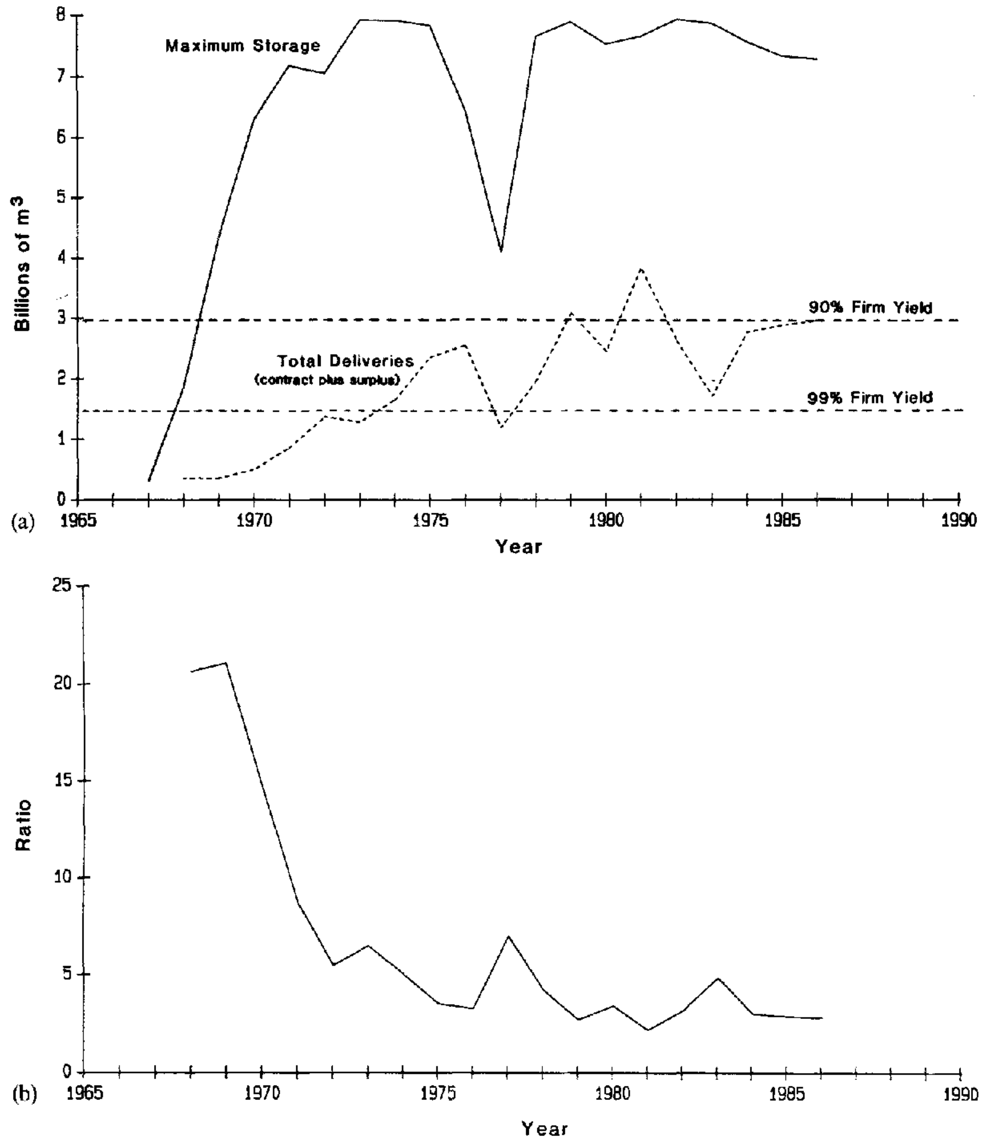


Fig. 4. Maximum annual storage, total deliveries, and firm yield estimates with 1980 facilities (a) and ratio of storage to delivery (b) for the California State Water Project. Source: California Department of Water Resources.

called for immediate adjustment. The drought was intense, resulting in new low rainfall and streamflow records, but it was also relatively short-lived compared to the 1928–34 design drought. Yet, because project managers could not predict its ultimate duration, they followed tradition by assuming that it would emulate historic, multi-year droughts, and thus imposed severe delivery restrictions to avoid eventual storage depletion in subsequent years. Firm agricultural water deliveries in 1977 were shorted by 60%, and municipal/industrial supplies were reduced by 10% (California Department of Water Resources, 1978). Total deliveries declined from 2.5 $bm^3$ in 1976 to 1.1 $bm^3$ in 1977.

