ADJUSTING WATER RESOURCES MANAGEMENT TO CLIMATE CHANGE

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Abstract. The nature of climate impacts and adjustment in water supply and flood management is discussed, and a case study of water manager response to climate fluctuation in California's Sacramento Basin is presented. The case illuminates the effect on climate impact and response of traditional management approaches, the dynamic qualities of maturing water systems, socially imposed constraints, and climate extremes. A dual pattern of crisis-response and gradual adjustment emerges, and specific mechanisms for effecting adjustment of water management systems are identified. The case study, and broader trends in U.S. water development, suggest that oversized structural capacity, the traditional adjustment to climate variability in water resources, may prove less feasible in the future as projects become smaller and new facilities are delayed by economic and environmental concerns.

1. Introduction

Growing concern over the Greenhouse Effect has prompted a debate on the ability of social systems to adjust to changing climate. The optimists in this debate contend that modern food, water, and energy systems are sufficiently flexible that serious disruption is unlikely, especially if climate changes gradually. Pessimists argue that changes in the frequency and intensity of threshold events like droughts and floods may shift climatic risks in ways with which individuals and institutions are poorly equipped to cope. The crucial question thus becomes: How adjustable are society's resource management systems?

Results from climate and society research cast some light on this question. We know that climate fluctuations of the magnitude observed in the historical record can adversely affect natural resources management and other economic activities, and methods have emerged to assess this impact (see Kates *et al.*, 1985). Cases of both successful and failed social adjustment to extreme climate events have been described (see, for example, Wigley *et al.*, 1981; Heathcote, 1985; Maunder, 1986; and Glantz *et al.*, 1987), though this empirical literature has not been reviewed in a fashion that identifies generalizable patterns of adjustment and maladjustment. Recent studies of how social institutions respond to climate fluctuations suggest a tendency for conservative or muddled decision-making, and inappropriate policies, that lead to substantial climate-induced losses (e.g., Glantz, 1982; Wilhite, 1984). This record of mixed success

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in social adjustment should concern us in the face of future climate change.

To anticipate impacts of future climate changes, we need to know how resource systems become more or less sensitive to climate fluctuations over time, and how system managers respond to persistent climate trends. This paper examines the process and mechanisms by which managers adjust water resource operations to climate-induced runoff changes. The goal is to illuminate some of the specific water management strategies that are affected by climate change, rather than to focus on more speculative, broad social changes (e.g., the development of water markets) that might be part of general societal adjustment. The paper begins with a review of general principles of climate sensitivity and adjustment in water supply and flood control systems, and moves on to a case study of recent climate fluctuations in northern California. Finally, the concluding sections identify adjustment mechanisms and assess how well they are likely to function in future climate change.

2. Climate Sensitivity in Water Resources

Research is rapidly defining the climate sensitivity of surface water runoff (see, for example, Revelle and Waggoner, 1983; Wigley and Jones, 1985; and Gleick, 1987), but less is known about how altered runoff affects water supply and flood control systems. Growing concern over the hydrological impacts of future climate changes associated with the Greenhouse Effect (Revelle and Waggoner, 1983; Wigley and Jones, 1985; Gleick, 1987; Beran, 1986), has thus far prompted only a few studies of effects on water management (Schwartz, 1977; Nemec and Schaake, 1982; Cohen, 1986). One potentially useful approach is to analyze water systems according to sensitivity criteria developed by water resources researchers (Fiering, 1982; Hashimoto *et al.*, 1982). They are:

- reliability: the frequency of system failure;
- resiliency: the rate of recovery from failure; and
- vulnerability: the consequence of failure.

We would add another, often neglected, criterion:

- adjustability: the range of adjustment in system characteristics available to, and perceived by, managers.

We subsume these concepts under the broad heading of climate sensitivity, and focus on system reliability and adjustability in the face of climate fluctuation.

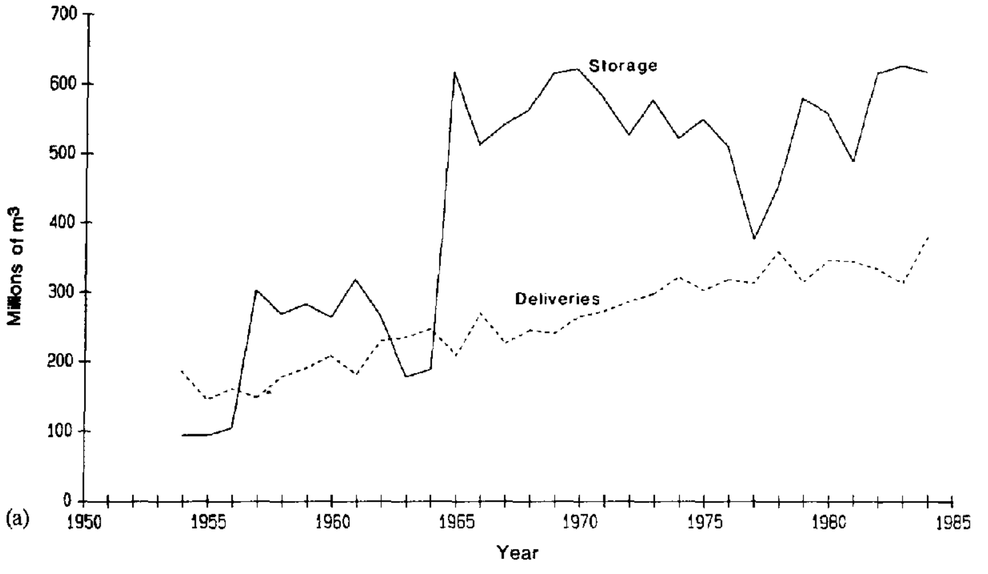
2.1. *Water Supply Sensitivity*

The long-standing management goal in U.S. water development has been to meet the demand for reliable water supply and flood protection no matter how that demand changes (White, 1969; Georgeson, 1986). Managers thus try to minimize uncertainties, including climate impacts. A simple principle of water supply sensitivity to climate is that impacts are greatest in areas where natural supply and use are closely matched (e.g., in some eastern urban water systems and in much of the semiarid and arid West). In humid-region systems without large reservoir storage, supply and use relationships can be defined as the useable flow of rivers and extraction by all users, respectively. In arid-zone water supply systems, where runoff variability is large and over-year reservoir storage is a standard management strategy, the ratio of storage capacity to runoff or use provides a simple, widely applicable measure of sensitivity. More detailed calculations of water storage and yield relationships are also possible given sufficient data (see MacMahon and Mein, 1978; Nemec and Schaake, 1982).

Greater climatic sensitivity implies lower reliability. While there is no universally accepted criterion for supply reliability, managers have converged on failure probabilities of 0.01 to 0.10 (see, for example, Russell, Arey and Kates, 1970; Nemec and Schaake, 1982; Klemes, 1985; and Dziegelewski, 1986). Most urban water systems are designed to provide a pre-determined minimum supply during roughly 99% of the time, though minor shortages might be acceptable more frequently. This minimum amount is often referred to as firm yield, and an extensive hydroclimatological methodology has been developed for designing the physical facilities needed to achieve firm yield targets (see, for example, McMahon and Mein, 1978; see also Klemes, 1985; and Beran, 1986, for literature surveys focussed on climate change). Technical, environmental and economic constraints, however, often prohibit following strict hydroclimatological guidelines in actual design and operational decisions, resulting in large climate sensitivity differences among systems.

Comparative water supply sensitivity is a fertile, yet relatively unexamined, subject in climate and society research. A useful first step would be to assess the overall climate sensitivity of major U.S. water systems. The ratio of storage, or firm yield, to use could be used to compare sensitivity among systems with similar characteristics, and to track changing sensitivity over time. Russell, Arey and Kates (1970) found a surprisingly large range of reliability when they used this approach to compare the drought adequacy of several Massachusetts water systems.

