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APPLICATIONS OF REMOTE SENSING TO STREAM DISCHARGE PREDICTION

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Abstract

A feasibility study has been initiated on the use of remote earth observations for augmenting stream discharge prediction for the design and/or operation of major reservoir systems, pumping systems and irrigation systems. The near-term objectives are the interpolation of sparsely instrumented precipitation surveillance networks and the direct measurement of water loss by evaporation. The first steps of the study covered a survey of existing reservoir systems, stream discharge prediction methods, gage networks and the development of a self-adaptive variation of the Kentucky Watershed model, SNOPSET, that includes snowmelt. As a result of these studies, a special three channel scanner is being built for a small aircraft, which should provide snow, temperature and water vapor maps for the spatial and temporal interpolation of stream gages. The reservoir system of the Western Division of the Bureau of Reclamation was chosen for future demonstration of how such remote observations might augment stream discharge estimates.

Acknowledgments

This paper would not have been possible without the cooperation of the Office of Atmospheric Water Resources of the Bureau of Reclamation and of Western Scientific Services and without a willingness on the part of personnel of these organizations to exchange direct and remote observations on a no-cost, no-interference basis. The aircraft scanner was built by Bendix under the direction of Joe Zimmerman from Marshall's Astrionics Laboratory. Aircraft surveys and the color photo mosaic of the Wolf Creek Drainage Basin were provided by Dr. J. E. Ruff, Colorado State University.

Introduction

Remote earth observations from aircraft are being utilized to study the feasibility of applying future space payloads to stream discharge predictions. Such predictions would help in breaking the cycles between floods and droughts by distributing water more uniformly throughout the year. The more uniform distribution will preserve fertile lands and improve the production of food and fiber. The associated management of agricultural and forest resources follows directly from the water resources management.

Damaging floods in the Mississippi and Tennessee River basins were frequent before the development of water resource management systems by the Corps of Engineers and the Tennessee Valley Authority. Similar systems are now needed for other major river systems in underdeveloped countries. The Department of Civil Engineering at Colorado State University has worked on such development projects for several years with the governments of East Pakistan, West Pakistan, India, Thailand, and Venezuela.

The following paper describes the first steps of a feasibility demonstration project. The long-range objective of this project is to integrate statistical methods for machine interpretation of earth observations with hydrological simulation models for predicting the stream discharge of large drainage basins for the design and operation of major reservoir systems, pumping systems, and irrigation systems.

The short-term objective is to utilize multispectral observations of the Colorado River basin that will be obtained with MSFC instrumented aircraft for the following two applications:

1. The interpolation of sparsely instrumented precipitation surveillance networks with remote surveys

2. The direct measurement of the water loss by evaporation.

Hydrological Models

Throughout the history of science the development of improved measurement techniques has stimulated the improvement of theoretical models of our physical environment. That is the situation with respect to remote sensing at this time. One very important area in which improved measurement techniques is stimulating the development of new models is that of water resources. Modern water resources management is based on hydrological simulation models. These fall into two categories: the first is statistical hydrology while the second consists of parametric hydrological simulation models. Statistical hydrological models may be used where many years of records are available but may not be readily extended to regions where historical records are not available.

Parametric simulation models may be used in regions where recorded streamflow data are not available and may be used to assess the effects of changes in watersheds as well as to extend records in regions where streamflow or precipitation records are inadequate.

Stanford University has developed one parametric model which is sufficiently general for applications to a great many different regions [1]. This model is illustrated in Figure 1. It may be described as a set of transfer functions which relate precipitation gage readings to stream gage readings. The precipitation gage readings are usually supplied from a measurement network within a drainage boundary. The standard format of the Bureau of Reclamation calls for hourly or daily readings of precipitation. These readings refer to the height of water or snow depth. During or shortly after rainfall or snowfall, the precipitation readings will give the direct input of available water. Measurements of evaporation from pans filled with water are used to indirectly estimate the water loss from wet soils and snow and by transpiration from plants. This loss is inferred by accounting for the changes of the measured evaporation due to soil materials, surface slopes and vegetation cover. In most drainage basins such actual evaporation losses exceed the stream discharge.

A successful hydrological simulation model should provide a reasonable agreement between the stream discharge that is predicted from the precipitation readings and the actual discharge readings of the stream gages. Such success has been achieved only for small and well instrumented drainage basins. The runoff prediction of larger watersheds is difficult for two basic reasons. The first is the inadequate coverage of larger watersheds with precipitation gages. A successful simulation model requires a precipitation surveillance network which covers various infiltration conditions (interflow), slopes, and vegetation covers. The second reason is the uncertainty in the accurate prediction of evapotranspiration losses from indirect measurements.

