SUSCEPTIBILITY OF WATER SUPPLY RESERVOIRS TO DROUGHT CONDITIONS

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ABSTRACT: The knowledge of the behavior of a water supply system during hydrological drought events is useful to assess the risk of shortages and to undertake the necessary actions to reduce drought impacts. In the present paper relationships between performance indices of a water supply reservoir and severity of hydrological droughts identified using the concepts of runs have been studied. A linear relationship between water shortage index and mean intensity (or cumulative deficit) of droughts of the same length was derived analytically and verified by simulation. Simulation has been carried out during drought periods for two demand patterns by using either standard operating policy (SOP) or different hedging policies. Plots of performance indices versus drought characteristics show in some cases a definite pattern whereas in others the points present a relatively high scatter. When a hedging operating policy is applied, though the scatter of the points increases, some relationships still preserve a definite pattern. The slope of such patterns can be used to evaluate the ability of different hedging rules in reducing drought impacts.

INTRODUCTION

Analysis of water supply systems under drought conditions has received increasing attention in the last years both from a methodological point of view and from a water management practice perspective (Wilhite et al. 1987; Tsiourtis 1995; Fontane and Frevert 1995).

Most investigations dealt with the assessment and comparison of the measures to be adopted to minimize harmful effects of droughts. These drought mitigation measures can be classified generally as follows:

- Long-term actions, oriented to improve the reliability of the system to meet future water demands through a set of appropriate measures (e.g., construction of new facilities, reduction of distribution losses, reuse of treated wastewater, etc.)
- Short-term management actions, which try to reduce the most negative impacts of a severe drought by using different management measures to reduce water demands (e.g., through publicity campaigns and/or mandatory delivery restrictions), to augment water availability with additional sources (generally characterized by lower quality or by greater cost than ordinary sources), and to make better use of available water resources by optimizing operating rules or by relaxing environmental constraints.

These two categories of drought mitigation measures have been defined, respectively, as strategic planning and tactical responses to droughts (Werick 1993).

The studies oriented to the assessment of drought effects on water supply generally deal with two aspects, namely, the evaluation of the adequacy of existing or planned water systems to satisfy water demands under drought conditions (including the assessment of residual risk of shortage) and the search and analysis of appropriate operating policies to mitigate the extreme impacts of drought events.

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Several procedures have been proposed to assess the long-term adequacy of a water supply system to satisfy water demands during drought events since the study of Russell et al. (1970), which proposed to estimate the expected losses due to drought as a function of the level of adjustment of the water system (defined basically as a demand-supply ratio) within the framework of a planning process. A few recent examples are summarized here.

Frick et al. (1990) assessed the adequacy of a water supply system to cope with drought conditions by simulating its performances during "design droughts" extracted from long-term synthetic hydrological records and by taking into account the planned expansions of the system. Johnson and Kohne (1993) explored the possibility of using the Palmer hydrological drought index for a preliminary assessment of the susceptibility of reservoirs to drought and analyzed the U.S. Army Corps of Engineers reservoirs on a national and regional scale in order to identify those mostly affected by drought and therefore in need of more detailed investigations.

However, most of the proposed procedures have been developed to assist water system managers to make drought mitigation decisions and particularly to choose preferable alternative operation rules or other emergency actions during severe drought events.

The risk of water crisis in the operation of a water supply reservoir under a set of assumptions regarding withdrawal rates and emergency actions was discussed by Hirsch (1978). Two techniques, based on simulation of the system using historical streamflow series, were used to evaluate the frequency of predetermined emergency actions and to evaluate the seasonal risk of water shortage related to different operating policies. In another study (Hirsch 1981) the risk of storage falling below some level over a specified time horizon was estimated by using 100 monthly streamflow series generated by an ARMA (1,1) model and computing the related reservoir storages based on current reservoir state and a constant withdrawal rate.

Bayazit and Unal (1990) studied how the performance indices of a water supply reservoir vary as different hedging policies are adopted by using a simulation model and a generated series of seasonal flows. Trade-offs among the performance indices that described reliability, resiliency, and vulnerability were computed for different parameters of a modified standard operating policy (SOP).

Shih and ReVelle (1994) compared two mathematical programming techniques to determine the parameters of a linear hedging rule for a reservoir operation during an historical 36-month drought that minimized the maximum monthly shortage. In particular, rationing is initiated when the sum of actual

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storage plus predicted inflow in the upcoming period is less than a trigger volume, computed as the demand to be met in the same period, and the demand reduction is determined by the ratio of the sum of storage and inflow to the trigger volume. Shen and Tabios (1995) explored the effect of the presence of reservoirs on the drought of the Sacramento River by using a very long series of tree-ring reconstructed annual flows and a few significant shortage indices. In particular, reservoirs reduced the number of drought events, increased significantly the interarrival time between droughts, and reduced the most severe water shortages and cumulative deficits.

The aim of this paper is to analyze the relationship between hydrological drought and reservoir performance in order to assess the water supply system's susceptibility to drought conditions. In particular, the investigation has been performed under the following framework:

- The identification of hydrological drought events is based on streamflows series (which is regulated by a reservoir), using the concept of negative runs to characterize a drought by means of its duration, cumulative deficit, and mean intensity, and the reservoir's annual demand as a threshold level.
- A comprehensive evaluation of the reservoir's performance during drought events can be carried out by means of various indices that measure the amount of the shortages related to monthly demands, the frequency of shortages, the length of shortage periods, and the severity of the maximum shortage.

Furthermore, because the relationship between drought characteristics and shortage indices also are affected by the demand patterns and the adopted operating rule, the operation of a water supply reservoir under drought conditions has been simulated considering two different demand patterns and several operating policies, which represent different degrees of hedging of current releases in order to reduce future shortages.