Storage and delivery data for the Denver, CO, water system illustrate this simple approach and the nature of changing climate sensitivity (Figure 1a and b). Periods of more or less climate buffering capacity are evident in the ratio of storage to use, as are three drought episodes: the mid-1950s, 1963–64, and 1976–77. The first two droughts occurred just before new supplies and reservoirs were developed, and managers were thus able to draw heavily on existing storage without threatening future operation. The 1976–77 drought occurred when no new supplies were in prospect, and mandatory conservation (something many water managers still view as outright failure) was invoked to avoid storage depletion.



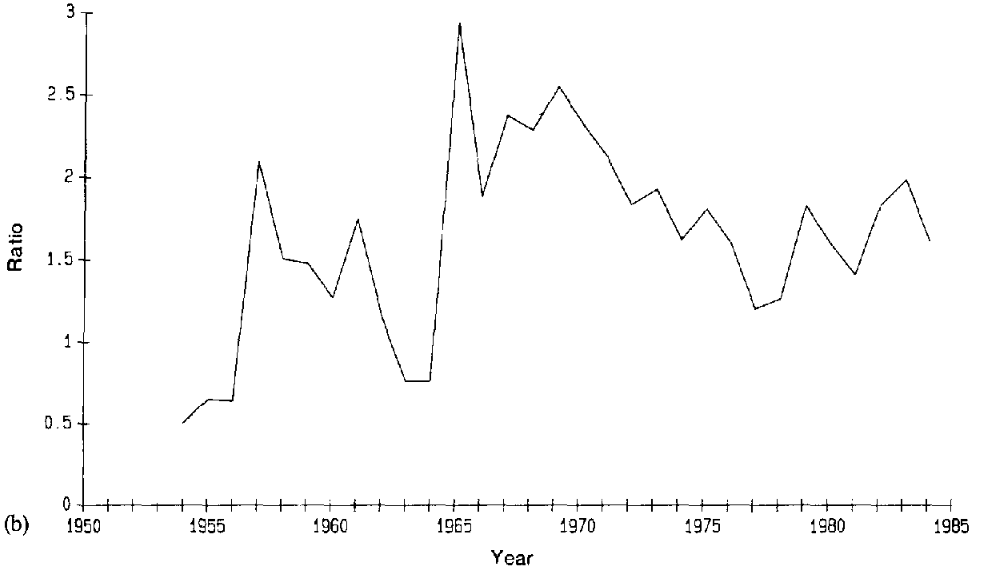


Fig. 1. (a) Annual storage and actual water deliveries in the Denver, Colorado, water system. (b) Ratio of storage to delivery for the Denver system. Source: Denver Water Board.

The Denver record illustrates changing climate sensitivity in a growing water system and reflects the step-like nature of structural development. Reservoirs completed in 1957 and 1963 provided large excess capacity and reduced sensitivity to climate fluctuation. This buffer was subsequently eroded by increasing water use. Only the recent run of wet years and voluntary conservation have maintained the spread between storage and use during the 1980s. Recognizing the system's heightened sensitivity to climate fluctuation, the Denver Water Board is trying to overcome loss of federal funds and growing public concern about environmental impacts to build a new large reservoir (which had not been approved at this writing; see U.S. Army Corps of Engineers, 1987). Assessments of other water supply systems might show similar patterns of climate sensitivity and adjustment.

2.2. *Flood Control Sensitivity*

Besides affecting overall water supply, climate change may alter the frequency and magnitude of flood-causing storms. Similarly, changes in flood management practices can affect sensitivity to climate fluctuations. Structural flood control practice in the U.S. developed rapidly after passage of the 1936 Flood Control Act, and a standard set of approaches relying chiefly on reservoirs and levees quickly evolved (see, for example, Hoyt and Langbein, 1955). Depending on flood vulnerability (likely damages and fatalities), planners typically design control works, and formulate operating procedures, to manage a flood of a certain magnitude, which is equated with its probability or return period (i.e., the average time interval between events of similar magnitude). Non-structural approaches, such as flood plain zoning and insurance, are also tied to benchmark flood magnitudes, and are codified in the National Flood Insurance Program (Federal Emergency Management Agency, 1987).

Flood control is typically tied to thresholds such as the 100-year event (a flood expected to occur, on average, once a century) in rural areas, or to the 200-year flood in heavily developed basins. In flood control systems based on reservoir storage, this event is refered to as the reservoir design flood (RDF). In flood plain management it is called the 'base flood', and zoning decisions are tied to it. A 'maximum probable flood', (MPF) usually a hypothetical event with a recurrence interval of 1000 years or more, may also be calculated to design critical control works like spillways, whose failure would be catastrophic. The design-flood return period is essentially an estimate of system reliability, because failure should not occur during more frequent (less severe) events.

Climate-sensitive elements of structural flood control include the size of the 'flood storage reservation' (open space maintained in a reservoir to absorb flood inflows), water release protocols, spill-way capacity, and downstream channel capacity, all of which are matched to the RDF or MPF. The chief climate-sensitive element of non-structural flood management is flood plain mapping and zoning. Because land-use restrictions are tied to a design flood, climate change can directly affect the efficacy of zoning and building practices as loss-reducing strategies.

3. Adjusting Water Supply and Flood Management

A large set of possible climate changes might provoke adjustment in water supply and flood management. Changes in total precipitation, its distribution or intensity, can change total supply and demand, and their seasonal distribution. Temperature changes may also affect supply and demand, but are probably less important than precipitation changes (Wigley and Jones, 1985). Changes in the frequency of extreme events, or the creation of new management problems (e.g., storm damage, icing, or new demand peaks), could also interfere with reliable supplies and flood protection.

Adjustments might be made at several points in the water management process. Managers make numerous choices that are sensitive to climate uncertainty as they formulate supply allocation rules, reservoir operating criteria, safety protocols, and plans for future development. Little examination of this process has appeared in the climate and society literature. A simple theory of adjustment would predict that managers continually respond to sensitivity and evolving climate risks by regularly updating the hydroclimatological data and reliability calculations to which decisions are tied. Indeed, U.S. Army Corps of Engineers regulations require 'continuous examination' of water system operating criteria in case adjustments are necessary (U.S. Army Corps of Engineers, 1982). If the evolving climate sensitivity or threat pushes the system past some critical reliability threshold, then adjustments are made in supply, demand, or flood control to bring performance back within acceptable limits. Adjustment is most likely to follow climate changes that reduce system reliability, though managers might also take advantage of a climate-induced increase in reliability, especially to increase deliverable supply.

In reality, however, several factors hinder smooth, rational adjustment. First, traditional hydrological analysis implicitly assumes climate stability, an assumption given greater credence as record length increases even in the absence of analytical procedures sensitive to secular trends in the data. Thus, planners may not recognize climate change until it has quite dramatic impacts on system operation.

Huff and Changnon (1987) bemoan this 'blind-spot' in hydrological analysis. They show, for instance, that significant temporal changes of intensity/duration relationships have occurred in Midwestern rainfall over the past few decades, changes large enough to require altered design specifications (see also Changnon, 1984; and Phillips and Jordan 1986 – on changing precipitation amounts in Arizona's Salt River Basin). Simply stated, changing climate invalidates the rationale behind traditional hydrological analysis: that the past is key to the future. But, the few treatments of climatic change in mainstream water resources literature do not appear to have evoked any fundamental change in approach (see, for example, Lettenmaier and Burges, 1978).

