Revised Surface-Water Supply Index for Western United States

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Abstract: The surface-water-supply index (SWSI) was introduced in Colorado in the early 1980s as a better indicator of water availability in the western United States than is the Palmer drought index. Similar indexes have been subsequently developed in Oregon and Montana. These indexes have found great usefulness in drought monitoring and in triggering specific drought-related activities by state governments. Two conceptual weaknesses exist in the current SWSIs: (1) Subjective assignment of values to coefficients; and (2) obscured statistical properties of the index. Revisions to overcome these weaknesses include a specific definition of *surface-water-supply*, use of streamflow volume forecasts, and appropriate handling of data to achieve the desired statistical properties of the index. It is also suggested that indexes for individual hydrologic components be developed to provide supporting information to the SWSI. An example of the development of the revised SWSI is given for the Flathead River basin in Montana.

Introduction

The surface-water supply index (SWSI) was introduced in Colorado in the early 1980s (Shafer and Dezman 1982; Dezman et al. 1982) to provide a more appropriate indicator of water availability in the western United States than the widely used Palmer drought index (Palmer 1965). The Palmer index is primarily a soil moisture indicator and does not account for snow accumulation and melt, which is important in the West. The general properties and limitations of the Palmer index were described by Alley (1984), and its limitations as an indicator of hydrologic drought were discussed by Alley (1985). Subsequent development of SWSIs in Oregon and Montana have followed the same basic procedure as in Colorado, with minor differences in coefficient estimation and data usage. These indexes have been used by their respective state governments as a tool in monitoring drought and as a mechanism to trigger specific activities by state drought committees and other related groups.

The purpose of the SWSI is to "be an indicator of basinwide water availability for the [mountain-water–dependent] sector, be predictive, and permit comparison of water supply conditions between basins to assess relative drought severity" (Shafer and Dezman 1982). The main sources of water in the West are reservoir storage and streamflow, hence this index is intended to be more specific than simply a general wet/dry indicator. The area covered by a SWSI is usually a major river basin, although Montana has developed SWSIs for some relatively small basins. SWSIs are calculated on a monthly basis.

A basic concept introduced in the original SWSI was the use of nonexceedance probabilities as a normalizing technique. This concept is of fun-

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damental importance and is what allows comparison of water supply availability among regions of differing variability. When water supply is expressed only as a percent of average, there is no indication of how unusual the value is. Expressing water supply as a probability of nonexceedance, obtained from its historical distribution, puts all areas on an equal footing. Equal probabilities in two or more areas indicate that the water supply is equal in terms of its frequency of occurrence, even though the percents of average differ.

The original SWSI was formulated as a rescaled weighted sum of nonexceedance probabilities of four hydrologic components: snowpack, precipitation, streamflow, and reservoir storage. The mathematical formulation of the SWSI is as follows:

$$\mathrm{SWSI} = \frac{aP_{\mathrm{snow}} + bP_{\mathrm{prec}} + cP_{\mathrm{strm}} + dP_{\mathrm{resv}} - 50}{12} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where a, b, c, and d = weights for each hydrologic component; $a + b + c + d = 1$; P_i = the probability of nonexceedance (in percent) for component i; and snow, prec, strm, and resv = the snowpack, precipitation, streamflow, and reservoir storage hydrologic components, respectively. Subtracting 50 centers the SWSI values around zero, and dividing by 12 compresses the range of values between -4.17 and $+4.17$. This centering and compressing was done to make the values have a similar magnitude as the Palmer index. Note that the SWSI is bounded, unlike the Palmer index.

The nonexceedance probabilities are taken from probability distributions fitted to each hydrologic component. The snowpack and precipitation variables are generally sums or weighted sums of data from several sites in or near the basin of interest. The streamflow and reservoir variables are sums of observed volumes at stations with readily available data. The snowpack and reservoir data are for the first of the month, while precipitation and streamflow data are for one or more previous months, depending on the season of the year. The coefficients can change seasonally (e.g., Colorado uses two seasons) or from month to month (e.g., Oregon).

Limitations of Existing SWSIs

Recognizing the usefulness of the SWSI and its spread into other states besides Colorado, the Soil Conservation Service (SCS), one of the developers of the original SWSI, saw the need for a reexamination of the index to ensure its soundness and to investigate its applicability to areas other than the Rocky Mountain region. In early 1990, a study was initiated jointly with the Colorado Climate Center at Colorado State University to examine the existing SWSIs and to consider alternative formulations. The results of this study were reported by Doesken et al. (1991a, 1991b). This study elucidated many heretofore unaddressed issues regarding the SWSI and served as a springboard for the development of the methodology presented here.

Two conceptual weaknesses of the original SWSI were identified during this joint study, which the revisions here attempt to overcome. One weakness involves how the basic input data are used, and the other involves the statistical properties of the index.

As shown previously, each hydrologic component of the original SWSI has a weight. In the case of Colorado and Montana, these weights are obtained by a subjective assessment of the impact of each component on

water availability in the basin. In the case of Oregon, the weights are obtained by an objective, but arbitrary, algorithm. All three of these SWSIs attempt to index *surface-water supply*, but this is not explicitly defined. Since there is no criterion variable, there is no way of knowing if the best weights have been found, and an optimization of weights is impossible.

