Final Report

DEVELOPMENT OF A SURFACE WATER SUPPLY INDEX FOR THE WESTERN UNITED STATES

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SUMMARY STATEMENT

The idea of a simple index to monitor surface water supply in the West has a great deal of appeal. The Surface Water Supply Index (SWSI) has been well-liked by managers, administrators and scientists involved in drought monitoring in three western states.

This paper summarizes the results of a cooperative study conducted at the Colorado Climate Center (Department of Atmospheric Science, Colorado State University) and supported by the U.S. Department of Agriculture Soil Conservation Service. The goals of this study were to review the SWSI concept, identify and test methods for computing SWSI, and explore the possibility of expanding its applications in monitoring drought and managing western water resources.

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1.0 INTRODUCTION AND BACKGROUND

Water supply has always been a key factor in the settlement and economic development of the Rocky Mountain West. Systematic monitoring of climatic conditions in the western United States began about 100 years ago with the initiation of the Cooperative Weather Observing Program. This program, originally operated by the U.S. Department of Agriculture, Weather Bureau and later by the Department of Commerce, National Weather Service, has provided invaluable information about the distribution of temperature and precipitation and the year-to-year variations in climate. In the West, most weather stations were located where people live – in the valleys. But most surface water originates as mountain snowpack. With the growth and development of the water-limited West, and with the construction of many water storage and delivery systems, greater knowledge of water supply conditions became necessary.

In the 1930s, the U.S. Department of Agriculture Soil Conservation Service (SCS) established a comprehensive network of mountain snowcourses for evaluating snowpack conditions and anticipating future water supplies on a monthly basis. This network gradually expanded and more recently shifted emphasis to automated daily data collection. Development of better techniques to predict summer water supply using winter snowpack and other hydroclimatic data has also been emphasized.

As the era of major federally assisted water supply and diversion projects in the West has come to an end, attention has been focused on improved water management. This has resulted in greater emphasis on climate monitoring by many different federal, state, local and private organizations. As we move into the 1990s, more hydroclimatic data are being collected than at any time in our history. The SCS and NWS data collection programs represent only a portion of the data being collected routinely that permit thorough analyses of current and anticipated water supply conditions in both large and small basins throughout much of the Western United States. But it is not data alone that allows wise and appropriate management of Western water and water-related resources. Information – products derived from data which are compiled and summarized to help answer important questions – is what is most needed.

One of the water management challenges in the West that places the greatest demands on data and information sources is **drought**. Drought is a nagging and never ending problem across much of the western United States. An understanding of drought --

its frequency, intensity, duration and areal extent – requires extensive information, both current and historic. Identification of drought-prone areas, recognition of emerging drought conditions, anticipation of future conditions once drought is established and many similar questions are all surprisingly difficult undertakings given our current data sources and information products.

As of 1991, most states in the West have adopted or are developing written drought response plans. For a drought plan to work there must be some thoughtful means to trigger specific decisions and actions based on known water supply conditions that will, in turn, reduce hardship and economic losses from drought. Because of the hydroclimatic and socio-economic complexity of drought combined with frequent public and technical confusion over what constitutes drought, there has often been a reluctance to initiate planned response. But if the severity of drought conditions can be evaluated in a way that is consistent with subsequent impacts, a rationale for decision-making can be developed. This process has been carefully evaluated (Wilhite, 1990). Wilhite suggests that an index or combination of indexes, which quantify complex water supply data into a single numeric value or series, is a functional way to trigger difficult decisions. However, Wilhite cautioned against heavy reliance on the Palmer Drought Severity Index (the only nationally-produced long-term drought index) because of its relative slow response to deteriorating conditions and because it does not include snowpack, the most important hydroclimatic variable for representing Western water supplies. Recent work documenting the response characteristics of the Palmer Drought Index (Guttman et al., 1991) gives even stronger justification for minimizing the reliance on the Palmer Index for comprehensive drought monitoring in the West.

Colorado was one of the first Western states to develop and implement a state drought response plan. In an effort to improve drought information for decision making, the SCS and the Colorado Division of Water Resources worked together in 1981 to produce an index better suited for describing water supply conditions in mountainous regions. The resulting index combined precipitation, snowpack, streamflow, and reservoir data for specified basins into a single number which was called the Surface Water Supply Index, SWSI. That index has been computed in its original form each month for ten years and has become an integral part of drought monitoring activities of the Colorado Water Availability Task Force (Romer, 1990).

As other Western states completed drought plans and began interagency drought monitoring, the interest in the SWSI concept grew. In 1987, Oregon developed a modified formulation for the index which utilized an arbitrary but quantitative method for combining the four primary hydroclimatic components of precipitation, snowpack, streamflow and reservoir storage. In 1989, Montana began routine computations of yet another version of SWSI.

The growing interest in SWSI was enhanced by severe drought conditions in 1988 and multi-year drought in California and adjacent southwestern states. This, in combination with general keen interest in drought monitoring for optimizing water management, is now motivating a more careful look at the SWSI concept. Instead of each state developing their own SWSI for their own use, perhaps a more generalized approach would make sense that could be computed, with appropriate data, anywhere in the West. To this end, the Colorado Climate Center, through joint agreement with the USDA Soil Conservation Service West National Technical Center initiated this present study in 1990 to explore the SWSI in greater detail.

2.0 EVALUATION OF THE SURFACE WATER SUPPLY INDEX

2.1 Goals

The three primary goals of this project were 1) to review the SWSI development progress of the past decade, 2) to investigate how well various Index computations describe observed water supplies under a variety of hydroclimatic conditions and 3) to explore the feasibility of a generalized SWSI that could be applied throughout the western United States and used by a wide variety of both technical and non-technical people involved in water management, drought monitoring and drought response. The following tasks were undertaken to help meet these goals.

1) Review the purpose of indexes and the original rationale for SWSI development.

2) Outline and evaluate current and potential methods for computing SWSI.

3) Conduct a quantitative comparison of SWSI computations using available hydroclimatic data from a diverse selection of watersheds.

4) Analyze and summarize hydroclimatic characteristics of western watersheds related to SWSI computation and use.

5) Develop recommendations for westwide SWSI development and testing.

6) Present study results to SCS-West National Technical Center scientists, engineers and administrators and to the American Meteorological Society's Applied Climate Conference.

2.2 The Purpose For a Surface Water Supply Index

Before getting into specific discussion of SWSI, it may be useful to consider indexes in general. They have been around for a long time, and they serve specific and important functions. An index is nothing more than an indicator – something that is easy to spot and interpret. A quantitative index often takes the form of a single numeric value computed from some select subset of a large and complex array of data and information. Indexes are intended to represent, as well as possible, the most significant characteristics (by some definition or arbitrary choice) of that array. Indexes may be arbitrary and they are almost always an over-simplification.

We are surrounded by examples of indexes. The Dow Jones Industrial Average, for example, is a long-standing and well known index that attempts to describe, in a most simplified form, the complex performance and overall value of stocks on the New York Stock Exchange. The Consumer Price Index attempts to indicate relative changes in the cost of living affecting the average American. Many other economic indexes are computed monthly to track the health of the national economy and project expected revenues. A test score is another common example of an index – a simplified indicator of what a person knows.

Indexes are used regularly in business, economics, education and various social sciences, but they also can be applied to natural resources. The first comprehensive effort to employ an index to look at drought in the United States was undertaken by Wayne Palmer (1965). Several references to his index have already been made in the introduction (page 2). Using precipitation and temperature, Palmer developed a method to fairly objectively evaluate the "abnormality" of weather conditions as they affected soil moisture over a period of time. This index soon became known as the Palmer Index (PI) or Palmer Drought Severity Index. It has been computed operationally and published as a national drought monitoring tool for many years (Figure 1). It has survived in something very close to its original form not because of its technical perfection. It has many weaknesses and uncertain assumptions (Alley, 1984). Rather, it has survived and found wide and popular use because it provided a type of easy-to-think-you-understand information that could not be obtained from any other source. Particularly, it made it possible to compare the "relative abnormality" of climate conditions on a single scale from the whole broad spectrum of differing climatic types and areas of the country.

If the Palmer Index were truly uniformly applicable and consistently accurate for drought monitoring in all parts of the United States, the idea of a Surface Water Supply Index would probably have never appeared. However, Palmer's Index was developed and tested for areas where local precipitation was the sole or primary source of moisture. When applied to the western United States, this becomes a serious limitation. In the West, the PI may apply to moisture available for forest growth, rangeland conditions and dryland agriculture. But for many water resources applications affecting the population of the West – urban and industrial water supplies, irrigation, recreation, water law – the only water that matters is what is available in rivers and reservoirs. This is known as surface water.

Over much of the West, a large portion of the available water resources originate as accumulated mountain snowpack. This snow melts and is available as streamflow or can be collected in storage reservoirs during a relatively short period of the year – typically the late-spring early-summer runoff period. The PI does not explicitly include this critical source of water. As a result, the PI only reflects the abnormality of surface water supplies to the extent that low elevation precipitation (most basic historic climate monitoring stations in the West are located in lower valleys where most of the population has traditionally resided) may be correlated to the snowpack accumulation in the mountains. The association between the PI and stored water in reservoirs is even less direct. So it is not surprising that water experts in western states are reluctant to trust or use the PI for monitoring surface water

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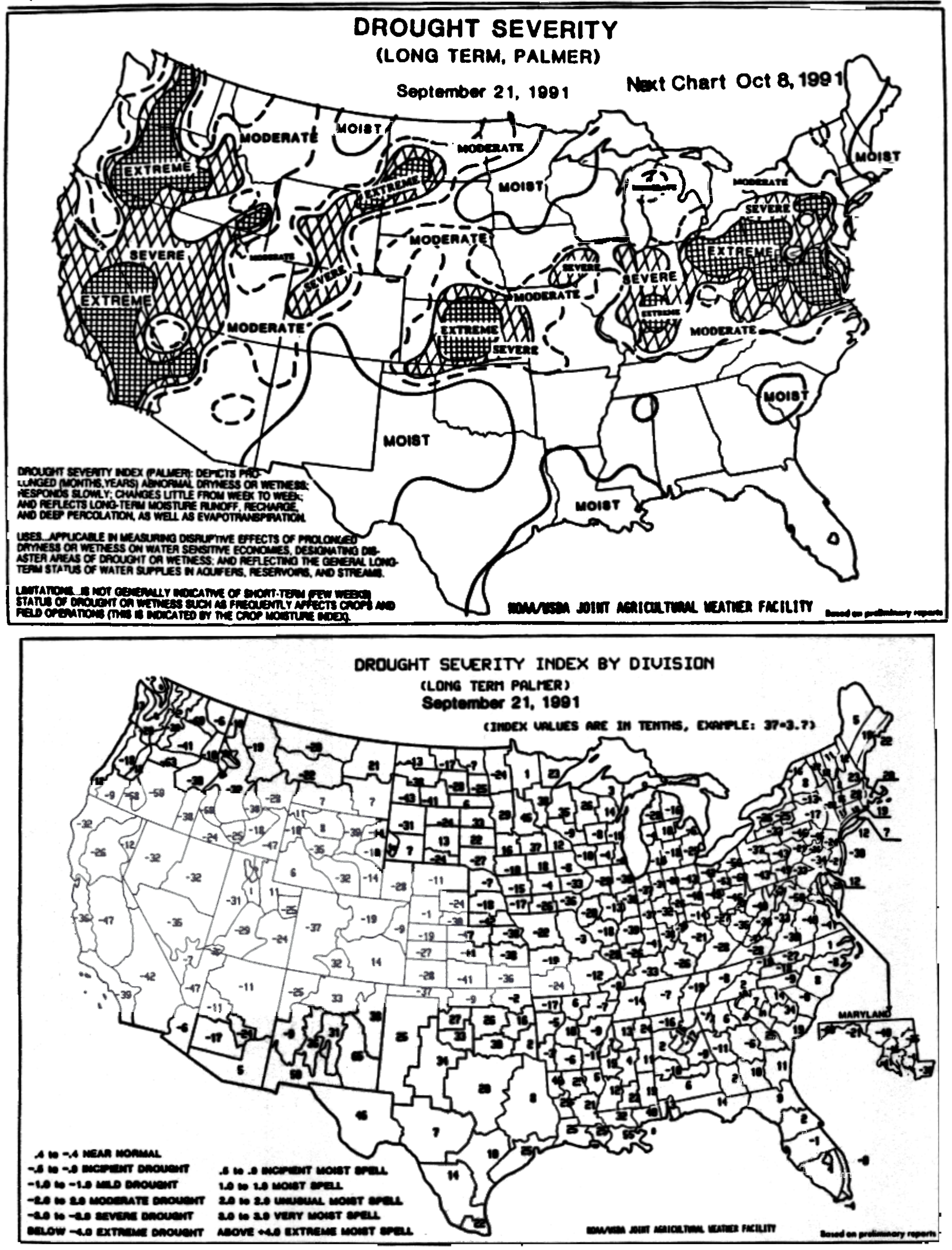


Figure 1. Example of Palmer Drought Severity Index information for the United States.

supplies. Nevertheless, there is great appeal for the idea of some sort of index that could provide simple information about current and projected water supplies to assist planners and decision-makers – various managers, administrators, public officials and, to a lesser extent, bankers and investors.

The purpose for the initial development of a SWSI ten years ago and the continued interest in such an index today is, therefore, quite clear. It is to provide a simple numeric value for monitoring abnormalities in surface water supply which compliments other information sources and communicates this information in a form that can be easily understood at both a technical and non-technical level (Figure 2). In the West, this means paying attention to the measurable hydroclimatic elements that contribute directly to water supply – precipitation, snowpack accumulation, streamflow and reservoir storage.

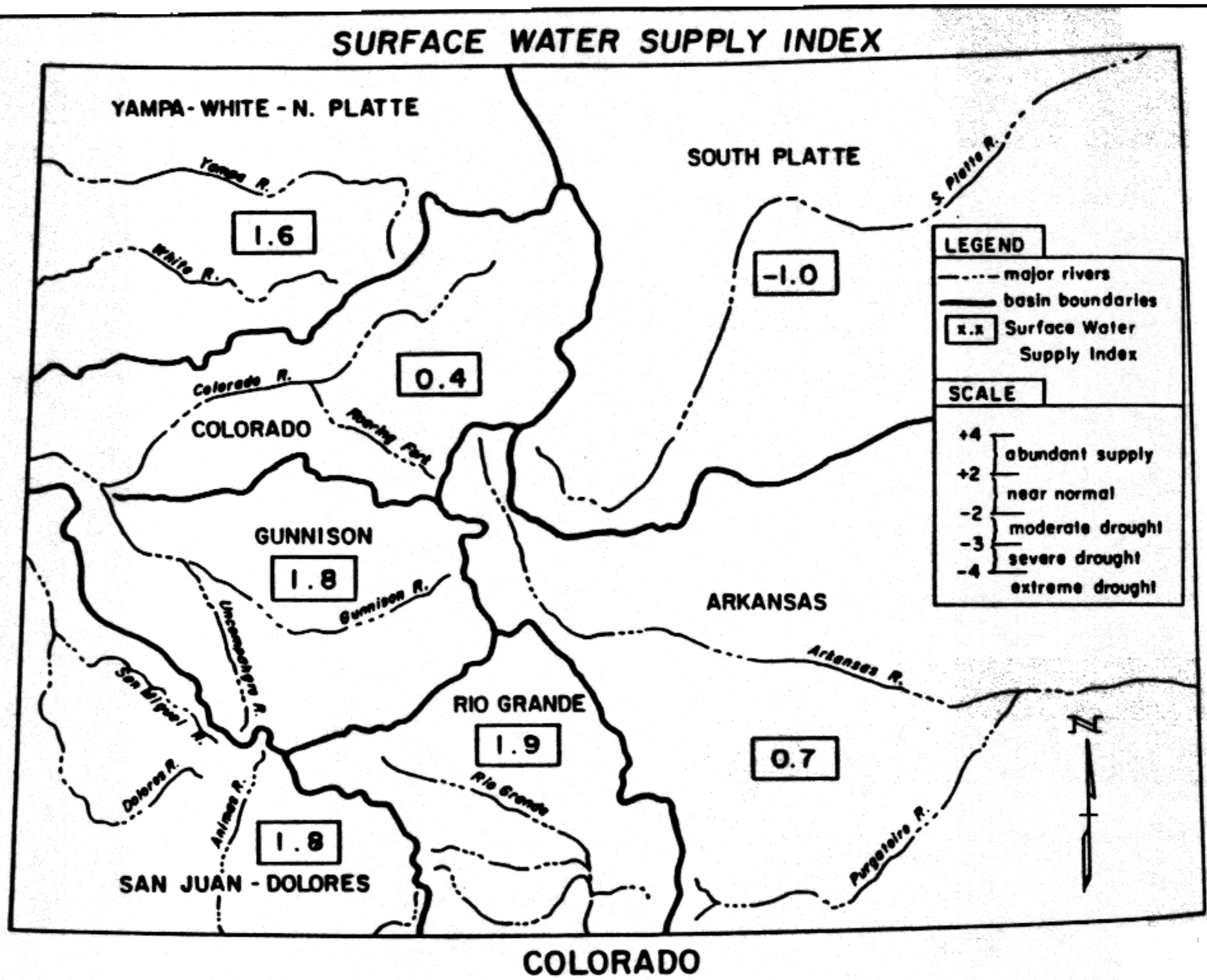
This purpose was convincingly stated in the original paper by Shafer and Dezman (1982). They selected the term "mountain water dependent" to describe the areas for which an index was most needed. The intent was to provide an index of current water supplies. But since the hydrologic system has inherent memory through lagged processes (such as snow accumulation and subsequent runoff), the index was also intended to be predictive. The original rationale for a SWSI also included an awareness that spatial differences in the magnitude of natural interannual variability in climate and surface water supplies could introduce difficulties in monitoring abnormalities and drought. For example, precipitation, snowpack and subsequent runoff are much more variable from year to year in southern Colorado than in the northern mountains near Steamboat Springs (Doesken and Shafer, 1981). As a result, a specific deficit, say 20% less streamflow than average, is much less likely to occur in the basins that drain west out of Colorado's northern mountains, than the basins that drain the southern mountains where such an anomoly is common. The original intent was to develop a SWSI that could statistically acknowledge these variations.

2.3 Methods for Computing SWSI

All recent activities to develop and employ a SWSI for water supply monitoring in the West has been influenced by the original efforts by Shafer and Dezman in Colorado. One of their most noteable contributions was the idea of expressing the status of each hydroclimatic component in terms of a non-exceedance probability.

The following section summarizes the methods that have already been used to compute SWSI and also describes several potential new methods. The suggested alternative methods were the product of several discussions among Colorado Climate Center and SCS staff interested in the SWSI concept. This is obviously not an exhaustive set, since there are an infinite set of possible ways to combine data into index form. Some of these are already similar in concept. Others represent substantially different approaches. There are undoubtedly other methods that could, and perhaps should, be considered. This list should suffice, however, to initiate a full discussion of the desirable attributes and the potential weaknesses of SWSI.

EXAMPLE OF A SURFACE WATER SUPPLY INDEX (SWSI) MAP



The Surface Water Supply Index (SWSI) is a weighted value derived for each major basin which generally expresses the potential availability of the forthcoming season's water supply. The components used in computing the index are reservoir storage, snowpack water equivalent, and precipitation. The SWSI number for each basin ranges from a -4.00 (prospective water supplies extremely poor) to a +4.00 (prospective water supplies plentiful). The SWSI number is only a general indicator of surface water supply conditions. Further data analyses may be required in specific situations to more fully understand the impacts of abnormally dry or wet conditions suggested by the SWSI. Development of the SWSI has been a cooperative effort between the Colorado State Engineers' Office and the Soil Conservation Service.

Figure 2. Example of a Surface Water Supply Index (SWSI) map.

2.3.1 Existing and potenial formulations for a SWSI

Existing Indexes:

1) Colorado SWSI

$$\frac{[(a*P(rs)+b*P(sf\ or\ sn)+c*P(pr))-50]}{12}$$

where P(__) represents the non-exceedance probability (%) based on available historical records of reservoir storage (rs), streamflow (sf), snowpack (sn) and precipitation (pr). a, b and c are weighting coefficients, determined subjectively, representing the approximate contribution of that component to surface water supplies. Snowpack is used during the period December through May. It is replaced by streamflow for the months of June through November. Coefficients remain constant during each half of the year. Subtracting by 50 (%) centers the sum of the weighted non-exceedance probabilities about zero. Division by 12 creates an arbitrary scale for the index running from −4.2 up to +4.2 making it similar to the typical ranges of the Palmer Index. The Colorado SWSI has been computed operationally for the past 10 years by the USDA SCS and the Colorado Division of Water Resources, State Engineer's Office.

Data requirements: Monthly values of snowpack, precipitation, streamflow and reservoir levels along with historical time series and probability distributions for each of these data sets for a selected set of stations within each computational basin. Basins were preselected to represent the seven primary water-management divisions in Colorado.

2) Oregon SWSI

$$\frac{[(a*P(sn)+b*P(pr)+c*P(rs)+d*[y*P(sf1)+z*P(sf2)])-50}{12}$$

similar to (1) except weighting functions are determined objectively and vary monthly. These weights are determined by first normalizing the average monthly values for each component by dividing through by the average value for the highest month. Then, the monthly coefficient for each component is determined by determining each components fractional contribution. The Oregon SWSI employs a smoothing function when used operationally.

Data Requirements: Same as Colorado. Minor differences in the rationale used for basin selection.

3) Montana SWSI

Very similar to Colorado SWSI in concept and form.

Very similar to the Colorado formulations but with different inputs and different subjectively determined weighting factors. Both precipitation and snowpack terms are based on data obtained from SNOTEL. Extra weight is given to recent (past two months) precipitation during the runoff season. A soil moisture term is included during late winter based on late summer – early fall precipitation or mid-winter streamflow. Streamflow is not an input to the calculation of SWSI except when used to represent soil moisture. Index values are only calculated February 1 through August 1.

Data Requirements: Similar to Colorado but with greater reliance upon SCS SNOTEL data for both snowpack and precipitation records. Smaller basin areas used than in the Colorado computations.

4) Palmer Drought Index

Semi-physical, semi-empirical water balance model.

This well-known, widely used drought index is essentially a physical water balance but contains a great deal of "black-box" empericism. It is assumed to be inappropriate for evaluating western water supplies, particularly surface water supplies. However, if it were set up for climate divisions that correspond to surface water supply production regions (instead of its current National Climatic Data Center climate divisions that are heavily weighted toward the more data-rich but drier lower elevation populated valleys) the results may be much more satisfactory.

Data Requirements: Areally averaged monthly temperature and precipitation for each computational area or division. Also, historical time series for both temperature and precipitation – ideally, at least 30 years. For each computational division, an estimate of average soil moisture capacity in a shallow and deep soil profile must be provided.

5) M. Roos Index (California)

Threshold Index on streamflow and reservoir levels.

This index uses monthly reservoir levels along with measured or predicted streamflow data. Rather than being a continuous function, M. Roos has identified a level of drought concern associated with certain experience-based streamflow and reservoir levels. From his own experience, he suggests that the appropriate level to begin significant drought concern is when reservoir storage falls to 70% of average or less and streamflow is in the lowest 10% of observed years. Anything better than that should not cause problems. But he admits these thresholds may differ by basin depending on the adequacy of current water storage-delivery systems relative to basin demand. Thresholds could be set up specific to each basin by people familiar with each basin – not objective but functional. It could be possible to make this a more continuous index by establishing more than one threshold or decision points to be more consistent with the stipulations of State Drought Response Plans.

Data requirements: monthly reservoir levels and measured or predicted seasonal streamflow expressed as departures from appropriate average values.

Other Possible Formulations:

6) Modified Colorado SWSI

Same as existing Colorado SWSI but with monthly-varying weighting coefficients. All components should be included in computation all year, even when their contribution is negligible. Coefficients should be determined according to each component's expected contribution to surface water.

Data requirements: Same as (1).

7) SCS Water Supply Forecast Method

Index based on forecasted water supplies in combination with reservoir storage values. Information combined into a single basin volume for indexing and statistical treatment.

Data requirements: SCS forecasted seasonal stream flow volumes for selected basins along with monthly reservoir level data and historical values and probabilities.

8) **Volume-equivalent Summation Index: Snowpack, Streamflow, Reservoir Method**

This proposed method would combine each of the hydrologic components by summing each component's volumetric contribution to the total available basinwide water volume. This total volume would then be compared to total volumes on the same date in previous years. Non-exceedance probabilities would then be used to convert the volume into a relative index each month.

Data requirements: Probably the same as (1).

9) **Precipitation, Snowpack, Streamflow and Reservoir Anomaly Index**

This proposed index would simply take monthly values or accumulated values of precipitation, snowpack, etc, determine their percentage departure from average, and combine them using "appropriate" weighting coefficients to determine a basin-wide departure from average. This value could then be assigned an index value.

Data requirements: monthly values and appropriate long-term monthly averages of precipitation, snowpack, streamflow, and reservoir levels for selected monitoring points within each SWSI division or basin.

10) **Precipitation Reservoir Index**

This proposed index would utilize selected NWS precipitation and/or SNOTEL precipitation measurements and assume they sufficiently represent the additional hydro-climatic components. The final index would combine a precipitation index with reservoir information. Results could be scaled either as an index of probability or of departure from average. If needed, a dual scale could be developed.

Data requirements: monthly values, records and appropriate long-term averages of precipitation and reservoir for selected monitoring points within each division or basin.

How then do we proceed to select a satisfactory index. The experiences in Colorado and in other Western states have led to a number of ideas and concerns which should prove helpful in evaluating existing or proposed SWSI formulations.

2.3.2 Considerations and constraints

It is not a simple matter to evaluate and determine which, if any, of the proposed list of SWSI formulations is best suited for operational water supply monitoring in the West.

The following is a list of important factors and key questions that should be considered when selecting a methodology for computing SWSI. It is the product of many discussions with individuals involved and familiar with the challenges and operational limitations of monitoring water supply and drought in the western United States. Some of these questions require thorough numerical comparative testing. Other questions are conceptional in nature and may not have clear answers. However, these questions must be addressed in order to attempt to determine the best method(s) for computing SWSI over the West.

1) What is **surface water supply**? Do we know what we are attempting to index?

2) Is the SWSI able to handle the wide range in hydroclimatic characteristics of Western watersheds? Do computed SWSI values have comparable meaning in areas that are hydroclimatically dissimilar.

3) Does the SWSI accurately depict current water supplies for the selected regions? Is it also predictive?

4) Is the SWSI physically valid? Does it make sense?

5) Are the statistical assumptions and statistical methods valid?

6) Does the SWSI identify appropriate levels of drought concern related to given water supply values?

7) Does the SWSI identify drought conditions at a frequency consistent with State response capabilities?

8) Is the SWSI applicable and meaningful year-round?

9) Does the SWSI really need to be computed monthly throughout the West?

10) Is the SWSI easy to compute? Are the equations easy to understand and explain?

11) How much time does it take each month to compute SWSI?

12) Should SWSI results be proportional to probability values or be expressed as a quantity (such as percent of average)?

13) How much and what type of input data are required for computing SWSI?

14) Are all input data for monthly SWSI computations readily available throughout the West?

15) Is there unnecessary redundancy and intercorrelation of input data?

16) Can SWSI still be computed despite some missing data?

17) Are consistent historical data available in each "basin" or "division" for valid probability and/or departure from average computations?

18) Can the SWSI be evaluated objectively?

19) Can the SWSI be evaluated against a truly independent variable? What would that variable be?

20) How big should each SWSI computational area be?

21) Who should compute SWSI? Should it be done centrally or done separately for each State?

22) Should SWSI be tested for other areas of the U.S. outside of the West?

23) Is the SWSI truly new and better information for drought monitoring or do other products or indexes already provide the same information?

The key points from this list are shown in Table 1. For an index to be useful it needs to be easy to compute and interpret and it must describe surface water supplies as accurately as possible.

Applying this list of constraints and considerations to the list of potential SWSI formulations is not straightforward. Some of the questions can be answered simply by looking at a potential SWSI equation and its data requirements. Other questions require that each model be run and their results compared before a justifiable answer could be obtained. Others can only be evaluated subjectively and experientially. Nevertheless, the considerations and constraints do provide a framework from which to examine each of these SWSI possibilities. For example, it is obvious that more development work and data are required for some of these index computations than others. If two methods give comparable results, the easier and faster index would be given preference.

TABLE 1.
Basic criteria for evaluating SWSI computational methods.

1) Physically appropriate?
2) Statistically valid?
3) Well correlated to water supply?
4) Adaptable to a wide range of hydroclimatic conditions?
5) Easy to compute?
6) Appropriate input data easily available?

2.3.3 Selection of SWSI formulations for comparative testing

Some effort was made at this point in the project to make a crude evaluation of which index formulations offered the greatest potential as a generalized index for the entire western United States. A working meeting was held in Fort Collins in December 1990 with David Garen (SCS–WNTC) and Colorado Climate Center staff with a goal to narrow down the list of candidate SWSI formulations. It was decided that all existing SWSI formulations should be included in subsequent testing even though the statistical validity of some of these indexes is questionable. The Roos Index may have considerable merit and is very easy to apply. However, since it is a single-threshold index, we decided not to include it in subsequent test procedures. Of the proposed new methods, the volume-sum method, while physically appealing, was thought to be impractical if not impossible. The proposed index based on water supply forecasts in combination with measured reservoir storage was determined to be reasonable and feasible. Other new methods all seemed to be offshoots from other SWSI formulations. While they may provide help in later fine-tuning, it was decided to do no specific testing with them at this time.

