DEVELOPMENT OF A SURFACE WATER SUPPLY INDEX (SWSI) TO ASSESS THE SEVERITY OF DROUGHT CONDITIONS IN SNOWPACK RUNOFF AREAS

By

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INTRODUCTION

Colorado has experienced recent periods of drought which have been detrimental to the state's economy. The droughts of 1976-77 and 1980-81 were the first periods of serious moisture shortage since the early 1950's. It became apparent to state officials that a method of assessing the onset, severity, and termination of drought conditions was needed to quickly and efficiently deal with the negative impacts which ensued from the lack of moisture. Although numerous sources of hydrometeorological data are available, an objective technique was lacking which adequately integrated them into a generalized indicator of water availability. The Palmer Index (PI), useful in quantifying drought periods in the eastern plains of Colorado, is seriously flawed when applied to the mountainous western region.

In response to this need, a Surface Water Supply Index (SWSI) was developed which incorporates multiple hydrologic/climatological components into a single, objectively derived index value for each major basin in the state. The index is an integral part of Colorado's Drought Response Plan (DRP) (Lamm, 1981), that outlines the state's organized reaction to identifiable drought conditions. SWSI is a joint endeavor of the Colorado Division of Water Resources (DWR) and the USDA Soil Conservation Service (SCS) collaborating with other state and federal agencies.

Within the framework of Colorado's DRP ten task forces are defined and assigned responsibilities for various aspects of drought assessment and response. The Water Availability Task Force (WATF) has primary responsibility for evaluating water supply conditions and forwarding the information to other task forces for their consideration and action. SWSI and the Palmer Index are the two indices that the WATF uses in judging whether a drought condition exists and if so, its severity. Thus they "trigger" both activation and deactivation of the DRP.

SWSI focuses on surface water supplies derived from melting snow which accounts for 65 to 85 percent of the annual flow of the state's major streams. Reservoir storage and current precipitation amounts are also taken into account in appraising available or forecasted water supplies. When spring arrives the moisture represented by the melting snowpack is translated into streamflow and is included in the water supply assessment. SWSI unifies these various components into a single index value useful for management decisions in times of impending or current water shortage. To give managers an overview, an index value is generated monthly for each of 7 Colorado basins and presented in map format.

RATIONALE FOR SWSI DEVELOPMENT

Information Available Prior to SWSI

Assessing drought severity requires extensive data analysis and subjective judgments. Prior to SWSI, several reports not specifically designed for the purposes of the DRP were used to obtain basic overviews. Among them were the SCS Water Supply Outlook (WSO), reports by DWR, the State Climatologist, the National Weather Service (NWS), and the U.S. Geological Survey (USGS), and expert's opinions. These reports, supplemented by expert opinions, often led to dissimilar conclusions.

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The Colorado WSO covers each major basin in the state presenting a summary of snow depth and water equivalents, reservoir storage volumes, monthly and seasonal high elevation precipitation, and streamflow forecasts. Most data are presented dimensionally and as a percent of long term averages. A narrative summarizes the water supply and precipitation situation in the state and notes critical regions. The WSO has been published for the past 30 years, but only during the winter months (December 1 to June 1) and most of the data are for specific locations within each basin.

Reports by DWR were strictly compilations of water resources data (streamflow and reservoir storage) giving cumulative data for the water year and averages for the previous 10 years. These data were submitted by Division (basin) offices about the first of the month as requested by the State Engineer when drought conditions were deemed to exist. No attempt was made to objectively summarize conditions in the basin.

The Colorado State Climatologist publishes a monthly climatic summary that is distributed about three weeks after the data are observed. Monthly and seasonal precipitation, and temperatures are presented dimensionally and as a percent of normal. A narrative highlights data presented on state maps.

The NWS publishes weekly weather and crop bulletins by state. Data are extensively smoothed, obliterating the effect of topographic variation. A notable feature of this bulletin are PI values in major drainage basins. The PI is essentially a soil moisture balance which quantifies regional moisture anomaly. It is generated monthly, April through October. During drought periods it is generated weekly.

USGS publishes the monthly Water Resources Review, which summarizes surface and groundwater conditions by region for the United States. The general nature of this publication limits its usefulness for drought impact and assessment at the state level.

Climatic and Hydrologic Variability

Colorado's climate exhibits systematic variation both in an east-west and a north-south direction. The east-west variation is primarily caused by the presence of high mountain ranges in the west and relatively flat plains in the east. The mountainous western half of the state has a pronounced north-south variability in winter precipitation and streamflow. Normalized basin snowpack frequency analyses for several drainages in Colorado (Figure 1) reported by Doeskin and Shafer (1981) demonstrates the relatively high degree of variation found in southern basins compared with northern basins. Using Bartlett's test (Wine, 1964) the normalized April 1 snowpack data as well as April-September streamflow volumes for the Rio Grande and Yampa River were tested for homogeniety of variance. The hypothesis of equal variance was rejected at the 5 percent level of significance in both cases. The results of these tests support the proposition of non-uniformity in climatic/hydrologic regimes across the state.