An objective, statistical assessment of the data for the components relating to snowmelt runoff (snowpack, precipitation, streamflow), however, is already being done in the form of forecasting procedures routinely used by the SCS and the National Weather Service (NWS) to produce monthly (January–May or June) water supply (seasonal streamflow volume) forecasts issued to the public. These procedures are optimized to forecast streamflow from the data for the hydrologic components and implicitly contain optimal weighting of the components (at least potentially—improvements continue to be made). In addition, the forecasts benefit from the hydrologist's interpretation and adjustment if he/she feels that the forecasting procedure is giving questionable results. Streamflow forecasts have uncertainty, of course, but they are more direct and accurate indexes of water availability from snowmelt than are the values calculated by the existing SWSI formulations.

The other weakness noted in the original SWSI is the way nonexceedance probabilities are handled. The hydrologic components can be considered to be jointly distributed random variables. The joint nonexceedance probability of a given realization of these variables is not equal to a weighted sum of the univariate nonexceedance probabilities. In addition, the result of a weighted sum of nonexceedance probabilities does not behave statistically like a nonexceedance probability itself. A basic statistical fact is that nonexceedance probabilities, which are simply values of the cumulative distribution function of a random variable, are uniformly distributed. That is, if X is a random variable with a cumulative probability distribution F, then $Y = F(X)$ (the probability integral transformation) has a uniform distribution over the interval (0,1) (DeGroot 1986). The central limit theorem of statistics states that the distribution of a sum of random variables, regardless of their individual distributions, is approximately normally distributed (DeGroot 1986). The (weighted) sum of four nonexceedance probabilities, then, is not uniformly distributed—its shape resembles a normal distribution. In fact, this property was noted by Shafer and Dezman (1982) and was verified empirically by Doesken et al. (1991b). This, however, completely negates the fundamental principle upon which the SWSI was based—that of having an index that would allow comparison of basins on an equal probability basis. A sounder characterization of the hydrologic components in the original SWSI would be to describe them by a multivariate probability distribution; a single joint nonexceedance probability would be obtained from this distribution, which would then be rescaled into the SWSI. A preferable method in this application, however, is to base the index on a single aggregated variable specifically designed to describe surface-water supply; as will be explained herein, this variable is the sum of reservoir storage and an expected streamflow volume. This is a straightforward and meaningful variable to describe water supply, and the streamflow forecast represents the best (if properly done) combination of the hydrologic components as predictors of expected water availability. By doing this, only one nonexceedance probability is used, and the index will have the appropriate statistical behavior (i.e., a uniform distribution).

Conceptual Basis of Revised SWSI

Definition of Surface-Water Supply

Before an index can be built, it must be known what is to be indexed. Shafer and Dezman (1982) were reasonably clear that they were indexing snowmelt runoff and reservoir storage, although a criterion variable was not explicitly defined, and at one point they compared the SWSI with diversion data rather than streamflow and reservoir data. In the intervening years, the quantity indexed has become very fuzzy in common practice, and nowhere has it been clearly defined.

The definition of *surface-water supply*, the quantity the SWSI is intended to index, is taken in this work to be the reservoir storage at the beginning of, plus natural streamflow during, the primary snowmelt and growing season relevant to the region of interest, or the remainder thereof. This is in accord with the goal of the original SWSI and represents the primary surface-water supply in the West. In keeping with the major use of water in the West, this definition emphasizes agricultural water users but does have wider applicability.

Further specificity is required with this definition. First, the beginning of the water year (October 1) will be used here as the point at which the revised SWSI will begin indexing the following snowmelt runoff season rather than indexing water remaining in the current season. Shafer and Dezman (1982) used December 1 as the turning point, but an alignment with the water year coincides better with the end of the growing season and the beginning of the next snow accumulation season. This date, however, could be adjusted as appropriate to the region of interest. Second, before the primary snowmelt season begins, reservoir storage at the beginning of this season is unknown, hence, an estimate is required. Most reservoirs exhibit high month-to-month correlation of storage volumes, so such estimates are possible and get better the closer in time one is to the beginning of the snowmelt period. Third, streamflow during the primary snowmelt season is estimated by the water-supply forecast. Finally, once the snowmelt season begins, surface-water supply is defined as the reservoir storage at the beginning of the current month plus the forecast streamflow for the remainder of the snowmelt season.

As an example, the following quantities would be appropriate definitions of surface-water supply in most areas of the West:

- October–March: forecast April 1 reservoir storage + forecast April–September streamflow.
- April–September: observed first-of-month reservoir storage + forecast month–September streamflow.

If appropriate, a different month could be used instead of April as the beginning of the primary snowmelt period.

Other revisions to this definition might be necessitated by local differences in hydrologic regime or reservoir management. For example, in the Willamette Valley of Oregon, most major reservoirs are operated primarily for flood control in the fall and winter. As a result, reservoir storage levels during the fall and early winter have little relationship to the April 1 level. In addition, spring snowmelt runoff is a smaller percentage of annual runoff than in most areas of the interior West. To define an appropriate criterion variable here, one must ask what *surface-water supply* means in the Willamette Valley. The answer depends on the time of year and on the type of water user being considered. In this work, attention has focused primarily on agricultural water users, for whom *surface-water supply* is most meaningful during the spring and summer. If April 1 reservoir storage or April–September streamflow cannot be predicted well early in the water year, then there is little that can be said to agricultural water users during this time. For municipal and industrial water users, however, surface-water supply is important year-round; to them, current reservoir storage and streamflow are important.