2.4 Comparison of Selected SWSI Formulations

Many of the constraints and considerations in the computation and use of SWSI are very important. However, the decision was made that the most important criteria for evaluating SWSI should be how well a computed index actually compares to observed water supplies. Therefore, project emphasis was directed toward coding several index formulations, computing index values from consistent data sets for a variety of test basins, and evaluating results. After comparing results of several methods and gaining hands-on experience with each method, then the more general evaluation criteria could again be incorporated.

2.4.1 Selection of test basins and input data

Four relatively small test watersheds were selected for all subsequent testing (Figure 3). The four test basins: the North Santiam in Oregon, the South Fork of the Flathead in Montana, the Sun River in Montana and the Upper Colorado River above Dotsero in Colorado were chosen to provide considerable hydroclimatic diversity and a wide range of reservoir capacities and management. A uniform data set of snowpack, precipitation, streamflow, SCS streamflow projections and reservoir levels were assembled for each basin to provide input data into the selected SWSI computations. In practice, SWSI's may be better suited and more useful at a larger scale – perhaps 7 to 25 basins per state based on current experience. Limiting the basin area for test purposes minimizes the range and spatial variability of hydroclimatic conditions within the basin. This allows clearer interpretation of the computed results.

Here is a brief description of the data used and the hydroclimatic characteristics of each of these test basins.

Santiam River, Oregon

Data used
- Marion Forks SNOTEL (1941-89) estimated from snowcourse
- Santiam Junction Snotel (1941-89) est. from snowcourse
- Detroit Dam Cooperative precipitation data, 1948-89
- Santiam Pass Cooperative precipitation data, 1963-89
- Detroit Lake reservoir storage, 1958-89
- North Santiam River at Mehama streamflow, 1948-89
- SCS Streamflow forecasts, 1953-88.

Optimum overall analysis period, 1958-1989

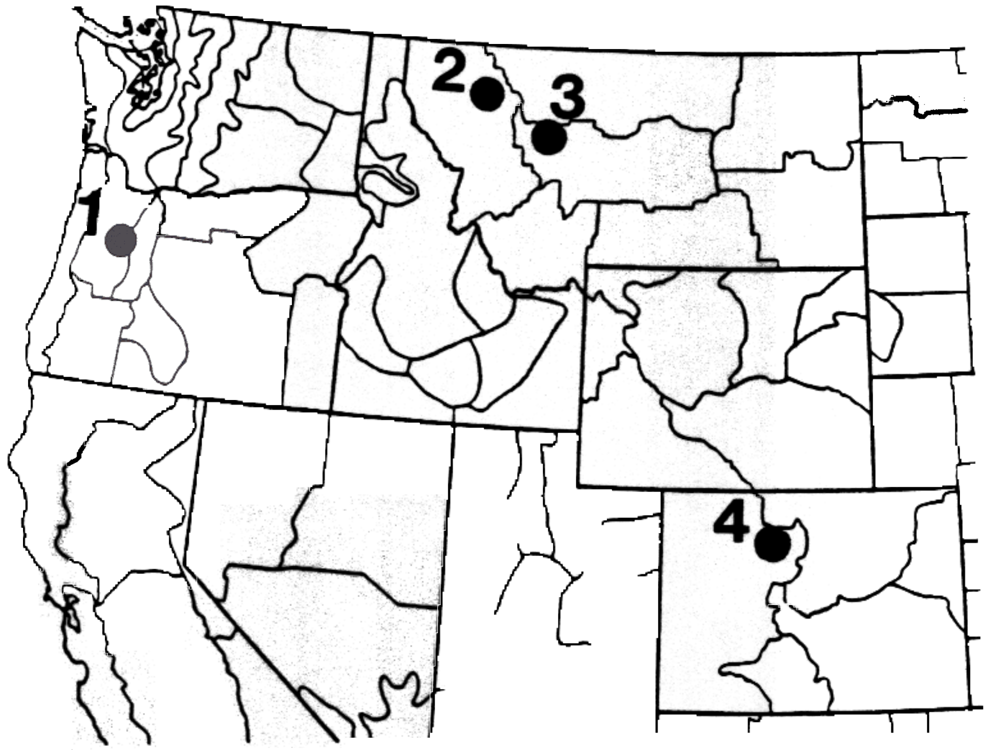


Figure 3. Watersheds used for SWSI comparison: 1) North Santiam River, Oregon; 2) South Fork of the Flathead River, Montana; 3) Sun River, Montana; and 4) the Upper Colorado River above Dotsero, Colorado.

Hydroclimatic characteristics:

This basin is unique among the four test basins in that it has a distinct winter maximum in precipitation and a summer minimum. Runoff usually peaks in the winter months and sometimes reaches a secondary snowmelt runoff peak during the spring. Snowpack may increase throughout the winter, or it can recede. On the average, only 34% of the average annual runoff occurs during the April-September season. The mean annual streamflow is 2,534,700 acre-feet for the period of analysis of which about 11% is typically held in storage in Detroit Lake. That reservoir behaves like a flood control structure with no water held during the winter. It is almost always filled in the summer, regardless of the variations in streamflow.

Upper Colorado River in Colorado

Data used: Berthoud Pass snowcourse, 1936-1989
Granby snowcourse, 1949-1989
Lake Irene snowcourse, 1938-89
Lynx Pass snowcourse, 1936-89
Grand Lake 1NW cooperative precipitation, 1950-89

Winter Park cooperative precipitation, 1950-89
Lake Granby reservoir storage, 1952-88
Williams Fork Reservoir, 1953-88
Colorado River at Dotsero streamflow, 1958-88
SCS streamflow forecasts, 1969-88

Optimum analysis period, 1958-1988

Hydroclimatic characteristics:

This is a fairly classic high-elevation Rocky Mountain watershed where snow accumulates throughout the winter and melts during a short period predominantly in May and June. Precipitation falls throughout the year but tends to be heaviest in mid-winter, spring and with yet another peak in mid-summer. The summer precipitation contributes very little to runoff, however. Annual streamflow averages 1,915,000 acre-feet at Dotsero of which 83% on average occurs during April-September. There are several reservoirs and high-elevation diversions in this basins, and considerable amounts of water are diverted out of this basin to the Front Range of Colorado. More than 40% of the annual runoff could potentially be stored in reservoirs within this area although the average storage is somewhat less.

South Fork of the Flathead River in Montana

Data used: Holbrook snowcourse, 1951-89
Spotted Bear Mountain snowcourse, 1948-89
Twin Lakes snowcourse, 1951-89
Hungry Horse Dam Cooperative precipitation, 1948-89
Summit Cooperative precipitation, 1939-89
Hungry Horse Lake reservoir storage, 1952-89
S. Fork Flathead near Columbia Falls streamflow, 1952-89
SCS-streamflow forecasts, 1953-89

Optimum analysis period, 1953-1989

Hydroclimatic characteristics:

This basin is similar to the Upper Colorado in that most runoff is produced from snowmelt in May and June. 84% of the 2,655,000 acre-feet mean annual streamflow occurs during April-September. Precipitation peaks in mid-winter and reaches a secondary peak in May and June. July and August is normally the driest time of year. A key feature of this basin is the huge reservoir capacity. Hungry Horse Lake reliably holds more than 3,300,000 acre-feet of water throughout the summer months and gradually releases water for power generation. It reaches its lowest point typically in April at about 57% of its normal summer level.

Sun River in Montana

Data Used: Mount Lockhart snowcourse, 1961-89
Mount Lockhart Snotel, 1961-89, estimates before 1974
Wrong Ridge snowcourse, 1949-89
Augusta Cooperative precipitation, 1931-89
Gibson Dam Cooperative precipitation, 1939-89
Gibson Reservoir storage, 1936-89
Sun River at Gibson Dam streamflow, 1943-89
SCS-streamflow forecasts, 1961-89

Optimum analysis period, 1961-1989

Hydroclimatic characteristics:

The Sun River in west-central Montana is a tributary to the Missouri River and drains eastward from the Continental Divide. Like most of the central and northern Rocky Mountain watersheds, the Sun River basin experiences steadily increasing snowpack from winter into spring followed by a rapid meltoff in May and June. The annual average streamflow is small in comparison to the other 3 basins used for SWSI testing and averages 634,000 acre-feet. About 86% of the streamflow occurs April-September. In this basin, runoff is enhanced by spring precipitation which also peaks in May and June especially in the lower elevation regions of the basin. In some years, unusually large or small spring precipitation seriously compromises the accuracy of water supply forecasts. Gibson Lake holds about 100,000 acre-feet of water, roughly 15% of the annual streamflow. This water is normally released quickly during the irrigation season and is gradually replenished throughout the winter until it is quickly filled again in May and June. Water levels can vary considerably depending on that years streamflow volumes.

2.4.2 SWSI model coding and computation

Prior to this test, the process of computing SWSI's operationally in Colorado, Oregon, and Montana has been predominantly done by hand using prepared probability graphs and look-up tables. This was not practical for our comparison. Four methods for computing SWSI, the operational indexes used in Colorado, Oregon and Montana and also the new water supply forecast-based SWSI were each coded using the programming language C. The actual computation of index values is quite simple and straightforward given appropriate input data. The more difficult task involved data management and the development of historical probability distributions for all of the hydroclimatic inputs and for the various individual months and accumulated periods.

The sequence in computing SWSI values for each of the models is as follows. Time series of each input element are read into arrays. Where data from multiple sites are used, a combined time series is formed which represents the sum or average of the individual site data. Missing or incomplete data become a major hindrance. Assumptions need to be made to handle these situations. Either estimated data must be provided so that all time series are complete, or procedures must be developed to interpolate or objectively provide estimates. For the 4 test basins, only those months and years when all data were complete were used in subsequent analyses. This approach would not be acceptable later in operational index production.

From the complete time series arrays, probability statistics were then generated for each month of the year. It is possible to compute empirical non-exceedance probabilities for any set of data. However, to simplify coding and data handling throughout this comparison, the assumption was made that all distributions could be represented by a fitted gamma distribution. For each data time series, gamma function coefficients were derived. Thereafter, the fitted distributions were used to compute non-exceedance probabilities. Figure 4 shows examples of how gamma-fitted distributions compare to actual empirical distributions. The characteristics of normal distributions are also shown for comparison. Generally, the results are good, but for certain distributions such as reservoir levels, fitted curves can be very misleading. This problem must be addressed before a generalized SWSI model is recommended for use in the West. For reference, up until this time there has been no consistency on how to handle data for use in the operational computation of SWSIs. Montana uses fitted curves and assumes normal distributions. Colorado has used a variety of distribution functions over the years including log-normal. Comparison of observed and fitted distributions within each of the four test basins are contained in Appendix 6.1.

The last step prior to actual index computations is the inclusion of weighting functions. The Colorado and Montana SWSIs each utilized arbitrary experience-based weights that must be supplied ahead of time and are then viewed as constant. The Oregon SWSI objectively determines its own weights from the relative seasonal distributions of each of the hydroclimatic components. Table 2 shows examples of monthly weighting factors used in the computation of index values for the North Santiam River in Oregon. Appendix 6.2 contains weighting coefficient used in the other three basins.

The only SWSI formulation selected for testing that does not require selection or computation of weighting functions is the streamflow forecast-based method using SCS forecast volumes added to current reservoir storage. Both of these components are expressed in volumetric units (acre-feet). They can be combined directly without needing weighting factors. This method is not currently suited for year-round computation since water supply forecasts are currently only issued each month from January 1 to June 1 and are only valid for the April-September runoff season (shorter or earlier seasons for selected areas of the West). For the purpose of this comparison, a simple method to extrapolate the June 1 forecast to July and August was employed. For example, a pseudo July 1 forecast was created by subtracting observed streamflow through the end of June from the initial June forecast of June-September flows. For year-round SWSI generation, a simple forecast method could be developed, but was outside the scope of this limited project.

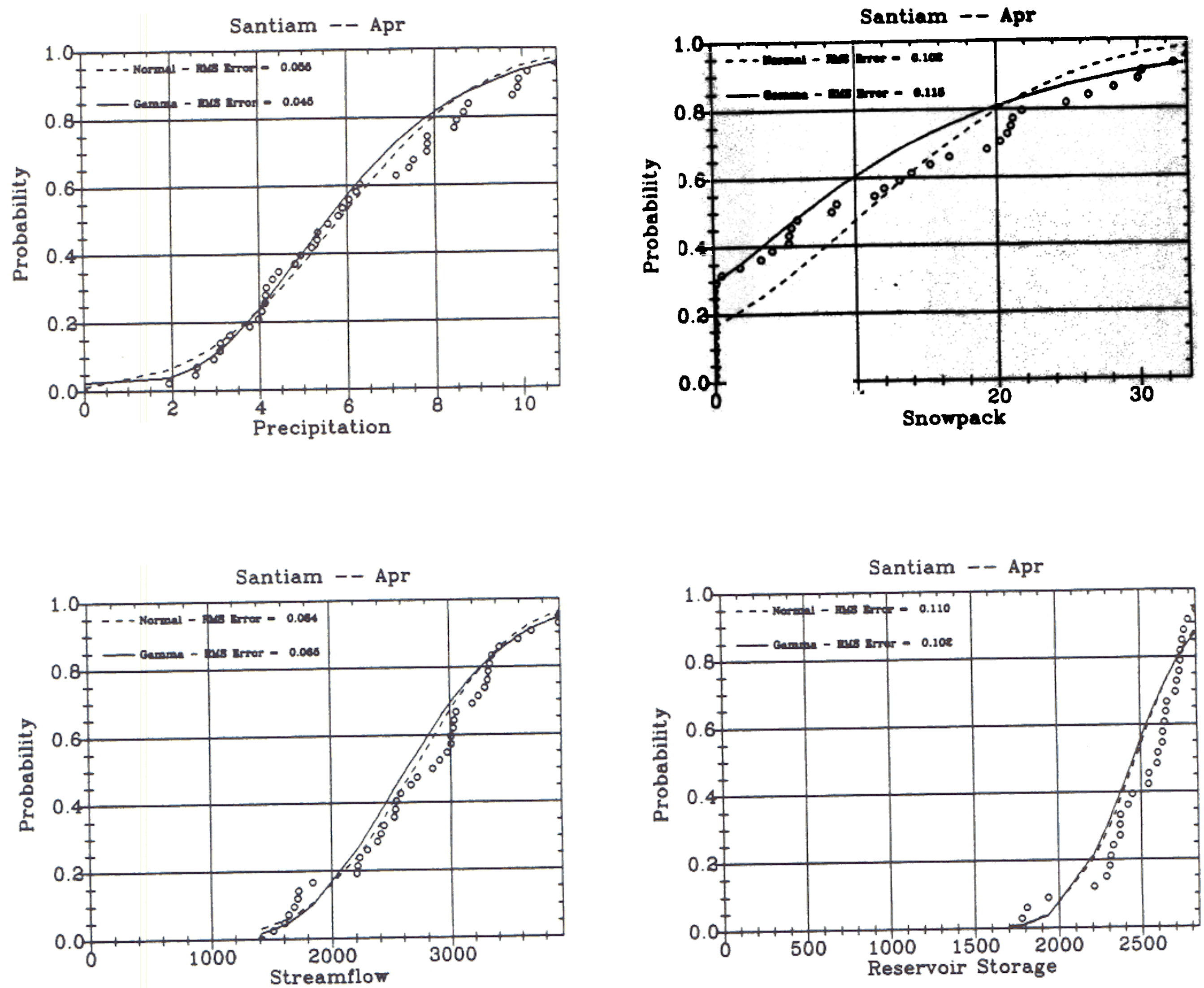


Figure 4. Observed distribution of monthly precipitation in the Santiam River Basin in Oregon for selected months and fitted distributions using a normal curve (dashed line) and a gamma curve (solid line). Root mean squared errors are shown in the upper left-hand corner to describe the goodness of fit.

TABLE 2.
SWSI Monthly Weighting Coefficients – Santiam at Mehama, OR

Mon.	Precipitation			Snowpack			Reservoir			Steamflow			Soil Moist.
	OR	CO[1]	MT[2]	OR	CO	MT	OR	CO	MT	OR	CO	MT[3]	MT[4]
Oct 1	.24	.20	--	0	0	--	.62	.20	--	.14	.60	--	--
Nov 1	.44	.20	--	0	0	--	.30	.20	--	.26	.60	--	--
Dec 1	.51	.45	--	0	.50	--	.07	.05	--	.41	0	--	--
Jan 1	.40	.45	--	.17	.50	--	.04	.05	--	.40	0	--	--
Feb 1	.33	.45	.27	.27	.50	.56	.05	.05	.11	.35	0	0	.06
Mar 1	.25	.45	.27	.32	.50	.56	.13	.05	.11	.30	0	0	.06
Apr 1	.24	.45	.27	.32	.50	.56	.20	.05	.11	.24	0	0	.06
May 1	.16	.45	.27	.22	.50	.56	.33	.05	.11	.28	0	0	.06
Jun 1	.16	.20	.22	.03	0	.21	.47	.20	.35	.34	.60	.22	0
Jul 1	.14	.20	.20	0	0	0	.59	.20	.60	.27	.60	.20	0
Aug 1	.05	.20	.17	0	0	0	.78	.20	.66	.17	.60	.17	0
Sep 1	.10	.20	--	0	0	--	.77	.20	--	.13	.60	--	--

[1] uses individual month precipitation June 1-Nov 1 and water-year accumulated precipitation Dec 1-May 1.

[2] uses water-year accumulated precipitation.

[3] uses combined precipitation for previous 2 months instead of streamflow.

[4] uses Nov-Jan streamflow.

2.4.3 Comparative results

Index values were computed for each month with available data for each of the four basins and for each of four SWSI models (Colorado SWSI, Oregon SWSI, Montana SWSI, and the SCS Streamflow Forecast SWSI). Figure 5 shows graphical time series computed SWSI values in the Sun River basin in Montana. Complete time series for the other 3 test basins are presented in Appendix 6.3.

Visual analysis suggests that all four indexes generally went up and down in similar ways, all responding similarly to anomalously wet and dry periods. A more quantitative comparison is needed, however, before any useful statement can be made regarding the performance of these various indexes. Therefore, it is crucial that an independent variable be found that would allow some sort of statistical evaluation of the "accuracy" of each index.

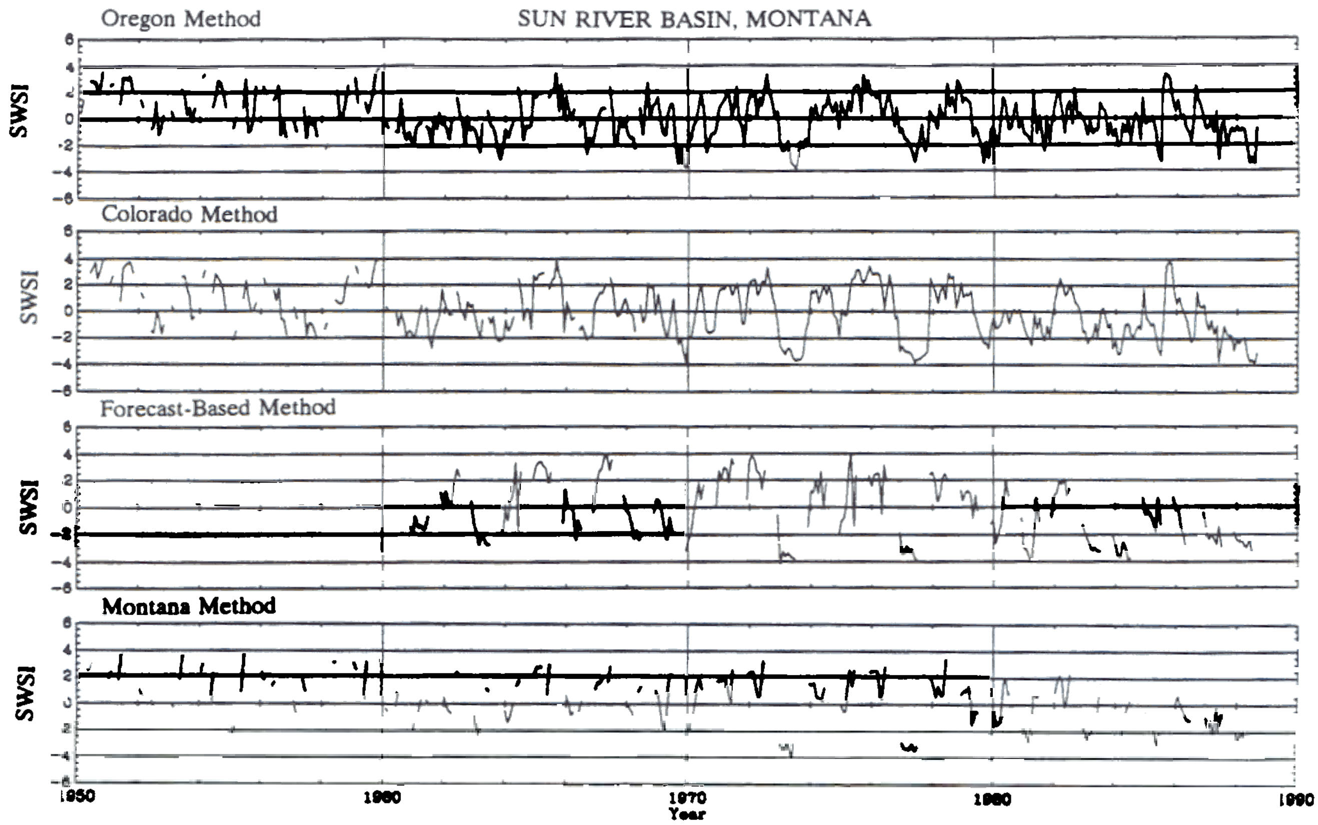


Figure 5. Comparative SWSI time series for the Sun River basin in Montana

No single satisfactory definition of surface water supply existed prior to this study, and no truly independent measure of actual water supply was identified. It was decided that a reasonable approach would be to simply correlate computed index values with a measure of surface water supply obtained from observed values of streamflow and reservoir storage. For this comparison, water supply was defined as the water available from surface sources during the April-September primary agricultural growing season. This definition could certainly be debated for parts of the Western U.S., but it was viewed by the authors that this was the best single definition that could be applied across the entire region for purposes of comparison.

There was still debate concerning what numbers to use as the verification April-September surface water supply. In the end, four different computations of water supply were assembled: 1) April-September virgin streamflow, 2) April-September virgin streamflow plus the available stored reservoir water averaged over June-August, 3) April-September virgin streamflow plus the stored water available on April 1, and 4) the non-exceedance probability equivalent of #3.

Correlations statistics were then computed for each month using linear regression. For example, the SWSI time series computed from all January 1 data for each basin were regressed against the time series of actual water supply. Results showing correlations as a function of month employing two of the definitions of April-September water supply are shown in Figures 6-9. We first used the April-September virgin streamflow alone and then did a second comparison using virgin streamflow combined with the stored water in the basin as measured on April 1. This type of correlation provides a crude test for evaluating which SWSI computations most closely relate to water supplies.

In the North Santiam basin, all methods behaved similarly with correlations (r^2) increasing to peaks of 0.4 to 0.5 at the end of April, declining sharply in May and improving again in June and July. The results were nearly identical for the two definitions of water supply. This suggests that in that basin the role of stored water contributed little to the overall variability of April-September water supplies. No single index clearly outperformed the others in this basin, although the Colorado SWSI showed the best results in May and June.

In the Sun and Upper Colorado basins, index correlations to summer water supply got off to a much better start with r^2-values already near 0.6 in January for some of the SWSI methods. This demonstrates that SWSI does have predictive value. Correlations generally improved into the runoff season and decayed later in the season. The Montana and forecast-based SWSI each tended to show a marked decline in correlation with water supply during the peak runoff season in June only to rebound again in July. The Colorado SWSI showed poorer correlations in May in the Colorado basin. This charactersitic has been noted on several occasions during operational use in Colorado and results from the fact that snowpack after May 1 is no longer included in the computation but still contributes to variations in water supply after that date. Still the Colorado SWSI produced excellent overall results in these two basins with correlation statistics exceeding 0.8 during the runoff season. The Montana and forecast-based SWSIs performed almost as well. The Oregon SWSI showed poorer correlation with water supply in these two Rocky Mountain watersheds, especially early and late in the season. Including reservoir volumes into the water supply verification data had almost no effect on correlations for the months of January through May but did produce r^2-values that were somewhat improved for the June-August period.

Finally, the South Fork of the Flathead River in Montana produced some unusual results. Correlations were fairly good in January but declined abruptly to near zero by May for all except the forecast-based SWSI before improving again in June and July. This unexpected behavior has not been throughly investigated but appears to result from the fact that a very high percentage of total water supplies in this basin are held in storage – a much higher percentage than in any of the other test basins. Therefore, the reservoir component is weighted heavily in the computation. Since variations in reservoir levels may relate more to particular management practices during certain times of the year than to changes in natural supply, this would likely degrade correlations with computed SWSIs. Also, the gamma distributions used to determine nonexceedance probabilities did not fit the observed distribution of reservoir levels well. Further study of SWSI performance in this basin is needed.

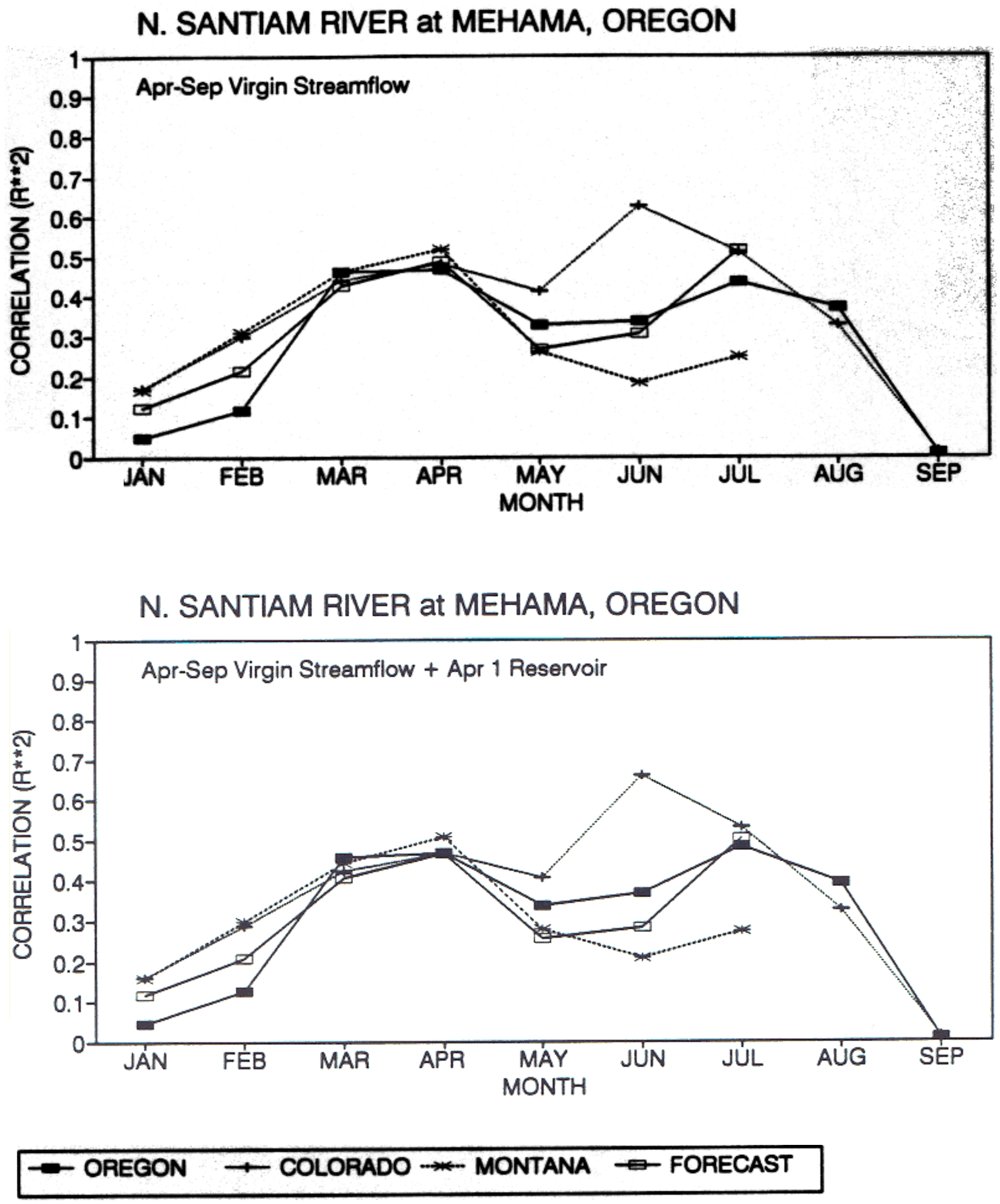


Figure 6. Correlations of computed SWSI values with April-September virgin streamflow (top) and with April-September virgin streamflow plus active reservoir storage on April 1 for the North Santiam River basin in Oregon.