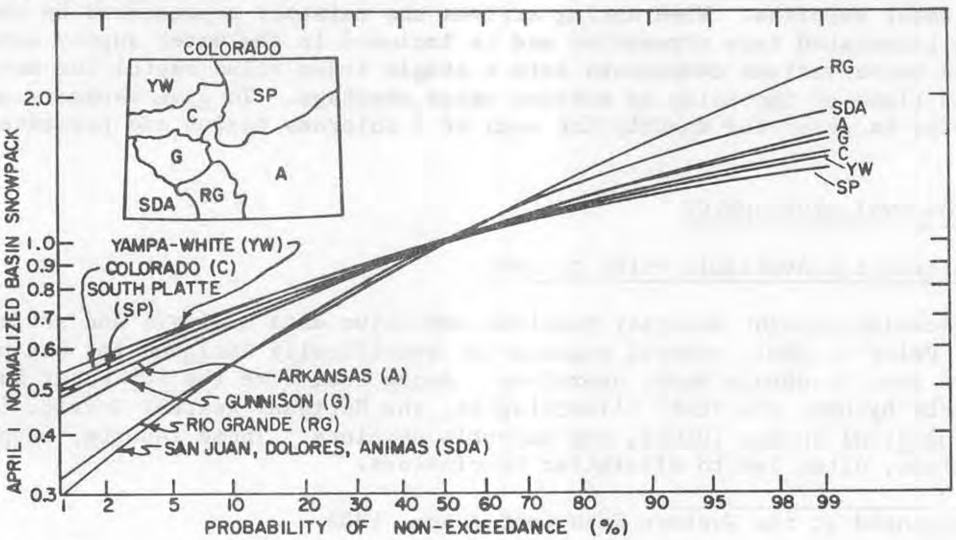

Figure 1. Frequency analysis of April 1 basin snowpack snow water equivalent (SWE) normalized to the median value.

The north-south variation is a consequence of two separate storm trajectories which influence the state. Central and northern Colorado mountains generally experience storms originating in the North Pacific which move inland across the Pacific Northwest. Precipitation events are, on average, relatively frequent and similar in magnitude. Southern Colorado, on the other hand, is most often affected by storms moving inland from California which draw in moisture from the tropics. These storms are less frequent than in the north but the magnitude of precipitation events is greater. The net effect of these two storm tracks is to produce nearly the same amount of average winter preciptitation in both regions of the state but introduces a much higher variability, i.e., more likelihood of extremes, in the southern portions.

Most professional engineers and hydrologists are aware of these climatological patterns, but a majority of the public including most managers and administrators are not. They have grown accustomed to hearing snowpack, streamflow, precipitation, and reservoir storage related as "percent of average" or "percent of normal". The public's interpretation of this terminology is generally adequate except for periods of extremes such as droughts and floods.

Therefore, it was believed that a procedure that statistically acknowledged the existing hydrologic variation between basins and expressed it in terms easily interpreted by the public would provide a more realistic appraisal of the probable impacts of extreme events. The concept of the SWSI, similar to the Palmer Index, was thus born.

Complementary Indices

To maximize the amount of information which could be incorporated into an index of the type proposed, it was first necessary to clarify the role such an index would serve as a complement to the PI. The PI was developed to identify the onset, severity and duration of a drought expressed as a departure of weather conditions from some norm (Palmer, 1965). Initially, its use was confined to describing moisture conditions in the Great Plains. Subsequently it has been universally applied to all regions of the United States. It is essentially a soil moisture accounting algorithm calibrated to relatively homogenous hydrologic areas. As such it has performed reasonably well in most parts of the United States where there are not large topographic variations. But, it was not designed for application in regions of permanent snowpack accumulation and runoff and therefore performs badly in such areas. Because of this, the PI is only valid in Colorado as a general indicator of moisture conditions in areas which are essentially mountain water independent (MWI), i.e., nonirrigated areas.

SWSI, by comparison, was conceptualized as an index that could serve areas that are mountain water dependent (MWD); areas that rely on snowmelt runoff as their main source of supply. SWSI and PI are mutually complementary indices descriptive of different hydrologic regimes; used together they more completely and accurately reflect overall moisture conditions in the state. The distribution and magnitude of current and potential drought regions as well as areas already afflicted can be identified more clearly, and rational response plans can be prepared that deal with different aspects of the problem as highlighted by the two indices.

FORMULATION OF SWSI

General

To be useful, the SWSI was designed so that it would be an indicator of basinwide water availability for the MWD sector, be predictive, and permit comparison of water supply conditions between basins to assess relative drought severity. To accomplish these requirements, many data with inherent predictive abilities are merged objectively to form basin index numbers, using the following steps:

1. Summing individual monthly station data to obtain a composite reservoir datum, snowpack datum, and precipitation datum. This reduces the number of data, smoothes the effect of anomalous events at individual stations, and enhances the applicability of statistical methods to reservoirs.

