A GRAPHICAL METHOD OF STREAM RUNOFF PREDICTION FROM LANDSAT DERIVED SNOWCOVER DATA FOR WATERSHEDS IN THE UPPER RIO GRANDE BASIN OF COLORADO

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ABSTRACT

Graphical methods of stream runoff prediction are empirical in nature and demonstrate general relationships among selected parameters affecting snowmelt and runoff. Two watersheds examined in the Upper Rio Grande Basin of Colorado exhibit a unique relationship among snowcover depletion, time and runoff. Snowcover data derived from Landsat has shown that for six years of record snow line regression followed similar patterns. A family of curves were developed for the drainage basins by plotting snow areal extent with time for each Landsat pass. Each year of data produced a curve which was displaced from the others by a near logarithmic relationship based on total annual streamflow. This relationship was used to predict the lowest streamflow on record for the watersheds in 1977. Application of the graphical method to the Upper Arkansas River basin was not successful and revealed definite limitations in the method. The graphical method demonstrates the direct use of satellite snowcover data in stream runoff forecasting. In addition, a method using indexed base lines was developed to estimate snowcover for a watershed from marginal images due to cloud cover. The accuracy of estimates is dependent upon watershed characteristics, index line frequency, and the number of index lines visible for a given image.

INTRODUCTION

In 1974, the U. S. Department of Agriculture, Soil Conservation Service Snow Survey and the Colorado Division of Water Resources began a cooperative study through NASA's Applications Systems Verification and Transfer (ASVT) program on Operational Applications of Satellite Snowcover Observations. The objective of the study was to determine the usefulness of satellite derived snowcover mapping to prediction of watershed seasonal volume of runoff and streamflow resulting from snowmelt. At the beginning of the program there was no proven method for using satellite derived snowcover information to predict annual or seasonal volume of runoff or streamflow. As an early attempt to evaluate the significant relationships between snow areal extent and runoff, a simplified graphical approach was investigated as well as a review of previous work in the area of snow hydrology. Annual, seasonal and short term runoff forecasts are an important part of stream administration throughout the state of Colorado.

Study Area

The upper Rio Grande drainage of Colorado was chosen as the primary study area and the Upper Arkansas River as a secondary basin (Figure 1). Within the Rio Grande drainage basin, five watersheds were identified for study, two of which were selected to test graphical methods of annual runoff prediction from snowmelt. These two basins are the Conejos River drainage and South Fork of the Rio Grande drainage. The Upper Arkansas River basin was included in the study to determine the limits of graphical prediction applications. The Conejos and South Fork basins are hydrologically similar in some respects but have certain physiographic characteristics which are significantly different. Hydrologic similarities are reflected by the repeated snowline recession patterns year after year, similar area-altitude distribution and altitude range. Physiographic differences are evident when the basins are compared. The South Fork of the Rio Grande basin is more or less symmetrical, with its length and width nearly equal, and its orientation is to the north. The Conejos, on the other hand, is an elongated, curved basin of irregular form oriented primarily east-west. Both the Conejos River and South Fork are moderate size basins, 734.4 km^2 (282 mi^2) and 562.5 km^2 (216 mi^2) respectively, while the Arkansas is a large basin, 3,171.9 km^2 (1,218 mi^2). Elevations for the Conejos River and South Fork of the Rio Grande drainages range from 2,460 m (7,500 ft) to over 3,963 m (13,000 ft) while elevations for the Arkansas River drainage range from 2,195 m (7,200 ft) to over 4,267 m (14,000 ft). Precipitation ranges from 17.8 cm (7 in.) on the floor of the San Luis Valley to 114 cm (45 in.) at the head of the watersheds. Nearly 80 percent of the water in the Rio Grande comes from snowmelt.