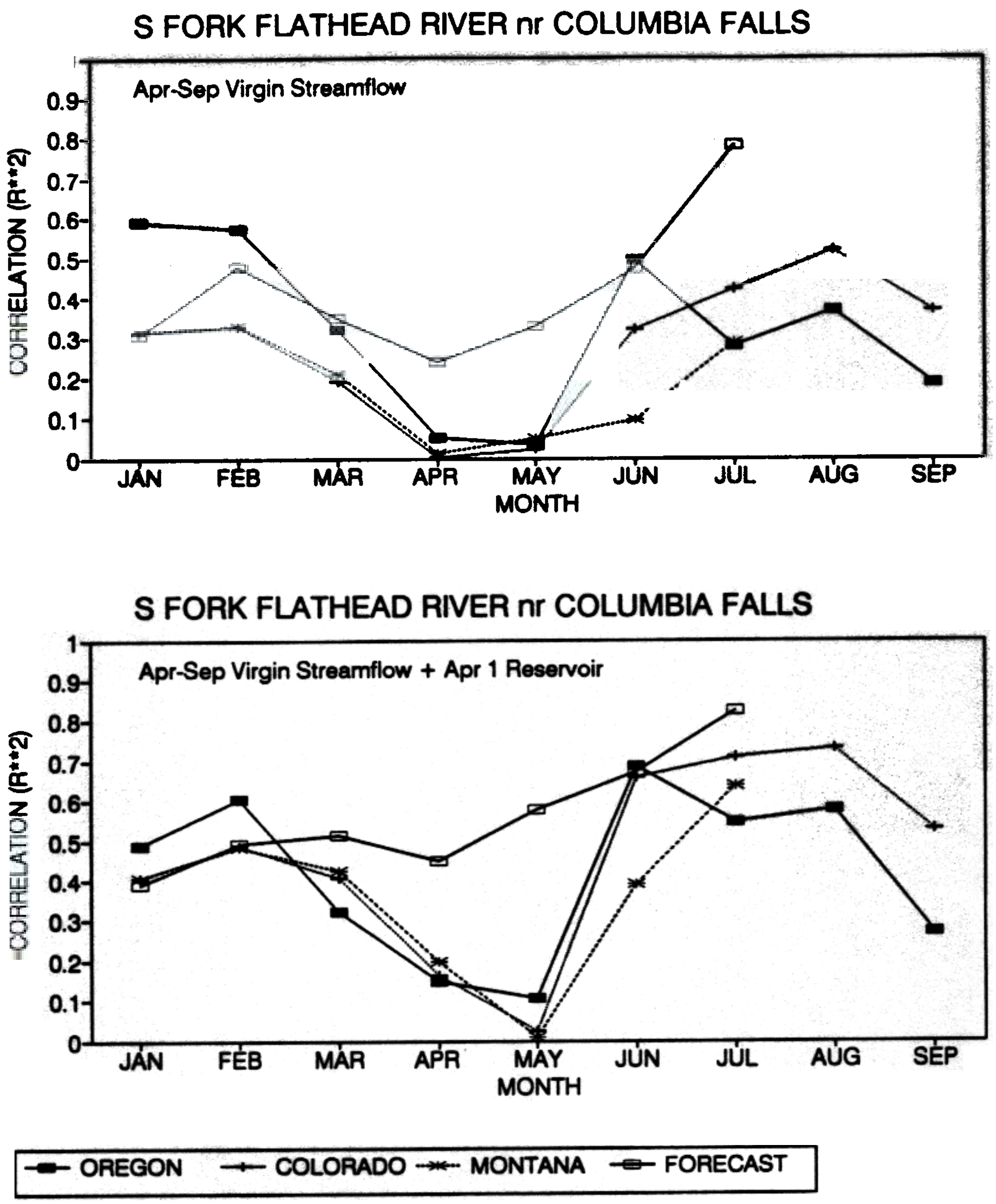


Figure 7. Correlations of computed SWSI values with April-September virgin streamflow (top) and with April-September virgin streamflow plus active reservoir storage on April 1 for the South Fork Flathead.

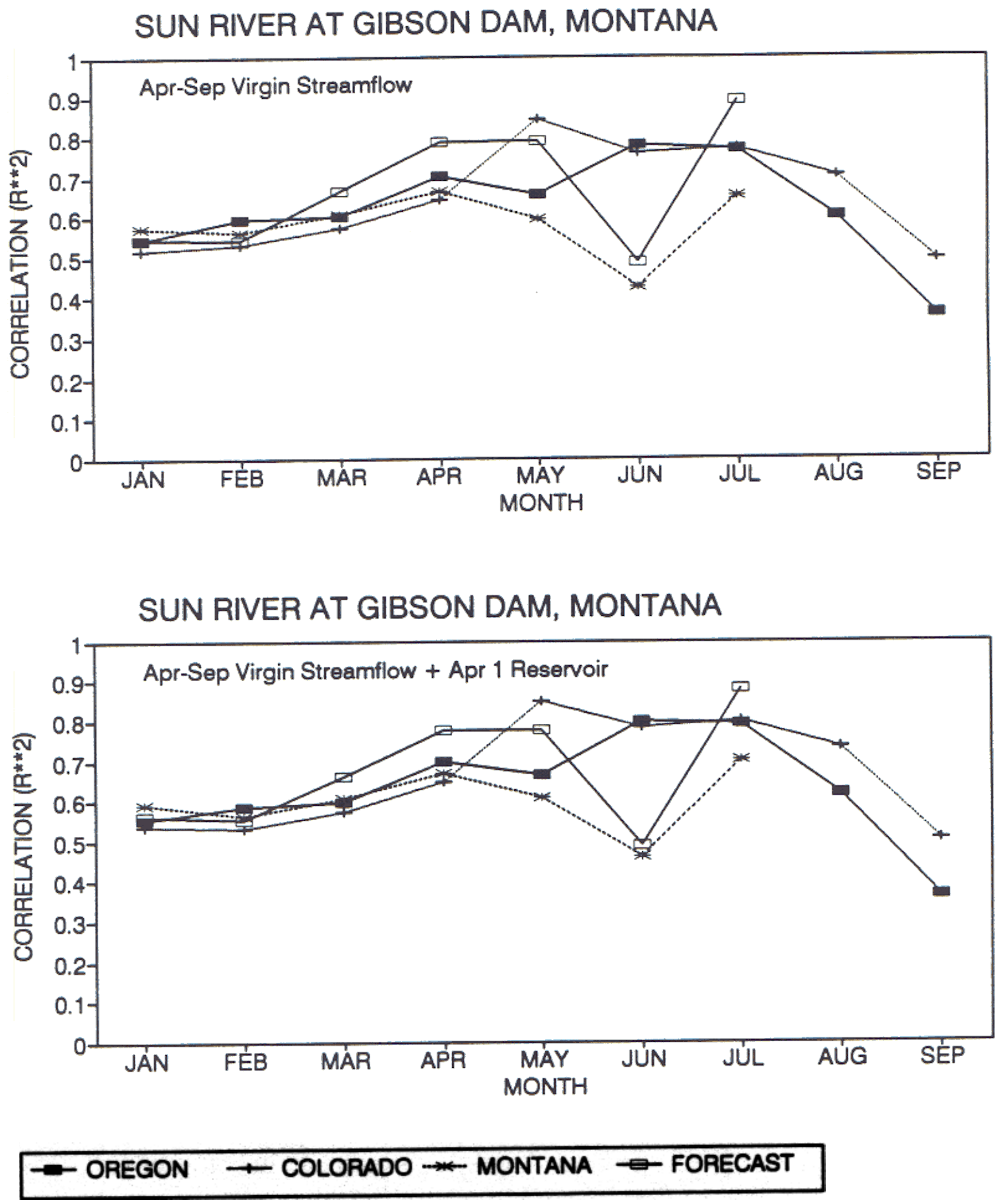


Figure 8. Correlations of computed SWSI values with April-September virgin streamflow (top) and with April-September virgin streamflow plus active reservoir storage on April 1 for the Sun River.

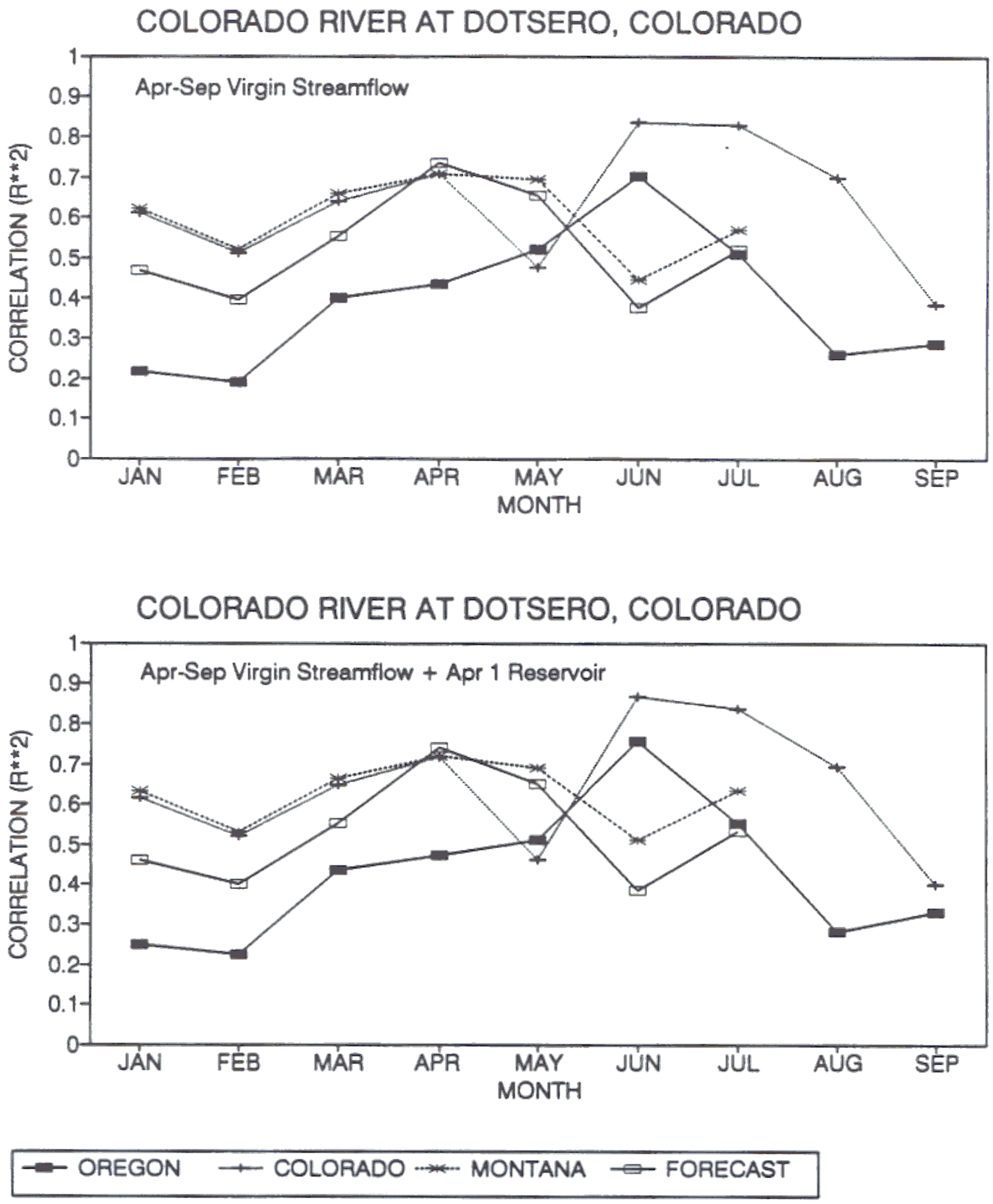


Figure 9. Correlations of computed SWSI values with April-September virgin streamflow (top) and with April-September virgin streamflow plus active reservoir storage on April 1 for the Upper Colorado River above Dotsero, Colorado.

From a total sample of 28 cases with complete comparative results (7 months in 4 basins), the Forecast-based SWSI had the best correlation with water supply in 11 cases. The Colorado SWSI scored best nine times. The Oregon and Montana method showed the best correlation in four cases each. The Oregon method was least correlated in 13 of the 28 cases. Montana and Forecast-based SWSI were each the worst in 6 cases. The Colorado SWSI had the worst correlation of the four methods in three cases. The Montana method performed well early in the season (January) while the Forecast-based SWSI was at its best from March to May. The Colorado SWSI was most consistent late in the period – May-July. The Oregon SWSI was consistently less correlated with water supply than the other methods early in the season (Jan-April) while the Montana SWSI had problems later in the season (June-July). No similar tests were made for the months of August through December since only two of the indexes are computed year-round.

Evidence from these simple tests suggest that computed SWSIs do explain a significant portion of the variance in observed April-September surface water supplies in four test basins in the Western United States. The SWSI shows predictive capabilities to the extent that current precipitation, snowpack, streamflow and reservoir values relate to future surface water. But these tests are not conclusive for establishing which index, if any, is best suited for broader application. It is useful to look at other characteristics of computed SWSIs before drawing conclusions. For example, the statistical properities of the four methods tested are quite different.

Figure 10 shows the frequency of observed index values on the scale from −4.2 to +4.2 in each of the four test basins. Table 3 presents this information in simplified form. The different SWSI methods produce markedly different index frequencies within selected index ranges. The Oregon SWSI produces the fewest values above +2 and below −2. The forecast-based SWSI is more uniformly distributed with a much higher frequency of both high a low values. This is not a mere coincidence. It is a property of the index formulation and the respective weighting functions. The forecast-based SWSI, which is simply the probability equivalent of a water supply volume, is uniformly distributed by definition. Any deviation from a uniform distribution is simply the result of sampling a subset of the climate from which the probabilities are derived or using fitted distributions that fail to duplicate the observed distribution of the hydroclimatic components. The other three formulations all are sums of separate non-exceedance probabilities. These sums no longer have the same properties of probability alone. The Oregon SWSI, for example, tends to produce index values that are nearly normally distributed about zero. This appears to occur because the Oregon method for determining the weighting coefficents tended to give more equal weights to the individual components in several of the test basins.

This points out the great significance of the weighting coefficients. While the Oregon, Montana and Colorado SWSI computations are all identical in general structure, the effect of using different weighting coefficients has large impacts on correlations and on statistical properties making each index essentially unique. Changing coefficients may be totally logical based on the known contributions of individual components to the total water supply, but it will affect the distribution of computed index values in ways that may not be predictable.

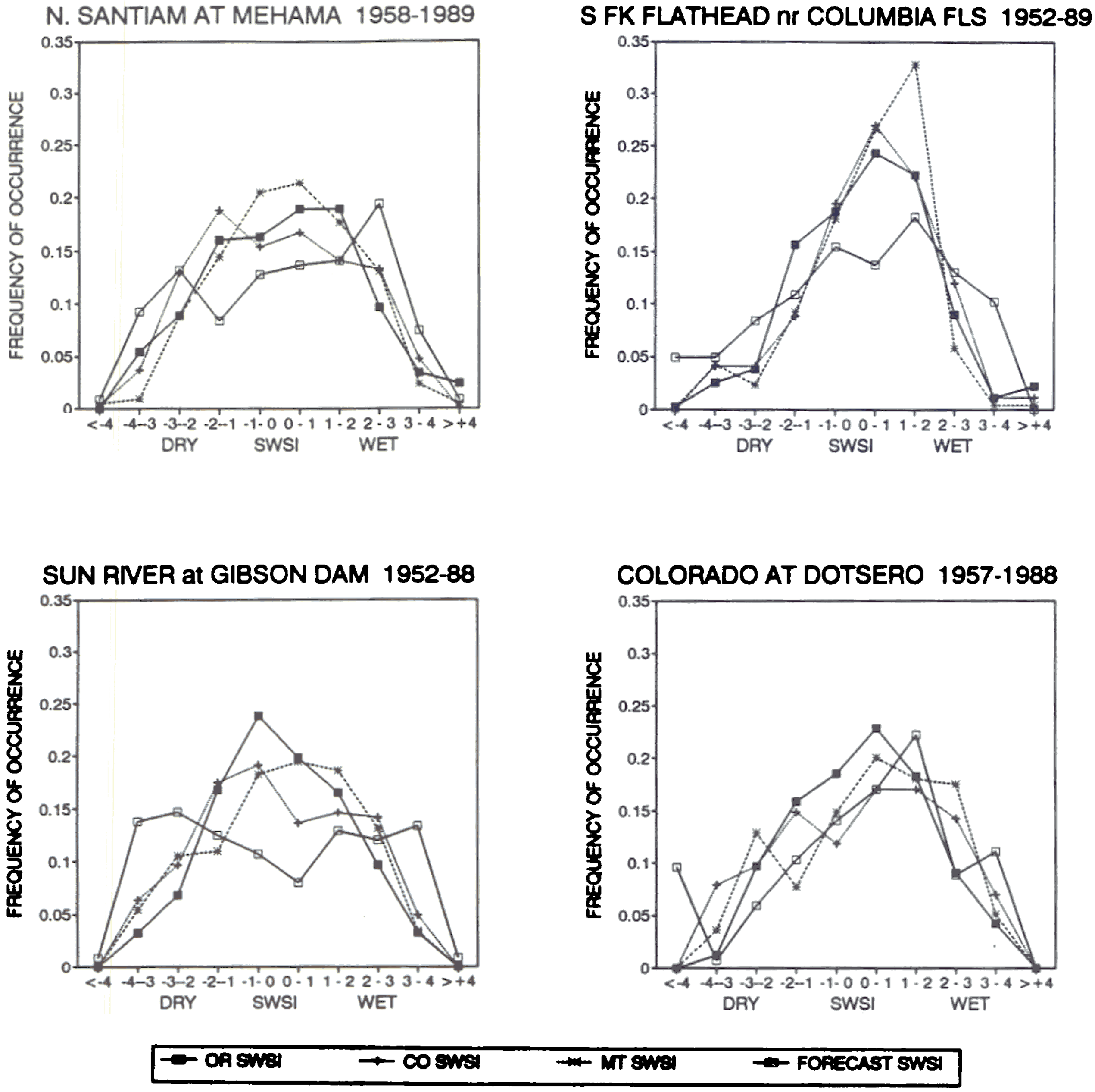


Figure 10. Frequency of occurrence of SWSI values by unit increment for each SWSI formulation.

Table 3.
Frequency of Computed SWSI Values in Selected Ranges (in percent).

METHOD	INDEX RANGE		
	< -2.0	-2.0 to + 2.0	> +2.0
Santiam at Mehama, OR 1957-1989			
OR	14.4	70.1	15.5
CO	17.0	65.0	18.0
MT	10.2	74.0	15.8
FCST	23.2	48.9	27.8
Colorado at Dotsero, CO 1957-1988			
OR	11.0	75.6	13.4
CO	17.7	61.0	21.3
MT	16.5	60.8	22.7
FCST	16.3	63.7	20.0
Sun at Gibson Dam, MT 1948-1988			
OR	10.1	76.9	13.0
CO	16.0	64.9	19.1
MT	16.1	67.4	16.5
FCST	29.5	44.2	26.3
S. Fork Flathead near Columbia Falls, MT 1952-1989			
OR	6.6	80.9	12.5
CO	8.4	77.3	14.3
MT	6.6	86.8	6.6
FCST	18.3	58.5	23.2
Combined Averages for all Four Basins			
OR	10.5	75.9	13.6
CO	14.8	67.0	18.2
MT	12.4	72.2	15.4
FCST	21.9	53.8	24.3

This may or may not be a problem for future applications of SWSI, but it does need to be recognized.

It is also interesting to note some of the differences in index distributions between test basins. The South Fork of the Flathead again stands out as unique. Very few occurrences of high or low index values are observed compared to the other basins. This is a realistic and expected outcome in a basin where large reservoir capacity reduces overall variability in surface water supplies. In such a case, the forecast-based SWSI should not experience the same reduction in extreme index values.

To conclude SWSI comparisons, we again evaluated the different models in terms of some the considerations and constraints listed previously. The experience gained during the comparison activites provided much more information from which to assess the models. Pros and cons of each index are listed below.

INDEX	PROS	CONS
Colorado SWSI	• Correlates well with water supply. • Identified major drought periods accurately. • Produced index values year-round. • Coefficient are relatively easy to use and understand. • Includes experiential wisdom.	• Weighting coefficients are arbitrary. • Discontinuous in May and Dec. • Statistical properties unpredictable. • Difficult to code. • Difficult data selection and requires excellent long-term and consistent data.
Oregon SWSI	• Objective weighting functions. • Identified major drought period fairly accurately. • Index values normally distributed. • Produces values year-round. • Relatively easy to code.	• Difficult data selection and requires long-term consistent data. • Does not indicate drought as often as other indexes based on uniform interpretation of drought scale. • Does not correlate with water supply as well as other indexes.
Montana SWSI	• Correlates quite well with water supply. • Identifies major drought periods well. • Can be adapted to use only SNOTEL data. • Includes experiential wisdom.	• Very difficult to code and machine implement. • Arbitrary coefficients. • Does not produce index values year-round. • Unpredictable statistical properties.

SCS Streamflow Forecast-based SWSI	• Relatively easy to code and machine implement. • Predictable statistical properties. • Does not have the strict data requirements of the other models. • Correlated fairly well with water suply. • Identified worst drought periods well.	• Correlations with water supply not systematically better than other indexes. • Indicates drought more often than the other indexes (based on consistent interpretation of scale). • Does not produce index values year round. • Would require significant effort to adapt to year-round computation.

2.5 Hydroclimatic Characteristics of the Western United States

The original development of the SWSI concept was brought about by the knowledge that melting snow from mountainous areas in Colorado accounts for 65 to 85% of the region's surface water supplies. But there is great diversity of climate and available water resources in the western states. Not only are there great differences in the quantities of precipitation, snowpack accumulation, runoff, streamflow and reservoir storage from basin to basin in the West. There are also elevational, seasonal and interannual variations which make interpretation of water resource information difficult. To select a SWSI formulation for more broader use and to help evaluate the significance and potential widespread application of a SWSI to the region requires a broad knowledge of the hydroclimatic characteristics of this expansive region. As a part of this project, a significant effort was made to document key features of the hydroclimate associated with SWSI computations and applications.

2.5.1 Monthly and seasonal distributions of hydroclimatic components

Several months of this study were dedicated to becoming as familiar as possible with the diverse hydroclimatology of the western United States. With the excellent help of an SCS intern, Larry Johnson, data from a large number of Western basins were analyzed and compared.

The four primary hydroclimatic components contributing to surface water supply: precipitation, snowpack, streamflow and reservoir storage, were analyzed for 31 watersheds (Fig. 11) using historic monthly data maintained on the SCS – Centralized Forecast System database at the West National Technical Center, Portland, Oregon. These watersheds are identified in Appendix 6.4 along with the individual sources of data within each basin. Using all available computerized data, monthly averages of each of the hydroclimatic variables were computed. Monthly averages were reduced to dimensionless units by dividing each monthly value by the mean value for the highest month. This normalization allowed for

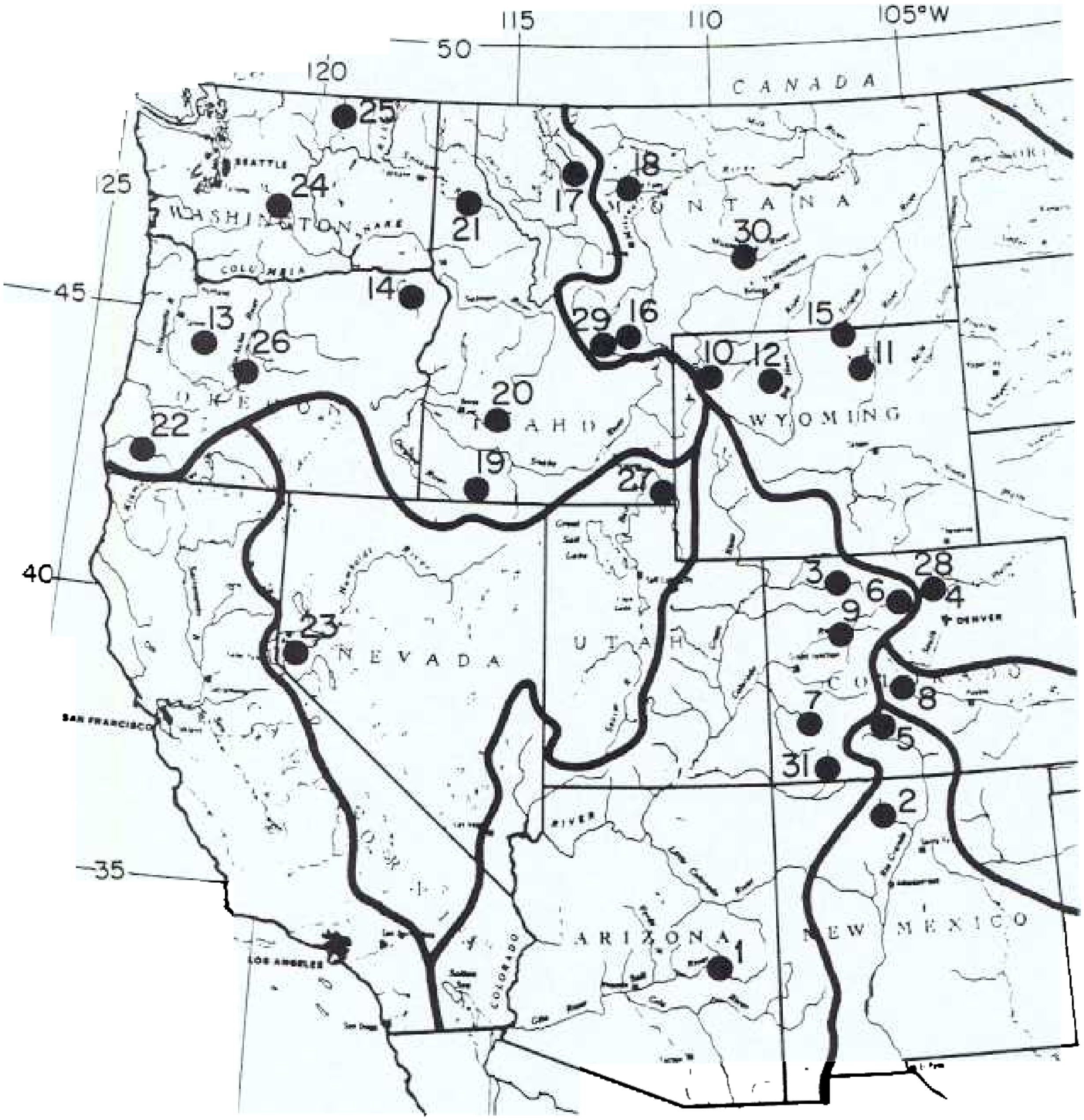


Figure 11. Locations of watersheds used to examine hydroclimatic characteristics in the Western United States. Basin names and data sources are indexed in Appendix 6.4.

simultaneous graphical comparison of all components, independent of their different units and magnitudes (Fig. 12).

Differences in the seasonal distributions of the hydroclimatic components influence the timing and efficiency of surface runoff and, hence, have a bearing on surface water supplies. Figure 13 shows the season of the year when, on average, the greatest quantities of precipitation are expected. Data from several other weather stations were included here to help give a more detailed look across the West at the variety of seasonal precipitation distributions. North and south along the West Coast and a few hundred miles inland, winter is clearly the wet season, and summers are very dry. However, in extreme eastern Washington and Oregon, some areas continue to get as much moisture in the spring as in the winter. Across most of Idaho there is a battle between winter and spring, but further eastward into Montana and across the Continental Divide, spring clearly becomes the wettest season of the year. Wyoming, the Colorado Front Range and parts of Utah also see spring as the wettest time of year, but a greater variety of seasonal precipitation distributions begin to appear. The high mountains in the central Rockies tend to have winter as their wettest season while a more even distribution of precipitation through the year is found in the valleys. Farther south, summer makes a bigger contribution to annual precipitation. For much of New Mexico, Arizona and southern and southeastern Colorado, summer is the wettest season and spring is very dry. Finally, to bring things full circle, a portion of the Colorado Plateau including southeastern Utah, extreme western Colorado and extreme northwest New Mexico experiences their wettest season, on average, in the fall.

Snowpack, which is related to precipitation but is very directly controlled by a more regionally consistent variable, temperature, has much less variation in seasonal distribution. Figure 14 shows the time of year when snowpack accumulation is normally the greatest. For the basins we examined, most areas have their greatest average snowpack water content close to April 1. However, in the high elevation central Rocky Mountain region, several basins reach maximum snowpack closer to May 1. In the southern areas, a few basins, such as the Salt River in Arizona, reach their peak already near March 1. In truth, within almost any basin there is a continuum of timing of maximum snowpack water content which varies with elevation. At the lowest elevations, maximum snowpack may occur as early as February with the date of maximum snowpack becoming later as a function of elevation. At the highest elevations, snowpack may actually reach its maximum after May 1 in some areas, but thereafter temperature and solar radiation dominate, and snow begins to melt.