Hydrological simulation models are needed to improve the operation of existing water resource management systems in large drainage basins and to design future reservoirs, irrigation systems, and cloud seeding operations for the more even distribution of water throughout the year. The need to improve the prediction of stream discharge for existing systems in the U.S. may be illustrated for the integrated water supply and utilization system of the Western Division System of the U.S. Bureau of Reclamation, which operates 22 reservoirs, 16 power plants, and 3 pumping stations (Fig. 2). Because of an inadequate precipitation network in an isolated region, the predictions of the Sweet Water River discharge, which originates in the Wind River Range, were off by 800 percent in 1969. This prediction would have led to extensive flood damage in Casper, Wyoming, if the reservoirs above Casper had been filled close to capacity early in the snowmelt season.

In mountainous regions, such as Colorado and Wyoming, the primary input for streamflow is winter precipitation and snowmelt. The detailed processes which produce streamflow from snowmelt are not well understood at this time [2]. However, many past investigations [3 through 10] have indicated that every watershed has characteristic relationships between snowpack depletion and streamflow runoff. Relatively simple relationships can be derived and incorporated into a model that may be used to synthesize streamflow in any given basin.

The Stanford Watershed Model [1] has been used for this purpose, but it is necessary to obtain the parameters through a trial-and-error adjustment procedure. This is not satisfactory since such a subjective approach makes extrapolation to undeveloped regions difficult. The model parameters obtained in this manner will be different depending upon the individual investigator and his understanding of the various phases of the hydrological sequence. This problem can be corrected by the use of a self-calibrating model which adjusts the parameters based upon a quantitative figure of merit.

A self-calibrating model called OPSET (Optimal Set of Parameters) [11] has been developed from an extension [12] of the Stanford Watershed Model. However, this extension does not allow for snowmelt [13], which is the primary input for streamflow runoff in the mountainous regions of interest. Another attempt at developing a self-calibrating watershed model was made at the University of London in 1970 [14]. This was also based on the Stanford Watershed Model and a numerical optimization technique developed by Rosenbrock [15]. The Rosenbrock technique was applied to the Kentucky Watershed Model by Colorado State University investigators but it was found to be entirely too consuming of computer time (Control Data Corporation 6400 computer) and consequently a gradient procedure was developed and incorporated into the Kentucky Watershed Model. This self-calibrating model includes snowmelt and has been designated as SNOPSET. The first results of this model are given here (pp. 112-113) and provide the basis for the approach toward utilization of remote observations.

The Existing Surveillance Network

The feasibility of discharge prediction in undeveloped regions might be demonstrated by expanding self-calibrating hydrological models from well to less well instrumented watersheds. The reservoir system of the Bureau of Reclamation provides such an opportunity as shown in Figure 2. Most of the region has only very few precipitation and streamflow gages, which have, however, been recorded for many decades. These few gages support the present use of statistical hydrological models for the operational discharge forecast. However, the Bureau has now a pilot program of increasing the winter snowpack (Project Skywater) by cloud seeding by at least 30 percent. If initiated, such change of precipitation patterns might decrease the validity of the present statistical forecast, and parametric models of the SNOPSET type might thus be considered.

A new precipitation and streamflow gage network is presently being installed by Western Scientific Instruments from Ft. Collins, Colorado, in the southern test region that is shown in Figures 3 and 4. This network is designed for testing the runoff and environmental effect of cloud-seeding operations. It also provides the ideal starting area for the expansion of SNOPSET from well to less well instrumented regions. Within this newly instrumented area also exist some old gages (see Fig. 3). The large ratio of planned versus existing gages clearly illustrates the large instrumentation requirement that would exist if parametric models were to replace the present statistical discharge prediction models.

The Skywater test site consists of a number of small drainage basins. One of these, the Wolf Creek Drainage Basin, was chosen as the initial starting point for the test of SNOPSET. This basin is shown in Figure 4. It varies in elevation from about 8700 ft to slightly more than 12 000 ft. It receives approximately 600 in. of precipitation annually, covers approximately 14.5 square miles, and is approximately 80 percent forested. It has steep slopes facing generally southeast and northwest. It is generally snow-covered from mid-October to mid-June and has past records of stream gage and precipitation and temperature.

Many instrumentation problems exist, such as freezing of ink and storm damage. To avoid such loss in input continuity, someone must regularly service and maintain all gages. This is a severe operations problem in the high mountain areas that hold most of the snowpack. To illustrate, from all existing old gages shown in Figure 3, only the single location near the summit of Wolf Creek Pass was kept operating continuously enough to support streamflow prediction. Clearly, the cost of developing and maintaining an adequate precipitation network for parametric stream discharge prediction in the main precipitation area of Figure 2 would be high. We hope that this cost might be reduced by augmenting a much smaller number of gages with remote observations.

Discharge Prediction Without Remote Observations

The Wolf Creek Drainage Basin has only a single location where the continuity of old precipitation readings is sufficient for parametric models. However, the use of only one precipitation gage is usually not sufficient to adjust the model parameters for a representation of the drainage basin at hand. The adjustment of SNOPSET was nonetheless attempted by augmenting precipitation with temperature records (daily maximum and minimum).