EFFECTS OF HYDROLOGICAL DROUGHTS ON WATER SUPPLY SYSTEMS

From the hydrological point of view, drought can be defined as a reduction of available water in natural water bodies (streams, aquifers, etc.) caused by meteorological drought. The social-economical system is affected by droughts through the filtering of the water supply system and in particular through the water shortages to the users. Such shortages depend also on the water demand levels and on the actions carried out in order to reduce drought effects. Also, economic losses and intangible impacts are affected by the actions undertaken to reduce drought effects. Fig. 1 depicts a simplified sketch of the complex process streaming from a meteorological drought event to its economic impact and social perception. Thus susceptibility of water supply systems to drought conditions can be assessed on the basis of the shortages resulting from drought periods of different severity by using appropriate system performance indices.

Hydrological droughts can be expressed in terms of different characteristics, such as the duration, magnitude of deficit, and intensity. According to the theory of run (Yevjevich 1967; Dracup et al. 1980) a drought event is defined as a consecutive time interval where the selected hydrologic variable such as streamflow is below a certain threshold representing water demand. The threshold level may be a constant or it may vary seasonally; usually it is chosen as the long-term mean under the assumption that the level of water demand corresponds to the mean availability of resources. A drought can be characterized by means of three indices, representing its duration L (run length), cumulative deficit RS (run sum), and average run

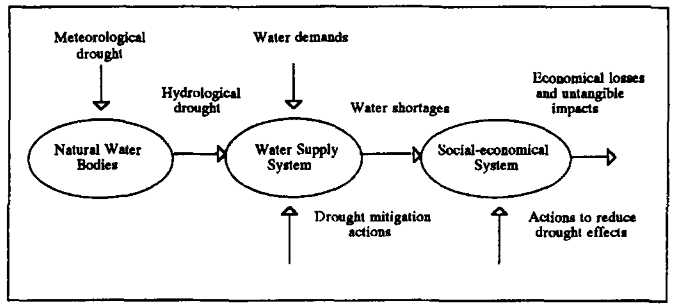

FIG. 1. Impacts of Drought Event

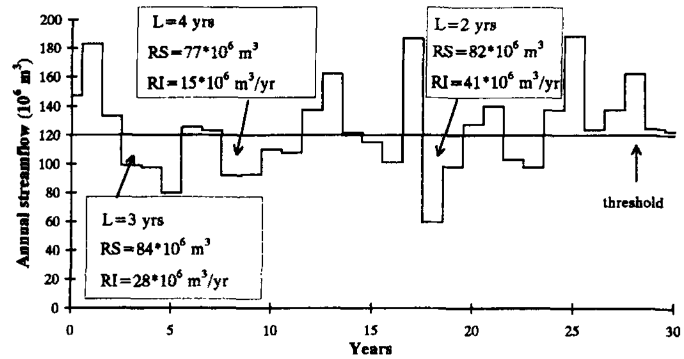

FIG. 2. Identification of Most Severe Droughts on 30-yr-Long Generated Series

intensity RI defined as the ratio between cumulative deficit and length. Fig. 2 shows a generated annual streamflow sequence and droughts are identified based on a threshold level equal to the long-term annual mean.

Performance indices usually are related to the concepts of reliability, resilience, and vulnerability (Hashimoto et al. 1982) and can be estimated on the basis of the releases series either observed or computed by simulating the system. Reliability, which is defined as the probability that a system is in a satisfactory state (i.e., all demands are satisfied), can be estimated as the ratio between the number of intervals in a satisfactory state and the total number of intervals. Sometimes, instead of reliability, the risk of shortage is used, which is simply one minus the reliability. Klemes (1969) estimated reliability on a volumetric basis as the ratio between total shortage and total demand. Resilience is a measure of how fast a system is likely to recover from failure once a failure occurs and is defined as the inverse of the average length of time a system's output remains unsatisfactory after a failure. Hashimoto et al. (1982) demonstrated that resilience is equivalent to the conditional probability to be in a satisfactory state given that the previous interval is a shortage interval. Vulnerability is a measure of the likely magnitude of failures and can be estimated by means of the expected maximum shortage (Hashimoto et al. 1982). An alternative vulnerability criterion has been given by Moy et al. (1986), who measured the maximum shortage during the period of operation. Beard (1964) proposed an index based on the sum of the squares of annual shortages, which emphasizes the most severe shortages and thus can be assumed as a vulnerability index. The use of more than one index even within each performance category (reliability, resilience, and vulnerability) may be necessary for a comprehensive assessment of the behavior of a water supply system (Alecci et al. 1986).

In the present paper, the performance of a reservoir under drought conditions has been evaluated by means of five indices that try to capture the different aspects of the response of the reservoir to hydrological drought. Hydrological droughts have been identified on an annual timescale whereas the performance indices have been computed at a monthly timescale.

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Each index is computed simulating the reservoir during each identified drought.

The following are the selected indices:

- Shortage Sh, defined as the ratio between the total shortage and the total demand during the drought spell

$$Sh = \frac{\sum_{\tau=1}^{12L} (d_\tau - e_\tau)}{\sum_{\tau=1}^{12L} d_\tau} \tag{1}$$

where d_τ = demand at month τ; e_τ = release at month τ; and L = length of the drought event (simulation period) expressed in years.

- Frequency of shortage Fs, defined as the ratio between the number of shortage intervals Nd (months) and the length of the drought spell expressed in months

$$Fs = \frac{Nd}{12 \cdot L} \tag{2}$$

- Average length of shortage periods Ls, computed as the ratio between the number of shortage intervals Nd and the number K of shortage periods during the drought event

$$Ls = \frac{Nd}{K} \tag{3}$$

- Maximum shortage in a single month

$$Ms = \max_\tau (d_\tau - e_\tau) \tag{4}$$

- Modified Beard index, defined as the sum of the squares of the fraction of monthly shortages to the demand, divided by the length of the drought spell expressed in months

$$Bi = \frac{1}{12 \cdot L} \sum_{\tau=1}^{12L} \left(\frac{d_\tau - e_\tau}{d_\tau} \right)^2 \tag{5}$$

RELATIONSHIPS BETWEEN DROUGHT CHARACTERISTICS AND PERFORMANCE INDICES

In general terms, it is not easy to assess the performances of a given water supply system under drought conditions only on the basis of the characteristics of the hydrological drought. Such a difficulty stems from the fact that, even in the simplest case of a single reservoir supplying a single demand, correlation between different drought characteristics and different performance indices exists only for particular pairings characteristic index, being not significant in all other cases. When the complexity of the system increases and different sources of supply and water users are considered, there might be no significant correlation between any characteristics of input drought and corresponding performance indices. Such a general lack of correlation should not be surprising because it reflects an intrinsic feature of a water system, which is to transform, through a storage mechanism, the hydrological input (usually characterized by a high variability) into a more suitable output (e.g., releases to water users).