The true realization of surface water supplies comes in the form of streamflow. The general feature that dominates the hydrology and water supply of much of the West is that melting snowpack produces a large portion of the subsequent streamflow. Therefore, although precipitation patterns vary widely across the western United States, the seasonal patterns of streamflow are quite consistent (Fig. 15). Throughout the central Rocky Mountain chain, streamflow is normally very low from late summer through the winter. Most of the annual streamflow occurs in just a few months from spring into early summer. June is typically the month of greatest streamflow. Some of the basins that drain lower elevation mountain ranges usually peak earlier and reach their maximum average

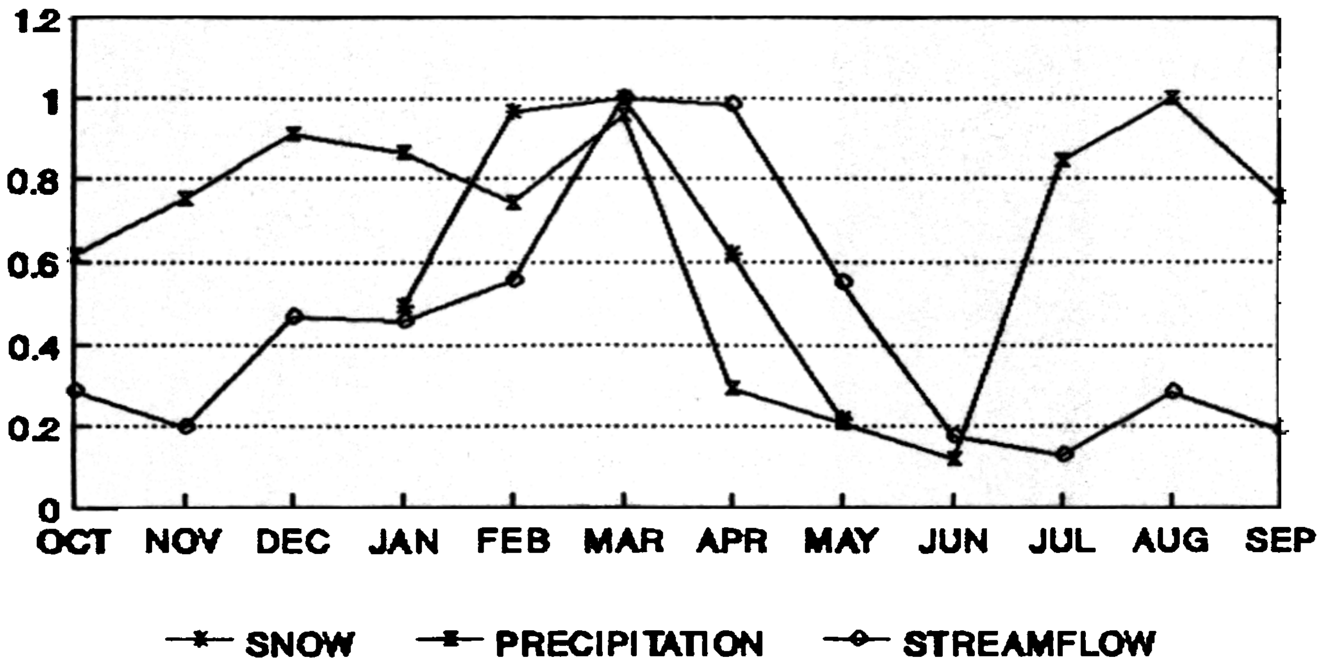


Figure 12. Dimensionless comparison of monthly average precipitation, snowpack and streamflow in the Salt River basin in Arizona.

streamflows in May. An interesting exception is the upper Yellowstone River in Yellowstone National Park where July has the average maximum streamflow volumes. The higher elevation watersheds of the Sierras and Cascades typically peak in May, but lower in elevation, peaks occur earlier. Some of the lower streams closer to the West Coast respond more to winter rains than to melting spring snow and, therefore, peak in mid winter when precipitation is greatest. There are also some differences in the southern Rockies. In Arizona, for example, the Salt River flows earlier than the rivers coming out of the Central Rockies. March and April are often the peak months. These southernmost watersheds also respond directly to midwinter precipitation that can fall as widespread rain and melting snow.

Another way of demonstrating streamflow characteristics is by looking at the percentage of streamflow that occurs during the primary agricultural growing season for the West, April-September (Fig. 16). Along the Continental Divide from the Canadian border to southern Colorado, more than 70% of the annual streamflow occurs in 50% or less of the year from April through September. In many cases, percentages are well over 80%. Two of the basins we examined, the Colorado Big Thompson and Rock Creek in Wyoming, receive an average of 91% of their annual virgin streamflow during the April-September growing season. Percentages then lower to the west and south as winter precipitation and earlier snowmelt begin to effect runoff distributions. The lowest April-September percentages were found in the Salt River in Arizona with just 43% and only 34% and 35%, respectively, in the Santiam and Rogue River of western Oregon. This information becomes very significant in the possible computations and applications of SWSI.

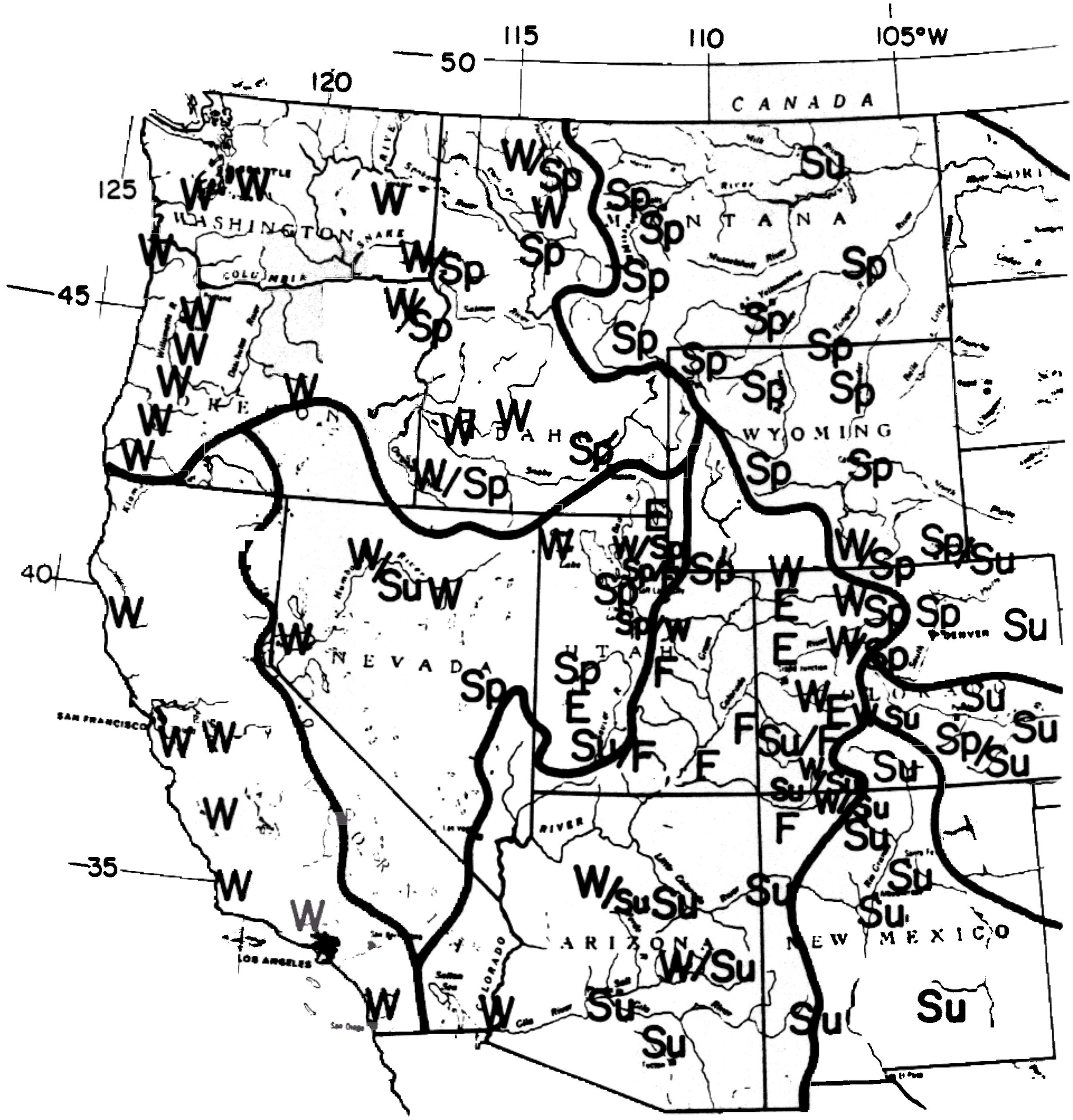


Figure 13. Season with the greatest expected total precipitation based on monthly averages. W = winter (Dec-Feb), Sp = Spring (Mar-May), Su = summer (Jun-Aug), F = fall (Sep-Nov), E = even distribution through the year.

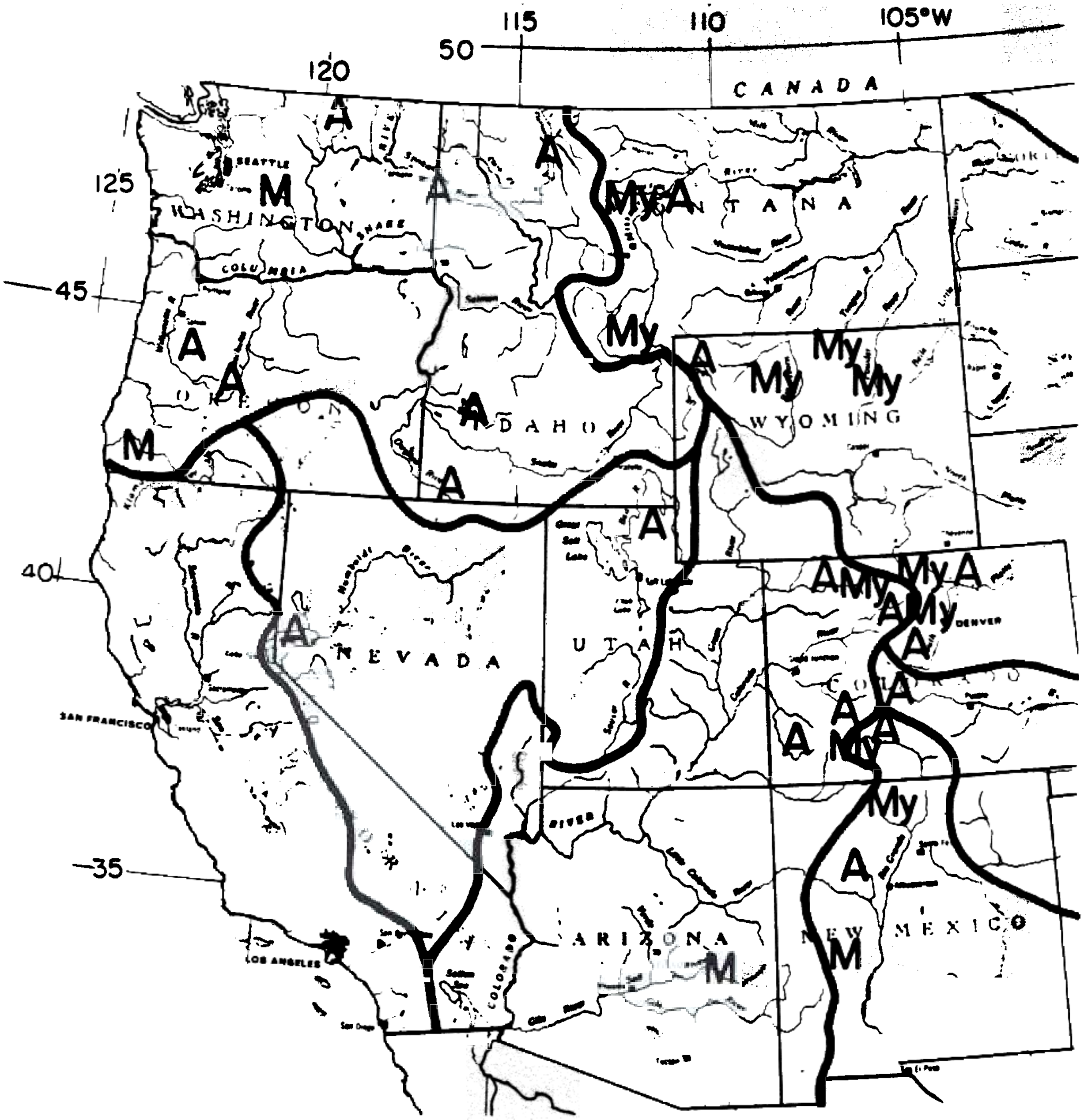


Figure 14. Typical date of maximum accumulation of snowpack water equivalent. M = March 1, A = April 1, My = May 1.

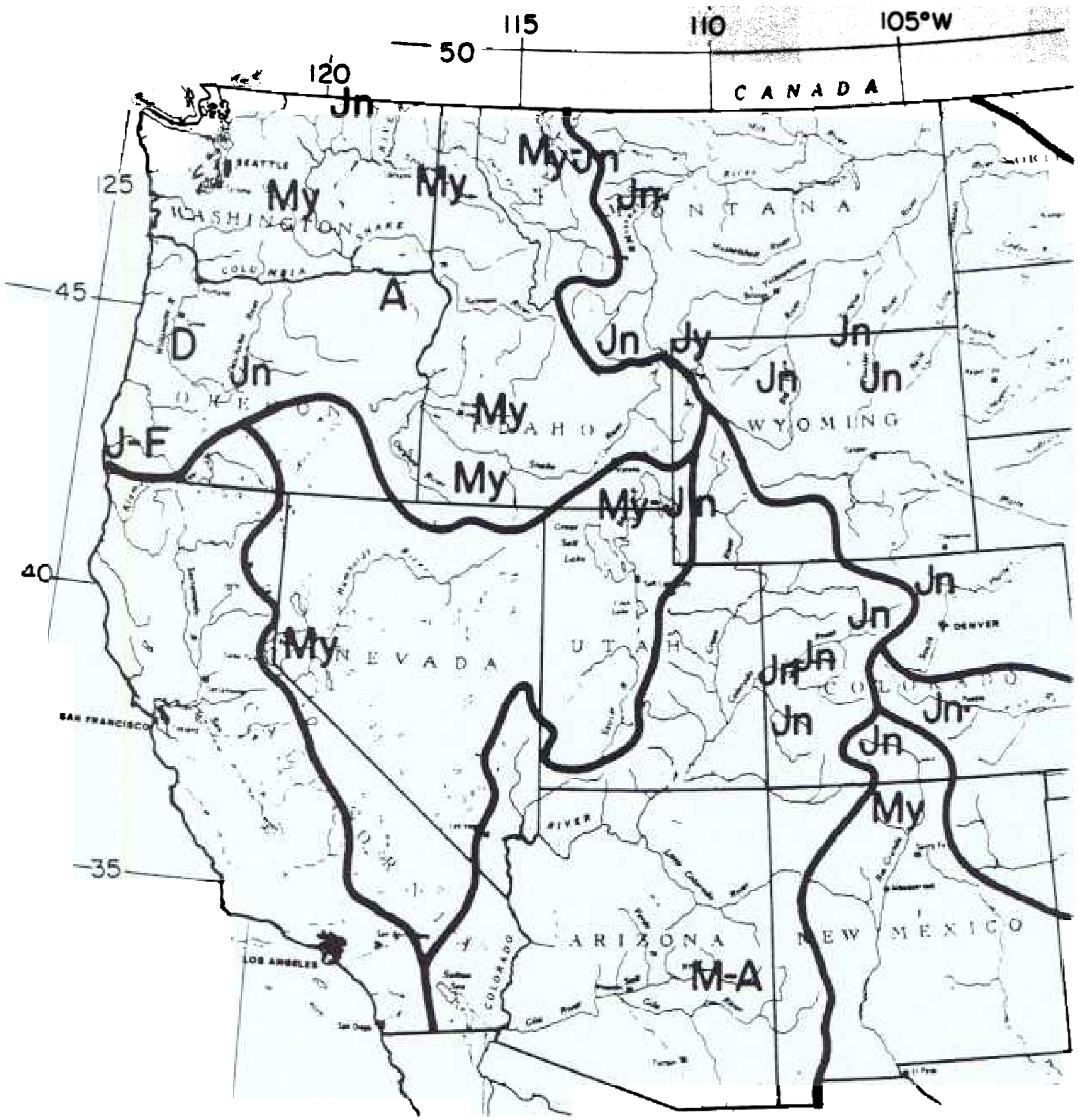


Figure 15. Calendar month of maximum total streamflow. D = December, J = January, F = February, M = March, A = April, My = May, Jn = June, Jy = July.

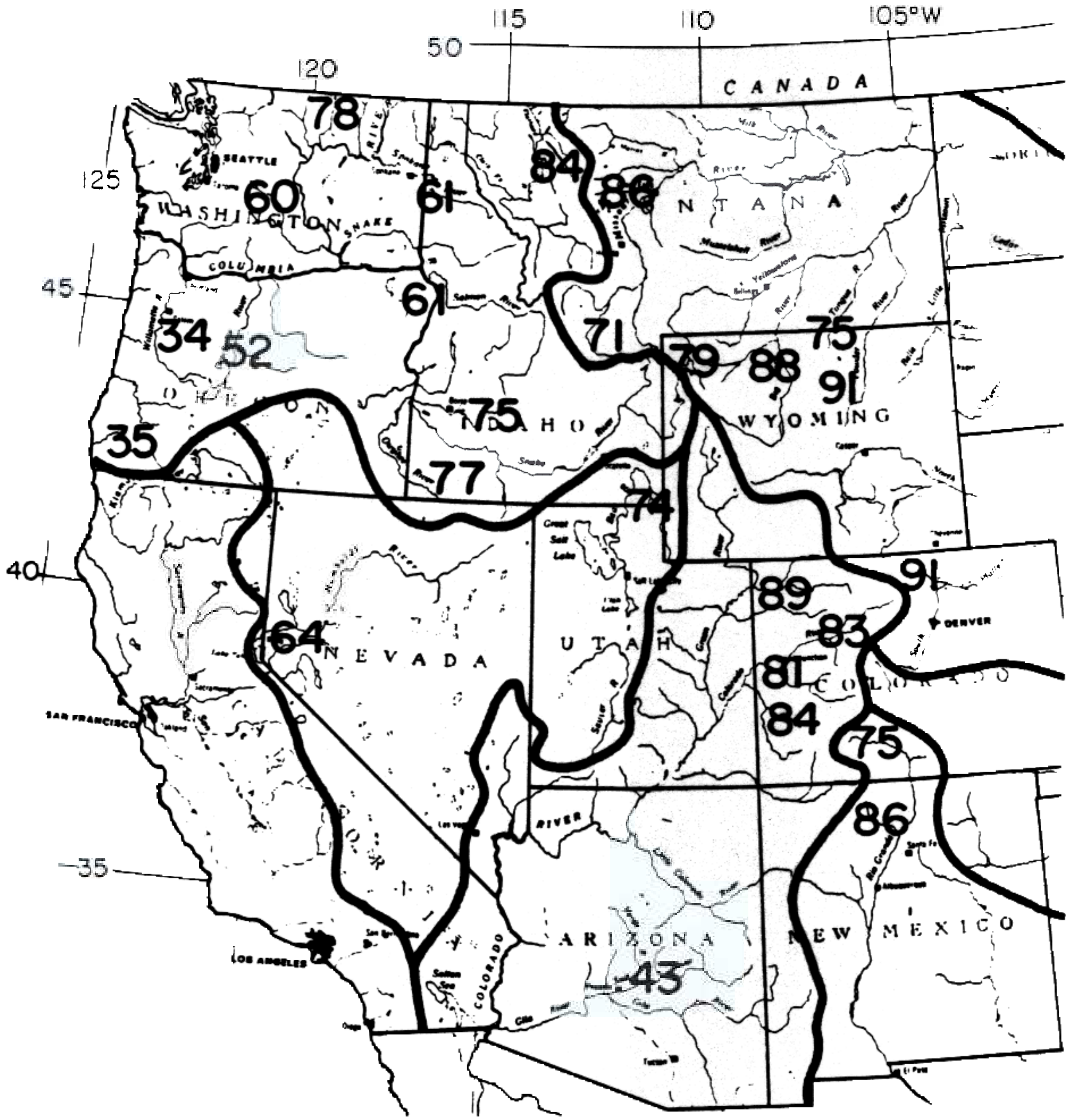


Figure 16. April September streamflow percent of total annual streamflow

The final hydroclimatic variable, reservoir storage, is the most complex because it includes both natural and management-related variations. It is not just a simple process of capturing water during peak runoff and then releasing it gradually during low-flow periods. Figure 17 shows the normalized monthly mean reservoir storage for five example reservoirs in the West. Seasonal water storage is not only a function of streamflow, but it is most importantly a function of management. These reservoirs represent several different purposes for water storage: Gibson Lake, MT and Arrowrock Reservoir, ID – irrigation, Lake Granby, CO – trans-basin diversion, Detroit Reservoir, OR – flood control, Hungry Horse Lake, MT – power generation and recreation. Carter Lake, CO – diversion retention and irrigation. Reservoirs are also used to receive water from diversions, to maintain water transportation, to regulate water to satisfy in-state water law and to meet interstate compacts, and to provide water for predominantly urban and industrial uses. These applications all dictate somewhat different management strategies. In fact nearly all reservoirs are managed for multiple water uses. The result is a great variety of seasonal distributions of stored water.

The amount of useable reservoir storage as a percentage of average annual streamflow also varies incredibly from basin to basin. Figure 18 shows the average stored water volume during the month of peak storage as a percentage of the annual average virgin streamflow for a number of watersheds in the West. Percentages range from less than 1% to as much as 274% in the watersheds we examined. Even greater variations would be found if all Western watersheds were evaluated. This number also varies considerably along a given river. For example, on the mainstream of the Colorado River the percentage of mean annual streamflow held in storage grows dramatically when you include the hugh lower basin reservoir.

2.5.2 Variability of hydroclimatic components

In addition to comparing monthly averages of the four primary hydroclimatic components contributing to surface water supplies, variability characteristics of each component were also analyzed. Changnon et al. (1990) showed that the amount of year-to-year variations in precipitation, snowpack and streamflow was not the same throughout the Rocky Mountain region. This was already known when the SWSI was first developed. In fact, the rationale for using non-exceedance probabilities arose from the knowledge that variability was not a constant. Since this could have a major bearing on use of SWSI, variability was examined in many test basins across the West.

Figure 19 show examples of the graphical presentation of this variability information for the Upper Colorado River basin in Colorado. Graphs of empirical and functionally-fitted distributions have previously been discussed. To generalize, it is noted that the natural variables; precipitation, snowpack and streamflow; all exhibit similar overall variability characteristics. Their probability distributions can be represented reasonably well by one or

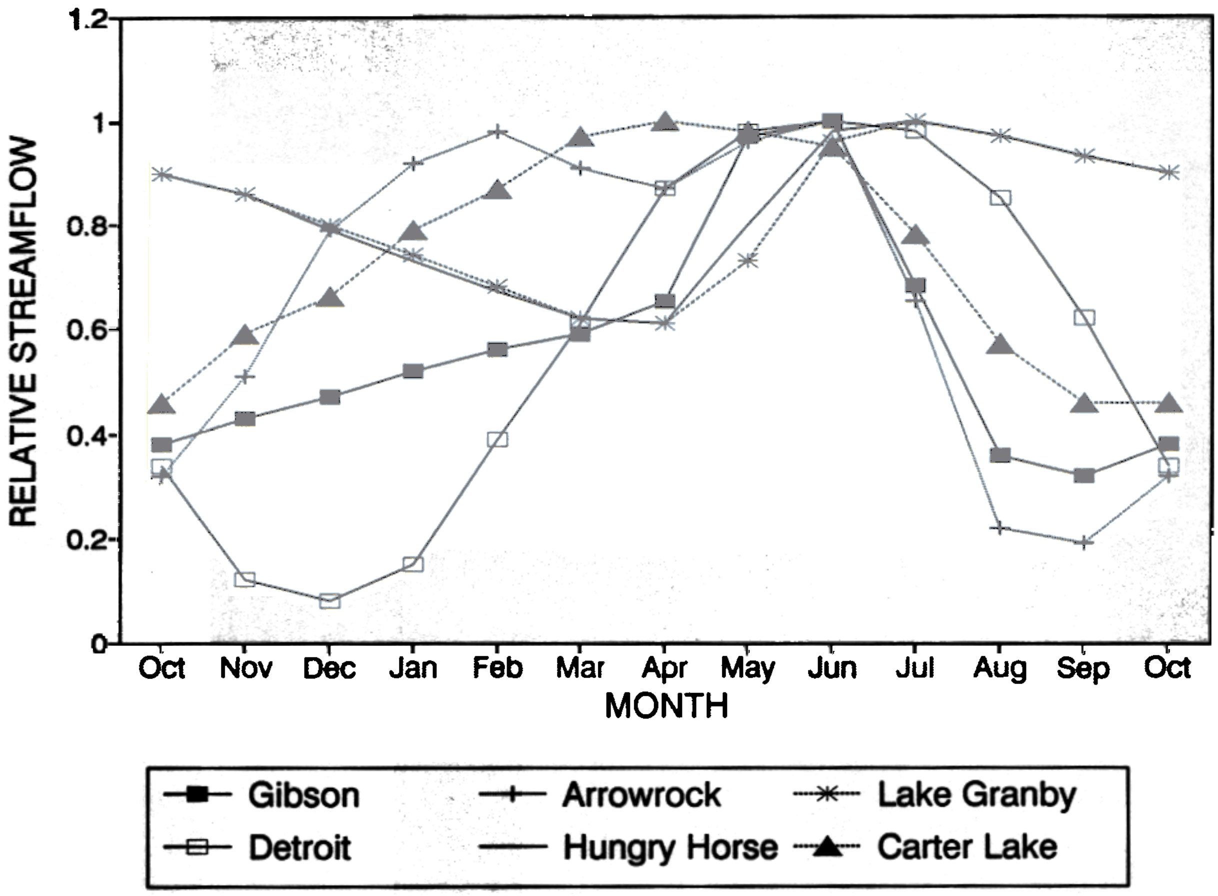


Figure 17. Comparison of normalized monthly average reservoir storage for selected watersheds in the West: Gibson Lake, Montana; Arrowrock Reservoir, Idaho; Lake Granby, Colorado; Detroit Lake, Oregon; Hungry Horse Lake, Montana; and Carter Lake, Colorado.

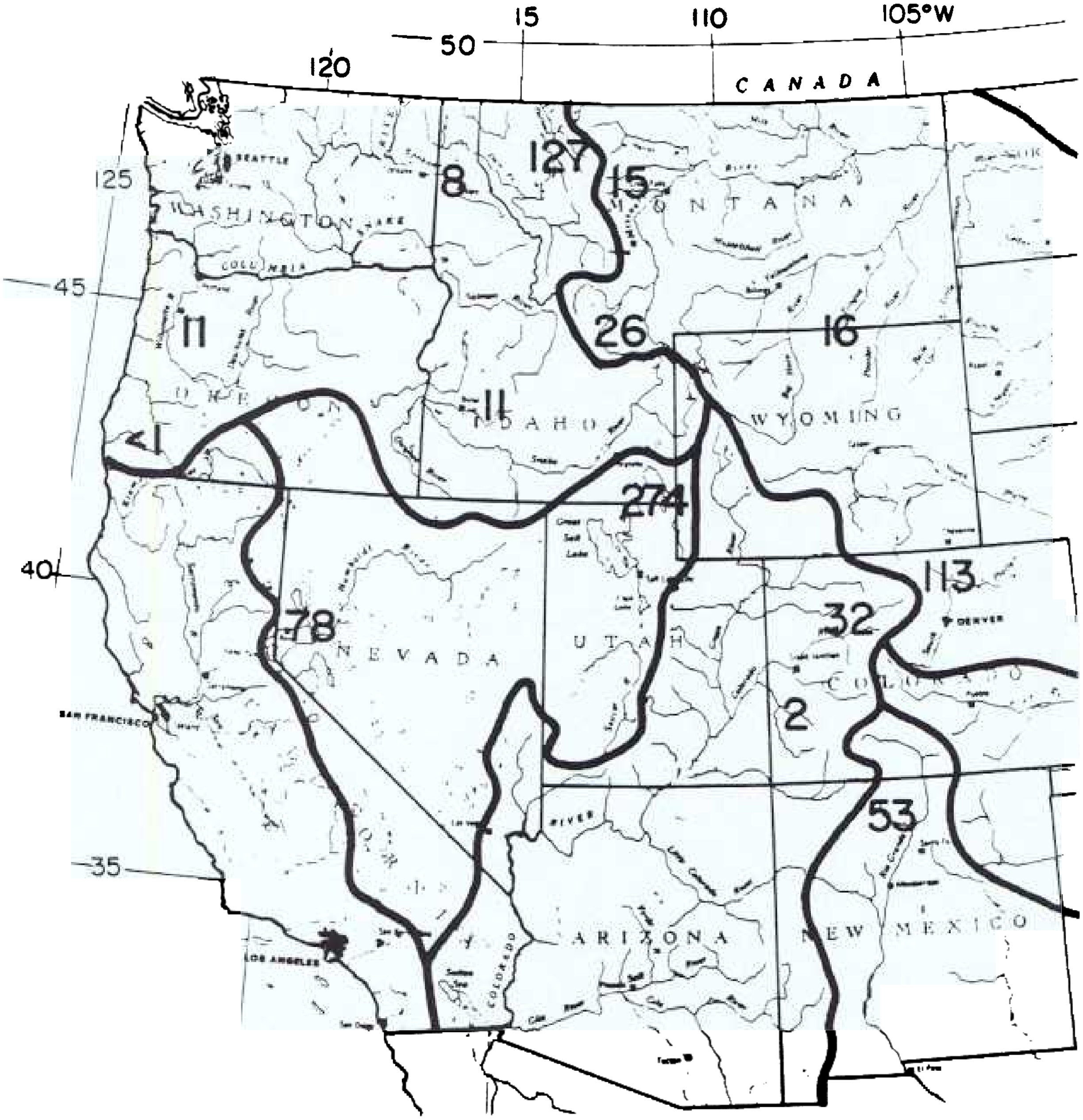


Figure 18. Average basin reservoir storage during month of peak storage shown as a percent of mean annual streamflow.