Of course, climate fluctuation is only one of several forces affecting water management. Growing funding problems for large projects and burgeoning public concern over environmental impacts limit the range of adjustments available to, or considered by, water planners (see Schilling *et al.*, 1987). Such constraints are illustrated in several recent studies of water development in regions where supply is short (see, for example, the institutional adjustment studies in Frederick, 1986; and Weatherford and Brown, 1986). The potential impacts of new water project cost-sharing formulae created by the 1986 Water Resources Development Act are just now being assessed (Schilling *et al.*, 1987), and their implications for climate impacts are unclear. For example, the project down-sizing likely to result from reduced federal support might provide less absorptive capacity, but may also yield greater operational flexibility.

Tradition is also a major constraint on adjustment to climate fluctuation. Water resources management has been dominated by a single adjustment mechanism: the maintenance of over-sized capacity to absorb climate shocks and other uncertainties. Managers seek to maintain a large enough buffer (e.g., excess supply, over-sized flood control structures, or so-called 'free-board', the difference between expected water levels and the top of control structures) to counter most threats to system reliability, including climate-induced changes in runoff. This approach is effective, conceptually and operationally simple, and can range from low-cost, incremental project enlargements to extremely expensive, dedicated buffer capacity. The ratio of capacity to actual use is typically quite large in public water systems due to risk-averse planning. Managers plan and operate systems so that water shortages or floods damaging to users occur less than once a century if it is technically and economically feasible, often planning for the worst conditions ever observed no matter how rare (Georgeson, 1986; Dziegielewski, 1986). The net social costs and benefits of this strategy are unknown (see Schilling *et al.*, 1987).

Over-sized capacity relies on the ability to build facilities and develop supplies ahead of growing demand and vulnerability. Yet, it was evident to some observers even a decade ago that the focus of water management in the U.S. was shifting from the development of new supplies to more flexible and efficient use of existing supplies (U.S. Water Resources Council, 1978), a trend that has continued in the 1980s (Wolman and Wolman, 1986).

Recent assessments testify to the impact of this trend: there exist few opportunities for major supply expansions in the U.S., especially in the western states (see Engelbert and Scheuring, 1984). While growing physical and social constraints on increased supply may be balanced by a wide range of alternative water use patterns (see, for example, White, 1984), the costs of adjusting use (e.g., transporting water from agricultural to urban areas) have not been assessed.

Managers are coming to view conservation, water reallocation between competing uses, water banking, and land use adjustment as legitimate responses to water problems. Wolman and Wolman (1986) argue that this more flexible approach is evident, for instance, in recent non-structural drought management plans for Washington, D.C. Yet, even while praising flexible operations, they admit that:

> Dangers are involved in the assumption that (operational) decisions can be sufficiently fine-tuned to assure that periods of low supplies can be handled with calculated and agreed-upon levels of disruption ... and deferring of reservoir construction can be extended to the point that the rate of demand expansion exceeds the rate at which provision for expanded supplies can be provided (p. 17).

Their moral: Look for flexible alternatives, but keep the concrete handy. Such ambivalence within the water management community suggests that future challenges, like climate change, may still be met with a limited roster of adjustment options.

Climate impact researchers have not evaluated how climate sensitivity trends, and social factors impinging on water planning and management, might affect adjustment to future climate change. Can we identify factors that heighten water system vulnerability to impacts? What sorts of impacts will provoke adjustment? How well would current approaches to water management – both structural and operational – accommodate climate change? Some light can be cast on these questions by observing impacts and adjustment in actual cases of contemporary climate anomalies, as in the following case study.

4. Climate Impacts and Adjustment: A Case Study in California's Sacramento Basin

The goal of the Sacramento Basin case study reported here was to observe managerial adjustment to impacts from actual climate anomalies in a major water supply and flood control system. We chose the Sacramento climate division from several cases of decadal-length precipitation increases, decreases and changed variability found in the post-1945 U.S. climate record by Karl and Riebsame (1984). We chose a western U.S. fluctuation because that region's water supply depends chiefly on surface runoff and storage, and because western runoff is particularly sensitive to climate change.

4.1. *The Climate Fluctuation*

Climate analyses and anecdotal evidence suggest that California's Sacramento Basin has experienced greater climate variability over the last decade or so compared to much of the current century. Indeed, new record dry (1977) and wet (1983) water years were recently established (Figure 2a and b).[1] Variations in basin precipitation are directly reflected in runoff (Figure 3a and b). Other researchers have noticed increasing precipitation variability in the region. Granger (1979) found a sharp increase in annual precipitation variability during the 1970s in northern California. Indeed, it was the most variable period

[1] A water year is defined as the twelve months beginning October first of the previous calendar year.

since the 1880s. Sacramento Basin precipitation recently appears also to have exhibited greater intra-annual variability. McGuirk (1982), analyzing monthly precipitation for seven West Coast stations, showed that the two closest to the Sacramento Basin – Eureka and San Francisco, CA – both experienced enhanced variability beginning around 1976, after two decades of relatively stable precipitation.

The 1970s and 1980s were marked by the juxtaposition of extremes. The 1976–77 drought followed relatively wet winters during 1973–75, and ended in

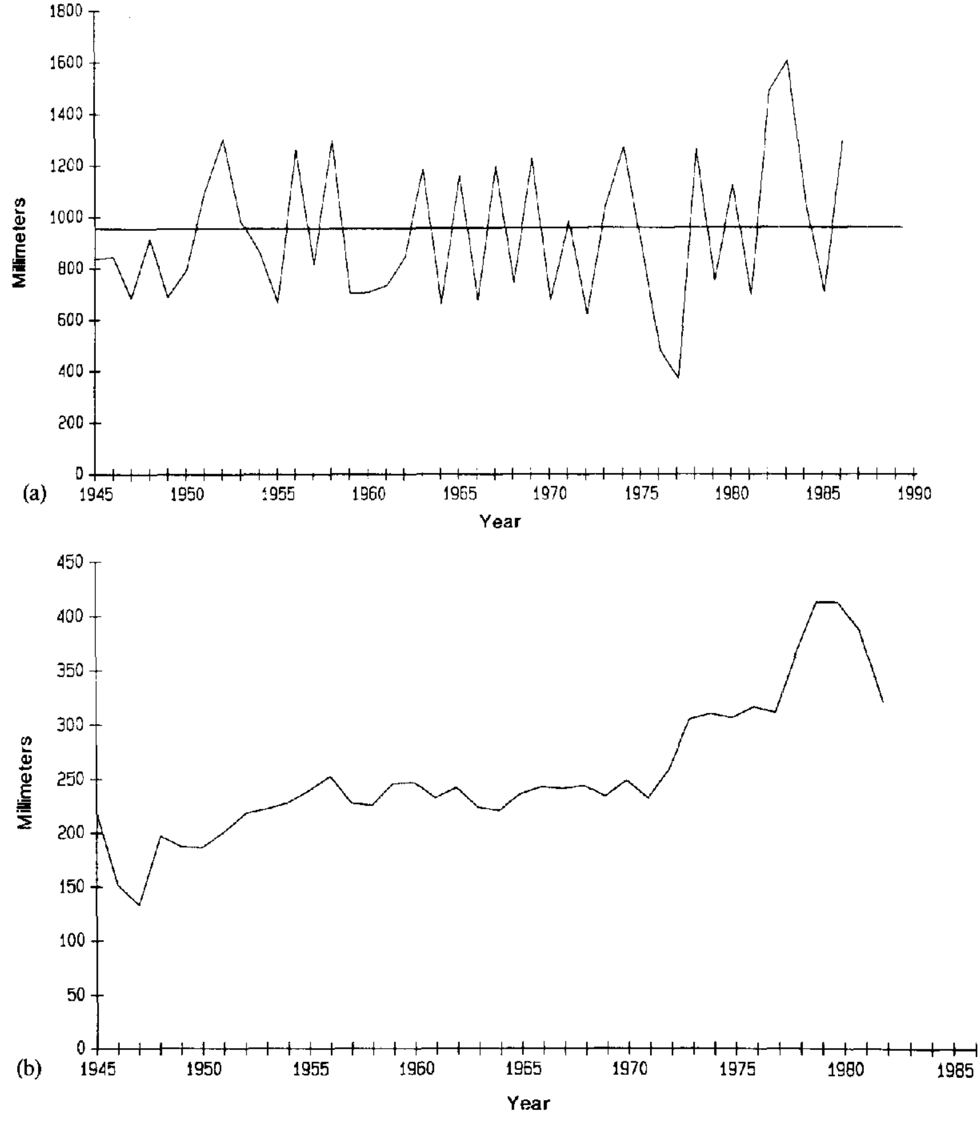


Fig. 2. Water-year precipitation (a) and 9-year running standard deviations of precipitation (b) for the Sacramento Basin climatic division. Source: National Climatic Data Center.