In general terms, relationships between drought characteristics and performance indices are affected by the monthly pattern of inflows and of demands and by the adopted operating policy as well. Characterization of droughts on the other hand is done only with respect to global quantities such as total deficit or duration, and thus no information is retained about the monthly pattern of flows. Therefore functional relations can be found only if either the performance index is representative of global quantities or the effects of the foregoing cited factors can be quantified. This is the case, for example, of the shortage index, as shown in the following paragraph.

With respect to a simple system consisting of one reservoir regulating surface flows and one demand, let's consider a drought period assuming as truncation level the annual demand D. Let L be the length and CD and ID the cumulative deficit and mean intensity of the identified drought each normalized with respect to annual demand. Mass balance over the whole drought spell implies

$$\sum_{\tau=1}^{12L} e_\tau = \sum_{v=1}^{L} I_v - \Delta \tag{6}$$

where I_v = yearly inflow at year v; and Δ accounts for losses (e.g., evaporation, spills, etc.) and for the difference between initial and final storage.

The following relation holds between monthly and annual demands:

$$\sum_{\tau=1}^{12L} d_\tau = \sum_{v=1}^{L} D = L \cdot D \tag{7}$$

Substituting (6) and (7) into (1) and observing that

$$ID = \frac{\sum_{v=1}^{L} (D - I_v)}{L \cdot D} \tag{8}$$

the following relation can be written

$$Sh = \frac{\sum_{\tau=1}^{12L} d_\tau - \sum_{v=1}^{L} I_v + \Delta}{\sum_{\tau=1}^{12L} d_\tau} = \frac{\sum_{v=1}^{L} D - \sum_{v=1}^{L} I_v + \Delta}{\sum_{v=1}^{L} D}$$

$$= \frac{\sum_{v=1}^{L} (D - I_v)}{L \cdot D} + \frac{\Delta}{L \cdot D} = ID + \frac{\Delta}{L \cdot D} \tag{9}$$

Therefore, Sh is a linear function of ID and it is also a function of drought length.

The relationship between the cumulative deficit CD and the shortage Sh can be derived easily from (9) by observing that

$$ID = \frac{CD}{L} \tag{10}$$

and thus (9) can be written as

$$Sh = \frac{CD}{L} + \frac{\Delta}{L \cdot D} \tag{11}$$

Therefore the shortage is a function of CD and of the inverse of L. Assuming the latter term fixed, Sh values are function of Δ, which conversely depends on the difference between initial and final storage of the simulation period; then, if the storage at the onset of the drought is fixed, the term Δ depends on the monthly distribution of inflows, of demands, and on the operating policy.

Eqs. (9) and (11) shed some light on the possibility of linking the drought characteristics with the other performance indices. In fact, any relationship involving another index would imply a relation between the same index and Sh but it is easy to observe that no analytical relationship can be found between Sh and the other indices.

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TABLE 1. Main Statistical Parameters of Generated Series of Streamflows

Statistical parameters (1)	November (2)	December (3)	January (4)	February (5)	March (6)	April (7)	May (8)	June (9)	July (10)	August (11)	September (12)	October (13)	Year (14)
Mean (10^6 m^3)	11.00	19.50	19.00	18.00	15.00	11.00	7.70	4.40	2.90	2.50	3.60	5.40	120.00
Standard Deviation (10^6 m^3)	6.20	13.60	12.30	13.10	9.80	6.30	4.40	2.40	1.50	1.20	1.70	2.80	41.49
$r1$	0.220	0.360	0.460	0.530	0.580	0.650	0.750	0.860	0.780	0.820	0.700	0.510	0.152

ANALYSIS OF SUSCEPTIBILITY OF RESERVOIR TO DROUGHT EVENTS

System under Study

To verify the aforementioned concepts, the performance of a simple reservoir system with an active storage capacity of 120×10^6 m^3 has been simulated. Unregulated inflows have been generated using a lognormal monthly PAR(1). The generation was extended just to include 200 droughts, which were viewed as an adequate number of events for the purpose of the present analysis. Table 1 reports the main statistical parameters of the generated series (i.e., monthly values of mean, standard deviation, and lag 1 autocorrelation coefficient $r1$).

As the interest here was to evaluate the effects of identified drought periods on the performance of the system and because effects of hydrological droughts generally are delayed with respect to their occurrence, identification of drought periods has been carried out at a timescale much larger than the one used for simulation. In particular, droughts have been identified on the long-term synthetic series by runs on a yearly timescale and adopting the long-term annual mean (120×10^6 m^3, equal to the annual demand) as truncation level. Table 2 shows the main statistical parameters of the characteristics of the identified droughts, namely, length L, cumulative deficit CD, and mean intensity ID. The latter two terms are normalized with respect to annual demand.

Two cases of different demand patterns have been considered. In the first case, a constant monthly demand of 10×10^6 m^3 has been assumed. In the second case, two demands, namely, a municipal demand of 5×10^6 m^3 per month and an agricultural monthly demand of 10×10^6 m^3 for 6 months (May–October) are used.

Simulations of the system have been performed for each drought period assuming an initial storage equal to 10×10^6 m^3. No evaporation losses have been considered in the simulation and spills never occurred.