Figure 5 indicates the results from the first guess at the hydrological parameters in the model using the 1968-1969 water year as a test case. The correlation between recorded and synthesized mean daily streamflows is quite poor. Figure 6 shows the same results after 19 self-calibrating iterations of SNOPSET. The correlation in this case is very good (0.94). The associated choice of model parameters was then verified by applying the unchanged model to the 1969-1970 water year.

The results are shown in Figure 7. It is apparent that the "plant transfer function" has been adequately determined by application of SNOPSET.

The good correlation between computer and predicted stream discharge indicates that the use of parametric models might offer opportunities for reducing the density of streamflow gages. However, Figure 7 does not imply any forecast ability since model input and output overlap in time.

The predictive ability of SNOPSET was tested by extrapolating the streamflow beyond the time of the precipitation and temperature inputs. The results are shown in Figure 8. The abscissa shows the forecast period; i.e., the period between the computed discharge and the last precipitation measurement. The ordinate shows the quality of the prediction in terms of a standard deviation between the daily averages of predicted and measured streamflow. This deviation is approximately 3 times the residual deviation that remained after adjusting the SNOPSET parameters as shown in Figure 7. Apparently, the model provides a good prediction over a forecast period of approximately 6 months. This is adequate for covering the period of snowmelt. During these forecasts, the predicted and measured streamflows correlate within approximately 75 percent. For a forecast in excess of 6 months, the deviation between measurement and forecast increases more and more. We believe that the above results warrant to base a continuation of our present demonstration project and suitable updated versions of SNOPSET, that would take remote observation in addition to readings from a few precipitation and temperature gages.

Aircraft Instrumentation for Augmentation of Precipitation Measurements

Our first demonstration on the interpolation of precipitation gage readings with remote observations will be restricted to the snowpack in high mountain areas. The area extent of snow can easily be detected from space and the depletion of the snow cover appears to be directly related to runoff characteristics [3 through 10]. Even the low resolution of the meteorological satellites gave adequate estimates of the yearly precipitation input in the Sierra Nevadas. Monthly inputs to smaller drainage areas can hopefully be derived from repetitive surveys that provide higher resoultion images, such as the Earth Resources Technology Satellite (ERTS-A). Additional significant information for discharge prediction can hopefully be derived from incremental changes of the melt line. The boundary of melting snow should be accessible from the 0° C contour of a thermal map.

Any application of space observations to stream discharge prediction would lose most of its value if the precipitation estimate does not include rain besides snow. Unfortunately, the interpolation of rainfall gages is much more difficult than the above extrapolation of snowfall measurements since soil moisture is much more difficult to detect.

Temperature anomalies and greening of dry vegetation have been proposed as qualitative and indirect indicators of rainfall. However, then indicators may have many other causes besides recent rain and are thus probably not feasible for the interpolation of rainfall gages. We propose instead to use a map of the vertically integrated water vapor mass. Incremental changes of such a map should provide information on the water loss by evaporation and transpiration, which is also indicated by the decrease of the precipitation level in the rain gages. Repetitive surveys of the water vapor mass distribution should thus allow interpolation of rain gages shortly after precipitation inputs when these levels decline. Hopefully, this interpolation will also hold for the immediately preceding period of rainfall that was indicated by rising gage levels.

The CSU aircraft with a special scanner to provide maps of snow cover, temperature, and vertically integrated water vapor mass (Fig. 9) is being instrumented by MSFC. This scanner has three channels, two for reflected sunlight (0.83 to 0.87μm and 0.91 to 0.95μm), and one for thermal emission (8 to 12μm). The restriction to only three channels was necessary to conserve weight and funds so that a small aircraft may be used for surveying hourly and daily variations of precipitation as required by the direct surveillance network.

The bandpass of the first reflectance channel is chosen so that atmospheric propagation effects of water vapor are minimized. This channel will be used to provide the snow maps. A normalizing factor is measured directly per scan line by viewing the above sky screen. By using this additional reference pulse, channel 1 can be used to correct for extraneous illumination factors such as partial cloud cover.

The thermal channel is viewing a sky screen once per scan mirror revolution to obtain a signal that is related to the ambient temperature of the aircraft housing. In addition, the thermal channel will record the emission of an adjustable and stabilized blackbody calibration source. These two additional calibration pulses are then used to convert the thermal signal into a radiometric temperature that should provide a good approximation of the surface temperature.

The bandpass of the second reflectance channel coincides with the absorption band of water vapor at 0.93μ. This channel should thus be used to map the transmission loss that is provided by the atmospheric water vapor.

This transmission must then be interpreted in terms of integrated water vapor mass (precipitable centimeters). Background for such spectroscopic interpretation is available from a 15-year informal and international cooperation on the propagation characteristics of the water vapor molecule. The results of this investigation are summarized by the Wave Propagation Laboratories of the National Oceanic and Atmospheric Administration (NOAA) [16]. Their Slant-Path computer codes have been made available to MSFC as part of a previous joint field test program.