several intense precipitation events. Some observers called it 'the wettest drought in history' (see Kneese and Bonem, 1986). The winter of 1982–83 was one of the wettest ever experienced in the West, as storms apparently associated with an intense El Nino repeatedly entered the West Coast (see Rasmussen and Wallace, 1983, and Wilhite *et al.*, 1987). The Sacramento Basin floods of

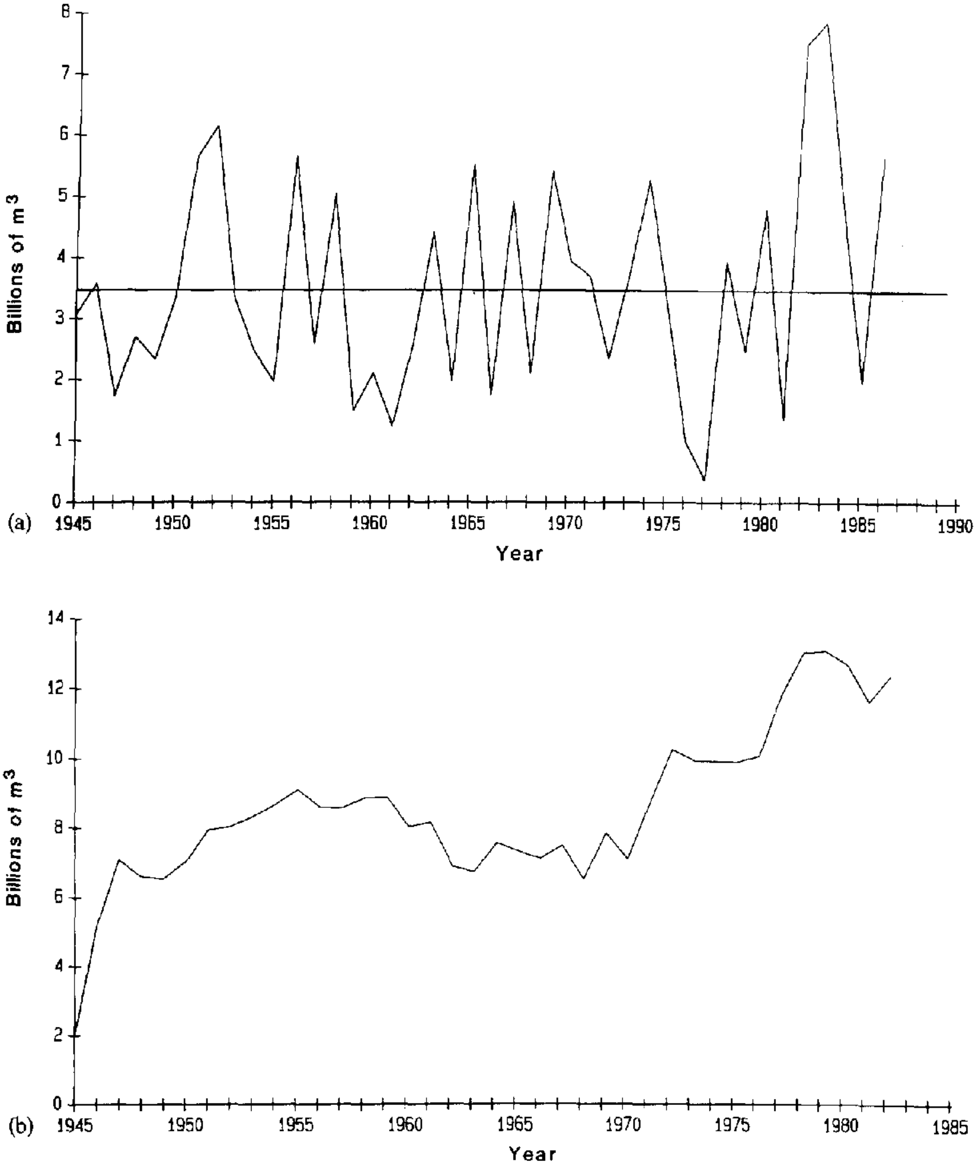


Fig. 3. Reconstructed water-year runoff (a) and 9-year running standard deviations of runoff (b) for the Sacramento Basin. Reconstructed flows are estimates of natural runoff without extractions for human use. Source: California Department of Water Resources.

February, 1986, associated with the heaviest precipitation of record, followed an abnormally dry early winter. By 1987–88, however, low Sierra Nevada snow-pack was again stressing water systems.

4.2. *System Sensitivity and Adjustment*

The Sacramento Basin encompasses two major water management systems: the California State Water Project (SWP) and the Bureau of Reclamation's Central Valley Project (CVP). Because its recent drought experiences are well documented, the water supply analysis focuses on the SWP. Flood management is best evaluated reservoir-by-reservoir, and that portion of the case study focuses on two key facilities, the SWP's Oroville reservoir and the CVP's Folsom reservoir.

Development of SWP facilities for storage, hydro-electric generation and long-distance water transport began in earnest after 1959 state legislation (the Burns-Porter Act) called for integrated water development; water was first delivered in 1962. Flood management in the basin dates to the 1880s, though contemporary reservoirs and levees were mostly in place by the mid-1960s (California Governor's Office of Planning and Research, 1979). Precipitation and runoff variability were relatively low during the early years of SWP water operation (Figures 2 and 3). From the mid-1970s to the present, however, water managers in the region faced a bothersome climate pattern, including more droughts and floods than anticipated from the historical record. This pattern should, theoretically, provoke adjustments in both supply and flood management.

4.2.1. *Water Supply Sensitivity to Climate Fluctuation*

The SWP derives most of its supply from precipitation and runoff in the Sacramento Basin. About 60% of the project's eventual yield is slated for use in southern California, though only 45% is currently sent south. Most of the remaining water fills irrigation and urban demand in the Sacramento and San Joaquin basins. Over the past several years an increasing amount of water has been sent through the system to maintain quality in the Sacramento-San Joaquin Delta and San Francisco Bay. Like all major water projects, SWP development is guided by a plan spanning several decades. The anticipated ultimate yield of roughly 5.3 billion cubic meters (bm^3)[2] was esentially fully contracted for by 1968, but full contract entitlements will not be used until after 2010 (California Department of Water Resources, 1983). While the development plan considers potential changes in demand, and incorporates margins of error and some uncertainty in supply (e.g., pending adjudication of water rights), like most such plans it does not incorporate the possibility of climate change.

[2] We use cubic meters rather than the traditional acre foot unit in this article. There are 1200 cubic meters in one acre foot. One million acre feet, then, equal 1.2 billion cubic meters.

