Natural Heritage Institute

Feasibility Study of a Maximal Program of Groundwater Banking

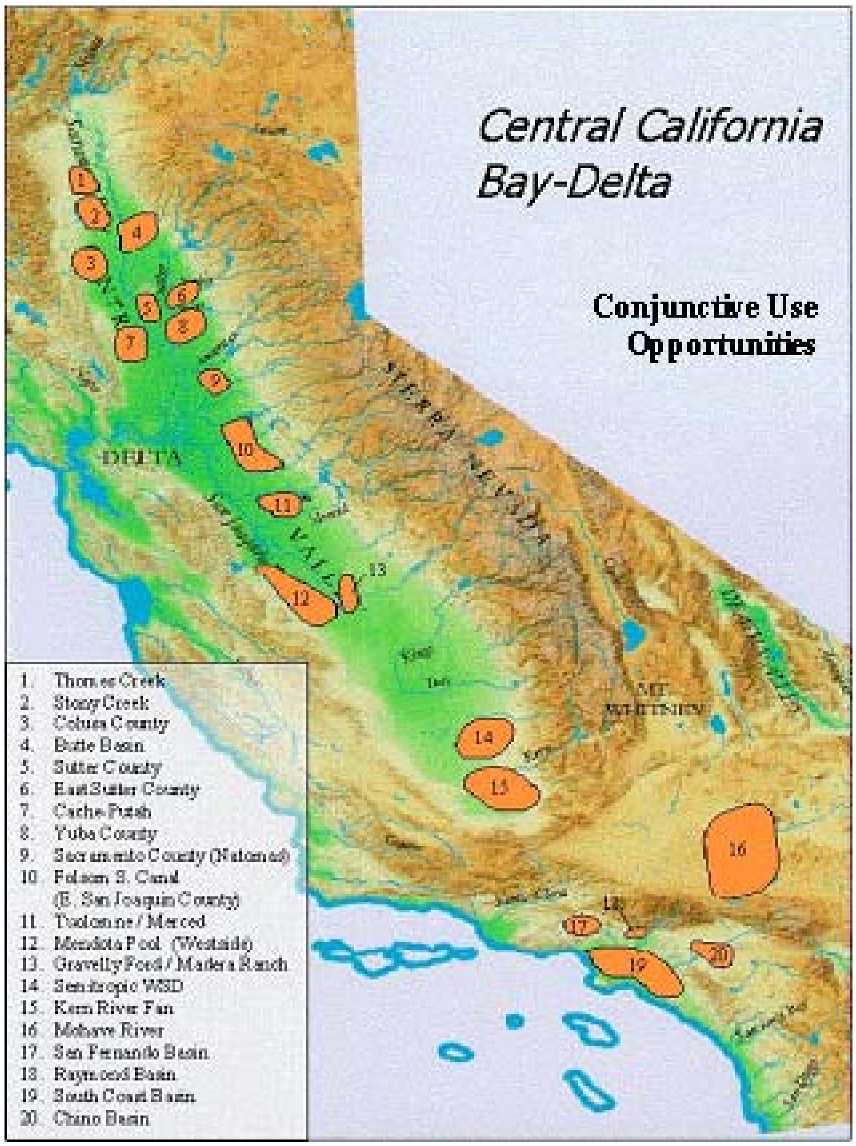

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Table of Contents

Acknowledgements

This report would not have been possible without the sustained support of the Ford Foundation. Recognizing the enormous contribution which groundwater banking could make towards diffusing water allocation conflict in California, indeed around the world, Ford was willing to underwrite several years of foundational research. By necessity, this research focused on framing the broad structural considerations and the general legal and institutional tenets of a maximal program of groundwater banking. Thanks to their generous financial assistance, however, we have also succeeded in adding form to the frame. The exciting payoff from the Ford Foundation's investment are the explorations of site-specific details of groundwater banking opportunities which are recounted in this report. Extending this analysis to the full suite of opportunities is now possible.

Our explorations have been facilitated by the availability of the Water Evaluation and Planning system (WEAP). This innovative river basin planning software, developed by the Tellus Institute in Boston, Massachusetts, underwent a major upgrade thanks to the financial support of the CalFed Bay-Delta Program, the U.S. Fish and Wildlife Service, the U.S. Bureau of Reclamation, and the Metropolitan Water District of Southern California. We sincerely appreciate the contribution of each of these valued partners and look forward to additional collaboration in the area of groundwater banking.

Finally, we would like to acknowledge you, the reader, for your willingness to read this document. We cannot promise that it will always make for gripping reading, although we are confident that it is an important contribution to the ongoing discussion of groundwater banking. Whatever your position in the California Water Community, it is in this context that we thank you. Only an open exchange of ideas will transform groundwater banking into a water management reality and we look forward to continued dialogue in the months and years to come.

Preface

Periodically since 1957, the California Department of Water Resources has published *The California Water Plan*. A review of these documents reveals that what began as an inventory of existing water supply and demand patterns, and projected future changes, has evolved into planning document which recommends options for balancing water demand and supply in the future. Bulletin 160-93, the 1993 version of *The California Water Plan Update*, was particularly noteworthy in terms of its recognition of the need to integrated the management of the state's surface water and groundwater resources (conjunctive use). According to *The Plan* (DWR 1994):

> In the future, carefully planned conjunctive use will increase and become more comprehensive because of the need for more water and the generally higher cost of new surface water facilities. Conjunctive use programs generally promise to be less costly than new traditional surface water projects because they increase the efficiency of water supply systems and cause fewer negative environmental impacts than new surface water reservoirs (page 103).

This statement is full of promise and expectation, positive tones which have sustained a conceptual discourse on conjunctive use and groundwater banking in California for many years. The end result of this promise and expectation is that groundwater banking has become an element of the standard litany of water management strategies for California, and is often held up as a win-win alternative for the state's disparate stakeholders.

When an attempt is made, however, to translate the conceptual model into actual yield enhancing projects, promise and expectation often give way to concern and uncertainty. Focusing attention on the conjunctive management of specific rivers and groundwater basins consistently raises "red flags" for those whose livelihoods depend on these resources. NHI does not seek to discredit these reactions. Given the level of investment in the current water management system and the hydrologic and economic uncertainly associated with conjunctive use, most are legitimate. Nonetheless, this report adopts the perspective that these concerns should catalyze analysis and dialogue, not extinguish them. The research we have conducted to date flows from this perspective and responds to many of the regularly waved red flags. In the interest of catalyzing increasingly site-specific analysis, the pages of this document report that:

- Re-operation of the terminal reservoirs on each of the major rivers between the Lake Shasta and Millerton Lake as part of a maximal groundwater banking program, in coordination with reservoirs located upstream, could generate approximately 1 MAF of average annual yield and increase the overall performance of the surface water infrastructure.
- Under existing law, there is no proscription against importing surface water for storage in a groundwater basin and eventual recovery for use off site.
- An inventory of potential aquifer storage sites discovered over 10 MAF of available storage a various places around the Central Valley, much of which could be accessed by re-operating and/or modifying conveyance infrastructure.
- Modification of conveyance infrastructure in a portion of the Sacramento Valley could enhance the yield of Shasta Dam by up to 40 TAF during dry years, while assisting water managers in Yolo County forestall future groundwater overdrafts.
- By increasing yield on the San Joaquin River, aquifer storage at Gravelly Ford could allow for downstream releases of approximately 144 TAF to restore the anadramous fishery while largely preserving the important agricultural economy in the southern San Joaquin Valley which currently diverts nearly the entire flow of the river.
- The proximity of a significant aquifer storage resource to the east of the Delta in San Joaquin County could increase the reliability of water supply south of the Delta, relieve chronic groundwater overdraft conditions and allow for enhanced Delta outflow when integrated with enhanced Delta conveyance infrastructure.
- At a cost which is generally less than $300 per acre-foot, groundwater banking projects similar to the examples cited above are must more affordable that surface water development projects which can cost up to $3000 per acre-foot.

These findings are an exciting step in the translation of a conceptual model of groundwater banking into actual programs which produce new water for both water supply and environmental restoration. We are optimistic that they are sufficiently compelling to allow some red flags to be lowered, if not furled. In keeping with this optimism, NHI anticipates that the analysis presented in this report will launch a useful dialogue about fulfilling the promise of groundwater banking. This analysis employs several innovative analytical tools which we expect will assist in developing a consensus around this management strategy. These including:

- The Conjunctive Use Potential model, or CUP, which can be used to assess the yield potential of the Central Valley reservoirs under a variety of assumptions regarding reservoir operating rules, conveyance capacities, and aquifer storage space.
- A legal matrix which weighs the relative strength of claims to various types of water stored in groundwater banking sites.
- A matrix of criteria which can be used to rank the suitability of specific groundwater banking sites.
- The Water Evaluation and Planning system, or WEAP, a monthly time-step water allocation model which allows for operational simulations which place specific groundwater banking sites in the context of surface water infrastructure and distributed water demand.
- An extensive database of existing groundwater banking activity in California which can be mined for important insights about avoiding potential pitfalls in the path towards groundwater banking.

We recognize that the task of fulfilling the promise of actual groundwater banking opportunities will only come from site-specific analysis which sufficiently resolves local details to allay the concerns of local actors and regional water managers alike. Our next phase of analysis will involve extending preliminary operational analysis similar to that conducted in Yolo and San Joaquin Counties and along the San Joaquin River to the other potential sites depicted on the cover of this report (also Figure 8). In all cases further refinement of site specific analysis will include:

- Facilitating stakeholder consultations;
- Defining operational changes required to practice groundwater banking;
- Assessing the suitability of groundwater banking in light of competing land uses;
- Evaluating potential environmental complications;
- Addressing local socio-economic and political realities;
- Optimizing the economic value of the site; and
- Resolving legal and institutional barriers.

The end result of this effort will be a suite of the most compelling groundwater banking opportunities ready for presentation to policy makers. The importance of this step cannot be underestimated. The policy making community must have this analysis in hand before making any final decisions about groundwater banking. Absent a well articulated strategy for capitalizing on this storage modality, it is unlikely that any storage enhancement program can be advanced. NHI offers ours analysis as an important contribution to this articulation.

I. Introduction

California's Central Valley watershed, made up of the San Francisco Bay-Delta Estuary and its upstream tributaries, is an extraordinary environmental resource for fish and wildlife. At the same time, the watershed provides much of the water that fuels California's enormous economy. Experience gained during the 1987-1992 drought indicates that operating the installed hydraulic infrastructure in the Central Valley under existing rules and proposed regulations will increasing bring economic and environmental water management objectives into conflict. The hard reality is that under rigid adherence to antiquated management arrangements, the Central Valley watershed cannot shoulder the enormous burden of simultaneously satisfying environmental and economic needs. Both the economy and the environment will ultimately suffer if this incompatibility remains unresolved.

One path towards resolution is increased water use efficiency and demand management. Environmentally benign water development which capitalizes on the storage capacity available in California's chronically dewatered aquifers is another. While in no way discounting the potential benefit of the first approach, this paper reports the findings of a feasibility study which rigorously explored the second path, specifically the potential for increasing both environmental and economic water supplies through an aggressive, maximal scale program of groundwater banking in the Central Valley water system. The results are very promising. Based on hydrologic considerations alone groundwater banking has the potential to provide approximately 1 MAF of additional annual yield, with the greatest benefit coming in new opportunities to supply consumptive demands and to enhance stream flows.

NHI's specific mission is to seek out and define opportunities for the conservation of natural resources. In responding to this objective, we cannot ignore the environmental benefit which an annual 1 MAF augmentation of water supplies in California would create. Cognizant of the pressing need to rededicate water back to the rivers and estuaries whence it has been diverted over the past century and a half, we have viewed this potential yield increase largely through the optic of environmental restoration. NHI, however, is also very pragmatic. Recognizing that powerful interests will naturally seek to defend the economic developments made possible through historic water diversion, ***we sought to demonstrate that groundwater banking can become one of the elusive win-win alternatives long desired by the California water community***. To make this case we adopted a very systematic approach towards analyzing and surmounting the physical, legal and institutional barriers which could stymie full realization of the yield potential associated with groundwater banking. The intent of this reductionist approach is to preemptively respond to the visceral reactions which are sure to greet a call to strengthen the ties between the management of California's surface water and groundwater resources. By addressing, and hopefully dispelling, some of these concerns in advance, this report lays the groundwork for to the full realization of the wide-spread benefit made possible through groundwater banking.

Funding from the Ford Foundation enabled NHI to produce this feasibility study. Although the work is the most comprehensive collection of analysis on the various aspects of groundwater banking in California produced to date, much work remains if we are to witness on the ground changes which capture the potential benefits of 1 MAF of new annual yield. NHI will use this feasibility study as a vehicle to actively solicit supplemental support from foundations, as well as from interested agencies and private sector beneficiaries, so that implementation of groundwater banking can help reduce the burden on the Central Valley water system.

I.1 The Problem: Imbalance Between Existing Stocks and Anticipated Flows

In the parlance of systems analysis, system reliability is a function of stock and flow characteristics. Systems where the desired flows are a large fraction of available stocks are vulnerable to disruption. This general axiom is true whether the system in question is a warehouse which furnishes goods in satisfaction of retail demand or a system of reservoirs which furnish water to cities and farms. Just as the warehouse which barely keeps up with retail demand in June will not satisfy the December rush, so a system of reservoirs which just covers demand under average hydrologic conditions will have difficulty providing adequate water supplies during times of drought. Municipal supply organizations have long understood the importance of system reliability. A survey conducted for the California Urban Water Agencies estimated the statewide value of water supply reliability to urban consumers at more than one billion dollars annually (Barakat & Chamberlin 1994). The Metropolitan Water District of Southern California began its recent Integrated Resource Planning process with the establishment of water supply reliability goals (MWD 1995). Only having set these goals did MWD begin to evaluate the anticipated levels of water supply and demand.