2. Normalizing the component data to one scale - the non-exceedance probability (PN) by using frequency analyses. This integrates the effect of hydrologic variability of each component and permits comparison between components.

3. PN's for each component are utilized in a basin weighting/scale equation to determine a SWSI for each basin in the state. A typical winter season SWSI equation follows:

$$SWSI = \frac{[(a \times PN_{SP}) + (b \times PN_{PCP}) + (c \times PN_{RS}) - 50]}{12} \quad \text{(EQN 1)}$$

where: a,b,c are weights for each component and must meet the condition a + b + c = 1. Each basin has a unique a, b, and c;
PN = probability of non-exceedance (%); and
SP, PCP, and RS refer to snowpack, precipitation and reservoir components, respectively. During summer, streamflow (PN_{SF}) replaces the snowpack component in the equation.

The weighting/scale equation (Eq. 1) does three things: (1) weights each component, (2) centers the SWSI about zero, and (3) compresses the scale. Centering the SWSI about zero and compressing the scale were done to produce numbers comparable to the PI. Subtraction of 50 centers the PN scale (in percent) about zero. Division by 12 compresses the range. Theoretically, the SWSI has a range of -4.2 to +4.2 but operationally the range is -4.1 to 4.1. PN's greater than 99% or less than 1% are not selected because the accuracy of frequency analyses is reduced at extreme values. Table 1 gives important scale points and their designations.

TABLE 1. SWSI SCALE

SWSI	DESIGNATION	SWSI	DESIGNATION
+4	Abundant supply	-2	Moderate drought-other task forces activated
+2	Near normal	-3	Severe drought-agency drought programs activated
-1	WATF activated	-4	Extreme drought

The flowchart show in Figure 2 depicts the stages of SWSI development and operational application.

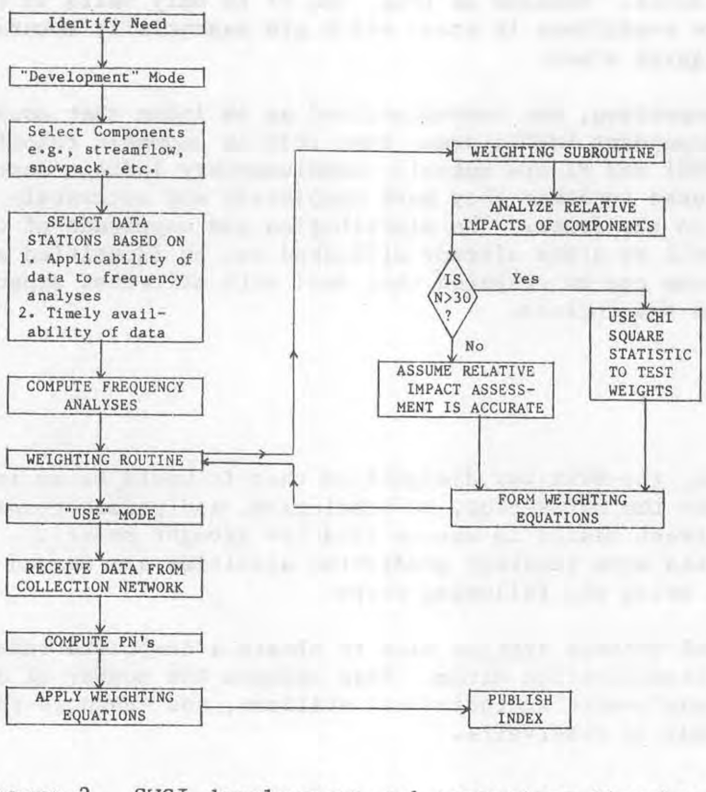

Figure 2. SWSI development and operations flowchart

The key step in the SWSI is use of the PN scale. The PN is superior in some respects to percent of average because it uses important additional information inherent in the collective data set i.e., the tendency toward dispersion (standard deviation). Percent of average incorporates the station's past history in computation of the mean value (central tendency) but ignores dispersion. Use of the standard deviation and the mean (parameters of the normal distribution) to determine PN permits comparison of SWSI's between basins and as well as comparison between components.

The next statistical moment (skewness) yields additional information about the data. Skewness was used in calculating some components, but typically it was small and its inclusion is inconsequential compared to inclusion of the standard deviation.

Steps 1, 2 and 3 above are done monthly for each of the seven major basins in the state. Results are published near the first of each month in map form (Figure 3) by DWR in the Colorado Water News and the SCS in the Colorado WSO.