First Case: Single User

Two distinct operating policies have been considered for the simulation of the reservoir supplying a single water user. In the first case no hedging is applied to releases, and therefore demand is satisfied, until the water is available in the reservoir. For each month, releases are determined as a function of present storage plus predicted inflow in that month on the basis of the so-called SOP shown in Fig. 3. According to this policy, demand is always fulfilled unless water availability drops below value T, which, in this case, equals the demand. In the second case, a preliminary hedging is applied by limiting the releases when future deficit conditions are expected, thus saving water to reduce heavier shortages in the future. This is obtained by hedging releases when water availability drops below T_τ, which obviously is greater than the demand. Releases for each month are determined according to the curve shown in Fig. 4, where the value T_τ varies from month to month.

Storage volume T_τ at month τ below which hedging of releases must be undertaken, has been evaluated by adding to the τ month demand a fraction of total demand between τ + 1 month and the end of water year and subtracting the future predicted inflows, estimated within the same time horizon. Future inflows have been predicted on the basis of monthly values corresponding to fixed nonexceedence probability levels, using a lognormal distribution.

Graphical verification of (9) and (11) is reported in Figs. 5 and 6, which show the relationships between shortage Sh, computed simulating the system during drought periods using the SOP, and the mean intensities of droughts ID and cumulative deficit CD, respectively. In both figures, points corresponding to different drought lengths are plotted using different markers; however, in Fig. 5 only points related to drought lengths L = 1, 2 are reported in order to improve the legibility of the graph. In the same figures the theoretical lines [see (9) and (11)] related to different drought lengths also are plotted, under the hypotheses of no losses and null final storage, assuming consequently the term Δ equal to the initial storage. As shown on the graphs, points generally lie on the two lines with some exceptions because of the presence of nonzero final storage.

TABLE 2. Main Statistical Parameters of Identified Drought Characteristics

Statistical parameters (1)	L (years) (2)	CD (3)	ID (4)
Mean	2.39	0.603	0.256
Standard deviation	1.79	0.521	0.129
Minimum	1	0.008	0.008
Maximum	10	3.214	0.691

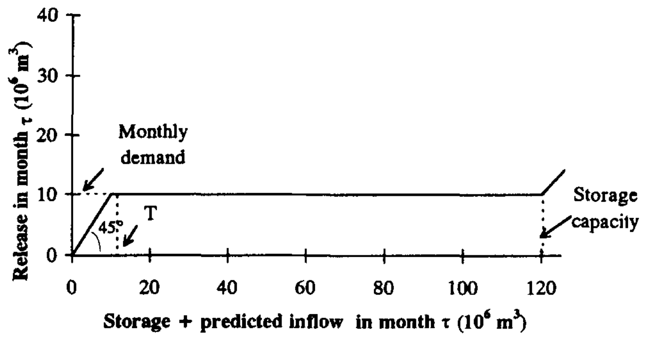

FIG. 3. Standard Operating Policy for Month τ

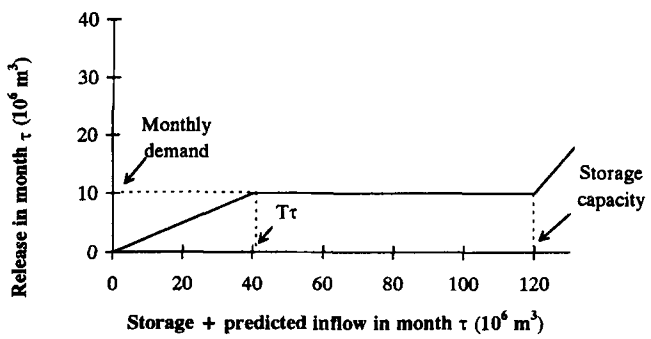

FIG. 4. Hedging Policy for Month τ

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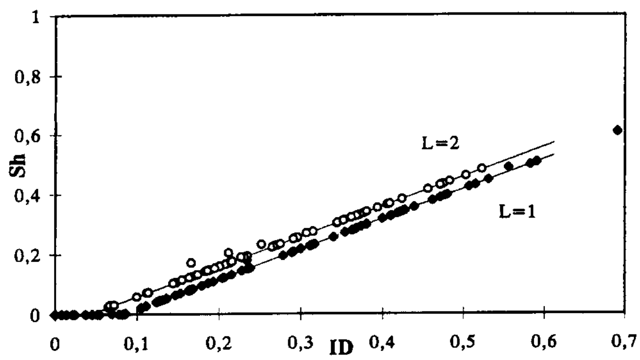

FIG. 5. Relationships between *ID* and *Sh* for Drought Lengths $L = 1, 2$

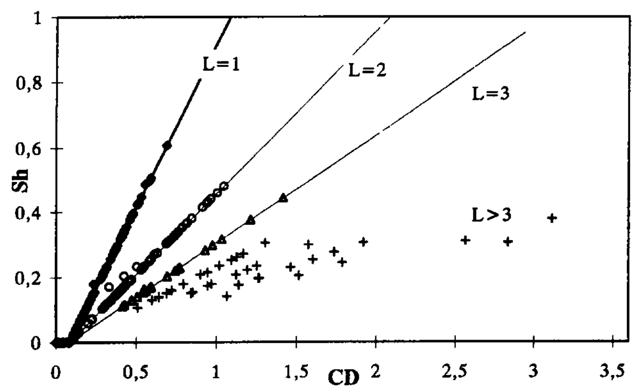

FIG. 6. Relationships between *CD* and *Sh*

When hedging is applied, the foregoing relationships do not present significant changes, as it was expected and therefore no graphs are presented. In fact, the only term affected by hedging in (9) and (11) is Δ, which, in turn, assuming zero losses, depends on the final storage at the end of the drought period. Small differences between the two cases thus can be explained in terms of variations in the final storage, which are limited.

In Fig. 7, the relationships between *ID* and the other performance indices are reported when no hedging is applied (SOP). Indices generally are correlated with the drought characteristic, the only exception being the maximum shortage *Ms*, which presents a general scatter of the points and therefore seems difficult to gain some indications about the type of link between *ID* and this index. However, it may be observed from the graph that as *ID* increases so does *Ms*, with a tendency to align around maximum value represented by monthly demand. Correlation between *ID* and the other three indices also is evidenced by the fitted regression lines that are forced to pass through the origin because no shortages are expected when drought mean intensities are zero.