In California, the anticipation is that municipal demand will increase in response to population growth. The important agricultural industry in California would like to preserve historic production levels while at the same time emerging environmental standards respond to the critical need for additional water to enhance stream flow, particularly during dry years. Once again in the parlance of systems analysis, the desired flows in the California water system are likely to increase. Historically, the response to increased demand has been to increase stocks by constructing massive surface reservoirs. This approach, however, has fallen out of favor due to its high economic and environmental costs and it is unlikely to prove useful in the future without exhaustive consideration of alternatives. However, when the existing stocks fail to capture the excess wet year supplies needed to satisfy higher anticipated system flows, both economic and environmental values will be threatened. To reduce future disruptions, the desired system flows should be regulated via demand management. In addition, however, opportunities for increasing stocks, to the mutual benefit of economic and environmental interests, should be explored. This report focuses on one particularly compelling strategy for enlarging the stock, groundwater banking.

I.2 A Solution: Groundwater Banking to Increase Future Stocks

Relative to the construction of surface water reservoirs, enlarging the stock via groundwater banking, the storage of excess wet year supplies in subsurface aquifers, is a less controversial, lower cost, more environmental benign approach. Groundwater banking has numerous economic and environmental advantages compared to surface water storage: it reduces losses from evaporation, thus allowing for long-term storage; it allows for greater regulation of natural inflows, without the construction of a huge new network of reservoirs;[1] and it is generally less expensive than surface storage. As with all water storage systems, however, the main purpose of groundwater banking is to convert a fluctuating input of water from precipitation and snowmelt, into a steady supply stream which responds to a water demand pattern which differs from the input stream. Also in keeping with other forms of storage, groundwater banking occurs when water is plentiful, and produces stocks to tap when water is scarce.

Based on this operational definition, the natural hydrologic system is the preeminent practitioner of groundwater banking. During wet years, excess precipitation and elevated stream flows result in high levels of infiltration. As a result, aquifer recharge exceeds pumping, which has been suppressed by well endowed surface water supplies, and there is a net inflow into the aquifer. Groundwater has been banked. When dry hydrologic conditions return, suppressing both infiltration and surface water supplies, pumping by those overlying the aquifer will exceed recharge and the bank will be tapped. Natural groundwater banking, which cycles volumes of water which are orders of magnitude larger than those contemplated here, is not the focus of the maximal program of groundwater banking. Nor will the program rely on shaving the peaks off of the relatively infrequent and limited duration large flow events which already occur below California's surface water reservoirs during wet years.

In order to increase the available stock, the maximal program of groundwater banking will start by intentionally transferring water from surface water storage to a groundwater bank during the late spring and summer. As this is the period of time when storage in California's reservoirs is generally highest, the transfers can be aggressive and sustained. They can be accomplished either directly, through percolation at spreading basins, or through "in lieu" surface water deliveries in areas which rely heavily on groundwater pumping . The result of several months of intentional transfer will be an increment of additional storage in an aquifer and the equal increment of potential storage space in the surface water reservoir. Final

[1]New facilities would be required but the unacceptable environmental and economic costs associated with primary dependence on surface storage could be reduced.

augmentation of the available stock in the system will be accomplished during subsequent winter storms and early spring runoff when the extra available reservoir space enable flood control operations which capture an increased volume of the reservoir inflow. Should a reservoir emerge from the wet season full, then the increment of water in the groundwater bank represents yield which would have otherwise gone unrealized. With these additional supplies in place, when the next dry year inevitably comes, economic demand for water may be satisfied from the groundwater bank, leaving the available surface water to be used to respond to the critical environmental need for enhanced stream flow.

1.3 Building a Case

This type of groundwater banking, which can help satisfy both economic and environmental water supply needs, has not developed on a significant scale in the Central Valley. The workplan which was implemented in carrying out this feasibility study was conceived to systematically address the barriers which have prevented aggressive groundwater banking from occurring. First among these is the perception that surface water reservoirs must be operated to serve only a narrow set of project beneficiaries. This parochial attitude towards the State's hydraulic infrastructure has discouraged the type of hydrologic analysis needed to determine the full water supply potential of a maximal program of groundwater banking. In a similar manner, the dependence of anadramous fish in the Central Valley on cold water releases from the major foothill reservoirs has forestalled consideration of aggressive reservoir re-operation.

> **Workplan Step 1: <u>Hydrologic Potential Analysis</u>**
> Assuming perfectly efficient storage and recovery potential, investigate the magnitude, frequency, and location of water that, absent reservoir re-operation as part of a maximal program of groundwater banking, would be released for flood control purposes and would otherwise be unavailable for environmental or consumptive purposes. Constrain the analysis only by the need to maintain suitable temperatures for fisheries downstream of the major foothill reservoirs.

The fear that this re-operation could further imperil Central Valley fisheries is not without merit. In one case where intentional transfers of surface water to aquifer storage have been accomplished, the environmental effects have been extreme. Because of the relatively small size of its central reservoir, the beneficiaries of the Friant-Kern unit of the Central Valley Project aggressively maximize pre-delivery from Millerton Reservoir on the San Joaquin River to the aquifers below their service area, to the point that a stretch of the San Joaquin below Friant Dam is frequently dry. The Friant-Kern example illustrates both of the potential for groundwater banking to enhance stocks, and the risk posed when the sole beneficiaries of the enhance groundwater storage are the local consumptive uses. This scenario is possible because water in groundwater storage in the Central Valley is viewed differently than surface storage. Whereas surface storage is endowed with specific user rights, even for distant beneficiaries, groundwater it is generally perceived of as a local resource, available only to overlying landowners. As a result, the use of groundwater storage to provide economic and environmental benefits for areas remote from the aquifer storage site is relatively rare in the Central Valley.

> **Workplan Step 2: <u>Legal and Institutional Analysis</u>**
> Investigate the legal support for the perception that the benefit of all water stored in a aquifer is the sole possession of overlying land owners and describe institutional arrangements, including voluntary contractual arrangements, that would be necessary to get overlying landowners and water districts to cooperate in a program of groundwater banking with broad economic and environmental benefit.

And yet, in the San Joaquin Valley the potential for maximal groundwater banking is massive. Past dependence on groundwater has produced areas where the water table is depressed, creating opportunities for storage. Moreover, heavy groundwater development has catalyzed a number of detailed hydrogeologic studies and information on aquifer characteristics is widely available. In the Sacramento Valley there are fewer areas of long term overdraft as there exists a high degree of interaction between rivers and groundwater. Thus, groundwater elevations tend to recover relatively quickly during wet period following dry years when heavy pumping occurs. While this natural interaction between river and groundwater is useful for local water users, it complicates

> **Workplan Step 3: <u>Site Analysis</u>**
> Identify groundwater basins which are well suited for direct recharge and retrieval and/or in lieu recharge and retrieval based on the physical characteristics of groundwater basin as well as land use patterns, ownership, water district jurisdiction and water supply systems. Display sites on a map.

efforts to use Sacramento Valley aquifers as a storage medium for non-local beneficiaries. While areas do exist within the Sacramento Valley where groundwater levels have been permanently depressed by pumping, there is less local incentive to pursue intentional groundwater storage north of the Delta. As a result the hydrogeology of the Sacramento basin remains poorly documented and accounting for the water stored can be a significant problem. In both the Sacramento and San Joaquin Valleys, however, detailed inventories of potential groundwater banking sites need to be elaborated and presented. Of particular interest should be the degree to which integration of a particular groundwater basin into the Central Valley water system facilitates the efforts of overlying water managers as compared with strictly local water management initiatives.

Even with this inventory in hand, however, developing an operational strategy to capitalized on specific groundwater banking opportunities will remain problematic. Surplus surface water for groundwater banking is most commonly available in the Sacramento Valley. The Mokelumne River, and the San Joaquin tributaries, while endowed with excess surface waters, have less substantial hydrologic potential. Hydrogeologically, however, many of the most promising storage sites lie in the San Joaquin Valley. Moving excess Sacramento Valley surface water to these sites may involve transit through the Delta, from which exports are increasingly constrained. Overcoming this potential barrier will turn upon the ability to investigate the operational details of linking reservoir operations to groundwater storage and recovery. This type of investigation requires a simulation tool which is both flexible and robust so that the scope of potential operating regimes can be defined.

> **Workplan Step 4: <u>Operational Analysis</u>**
> Investigate if changes in the current operating regime in the Central Valley can overcome constraints on moving water from re-operated reservoirs to groundwater banking sites, and from there to points of economic and environmental use. These changes may be both physical (e.g., the capacity and availability of conveyance facilities) and regulatory (e.g., Delta pumping standards) in nature.

In addition to operational considerations, economic obstacles to the realization of a maximal program of groundwater banking must be identified and overcome. As both the physical and institutional arrangements for aquifer storage differ from surface storage, so to must the financial considerations. In terms of planning and construction costs, aquifer storage and recovery is significantly less expensive then dam construction. However, some of the ancillary benefits of surface storage, such as hydroelectric power generation, flood control and recreation, which have been used to offset these costs are not associated with groundwater banking. In fact, reservoir re-operation as part of the program may either enhance or detract from these uses of California's reservoirs. In order to build a case for the program, these issues must be studied.

> **Workplan Step 5: <u>Economic Analysis</u>**
> Investigate the costs of groundwater banking programs relative to surface water development and define the potential benefits. Comment on unique economic aspects of capturing the available surface water supply, conveyance to a groundwater banking site, and storage and recovery for a prescribed end-use.

NHI began this groundwater banking feasibility study with the hypothesis that: (1) It is physically possible to generate substantial amounts of new water for the environment and the economy using groundwater storage; (2) The environmental and economic benefits of such a program outweigh the costs; and (3) any institutional barriers to the use of groundwater for this purpose can be overcome. By implementing of the five broad programmatic workplan steps described above, NHI sought to test whether this hypothesis is true and under what conditions. NHI recognizes that local concerns over the possible local impacts of groundwater banking **<u>must be</u>** overcome before a maximal scale program can become a reality. Prior to engaging in the difficult negotiations needed to address local concerns, however, some sense of the ultimate payoff is needed. By describing the outcome of the five program steps, this report provides that sense. It is intended to be eminently practical, not theoretical in its approach; it is not an academic exercise, but is intended to lead to action. Our premise is that this convincing portrayal of the potential of a maximal program of groundwater banking will generate an action plan which is useful to the governmental entities and stakeholder groups empowered to craft and implement such an ambitious, yet promising program.

II. The Context

Prior to presenting the conclusions of the five workplan steps, a description of the physical setting for a maximal program of groundwater banking is required. The following sections provide a context and a rationale for elaborating the link between the management of California's installed surface water hydraulic infrastructure and potential groundwater banking sites.

II.1 Surface Water Supply

On average, California is not short of water. Annual runoff averages roughly 71 MAF (78 MAF when out of state supplies are included). In 1990, a relatively dry year, environmental uses such as instream flow standards and wild and scenic river designations accounted for 24 MAF, irrigated agriculture for 24 MAF, urban use for 6 MAF, and "other uses" for 1 MAF. Roughly 30 MAF of the 1990 total was accounted for as "other outflow" -- e.g. not allocated to any specific use (DWR 1994).[2] These long-term averages, however, mask the variability which characterizes California hydrology. Consider that:

- Extended droughts are common. Over the six year periods from 1929-34 and 1987-92, cumulative runoff in the Sacramento and San Joaquin Rivers was slightly above half the long-term average. Runoff in 1976-77 was only 33% of the long-term average for the two rivers.
- Much year to year variability exists. In the period between 1906 and 1993, 27 years were dry to critical while 34 were wet.
- Runoff in California is highly seasonal. Much of the flow occurs during a few months when snow melt and rainfall coincide.
- Surface water supplies are spatially non-uniform. Roughly 75% of the natural runoff is north of Sacramento while 75% of the demand is south (DWR 1994).

The existing storage and conveyance infrastructure is designed to "even out" this variability in surface water supply. However, given the location and intensity of current and anticipated water demand, DWR projects a supply shortfall of between 2.1 and 5.2 MAF by the year 2020 if the capacity of the system remains static.[3]

II.2 Groundwater Supplies

Under current working assumptions one method of covering the anticipated shortfall will be an increased reliance on groundwater. Already, during dry years such as 1990, increased pumping results in a statewide groundwater overdraft of roughly 1.3 MAF. Future increases in demand would suggest that these overdrafts will continue at high levels indefinitely unless major changes in water management occur, particularly in the San Joaquin Valley (DWR 1994). Plans to cope with these changes must be tempered by hydrogeologic realities.

Structurally, the deposits which form the aquifer system in the Central Valley range from a few tens to a few thousands of feet in depth. Total estimated fresh water within the upper 1,000 feet of these sediments is 830 MAF (Table 2). Traditionally the Sacramento Valley has been thought to consist of

Table 1: Estimated Central Valley Groundwater Storage

Aquifer	Estimated Storage (MAF)
Sacramento Valley	170
Delta	130
San Joaquin Valley	160
Tulare Basin	370
Total Central Valley	830

[2] It is important to recognize that this "other outflow" probably generates environmental benefits and should not be viewed entirely as surplus. The outflow is simply excess to minimum environmental flow standards that have been established for various streams and wetlands

[3] In reality, such shortages would not occur. Rather, water demand would be brought into balance with supply by some means -- water conservation, water recycling, water transfers, or desalinization. However, the economic and social costs and the political consequences of such a large reduction in demand make it highly likely that other means would be found to meet demands, such as additional diversions from the environment. The point of groundwater banking is to find ways to meet growing economic and environmental needs in ways that are acceptable to each side.

a single unconfined aquifer while the San Joaquin Valley was conceived of as an upper unconfined system and a lower confined system below the dense Corcoran Clay member of the Tulare formation. More recent studies conclude, however, that the Central Valley ground water reservoir is more accurately portrayed as a single heterogeneous aquifer, characterized by water bearing sediments interspersed with clay lenses.