The cycle of water management in the SWP begins at the start of the rain/snow season in late fall, as the 'water crop' begins to develop. Managers must store as much of this wet-season supply as possible for delivery during the summer peak demand period. The SWP's supply reliability is defined in its statutes and user contracts as the ability to meet requests in all but the most 'extraordinary conditions'. Until 1977 this reliability was supported by a large buffer between supply and delivery (Figure 4), which not only assured long-term supply, but made seasonal supply projections more reliable. If the rains stopped late in the wet season, managers could still meet projected deliveries by drawing on the large buffer supply.

Water supply projection and allocation was largely by tradition and intuition during the first decade of SWP operations (see California Department of Water Resources, 1983). Because the project was in many respects a response to severe drought in 1928–34 (when the need for drought-proofing was first voiced), managers tended to treat every dry spell as if it were a recurrence of this historical event. Thus, the worst drought on record became the project's design target, a water planning practice common throughout the country. The logic of planning for such multiple-year droughts was further supported by the occurrence of several back-to-back dry years in the mid-1950s.

Such risk-averse planning and operation creates a situation in which actual supply exceeds firm yield most of the time. SWP managers deal with this by declaring the excess for delivery as surplus rather than contract water. Contract amounts are tied to firm yield, while surplus water is not guaranteed from year to year, and thus acts as a flexible buffer to contracted supplies.

A climate and a social trend converged in the mid-1970s to erode the supply buffer and to heighten climate sensitivity in the SWP: interannual precipitation variability increased while planners faced growing constraints on the process of adding new facilities to maintain the spread between supply and demand. Storage capacity increased little after the early-1970s, while contract water requests, which quadrupled (from 0.4 bm^3 to 1.6 bm^3) between 1970 and 1975, approached the project's 90% firm yield of 2.96 bm^3 in the mid- 1970s (Figure 4). Managers responded by pushing for additional storage. However, a major new reservoir, and other projects needed to maintain the buffer between firm yield and contract requests (such as the proposed Sacramento-San Joaquin Delta peripheral canal), were delayed on environmental and economic grounds (Sudman, 1983b). The push for greater state and local water project cost-sharing further slowed facilities development (Franceschi and Sudman, 1983). The project's long-term reliability was threatened. Users could reasonably ask whether it would protect them from future drought if new facilities were further delayed.

4.2.2. *Water Supply Adjustment to the Climate Fluctuation*

Amid the project's growing sensitivity, the 1976–77 drought created a crisis that

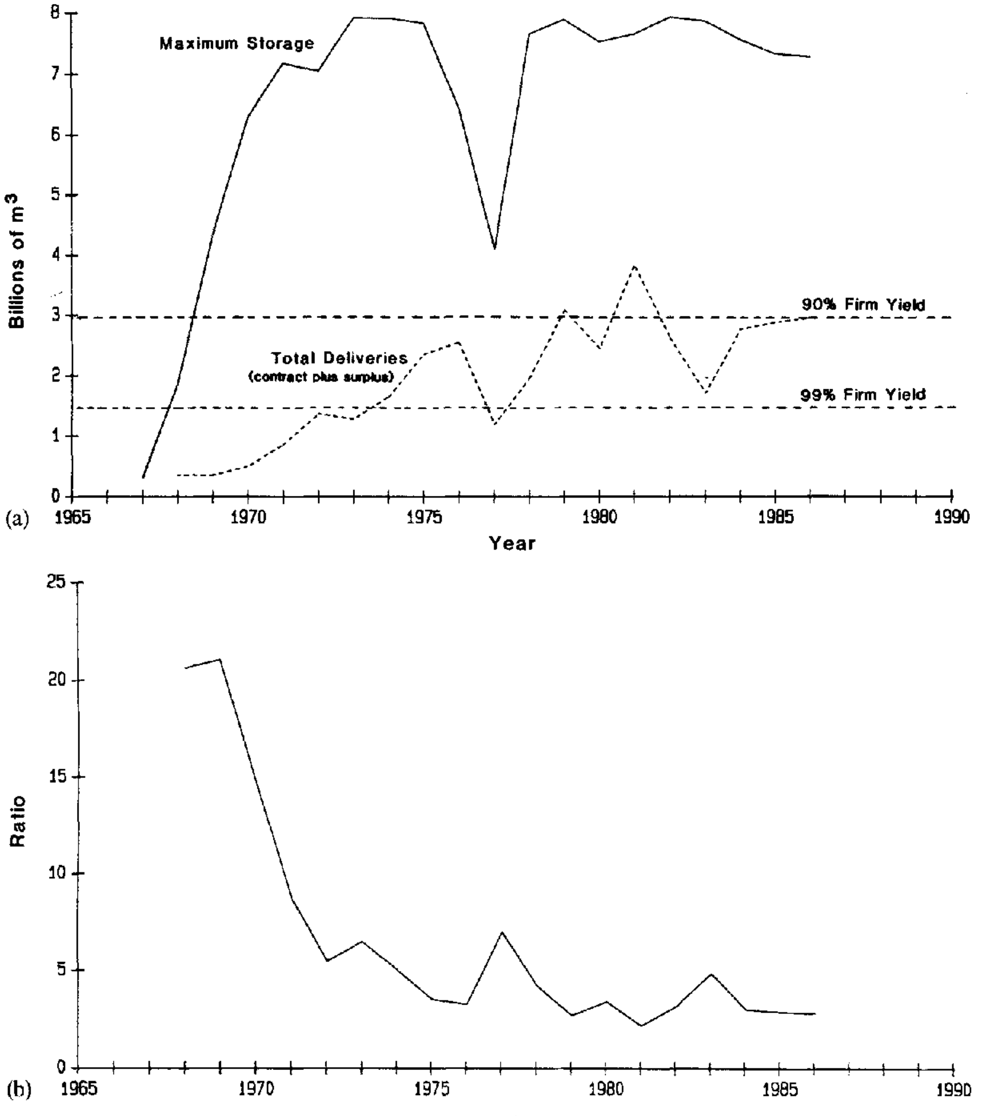


Fig. 4. Maximum annual storage, total deliveries, and firm yield estimates with 1980 facilities (a) and ratio of storage to delivery (b) for the California State Water Project. Source: California Department of Water Resources.

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.

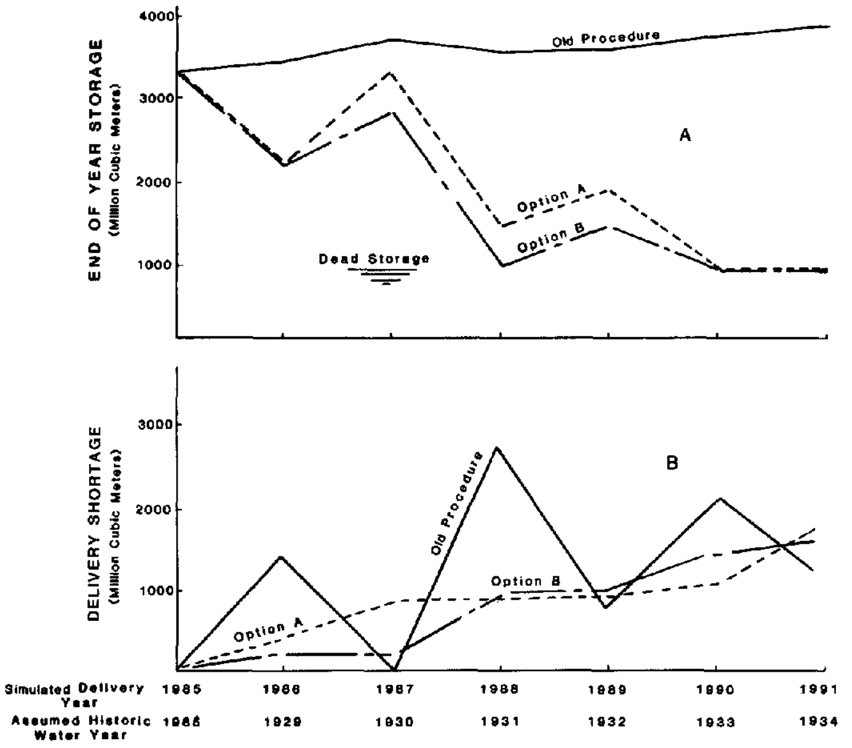


Fig. 5. Simulated SWP operations based on the 1977 rule curve and two alternatives proposed in 1985, for a hypothetical drought beginning with 1985 precipitation and storage conditions, and following the pattern of the 1929–34 design drought: (a) Total project storage at the end of each simulated year;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