The Graphical Method of Runoff Prediction

The graphical approach to solving problems and isolating significant variables in cause and effect relationships is probably

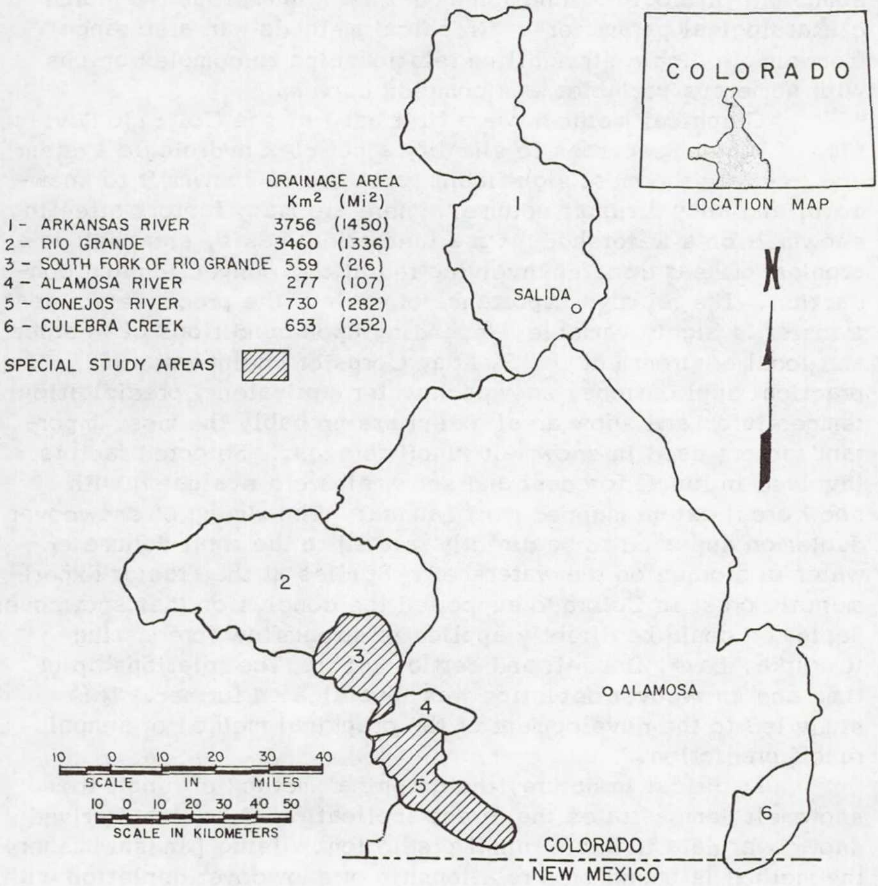

Figure 1. Index map of the study area.

one of the oldest techniques in the scientific method. The results are quite often empirical in nature particularly in a highly complex system such as snow hydrology. Graphical methods as applied to snow hydrology are mentioned in some detail in the U. S. Army Corps of Engineers' manual of Snow Hydrology (1956). Standard seasonal and annual forecast methods may range from multiple linear regression analysis using snow courses as indices to the complex hydrologic simulation model using numerous basin and climatological parameters. Graphical methods can also range from simple single straightline relationships to complex graphs with numerous variables and complex curves.

Graphical methods were first used by the Colorado Division of Water Resources to simplify a complex hydrologic system and to relate the most significant variables of snowmelt to snowcover and annual runoff volume. There are many factors affecting snowmelt on a watershed. On a theoretical basis, snowmelt is a problem of heat transfer involving radiation, convection and conduction. The relative importance of each of the processes of heat transfer is highly variable, depending upon conditions of weather and local environment (U. S. Army Corps of Engineers, 1960). In practical applications, snowpack water equivalent, precipitation, temperature, and snow areal extent are probably the most important factors used in snowmelt runoff forecast. Selected factors involved in runoff forecast and snowmelt were evaluated with snow areal extent mapped from Landsat. The timing of snowcover depletion appeared to be directly related to the total volume of water in storage on the watershed. Studies at the Frasier Experimental Forest in Colorado supported the conclusion that snowcover depletion could be directly applied to streamflow forecasting (Garstka, Love, Goodell and Bertle, 1958). The relationship of time and snowcover depletion was investigated further. This study led to the development of the graphical method of annual runoff prediction.

Empirical in nature, the graphical method of runoff from snowmelt demonstrates the direct application of Landsat derived snowcover data to basin runoff prediction. Using Landsat imagery, the method is based on a relationship of snowcover depletion with time. The method consists of two graphs. The first is a comparison of time and percent of snow areal extent remaining for a given basin (Figure 2). The second graph is a semi-logarithmic plot of annual runoff volume for the basin and linear displacement of annual snow area depletion curves measured from the first graph (Figure 3). Annual runoff volume is read directly from the second graph in cubic meters (ac-ft).