Largely according to the nature of local interactions between surface water and groundwater, this vast water bearing reservoir has been divided into four hydrographic subregions: Sacramento Valley, Delta, San Joaquin Valley, and Tulare Basin. In each of the sub-region, all significant streams emerge from the Sierra Nevada or Cascade Mountains to the east. The sole exception is the Sacramento Valley where Stony Creek, Cache Creek, and Putah Creek flow into the valley from the Coast Range Mountains to the west. The mean annual runoff into the Central Valley from the surrounding mountains is about 32 million acre feet. Under historic conditions, the Central Valley rivers recharged the aquifers below the valley floor during periods of high flow and the groundwater sustained the low flow stage in rivers. By comparison, recharge via direct precipitation on the valley floor was a relatively minor component of the historic water balance ($\pm$ 1.5 MAF/year according to Williamson et al 1989).

The regulation of high flows in the rivers of the Central Valley, combined with extensive groundwater pumping, substantially altered this annual cycle. In many parts of the Central Valley, groundwater no longer contributes to low stage stream flow, which is now comprised primarily of agricultural return flows. Across the region, current groundwater flow patterns are linked to the confounding alterations of the natural system which have accompanied decades of groundwater extraction and the hydraulic manipulation of surface water. In the western San Joaquin Valley, for example, the arrival of imported surface water from the Sacramento Valley raised the water table by as much as 170 feet. Further south in the Tulare Basin, where groundwater remains the primary source of irrigation water, the free surface has fallen as much as 400 feet. In the Sacramento Valley, where the interaction between rivers and the underlying aquifer remains closer to the natural regime, groundwater levels are generally stable. Even this general observation is violated, however, in the rapidly urbanizing regions around Sacramento and in numerous locations along the relatively dry west side of the valley.

The overall impression one gains is that the condition of the Central Valley aquifer has evolved through time and is at present extremely variable across the landscape. Williamson and other (1989) documented the steps leading to this dynamic situation:

- The total flow through the aquifer system increased from about 2 million acre-ft/yr prior to hydraulic development to nearly 12 million acre-ft/yr at the current time.
- Increased groundwater pumping prior to the 1960's, to nearly 11.5 million acre-ft/yr, drove the increase in groundwater flow.
- The groundwater pumping prior to the 1960's depleted total groundwater storage by some 20 MAF and was accompanied by increased pumping costs and dramatic land subsidence.
- Increased importation of surface water to some areas of the Central Valley, beginning in the 1960's, prompted local declines in groundwater pumping.
- During the early 1980's, groundwater pumping decreased to a level approximately equal to the estimated rate of aquifer recharge.
- Since the arrival of surface water, groundwater levels have risen in most areas benefiting from imported surface water, and elsewhere further decreases in ground-water storage have been arrested.
- From a valley-wide perspective the system has achieve a state of quasi equilibrium where persistent zones of dewatered aquifer are largely in balance with adjacent zones of net aquifer recharge from overlying streams and imported surface water. In this context, any additional increment of groundwater pumping will eventually reduce surface flows.

This is not a system which can sustain the practice of satisfying increases in demand in the coming decades with a steadily increasing reliance on groundwater pumping. Such a strategy would likely return the system to the period of rapidly falling water tables, increased pumping cost, and land subsidence which plagued the first epoch of groundwater dis-equilibrium. There must be some consideration given to the need to increase storage in order to avoid a potentially destabilizing increase in groundwater pumping.

II.3 Storage Opportunities

The ability to store additional water and further "even out" natural variability would ease the predicted water availability shortfalls. Although California has a network of some 1400 major reservoirs, total storage in these reservoirs is approximately 42 MAF – only 60% of the average annual runoff (DWR 1994). The creation of sufficient additional surface storage to substantially even out variability is unrealistic. For example, proposals to build Auburn dam, a facility capable of storing 2.3 MAF, have been so controversial that funding has been blocked since Congress initially authorized the project in 1965. Even if Auburn dam were constructed, it would only increase the total system storage from 60 to 62.5% of annual runoff. Construction of all the new proposed surface storage facilities identified in Table 2 would increase the total capture of the system to 71% of annual runoff – and at an unacceptably high financial and environmental cost. Enlargement of the existing facilities in Table 2 would increase the system capture to just above the average annual runoff. As with new facilities, however, the financial and environmental costs of facility enlargement would be high.

Table 2: New/Enlarged Surface Storage

New Facilities	**Storage (MAF)**	**Cost ($/acre-ft)**
Cottonwood	1.6	480
Auburn	2.3	420
Marysville	1.05	1240
Los Banos Grande	1.73	660
Facility Enlargement		
Shasta	14.3	430
Folsom	1.34	1080
Friant	1.4	2920
Pardee	0.36	1640
Farmington	0.16	300
Berryessa	13.0	610
Total	30.56	

That underground aquifer storage is the primary supply-side alternative to the construction of new surface water reservoirs is widely recognized. As stated by the Department of Water Resources: "In the future, carefully planned conjunctive use will increase and become more comprehensive because of the need for more water and the generally higher cost of new surface water facilities." (DWR 1994). Groundwater banking was also recognized as one of the least cost sources in a review of yield enhancement opportunities undertaken under the Central Valley Project Improvement Act (USDOI, USBR et al., 1995) with cost estimates ranging from $60/acre-ft to $120/acre-ft of yield at source – greatly below the $300-$2920 unit cost of new surface storage.

This then is the hydrologic context for a maximal program of groundwater banking. Adequate surface water supplies exist in California if they can be further "even out" in space and time. Absent an effort to accomplish this management change, future anticipated growth in the State's water demand will likely lead to an increased reliance on groundwater pumping, disrupting the quasi-equilibrium currently in place and re-initiating problems with rapidly falling water tables and land subsidence. As the will to accept the high financial and environmental costs of additional surface water development has dissipated, the most viable alternative is to capitalize on the existence of regions of aquifer dewatering which developing prior to the 1970's, and which continue to plague overlying landowners. This is a scenario which can produce widespread benefit across the spectrum of water interests and which is the focus of the programmatic analysis which follows.

III. Workplan Step 1: Hydrologic Potential Analysis

A maximal program of groundwater banking seeks to divert surplus surface water to storage in suitable groundwater basins. This diversion would permit immediate storage and eventual recovery of water which would otherwise flow out to sea. The image most frequently conjured up by the aforementioned description is one of massive pumps and diversion canals, installed and ready to capture water during peak winter and spring flow events. Direct diversion during peak flows is depicted in the hypothetical example in Figure 1. In this case when the average daily flow in the Tuolumne River at Modesto exceeds 4000 cfs, 300 cfs of the large flow event is diverted to groundwater banking. Over the course of the 1994 and 1995 water years this approach generates approximately 80 TAF of storage. The important thing to note about this approach is that it involves manipulation of the hydrograph in the lower Tuolumne River while the storage in New Don Pedro Reservoir upstream remains unaltered.

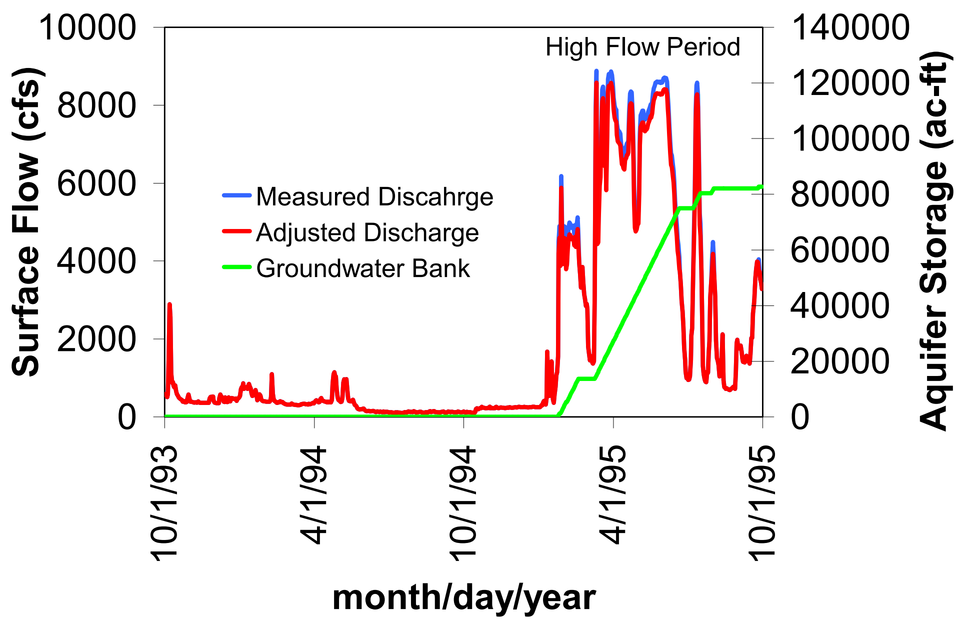


Figure 1: Banking Groundwater by Diverting Peak Flows from the Tuolumne River near Modesto

An alternate, and potentially complementary, strategy for groundwater banking involves the pre-delivery of water from surface water reservoirs to groundwater banking sites. Under this arrangement, water would be released from storage in California's major foothill reservoirs for transfer to aquifer storage during the summer and fall. This transfer could be accomplished directly through percolation at spreading basins or indirectly through *in lieu* deliveries to farms which would otherwise rely on groundwater for irrigation. Instead of directly altering downstream hydrographs during peak flow events, pre-delivery results in a decline in upstream reservoir storage levels. In the hypothetical example in Figure 2, each day between March and September, 1994 a supplemental release of 300 cfs is pre-delivered to groundwater banking from New Don Pedro Reservoir on the Tuolumne River. This re-operation causes a decline in reservoir storage relative to the historic trace which is balanced by a 130 TAF increase in aquifer storage. This aquifer storage becomes "new" water when, during the 1995 water year, measured reservoir releases in excess of 4000 cfs are cutback by 300 cfs. In effect, the excess available flood control capacity in New Don Pedro Reservoir allows for the eventual recovery of surface storage back to the historic trace.

Once storage in New Don Pedro recovers back to historic levels, the water stored in the groundwater bank becomes yield which would have otherwise been released during the peak flow events. It should be pointed out that a 300 cfs pre-delivery is relatively conservative as *in lieu* deliveries to farms could far exceed this level if a suitable distribution network were in place. The subsequent cutback of reservoir releases could also have been more aggressive than assumed in this example. Finally, the re-operation of surface reservoirs is a much more intentional and approach to groundwater banking than the periodic capture of peak flows as it does not require the installation of large diversion capacity which will only be used during short time windows. By "evening-out" the transfer of surface water to aquifer storage, pre-delivery allows for continual benefit to be derived from the physical and operational changes associated with groundwater banking.

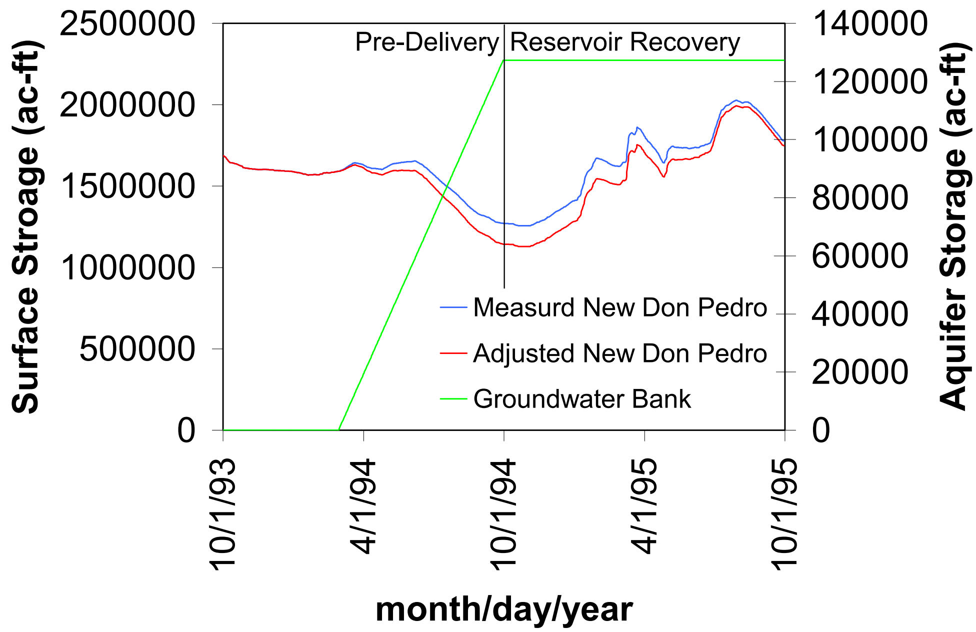


Figure 2: Banking Groundwater by Re-Operating New Don Pedro Reservoir on the Tuolumne River

III.1 Conjunctive Use Potential (CUP)