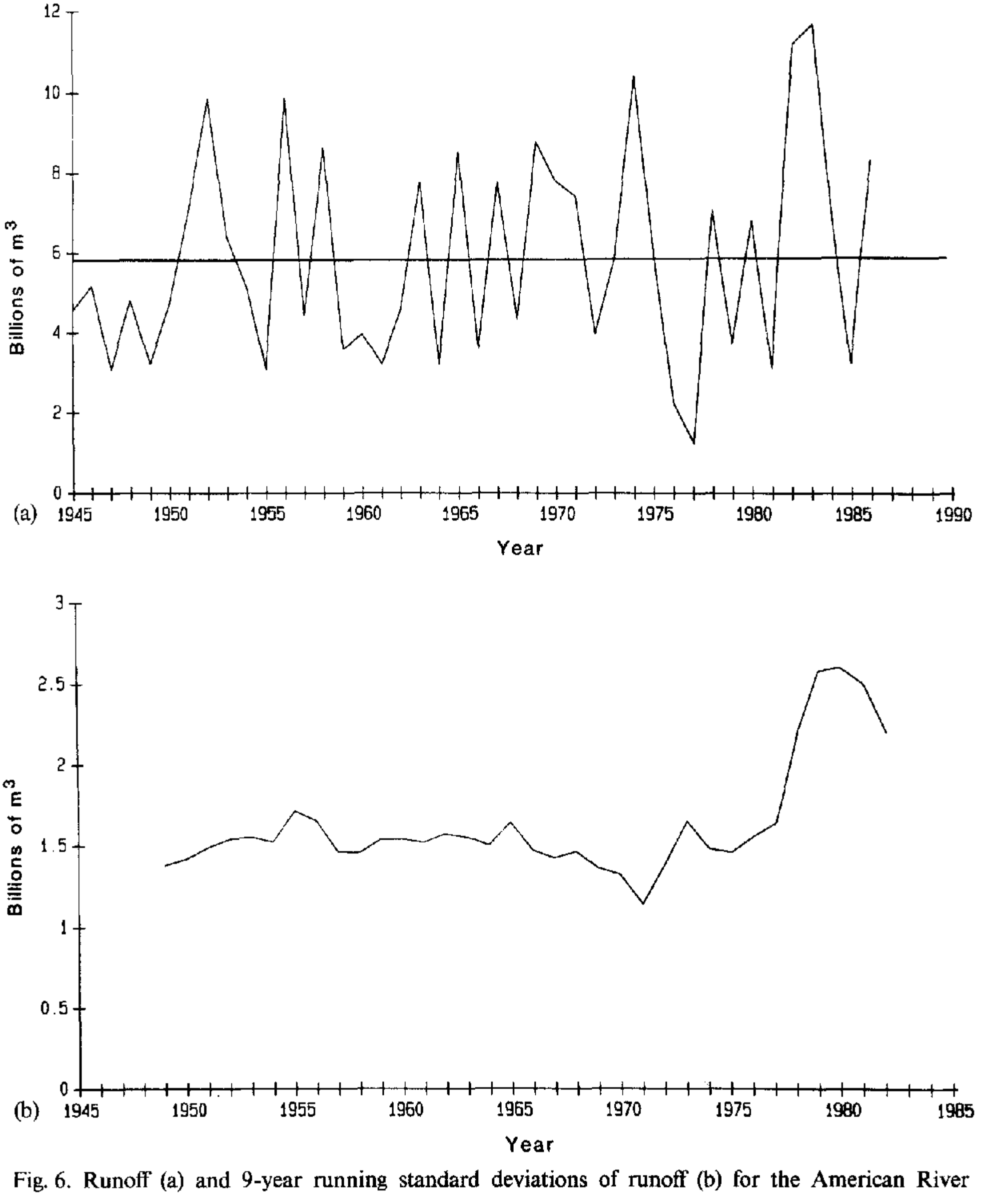


Fig. 6. Runoff (a) and 9-year running standard deviations of runoff (b) for the American River at Folsom reservoir. Source: California Department of Water Resources.

space available. Drier conditions allowed them to save more inflow to increase the chances of achieving a full reservoir before the runoff season ended. Oroville's flood control diagram (Figure 9) is similar, allowing conditional storage throughout the flood season. The 1977 revision of Folsom's diagram (Figure 8b) eliminated the conditional flood control reservation early in the flood season. Incursion into the flood space was proscribed, even under dry