In developing a SWSI for places like the Willamette Valley, then, one must consciously decide on the target water users and the information most critical to them. A criterion variable can then be developed and a SWSI calculated from the probability distribution of this variable. If agricultural water users are targeted, one must face the fact that April 1 reservoir storage and April–September streamflow cannot be predicted well in the fall and early winter, so a SWSI during this time would be less meaningful than during the late winter and spring.

Predictive Relationships Required

If the SWSI is to be available year-round, predictive relationships to calculate streamflow forecasts during the fall and summer are required. Streamflow forecasts during the winter and spring (January–May or June) are available from the water supply forecasting activities of the SCS and the NWS; no new relationships need be developed for these. In addition, predictive relationships are required to forecast April 1 reservoir storage for the months prior to April. These relationships should be considered to be internal calculations analogous to the weightings used in the existing SWSIs. They are not forecasts in any official sense; they are simply a way to establish optimal weightings on the basic data in a more objective fashion than in the existing SWSIs.

For predicting April 1 reservoir storage, an obvious relationship would be a simple linear regression against the current month's storage. For fall and summer streamflow predictions, candidate variables for multiple linear regression or principal components regression (Garen 1992) relationships would be precipitation and streamflow in previous months and possibly snow water equivalent at SCS snow telemetry (SNOTEL) sites (although most of these have a short period of record). In addition, the southern oscillation index (SOI), a measure of large-scale atmospheric circulation patterns, can be used as a predictor variable; in some parts of the West, it provides the best early indication of spring and summer streamflow of any single variable available before the snow accumulation season. Recent work has demonstrated the relationship of the SOI to precipitation and streamflow (Cayan and Peterson 1989; Koch et al. 1991; Redmond and Koch 1991), and it is currently being used as a variable in many of the forecasting equations used by the SCS for water supply forecasting.

Current Conditions versus Forecast SWSI

A concern that has been voiced is that the aforementioned definition of *water supply* contains forecasts. Some would rather interpret the SWSI as a statement of current, instead of forecast, conditions. Before insisting that one or the other interpretation is correct, some reflection on the meaning of *current conditions* with respect to water supply is necessary.

For reservoir storage, the meaning of *current conditions* is clear enough—the amount of water in storage at the current time. The usefulness of this information, however, varies with the season and type of water user. For municipal and industrial water users who depend primarily on stored water and whose demand is significant throughout the year, current reservoir storage is important information. For agricultural water users, reservoir storage during the irrigation season is far more important than during the fall and winter. They are interested in reservoir storage during the fall and winter primarily to the extent that it is a precursor to the storage at the beginning of the irrigation season. Since in this work the focus is on agricultural water users, fall and winter reservoir storage is translated into an estimate of storage at the beginning of the irrigation season via predictive relationships, as described previously. Current reservoir storage, however, remains an important piece of information, and it is recommended that this be presented along with the SWSI as supporting information.

The meaning of *current conditions* with respect to streamflow is not as straightforward as with reservoir storage. Water year streamflow to date or the previous month's streamflow can indicate how dry or wet it has been, but since this water has already flowed downstream and is now unavailable, these quantities are not particularly informative with respect to water currently available. The term *water supply* implies a volume of water available for use, hence water supply from streamflow must be understood to be a volume of water that will be available over an appropriate planning horizon, which, in this work, is taken to be the spring and summer seasons through September.

Spring and summer snowmelt runoff, the very essence of water supply in the West, is indexed implicitly in the existing SWSIs by the snowpack, precipitation, and streamflow components. As mentioned earlier, these same data are also used in the preparation of water supply forecasts. Unlike the existing SWSIs, however, forecasting procedures are calibrated against observed streamflow, therefore making more nearly optimal use of the input data and integrating them into the quantity useful for decision making, that is, water. As stated by Shafer and Dezman (1982), the original SWSI was intended to be predictive of spring and summer runoff. It is merely a matter of semantics, then, whether one considers the snowpack, precipitation, and streamflow data as current conditions or as a forecast of water available in the future; in this situation, they refer to the same thing. Because the water supply forecasts make better use of the basic input data in predicting snowmelt runoff than does the formulation of the existing SWSIs, it is preferable to use the forecasts as input to the SWSI rather than using the basic input data directly as in the existing SWSIs. The fact that water supply forecasts are uncertain is simply a result of water availability being imperfectly known. Of course, the more uncertain the forecast, the less the utility of the SWSI, but the situation cannot be improved upon by using the basic input data as in the existing SWSIs instead of the water supply forecast. The uncertainty is unavoidable, and using the water supply forecast at least minimizes the uncertainty.

There need be no confusion between a current conditions SWSI and a forecast SWSI once one focuses on the precise quantity being indexed. Confusion exists if the quantity indexed is left undefined or only vaguely defined, as with the existing SWSIs. Once a specific definition of surface-water supply is established, the meaning of the SWSI is clear.