Fig. 8 shows the same graphs which are obtained when the hedging rule with a nonexceedence probability of predicted inflows equal to 0.3 is applied. Hedging affects significantly the relationships, as is shown by the increased scatter of the points and by the changes in the slopes of the fitted lines. Particularly, frequency of shortage *Fs* shows a general increase, which also is evidenced by the upward translation of the fitted line. Furthermore, several times *Fs* equals 1, which means that in these cases demand is fulfilled completely in no month of the drought event. The average length of shortage periods *Ls* generally increases, though showing a greater scatter of the points and a lack of a definite pattern. Such an increased scatter also is shown by the maximum shortage values *Ms*, which, however, present a general reduction. Beard index values show generally lower values with respect to those obtained without hedging.

No significant relationships can be observed for the graphs between cumulative deficit *CD* and the other performance indices and thus no graphs are reported.

Second Case: Two Users

As mentioned earlier, this case includes two uses, namely, a municipal constant demand and a seasonal agricultural demand. Allocation of releases between the two uses (during the 6 months of contemporaneous demand) has been carried out on the basis of the total water availability by imposing that when there is not enough water to satisfy both demands, municipal release must be a function of the square of the agricultural one (Fig. 9). By means of this rule, a significant priority has been given to municipal demand, which reflects a realistic management of the system.

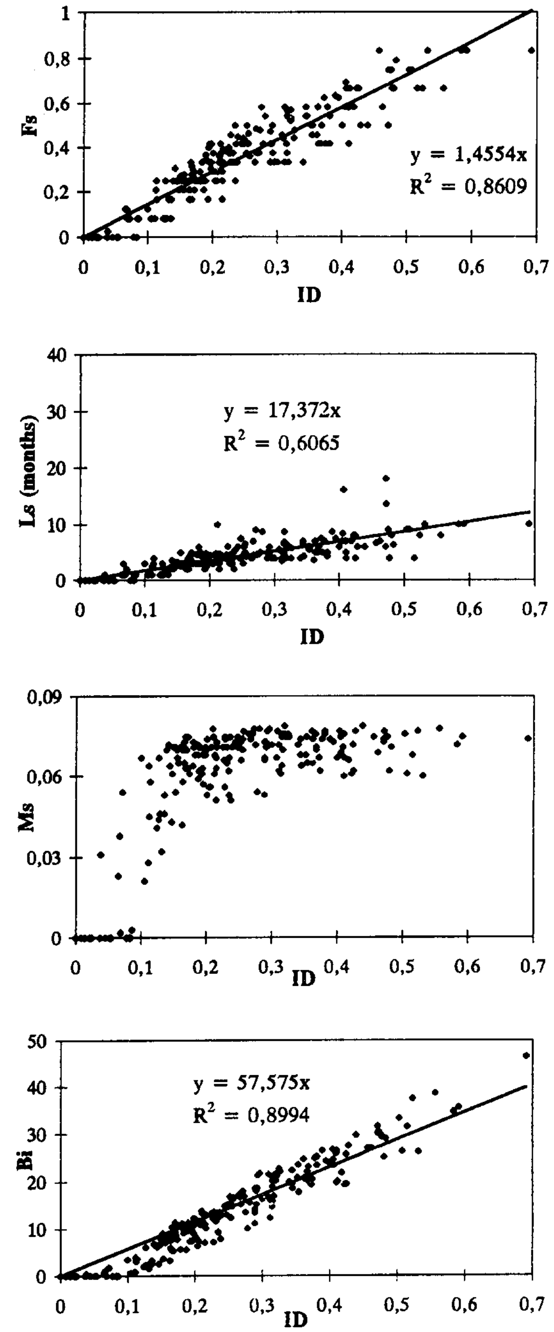

FIG. 7. Relationships between Mean Intensities of Droughts *ID* and Performance Indices Computed Adopting SOP

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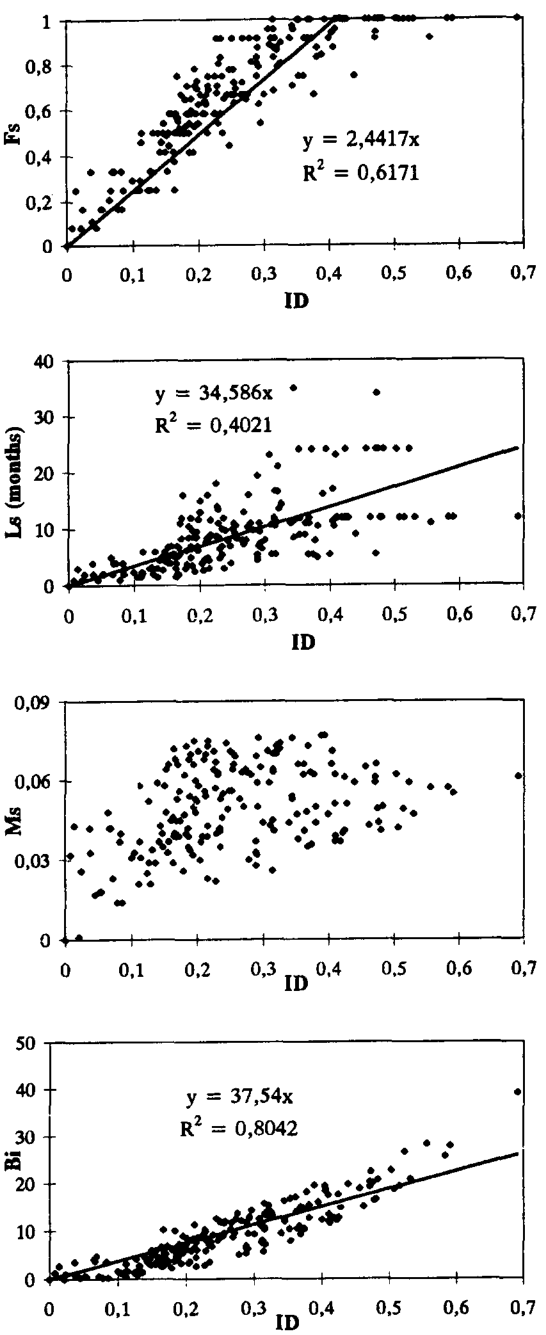