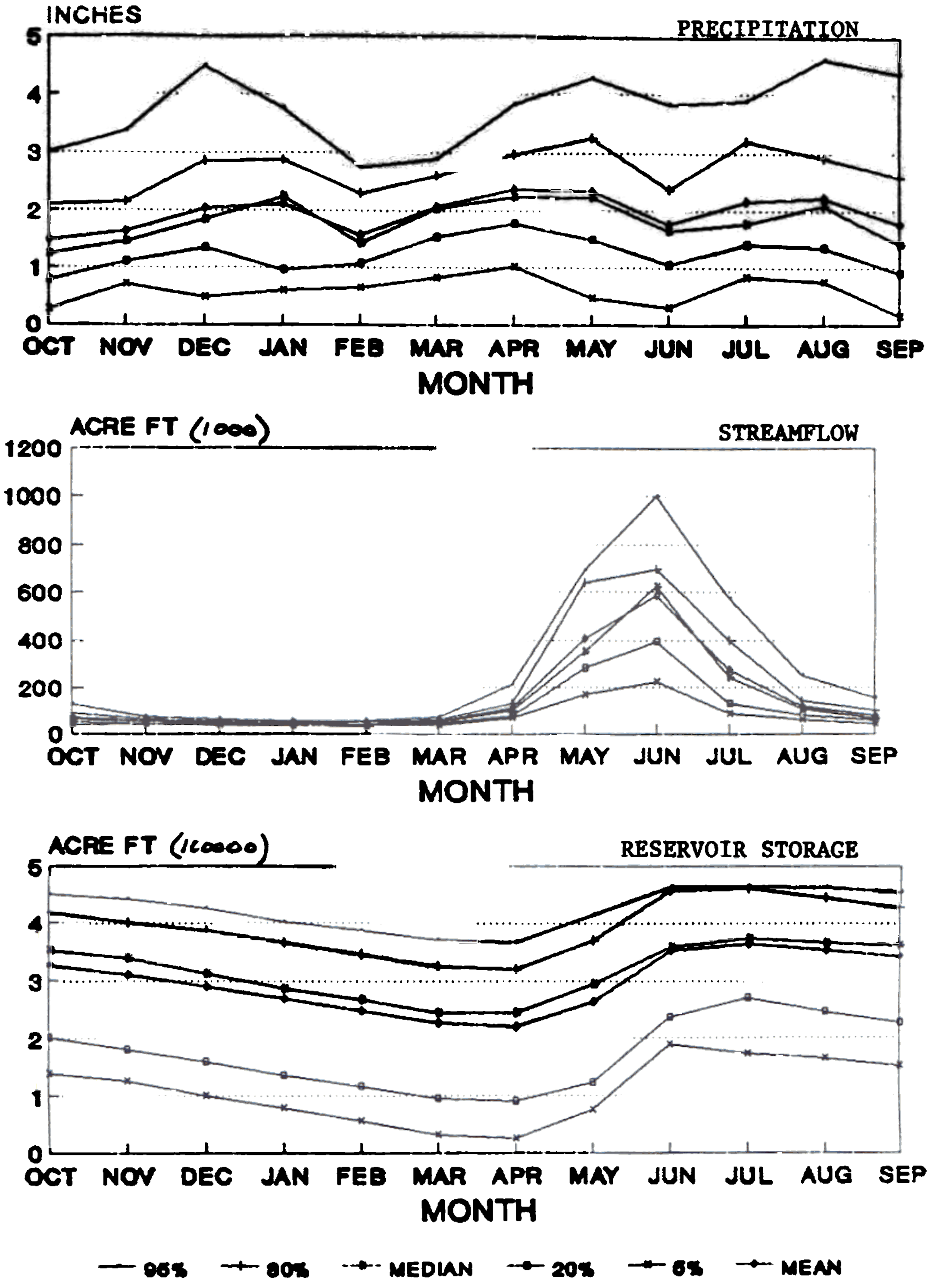


Figure 19. Nonexceedance probabilities, by month, associated with precipitation, streamflow and reservoir storage in the Colorado River above Dotsero, Colorado.

more mathematical/statistical functions such as the gamma, normal or log-normal distributions. However, the shapes of these distributions (similarly the magnitudes of variability) vary geographically. Snowpack, for example, is least variable in the northern and central Rockies immediately west of the Continental Divide and in the higher elevations of the Pacific Northwest. Greatest variability is found in the southern Rockies, Sierras and west of the summit of the Cascades. Streamflow variability follows similar patterns to the snowpack but is complicated by geological aspects of the basins. The Deschutes River, in Oregon, for example, has markedly reduced streamflow variations than any other river we examined (Figure 20).

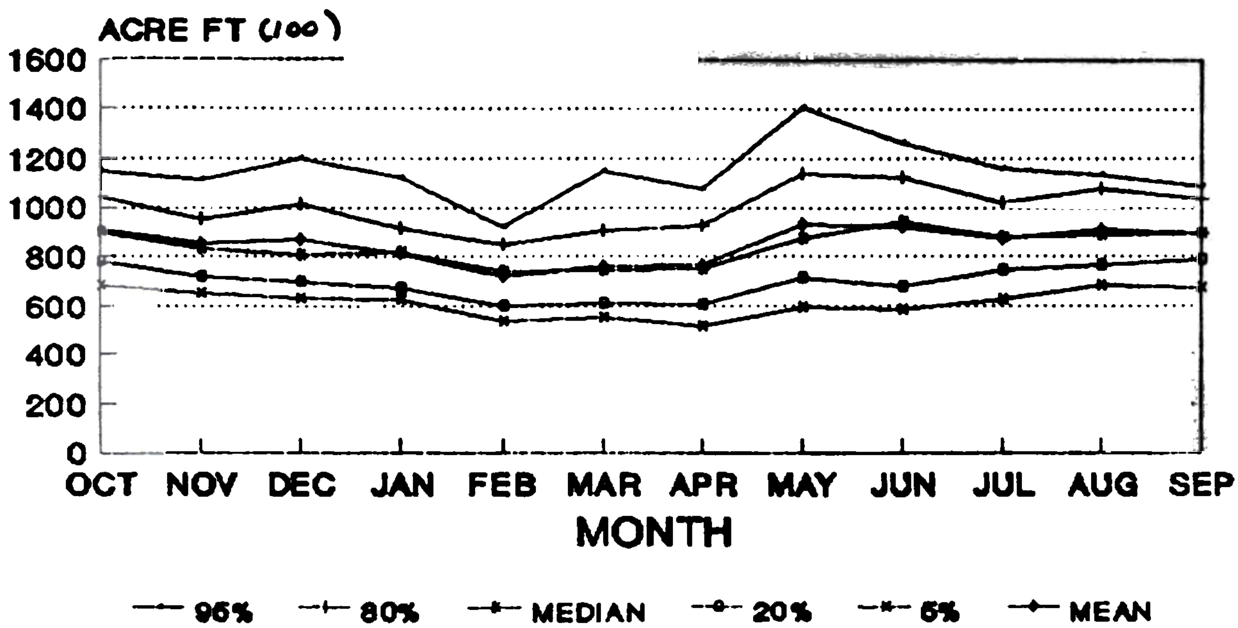


Figure 20. Nonexceedance probabilities, by month, associated with observed values of streamflow in the Deschutes River, Oregon.

The interannual variations in reservoir storage is more complicated owing to the role of human intervention. Several reservoirs are reliably maintained near a fixed level at certain times of year. Small deviations from these fixed levels may represent very small differences in total water supply but may equate to extreme non-exceedance probability values.

2.5.3 Implications for SWSI development and use

The analysis of hydroclimatic characteristics in the West – seasonal patterns and interannual variability – points out the great diversity that exists across the West that would certainly impact on the computation of SWSI and its subsequent interpretation. Key results include:

No unique definition of surface water supply will apply equally and have the same meaning in all parts of the West.

2) If the April-September streamflow plus available reservoir storage is used to define surface water supply (as suggested in this paper), that will describe anywhere from less than half of the total annual surface water supplies in some West Coast and southern watersheds to as much as 90% in some of the high-elevation Central Rocky Mountain watersheds.

3) No single set of weighting coefficients can be applied equitably to all basins in the West.

4) The magnitude of natural variations in hydroclimatic components differs across the area. Therefore a given non-exceedance probability will equate to greater departures from average in some areas than in others. If index values are made to be proportional to non-exceedance probabilities, this will become a defined property of the SWSI.

5) The probability distributions for precipitation, streamflow and snowpack are all well behaved and can be represented by empirical or mathematical distributions.

6) Reservoir volumes may be poorly suited for representation by non-exceedance probabilities. Mathematical functions may not adequately portray probability distributions for some reservoirs and at some times of year.

3.0 CONCLUSIONS AND RECOMMENDATIONS

It is the case with most drought-related research that clear answers and obvious solutions are rarely found. Much of this is due directly to the difficulty in defining drought. This is indeed what we found in the process of exploring SWSI. But we need not despair. Sufficient knowledge has been gained to draw a number of meaningful conclusions and to pose several recommendations.

3.1 Conclusions

1 The SWSI concept has broad appeal and has become a popular indicator of relative water supplies in the states where it is being produced.

2) The development and testing efforts described in this report have defined many important aspects of SWSI.

3) The SWSI is an empirical index, not a model of a physical process. It is most useful in combination with other climate and water resources information.

4) The SWSI is a current-state water supply indicator but has inherent predictive capabilities due to lagged hydrologic response in high-elevation, cold-temperature watersheds.

5) The SWSIs tested here can explain 60% or more of the variance in April-September surface water supplies in parts of the West several months in advance and as much as 80% of the variance near the peak of the runoff season.

6) SWSI testing and evaluation is hindered by the lack of a single definition of surface water supply. No measure of surface water supply has been identified that allows correlating SWSI with a totally independent variable.

7) Hydroclimatic differences are sufficiently great across the West that no unique interpretation can be given to SWSI.

8) The various SWSIs currently being computed, while similar in structure, do not share identical statistical behavior. A weighted sum of component non-exceedance probabilities is no longer a probability.

9) The forecast-based SWSI described in this paper is truly equivalent to a water supply probability and, therefore, has a unique interpretation.

10) Of the SWSIs tested, none was clearly superior in terms of correlation with water supplies as defined by April-September streamflow and April-September streamflow plus April 1 reservoir storage. Since SWSI was originally conceived as a non-exceedance probability, correlations with water supply defined as the non-exceedance probability equivalents of the definitions used would probably produce different verification results.

3.2 Recommendations

1) Extension and development of SWSI for broader application should be pursued.

2) A definition of surface water supply must be agreed upon prior to the selection of a generalized SWSI formulation. We suggest that April-September virgin streamflow plus water in storage on April 1 is an excellent functional definition, but concensus from the water resources community should be obtained.

3) Desired statistical properties for SWSI should be pre-specified and would permit better SWSI optimization and comparative testing.

4) Closer examination of reservoir management strategies and the impact of unusual probability distributions of reservoir data is needed.

5) In order to assure appropriate use and application of a potentially west-wide SWSI two alternatives should be considered. Either:
   a) define water supply very specifically and tailor the index only to that defined supply, or
   b) use the hydroclimatic information described here to isolate those areas where SWSI is most meaningful and apply it only to those areas.

6) Conduct further SWSI tests exphasizing: a) a larger number of test basins, b) alternative verification statistics such as probability of detection and false alarm rate, c) month-to-month index stability and d) potential ways of displaying and disseminating SWSI information.

7) Published peer-reviewed (by both the water resources and climate communities) documentation and testing of SWSI is essential before or at the time of deployment of a generalized monitoring index.

More scientific investigation is warranted and perhaps necessary prior to regional use of SWSI. But at some point it also becomes necessary to weigh the factors presented here, make judgements and move forward. Inevitably, there will be criticism of whatever path is taken. Afterall, a perfect drought monitor that meets all needs is yet to be discovered. What is important to remember is that in the end the true test of SWSI will not be a scientist's computer evaluation or a some elaborate statistical test. The true test will come, instead, in State capitols, in State and Federal resource management offices and in emergency management meetings. If an Index can facilitate good and confident decision making to the benefit of the wise use of western water resources, it will be a success.

4.0 PRESENTATIONS AND MEETINGS

4.1 Initial SWSI Technical Review

A meeting was held 22 May 1990 at Colorado State University with a SCS WNTC staff representative, David Garen, Colorado Climate Center staff, SCS Snow Survey staff in Colorado and also staff of the Colorado State Engineers office (who have been working closely with SCS staff since 1981 in the development and routine computation of the Colorado SWSI). The main purposes of this meeting were to review the historical basis for SWSI development in Colorado, to discuss how the Colorado SWSI has been used in decision making, to discuss how well it has performed during the 9 years since development, to review the range of hydroclimatic characteristics found in the West and to look at the pros and cons of different existing and potential computational methods for SWSI.

Discussions were fairly general in nature. There was consensus among Colorado representatives that the SWSI was a significant and informative tool for monitoring drought and general water supply conditions. It was strongly believed that the SWSI is most valuable when used along side a variety of other water supply data and information products. There was also general agreement that the Palmer Drought Index did not adequately represent surface water supplies and drought conditions in Colorado. Several apparent flaws were discussed that limited the credibility of the Colorado SWSI. The statistical validity of combining individual non-exceedance probabilities to form an index seemed questionable to some participants. Others believed that it mattered little as long as the resulting index reasonably depicted the intergrated water supply conditions. The fact that the Colorado SWSI did not include snowpack after May 1 was viewed by all as an unacceptable problem that would have to be changed before adapting the Colorado SWSI elsewhere in the West.

4.2 SCS-West National Technical Center Review

A meeting was held at the SCS-WNTC in Portland on February 26-27, 1991 to review this SWSI project and to discuss results. The meeting consisted of two presentation sessions and considerable discussion. The first presentation was a project summary given by Nolan Doesken to a portion of the Water Supply Forecasting Staff most familiar with the SWSI project. Much of the materials described in the previous pages was included in that initial presentation. That was followed by a presentation later on the 26th to a somewhat broader audience of WNTC staff. This second presentation included talks by Stan Fox of the Oregon SCS and Mike Gillespie from Colorado. More detail of the actual application and operational use of SWSI was included in this session.

Lengthy discussions followed that brought up many of the same questions that seem to arise every time that a group meets to discuss the intent of such an index. For example, the definition of surface water supply was again debated. The whole question of what the SWSI really should be – an index of growing season water supply, or something else, like a general wet-dry index. Despite, a number of discussions that made it seem that no progress had been made in the past 2 years, there was surprising agreement that the SWSI is a very important addition to currently available water supply information and should be perfected and implemented. Several excellent ideas came out of the meeting on how best to communicate hydroclimatic information pertaining to SWSI.

4.3 Seventh American Meteorological Society Conference on Applied Climatology.

Results of this project were presented to many professional climatologists at a session on drought at the 7th Conference on Applied Climatology in Salt Lake City, Utah, September 10-13, 1991. Appendix 6.2 contains a copy of the paper published in th conference proceedings.

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6.0 APPENDICES

6.1 Probability Curves for Hydroclimatic Components

Comparisons of observed and fitted distributions of monthly hydroclimatic data in each of the four SWSI test basins, using normal and gamma distributions, are displayed in the following series of graphs. Where more than one data point were available in a basin, such as for basin precipitation and snowpack, these distributions are the combined basin values (the average of the available point data). Discontinuities appear in several of the fitted curves. This is an artifact of the plotting routine that was used and <u>does not</u> represent the values that were actually used in SWSI computations. Units are inches of precipitation, inches of snowpack water equivalent and 10^2 acre-feet of streamflow and reservoir storage (10^3 for S. Fork Flathead).

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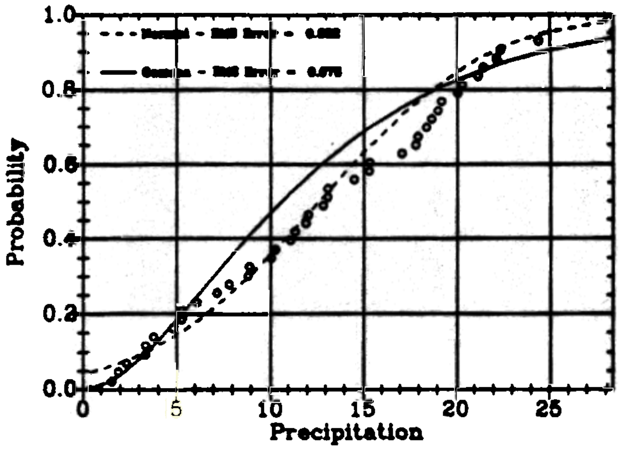

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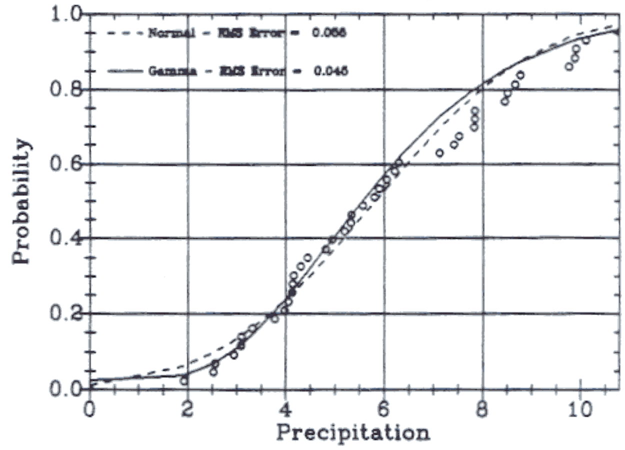

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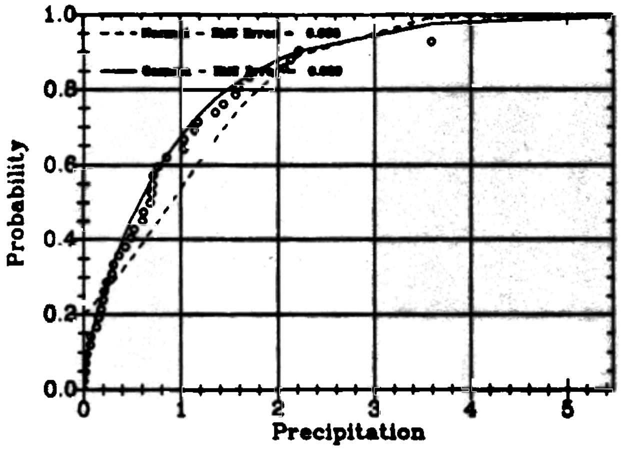

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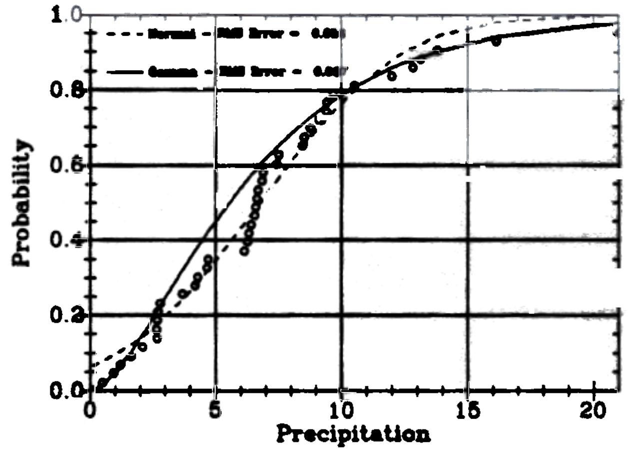

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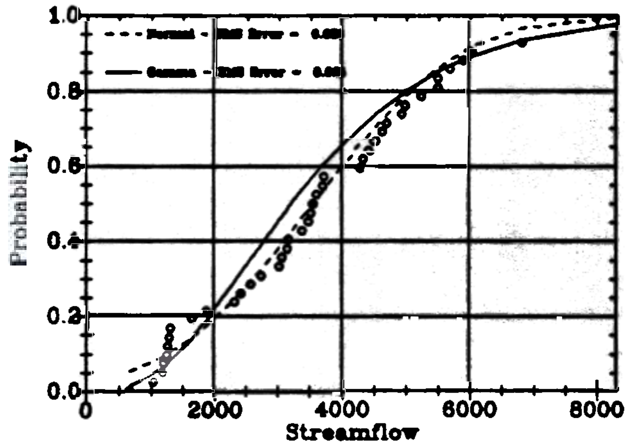

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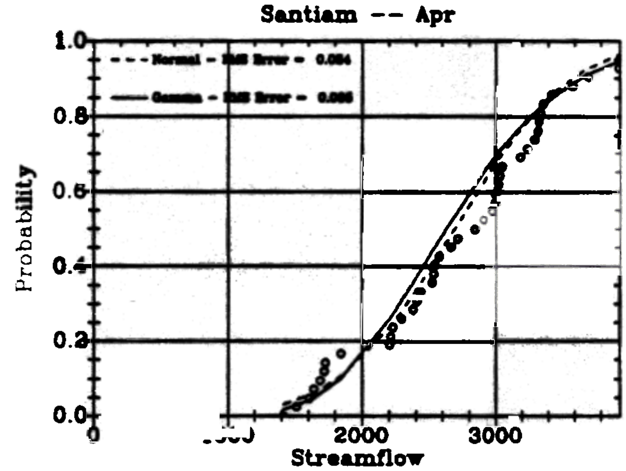

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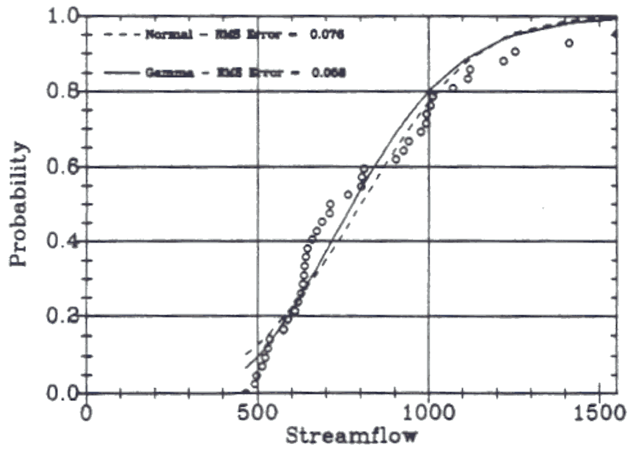

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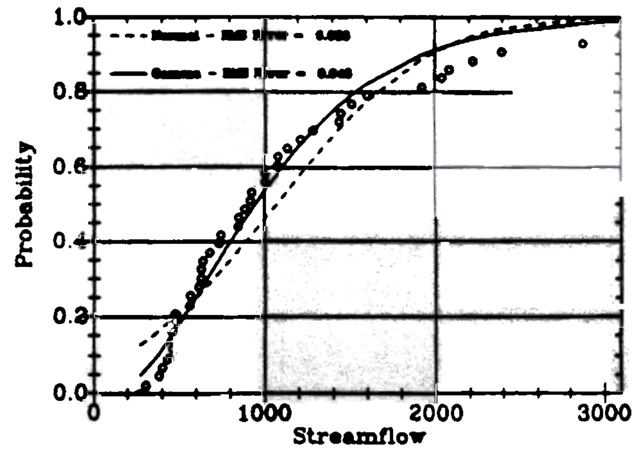