To estimate the hydrologic potential of the pre-delivery of surface water to groundwater banking in the Central Valley watershed, NHI developed the Conjunctive Use Potential model, or CUP (see the model methodology in the sidebar, parameters in bold italics must be provided by the user). CUP, which was developed for each of the river systems described in Table 3, is based on liberal assumptions about: (1) the existence of infrastructure; (2) a limited scale investment in the direct diversion of high flows to aquifer storage (as in Figure 1); and (3) the availability of suitable groundwater banking sites. On the other hand, CUP adopts a very conservative posture towards the need to preserve adequate cold water in the major foothill reservoirs. This cold water resource is needed to maintain suitable temperatures in the spawning and rearing reaches downstream of the reservoirs in Table 3. The conservative posture should help allay concerns over impacts to hydropower production targets or lake recreation opportunities, although these uses of surface

CUP Model Methodology

1. Compare ***historic daily reservoir releases*** to minimum ***required economic and environmental flows***. Historic releases in excess of required flows are considered "surplus", while smaller historic releases create a "deficit". Accumulate daily differences over the entire year to determine whether the year is wet or dry.
2. When environmental requirements create a deficit, adjust September 30 reservoir storage levels by this increment. Should the adjusted storage falls below a ***minimum carryover storage target*** set to preserve adequate cold water for anadramous fish below the dam, a shortage equal to the amount needed to meet the minimum carryover is applied to economic uses.
3. When a net surplus exists, the adjusted storage from Step 2 is compared to the ***target carryover storage***. If adjusted storage exceeds this parameter, water is pre-delivered to aquifer storage at a rate dictated by user defined ***transfer and storage constraints***. Surface storage is reduced by the same amount. Pre-delivered water is initially "provisional" storage as it can be recalled if needed.
4. Subsequent surplus flows will be held in surface storage until the Step 2 storage trace has been regained, transforming a similar amount of "provisional" storage to banked groundwater. If sufficient surpluses exist to transform all "provisional" storage to banked groundwater, additional surpluses can be transferred into the provisional groundwater account, provided that space is available in the bank.
5. Subsequent deficits which result in adjusted storage below target carryover initiate a search for replacement water and, if necessary, the recall of "provisional" storage at a rate dictated by ***user defined recovery constraints***. A shortage is declared when reservoir storage remains below the minimum target.

reservoirs are not specifically considered in the CUP analysis. The most important lesson to derive from Table 3 is that in six of the ten important rivers in the Central Valley, annual flows exceed the available storage and the improved flood control flexibility made possible through pre-delivery can help capture "new" water without imperiling anadramous fish below the dam.

Table 3: Details of the Major Foothill Reservoirs in the Central Valley

River	Reservoir/Dam	Operator	Storage (TAF)[4]	Mean 1921–1983 Unimpaired Flow[5]
American	Folsom	USBR/CVP	974	2,660
Calaveras	New Hogan	USBR	317	163
Feather	Oroville	DWR/SWP	3,538	4,441
Merced	New Exchequer	MeID	1,025	967
Mokelumne	Camanche	EBMUD	417	730
Sacramento	Shasta	USBR/CVP	4,552	8,303
San Joaquin	Millerton Lake	USBR/CVP	520	1,740
Stanislaus	New Melones	USBR/CVP	2,420	1,131
Tuolumne	New Don Pedro	MoID/TIDD	2,030	1,841
Yuba	New Bullards Bar	YCWA	966	2,333

III.1.1 Protecting Anadramous Fish

Prior to the development of the major foothill reservoirs, listed in Table 3, anadramous fish generally spawned in California's mountain streams. Construction of the dams which impound these reservoirs blocked passage to these sites, forcing fish to spawn in foothill and valley reaches which were historically warm during the summer and early-autumn. Figure 3 compares the water temperature in the Sacramento River downstream of the current Shasta Dam site. Before dam construction the summer water temperature was in excess of 70 ^{o}F and remained around 60 ^{o}F well into the autumn. Temperature moderation following dam construction resulted from the release of cold water found on the bottom of the reservoir. Similar temperature changes have been observed downstream of the other major Central Valley reservoirs.

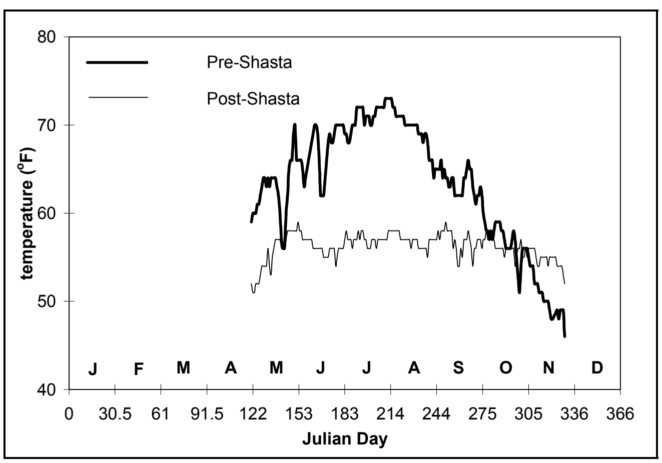


Figure 3: Sacramento River Water Temperature Downstream of Shasta Dam Site
(heavy line: Anderson-Cottonwood Diversion Dam; light line: Balls Ferry)

[4]Draft of the California Water Plan Update, Department of Water Resources, California Water Commission, November 1993.
[5]California Central Valley Unimpaired Flow Data, 2nd Edition, California Department of Water Resources, Division of Planning, February 1987

The Central Valley Project Improvement Act (CVPIA) enacted in 1992 sought to elevate fish and wildlife protection, and restoration to a level of parity with the other project purposes (U.S. Fish and Wildlife Service 1995). The act also called for a "program which makes all reasonable effort to ensure that, by the year 2002, natural production of anadromous fish in Central Valley rivers and streams will be sustainable, on a long-term basis, at levels not less than twice the average levels attained during the period of 1967-1991" (CVPIA 1992). For the rivers evaluated using CUP, a variety of temperature related actions were proposed as part of the U.S. Fish and Wildlife Service's Anadramous Fish Recovery Plan (AFRP). Some of these were specific prescriptions, others vague recommendations (see the adjacent sidebar). Table 4 describes specific reservoir carryover targets included in the AFRP.

Table 4: AFRP Reservoir Carryover Targets in the Rivers Evaluated Using CUP

River	Specific Carryover Targets	No Clear Carryover Targets
Sacramento	1.9 MAF	
Feather		X
Yuba		X
American		X
Mokelumne	~108 TAF	
Calaveras	85 TAF	
Stanislaus		X
Tuolumne		X
Merced		X

Relevant USFWS Temperature Prescriptions

In order to maintain water temperatures below 56°F in the **Sacramento River**, Shasta Reservoir should be operated to attain a minimum October 1 carry over storage of 1.9 MAF under all runoff conditions except the driest 10% of water years.

In the **Feather River** pulse releases from Lake Oroville are needed to reduce the temperature difference between the low flow channel and the reach immediately downstream of the Thermalito outlet.

In the **Yuba River**, colder temperatures for chinook salmon could possibly be maintained by drawing Englebright Reservoir down in August and refilling with cold water from New Bullards Bar. Reservoir

In the **American River**, by re-operating the reservoir release shutters to provide greater flexibility, downstream releases during October would be 1-9°F colder than the temperature attained under current protocols and shutter configurations.

In the **Mokelumne River**, a minimum pool in Camanche Reservoir of 190 feet from April through September and a minimum pool of 170 feet from October through March, should be maintained to protect anadramous fish.

In the **Calaveras River**, temperatures could be kept cool enough for chinook salmon production with a minimum New Hogan Reservoir pool size of 85,000 ac-ft.

Water temperature in the **Stanislaus River** should be maintained below 56°F between October 15 and February 15 and below 65°F between April 1 and June 30 in order to enhance salmonid productivity below Goodwin Reservoir.

Water temperature in the **Tuolumne River** should be maintained below 56°F between October 15 and February 15 and below 65°F between April 1 and June 30 in order to enhance salmonid productivity below LaGrange Dam.

In the **Merced River** the same river temperature standards as for the Stanislaus and Tuolumne Rivers are suggested in order to enhance salmonid productivity below the Crocker-Huffman Diversion.

In CUP, constraining the pre-delivery of water from reservoir storage to a groundwater bank based on the need to preserve the cold water pool requires the definition of both minimum and target carryover parameters. These parameters should be defined based on analysis of the physical juxtaposition of warm water in the Central Valley reservoirs with the release works on the face of the impounding dams, and on the thermal requirements of downstream fisheries. The carryover storage levels contained in Table 4 can be used as targets values in CUP. The remaining target parameters and all minimum carryover parameters must be set by the user.

III.1.2 Setting Carryover Targets

The derivation of these carryover parameters rests on physical principles, particularly a solid understanding of the tendency of reservoirs to stratify into warm and cold water pools during the summer and early autumn, and the potential for wind driven oscillation or *seiches* in stratified reservoirs. The limnological basis for this analysis is presented in Appendix I.

III.1.2.1 Required Data

The data required to carry out the required limnological analysis for the major foothill reservoirs in the Central Valley include:

- Historic EOM storage levels;
- Late summer vertical temperature profiles collected when the reservoirs were in a drawn down state;
- Late summer wind speed data from the vicinity of these reservoirs; and
- Information of the physical configuration of each reservoir and the impounding dam's release works.

Table 5 presents a matrix describing the data availability for each of the systems under investigation. In general, data for the Central Valley and State Water Project facilities was more easily acquired than in the case of projects managed by local-agencies. Gaps in the data availability were overcome by substituting the most appropriate data set available.

Table 5: Data Availability Matrix for Analysis of Minimum Carryover Storage Values of the Major Foothill Reservoirs

Reservoir	Operator	EOM Storage	Temperature	Wind Speed	Configuration
Shasta	USBR	✓	✓	✓	✓
Oroville	DWR	✓	✓	✓	✓
New Bullard Bar	YCWA	✓	✓	✓	✓
Folsom	USBR	✓	✓	✓	✓
Camanche	EBMUD	✓	✓	✓	✓
New Hogan	USACE	✓	✓	✓	✓
New Melones	USBR	✓	✓	***Use New Hogan***	✓
Don Pedro	TID	✓	***Use New Melones***	✓	✓
McClure	MID	✓	***Use New Melones***	✓	✓

III.1.2.1.1 Reservoir Storage

Figures 4A (Sacramento Valley) and 4B (San Joaquin Valley) depict the yearly October 1st reservoir storage values, for each of the major foothill reservoirs in Table 3, ranked in ascending order. The five lowest storage values are labeled, excluding the first five years of operation when filling could have influenced the storage levels as much as hydrologic conditions. The severity of the 1976-1977 drought is revealed in the fact that October, 1977 represents the lowest recorded level in eight of the nine reservoirs. The impact of the 1987-1992 drought is also revealed as many of these years also figure among the lowest measured storage levels. By examining the disposition of the cold water resource under these drawn down conditions appropriate carryover parameters can be established.

III.1.2.1.2 Vertical Temperature Profiles

Unlike reservoir storage data, data on the water temperature as a function of depth in the major foothill reservoirs is not collected and reported in a regular fashion. Every attempt was made to acquire temperature data corresponding to the lowest measure reservoir storage (see Figures 4A and 4B). Given the irregular character of this data, however, such a correspondence was not universally achieved. Table 6 summarizes the quality of the vertical temperature profile data collected for this analysis.

Table 6: Availability of Vertical Temperature Data for the Major Foothill Reservoirs Under Drawn Down Conditions

Reservoir	Measurement Date	Storage Rank	% Above Minimum
Shasta	Sept, 1976	3	8.9
Oroville	Sept, 1992	3	8.9
New Bullards Bar	Oct, 1992	>5	112.7
Folsom	Oct, 1977	1	0
Camanche	Oct, 1990	>5	28.0
New Hogan	Aug, 1990	3	1.6
New Melones	Sept, 1992	1	0
Don Pedro	N/A	N/A	N/A
McClure	N/A	N/A	N/A

Figure 4A: Ranked Historic October 1st Storage in the Major Sacramento Valley Foothill Reservoirs with Values of the First Operational Year (bold) and the Five Lowest Years Identified

(A: Shasta; B: Oroville; C: New Bullards Bar; D: Folsom)