The shortages provoked an evaluation of dry-year delivery protocols. Managers saw the problem as a narrowing of the supply buffer which, in the past, had allowed them to guarantee long-term contract supplies and to project deliveries (including surplus) with great confidence well before the peak use season. Using the large buffer, they could fulfill delivery promises without risking reservoir depletion even if a rainy season suddenly turned into a worst-case dry spell. As demand approached developed supply, however, this approach became less effective.

In the mid-1970s SWP managers fully expected to increase project supplies substantially in the near future, though not in time to alleviate some problems if drought were to recur in the next few years. Thus they were forced to consider two options: (1) maintain full water deliveries early in a near-future drought and accept greater risk of eventually depleting stored supplies (i.e., decreased long-term reliability), or (2) curtail deliveries early in a drought to assure subsequent-year supplies.

The first approach seemed an unappealing retreat from the long-term certainty of supply which was the project's original rationale. Managers thus chose to protect the project's ability to absorb multi-year droughts by adopting a delivery protocol requiring curtailments early in future dry spells. This strategy fit user perceptions of the supply problem in the mid-1970s: most were still developing the capacity to use their contract allotments through long-term capital investment, and the 1977 drought made the system look less reliable over the long haul than their contracts and past experience implied. They became more skeptical of the informal approaches used in allocation decisions (Snow, 1976; and Robie, 1976). Users thus supported implementation of an objective protocol for making allocation, carry-over, and subsequent-year delivery decisions that protected long-run reliability (California Department of Water Resources, 1977).

A formal allocation protocol was codified in a 'rule curve' which determines deliveries and carry-over storage during periods of short supply. The rule curve was formulated in 1977 initially to set allocations for 1978 (see California Department of Water Resources, 1977 and 1978). Assuming continued drought, it required large year-end storage to achieve 1978 delivery projections approaching 99% reliability. Large carry-over increases the likelihood of meeting subsequent year water requests, but decreases the amount of water which can be delivered in the current year, a trade-off common to most storage-based water systems. By mandating carry-over to meet future-year contract entitlements (with allowable deficiencies) even in a repeat of the 1928–34 design drought, the rule curve was biased toward large carry-over storage at the expense of current-year deliveries. But, in retrospect it appears that the 1977 rule curve was maladapted to the more variable climate pattern that had emerged.

The rule curve was not invoked again for several years. Heavy precipitation late in 1978, and again in 1980, quickly replenished project storage. Short-lived dry spells in 1979 and 1981 (Figure 3) were managed without delivery curtailments partly due to conservation measures implemented during the 1976–77 drought. Wet conditions in 1982–1983 significantly lowered user requests (Figure 4). Yet, in the face of continued demand growth, tightened water quality standards that required larger freshwater releases to the Sacramento-San Joaquin Delta, and a referendum blocking construction of new facilities, SWP managers estimated that contract requests would only be satisfied in normal or above normal runoff years by 1986, and met in only very wet years by 1990. Using 1980 facilities, managers calculated that they could deliver 2.96 $bm^3$ 90% of the time, and only 1.36 $bm^3$ 99% of the time (California Department of Water Resources, 1983). But, contract requests are expected to reach 3.58 $bm^3$ by 1990. Given this squeeze on supply, managers again urged construction of a new reservoir at Auburn, CA, that, under a joint operating agreement with the CVP, would augment dry year supplies. They were guardedly optimistic then that it could be operating by 2000 (California Department of Water Resources, 1983, p. 259).[3]

Another short, sharp drought developed in 1985. The rule curve was invoked, requiring a marked decrease in previously declared supplies in order to assure entitlement deliveries for 1986 and beyond. Reflecting on the 1977–78 drought and the wet years that followed, however, users and managers had become wary of short-term curtailments that might later be proved unnecessary. They now began to question the strategy of operating the project in constant anticipation of the design drought if it meant curtailing current year deliveries. Perhaps, they reasoned, unnecessary delivery shortages – a frequent problem in a more variable climate – are worse than simply running out of water further into a multi-year drought.