The first graph (Figure 2) is a family of similar curves comparing time to the percentage of snowcover remaining on a

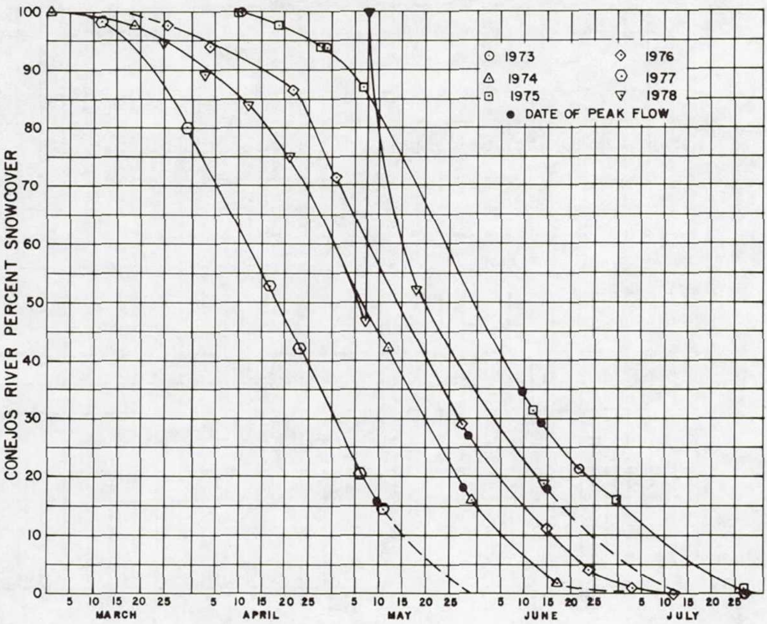

Figure 2. Time vs. percent of snowcover remaining for the Conejos River watershed.

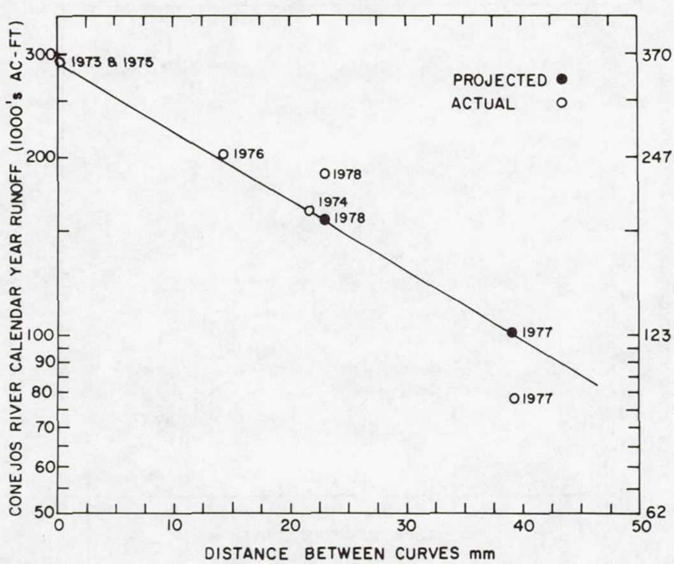

Figure 3. Annual runoff volume vs. snowcover depletion curve linear displacement for Conejos River watershed.