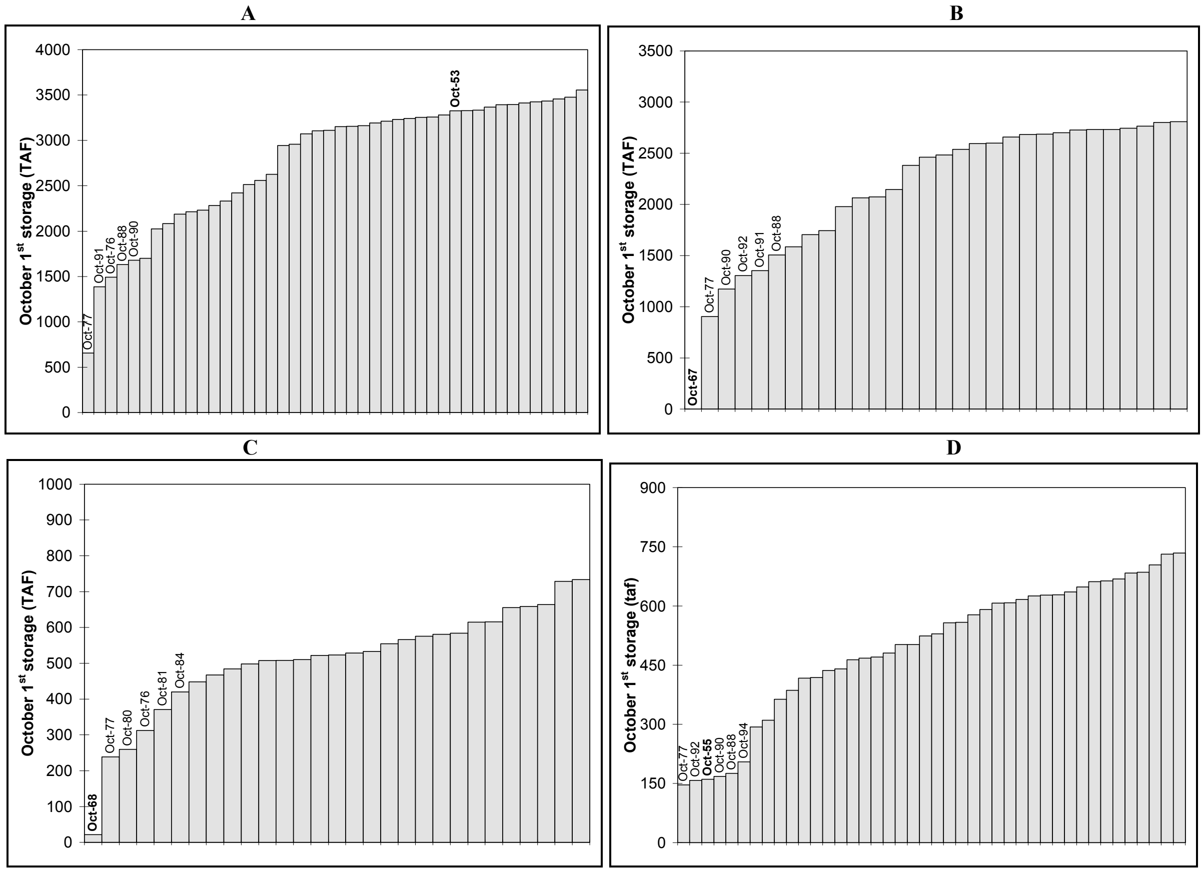
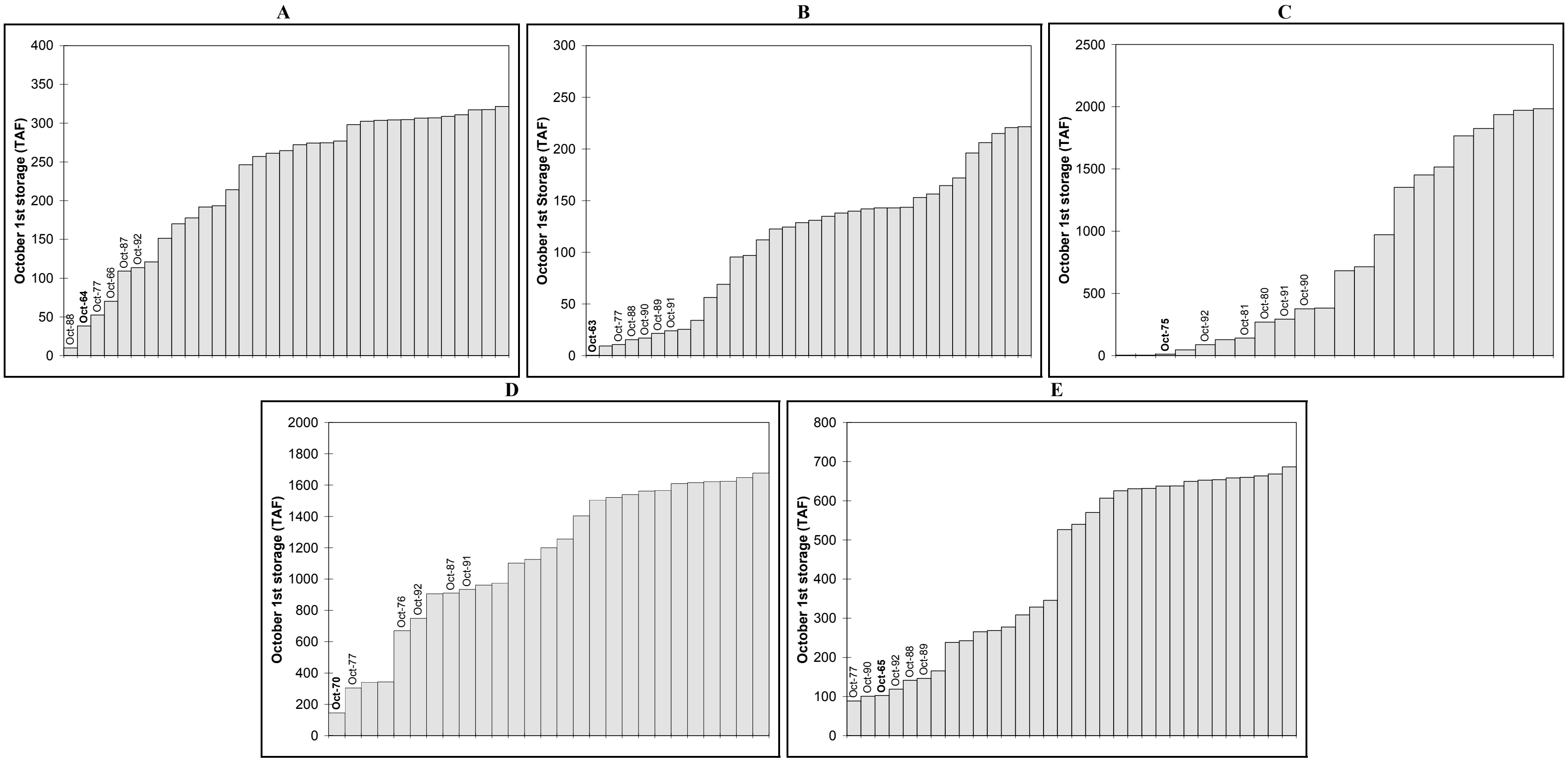


Figure 4B: Ranked Historic October 1st Storage in the Major San Joaquin Valley Foothill Reservoirs with Values for the First Operational Year (bold) and the Five Lowest Years Identified

(A: Camanche; B: New Hogan; C: New Melones; D: Don Pedro; E: McClure/Exchequer)



Using these data to establish acceptable carryover levels relies on the implicit assumption that the interaction between the incoming solar radiation, the prevailing wind, and the volume of the body of water behind the dam remains essentially constant across the range of drawn down conditions. Given the fairly uniform climatic patterns which characterize Central Valley summers, applying this assumption to the two climatic factors seems reasonable. The last column of Table 5 contains the percent increase in reservoir storage at the time of the temperature sounding, relative to the minimum observed October 1st storage reported in Figure 4. With the exception of New Bullards Bar and Camanche Reservoirs, the storage levels at the time of the temperature sounding were not substantially above the minimum observed storage level. Figure 5 contains the vertical temperature profiles plotted as a function of the depth below the lake surface for each of the reservoirs where data was available. The soundings reveal the well developed nature of temperature stratification in these reservoirs during the late summer/early autumn. Any appropriate carryover parameters used in CUP must consider the disposition of the cold water pool in the hypolimnion relative to the physical works controlling downstream releases.

III.1.2.1.3 Wind Speed

The disposition of the cold water resource in the major foothill reservoirs cannot be considered static. Shear stress generated by wind passing over the lake surface performs work on the water body which can disrupt the patterns of thermal stratification observed in Figure 5. In order to assess the potential for disruption, or mixing, the wind speed in the vicinity of the major foothill reservoirs must be characterized. The major foothill reservoirs generally lie somewhere between the elevations of two common wind speed databases containing data collected in the Central Valley (CIMIS) or at higher elevations in the Sierra (CDEC). In order to minimize the potential error associated with the use of this data, the maximum available measured daily average wind speed for each reservoir was used to assess the potential for wind driven mixing. These are shown in bold in Table 7.

Table 7: Wind Speed Measurement Stations Associated with the Major Foothill Reservoirs
(stations with maximum daily average wind speed in bold)

Reservoir	Station	CDEC	CIMIS	Reservoir	Station	CDEC	CIMIS
Shasta	McCloud	✓		Camanche	Beaver	✓	
	Thomes Creek	✓			Mt. Zion	✓	
	Whitmore	✓			**Lodi**		✓
	Gerber		✓	New Hogan	Esparanza	✓	
Oroville	**Butte Meadows**	✓			**Manteca**		✓
	Chester	✓		Don Pedro	**Green Springs**	✓	
	Quincy Road	✓			Tuolumne Meadows	✓	
	Westwood	✓			Modesto		✓
	Durham		✓	McClure	**Crane Flat Lookout**	✓	
New Bullards Bar	Bangor	✓			Mariposa Grove	✓	
	Dorris Ranch	✓			Mariposa Ranger Station	✓	
	Browns Valley		✓		Merced River	✓	
Folsom	**Buffalo Creek**	✓			Modesto		✓
	Camino		✓				
	Linclon	✓					

From the maximum data set, the highest single daily average wind speed was extracted. The assumption implicit in the use of the peak value is that energy imparted to the system by a steady wind blowing for a single day will be sufficient to fully induce wind-driven water movement in the reservoir. The time series of wind speed data from these most windy sites are shown in Figure 6.

Figure 5: Late Summer/Early Autumn Vertical Temperature Profiles for the Major Foothill Reservoirs
(A: Shasta; B: Oroville; C: New Bullards Bar; D: Folsom; E: Camanche; F: New Hogan; G: New Melones)

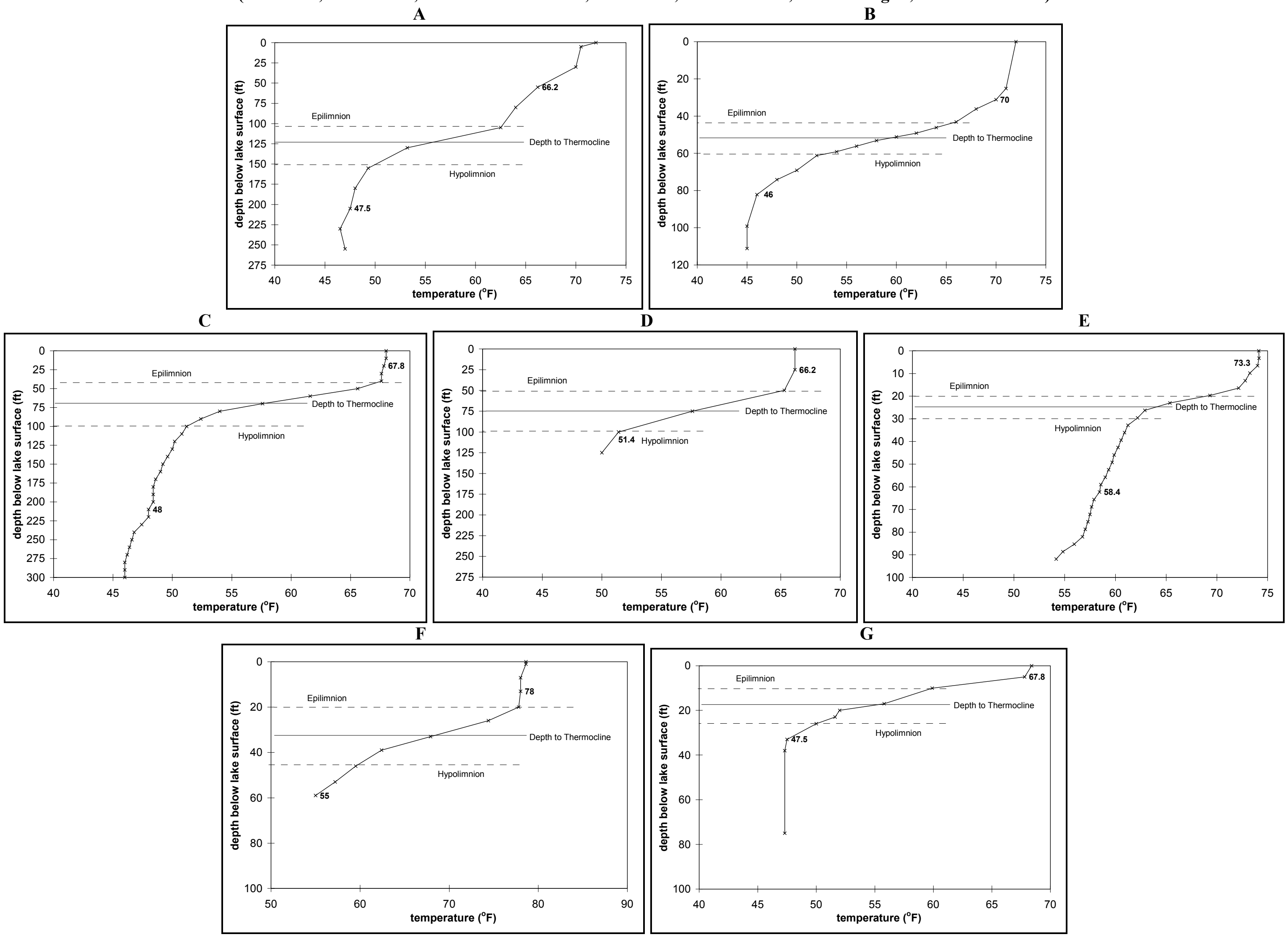
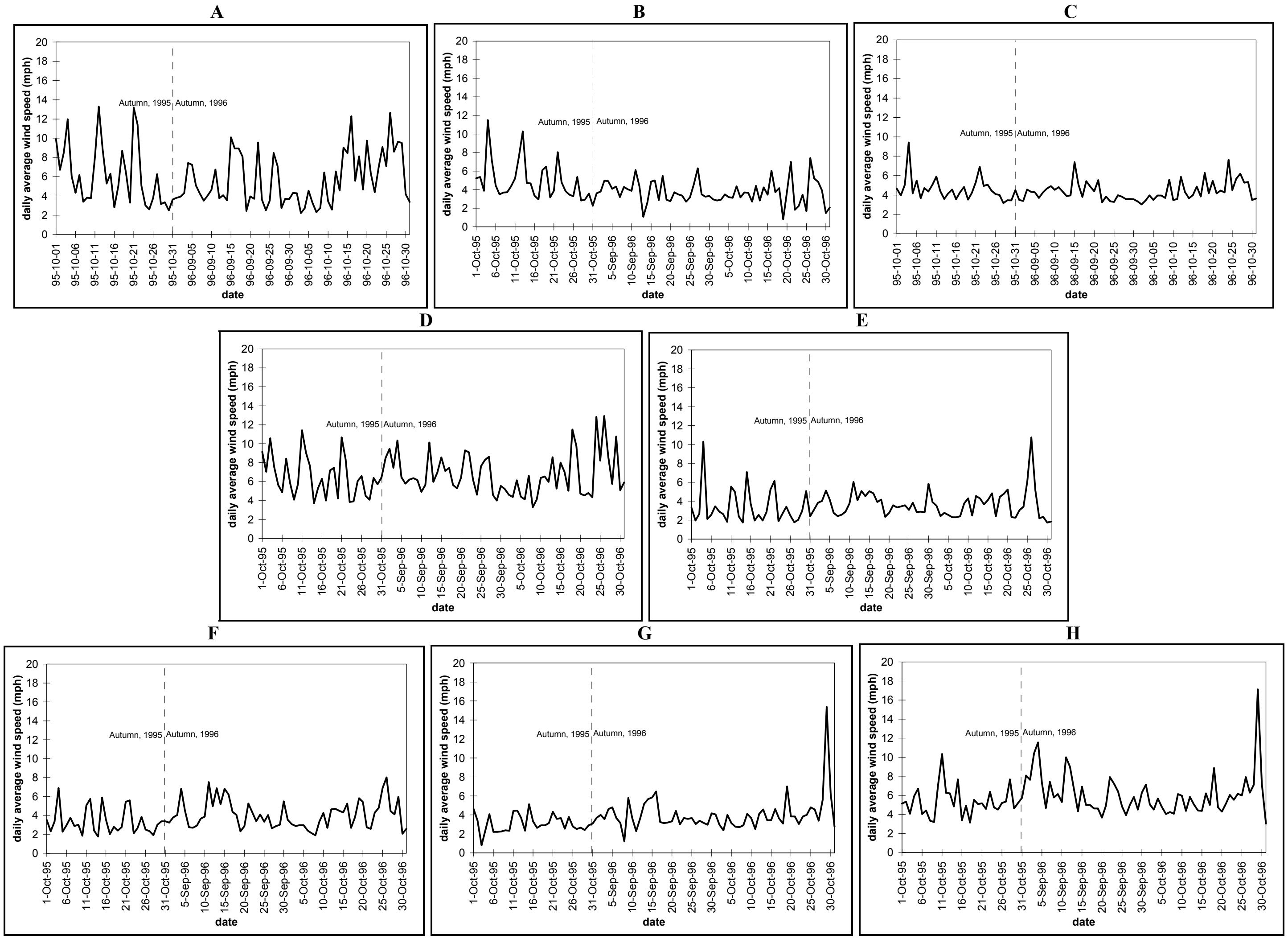