This attitude change is evident in SWP documents. Noting that the 1977 rule curve "...emphasized credibility at the expense of useability – probably due to the unprecedented drought conditions prevailing at the time it was designed" (California Department of Water Resources, 1985a, p. 2), SWP managers began to question its usefulness given the growing inadequacy of average supply. The situation had, perhaps, been anticipated two years earlier in the 1983 up-date of the state's water plane:

...uncertainty regarding the capability of increasing developed supplies over the next several decades

[3] At this writing it appears that plans for the Auburn dam will not surmount environmental and financial hurdles. Plans released in 1987 call for several smaller projects and efficiency increases that will increase firm yield 1.08 $bm^3$ by 2010 (California Department of Water Resources, 1987a).

may justify and in fact may require taking greater risks in delivering water to customers.... Some water projects (could) take greater risks by delivering a higher annual supply, leaving less carryover storage in case of drought. This would allow growing needs to be met in normal years.... (E)xisting facilities may be operating in a more conservative manner than is necessary (California Department of Water Resources, 1983, p. 255).

A new policy emerged: maintain full contract deliveries early in a drought by drawing more liberally on reservoir storage, thus accepting greater risk of failing to meet subsequent year demands. This would help managers avoid imposing unnecessary shortages during short dry spells, and would make seasonal supply projections more reliable (i.e., less likely to be revised downward). The importance of such projections was amply illustrated in Glantz's (1982) study of the effects of changing water supply forecasts in Washington's Yakima Basin during 1977. In the Yakima case, predictions of substantially less runoff than actually occurred were quite costly and disruptive to users, perhaps as costly as overly optimistic forecasts would have been.

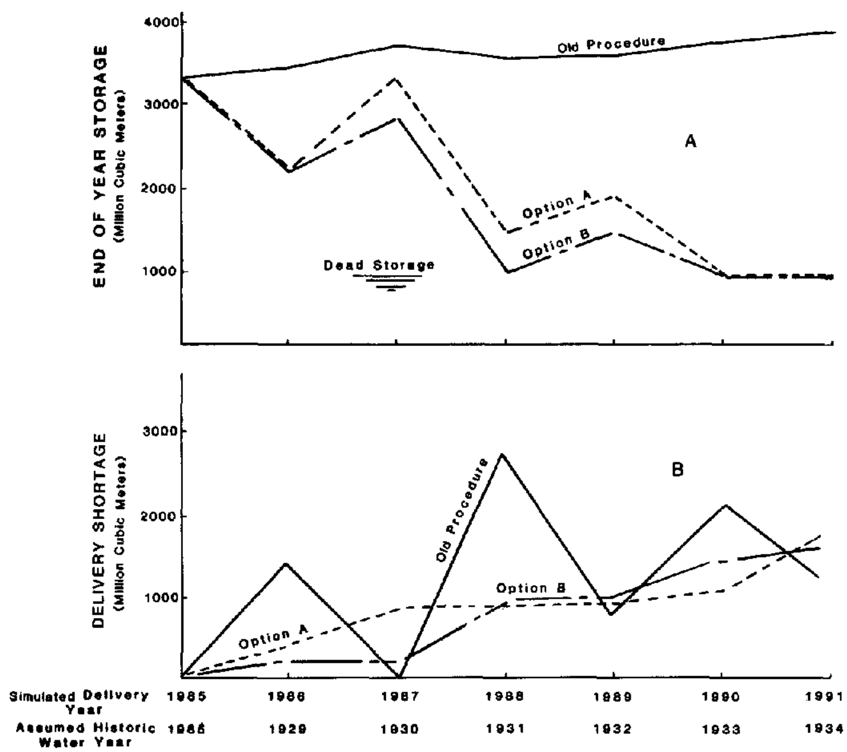


Fig. 5. Simulated SWP operations based on the 1977 rule curve and two alternatives proposed in 1985, for a hypothetical drought beginning with 1985 precipitation and storage conditions, and following the pattern of the 1929–34 design drought: (a) Total project storage at the end of each simulated year; (b) Delivery shortfalls from contract amounts. Source: California Department of Water Resources.

New SWP rule curves were designed to deliver more water at slightly lower reliability levels. Managers argued that the change was needed "to provide greater water service capabilities during short-duration droughts" (California Department of Water Resources, 1985b, Appendix A). The key words here are 'short-duration droughts'. Having seen how quickly drought could end and storage be replenished in 1978, and reflecting on the recent experience of short seasonal dry spells rather than multi-year droughts, managers proposed, in essence, to abandon an operating approach aimed at absorbing the design drought.