Calculation of SWSI

Calculating the SWSI on a real-time basis involves adding a forecast or observed reservoir storage to a forecast of streamflow volume during an appropriate period and determining the nonexceedance probability of this value from an empirical or a fitted distribution. The distributions used are determined from historical series of observed reservoir storages and streamflows. That is, the reservoir storage and streamflow volume sum is compared to the historical distribution of observed values of this sum. Early in the water year, when forecasts are not very accurate, this has the effect that the SWSI will be unlikely to reach extreme values because the forecasts will not be distant from mean values. Later in the year, when forecasts are better, the SWSI will have a greater ability to reach extreme values. This behavior is intuitively pleasing, as one should be reluctant to flash a danger signal early in the water year when relatively little is known yet about the water supply and when water demand is small. During the spring and summer, when water demand is at its peak, the water supply is known with high confidence, and this is exactly when extreme values of the index are needed, if conditions warrant.

Development Procedure for Revised SWSI

A step-by-step procedure for developing the SWSI is given herein. As before, April will be used as the beginning of the spring runoff season for purposes of illustration. The steps for developing the historical time series of the SWSI are optional, but this series can be instructive in showing the distribution and behavior of the index. The variables and predictive relationships described later include all those required to calculate the index year-round; those for fall and summer can be deleted if one wishes to calculate the index only during the winter and spring when official water supply forecasts are available.

1. Select regions. The original intention was for regions to cover major drainage basins, with perhaps six to 12 per state. Montana has chosen to use smaller regions than this, and there is no conceptual hindrance from doing so.
2. Identify reservoirs and streamflow forecast points in each region.
   a. Reservoirs must have a historical record and have been managed similarly over time. Data must be available in real time.
   b. If the region is a single river basin with a forecast point at the outlet, this single forecast point is all that is needed. If there is no single point that represents the integrated runoff for the basin/region, then all of the most downstream forecast points in the region are needed.
3. Compute empirical distributions of, and if desired, fit analytical probability distributions to, each of the six time series formed as the sum of first-of-month reservoir storage and month–September streamflow for the months April–September. If fitting a distribution, typical choices are normal, lognormal, and gamma. Because reservoirs are managed, as opposed to natural, systems, the influence of reservoir storage can make fitting a distribution problematic. If this is the case, it is probably preferable to use the empirical or a smoothed empirical distribution.
4. Develop predictive relationships to make unofficial forecasts for the following:

- October–March: forecast of April 1 reservoir storage (first of month).
- October–December: forecast of April–September streamflow (first of month).
- July 1: forecast of July–September streamflow.
- August 1: forecast of August–September streamflow.
- September 1: forecast of September streamflow.

The following additional steps are required to develop a historical time series of the SWSI:

5. Obtain a historical series of water supply forecasts, either published values, or preferably, reconstructed forecasts from the development of the current forecasting procedure.
6. Develop the following time series:

- October–March: forecast April 1 reservoir storage + forecast April–September streamflow.
- April–September: observed first-of-month reservoir storage + forecast month–September streamflow.

7. Generate SWSI historical time series.
   a. Find the nonexceedance probabilities P (in percent) for the variables in step 6 using the distributions in step 3.
   b. Compute the SWSI as

$$\text{SWSI} = \frac{(P - 50)}{12} \qquad (2)$$

To calculate SWSI values operationally, step 7 is followed but with current data instead of historical data.

Meaning of Numerical Values of SWSI

The original SWSI had subjective descriptors associated with ranges of index values. These are as follows (Shafer and Dezman 1982):

- +2 or above—abundant supply.
- −2–+2—near normal.
- −3–−2—moderate drought.
- −4–−3—severe drought.
- −4 or below—extreme drought.

The Colorado Drought Response Plan (Lamm 1981) uses two SWSI values to trigger drought activities:

- −1 or below—Colorado Water Availability Task Force activated.
- −2 or below—other task forces activated and reports made to governor.

Further drought responses are made at the recommendation of the task forces. Oregon and Montana also use the SWSI in their drought plans.

The ranges of values and their respective descriptors were apparently

chosen to be similar to those used with the Palmer index. Because the basis of the numerical values of the SWSI is a probability distribution, however, each value has an implied frequency of occurrence. This appears not to have been considered when the ranges and descriptors were selected, nor was it probably considered when the triggering levels in *The Colorado Drought Response Plan* were set. The selection of the triggering levels and the ranges of SWSI values corresponding to the descriptors ought not to be taken lightly; this has highly significant effects on the frequency that drought responses must be activated. The frequencies of occurrence for the values of SWSI need to be understood so that appropriate descriptors can be assigned and so that the triggering levels are reached at frequencies that coincide with generally accepted notions of how often a drought occurs and with the ability and willingness of government to respond.

If the SWSI truly behaved as a rescaled nonexceedance probability (i.e., a uniformly distributed random variable over the interval −4.17–+4.17), the following are the theoretical frequencies of occurrence for these ranges of SWSI values:

- +2 or above—26% of the time.
- −2–+2—48% of the time.
- −3–−2—12% of the time.
- −4–−3—12% of the time.
- −4 or below—2% of the time.