FIG. 8. Relationships between Mean Intensities of Droughts *ID* Performance Indices Computed Adopting Hedging Policy

Anticipatory hedging of releases has been implemented by computing monthly trigger volumes $T_τ$ as in the previous case, considering the different demands. Fig. 10 shows monthly values $T_τ$ as a function of different nonexceedence probabilities when two users are present in the system. The same droughts identified for the previous case have been adopted as hydrological input. Performances of such a system can be assessed with respect both to total demand and to the single ones. In the former case, the considerations expressed in the previous paragraphs (single user) obviously are valid. Therefore linear relationships can be derived between *Sh* and drought characteristics *ID* and *CD*. However, when several users are present in the system, the interest generally lies in estimating the performances related to each user.

Fig. 11 shows the relationships between the mean intensities of droughts *ID* and the performance indices related to municipal and agricultural uses, computed when no hedging is ap-

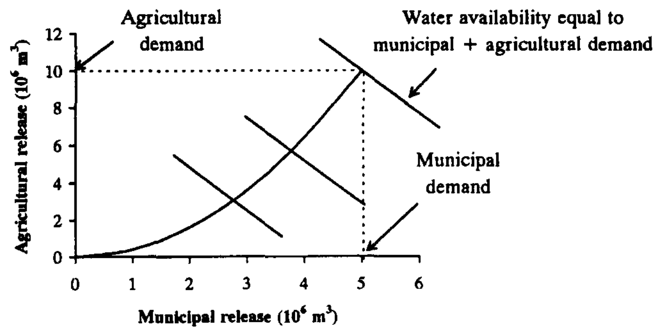

FIG. 9. Allocation Rule between Municipal and Agricultural Demand

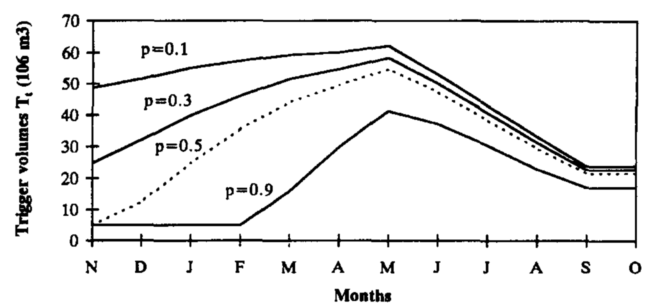

FIG. 10. Monthly Trigger Volumes of Reservoir as Function on Nonexceedance Probabilities of Inflows When Two Users Are Present in System

plied. The pattern of the points is similar to the one observed in the case of a single user. It is evident from the graphs that municipal demand is less susceptible to drought conditions than the agricultural one, as a result of the allocation rule. This also is shown by the different slopes of the fitted regression lines, which present greater values in the case of agricultural demand [Fig. 11(b)].

To investigate how hedging affects susceptibility of water systems to droughts, the relationships between mean intensities of droughts and performance indices have been characterized by means of one parameter, namely, the slope of the regression line fitting the points and passing through the origin. This parameter is a somewhat simplified measure of the tendency of the points (i.e., how performances vary as increasing drought severities are considered) and thus it can be assumed as a measure of susceptibility of the index to drought conditions. Regression lines are forced to pass through the origin because no shortages are expected when drought mean intensities are zero. This hypothesis is not exactly true because small droughts don't necessarily cause shortages on the releases due to the initial storage present in the reservoir. However, for the purpose of our investigation this effect has been assumed negligible. It must be stressed that the regression lines used here are not intended to be used for assessing performance indices as a function of mean intensities of droughts (in fact no hypothesis about linearity has been stated) but only to allow the analysis of the effects of different hedging on the relationship between drought characteristics and performance indices.

Then several series of simulations have been performed by varying the nonexceedence probabilities of expected inflows and therefore implementing different trigger volumes curves for hedging. For each series of simulation, four slopes have been computed on the basis of the relationships between mean intensities *ID* and shortage, frequency of shortage, average length of shortage periods, and Beard index, respectively. No slopes have been computed for the maximum deficit *Ms* because of the lack of fit of the regression lines.