Figure 6: Recent Maximum Late Summer/Early Autumn Daily Average Wind Speed Date for the Major Foothill Reservoirs

(A: Shasta; B: Oroville; C: New Bullards Bar; D: Folsom; E: Camanche; F:New Hogan; G: Don Pedro; H: McClure)



III.1.2.1.4 Physical Configuration

In order to evaluate the disposition of the cold water resource with respect to the release works of a given dam, data describing the physical configuration of the reservoir system is required. This data set includes information on the length of the lake, the elevation of the foot of the dam and the elevation of the release works used to discharge water downstream. Two complications influence the compilation of this data set. First, the major foothill reservoirs are not uniformly long and narrow, which makes it difficult to define the length of the lake corresponding to the fetch of open water above the dam. For this analysis the length was defined as the longest unobstructed distance over water which can be traced at high water from the dam itself. Second, stating the elevation of the release works was complicated by the fact that many of the major foothill reservoirs include installed hydroelectric generating capacity. The elevation from which water is released to the powerhouse is usually higher then the low level release works used for flood control. In order to minimize the potential impact on hydroelectric power production, in this analysis the elevation at which water is released to the powerhouse served as the reference for a comparison with the disposition of the cold water pool. Table 8 summarizes the requiired information for the reservoirs of interest.

Table 8: Physical Configuration Data for the Major Foothill Reservoirs

Reservoir	Length (mi)	Elevation Foot (ft)	Elevation Release (ft)
Shasta	5.9	576	725
Oroville	4.7	180	640
New Bullards Bar	2.3	1400	1622
Folsom	7.8	200	218
Camanche	6.8	100	104
New Hogan	2.0	525	534
New Melones	3.3	500	760
Don Pedro	4.1	290	600
McClure	3.1	400	477

III.1.2.2 Computational Steps

In this analysis, the evaluation of the ability to release cold water downstream from a stratified lake relies upon three sequential calculations carried out for an assumed reservoir storage level and vertical temperature profile. These are

- Determine the set-up of the lake caused by the passage of wind over the lake surface;
- Determine the displacement of the warm water pool, in response to the set-up; and
- Determine the juxtaposition of the warm water relative to the reservoir release works.

Appendix II examines these three computational steps in greater detail, focusing on the physical rationale behind each step.

III.1.2.3 Defining the Minimum and Target Carryover Parameters

Table 4 contains carryover storage targets for Shasta, Camanche, and New Hogan Reservoirs as defined in the Anadramous Fish Recovery Plan (USFWS 1995). These will be used as target carryover parameters in CUP. Appropriate carryover targets for the remaining facilities, as well as the minimum carryover levels for all of the reservoirs, remain unresolved. These values are set according to the following criteria:

$$CS_{target} = \left| \begin{array}{l} CS_{AFRP} \\ CS \text{ where } HT \approx 50ft \end{array} \right. \text{ or if none} \quad (1)$$

$$CS_{minimum} = CS \text{ where } HT \approx 20ft \quad (2)$$

where CS is the carryover storage and HT is the minimum thickness of the cold water pool lying above the release works during wind driven oscillations. In those cases where no carryover standards are available, storage levels were adjusted in a trial and error fashion until conditions yielding HT values of 20 ft and 50 ft were identified. Table 9 presents the final CUP carryover parameter values for each of the nine simulated rivers (The San Joaquin was omitted from this analysis as extensive pre-delivery of surface water already takes place in the Friant Unit). These parameters were not based on political considerations, the sole consideration was the difference between the maximum downward displacement of warm water under *seiche* oscillations and the release works of a given facility. Obviously dams where the power plant intake is located well down the dam face are found to have much lower carryover requirements.

Table 9: CUP Carryover Parameters Developed According to Analysis of the Juxtapostion of Warm Water Relative to Reservoir Release Works (in ac-ft)

River	Carryover Target	Minimum Carryover
Sacramento	1,900,000	910,000
Feather	1,705,00	1,507,000
Yuba	210,000	190,000
American	190,000	100,000
Mokelumne	108,000	70,000
Calaveras	85,000	17,000
Stanislaus	382,000	268,000
Tuolumne	750,000	570,000
Merced	50,000	30,000

III.1.3 Tapping Upstream Storage

In CUP, when the re-operated storage falls below the minimum carryover parameter the model seeks to redress the deficit. The first place where CUP looks for replacement water is upstream towards storage in Sierra Nevada reservoirs. A time series of combined upstream storage for each river has been input into CUP and the user can specify the percentage of the upstream storage which can be tapped to make up any deficit. In CUP, water is returned to the surface reservoir from “provisional” storage only when the available upstream storage is insufficient to fill the gap. Figure 7 presents the time series of available upstream storage volumes.

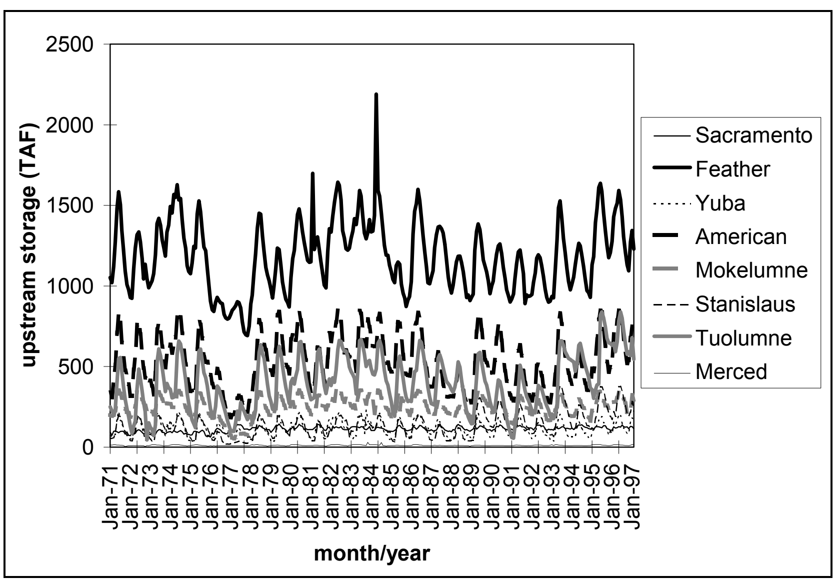


Figure 7: Time Series of Total Storage Upstream of the Major Foothill Reservoirs

III.1.4 CUP Simulations

Four different scenarios were simulated using CUP. These are summarized in the matrix shown in Table 10. The base case represents the case where instream flow standards are set to the highest possible level, carryover standards set in the AFRP are used where available to define the carryover target parameter, and 20% of the upstream storage can be tapped to make up any deficit relative to the minimum carryover. The other three simulations are departures from this base case. Scenarios 2 through 4 are designed to evaluate the sensitivity of the estimated average annual yield to various management strategies. Scenario 2 in particular merits some explanation. In this simulation the AFRP prescribed carryover targets are set aside in favor of the more aggressive targets derived from the application of the equations (1) and (2) to Shasta, New Hogan, and Camanche Reservoirs. Under each of these scenarios, a small simulated capacity to capture flow during peak winter and spring flow events was included (as depicted in Figure 1). It is important to keep in mind, however, that this approach is considered secondary to reservoir re-operation in CUP.

Table 10: Simulation Matrix for Revised CUP Model

Scenario	Carryover Target	Instream Standard	% Upstream Available
1. Base Case	AFRP if available, otherwise HT =50 ft	HIGH	20%
2. Set Aside AFRP	HT =50 ft everywhere	HIGH	20%
3. Relax Standards	AFRP if available, otherwise HT =50 ft	MEDIUM	20%
4. Full Upstream	AFRP if available, otherwise HT =50 ft	HIGH	100%

III.1.5 Results

The estimated average annual yield in the base case simulation is 894.4 TAF, a significant quantity of water which could contribute mightily to the quest for consensus in California's water sector. In addition, the alternative management strategies described in scenarios 2 through 4 improve the performance of the groundwater banking program. Table 11 summarizes the results for each simulated river under each of the management scenarios.

Table 11: Average Annual Yield Estimates from Revised CUP Model (in TAF)
(CU: conjunctive use re-operation; HP: capture of hydrograph peak)

	Base Case			Set Aside AFRP			Relax Standards			Full Upstream		
River	CU	HP	Total	CU	HP	Total	CU	HP	Total	CU	HP	Total
American	64.8	15.6	80.4	64.8	15.6	80.4	72.9	17.4	90.3	137.1	15.2	152.3
Calaveras	12.8	12.6	25.4	15.9	11.5	27.4	14.7	13.2	27.9	12.7	12.6	25.3
Feather	107.3	19.6	126.9	107.3	19.6	126.9	122.8	21.7	144.5	117.1	19.6	136.7
Merced	92.9	15.2	108.1	92.9	15.2	108.1	134.7	22.4	157.1	93.0	15.2	108.2
Mokelumne	53.7	15.7	69.4	51.6	15.7	67.3	77.6	23.3	100.9	59.6	15.0	74.6
Sacramento	170.8	26.0	196.8	184.5	26.0	210.5	195.3	31.2	226.5	170.8	26.0	196.8
Stanislaus	51.6	13.4	65.0	51.6	13.4	65.0	79.5	26.4	105.9	58.3	13.4	71.7
Tuolumne	65.3	12.6	77.9	65.3	12.6	77.9	116.4	24.8	141.2	72.1	12.4	84.5
Yuba	117.5	27.0	144.5	117.5	27.0	144.5	157.8	31.3	189.1	122.6	27.1	149.7
Total			894.4			908.0			1183.4			999.8

Relative to the base case, the most dramatic improvements come from reducing the simulated instream flow standards from high to medium. Even without relaxing the instream flow standards, however, the performance of the system can be improved by taking full advantage of the opportunity to release water from storage in upstream reservoirs when it is needed to re-establish the minimum carryover level on October 1st. Table 12 details the pattern of reliance on upstream storage which emerges from this simulation. Although the use of this water affords extra benefit to the ground water banking program, any advantage gained must certainly be weighed against power generation potential which might be lost in the process. This analysis suggest, however, that the notion of integrating storage upstream of the major foothill reservoirs into the maximal statewide groundwater banking program is certainly worth pursuing. This type of integration, however, would involved a wide array of actors running from the electric utilities which operate the upstream reservoirs, the water agencies which operate the major foothill reservoirs and their customers, and the land owners overlying the potential aquifer storage sites. The complexity of negotiating arrangements acceptable to all these parties will require a keen eye towards the legal and institutional nuances governing groundwater in California. Given the enormous potential payoff, however, there should be ample incentive to address any potential problems.