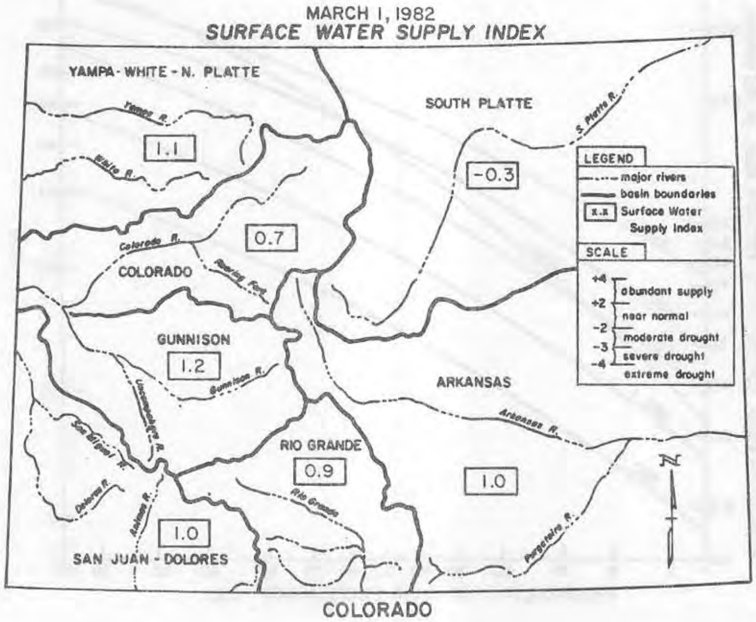

Figure 3. Surface Water Supply Index (SWSI) map of Colorado. These maps are generated monthly throughout the year.

Data Requirements

Stations selected for each component were required to give representative geographical coverage. Major considerations in satisfying this requirement were finding gages with sufficient length of record to develop frequency analyses that could submit data in a timely manner for actual operations.

Streamflow and reservoir storage stations had to meet the requirements of compatible sizes. A change in storage in a large reservoir can mask variations in small reservoirs and render the small reservoir data useless. A similar situation occurs with large and small streams.

Because of changing impact of the various water components through the year the winter and summer SWSI's are based on different components. Equation 1 is for a winter SWSI, based on snowpack, precipitation, and reservoir storage components. For summer, snowpack is replaced by a streamflow component. This exchange is based on the following:

1. Snowpack rapidly disappears and an operational system to comprehensively monitor its recession is not available,
2. Winter streamflows are principally base flow (groundwater), and
3. Snowpack and summer streamflow represent the same component, since 65 to 85 percent of summer streamflow is derived from melted snow.

Some form of cumulative data is used for all components, except summer precipitation, to enhance the SWSI's predictive abilities. Each component is addressed in more detail below.

Snowpack (snow water equivalent)

Snow water equivalent was chosen because it represents the major moisture source for the state. Six or seven SCS operated snow courses were chosen in each basin. Early season (December and January) PN's were based on SNOTEL data and trends in later month statistics, since no long-term records exist for these months. Figure 4 is a graph of snowpack PN's for the Rio Grande basin for the December 1 - May 1 period.

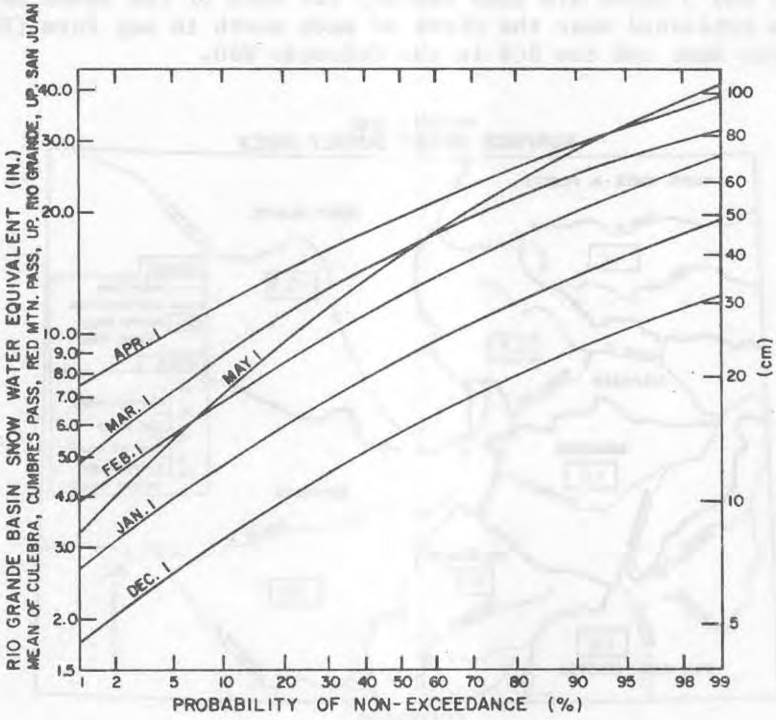

Figure 4. Rio Grande basin snowpack probabilities of non-exceedance (PN_{SP}) for winter season.