The proposed water-vapor map would account for the total water-vapor mass between the ground and the scanner; whereas, the hydrological applications refer only to the portion that is related to the evaporation from the underlying soil and the transpiration from plants. The balance is provided by humidity in converted air masses. As long as this convection circulates the air within the large drainage area of interest, one might expect that its effect would cancel out in the integration across this area [17]. However, a significant influx of atmospheric moisture into the drainage area might present interpretation problems. In such an event, statistical correlation concepts are conceivable which might retrieve the evapotranspiration component by a digital correlation of water-vapor and temperature maps.

Conclusion

The successful statistical prediction of stream discharge from historical records of a few gages implies that the spatial interpolation of precipitation gages does not need high local accuracy for obtaining acceptable overall precipitation inputs. Remote observations might thus have a chance for spatial interpolation of a few gages over large regions, as shown in Figure 2. The above successful forecast over 6 months also implies that the temporal interpolation between successive overflights does not need a great local accuracy. Temporal interpolation errors are obviously acceptable within the deviations of daily averages that are indicated by the statistical hydrological models in present use. A 9-day interval between remote observations of half the drainage area is within the capability of existing unmanned satellites (ERTS) and might suffice for the temporal interpolation.

A special aircraft scanner is being built and tested which should provide maps on the aerial extent of snow, on surface temperature and on the vertically integrated water vapor mass for the spatial and temporal interpolation of a few precipitation gages. Such demonstrations should be conducted in large drainage areas where statistical hydrological models are being used. The errors of the local interpolation can be spot checked in small subregions, where the existing gage network is sufficient to support the adjustment of the SNOPSET parameters for local streamflow estimates without remote observations. The errors of the local space and time interpolation would thus be established by reducing the number of gage inputs while simultaneously using remote observations. The errors of the overall precipitation inputs and evapotranspiration losses would subsequently be established by estimating the propagation and self-cancellation of the local interpolation errors in the space and time integrals that establish the overall precipitation inputs to the drainage area. The feasibility of using space observations for precipitation estimates becomes apparent by comparing the estimated overall errors with the tolerances that were established when using the statistical forecast method. If feasible, the use of space observations would then provide for adjusting the statistical methods for changes in the drainage area by cloud-seeding operations, new river channels, new reservoirs, etc. Equally, if not more important, the use of space observations might provide stream discharge forecasts in undeveloped regions, where several decades of precipitation and discharge records do not yet exist.

Evaporation losses usually exceed the water flowing in the tributaries and their accurate knowledge is thus necessary if one wants to predict discharge by subtracting precipitation and evaporation. Most parametric hydrological models estimate evaporation losses with empirical factors which account for various soils, vegetation covers, slopes, etc., in the drainage basin. Many of these factors might not be needed if the evaporation loss can be estimated from the water vapor mass. The survey of atmospheric water vapor distribution is thus not only needed for estimating overall rainfall, but may also assist in developing parametric stream discharge prediction models in sparsely instrumented drainage areas.

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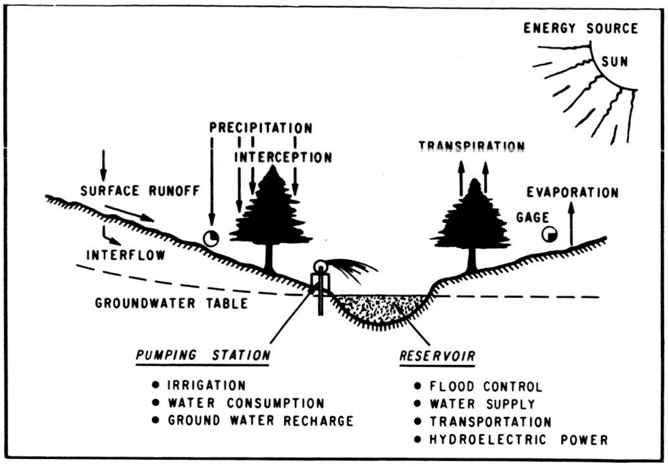

Figure 1. Hydrological applications in Colorado and Tennessee Valley.

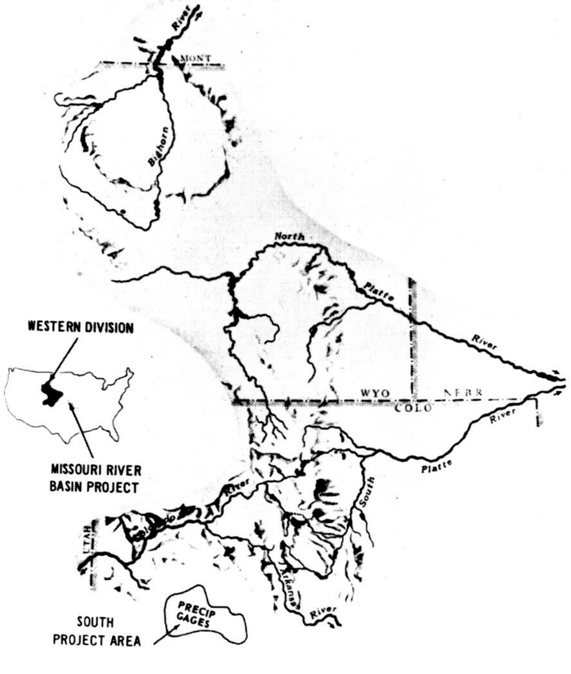

Figure 2. Reservoir operations by Bureau of Reclamation.