That is, each interval of one SWSI unit represents 12% of the probability density. Using the original SWSI's subjective descriptors previously listed, this says that a moderate drought or worse occurs 26% of the time, a severe drought or worse occurs 14% of the time, and an extreme drought occurs 2% of the time. Also, the Colorado Water Availability Task Force would be activated 38% of the time, and the other task forces would be activated 26% of the time.

Unfortunately, the actual frequencies of SWSI values are not as clear cut as this. As discussed previously, the existing SWSIs do not have the statistical properties of a nonexceedance probability; theoretical frequencies of occurrence for their values are therefore unavailable. The revised SWSI has much clearer statistical properties, but its frequencies of occurrence only approximate the theoretical frequencies due to the use of imperfect streamflow forecasts; these make the frequency of extreme SWSI values less than the theoretical frequency early in the water year. This behavior of the revised SWSI was discussed in a previous section. The best way to understand the statistical properties of any SWSI is to compute empirical distributions from actual or reconstructed time series of SWSI values, as did Doesken et al. (1991b).

With all of this as background, the question remains whether the subjective descriptors and trigger levels are appropriate. A complete understanding of the frequency of occurrence of SWSI values through time and among regions within a state requires an extensive empirical analysis of SWSI time series for each region. Even without such analyses at hand, one can make some judgments based on the theoretical considerations described. For example, it can be expected that a SWSI value of −1 will occur at least once per year somewhere in a state for a high percentage of years. Whether this is desirable depends on how conservative one wishes to be. If the SWSI is intended to be an early warning signal, then one must be prepared to

endure some false signals and often be on the alert. If this level of sensitivity requires more effort than one is prepared to handle, then triggering levels need to be adjusted. This, however, may or may not be feasible depending on the flexibility of the drought response plan. Certainly, if the plan is to be cast in stone and difficult to change, care is warranted in setting triggering levels so that the decisions are informed, not arbitrary.

Limitations of Revised SWSI

The revised SWSI has overcome many of the limitations of the existing SWSIs, but it has limitations of its own that need to be acknowledged and described.

The revised SWSI does not explicitly analyze the four hydrologic components; they are only implicit in the streamflow forecast and reservoir volume sum. This masks important information about the behavior of each component. It is possible for components to compensate for one another in such a way that the SWSI value indicates little cause for concern, but an individual component may be at a level of concern. Alternatively, identical SWSI values may be produced by different configurations of the components; the appropriate water management response may well depend not just on the SWSI value but also on which component is the most critical. This demonstrates that no one number can completely convey the complex nature of surface-water supply. A solution to this problem is to calculate component indexes as supplemental information to the SWSI; this, in fact, is done as an intermediate step in the existing SWSIs (although, as already pointed out, their combination has been done improperly). This will be discussed more fully in the next section.

Another difficulty that can sometimes manifest itself is that if the distribution used to obtain a nonexceedance probability has a small variance, large changes on the probability scale can occur for small changes in water volume. This problem is caused primarily (but not necessarily only) by the reservoir component. Due to the adherence to rule curves, reservoir levels often do not vary much over the years for a given month. If this is the case, it is possible that even small volume differences from the average level can be near the extremes of the probability distribution. In basins where reservoir storage is small compared to streamflow, this effect, if present, will be largely subsumed in the behavior of the streamflow, and it should not have a large effect on the SWSI value. The issue arises in basins where reservoir storage is a significant portion of the water supply and when a reservoir component index is being calculated. Expressing the SWSI and the hydrologic components in terms of percent of average in addition to the rescaled nonexceedance probability should help clarify the behavior of the indexes; the use of both types of values is discussed in the next section.

Complete Description of Surface-Water Supply

To help overcome the limitations of the SWSI and to portray a fuller picture of surface-water supply, it is recommended that values representing the hydrologic components separately be calculated along with the SWSI. These values should be expressed both in terms of a rescaled nonexceedance probability (on the same scale as the SWSI) and in terms of percent of average. By presenting this supporting information along with the SWSI, the limitations noted can be minimized.

The hydrologic components include the ones used in the original SWSI:

snowpack, precipitation, streamflow, and reservoir storage. For snowpack and precipitation, a single variable could be constructed by a sum or weighted sum of the values from a number of sites. The snowpack variable would be the current month's snow-water equivalent, and the precipitation variable would be water-year precipitation to date. Streamflow could have two indexes, observed and forecast. The observed streamflow variable would be the total water-year streamflow volume to date, and the forecast streamflow variable would be the sum of the forecasts for the streams in the region. Reservoir storage could also have two indexes, one being the sum of the current month's storage and the other being the sum of the forecast storage for the reservoirs in the region.

Probability distributions can be determined for each hydrologic component separately. One may wish to fit an analytical distribution to the data, or one can use the empirical distribution. An index can then be calculated using the same equation as the SWSI, that is

$$\text{component index} = \frac{(P - 50)}{12} \qquad (3)$$

where P = the nonexceedance probability (in percent) of the value of the hydrologic component variable. This value can also be expressed as a percentage of a long-term mean.

By showing the hydrologic components separately, one can see exactly where a problem might exist. Without this breakdown, a problem in one component could be masked when combined into the SWSI. By displaying the percents of average, one would be able to see if large changes in the indexes were caused by only small physical changes. An example of the display of all of this information is given in the next section.