Table 12: Simulated Transfers from Upstream Storage to the Major Foothill Reservoirs under the Full Upstream Scenario (transfers in ac-ft)

River	No. of Transfers	Average Transfer
American	10	182,649
Calaveras	0	0
Feather	7	182,764
Merced	5	9195
Mokelumne	9	55,427
Sacramento	6	106,904
Stanislaus	3	87,343
Tuolumne	8	131,810
Yuba	3	53,935

IV. Workplan Step 2: Legal and Institutional Analysis

The infusion of approximately 1 MAF of new water into the California water system on an annual basis would undoubtedly help water managers in the state to meet water supply and environmental objectives. Realizing this hydrologic potential, however, requires that legal and institutional barriers be identified and surmounted.

IV.1 Basic Premise

Basically, the incentives for a maximal program of groundwater banking would be as follows, landowners overlying the storage site would agree to store the water as part of the program in exchange for a portion of the "new" water, or for a cash payment. Water will be regarded as "new" water if it would otherwise have been released for flood control purposes and flowed out to sea. Well monitoring may be necessary in selected areas to prevent increased pumping by overlying and adjacent landowners in storage areas, who could be tempted to irrigate new lands, avoid higher surface water costs, and/or to compensate for unrelated market transfers of surface water rights. Opportunities may exist to incorporate storage entities as a part of AB 3030 groundwater management plans for districts throughout the state, indeed in the case of *in lieu* storage this may be the preferred approach. Potential beneficiaries of the groundwater banking program would be invited to participate in the arrangement under agreements that would give them access to purchase a specified amount of the banked groundwater. The funds collected from the beneficiaries would be used to defray the costs of the program, which are expected to include the construction of new infrastructure and electricity for pumping the stored water.

IV.2 Basic Approach

A preliminary analysis of California groundwater law has been conducted to explore how a groundwater banking program could be set up so that the rights to the program water stored in groundwater basins could be protected against claimants which are not participating in the program. In pursuing this legal research two program designs were considered: (1) groundwater banking through active recharge and (2) groundwater banking through *in lieu* arrangements. Both designs would tap flood control releases that otherwise escape beneficial use. Thereafter the program designs diverge somewhat as they are predicated on different legal entitlements to extract and use the stored groundwater. The details of this legal research are included in an August, 1994 NHI document entitled *Analysis of Preferences in Rights to Groundwater Under California Law & Implications for Design of Conjunctive Water Use Programs*.

In this analysis NHI defined a number of distinct "types" of groundwater. While from a hydrologic perspective, a molecule of groundwater in a basin is not physically distinguishable from any other molecule, our analysis suggests that from a strictly legal perspective there are multiple groundwater types in the State. Our conception of a maximal scale groundwater banking program will focus on Groundwater Type 5, where the organizer of a groundwater banking program would seek to obtain rights to groundwater that is *percolating, used off-tract, imported to the watershed of use, and required for reasonable beneficial use, where area of origin statutes are inapplicable*. In more practical terms, this is groundwater which was imported from outside the groundwater basin, which has not become the underflow of a surface stream nor an underground stream, and which will be put to beneficial use at a location physically removed from the land overlying the basin. This type of groundwater offers several important protection to the organizers of a groundwater banking program. The most salient details of the legal analysis on the active and *in lieu* program designs are framed as responses to pertinent questions.

IV.3 Legal and Institution Questions

The questions posed below go right to the heart of perceptions that the benefit of water stored in an aquifer is the sole possession of overlying landowners. The responses assert that for groundwater of Type 5, at least, this perception is not universally valid. Having established this conclusion, questions related to how to best capitalize on potential storage opportunities can be posed.

IV.3.1 Could parties with potential claims on Groundwater Type 5 hamper the eventual recovery of stored groundwater?

IV.3.1.1 In the Case of Active Recharge

The universe of parties with potential claims to Groundwater Type 5 includes: the people of California through the public trust, as well as importers, prescribers and appropriators--both private and public.

The public trust is omnipresent. No disadvantage is incurred by using water of this type, since no type of water escapes the reach of the trust.

Prescribers, overlying users, and other importers are not of concern, if water of this type is used. If the organizer of the groundwater banking program is a public entity, as described below, prescribers are eliminated from competition for water imported by the organizer. The only colorable claim of overlying groundwater users to water of Type 5 would result if the importer abandoned the imported water once it was in the ground. Spreading does not constitute such abandonment.[6] Other importers can claim only rights to a quantity of water attributable to their own imports--a situation that does not threaten the operation of a groundwater banking program. Thus, a public importer of water of this type need only be concerned about being displaced by appropriators.

Appropriators have a superior claim to water of this type only if the importer fails to require the water for reasonable beneficial use--that is, if the water is considered "surplus." The burden of proof would be on the would-be appropriator to show that such water was, in fact, surplus.[7] Storage of groundwater for domestic, irrigation, and municipal purposes is typically considered a reasonable beneficial use.[8] Storage of groundwater is a beneficial use if the water is later applied to the beneficial purposes for which the water was first appropriated on the surface.[9] Thus, it is important that, in addition to manifesting an intent to recapture imported waters stored in the ground, the organizer of the groundwater banking program demonstrate that such waters are being stored for later application to reasonable beneficial uses. In this way, the storage itself will be considered beneficial.

Thus, if the organizer of the groundwater banking program holds rights to groundwater of Type 5, the program should be able to deposit water in the ground and, by right, withdraw it again.

IV.3.1.2 In the Case of *In Lieu* Arrangements

Under an in lieu system, the program would enter into arrangements with overlying landowners who already have access to groundwater. During periods when the program desires to recharge groundwater, the landowners would forego pumping and accept a substitute surface delivery from the program instead. In the case where the landowner has access to surface water, when the program desires to withdraw groundwater, the landowner would curtail its surface water use and substitute groundwater pumping. When the landowner has no independent claim to surface water, recovery by the program would rely on the physical extraction of stored groundwater.

The basic problem with such an arrangement is that the program will not be withdrawing groundwater that it has physically put into the aquifer through an active recharge program. Instead, it will require groundwater rights holders to forego pumping water that they are otherwise legally entitled to

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[6] City of Los Angeles v. City of Glendale, 142 P.2d 289, ___, 23 Cal.2d at 76-78 (Cal. 1943).

[7] Miller v. Bay Cities Water Co., 107 P. 115, ___ (Cal. 1910); Allen v. California Water & Tel. Co., 176 P.2d 8, ___ (Cal. 1947) (burden on appropriator to show existence of surplus); Monolith Portland Cement Co. v. Mojave Public Utilities Dist., 316 P.2d 713, ___ (Cal. Ct. App. 1957) (burden on off-tract user to show existence of surplus); 62 Cal. Jur. 3d, Water § 410 (1981).

[8] Rank v. Krug, 142 F.Supp. 1, 111-12, 113-14 (S.D. Cal. 1956), *affirmed in part and reversed in part*, California v. Rank, 293 F.2d 340 (9th Cir. 1961), *modified upon rehearing*, 307 F.2d 96 (9th Cir. 1962), *affirmed in part*, City of Fresno v. California, 372 U.S. 627 (1963), *overruled*, California v. FERC, 495 U.S. 490 (1990).

[9] CAL. WATER CODE § 1242 (West 1971).

extract in some years and to offset that forbearance by drawing more heavily on the aquifer in other years. The problem is that the contracting landowners have no better right to the underlying groundwater than do all of the other landowners overlying that same aquifer. The rights are "correlative", that is, of equal stature and limited by the principle of mutual avoidance of harm. Thus, in years of forbearance, the other pumpers would be entitled to extract the water that the program intended to store. In years of extraction, the contracting landowner's rates of withdrawal may impair the rights of the correlative pumpers.

Recognizing in the organizer a superior right to groundwater stored when surface water is used in lieu, could involve upsetting an established set of property rights and investment-backed expectations, something courts are typically loathe to do. Fortunately the only colorable claim of overlying groundwater users to water of Type 5 would result if the importer abandoned the imported water once it was in the ground. Delivery for surface use does not constitute such abandonment.[10] The important point when imported water is used is that the mass balance in the groundwater basin will be the same whether the water is actively recharged or delivered *in lieu* of groundwater pumping. In both cases during years or storage, more water is contained within the basin than would have been stored absent the program.

Of course, the problem associated with *in lieu* recharge may be avoided where groundwater basins have been adjudicated such that the particular extraction rights have been quantified. This is the situation with a number of groundwater basins in Southern California. A potential shortcoming of adjudication, other than the time and cost associated with the process, is that the final judgements in Southern California often proscribe out of basin transfers of groundwater. This may hinder the ability to recover groundwater of Type 5.

The technique of in lieu storage can be also used outside adjudicated groundwater basins, but special arrangements will be necessary. There are several potential approaches:

- The correlative rights problem can be avoided by bringing all of the correlative rights holders into the contractual arrangement, or mitigated by bringing most of them into it. The ability of any one rights holder to upset the program by withholding consent remains, however. This is were incorporation of storage entities as part of AB 3030 management plans could prove particularly beneficial.

- The program could be operated in a manner that would presumptively avoid injury to correlative rights holders by foregoing pumping for a period sufficient to assure that when accelerated pumping occurred, it would not disadvantage the correlative rights holders compared to the status quo. That might mean designing the program so that the number of sequential years of accelerated pumping was limited.

- Special legislation might be enacted to preclude suits against the program by non-contracting landowners where the groundwater that the program causes to be extracted in any one year was limited to amounts that could have been extracted in any previous year but for the forbearance imposed by the program. This would be a legislative interpretation of the "no harm" rule as applied in the narrow context of an in lieu groundwater banking program. While a general groundwater management regime may be beyond reasonable legislative expectations, a modest enactment of this sort may be realistic.

IV.3.2 What sort of entity should operate the program?

The organizer of the groundwater banking program will enjoy the best legal position to recover the groundwater that it has stored if it is a public agency managing groundwater of Type 5. Under these circumstances, the right to extract the stored groundwater enjoys a high priority. Such a right prevails over all rights except in the following circumstances:

(1) It is inferior to the state-held public trust interest of the people of California, as are all usufructory rights;

[10] City of Los Angeles v. City of Glendale, 142 P.2d 289, ___, 23 Cal.2d at 76-78 (Cal. 1943).

(2) It is of equal priority with pueblo rights, but, since pueblo rights apply only to native water, disputes between the two result in apportionment to the importer of the quantity of groundwater attributable to imports;[11]

(3) It is of equal priority with other public and private importers in the watershed of destination and use, but disputes between these parties are also resolved by apportioning to each importer "the amounts attributable to the import deliveries of each."[12]

An importer's right to recapture imported recharge water is established by manifesting such intent prior to importation.[13] A groundwater banking program is predicated upon such an intent.

The advantage of the program organizer being a public entity is that that status precludes the potential for adverse rights attaching to the program's stored groundwater through prescription. While CAL. CIVIL CODE § 1007 (West 1982) literally protects "any public entity" from prescription, the courts have been reluctant to afford the statute its broadest application[14] and may try to limit the definition of "public entity" to exclude some marginal parties. Therefore, care should be exercised in choosing or establishing the program organizer. Further research is needed regarding the outer bounds of the "public entity" definition. For instance, it would be useful to know whether a groundwater banking program organizer that was the creature of a memorandum of understanding between the state and federal government might qualify.

IV.3.3 Where should the program store the imported water?

In the most general sense, in order to simplify the legal situation, the target groundwater storage basin should be composed of percolating strata and be isolated from surface waters, such as streams or the underflow of streams. This would minimize the interplay of various legal doctrines, avoid factual disputes, and make the legal outcomes more predictable. As a result, the participants in the program will feel more secure about their rights and about the investments required to implement active recharge.

