of the spatial and temporal variabilities of the snow accumulation and ablation processes.

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