Example—Flathead River, Montana

The Flathead River in northwestern Montana will be used to illustrate the revised SWSI procedures. The Flathead River near Polson, Montana (USGS station 12372000), is the farthest downstream station on the river and is therefore the best station to represent the basin as a whole. Fig. 1 shows the location of the basin, its main hydrologic features, and the snow and precipitation data sites used in this analysis.

The Flathead River near Polson is an SCS water supply forecast point. There are several other forecast points in the basin, but they are all tributary to this point and are therefore not needed for the calculation of the SWSI.

There are two major reservoirs in the basin, Hungry Horse Lake and Flathead Lake, both of which are operated for hydropower, flood control, irrigation, and recreation. Hungry Horse, which began storing water in 1951, is operated by the U.S. Bureau of Reclamation. Flathead Lake, which is controlled by Kerr Dam (storage began in 1938), is operated by Montana Power Co.

Following the procedure outlined previously, the predictive relationships and probability distributions required to calculate a year-round SWSI for the Flathead River were developed. The following relationships were used for predicting streamflow (natural flow—adjusted for changes in reservoir storage) in the fall and summer, when official water supply forecasts are unavailable:

- October: April–September streamflow (10^6 m^3) = [443.6 × July + August southern oscillation index] + 8,799.9.

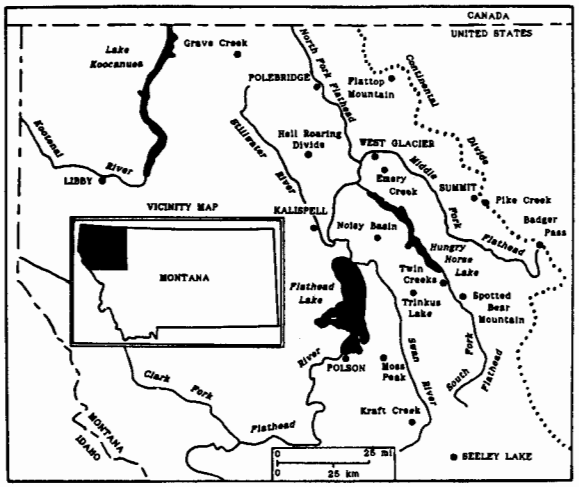

FIG. 1. Flathead River and Vicinity, Showing Locations of Precipitation (All Capitals) and Snow (Capitals and Lower Case) Data Sites

- November: April–September streamflow (10^6 m^3) = [288.9 × July + August + September southern oscillation index] + 8,781.0.
- December: April–September streamflow (10^6 m^3) = [200.3 × July + August + September southern oscillation index] + [7.7 × Kalispell November precipitation (mm)] + [4.5 × Polebridge November precipitation (mm)] + [8.1 × Seeley Lake November precipitation (mm)] + [2.3 × Summit November precipitation (mm)] + [4.7 × West Glacier November precipitation (mm)] + 7,222.5.
- July: July–September streamflow (10^6 m^3) = [114.7 × March + April + May southern oscillation index] + [0.2 × Flathead River near Polson June streamflow (10^6 m^3)] + 1,126.2.
- August: August–September streamflow (10^6 m^3) = [12.6 × March + April + May southern oscillation index] + [0.3 × Flathead River near Polson July streamflow (10^6 m^3)] + 314.1.
- September: September streamflow (10^6 m^3) = [4.4 × April + May southern oscillation index] + [0.7 × Kalispell August precipitation (mm)] + [0.7 × Polebridge August precipitation (mm)] + [0.7 × Seeley Lake August precipitation (mm)] + [0.5 × Summit August precipitation (mm)] + [0.6 × West Glacier August precipitation (mm)] + [0.1 × Flathead River near Polson August streamflow (10^6 m^3)] + 127.2.

Table 1 gives the statistics for these equations and for those used during the regular water supply forecasting season. Table 2 gives the relationships for predicting April 1 reservoir storage (sum of usable storage [10^6 m^3] in Hungry Horse and Flathead Lakes) from the first-of-month storages during the fall and winter. All of the reservoir equations were calibrated on the period 1955–1989.

The empirical distributions for the variables defined in step (3) of the section "Development Procedure for Revised SWSI" were calculated; these

TABLE 1. Strean
MT

Forecast month (1)	Forecast period (2)	Correlation coefficient (3)	Standard error (10^6 m^3 and percent of average) (4)	Calibration period (5)
October	April–September	0.44	1,735.1 (20%)	1952–1989
November	April–September	0.44	1,732.5 (20%)	1952–1989
December	April–September	0.57	1,607.6 (18%)	1952–1989
January	April–September	0.70	1,445.0 (16%)	1964–1989
February	April–September	0.88	962.3 (11%)	1964–1989
March	April–September	0.92	796.4 (9%)	1958–1989
April	April–September	0.92	748.8 (8%)	1952–1989
May	May–September	0.94	674.7 (9%)	1964–1989
June	June–September	0.97	410.9 (8%)	1964–1989
July	July–September	0.62	544.5 (29%)	1951–1989
August	August–September	0.69	176.0 (25%)	1951–1989
September	September	0.62	111.5 (37%)	1951–1989

TABLE 2. Fall and Winter Prediction Equations for April Reservoir Storage, Flathead River near Polson, MT