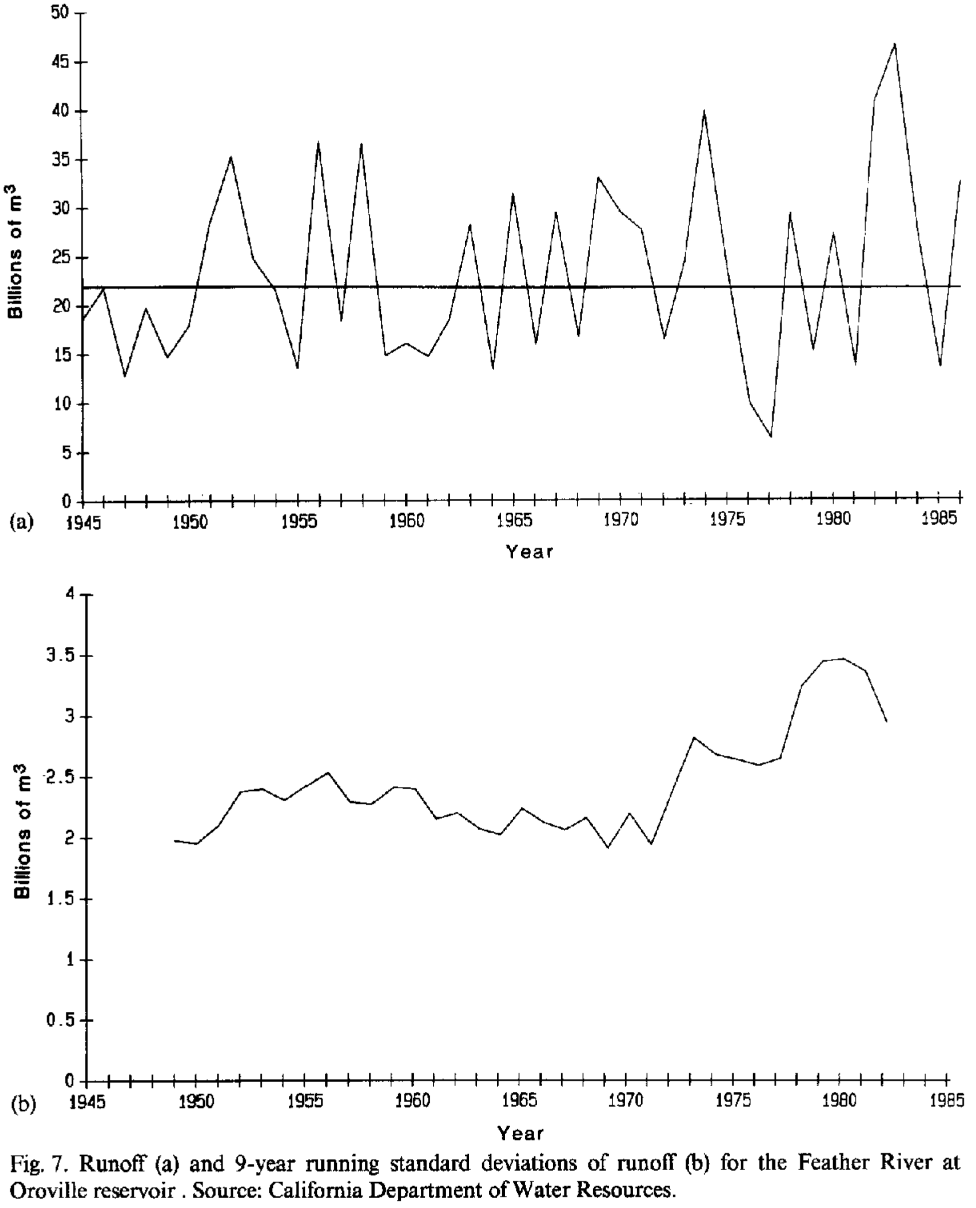


Fig. 7. Runoff (a) and 9-year running standard deviations of runoff (b) for the Feather River at Oroville reservoir . Source: California Department of Water Resources.

basin conditions, until after January 1 (many of the recent floods occurred in November and December).

In February, 1986, heavy storms caused the worst flooding on record in the Sacramento Basin (California Office of Emergency Services, 1986). The six-day inflow to Folsom of 1.41 bm^3, which would more than fill the completely dry reservoir, exceeded the RDF by 203 million m^3. Peak inflow rates at Oroville of 7,545 m^3 sec^{-1} also exceeded previous records, but not the RDF. Folsom

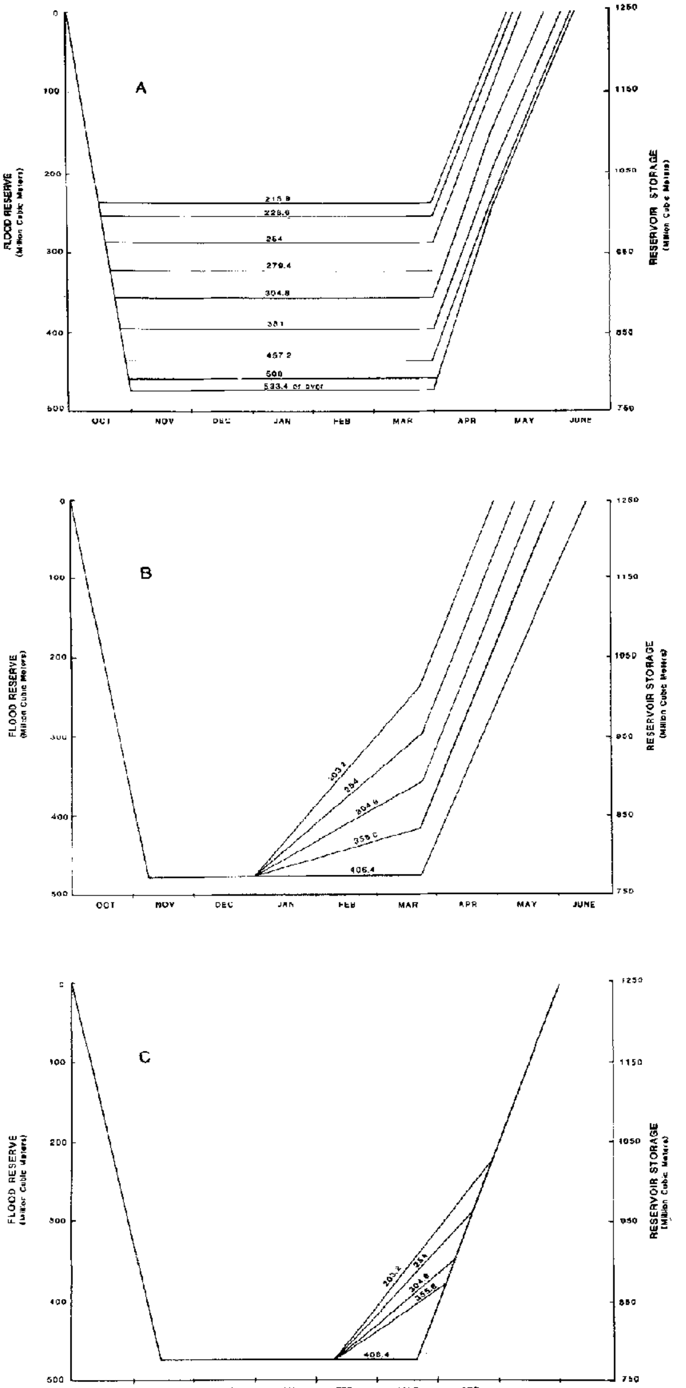


Fig. 8. Flood control diagram for the Folsom dam and reservoir showing adjustments through time: (a) original design, (b) 1977 change, and (c) 1987 change. The diagram specifies allowable reservoir levels at different times of the flood season based on previous basin precipitation. The lines with labels running from 215.9 to 533.4 (mm) represent basin wetness based on precipitation recorded during the previous six weeks. Source: U.S. Army Corps of Engineers, Mid-Pacific Region, Sacramento, CA.

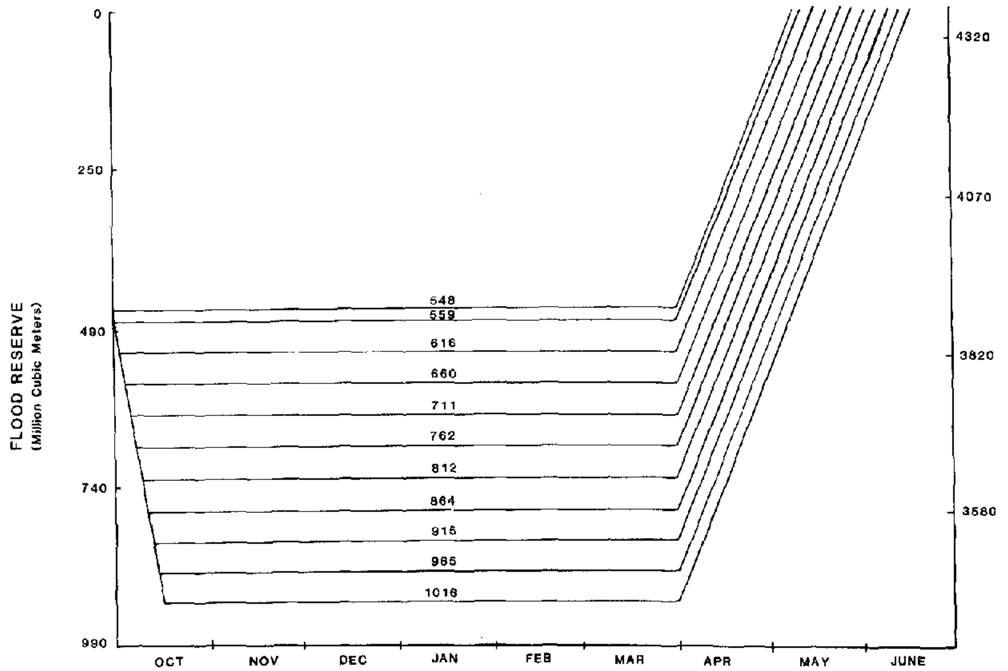


Fig. 9. Flood control diagram for the Oroville dam and reservoir. The lines labeled from 548 to 1016 (mm), as in Figure 8, delimit allowable reservoir levels based on precipitation observed in the basin during the previous six weeks. Source: U.S. Army Corps of Engineers, Mid-Pacific Region, Sacramento, CA.