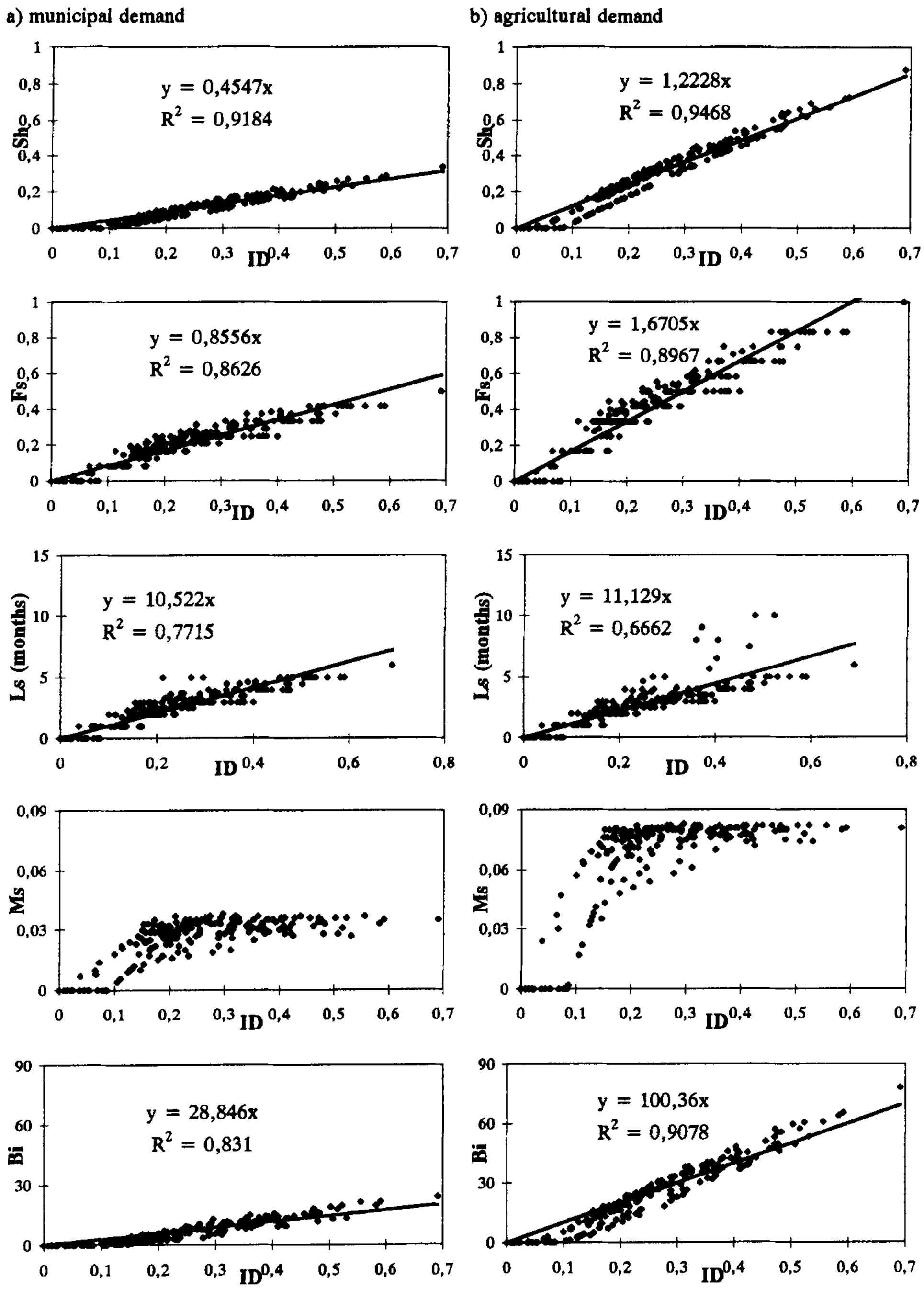

FIG. 11. Relationships between *ID* and Performance Indices for: (a) Municipal Demand; (b) Agricultural Demand Adopting SOP

The relationships between nonexceedence probabilities p and the aforementioned slopes, computed with respect to municipal and agricultural demand, are reported in Fig. 12, where the slopes computed adopting the SOP also are indicated. In general hedging reduces Beard index Bi while increasing the frequency of shortage Fs and the average length of shortage Ls. Slopes related to municipal demand are generally lower than the ones related to agricultural demand. Furthermore, hedging affects differently the shortage Sh related to the two demands because the two slopes (municipal and agricultural) at first are almost constant, while they tend to join as increasing hedging severities are applied. Such a joining tendency also is shown by the other indices, though with different patterns, and is particularly evident in the cases of shortage risk Fs and average length of shortage periods Ls, where the curves intersect. However, in the latter cases it must be pointed out that some of the computed slopes may not be representative of the sensitivity of the indices to drought conditions because of the great scattering of the points (Fig. 11). Thus, to verify the goodness of fit of the regression lines and therefore assess the significancy of the slopes as a measure of susceptibility, the coefficients of determination R^2 have bee used. Fig. 13 shows the computed coefficients R^2 related to the four indices plotted as a function of nonexceedence probabilities of inflows p (hedging severity). As shown in the graphs, R^2 values are particularly low only in the case of average length of shortage periods Ls related to agricultural demand and therefore the associated slopes cannot be considered significant. On the other hand, the high values of the R^2 corresponding to shortage Sh and Beard index Bi confirm the aforementioned joining tendency of the slopes related to the municipal and agricultural demand.

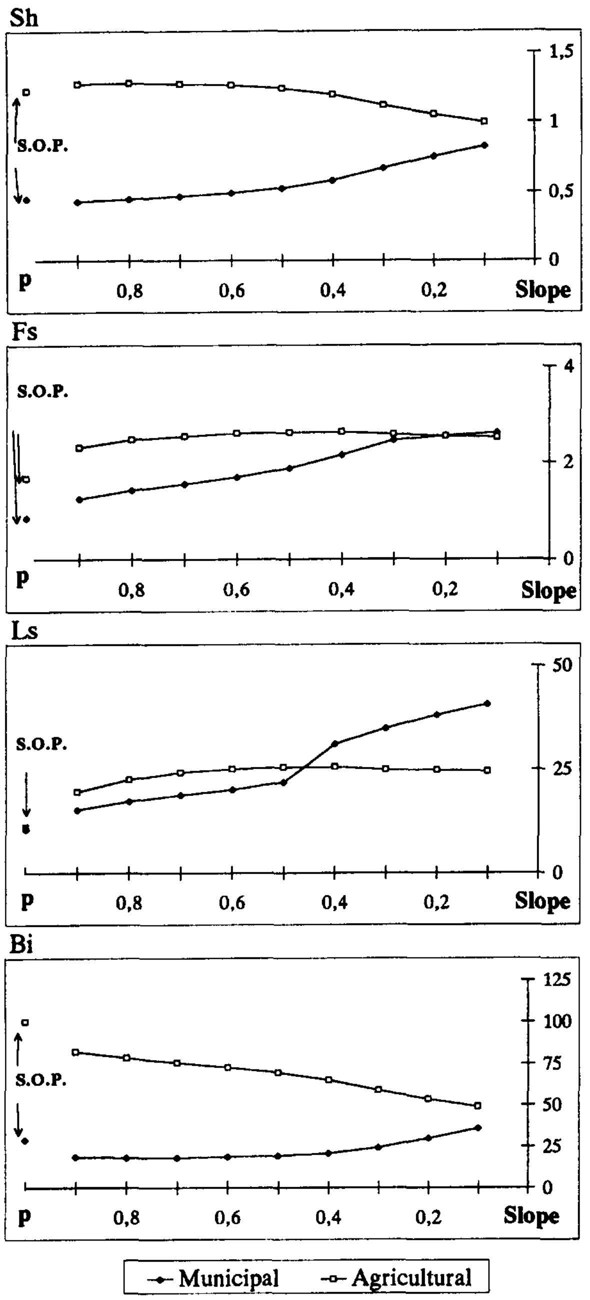

FIG. 12. Relationships between Nonexceedence Probability of Expected Inflows and Slopes of Regression Lines