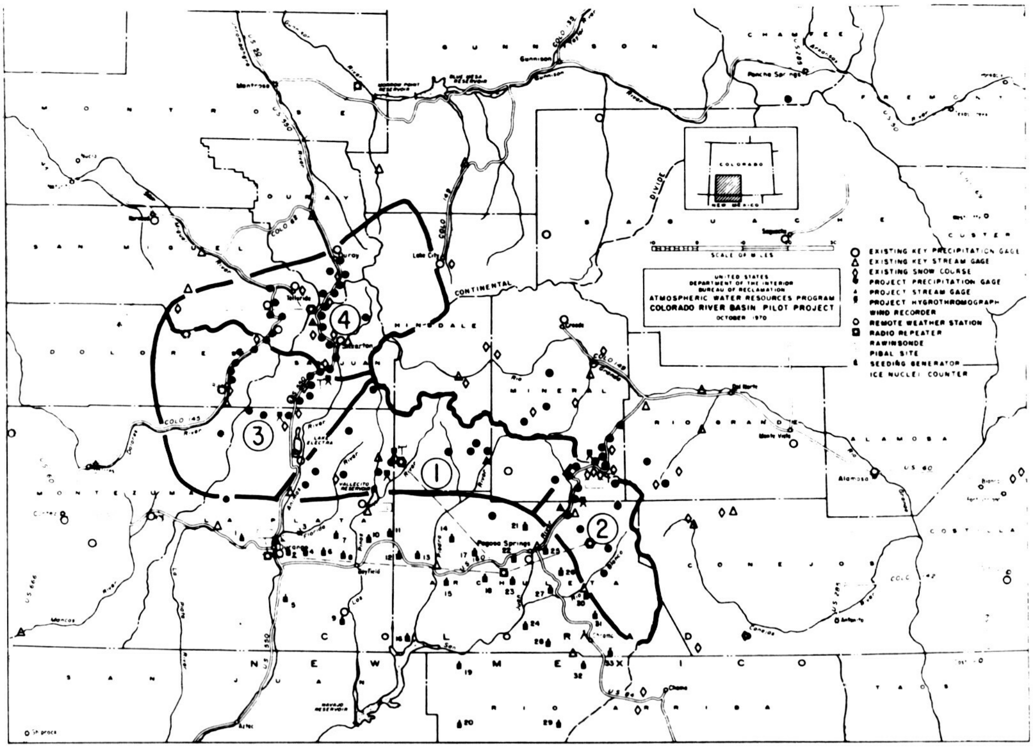

Figure 3. Precipitation surveillance network in the Colorado River Basin.