Streamflow

Whenever possible stream gage stations on major streams were chosen above the primary use area of mountain water. Ideally, one would like to use gages uninfluenced by upstream diversions, i.e., free-natural flow, but this was not always possible. The one to four gages per basin ultimately chosen were a compromise between location, regulation, and data availability. Most of the gages selected are operated by DWR, and the remainder by USGS.

Monthly streamflow rather than cumulative data was used to represent potential water supply. The position on the streamflow hydrograph (Figure 5), because of the snowmelt type stream selected, indicates the amount of water yet to pass the gage (Figure 5).

Computations of streamflow frequency analyses used data in the streamflow statistical summaries by Petsch (1979,1980) of the USGS. The probability distribution shown on Figure 6 graphically illustrates how PN's for streamflow (PN_{SF}) were obtained in the Rio Grande Basin. Because of the form of the streamflow statistics in Petsch's work a method was developed to aggregate streams into a single PN. This was done by weighting each stream's PN in proportion to the stream's average contribution to the cumulative basin flow (Figure 6).

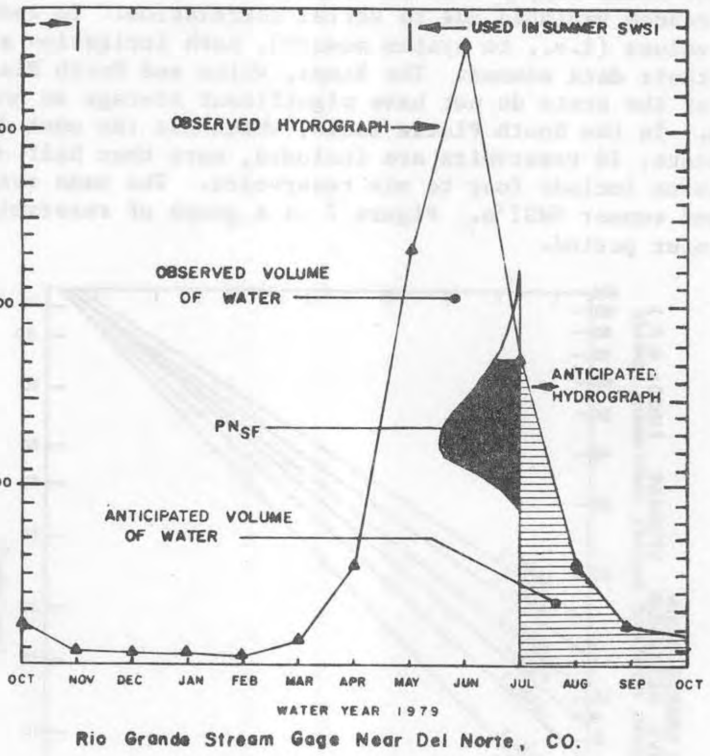

Figure 5. Streamflow hydrograph with superposed probability distribution for July 1.

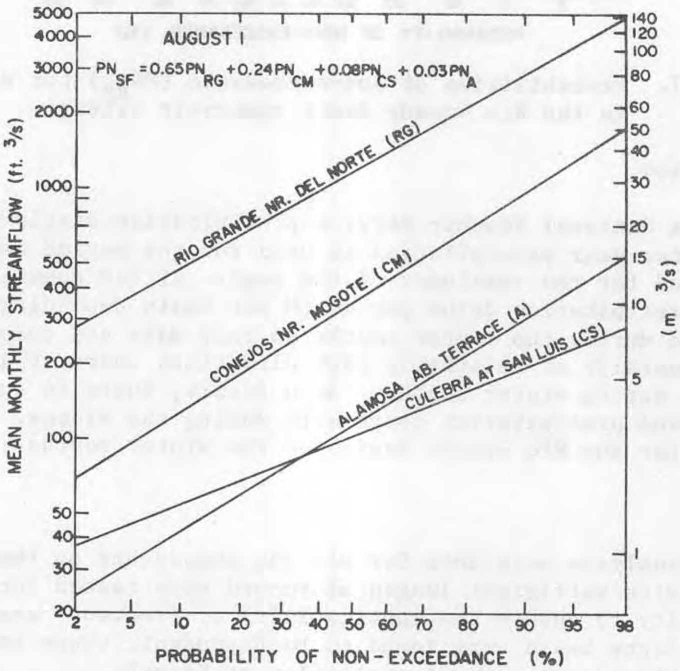

Figure 6. Probability of non-exceedance for Rio Grande Basin streamflow (PN_{SF}) for August 1. Weightings for each stream are based upon its mean contribution to the cumulative average basin flow.

Reservoir Storage

Reservoir storage is used in the SWSI for the entire year to represent the component of the surface water supply that is held in transit. It is the only component that is not clearly a random variable due to serial correlation. To reduce the dependence of data on previous values (i.e., to system memory), both irrigation and municipal reservoirs are selected and their data summed. The Yampa, White and North Platte basins in the northwest corner of the state do not have significant storage so no reservoir component is included for them. In the South Platte basin, which has the most developed storage capabilities in the state, 18 reservoirs are included, more than half of which are on the plains. Other basins include four to six reservoirs. The same reservoirs are used in both the winter and summer SWSI's. Figure 7 is a graph of reservoir PN's for the Rio Grande for the winter period.