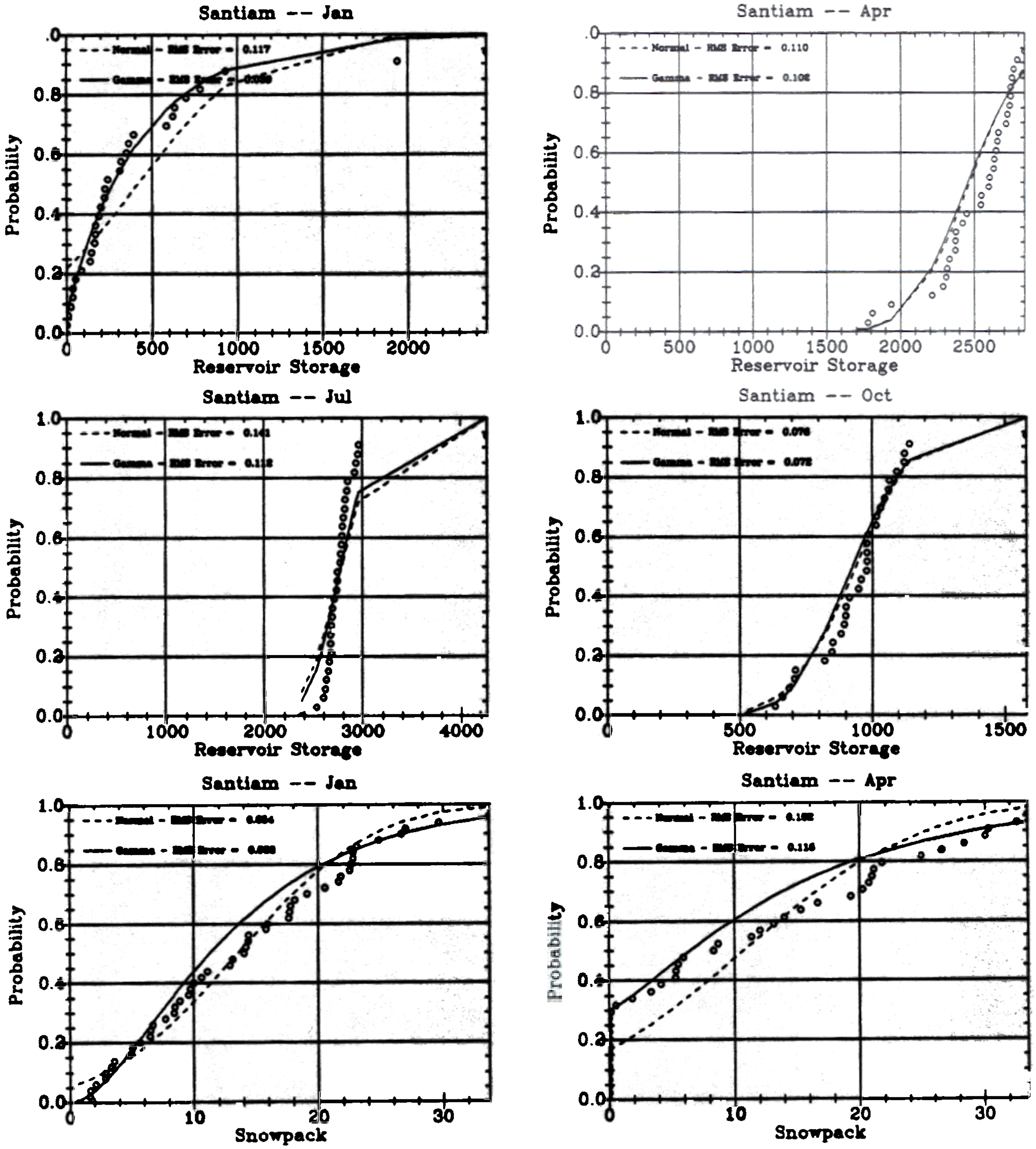
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Probability
Reservoir Storage
Snowpack
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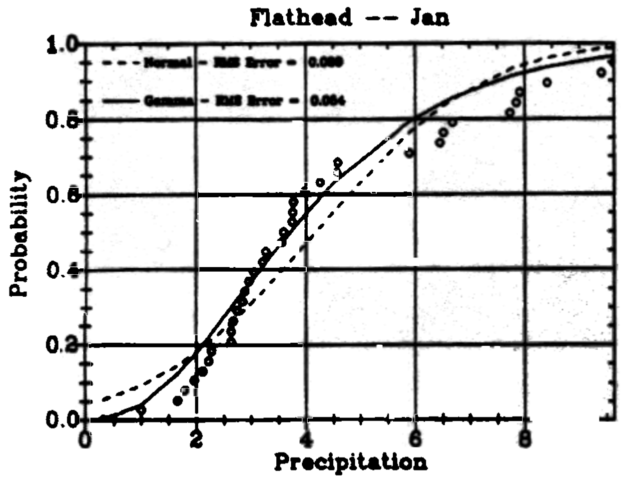
Gamma - RMS Error = 0.106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Normal - RMS Error
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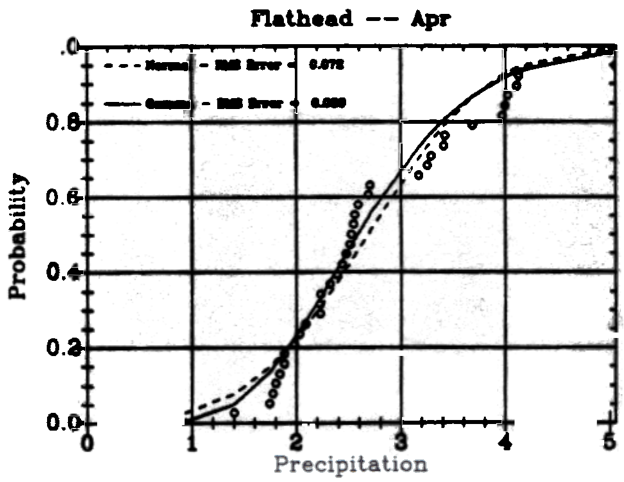
Probability
Precipitation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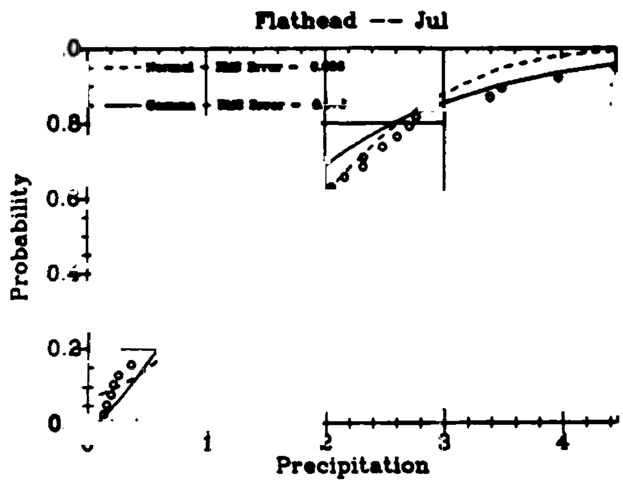
Gamma - RMS Error
Probability
Precipitation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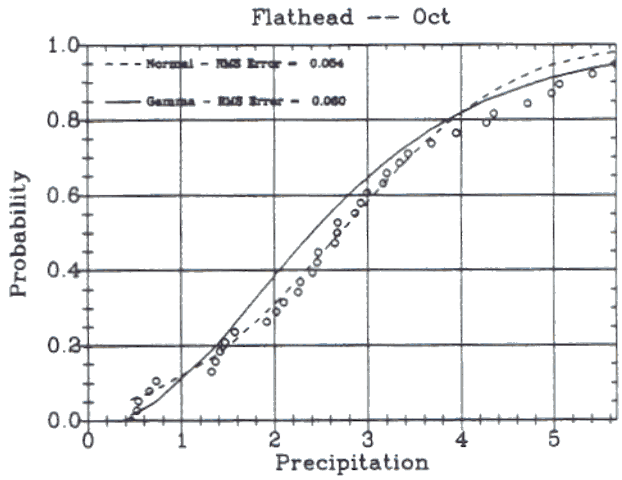
Gamma - RMS Error
Probability
Precipitation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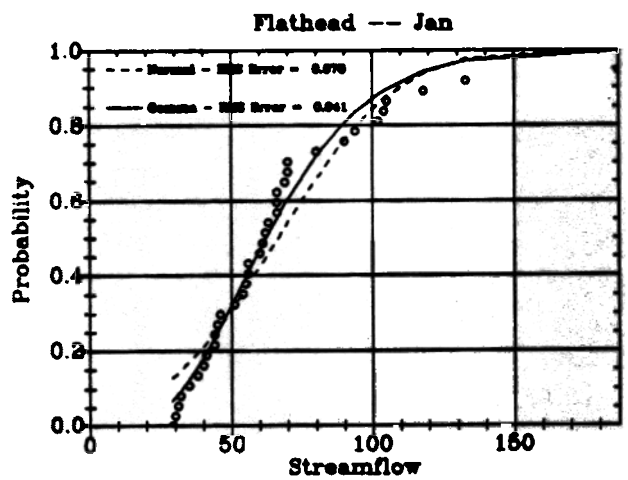
Probability
Precipitation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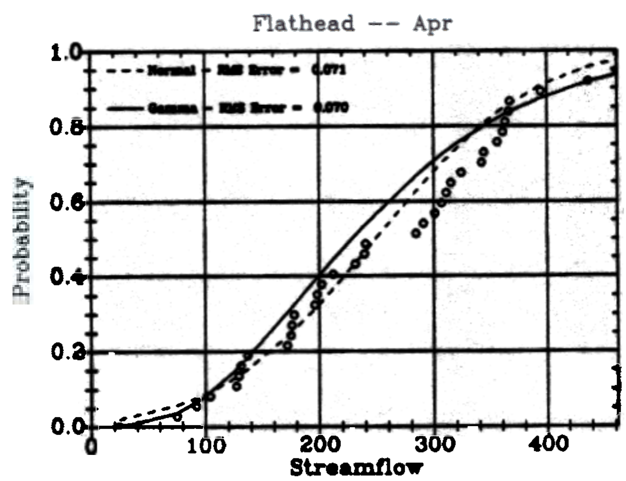
Probability
Streamflow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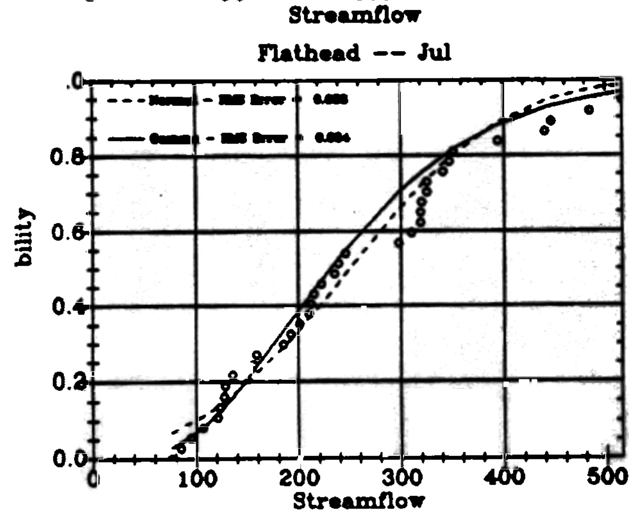
Probability
Streamflow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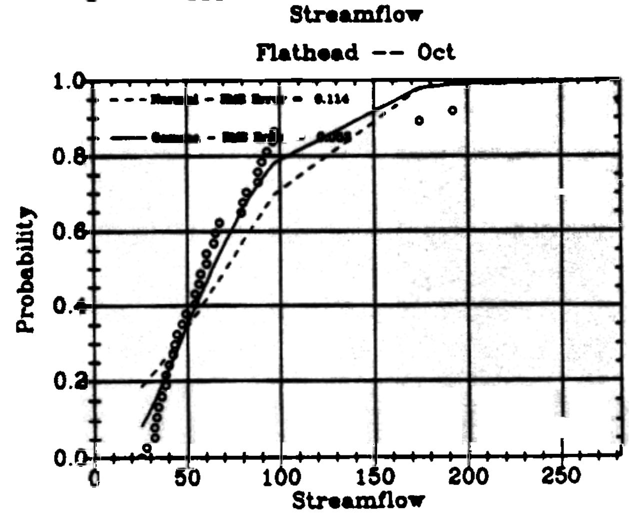
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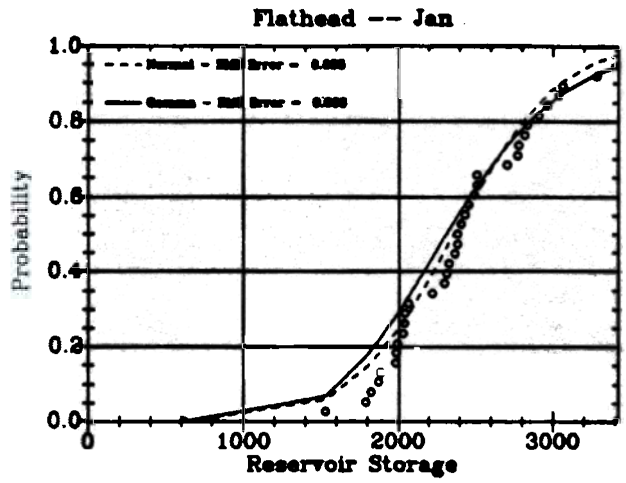
Normal - RMS Error
Gamma
Probability
Streamflow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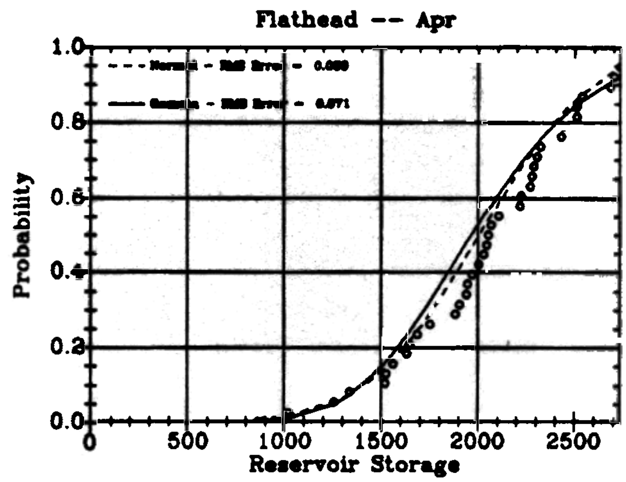
Probability
Reservoir Storage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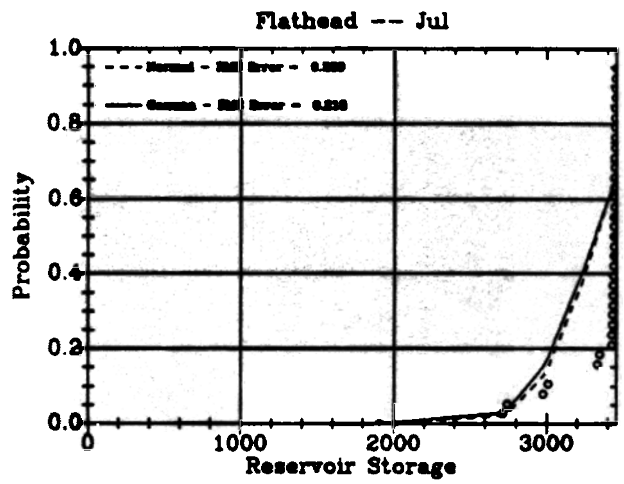
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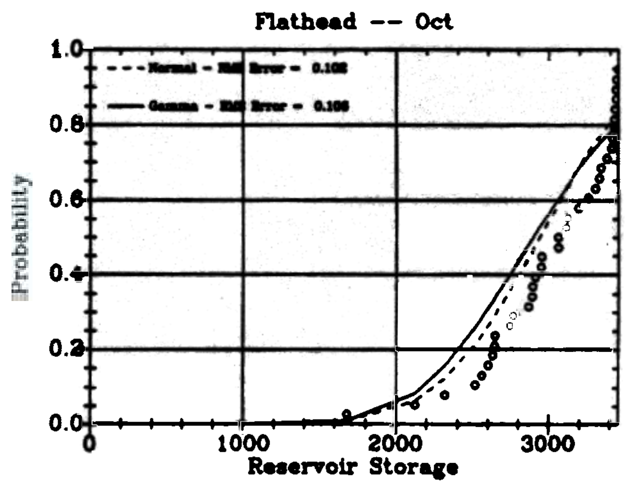
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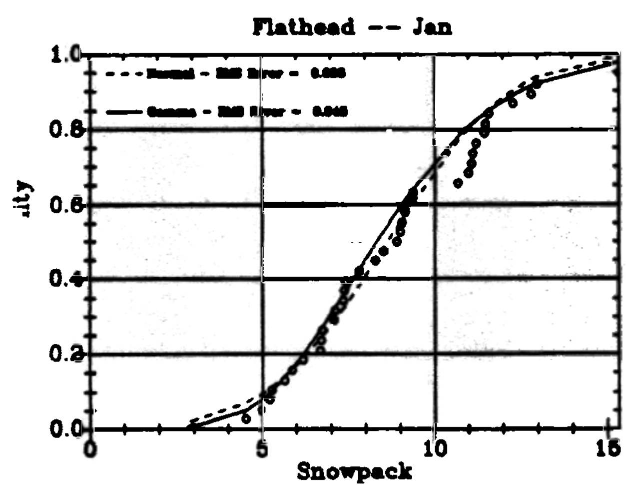
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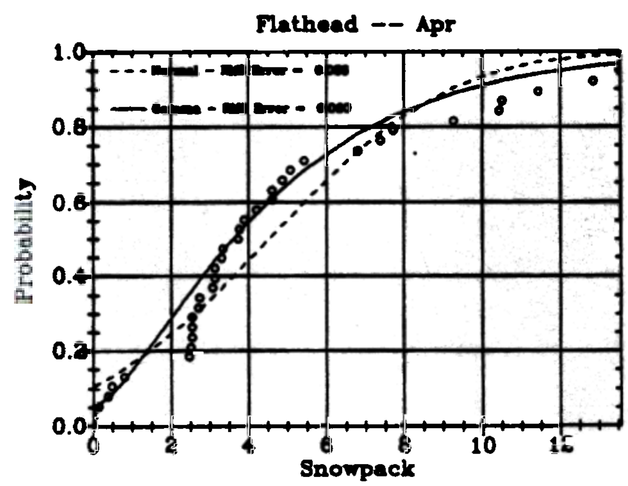
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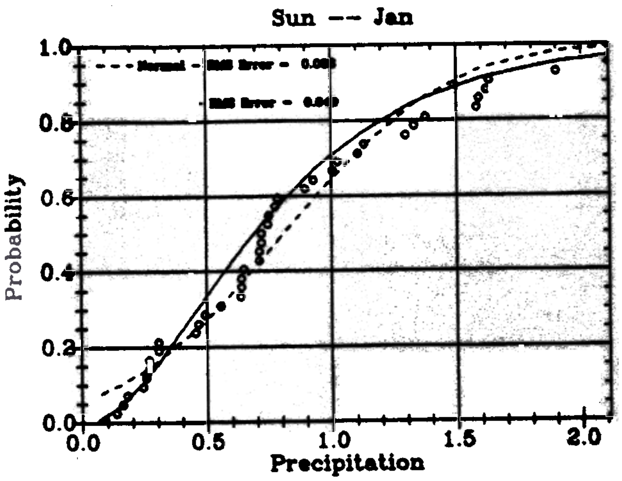
Probability
Snowpack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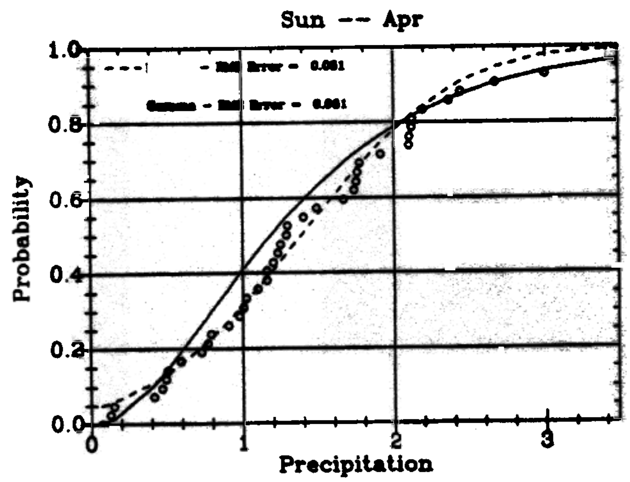
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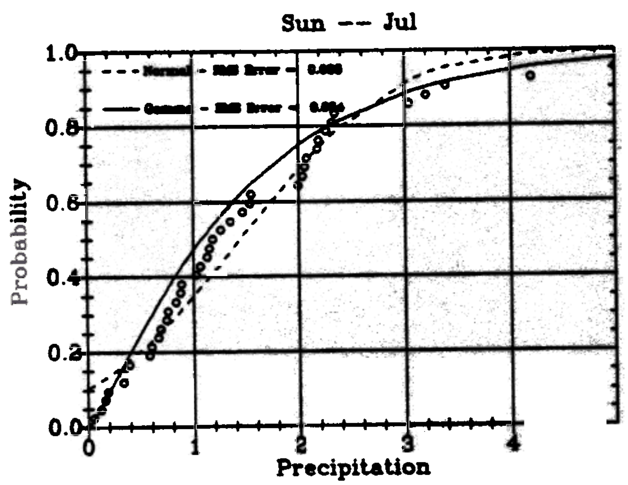
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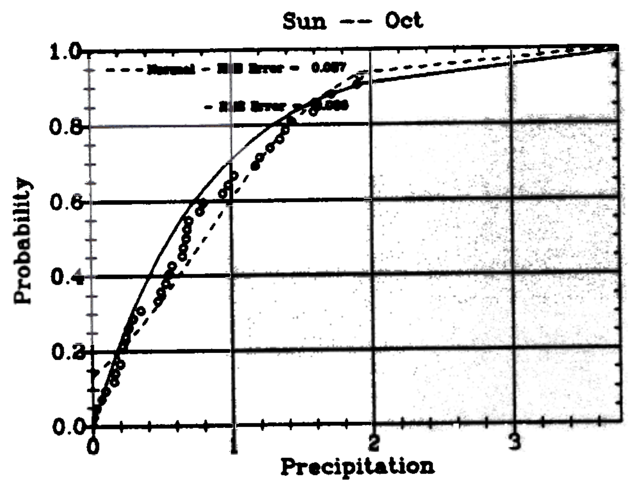
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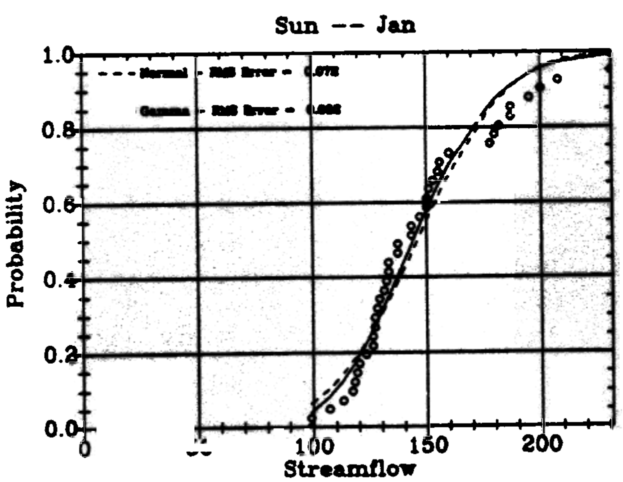
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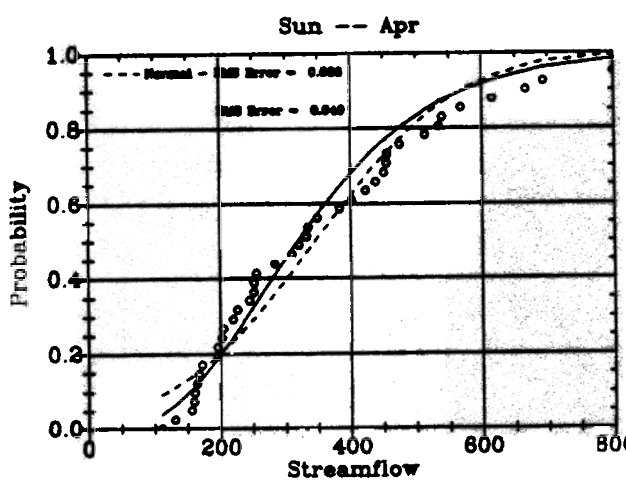
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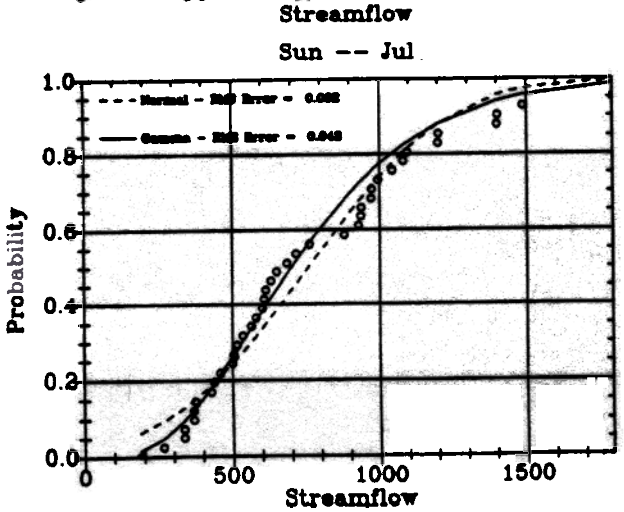
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Streamflow
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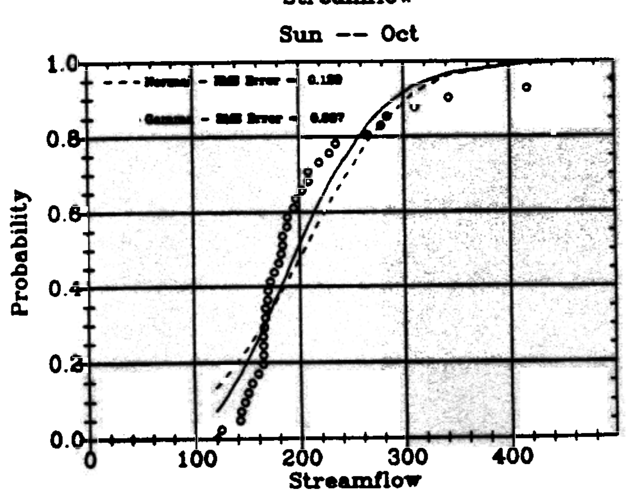
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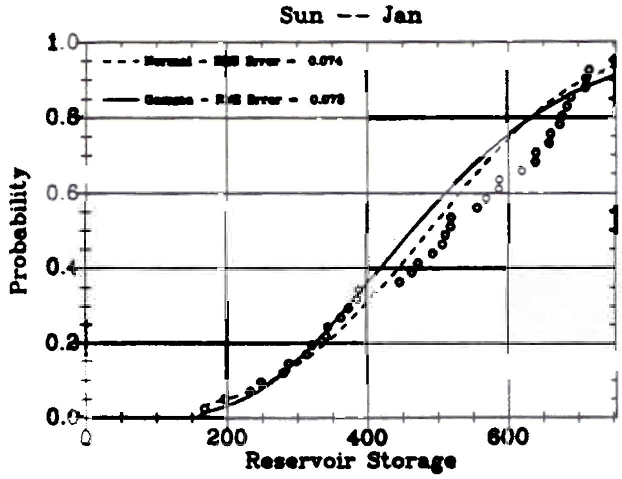
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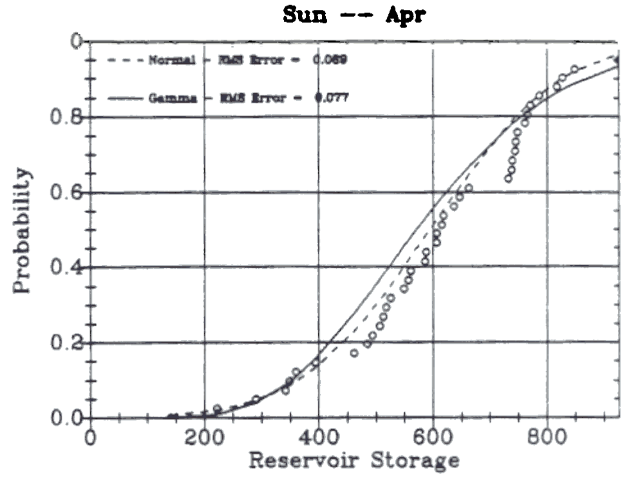
Probability
Reservoir Storage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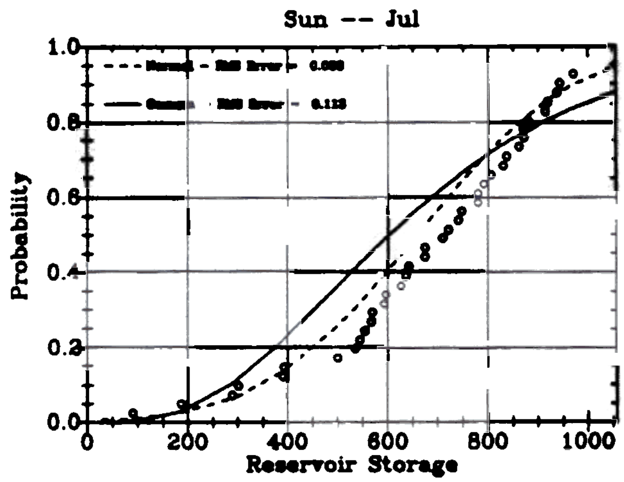
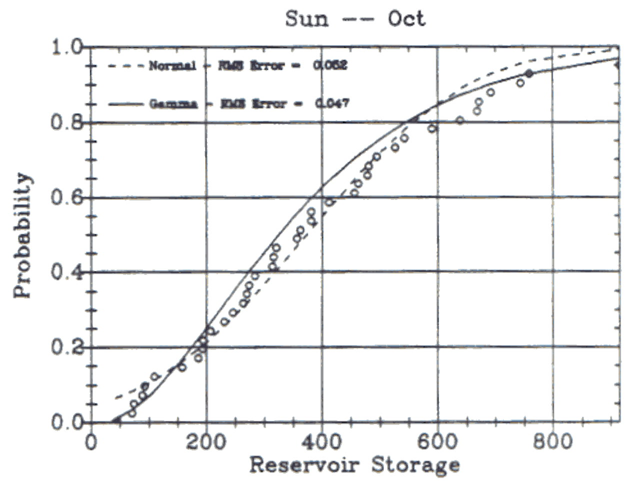
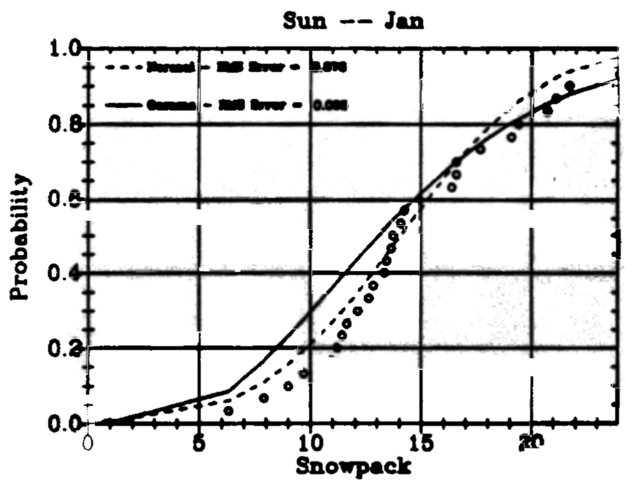
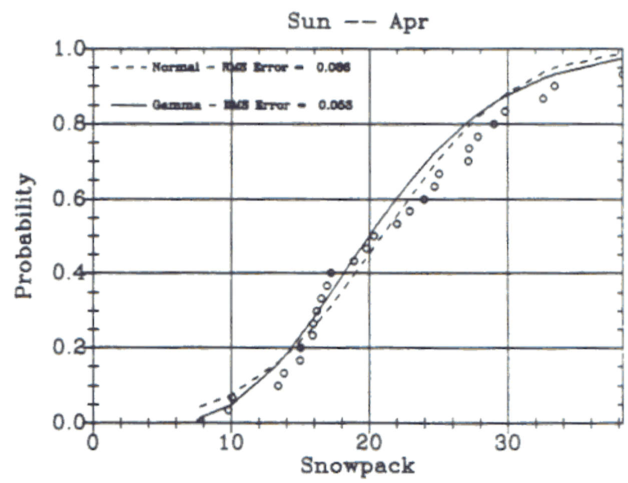
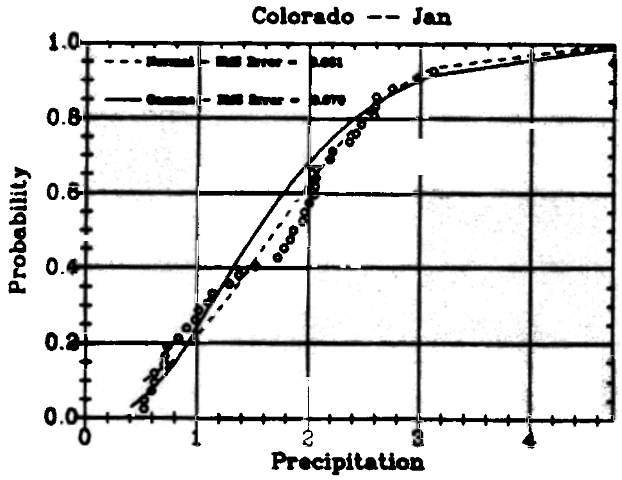
Normal - RMS Error = 0.069
Gamma - RMS Error = 0.077
Probability
Reservoir Storage

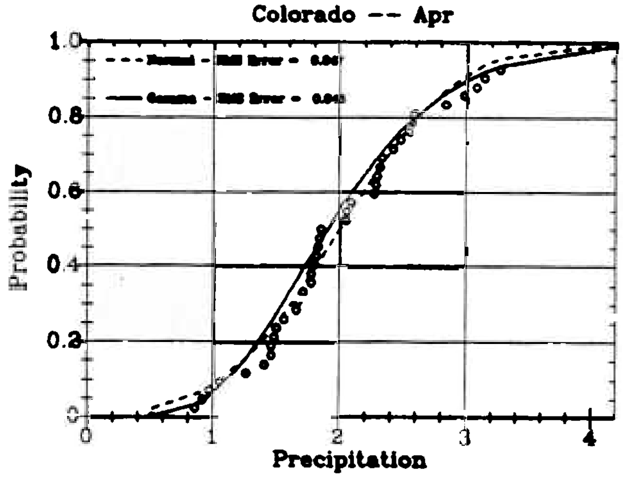

Sun -- Jul
Probability
Reservoir Storage

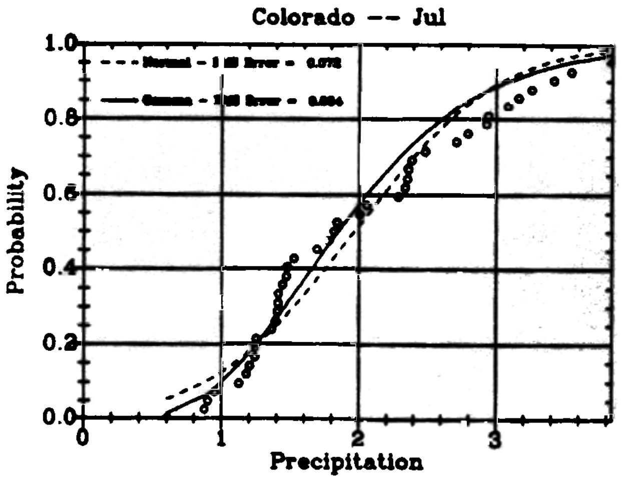

Sun -- Oct
Normal - RMS Error = 0.052
Gamma - RMS Error = 0.047
Probability
Reservoir Storage