Reservoir 'failed' in two ways during the 1986 flood. Storage reached a maximum of 1.27 bm^3, roughly 22 million m^3 above normal capacity. Peak releases exceeded the safe downstream channel capacity for over 48 hours, causing considerable flood damage. Five days were required to empty the Folsom flood pool (California Department of Water Resources, 1986; U.S. Bureau of Reclamation, 1986). At Oroville, on the other hand, storage peaked at 4.03 bm^3, leaving 0.3 bm^3 of flood buffer available. Releases from Oroville reached, but did not exceed, the maximum safe rate.

This flood forced another evaluation of flood control in the Sacramento Basin, and the Corps of Engineers again recalculated RDF recurrence intervals. The new value for Oroville remained well over the 200-year threshold often applied to developed basins, but Folsom's RDF return interval decreased to 63 years (Neal, 1986; and U.S. Army Corps of Engineers, 1956, revised 1987). This led to another revision of Folsom's flood control diagram (Figure 8c), further reducing the conditional flood storage strategy in favor of greater fixed flood reservation through mid-February. Managers are now much more wary of conditional reservoir levels based on basin wetness, since the February, 1986, storms followed a dry winter, and roughly 123 million m^3 of the flood buffer was filled when they occurred (U.S. Bureau of Reclamation, 1986). Indeed, the

CVP has maintained an extra 12.5 million m^3 of flood reservation in Folsom lake since the 1986 floods. But, reduced reservoir levels lower the probability of reaching full supply later in the season, and in 1987–88 the CVP asked local governments to compensate it for water supply capacity lost to greater flood protection (*The Sacramento Union*, 1988).

Changes now being considered for Oroville's flood storage rules provide a striking contrast to adjustments at Folsom. The 1986 flood showed that Oroville dam was more than adequate to handle design floods. To increase their supply capacity, SWP managers have asked the Corps of Engineers to allow more rapid fill of the flood reservation in the spring to increase the probability of reaching full reservoir capacity each year.

4.3. *Summary and Implications of the Case Study*

During the last three decades of rapid water development in the Sacramento Basin managers relied initially on over-sized capacity to absorb climate fluctuations. This strategy was constrained in recent years as new facilities were delayed by economic and environmental factors. In responding to increased climate variability beginning in the mid-1970s, managers have focused on adjusting operational aspects of the existing system.

In terms of SWP water supply, room for operational adjustment is found in the difference between planning for multiple-year and short-duration droughts. In the formal allocation protocol implemented during the 1976–77 drought, managers implicitly chose to operate the system to absorb multi-year, cumulative droughts like those of the 1930s and 1950s. But, the drought ended abruptly – with quickly replenished supplies – and subsequent droughts, including the 1985 crisis that provoked new rule curve designs, were also short-lived events. The system is now operated using more flexible allocation procedures that adjust dry-year operations to shorter droughts.

The apparently growing threat of flooding in the Sacramento Basin over the last decade also evoked operational adjustments. CVP managers adjusted by enlarging the fixed flood reservation behind Folsom Dam during larger portions of the wet season. Conversely, at Oroville, a reservoir with more demonstrated absorptive capacity, SWP managers argued for more rapid reservoir filling in the spring to improve its water yield reliability.

Whether the power of such operational adjustments to absorb climate fluctuations carries over to long-term climatic change, depends, of course, on the nature of future climate. The seasonal shifts in Sacramento Basin runoff simulated by Gleick (1987) may be accommodated by such adjustments, but large changes in runoff will eventually outstrip operational as opposed to structural responses. Then larger supply and storage, decreased demand, or lower delivery reliability will be required. In this process it is reasonable to expect managers to make relatively inexpensive operational adjustments first, especially before they recognize fluctuations as fundamental climate change. The case study, thus, may presage the early stages of adjustment to CO_2-forced climate change over the next decade or so, before there is widespread belief that the climate is, indeed, changing.

Responses to climate variability in the Sacramento Basin also illustrate several general aspects of water management adjustment discussed in the first three sections of this paper. The case shows the interaction of changing climate sensitivity and climate fluctuation as water systems mature, and the effect of growing constraints on traditional adjustments to climate stress. Evolving water systems exhibit windows of climate vulnerability that should be considered in assessing long-term reliability under climate change. Calculations of average reliability may not fully represent the potential for climate impacts during periods when planned facilities development is delayed or operational procedures become out-dated. If trends of growing water demand, intensified floodplan development, and tightening economic and environmental constraints continue, the physical buffer that can be maintained to absorb climate fluctuations will be lessened. Emphasis will thus shift to short-term, operational adjustments, the efficacy of which, in the face of climate change, remains to be assessed.

5. Some Conclusions on the Mechanisms of Adjustment

The Sacramento case study and preceding general discussion point to certain climate adjustment patterns common to water and, perhaps, other resource systems. Both small, incremental adjustments and more drastic, crisis-oriented responses (a distinction discussed by Glantz, 1979) appear. While the forces behind adjustments in crises are obvious (and the processes and mechanisms involved have been studied extensively under the rubric of natural hazards research), we know much less about how incremental or gradual adjustment is effected. The case study points to several types of gradual adjustment worth further study. First, an "automatic" adjustment pattern emerges. When system operating criteria, such as allocation rule curves and conditional reservoir flood pool levels, are tied to empirical climate indices, they function as self-adjusting mechanisms. That is, within limits, they adjust systems to changing climate without overt manager action. For instance, a greater frequency of dry spells would result in more frequent application of the SWP rule curve to reservoir storage requirements. The system would, thus, adjust incrementally and automatically through reduced water declarations. Eventually, however, a drying trend would antiquate the rule curve, and conscious action would be needed to update it.

Another mechanism of gradual adjustment is the occasional up-dating of management criteria as climate records lengthen. Any water system undergoing periodic evaluation of, say, its design flood return period, can incorporate climate change, even if managers do not recognize the change. Of course, different rates of climate change should, optimally, be matched with different up-date frequencies. In current practice, however, reassessments are mostly made only after extreme events, an approach that would not facilitate smooth adjustment to a changing climate.

Both of these adjustment mechanisms are incidental. If resource managers choose to create adjustment mechanisms specifically to deal with long-term climate change they will be forced to decide how much absorptive capacity should be maintained, a process requiring answers to several questions: How much should be spent now to avert furture impacts? How should expenditures and impacts be distributed? What certainty of future climate change is necessary to prompt incorporating adjustment mechanisms into current resource systems?

At least in those regions where climate sensitivity of water supplies is growing, it would be prudent to examine these questions and to explore water planning procedures that explicitly include climate change as a risk factor. For example, hydrologists should explore the effects of weighing recent events more heavily than earlier episodes in statistical analyses. Once convinced that the climate is changing, resource managers would then be able to call on greater experience with analyses sensitive to secular trends. Of course, the weight given to recent trends would depend on the strength of belief that climate change is underway. If current predictions of climate change associated with CO_2 are correct, this belief will eventually overwhelm traditional assumptions of climate stability. In the interim, the incidental adjustment mechanisms described above will probably dominate. Given this, climate impacts researchers should develop and apply more incisive measures of water system sensitivity to climate disruption in order to identify vulnerable areas and to monitor adjustment trends that might exacerbate or ameliorate future impacts.

Finally, in the optimistic view of social adjustment to climate change alluded to in the introduction to this paper, the existence of several operational adjustment mechanisms in water resources can be interpreted as support for the assertion that resource systems have the requisite flexibility to accommodate future climate change without significant disruption. However, there are limits to the absorptive power of flexible operations. Major structural solutions may be called for eventually if climate continues to change. What is needed to clarify the debate, then, is a more definitive assessment of the absorptive capacity currently incorporated in physical facilities and likely obtainable from operational adjustments given a reasonable range of climate futures.

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