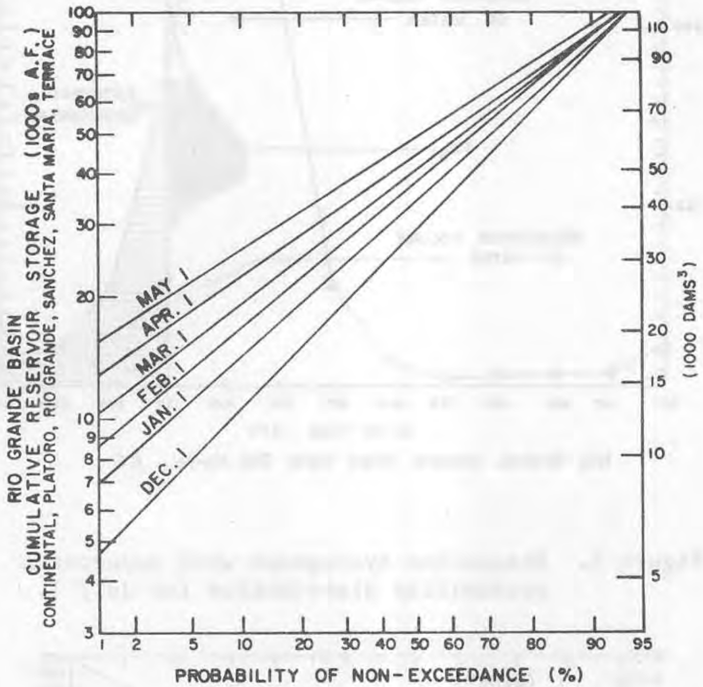

Figure 7. Probabilities of non-exceedance (PN_{RS}) for winter in the Rio Grande Basin reservoir storage.

Precipitation

Four to six National Weather Service precipitation stations per basin were chosen. Cumulative water year precipitation is used for the period December 1 to May 1 and monthly data are used for the remainder of the year. Either cumulative or monthly data are summed to one precipitation datum per month per basin depending on the season. Cumulative data are used during the winter months so that data are comparable to snowpack. The stations are generally at relatively high elevations where at least some precipitation accumulates as snow during winter months. As a result, there is an interdependency between the snowpack and precipitation components during the winter. Figure 8 depicts precipitation PN's for the Rio Grande Basin for the winter months.

Frequency Analyses

Frequency analyses were done for all the components so that PN could be determined. Components with sufficient length of record were tested for stationarity, independence, and homogeneity to ensure the applicability of frequency analyses. Only reservoir data in the South Platte basin were found to be dependent; these reservoirs can store two and one half times the average annual streamflow at Kersey.

Probability distributions were analytically fitted, using methods that are amenable to automation and facilitate reproducability. This reproducability is important in planning for future refinements of the SWSI and in monthly updating of frequency analyses for short-record components. Goodness of fit to those components with adequate length of record was checked by the Chi-square statistic.

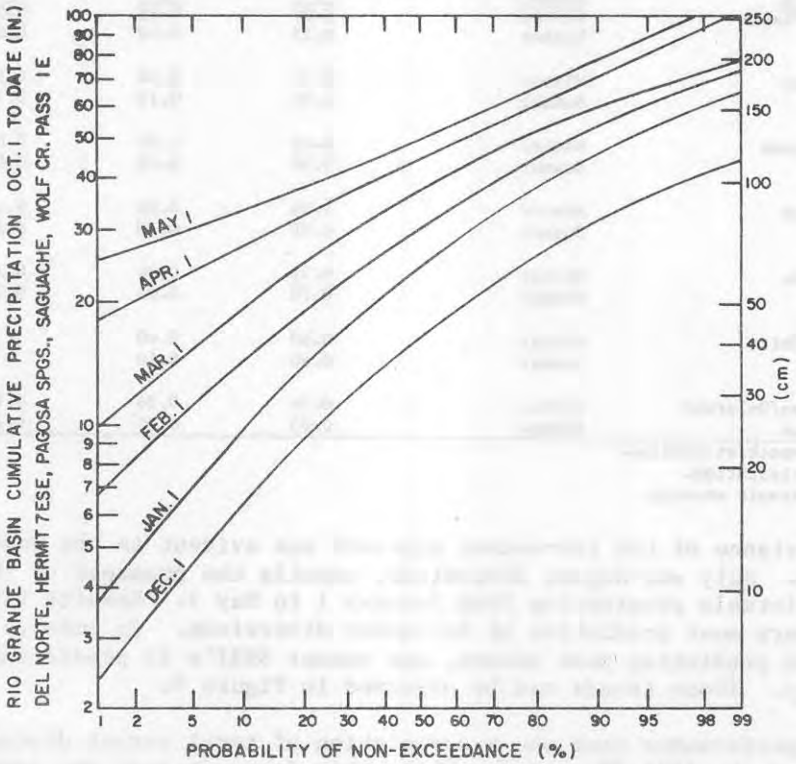

Figure 8. Probabilities of non-exceedance (PN_{PCP}) for winter precipitation in the Rio Grande Basin.