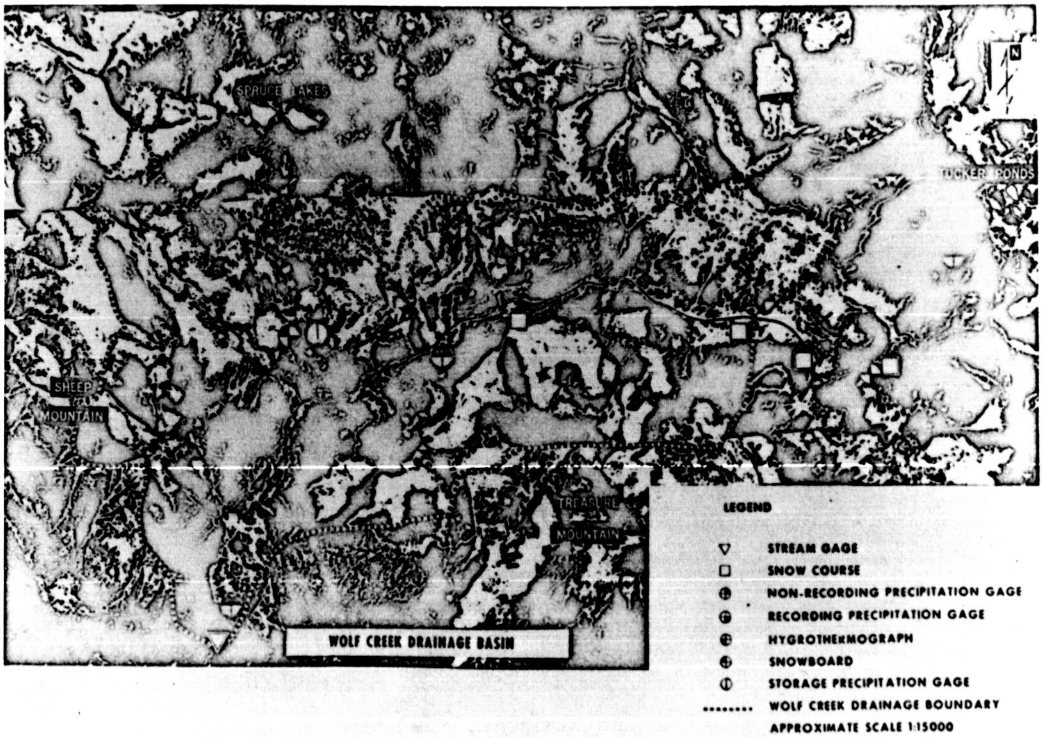

Figure 4. NASA/MSFC regional application of Colorado State University aircraft surveys, December 1970.

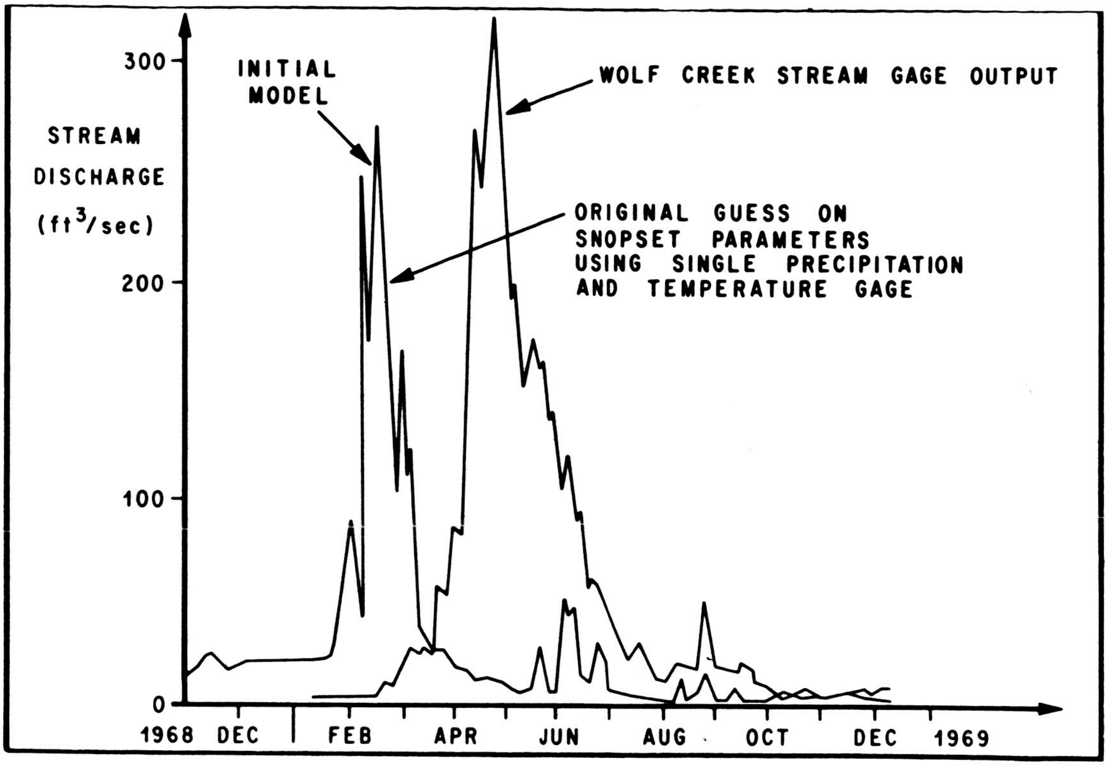

Figure 5. Calibration of hydrological model parameter for Wolf Creek Drainage Basin.