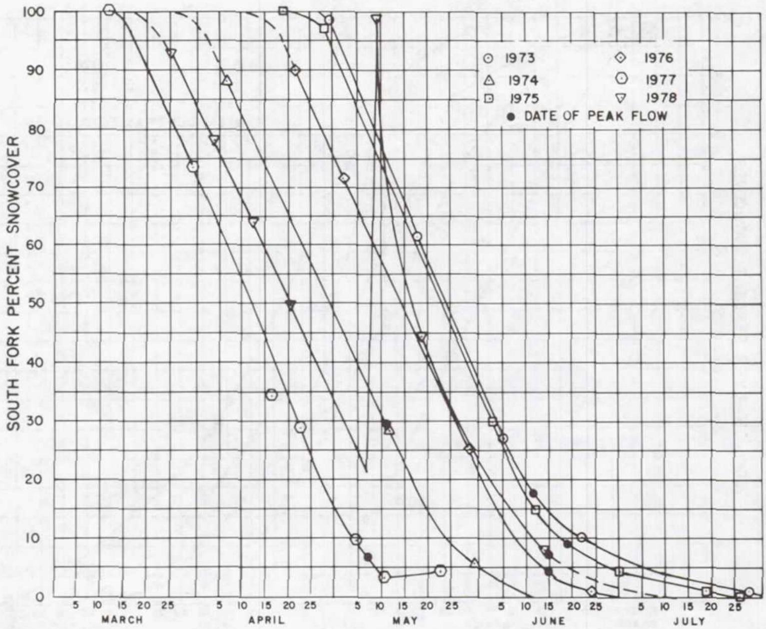

Figure 4. Time vs. percent of snowcover remaining for the South Fork watershed.

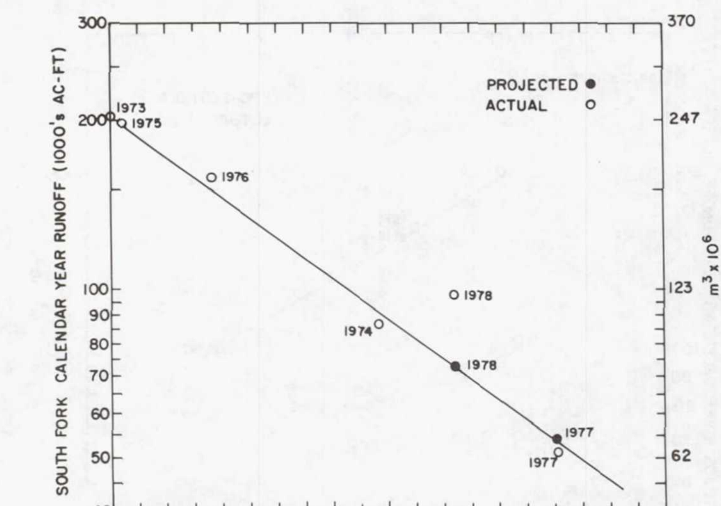

Figure 5. Annual runoff volume vs. snowcover depletion curve linear displacement for the South Fork watershed.

given watershed. Each curve represents a snowmelt runoff season and they are displaced relative to one another according to total annual streamflow volume. Every drainage basin studied appears to have a unique set of curves, so that a new set of curves must be constructed for each basin. The curves are plotted on standard 10 squares to the inch graph paper with time on the x-axis and the percentage of snowcover remaining as the y-axis. Snowcover remaining data taken from an image is plotted relative to the time of the Landsat pass. As the snow season progresses, each new data point is plotted until a straightline segment can be positively identified. This usually occurs when snow area remaining on the basin is around 80 to 90 percent. Once this straightline segment has been identified, the displacement between the new curve and a reference curve can be measured. The reference curve may be the maximum volume runoff curve or some convenient curve common to the family of curves. Displacement is relative; therefore, any convenient measurement system can be used (milimeters are used in this study as a standard unit). Each curve is unique and reflects climatological variations for each season. In the Conejos and South Fork basins, the straightline segments common to all of the curves are not necessarily parallel although they approximate parallel lines. The straightline segments of the different curves are a best fit of the data points as these points are not absolute values of snow areal extent. Also, these data points reflect image error and interpretation error which are significant and to a greater extent random.

The displacement of the family of curves (time vs. percent of snow areal extent remaining) has been found to be a near logarithmic relationship with total annual volume of runoff. The displacement when plotted on semi-logarithmic paper with total annual runoff volume in m^3 (ac-ft) results in a near straight line (Figure 3). Annual runoff volume can be found for a new snowcover depletion curve by plotting the curve's displacement directly on the semi-log paper. This relationship exists for two of the study basins tested, the Conejos River and South Fork of the Rio Grande.