Component Weightings

The weightings a, b and c in Eq. 1 are based on the component's potential impact on water available in the basin. Annual streamflow and reservoir volumes were compared to determine relative weightings. Expert opinions by the National Weather Service, the Colorado State Climatologist and the SCS yielded initial approximations of the impact of precipitation and snowpack.

Final weightings were fine tuned by checking goodness of fit and adjusting to the actual situation. It was hypothesized that the additive nature of the components cause the SWSI to be normally distributed. In most cases tested that had sufficient data, the components were normally distributed. This would yield a normally distributed SWSI composed of underlying additive normal distributions. The Chi-square statistic was used to optimize goodness of fit.

May 1 data for the Rio Grande was used to adjust winter season weights for that basin. Difficulty in obtaining monthly data for all stations, components and basins precluded similar checks for other basins. As an alternate, monthly component data for the period 1974 to 1979 was broken into winter and summer sets and tested with the Chi-square statistic. An objectionable feature of this method lies in the set's dependent data from each year. This necessitated seasonal rather than monthly component weightings since more resolution was not possible. Table 2 summarizes component weights.

SWSI PERFORMANCE

Rio Grande Basin surface diversions were used to measure SWSI performance. Correlations between monthly Rio Grande north bank diversion data (dependent variable) and SWSI (independent variable) were investigated (Figure 9). The years 1974 through 1979 were used since they include extreme years and near-normal years. Future performance investigations will focus on lengthening the historical data base for comparison with SWSI.

TABLE 2. SWSI COMPONENT WEIGHTS

Basin	Season	Weights a (1)	b (2)	c (3)
South Platte	Winter	0.27	0.18	0.55
	Summer	0.25	0.10	0.65
Arkansas	Winter	0.51	0.34	0.15
	Summer	0.55	0.10	0.35
Rio Grande	Winter	0.63	0.32	0.05
	Summer	0.90	0.05	0.05
Gunnison	Winter	0.54	0.36	0.10
	Summer	0.60	0.10	0.30
Colorado	Winter	0.51	0.34	0.15
	Summer	0.70	0.05	0.25
Yampa/White	Winter	0.60	0.40	-
	Summer	0.90	0.10	-
San Juan/Dolores/ Animas	Winter	0.54	0.36	0.10
	Summer	0.85	0.05	0.10

(1) Snowpack/streamflow.
(2) Precipitation.
(3) Reservoir storage.

The importance of the two-season approach was evident in the results of the regression analysis. July and August diversions, usually the greatest of the year, appear increasingly predictable progressing from January 1 to May 1. Results indicated the August 1 SWSI's were most predictive of September diversions. In summary, winter SWSI's are most useful in predicting peak season, and summer SWSI's in predicting late season water availability. Those trends can be observed in Figure 9.

Another performance test was a correlation of total annual diversions with average annual SWSI for the 1974-79 period. While this does not test the predictive ability of monthly SWSI's, it shows a high degree of correlation ($r = 0.99$) between the variables and affirms the conceptual basis of the SWSI.

Operational Considerations

The SWSI appears in the monthly Colorado WSO, December through May, and in the DWR newsletter issued monthly for the entire year. Because much of the value of these reports lies in their timeliness, it is important that any new product they contain be producible within the first 5 days of each month. The SWSI computational procedure is straightforward and entails less than an hour once the requisite data are assembled. All calculations can be programmed on a small desk calculator. Frequently some data needed in the calculations are unavailable and must be estimated but this may mean only another hour of analysis to complete the data set. Data used to compute SWSI's during the December - May period are already being collected for other purposes, so additional efforts are minimal. In many cases, the missing data has already been estimated for insertion into streamflow forecast equations or analyses of basin snowpack, precipitation, and reservoir storage. Consequently, missing data has not proven to be a major obstacle in meeting publication deadlines.

A more significant operational problem is the discontinuance of stations used in computing the SWSI. On a short-term basis this can be offset by estimation techniques. However, eventually an entirely new set of frequency curves must be generated from other selected stations. A related problem is the case when one or more extreme events occurs which is outside the range of conditions experienced in the current frequency distribution. These occurrences dictate a reanalysis of the historical time series to produce a more realistic SWSI.

Changes in water management activities within a basin can also significantly affect SWSI's accuracy in portraying prevailing conditions. For example, a new reservoir may add 30 percent to a basin's total storage capacity. In the absence of historical records necessary for frequency analyses it would be impossible to assess the effect on water availability within the basin as reflected by the SWSI. Similar problems are encountered when reservoirs are enlarged or major transbasin diversions are built after a SWSI algorithm is developed.