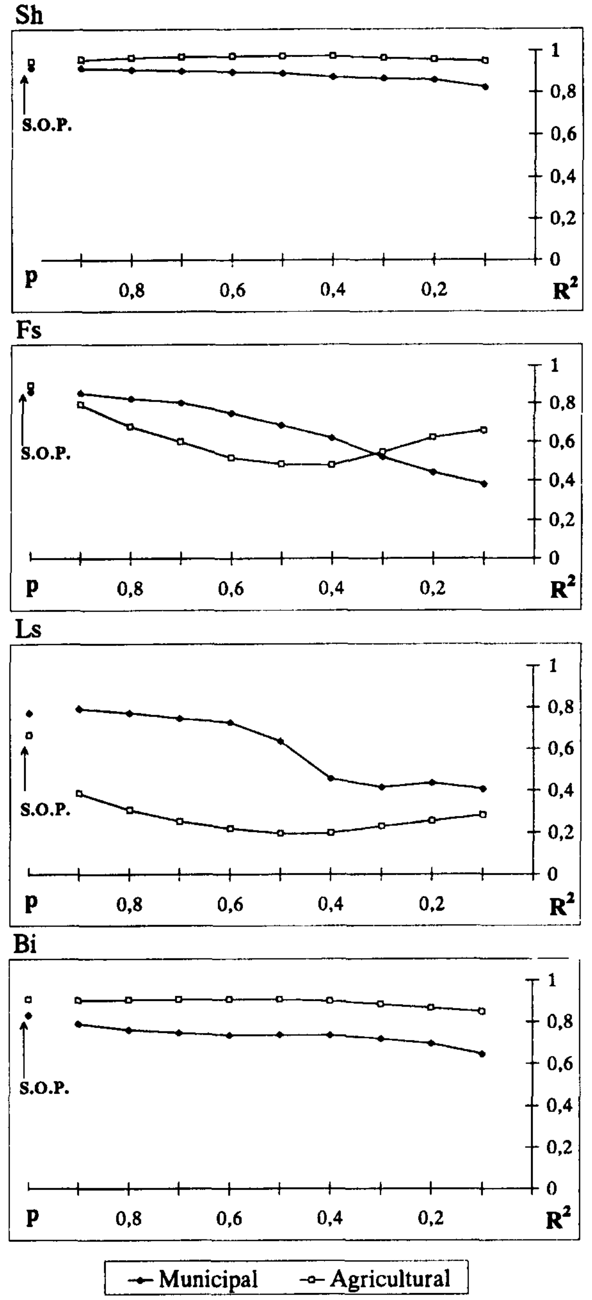

FIG. 13. Relationships between Nonexceedence Probability of Expected Inflows and Determination Coefficients of Regression Lines

CONCLUSIONS

Susceptibility of a water supply reservoir to drought conditions has been investigated for two different demand patterns (uniform along the year and sum of uniform and seasonal demands) by using the SOP and several hedging policies, which save some of the available stored water to prevent future severe shortages, on the basis of different estimated future streamflows. Two hundred drought events were identified at a yearly scale based on a series of monthly streamflows generated by a PAR(1) model and were used as hydrological inputs for simulation. The failure of the reservoir to meet water demands during the drought events was described through various performance indices describing shortages.

Analytical relationships between shortage index and mean intensity (or cumulative deficit) of droughts have been developed and verified graphically for the single user case; the relationships were found to be a linear function, which fits well the points corresponding to droughts of the same length in years. Hedging does not affect significantly the relationships because the only term influenced by the operating rule is the difference between initial and final storage.

The relationships between the other performance indices and the characteristics of the drought events, assumed as input for the simulation model, have been investigated numerically and graphically for each of the two demand patterns and for different anticipatory hedging rules. Graphs present different degrees of scattering of the points, which is particularly evident in the case of maximum shortage. Also, scattering varies as different operating policies are taken into account. However, the relationships still conserve a definite pattern, which is indicative of the efficacy of hedging rules to reduce drought impacts. In particular, as increasingly stringent hedging is applied, the maximum monthly shortage generally de-

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creases but, on the other hand, the frequency of shortage and the mean length of shortage periods increase significantly.

The spread of the points leads to the conclusion that assessment of the performance of a water supply system under drought conditions cannot be done on the basis of a single design drought (i.e., drought with a specific severity or worst drought observed on an historical record) because shortage indices are affected not only by the characteristics of the whole drought event (mean intensity and cumulative deficit) but also by the temporal distribution of inflows during the drought period as well as by the initial storage in the reservoirs.

Further research is needed to analyze the relationships between drought characteristics and performance indices in the case of a complex water system with different sources of supply and to assess whether the use of a different drought identification method would lead to improved correlations.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

Bi = modified Beard index;
CD = cumulative deficit of drought period divided by the annual demand D;
D = annual demand;
d_τ = water demand in month τ;
e_τ = water release in month τ;
Fs = frequency of shortage;
ID = mean intensity of drought period divided by the annual demand D;
K = number of shortage periods (consecutive shortage months);
L = length of drought period;
Ls = average length of shortage periods;
Ms = maximum monthly shortage over a drought spell;
Nd = number of shortage months during the drought spell;
p = nonexceedence probability of predicted inflows;
RI = mean intensity of drought period;
RS = cumulative deficit of drought period;
Sh = shortage index;
T_τ = trigger level in month τ; and
Δ = difference between initial and final storage plus reservoir losses.

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