Results

This method evolved over a period of time from Landsat derived snowcover data for the Conejos River and South Fork of the Rio Grande. The method was used to make quasi-operational annual runoff volume forecasts for the Conejos River and South Fork of the Rio Grande in 1977 and 1978. The 1977 forecasts were successful in predicting the lowest annual runoff on record for both rivers. Annual runoff volume for the Conejos River was found to be approximately 113.3×10^5 m^3 (100,000 ac-ft). Actual annual runoff was 883.7 x 10^4 m^3 (78,000 ac-ft). The prediction was in error by 249.3 x 10^4 m^3 (22,000 ac-ft) or 28 percent; however, average annual runoff volume for the river is 275.3 x 10^5 m^3 (243,000 ac-ft). If we compare the 249.3 x 10^4 m^3 (22,000 ac-ft) to the average annual runoff volume, error appears to be relatively small, or about nine percent. The lowest runoff recorded was 117.8 x 10^{-5} m^3 (104,000 ac-ft) in 1934. This prediction was made before April 5, 1977, prior to the snowmelt runoff season. The 1977 predicted annual runoff volume for South Fork was 609.5 x 10^4 m^3 (53,800 ac-ft) (Figures 4 and 5). Actual annual runoff volume was 586 x 10^4 m^3 (51,721 ac-ft), a difference of 240.3 x 10^3 m^3 (2,121 ac-ft) representing an error of four percent. The average annual runoff volume for South Fork is 190.3 x 10^5 m^3 (168,000 ac-ft) for 26 years of record. When the difference between actual and forecast annual runoff volume is compared to average annual runoff volume, the relative error is approximately one percent. The lowest flow recorded was 846.3 x 10^4 m^3 (74,700 ac-ft) in 1940.

The 1978 annual runoff volume predictions were less successful because of a late massive snow storm, May 8, 1978, that left up to 5.08 cm (2 in.) of water equivalent snow on the basins. A prediction of 196.4 x 10^6 m^3 (161,000 ac-ft) was derived for the Conejos before the May 8, 1978, snow storm, and 878.2 x 10^5 m^3 (72,000 ac-ft) for the South Fork. The effects of this storm on total runoff cannot be fully assessed because of lack of adequate recording instrumentation. However, the Conejos watershed may have received as much as 366.9 x 10^5 m^3 (30,000 ac-ft) of water. If 50% of this water reached the stream as runoff and the estimate revised, the new estimate would have been 214.6 x 10^6 m^3 (176,000 ac-ft). Actual annual runoff for the Conejos was 214.6 x 10^6 m^3 (175,920 ac-ft). The uncorrected estimate for the Conejos was approximately 182.9 x 10^5 m^3 (15,000 ac-ft) or 8.5 percent in error, and the corrected estimate was in error by less than one percent.

The May 8, 1978, storm may have added as much as 281.0 x 10^5 m^3 (23,000 ac-ft) of water on the South Fork watershed; and if 50 percent, 140.3 x 10^5 m^3 (11,500 ac-ft), of this water reached the stream as runoff, the revised estimate would have been 101.8 x 10^6 m^3 (83,500 ac-ft). The approximate annual flow for South Fork was 118.3 x 10^6 m^3 (97,000 ac-ft). The uncorrected estimate was in error 304.8 x 10^5 m^3 (25,000 ac-ft) or 26 percent, and the corrected estimate was in error by 164.6 x 10^5 m^3 (13,500 ac-ft) or 14 percent.

It is obvious that major snow storms of the May 8, 1978, magnitude must be considered in any snowmelt runoff prediction. How much weight should be given to such a storm must be determined at the time of occurrence. Before an effective method of revising forecast can be developed, additional study and better instrumentation are needed.

The graphical method was also applied to the Arkansas River drainage basin of Colorado above the Salida, Colorado, stream gage. The basin differs significantly from the Conejos and South Fork of the Rio Grande in size, snow conditions and watershed characteristics. The Arkansas drainage basin covers an area of 3,155 km^2 (1,218 mi^2) compared to the Conejos and South Fork which are less than 777 km^2 (300 mi^2) each. Elevations for the Arkansas range from 2,194.5 m (7,200 ft) to over 4,267 m (14,000 ft) with a larger percentage of the basin at lower elevations. Snow conditions are significantly affected by the high range of mountains along the Continental Divide on the west side of the valley. This range of mountains exceeds 4,267 m (14,000 ft) and its eastern slopes are the principal catchment areas for the Arkansas River. The valley floor and a large part of the east side of the valley are in a precipitation shadow and near desert conditions prevail.

Landsat snow areal extent data produced by the USDA Soil Conservation Service Snow Survey was plotted relative to the times of satellite passes in an effort to construct a family of snowcover depletion curves (Figure 6). The data points did not produce a systematic family of curves with the same relationship of total annual runoff as found in the other basins studied and the curve for the 1978 snowmelt season was out of sequence. The relationship between curve displacement and total annual runoff did not approach a near logarithmic function (Figure 7).