The effect of the old and proposed new rule curves can be seen in simulated water allocation during a drought sequence beginning with 1985 conditions and following the 1929–34 pattern (Figure 5). The old (i.e., 1977) procedure favors end-of-year storage over current year delivery (Figure 5a), resulting in substantial delivery shortages every other year of the hypothetical drought (Figure 5b). The new protocols draw more liberally on stored supply, and result in slowly accumulating shortages as the drought progresses, with decreasing assurance of meeting subsequent-year demand (Figure 5b). If drought lasts only a year or two, then less drastic shortages will have been imposed on users. If the drought persists, however, total storage depletion – system failure – may result. To date managers have not codified a single new rule curve, but rather have chosen to revise the protocol annually (see, for example, California Department of Water Resources, 1987b). In recent years they chose rule curves that allow more variable response, reducing the tendency to curtail deliveries early in droughts, an approach exemplified by the two alternatives in Figure 5.

Before further discussing the implications of these adjustments for the project's climate sensitivity, recent changes in Sacramento Basin flood control practices are described.

4.2.3. *Flood Control Sensitivity to Climate Fluctuation*

Flood control practice is more uniform among water systems than is drought management because the U.S. Army Corps of Engineers develops and enforces regulations governing flood control nationwide (see U.S. Army Corps of Engineers, 1982). Flood-control operation manuals are developed for each reservoir, defining the reservoir design flood (RDF), the flood season, fixed and flexible flood storage space requirements, and safe fill and release rates. All of these criteria can, theoretically, be adjusted to accommodate climate fluctuations affecting flood frequency, magnitude, or seasonality.

The recent increase in Sacramento Basin precipitation variability included several large runoff events, one of which was the worst flood on record. Space in six reservoirs in the basin is devoted to absorbing flood flows during the winter and early spring. We focus here on two: Folsom, a facility of the CVP; and Oroville, chief reservoir of the SWP.

Simple comparison of flood control requirements for Folsom and Oroville dams indicates large differences in climate sensitivity. The most striking contrast is the estimated return periods of their respective RDF's – a direct indicator of reliability. Both design floods had estimated recurrence intervals of roughly 500 years when the dams were designed. Subsequent flood events have, however, resulted in reduced RDF expected return intervals.

Folsom Dam's original RDF was based on the rainstorm of December, 1937, then the worst on record. Using daily runoff data through the late-1940s, hydrologists estimated that its return period was over 500 years. But, precipitation episodes in 1950 and 1955, while the dam was under construction, would have exceeded the RDF. When factored into updated hydrologic analyses in 1977, these events (and floods in 1964–65 which slightly exceeded the RDF) yielded a recurrence interval of roughly 120 years (Neal, 1986). On the other hand, designers of Oroville Dam, built in 1965, had benefit of the 1950s floods in their calculations, and enlarged its capacity accordingly. Its flood control capacity was not severely stressed until 1986.

Under traditional assumptions of flood frequency analysis, hydrologists would not necessarily be surprised at return periods that appear to change as the period of record lengthens. However, traditional analysis would not differentiate between changes due to sampling variations from a stationary parent population of runoff events, and changes deriving from actual climate change (see, for example, Lettenmaier and Burges, 1978). Analysts would argue that longer records simply allow better description of a region's basic climate characteristics. The implications of this assumption are discussed below.

#### 4.2.4. *Flood Control Adjustment to the Fluctuation*

Figures 6 and 7 show annual runoff into Folsom and Oroville reservoirs which lie, respectively, on the American and Feather Rivers. Both rivers flooded in 1956, 1964–65, 1969–71, 1974, 1982–83 and 1986, and both exhibit the increased runoff variability evident in the basin as a whole (cf. Figure 3). Concern has grown especially over Folsom's flood control capability during the last decade. The reservoir tended to operate close to design flood standards more frequently than expected, and the new RDF return period of 120 years calculated in 1977 was a dramatic drop in apparent reliability. Flood vulnerability also grew rapidly during the 1960s and 1970s as considerable development occurred in the floodplain behind to the American River levees.

In response to growing flood sensitivity, Folsom reservoir's flood control diagram has been revised twice since original design to increase its reliability (Figure 8). The initial protocol (Figure 8a) allowed managers to base reservoir levels during the entire fall and winter flood season on moisture conditions in the basin (the conditional flood reservation). The flood storage reservation could be varied between 493 and 246 million m$^3$, depending on how much precipitation had been recorded in the watershed over the previous six weeks. A six week precipitation total of 533 mm required that managers keep the full flood storage