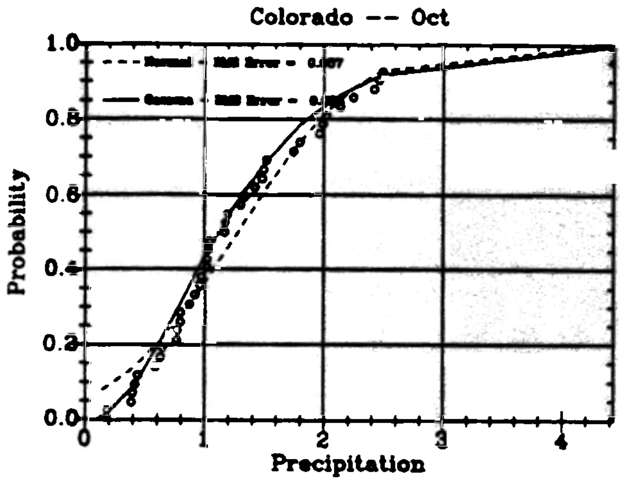

Sun -- Jan
Probability
Snowpack

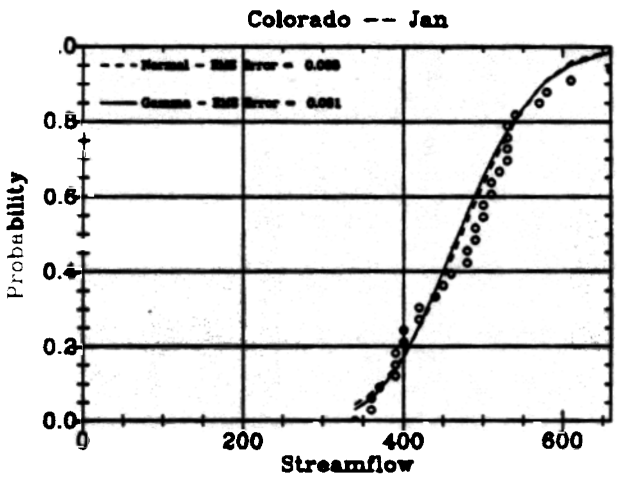

Sun -- Apr
Probability
Snowpack

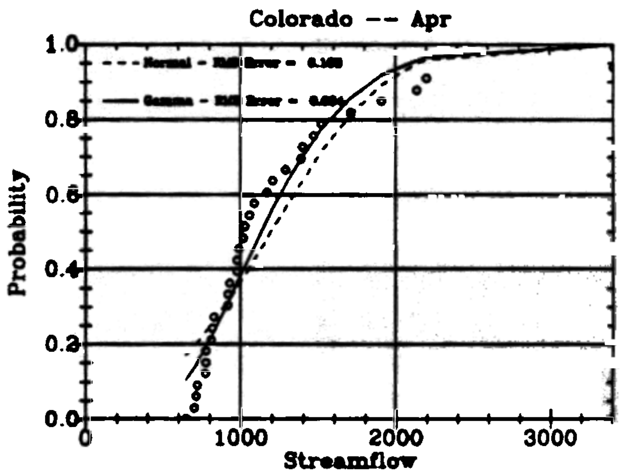

Colorado -- Jan
Probability
Precipitation
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4

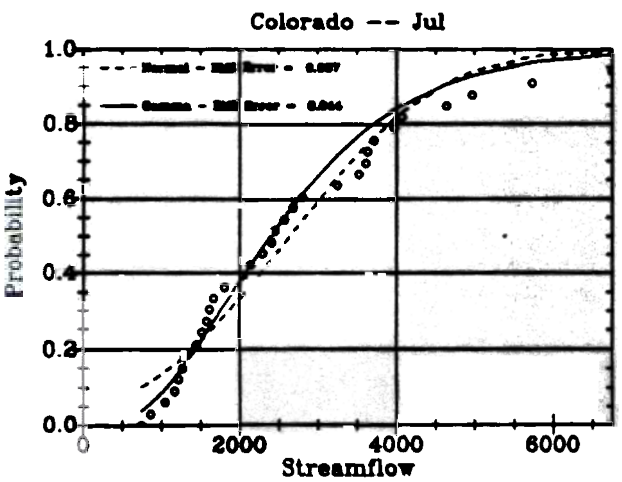

Colorado -- Apr
Probability
Precipitation
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4

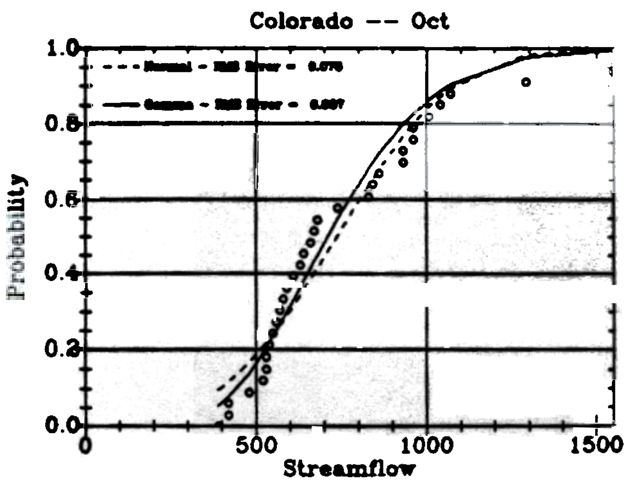

Colorado -- Jul
Probability
Precipitation
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3

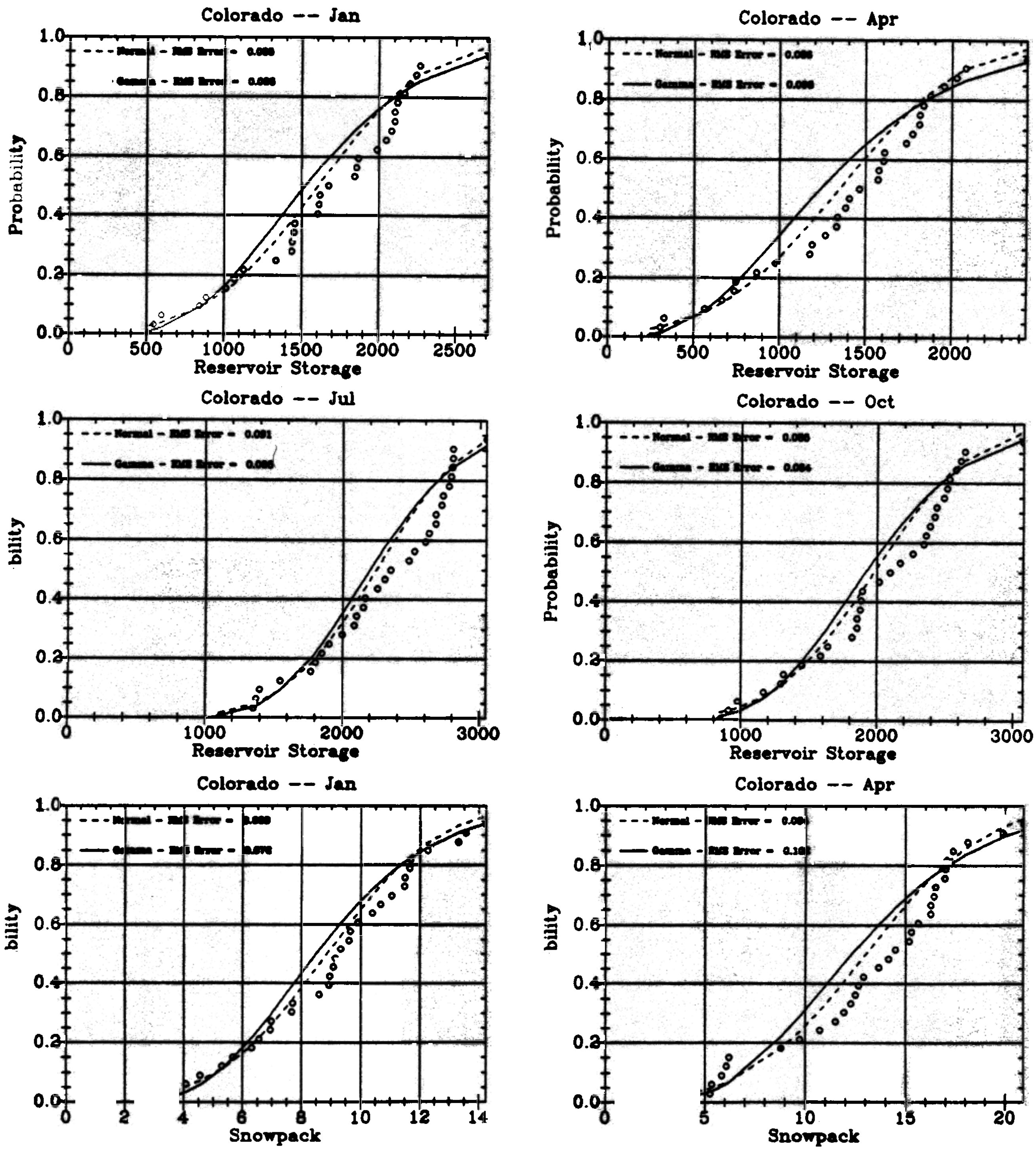

Colorado -- Oct
Probability
Precipitation
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4


Colorado -- Jan
Probability
Streamflow
0.0
0.2
0.4
0.6
0.8
0
200
400
600


Colorado -- Apr
Probability
Streamflow
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000


Colorado -- Jul
Probability
Streamflow
0.0
0.2
0.4
0.6
0.8
1.0
0
2000
4000
6000


Colorado -- Oct
Probability
Streamflow
0.0
0.2
0.4
0.6
0.8
1.0
0
500
1000
1500


Colorado -- Jan
Probability
Reservoir Storage
0 500 1000 1500 2000 2500
0.0 0.2 0.4 0.6 0.8 1.0
Colorado -- Apr
Probability
Reservoir Storage
0 500 1000 1500 2000
Colorado -- Jul
bility
Reservoir Storage
0 1000 2000 3000
Colorado -- Oct
Probability
Reservoir Storage
0 1000 2000 3000
Colorado -- Jan
bility
Snowpack
0 2 4 6 8 10 12 14
Colorado -- Apr
bility
Snowpack
0 5 10 15 20

6.2 Weighting Coefficients for SWSI Computations

SWSI Monthly Weighting Coefficients used in SWSI Comparative Tests
S. Fork Flathead River nr Columbia Falls, MT

Mon.	Precipitation			Snowpack			Reservoir			Steamflow			Soil Moist.
	OR	CO[1]	MT[2]	OR	CO	MT	OR	CO	MT	OR	CO	MT[3]	MT[4]
Oct 1	.39	.10	--	0	0	--	.57	.65	--	.05	.25	--	--
Nov 1	.40	.10	--	0	0	--	.55	.65	--	.05	.25	--	--
Dec 1	.50	.18	--	0	.27	--	.45	.55	--	.05	0	--	--
Jan 1	.42	.18	--	.21	.27	--	.33	.55	--	.04	0	--	--
Feb 1	.39	.18	.22	.30	.27	.22	.28	.55	.50	.03	0	0	.06
Mar 1	.32	.18	.22	.39	.27	.22	.26	.55	.50	.03	0	0	.06
Apr 1	.28	.18	.22	.42	.27	.22	.26	.55	.50	.04	0	0	.06
May 1	.33	.18	.22	.20	.27	.22	.31	.55	.50	.16	0	0	.06
Jun 1	.29	.10	.13	0	0	.14	.32	.65	.60	.39	.25	.13	0
Jul 1	.28	.10	.12	0	0	0	.36	.65	.76	.36	.25	.12	0
Aug 1	.23	.10	.09	0	0	0	.58	.65	.82	.18	.25	.09	0
Sep 1	.31	.10	--	0	0	--	.64	.65	--	.06	.25	--	--

[1] uses individual month precipitation June 1-Nov 1 and water-year accumulated precipitation Dec 1-May 1.

[2] uses water-year accumulated precipitation.

[3] uses combined precipitation for previous two months instead of streamflow.

[4] uses 1/2 August and September precipitation estimate soil moisture.

SWSI Monthly Weighting Coefficients used in SWSI Comparative Tests
Sun River at Gibson Dam, Montana

Mon.	Precipitation			Snowpack			Reservoir			Steamflow			Soil Moist.
	OR	CO[1]	MT[2]	OR	CO	MT	OR	CO	MT	OR	CO	MT[3]	MT[4]
Oct 1	.51	.10	--	0	0	--	.38	.30	--	.11	.60	--	--
Nov 1	.37	.10	--	0	0	--	.51	.30	--	.12	.60	--	--
Dec 1	.34	.34	--	0	.51	--	.56	.15	--	.10	0	--	--
Jan 1	.21	.34	--	.34	.51	--	.39	.15	--	.06	0	--	--
Feb 1	.19	.34	.28	.43	.51	.56	.34	.15	.11	.04	0	0	.05
Mar 1	.13	.34	.28	.51	.51	.56	.32	.15	.11	.04	0	0	.05
Apr 1	.14	.34	.28	.52	.51	.56	.30	.15	.11	.04	0	0	.05
May 1	.22	.34	.28	.43	.51	.56	.28	.15	.11	.07	0	0	.05
Jun 1	.30	.10	.26	.14	0	.26	.31	.30	.23	.25	.60	.25	0
Jul 1	.34	.10	.22	0	0	0	.33	.30	.56	.33	.60	.22	0
Aug 1	.33	.10	.11	0	0	0	.45	.30	.78	.22	.60	.11	0
Sep 1	.52	.10	--	0	0	--	.36	.30	--	.12	.60	--	--

[1] uses individual month precipitation June 1-Nov 1 and water-year accumulated precipitation Dec 1-May 1.

[2] uses water-year accumulated precipitation.

[3] uses combined precipitation for previous two months instead of streamflow.

[4] uses Nov-Jan streamflow to estimate soil moisture.

SWSI Monthly Weighting Coefficients used in SWSI Comparative Tests
Colorado River at Dotsero, CO

Mon.	Precipitation			Snowpack			Reservoir			Steamflow			Soil Moist.
	OR	CO[1]	MT[2]	OR	CO	MT	OR	CO	MT	OR	CO	MT[3]	MT[4]
Oct 1	.43	.05	--	0	0	--	.50	.25	--	.07	.70	--	--
Nov 1	.39	.05	--	0	0	--	.53	.25	--	.08	.70	--	--
Dec 1	.44	.34	--	0	.51	--	.50	.15	--	.06	0	--	--
Jan 1	.41	.34	--	.16	.51	--	.38	.15	--	.04	0	--	--
Feb 1	.41	.34	.26	.20	.51	.53	.35	.15	.16	.04	0	0	.05
Mar 1	.35	.34	.26	.28	.51	.53	.33	.15	.16	.04	0	0	.05
Apr 1	.38	.34	.26	.30	.51	.53	.27	.15	.16	.04	0	0	.05
May 1	.41	.34	.26	.25	.51	.53	.25	.15	.16	.09	0	0	.05
Jun 1	.29	.05	.23	.29	0	.23	.21	.25	.32	.21	.70	.22	0
Jul 1	.28	.05	.21	0	0	0	.35	.25	.58	.37	.70	.21	0
Aug 1	.40	.05	.14	0	0	0	.41	.25	.72	.19	.70	.14	0
Sep 1	.46	.05	--	0	0	--	.45	.25	--	.09	.70	--	--

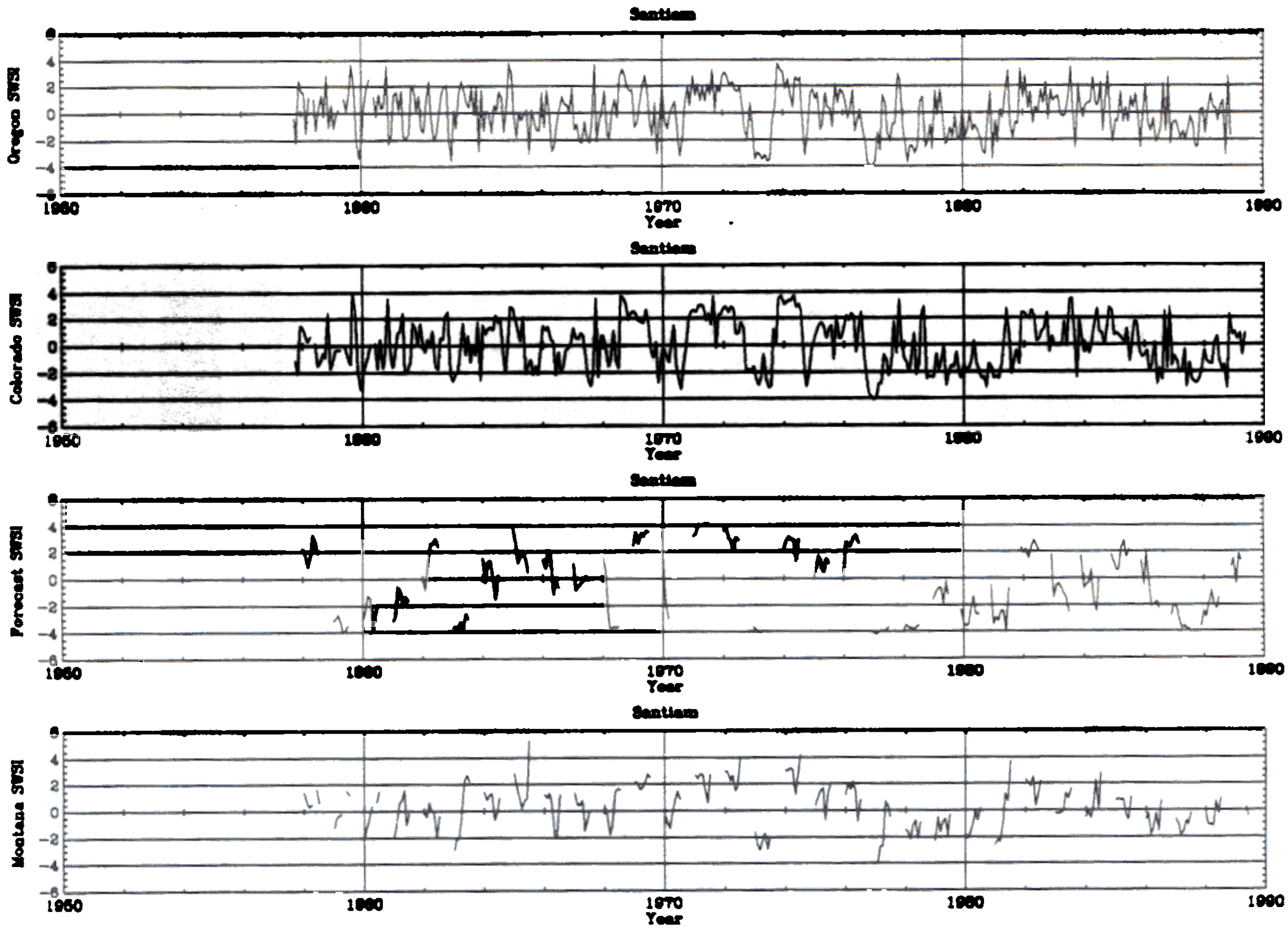
[1] uses individual month precipitation June 1-Nov 1 and water-year accumulated precipitation Dec 1-May 1.

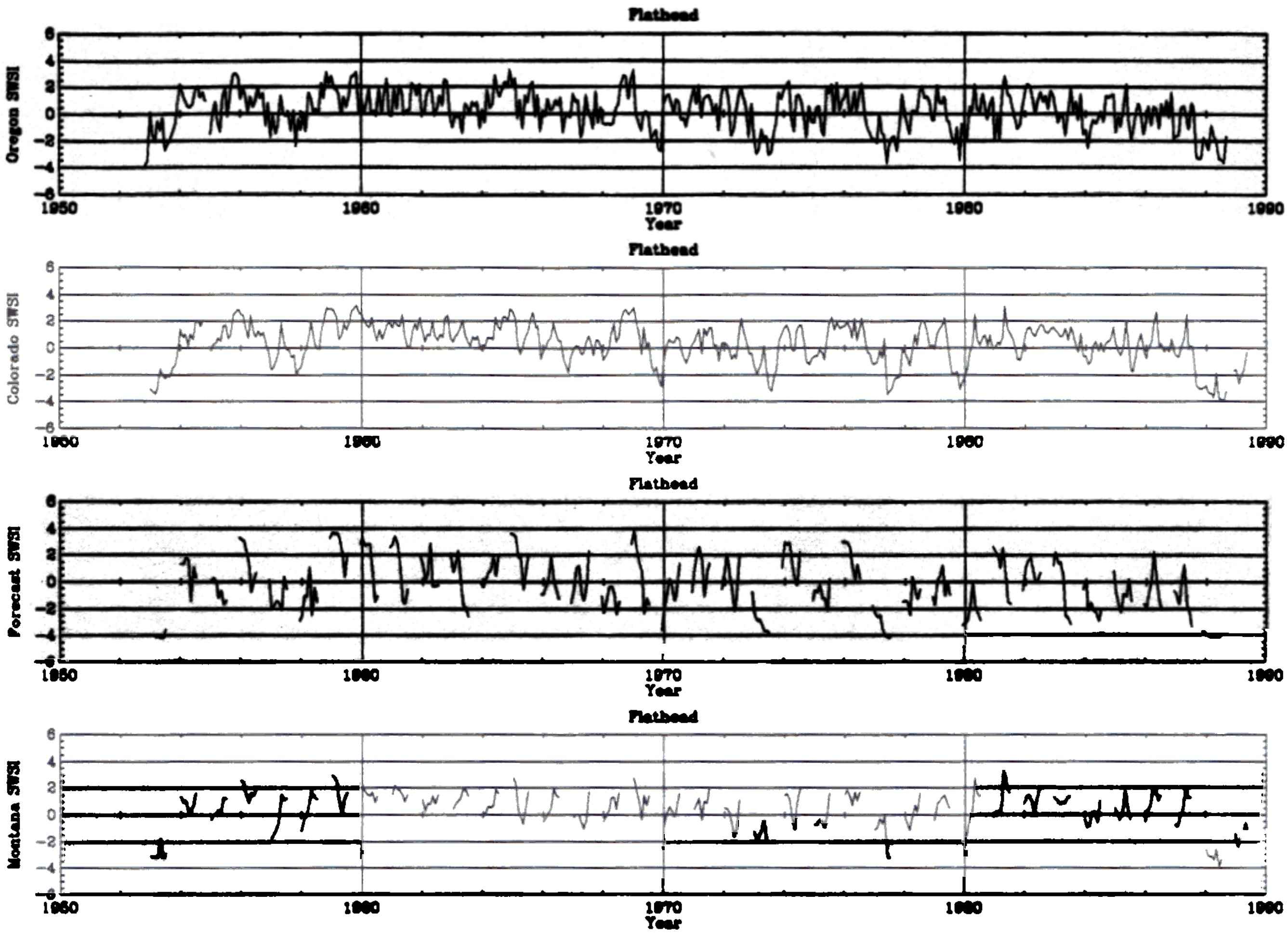
[2] uses water-year accumulated precipitation.

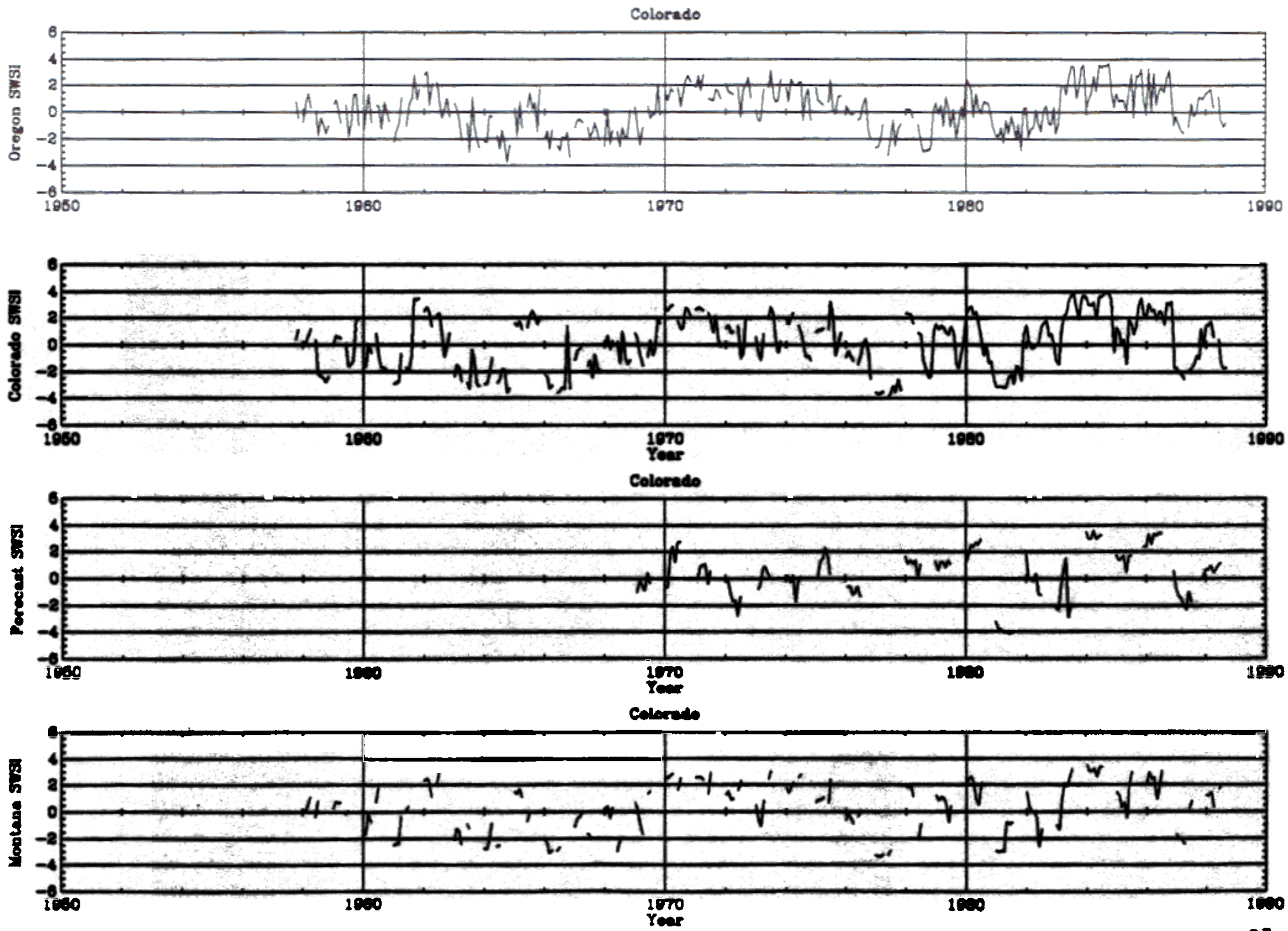
[3] uses combined precipitation for previous two months instead of streamflow.

[4] uses 1/2 August and September precipitation to estimate soil moisture.

6.3 Computed SWSI Time Series




Flathead
Oregon SWSI
Year
Flathead
Colorado SWSI
Year
Flathead
Forecast SWSI
Year
Flathead
Montana SWSI
Year


Colorado
Oregon SWSI
Colorado SWSI
Year
Colorado
Forecast SWSI
Year
Colorado
Montane SWSI
Year
1950
1960
1970
1980
1990
6
4
2
0
-2
-4
-6

22

6.4 Index of Watersheds and Data Sources Used and Analyses Completed in Evaluating Hydroclimatic Characteristics of the Western United States

The number preceeding each basin name corresponds to the number shown on the basin location map in Figure 11. The letters under the heading "Hydroclimatic Analyses" describe which analyses were performed in that basin.

A = Normalized Monthly Averages computed and graphed
B = Raw Data Tabulations prepared
C = Monthly Nonexceedance Probabilities computed and graphed
D = Basin statistics computed by combining multiple inputs
E = Monthly values of hydroclimatic components analyzed and graphed for extreme high and low streamflow years.
F = SCS streamflow forecast equations obtained and investigated.
G = Selected as a test basin for detailed SWSI intercomparisons.

Individual data sources used in these analyses are listed by station name and identification number. The years of data used in analyses are shown. The following abbreviations denote the type of data used at each site.