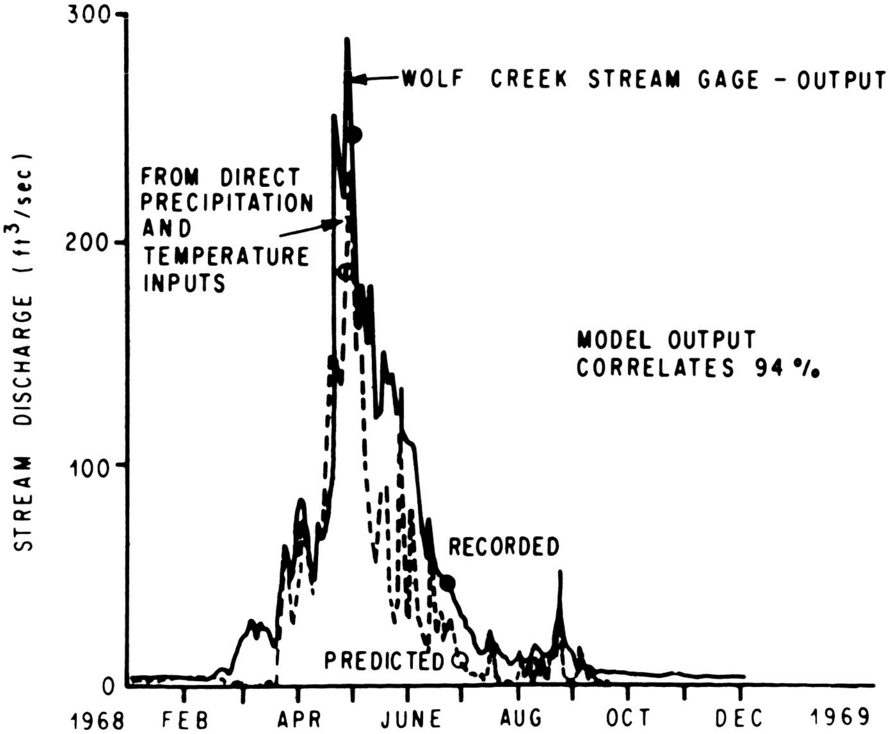

Figure 6. Records used for establishing hydrological model of Wolf Creek Drainage Basin.

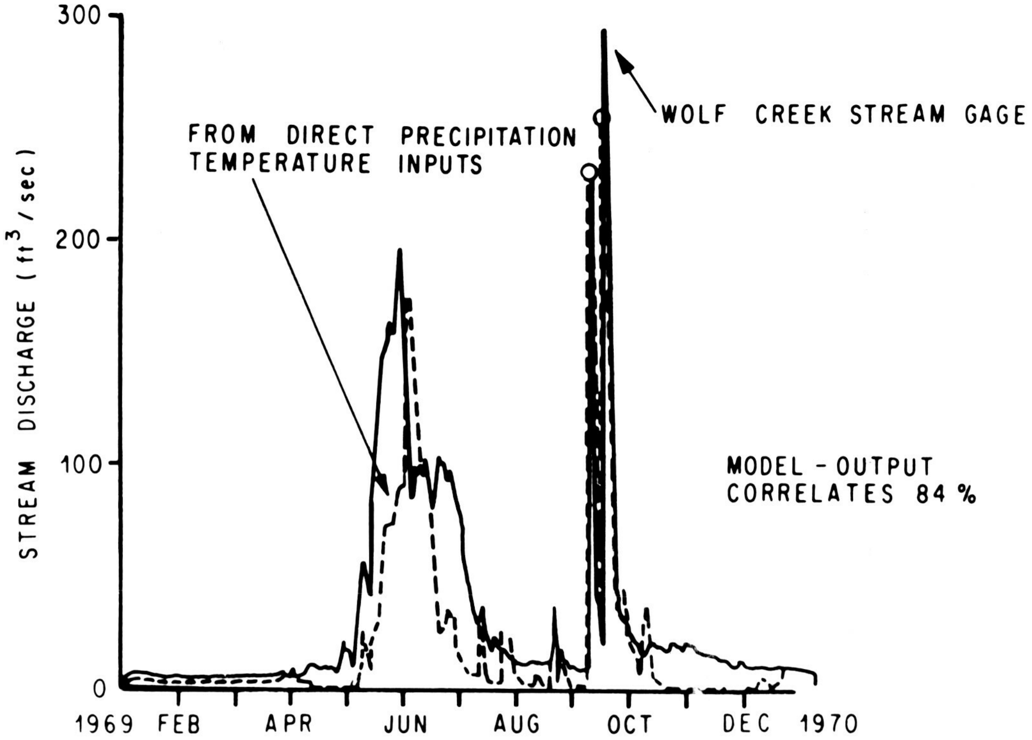

Figure 7. Verification of hydrological model through 1969-1970 stream discharge prediction.