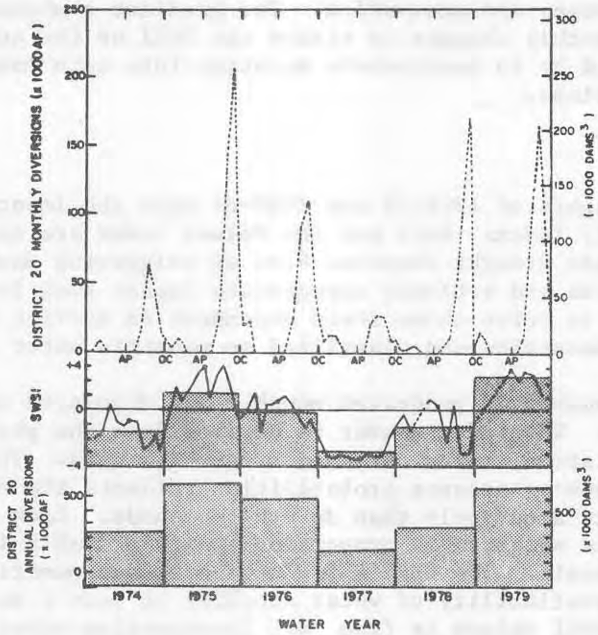

Figure 9. Selected Rio Grande Basin surface diversions and SWSI time series.

Consumer Response

Many individuals who see and use SWSI are not familiar with the mathematical concepts of frequency distributions and recurrence intervals. Therefore, the SWSI must be explained in terms they can understand. The concept of an index number to impart technical information in a nontechnical way is ideal. Such an approach is both useful and valid and serves one of the primary purposes intended.

To date, most comments have been favorable and point out the usefulness of two complementary indices (SWSI and PI) as improved management tools. By examining time series of SWSI and Palmer values for various basins, a clearer picture emerges where problems are developing and where none may exist. These indices are also helpful in conveying to special interest groups and the news media the overall surface water supply outlook by basin.

The Water Availability Task Force has used SWSI and PI thresholds according to plan. Response by the professional community concerning both the concept and results through the 1981 drought period have been favorable. One water engineering consultant stated that the SWSI was agreeing with the water supply index he uses based on a South Platte River stream gage. Field division offices of DWR have been enthusiastic in gathering data; they have observed that the SWSI is indicative of the amount of water they will administer. Several recipients of the WSO have commented on the ease with which they obtain a quick overview of Colorado's water supply situation from SWSI without extensive analysis of each basin's data summaries.

Refinements

Several refinements of the SWSI show promise for future investigation. One of immediate importance to the WATF is the applicability of the SWSI as an indicator of flood potential. The same factors necessary for drought quantification apply to floods, i.e., include major surface water components in a form to enhance their predictive abilities. A test of historical data involving river discharges and regional flood plain maps may be appropriate.

Monthly SWSI's indicate drought intensity, but not explicitly duration. A time series of recent month SWSI's included on the reporting map (Figure 3) would indicate duration but would require subjective interpretation by the consumer. An objective means of quantifying duration would involve a gradient component in addition to snowpack, precipitation, reservoir storage, and streamflow. The gradient component would be based on frequency analyses of monthly changes in either the SWSI or the other components. The net effect of this step would be to incorporate duration into each month's SWSI and thereby damp wide monthly variations.

SUMMARY

Colorado's droughts of 1976-77 and 1980-81 were the impetus for the development of a Surface Water Supply Index. SWSI and the Palmer Index are currently the two indices recognized in the Colorado Drought Response Plan as triggering mechanisms to officially monitor drought conditions and activate appropriate impact task forces to deal with its effects. SWSI is meant to serve those areas dependent on surface water supplies originating as snowmelt in the mountains and classified as mountain water dependent.

A single SWSI number is generated monthly and displayed in map form for each major basin in Colorado. The index number is derived from the probability distributions of snow course, precipitation, reservoir, and streamflow data. The representation of these data in terms of non-exceedance probabilities reflects the hydrologic variability inherent in Colorado more accurately than do other methods. Each of the constituent variables in the index is weighted in proportion to its probable impact on total surface water resources in the basin. The SWSI's produced are thus numerical values that express the current and future availability of water supplies to meet a multitude of competitive demands. The range of SWSI values is from -4.0 (prospective water supplies extremely poor) to +4.0 (prospective water supplies abundant). The SWSI number is a general indicator of surface water supply conditions. Further data analysis may be required to more fully understand the impacts in specific situations of abnormally dry or wet conditions suggested by SWSI.

Development and implementation of the SWSI concept have been joint endeavors of the Colorado Division of Water Resources and the Soil Conservation Service. Its reception by the user community has been very favorable. It is anticipated that the approach so far developed in Colorado will be further refined. However, the methodology is thought to have application in other states with diverse climatic variability in snowmelt runoff environments and merits study by other engineers and hydrologists.

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