Month (1)	Slope (2)	Intercept (3)	Correlation coefficient (4)	Standard error (10^6 m^3 and percent of average) (5)
October	0.669	−544.8	0.56	481.4 (14%)
November	0.657	−258.8	0.66	435.2 (12%)
December	0.621	151.6	0.74	391.3 (11%)
January	0.623	444.3	0.77	371.2 (11%)
February	0.646	683.5	0.77	369.1 (11%)
March	0.823	309.9	0.78	278.5 (8%)

were used here rather than fitted distributions because the influence of reservoir storage made the water supply variables have oddly shaped and negatively skewed distributions, not conforming to commonly used distributions. Monthly empirical distributions for each of the individual hydrologic components were also calculated. The snowpack and precipitation indexes were based on the sum of data from the sites shown in Fig. 1. A time series of reconstructed streamflow forecasts from the current SCS forecasting procedures was obtained, and historical time series of index values were calculated for each component and for the SWSI. The SWSI time series is plotted in Fig. 2.

The distribution of SWSI values is shown in Fig. 3. Note that the values are nearly uniformly distributed, but some extra density exists near the center, as expected, due to the use of (imperfect) streamflow forecasts and predictions of reservoir storage. Table 3 shows the percentage of years in which at least one month had a SWSI less than or equal to specified values. Note that the percentages are quite high, reemphasizing the point that care

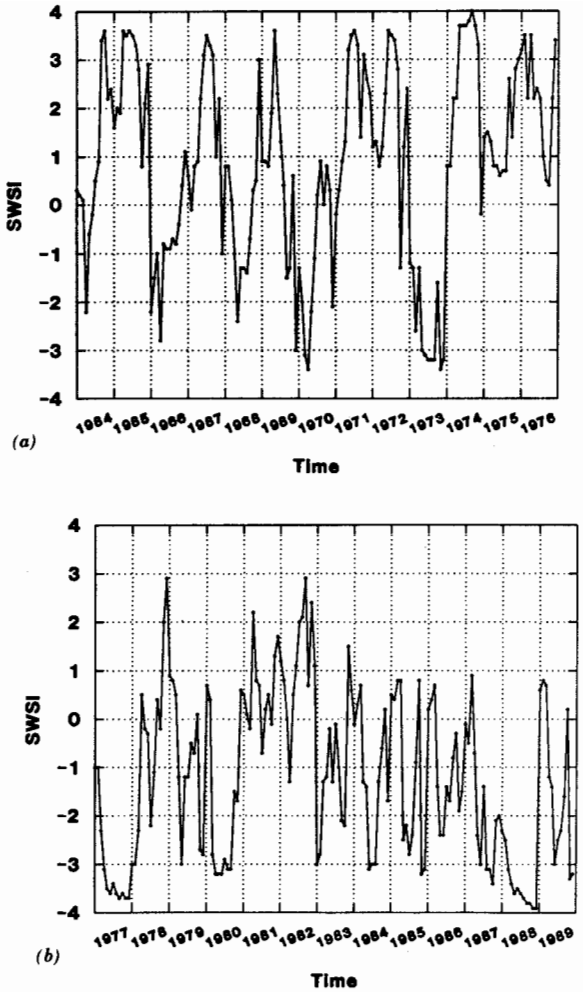

FIG. 2. (*a*) Time Series of Flathead River SWSI (Water Years 1964–1976); and (*b*) Time Series of Flathead River SWSI (Water Years 1977–1989)

must be taken in selecting triggering SWSI values so that drought responses are activated at appropriate frequencies.

Verification of the SWSI can be accomplished by correlating the computed values (based on forecasts) with the index of the criterion variable (based on observed data); these results are shown in Table 4. The correlations increase month by month and reach a plateau during March–June before declining again. The correlation in September is quite high because most of the water supply is reservoir storage at this late point in the water year, and this quantity is known, not forecast. Correlating the SWSI with an index of the observed data is the appropriate verification test; Doesken et al. (1991a, 1991b) correlated SWSI with observed data directly (not the index thereof), and this is an incorrect test.

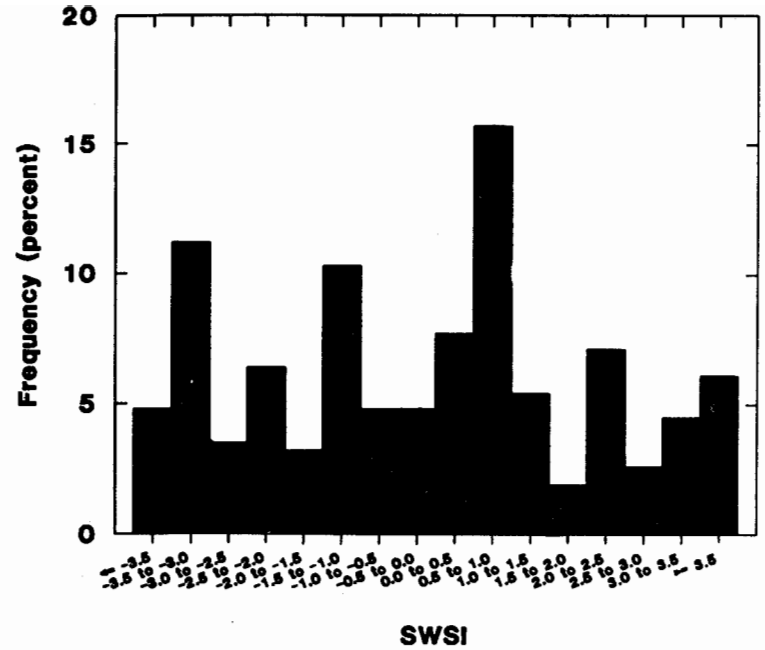

FIG. 3. Distribution of Flathead River SWSI Values

TABLE 3. Percent of Years With at Least One Monthly SWSI Value Less than or Equal to Specified Values