There are a number of possible explanations for the negative results. The most probable cause is due to significant differences in watershed characteristics and climatic factors previously mentioned. The Arkansas River basin has proven to be a difficult basin to predict using statistical as well as simulation models. This can be attributed to a number of factors: (1) the snowpack contribution to runoff is less than in the other basins, (2) complex water distribution systems exist in the basin bringing water from the west side of the Continental Divide, (3) spring and summer precipitation can substantially affect runoff predictions in any given year (Bernard Shafer, USDA SCS Snow Survey, personal communications).

Problem Areas

Successful application of the graphical method is dependent upon consistent snow mapping data. When different image interpretation techniques are used, significant variations in snow

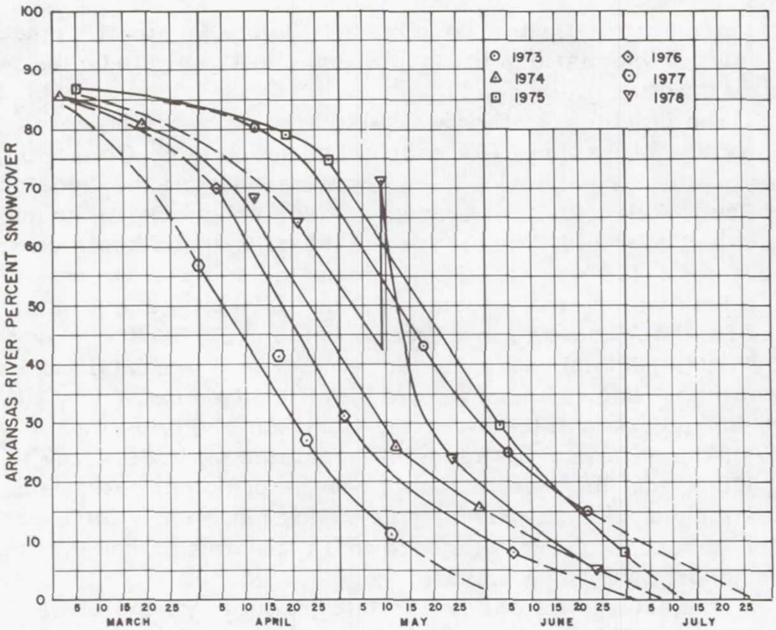

Figure 6. Time vs. percent of snowcover remaining for the Upper Arkansas River watershed.

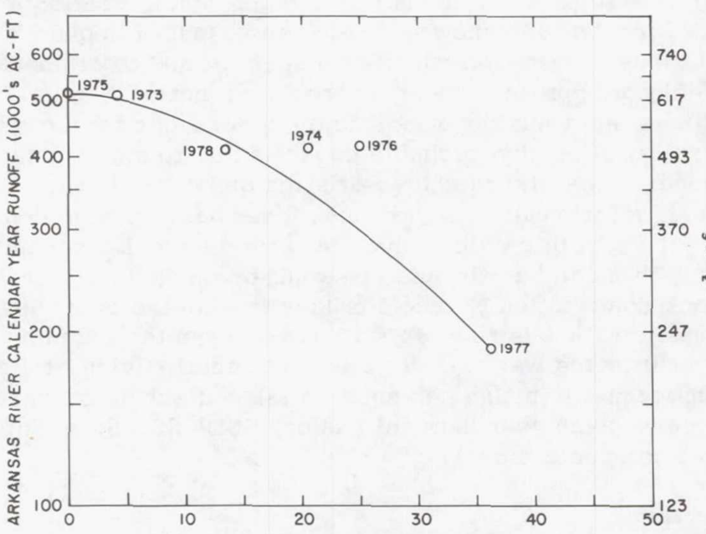

Figure 7. Annual runoff volume vs. snowcover depletion curve linear displacement for the Upper Arkansas River watershed.

areal extent mapping are found. Differences of a few percent will significantly affect plotting of snowcover depletion curves and affect the resulting displacement between curves.

Predictions based on graphical method are dependent upon snowcover depletion which is a function of total water content of the snowpack, temperature and precipitation. For a larger than average runoff year, snowcover recession will begin later than in a low water year. As a result, a runoff prediction may not be possible until fairly late in the season and after watershed management decisions must be made.