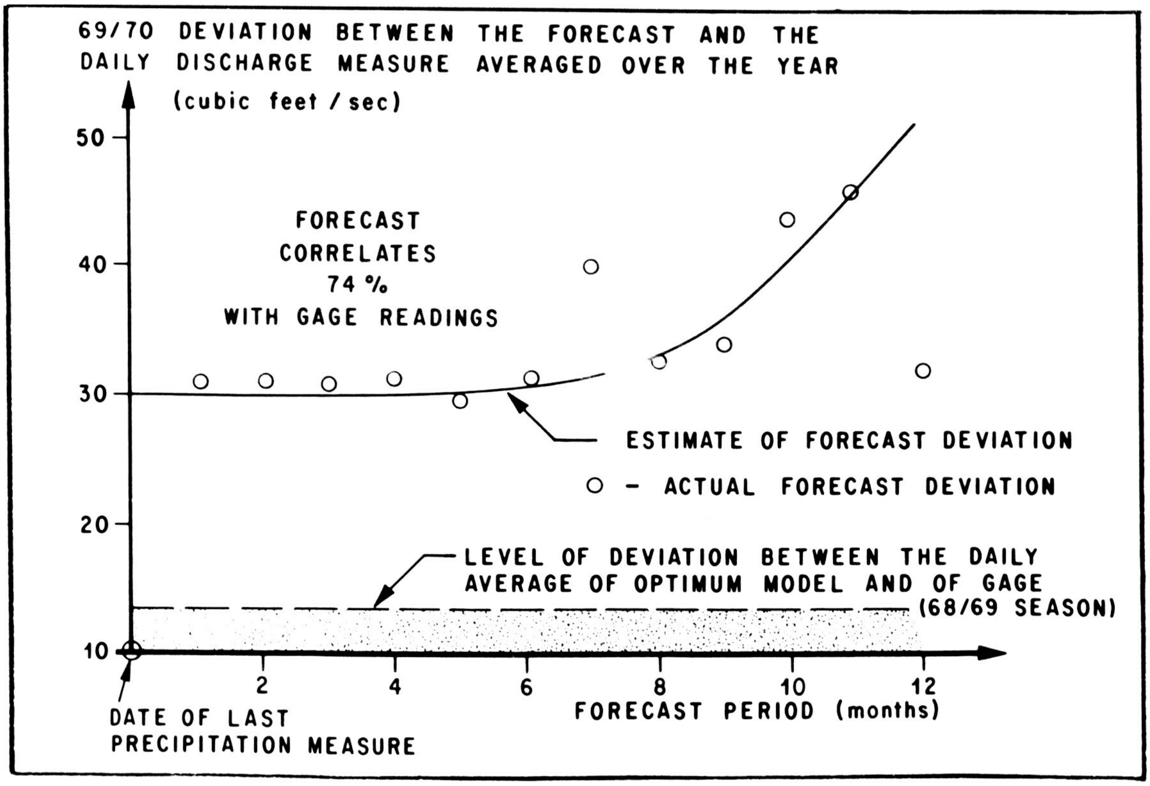

Figure 8. Streamflow prediction with self-calibrating extension at Kentucky Watershed Model.

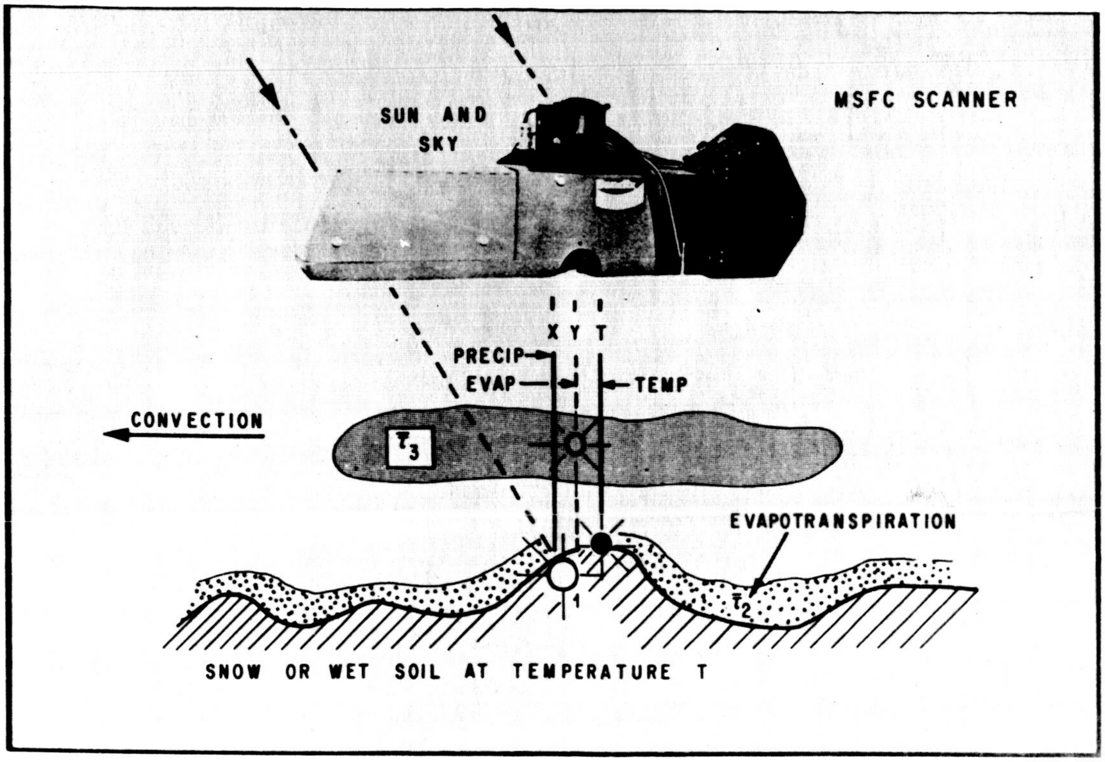

Figure 9. Precipitation estimates from change of water vapor and temperature maps.