Less than or equal to (1)	Percent of years (2)
0	88
−1	77
−2	65
−3	50

Note: Period covered: 1964–1989.

Table 5 displays the complete set of water supply information for selected months and years. These examples demonstrate some of the behaviors of the SWSI and show the importance of supplying the supporting information along with the SWSI. In 1974, a wet year, one can see that the anticipated streamflow is the dominant factor in producing the SWSI value. In 1977, a dry year, reservoir storage is near normal, and again the anticipated streamflow is the dominant factor. In 1988, another dry year, reservoir storage was at an extremely low level, and anticipated streamflow was also low. The combination of the two gave the SWSI the same value as in April 1977, but for different reasons. The supporting information supplied by the component indexes is very helpful in understanding why the SWSI takes on the value it has.

Several additional observations can be made about the behavior of the SWSI and the component indexes:

TABLE 4. Correlation of SWSI with Observed Index

Month (1)	Correlation (2)
October	0.44
November	0.45
December	0.52
January	0.66
February	0.86
March	0.93
April	0.90
May	0.90
June	0.93
July	0.70
August	0.78
September	0.95
Year	0.77

Note: Period covered: 1964–1989.

TABLE 5. Surface-Water Supply Information for Selected Months and Years

Component (1)	February 1974 Index (2)	February 1974 Percent of average (3)	April 1977 Index (4)	April 1977 Percent of average (5)	January 1988 Index (6)	January 1988 Percent of average (7)
Snowpack (current month)	2.9	134	−3.2	75	−3.9	56
Precipitation (water year to date)	2.7	136	−4.0	49	−3.6	43
Streamflow (water year to date)	2.8	157	−3.5	58	−3.9	36
Reservoir storage (current month)	1.4	110	0.0	98	−3.7	75
Streamflow (forecast)	3.6	134	−3.5	64	−3.1	72
Reservoir storage (estimated April 1)	2.3	109	—	—	−3.5	80
SWSI	3.7	127	−3.4	74	−3.4	74

1. SWSI values of zero do not, in general, correspond to 100% of average due to skewness in the probability distributions.
2. Extreme SWSI values are not particularly extreme in terms of percent of average due to the low variability in the Flathead River. This is not necessarily true elsewhere.
3. The distribution of reservoir storage in the late spring and summer has a very low variance and a negative skewness. Small changes in storage can produce large changes in the SWSI and in the reservoir component index.
4. Once the main snowmelt season is over, the SWSI values show more month-to-month variability than during the snow accumulation season. This is due to the effect just mentioned in item 3, and to the change in the time period covered by the streamflow forecast.
5. There is usually a discontinuity in October due to the change in reference period from the current to the next water year. This is unavoidable.
6. The SWSI is not a linear index; that is, a given change in terms of water volume or percent of average does not result in a proportional change on the SWSI scale.
7. The SWSI is not always between the reservoir index and the forecast streamflow index in magnitude. This is only true if the component indexes are are of opposite sign. If they are of the same sign, the SWSI will often have a magnitude greater than either of the component indexes. This is easily understood, because the concurrence of extreme values (of the same sign) for the two components is rarer than the occurrence of extreme values for either of the two components individually. This kind of behavior has heretofore not been noticed or understood, and it demonstrates the statistical weakness of the existing SWSI formulations. Examples of this behavior are

- January 1970—estimated reservoir storage index = −2.9; forecast streamflow index = −3.2; and SWSI = −3.4.
- March 1974—estimated reservoir storage index = 2.3; forecast streamflow index = 3.6; and SWSI = 3.7.

Some of these behaviors may be perceived to be undesirable from a lay point of view. It may be possible to reduce some of them with refinements such as modifying the definition of surface-water supply (criterion variable), using smoothed empirical or fitted probability distributions, or by making improvements in forecasting methods. If it is kept in mind exactly what the SWSI is, however, these behaviors should be understandable and less troublesome.

Conclusions

The SWSI has proven to be a useful tool in drought monitoring and management in the West. The revisions presented here make the index more theoretically sound and statistically valid. With an appropriate definition of surface-water supply, these concepts and techniques should be widely applicable throughout the West.

One of the goals of this work has been to define the index as concretely and meaningfully as possible to eliminate the lack thereof in the existing SWSIs. As with any attempt to convey complex, technical information to the layperson, however, some potential for misunderstanding and misuse remains. The primary burden of clearly communicating what the SWSI is and what it means rests with those who develop and disseminate the index. The recipients of this information also must sincerely seek to understand it and not expect complex reality to be entirely expressed in simple bottom lines.

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