Cloud cover at the time of satellite passes has resulted in approximately 40 percent of the images being unusable or marginal. As many images as possible must be used to accurately plot snowcover depletion curves because the loss of a critical point can delay development of the curve. The Colorado Division of Water Resources has developed a method of indexed baselines for estimating snow areal extent on a basin from marginal Landsat images due to cloud cover. The method uses a network of indexed baselines that are optically superimposed over an image through a Zoom Transfer Scope (Figure 8). Where intersections of a baseline and the snowline can be recognized, the index line is measured and referenced to a table of index snowcover for that basin. The more index lines measured, the more accurate will be the overall snowcover estimate. Past results have shown that index baseline estimates are within five percent of standard Landsat snow mapping methods. For an operational forecast system to be useful, Landsat images must be received and processed without delay. A near real time processing of images is essential for short term forecast.

Conclusion

In conclusion, the graphical method of annual runoff volume prediction represents a simplified relationship of snowcover depletion with time and runoff. The graphical procedure for predicting annual flow using Landsat snowcover data is relatively inexpensive and fairly reliable, particularly in regions lacking historical precipitation and snow course records. The method can be used as an independent means of checking other forecast techniques. Graphical methods appear to have definite limitations in application to large basins, in accounting for abnormal weather conditions, and variable watershed characteristics. It is possible to update early forecasts by using standard hydrologic methods of estimating runoff from late precipitation events. Additional empirical relationships other than those tested in this study may exist in snow hydrology that relate snowcover depletion

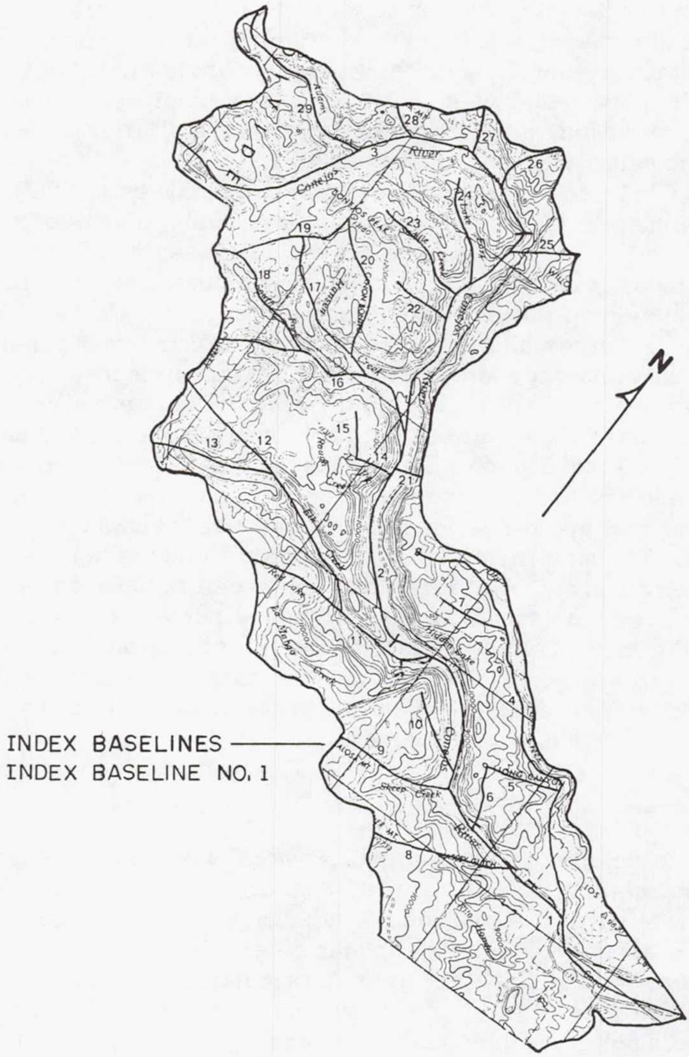

Figure 8. Index baseline network for the Conejos River watershed.

to watershed runoff. Graphical methods presented in this study are limited in scope; however, they may find wider applications as additional basins are studied. Each drainage basin appears to be unique and the graphical method must be applied independently. The successful application of graphical procedures is dependent upon consistent snowcover information on a repeated basis, a function well served by Landsat.

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