SN = Snowpack
PR = Precipitation
ST = Streamflow
RS = Reservoir storage

Basin Name and Predominant State (Inventory of data sources used in each basin)	Hydroclimatic Analyses	
1) Salt River, Arizona	A, B, C, D	
SN Heber	10R04	1950-89
SN Workman Creek	10S01	1952-89
PR Pleasant Valley Ranger Stn	6653	1949-87
PR Sierra Ranch	7876	1939-87
ST Salt River nr Roosevelt	09498500	1913-88

2) Chama River, New Mexico		A, B, C, D	
SN	Cumbres Trestle Pillow	06M22S	1961-88
SN	Chama Divide	06N02	1940-89
PR	El Vado Dam	2837	1958-87
PR	Tierra Amarilla 4 NNW	8845	1958-87
ST	Rio Chama inflow to El Vado Res.	08285500	1958-88
RS	El Vado Reservoir	08108060	1953-87
3) Yampa River, Colorado		A, B, C, D, F	
SN	Dry Lake	06J01	1936-89
SN	Elk Rover #2	06J15	1936-89
SN	Yampa View	06J10	1951-89
PR	Hayden	3867	1950-89
PR	Steamboat Springs	7936	1950-89
PR	Yampa	9265	1950-89
ST	Elk River at Clark	09241000	1958-87
ST	Yampa River at Steamboat Springs	09239500	1958-87
4) Big Thompson River, Colorado		A, B, D	
SN	Deer Ridge	05J17	1949-89
SN	Hidden Valley	05J13	1941-89
SN	Longs Peak	05J22	1951-89
PR	Estes Park	2759	1950-88
PR	Waterdale	8839	1950-88
ST	Big Thompson River at Drake	06738000	1958-88
RS	Boyd Lake	06016040	1953-88
RS	Carter Lake	06016060	1953-88
5) Saguache Creek, Colorado		A, B, C, D	
SN	Cochetopa Pass	06I06	1949-89
PR	Saguache	7337	1950-88
ST	Saguache Creek nr Saguache	08227000	1958-85
6) Upper Colorado River, Colorado		A, B, C, D, E, F, G	
SN	Berthoud Pass	05K03	1936-89
SN	Granby	05J16	1949-89
SN	Lake Irene	05J10	1938-89
SN	Lynx Pass	06J06	1936-89
PR	Grand Lake 1NW	3496	1950-88

PR	Winter Park	9175	1950-88
ST	Colorado River nr Dotsero	09070500	1958-85
RS	Lake Granby	09009060	1952-88
RS	Williams Fork Rservoir	09009150	1953-88

7) San Miguel Basin, Colorado — A, B, C, D

SN	Telluride	07M02	1936-89
SN	Trout Lake	07M09	1949-89
PR	Ames	0228	1950-85
PR	Norwood	6012	1950-88
PR	Placerville	6524	1950-88
ST	San Miguel River nr Placerville	09172500	1958-88
ST	W Fk Naturita Crk. at Up. Stn.	09174700	1951-83

8) Arkansas River — A, B, C, D

SN	Four Mile Park	06K07	1936-89
SN	Tennessee Pass	06K02	1936-89
PR	Buena Vista	1071	1950-88
PR	Climax	1660	1950-88
PR	Westcliffe	8931	1950-88
ST	Arkansas River at Salida	07091500	1958-88
RS	Turquoise Lake	07007110	1953-88

9) Colorado River, Colorado — A, B, C, D

SN	Mesa Lakes	08K04	1937-89
SN	Trickle Divide	07K05	1940-84
PR	Collbran	1741	1906-89
PR	Glenwood Springs 1N	3359	1950-89
PR	Grand Junction WSO AP	3488	1950-89
ST	Colorado River nr Cameo	09095500	1958-89
RS	Vega Reservoir	09009140	1959-89

10) Upper Yellowstone, Wyoming — A, B, C, D

SN	Northeast Entrance Yel. Ntl. Prk.	10D07	1937-89
SN	Thumb Divide	10E07	1938-89
PR	Lake Yellowstone	5345	1937-89
PR	Yellowstone Park	9905	1901-89
ST	Yellowstone Rv. @ Lk. Yellowstn	06186500	1927-89

11) Rock Creek, Wyoming — A, B, C, D

SN	Cloud Peak	07E36	1960-89
SN	Sour Dough	06E01	1937-89
PR	Billy Creek	0740	1961-89
PR	Powder River Pass	(SCS) S307	1950-89
ST	Rocky Creek nr Buffalo	06320000	1945-88

Greybull River, Wyoming — A, B, C, D

SN	Timber Creek	09E03	1949-89
SN	Carter Mountain	09E04	1957-89
PR	Sunshine 2ENE	8758	1961-89
PR	Timber Creek	(SCS) X025	1967-89
ST	Greybull at Meeteetse	06276500	1931-89

13) Santiam River, Oregon — A, B, C, D, E, F, G

SN	Marion Forks Pillow	21E04	1941-89
SN	Santiam Junction SNOTEL	21E05S	1941-89
PR	Detroit Dam	2292	1947-89
PR	Santiam Pass	7559	1963-89
ST	N. Santiam River at Mehama	14183000	1922-89
RS	Detroit Lake	14180500	1958-89

14) Grande Ronde, Oregon — A, B, C, D

SN	Bald Mountain AM	17D10	1960-89
SN	Beaver Reservoir	18D22	1939-89
SN	Moss Springs	17D06	1938-89
PR	La Grande	4622	1937-89
PR	Union Exp. Stn.	8746	1937-89
PR	Cove 1ENE	1924	1937-89
ST	Grande Ronde at La Grande	13319000	1904-89

Upper Tongue River, Montana — A, B, C, D

SN	North Tongue	07E15	1960-89
SN	Sucker Creek Pillow	07E12S	1961-89
PR	Burgess Junctions	1220	1961-89
PR	Sheridan WSO	8155	1960-89
ST	Tongue River at Dam nr Decker	06307500	1940-89
RS	Tongue River Reservoir	06307000	1940-89

16) Ruby River, Montana — A, B, C, D

SN	Notch	12E06	1961-89
SN	Divide Pillow	12E07	1961-89
PR	Alder 17S	0110	1957-89
PR	Virginia City	8597	1938-89
ST	Ruby River above Reservoir	06019500	1938-89
RS	Ruby River Reservoir	06020500	1939-89

17) S. Fork Flathead River, Montana — A, B, C, D, E, F, G

SN	Holbrook	13B13	1951-89
SN	Spotted Bear Mountain	13B02	1948-89
SN	Twin Creeks	13B11	1951-89
PR	Hungry Horse Dam	4328	1948-89
PR	Summit	7978	1939-89
ST	S Fk Flathead nr Columbia Falls	12362500	1911-89
RS	Hungry Horse Lake	12362000	1952-89

18) Sun River, Montana — A, B, C, D, E, F, G

SN	Mount Lockhart	12B12	1961-89
SN	Wrong Ridge	12B03	1949-89
SN	Mount Lockhart Pillow	12B12S	1961-89
PR	Augusta	0364	1931-89
PR	Gibson Dam	3489	1939-89
ST	Sun River at Gibson Dam	06078600	1943-89
RS	Gibson Reservoir	06079500	1936-89

19) Bruneau River, Idaho — A, B, C, D

SN	Bear Creek	15H01	1941-89
SN	Goat Creek	15H13	1955-89
SN	Seventy-six Creek	15H03	1946-89
PR	Bruneau	1195	1962-89
PR	Mountain City Ranger Stn.	5392	1955-89
ST	Bruneau River nr Hot Springs	13168500	1951-89

20) Boise River, Idaho — A, B, C, D

SN	Bogus Basin	16F02	1942-89
SN	Trinity Mountains	15F05	1932-89
SN	Atlanta Summit	15F04	1931-89
SN	Jackson Peak	15E09	1950-89
PR	Anderson Dam	0282	1942-89

	PR Arrowrock Dam	0448	1956-89
	PR Centerville Arbaugh Ranch	1636	1950-89
	PR Idaho City	4442	1939-89
	ST Boise River nr Boise	13202000	1955-89
	RS Arrowrock Reservoir	13194000	1918-89
21)	Spokane River, Idaho	A, B, C, D	
	SN Fourth of July Summit	16B03	1960-89
	SN Lookout	15B02	1945-89
	SN Sherwin	16C01	1960-89
	PR Spokane, WA WSO AP	7938	1951-89
	PR Saint Maries	8062	1931-89
	PR Wallace Woodland Park	9468	1931-89
	ST Spokane River nr Post Falls	12419000	1951-89
	RS Coeur d'Alene	12415500	1904-88
22)	Rogue River, Oregon	C	
	-- Station Information not available --		
23)	Carson River, Nevada	C	
	-- Station Information not available		
24)	Yakima River, Washington	C	
	-- Station Information not available --		
25)	Okanogan River, Washington	C	
	-- Station Information not available --		
	Deschtes River, Oregon	C	
	-- Station Information not available --		
	Upper Bear River, Idaho	C	
	-- Station Information not available --		
28)	St. Vrain River, Colorado	E, F	
	-- Station Information not available --		

29) Beaverhead River, Montana **E, F**

-- Station Information not available --

30) Musselshell River, Montana

-- Station Information not available --

31) Animas River, Montana

-- Station Information not available

6.5 "Drought Monitoring in the Western United States Using a Surface Water Supply Index," Proceedings of the 7th American Meteorological Society Conference on Applied Climatology, Salt Lake City, Utah, September 10-13, 1991.

7th Conference on Applied Climatology
September 10-13, 1991 Salt Lake City, UT

DROUGHT MONITORING IN THE WESTERN UNITED STATES USING A SURFACE WATER SUPPLY INDEX

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Introduction

Drought monitoring activities have grown in magnitude and sophistication in the western United States during the past 15 years. The 1976-77 drought, which brought unprecedented low streamflow volumes to numerous western rivers, helped focus attention on the need for more aggressive drought management. More recently, drought episodes have brought severe water shortages to parts of the West culminating in the multi-year drought that continues in California, Nevada, and portions of adjacent states. In combination with the end of the era of major water development projects in the West, this has helped direct more attention toward drought monitoring and water supply management.

In the midst of a short but intense drought in 1981, Colorado implemented the Colorado Drought Response Plan which stipulated the use of numerical values or indexes of water supplies to trigger State preparations and response actions. That same year, participants in the newly formed Colorado Water Availability Task Force teamed up to develop an index, called the Surface Water Supply Index (SWSI), for monitoring water supplies in areas where most surface water supplies originate as mountain snowpack. Since that time, other western states have implemented drought response plans. At least two other states, Oregon and Montana, have developed customized SWSIs based on the original Colorado approach.

In 1990, the USDA Soil Conservation Service (SCS) initiated a cooperative agreement with Colorado State University to examine more closely the SWSI concept and to explore the possibility of expanding its use and application in managing western water resources. This paper describes briefly the SWSI concept. Comparisons are made between three existing SWSI methods and a newly formulated SWSI.

Surface Water Supply Index Concept

The purpose of any index is to combine an extensive and complex array of data into a single numeric value that represents, as well as possible, the most significant characteristics of those data. Indexes are useful to guide decision makers, who may not have the time or knowledge base to become totally familiar with all the data and interactions associated with the process in question. Water supply and drought are topics ideally suited for indexing because they are complex physical processes that involve a great deal of data and which have far-reaching impacts. This means that many managers, planners, political leaders and other decision makers, who are not involved in water management and drought response on a day-to-day basis, may need to respond to critical drought situations and water supply fluctuations. Indexes have the potential to provide concise integrated information to guide decision making.

The most widely used and accepted index for monitoring drought in the United States is the Palmer Index (Palmer, 1965). Despite numerous shortcomings (Alley, 1984), the Palmer Index has broad popularity and is used by many organizations as a planning and management tool. The Palmer Index, however, is an index of relative soil moisture resulting from observed regional temperature and precipitation patterns. In the western United States, this is applicable for forest growth, rangeland conditions and productivity of dryland agriculture. But for many applications such as urban water supplies, irrigation, and recreation, it is the availability of surface water -- the water in rivers and reservoirs -- that has the greatest impacts.

The idea for a SWSI originated in Colorado where the Palmer Index does not appropriately reflect surface water supplies. A very large portion of available water resources in Colorado and other western states originates as accumulated mountain snowpack which the Palmer Index does not explicitly include. The intent of the Colorado SWSI was to index surface water conditions by including each of the components that contribute directly to surface water supplies -- precipitation, snowpack, streamflow and reservoir storage. The SWSI was developed to be a relative indicator of current water supplies, but it is also predictive in so far as several of the components, most notably snowpack, are measures of how much water will be available as surface water in the months ahead.

In concept, the original SWSI was developed to index water supplies in terms of probability (Shafer and Dezman, 1982). They divided Colorado into 7 watersheds and selected several representative precipitation stations, snowcourses, stream gages and indicator reservoirs within each basin where many years of historical monthly data were available. The data for each component were combined and sorted to form probability distributions. The final index is a sum of individual component non-exceedance probabilities weighted subjectively according to each component's perceived relative contribution to total water supplies.

The original SWSI equation was expressed as:

$$SWSI = \frac{[(a \times PN_{SP}) + (b \times PN_{PR}) + (c \times PN_{ST}) + (d \times PN_{RS}) - 50]}{12}$$

where a, b, c and d are experience-based weighting factors which must sum to 1; PN = probability of non-exceedance (%); SP, PR, ST, and RS refer to snowpack, precipitation, streamflow and reservoir storage, respectively. Subtracting by 50 centers the PN scale (in percent) about zero. Division by 12 scales the index to run from -4.2 to +4.2 making it similar to the typical ranges of the Palmer Index. The Colorado SWSI has been computed operationally for the past 10 years by the USDA Soil Conservation Service and the Colorado Division of Water Resources and used in state drought monitoring activities. There are only two sets of weighting factors for each basin -- a winter set (Dec - May) and a summer set (Jun - Nov).

Variations on SWSI

Since its inception, the Colorado SWSI has often been cited as an example of a practical contribution to the drought monitoring process (Wilhite, 1990). Yet, no other group has ever used the Colorado SWSI in its original form for drought monitoring. In the late 1980s, Oregon and Montana each utilized the basic approach of the Colorado SWSI but made changes to adapt the index to their own specific needs and wishes. In Oregon, a method was developed to compute index weighting factors based on the seasonal distributions of each of the four components. Montana reconfigured the SWSI to accomodate the use of USDA SCS SNOTEL data (Farnes, 1989), added a term to the equation that is a surrogate for soil moisture, and made the decision to only compute the SWSI from early winter through the summer.

The investigation of SWSI by the SCS and Colorado State University in 1990 motivated experimention with another variation on SWSI (Doesken et al, 1991). Instead of using and summing non-exceedance probabilities for individual hydro-climatic components, a SWSI derived from a single water volume was proposed -- the sum of the SCS forecasted basin water supply and the stored reservoir volumes available for use.

SWSI Comparison with Observed Water Supply

Before it is possible to evaluate how well the Colorado SWSI and these several variations depict surface water supplies, surface water supply must be strictly defined. This proves to be no simple matter. Is it the amount of streamflow passing the point of interest at a particular time, or is it the accumulated streamflow over a period of time? What period of time -- all year, or just during the primary growing season? Do you use actual measured volumes or computed virgin streamflow? What about reservoir volumes -- do you include all usable content in storage or only that portion which is being released at a particular time or during a particular period? Or do you include that volume which could conceivably be released during the time in question? Do you include precipitation and snowpack, or do you wait until they appear as streamflow?

These are only a few of the questions that come up when attempting to define surface water supply. In order to compare the Colorado SWSI and these other SWSI variations, some arbitrary decisions were made. For many primary water users, including irrigated agriculture, residential and recreation, the greatest water demand occurs during the months of April through September. Therefore, for this SWSI comparison, surface water supply is defined as the total virgin streamflow during the April-September period plus the amount of reservoir water in active storage at the beginning (April 1) of the period.

Four test basins were used to compare the SWSI computations: the North Santiam basin in Oregon, the South Fork of the Flathead and the Sun River in Montana and the Upper Colorado in Colorado (Figure 1). When used operationally, the SWSI has been computed for relatively large watersheds. For example, Colorado has used just seven climatic divisions for SWSI computations. For testing purposes, however, smaller basins were selected. Small basins have less internal hydroclimatic diversity and therefore lend themselves to easier interpretation of SWSI results.

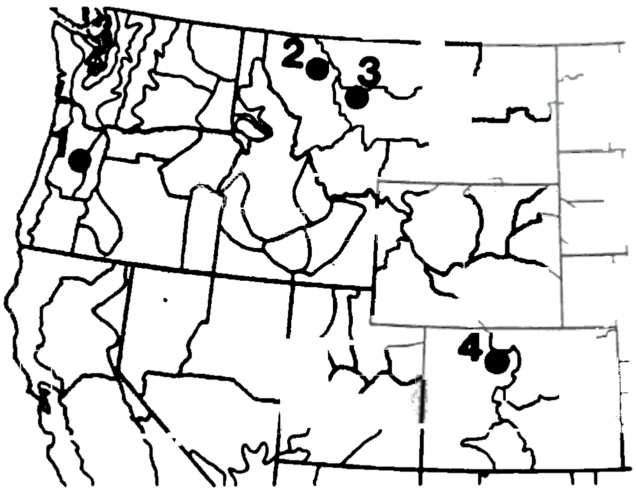

Fig 1. Watersheds used for SWSI comparison: 1) North Santiam River, Oregon, 2) South Fork of the Flathead River, Montana, 3) Sun River, Montana, and 4) the Upper Colorado River above Dotsero, Colorado.

To perform the comparative tests, sets of consistent monthly hydroclimatic data within each basin were assembled for as many years as possible: calculated virgin streamflow at one point, monthly snowpack water contents from at least 2 locations high in each watershed, precipitation data from at least 2 sites in the basin, and end of month active reservoir storage in the primary reservoirs in each basin. Also, historic time series of SCS forecasted Apr - Sep total streamflow volumes were gathered for each month when forecasts are made (usually Jan 1 through Jun 1). Generally 25 to 35 years of consistent data were available in each test basin. A verification data set was compiled consisting of the sum of the Apr - Sep streamflow volumes and the active reservoir storage at the end of March.

Index values were then computed for each of the four SWSI procedures. The assumptions and methodologies previously developed for each of the Colorado, Oregon and Montana indexes were applied. Both the Colorado and Oregon SWSI were computed for all months of the year while the Montana and forecast-based SWSIs were only computed January through July. Figure 2 shows SWSI time series for each of the four methods computed for the Sun watershed in Montana.

Correlation statistics were then computed for each month using linear regression. For example, the SWSI time series computed from all January 1 data for each basin were regressed against the time series of actual surface water supply, the verification data of April-September streamflow plus reservoir storage. This type of correlation provides a crude test for which SWSI computations most closely relate to water supplies. In the North Santiam basin, all methods behaved similarly (Fig. 3) with correlations (r^2) increasing to peaks of 0.4 to 0.5 at the end of April, declining sharply in May and improving again in June and July. In the Sun and Upper Colorado basins, index correlations to summer water supply got off to a much better start with r^2-values already near 0.6 in January for some of the methods. Correlations generally improved into the runoff season and decayed later in the summer. The Colorado SWSI produced some of the best individual monthly correlations with values higher than 0.8 later in the season. The Oregon SWSI showed poorer correlation with water supply in these two Rocky Mountain watersheds. Finally, the Flathead River provided some unusual results. Correlations began reasonably high, but declined to near zero for all except the forecast-based SWSI in May before improving again in June and July. This behavior has not been thoroughly investigated but is assumed to result from the fact that a much

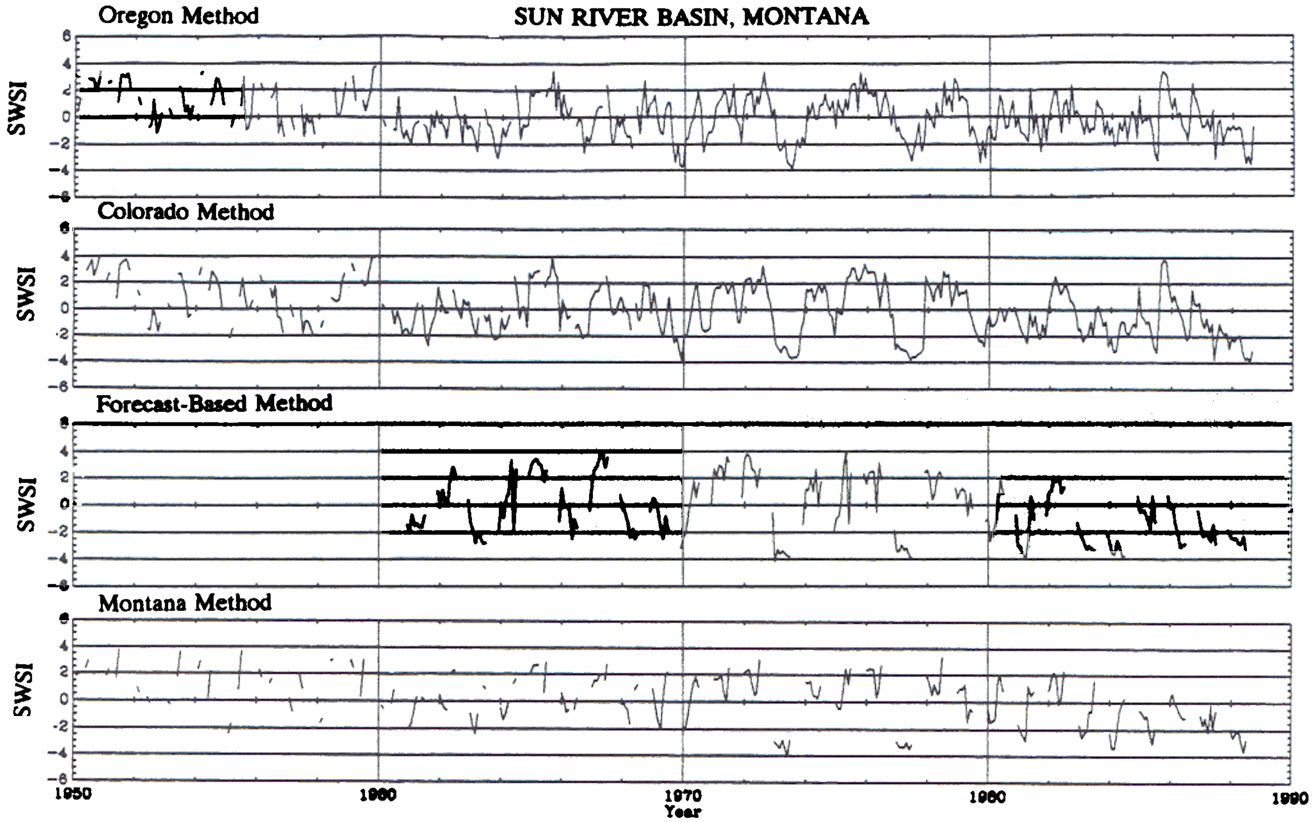

Fig 2. Comparative SWSI Time Series for the Sun River basin in Montana.

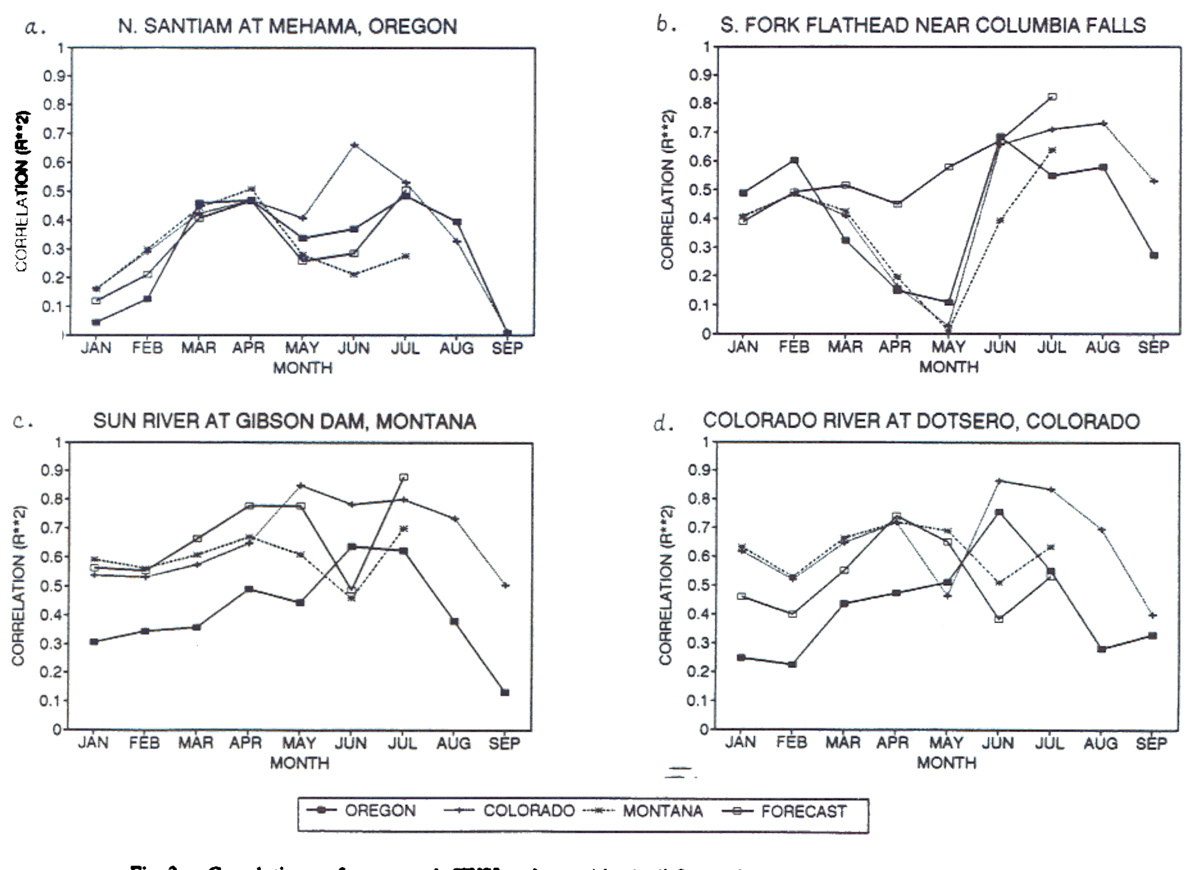

Fig 3. Correlations of computed SWSI values with April-September water supply (April-September virgin streamflow plus active reservoir storage) for four test basins: a) N. Santiam basin, Oregon, b) S. Frk Flathead, Montana, c) Sun River basin, Montana and d) Colorado River above Dotsero, Colorado.

higher percentage of total water supplies are held in storage in this basin than in any of the other test basins. Therefore, the reservoir component is weighted heavily in the computation, although reservoir levels at certain times of year may vary as much with management practices as with changes in natural supply.

These comparisons, while indeed interesting, do not conclusively identify which index, if any, is better or worse than the others. This test covered a variety of watersheds with different hydroclimatic characteristics. The differing assumptions, selection of inputs and weights, and methods of combining data all have a bearing on results in such a way that although these SWSIs are similar in structure, they are each separate indexes representing surface water supplies in different ways. For example, the frequency of occurrence for any given index value on the scale from -4.2 to +4.2 is known to differ for each of these formulations. The Oregon SWSI is nearly normally distributed about zero. On the other hand, the forecast-based SWSI, which is a scaled nonexceedance probabililty of a single water volume, is uniformly distributed. The Colorado and Montana SWSIs fall somewhere between. This outcome is a direct result of weighting and summing individual nonexceedance probabilites. The sum is no longer a probability, but is simply an imperical index. These differences in statistical properties, in turn, affect correlation statistics. This will need to be accounted for in more rigorous future evaluations of index performance.

6. Hydroclimatic Characteristics of the Western United States

To honestly evaluate the significance of each SWSI, it is critical to understand both the formulation of the index and the hydroclimatic characterstics of the region where it is applied. Doesken et al, (1991) described some of the key hydroclimatic features influencing SWSI computation and interpretation. The quantity, seasonality and interannual variability of precipitation, snowpack, streamflow and reservoir storage in 31 western watersheds were analyzed. The percentage of annual streamflow occurring during the April-September period was found to range from 91% in some of the high-elevation watersheds in the Central Rockies down to less than 35% near the West Coast. Seasonal distributions of precipitation vary dramatically across the West, especially in the Central Rockies. This affects the coefficients in the Oregon SWSI, which are objectively determined from monthly averages. However, these different seasonal patterns have little effect on surface water supplies in the high Rockies which respond almost exclusively to the melting of accumulated snow. Then there is the problem of reservoirs. Stored water volumes range from little to none in some basins up to several years worth of streamflow. What this means is that the nature of water supplies in the West can vary significantly from basin to basin. This information is critical for establishing a satisfactory definition of surface water supply. It also points out that a computed SWSI will likely mean more in some parts of the West and in some seasons of the year than in others.

Results and Conclusions

The SWSI has a great deal of appeal as a simple indicator of relative surface water supplies to use in combination with other information to help decision makers. The SWSI is an empirical index rather than a model of a physical process. But this has not detracted from its utility. The experiences from three states have shown the SWSI to be very useful. This is substantiated by comparative test results in four basins in the western United States. Current SWSIs can explain 60% or more of the variance in April-September surface water supplies in parts of the West several months in advance and as much as 80% of the variance during the peak of the runoff season. No systematic optimization has yet been performed on any of the SWSI computations, so further improvement in these correlations may be possible.

Despite these positive results, there are a number of legitimate concerns about SWSI. With the hydroclimatic differences that characterize the West, SWSIs do not have the same meaning and significance in all areas and at all times. The fact that adding individual nonexceedance probabilities and changing weighting factors produces indexes with differing statistical properties is also unsettling.

Further extension of the use of the SWSI for drought monitoring and water management appears to be a worthy goal despite obvious limitations. For this to be possible, a generalized and consistent SWSI may be necessary. There are at least two alternatives. First, if a single acceptable definition of water supply can be agreed upon, such as the one put forward in this paper, then optimization procedures could be employed to establish the best SWSI. Specifying the desired statistical properties for SWSI prior to correlating with observed surface water supplies will permit a more systematic comparative test than what has been done to date. The second alternative is to use the descriptive hydroclimatic information to isolate those areas where SWSI is most meaningful and apply SWSIs only to those areas. For example, SWSI computations may be limited to areas where streamflow is primarily produced by snowmelt runoff and where some large percentage, say 75% or more of the annual streamflow, occurs during the April-September or March-August period. There are advantages and disadvantages to both of these methods, but without setting some limits, inappropriate use of the SWSI is possible that could easily undermine, not enhance, its value. Investigation of the SWSI is continuing, and the various concerns and alternatives are being addressed.

8. References

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