Under the groundwater banking arrangements explored here, however, water might be introduced into a groundwater basin at one location and extracted at another some distance away. This raises the question of the hydrologic interconnections that must be maintained between the imported recharge water and the extracted water in order to preserve the importer's preference right. "Imported water" is "foreign water imported from a different watershed."[15] The advantage of obtaining the rights of an importer is that California law gives high priority to these rights in order "to credit the importer with the fruits of his expenditures and endeavors in bringing into the basin water that would not otherwise be there."[16] Under this rationale, it would appear that the area of recharge must be hydrologically connected to the area of discharge such that the program is pumping groundwater that "would not otherwise be there" but for the recharge. In other words, the two areas much be sufficiently proximate and interconnected so that the recharge water would be expected to replenish the area of discharge within the timeframe of the two events.[17]

Establishing proximity and interconnectedness is very important. Many California cases determining groundwater rights turn on geohydrologic characteristics of the groundwater aquifers. In

[11]City of Los Angeles v. City of San Fernando, 537 P.2d 1250, ____, 14 Cal.3d at 288 (Cal. 1975).
[12]City of Los Angeles v. City of San Fernando, 537 P.2d 1250, ____, 14 Cal.3d at 260-62 (Cal. 1975).
[13]City of Los Angeles v. City of Glendale, 142 P.2d 289, ___, 23 Cal.2d at 78 (Cal. 1943); City of Los Angeles v. City of San Fernando, 537 P.2d 1250, ____, 14 Cal.3d at 257-58 (Cal.1975).
[14]*See* City of Los Angeles v. City of San Fernando, 537 P.2d 1250, ____, 14 Cal.3d at 272, 274, 276 (Cal. 1975).
[15]City of Los Angeles v. City of San Fernando, 537 P.2d 1250, ____, 14 Cal.3d at 261 n.55 (Cal. 1975).
[16]City of Los Angeles v. City of San Fernando, 537 P.2d 1250, ____, 14 Cal.3d at 261 (Cal. 1975).
[17]One of the cases holds that it is possible to establish a right to imported water by making deliveries and withdrawals within one's own reservoir and alleging in a complaint that one intended to capture return flow from waters imported into the basin. City of Los Angeles v. City of Glendale, 142 P.2d 289, ___, 23 Cal.2d at 78 (Cal. 1943); City of Los Angeles v. City of San Fernando, 537 P.2d 1250, ____, 14 Cal.3d at 257-58 (Cal.1975). The issue, then, is whether the conjunctive use program would be viewed as delivering and withdrawing water from within the same underground reservoir.

addition to locating a storage site that is factually simple, it would be useful to locate one that is scientifically well-studied; ideally, one where the pertinent scientific facts have been determined in prior judgements. Such prior judicial fact finding may not be binding on parties to any future suit but would at least serve as an advance indicator of what the program might expect from future litigation.

IV.3.4 From what source(s) should the program obtain surface water for storage?

One consideration in selecting a source of program water is the fixed capital requirements of the program. If the program requires appreciable new physical infrastructure, as will likely be the case for a maximal program of groundwater banking, the costs of those capital investments will presumably have to amortized by the project itself over a period of time. In that circumstance, the program will require a reliable source of water over that same time horizon. If, by contrast, the program requires only limited capital investment, the program water can be intermittent or less reliable. Therefore, an early question to be resolved is whether the program can be based on an interruptible source of water, or does it require a durable source? The hydrologic distinction between capturing peak floods (intermittent) and re-operating reservoirs (reliable) will certainly bear on the appropriate response to this question.

IV.3.5 What parties should be involved?

The program organizer should seek contractual arrangements with parties owning land overlying groundwater since they may possess both spreading grounds and a right to extract groundwater. Their participation and cooperation may be secured by sharing the benefits of the program with them, either in terms of new water or monetary compensation. The presumption in this case is that the sharing of benefits made available to the overlying landowners will be sufficient to surpass the water management opportunities afforded by strictly local opportunities.

V. Workplan Step 3: Site Analysis

The hydrologic potential analysis described in Section III relied upon making assumptions about the ability to convey surface water and to store it in a suitable groundwater banking site. The assumed conveyance and groundwater storage capacities input for the simulated foothill reservoirs in CUP are presented in Table 13. By virtue of is large flows and significant existing surface water storage capacity, the Sacramento-Shasta system was accorded the largest portion of the assumed 2 MAF storage capacity. The relatively small Caleveras-New Hogan system lies at the other end of the conveyance/storage spectrum.

Table 13: Partition of System Capacity Among the Nine Simulated Rivers in CUP

River	Conveyance Capacity (cfs)	Provisional Storage (TAF)
Sacramento	648	370
Feather	518	296
Yuba	387	222
American	387	222
Mokelumne	260	148
Calaveras	130	74
Stanislaus	387	222
Tuolumne	387	222
Merced	387	222

At first glance, the values in this table may seem to indicate that conveyance infrastructure and potential storage sites are located in close physical association with each surface water system. Any such impression is an artifact of the way CUP operates as it simulates each river as an independent system. Given the highly engineered character of the Central Valley water system, it is more likely that surface waters from various rivers diverted as part of the groundwater banking program will co-mingle during the aquifer storage process. This section deals with identifying the sites which can provide the required aquifer storage resource.

Much work in this area has already been carried out by the CalFed Bay-Delta Program. as part of its Storage and Conveyance Component, the ongoing water planning forum produced and inventory of 17 potential groundwater storage sites. These were described in a matrix which included a number of attributes, including: the active storage capacity; the extent to which groundwater banking will alter groundwater elevations; required infrastructure; long-term regional groundwater conditions; and environmental concerns. Details of the active storage attribute, which total over 10 MAF are shown in Table 14.

Table 14: CALFED Estimates of Active Groundwater Storage Capacity

North of Delta Storage	Potential Storage	South of Delta Storage	Potential Storage
Butte Basin	470 TAF	Folsom S. Canal (east S.J. County)	860 TAF
Cache Creek Fan (Cache-Putah)	450 TAF	Kern River Fan	930 TAF
Colusa County	320 TAF	Gavelly Ford/Madera Ranch	350 TAF
Eastern Sutter County	470 TAF	Medota Pool (Westside)	900 TAF
Sacramento County	260 TAF	Mojave River	200 TAF
Stony Creek Fan	640 TAF	Semitropic WSD	1000 TAF
Sutter County	1180 TAF	Tuolumne/Merced Basin	1250 TAF
Thomes Creek Fan	220 TAF		
Yuba County	540 TAF		
Total North of Delta	**4,550 TAF**	**Total South of Delta**	**5,490 TAF**

The spatial distribution of these sites, along with other potential storage targets located in Southern California, is depicted in Figure 8. When compared with the hydrologic potential of the rivers considered in CUP (Table 11), the first observation one makes is that while most of the yield associated with reservoir re-operation will be generated in the Sacramento Valley, much of the potential storage is located south of the Delta. This raises the issue of how best to convey water across that keystone of the California water system. It should not be assumed that the ability to realize the full potential of groundwater banking in the Central Valley is neutral with regards to the three Delta conveyance opportunities under consideration by CalFed. What is required is operational analysis of specific groundwater banking opportunities which can explore the full implications of various assumption about the existence and operation of conveyance infrastructure. This sort of operational analysis which is presented in the Section VI.

By virtue of their inclusion in the CalFed inventory, the storage sites listed in Table 14 likely comprise a likely constellation of potential groundwater banking sites. NHI has neither the resources nor the desire to redevelop the CalFed list. From our vantage point, however, there are issues other than the active storage capacity which go to the relative merits of a particular groundwater banking site. In fact, prior to the release of the CalFed inventory NHI had already completed a first assessment of promising groundwater banking sites. Based on consultation with experts,[18] and on a literature review,[19] we chose several criteria for selecting candidate sites for new or enhanced artificial or *in lieu* recharge of ground water:

1. Aquifer storage capacity available for groundwater banking
2. Opportunities to solve collateral problems
3. Impact on habitat and species of fish and wildlife
4. Infiltration characteristics of soils and water courses
5. Hydraulic properties of aquifers
6. Extent of well development and yields of wells
7. The magnitude of surface water/groundwater interaction
8. Water quality effects of recharge
9. Land use effects of recharge

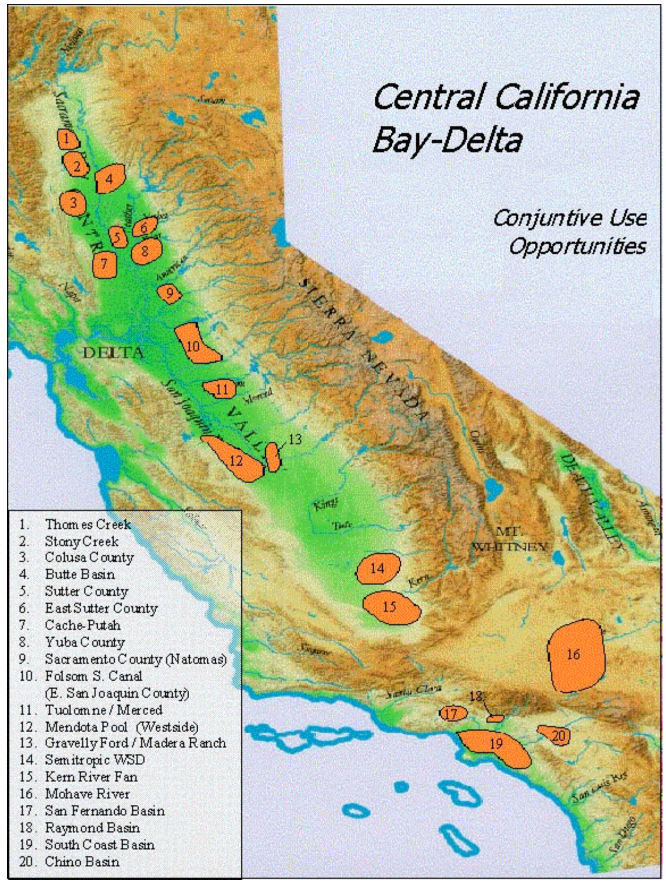

Figure 8: Spatial Distribution of Potential Groundwater Storage Sites in California

This listing has been selected to cover the broad range of conditions occurring in California with respect to groundwater banking. Appendix III contains the results of a survey conducted by NHI which sought out examples of where the convergence of these criteria have already generated interest or activity in groundwater banking. It is important to keep in mind that each site listed in the inventory could

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[18]Bertoldi, Gilbert, 1993, Senior Scientist, U.S. Geological Survey, Sacramento, California; Durbin, Tim, 1993, Professional Engineer, vice-president, Hydrologic Consultants, Inc., Davis, California; Fielden, John R., Hydrologist, 1993, California Dept. of Water Resources, Sacramento, California; Wilson, Laurence, April, 1993, Ground Water Protection Supervisor, Santa Clara Valley Water District, San Jose, California.

[19]Asano, Takashi, and others, 1985, <u>Artificial Recharge of Groundwater</u>, Butterworth Publishers, Boston.

potentially become more productive with an infusion of new yield derived from reservoir re-operation. The nature and importance of these criteria are explored in greater detail in the following comments.

The volume of water which can be stored in the subsurface is dependent on the **aquifer storage capacity**. At an given moment, however, most of the water in storage will be the result of basin scale hydrologic processes. An intentional program of groundwater banking seeks to capitalize on the increment of storage capacity which could be integrated with the yield estimated in Section III. The challenge is defining the increment of storage capacity available to the groundwater banking program.

In areas of severe groundwater depletion that increment of storage clearly exists in the form of a persistent cone of depression. The presence of a cone of depression on the water table surface, a fairly common phenomenon in the Central Valley south of the Mokelumne River drainage, indicates that local pumping historically exceeded the natural recharge to the aquifer. If the cone is stable, then a water balance has likely been re-established via enhanced seepage from overlying rivers and streams in response to the increased hydraulic gradients associated with the drawdown feature. Defining the increment of groundwater storage in this case involves a fairly straight forward computation of filling the basin with known quantities of water and discounting the reduction in the induced seepage from overlying rivers and streams. This increment of enhanced stream flow would be a direct environmental benefit of the program. In addition, the net rise in the water table during periods of aquifer storage would have direct and quantifiable local benefit relative to the persistent cone of depression currently plaguing local groundwater users. The primary disadvantage of utilizing this increment of storage are the pumping costs associated with recovery from a deep cone of depression and the need to carry out a period of storage before any recovery can be achieved.

A second increment of storage available for groundwater banking should be viewed in more speculative terms. In locations where there has been no sustained, long-term imbalance between basin scale hydrologic process, as is commonly the case in the Sacramento Valley, the water table is generally more stable and closer to the surface than in zones of persistent dewatering. In order to create the increment of storage required for groundwater banking, recovery, either through increased local reliance on groundwater pumping or though the export of groundwater, must precede storage. This is somewhat akin to the situation in the drought water bank of the early 1990's when Sacramento Valley farmers sent groundwater to water strapped communities in Southern California in exchange for monetary compensation. Achieving this increment of storage essentially involves treating the aquifer as a direct extension of the reservoir. As in a reservoir where the lake surface fluctuates from month to month, the end result of this integration would be a water table which fluctuates within a prescribed management range. While a case can be made that the optimal overall system yield will emerge from this integration it is more difficult to demonstrate the local benefit of this type of storage and recovery.

For that reason we initially focused our attention in this feasibility study on zones where groundwater overdraft has already created a cone of depression. This focus should not be understood as completely discounting the potential role of the more integrated form of groundwater banking. In fact, given the imbalance in hydrologic potential towards the Sacramento Valley (Table 11) and the potential complexity of conveying water across the Delta, it may ultimately be necessary to explore the full range of Sacramento Valley alternatives. The premise of the program, however, should remain the same whether storage takes place in persistently de-watered or stable hydrologic regimes. Namely the use of any available aquifer storage resource must provide sufficient local benefit to inspire substantial local enthusiasm.

The best way to motivate local enthusiasm for groundwater banking is to demonstrate that implementation of the program might help **solve collateral water problems**. Our starting premise for this assertion is that even in relatively stable hydrogeologic provinces, water managers face challenges which call for action. These challenges often involve water quality consideration, the desire to resolve emerging conflicts between municipal and agricultural water use sectors, or the need to redress the degradation of aquatic habitat. In all such cases, controlling the rate and place of ground water recharge and pumping may create opportunities to accomplish local water management goals which would go unrealized save for the introduction of new yield into the system. Examples of the types of collateral problems which could be resolved in this manner include land subsidence and ground water quality degradation in Yolo County and increasing pumping lifts in eastern San Joaquin County.

Attention must also be paid to the **impacts, both positive and negative, which groundwater banking can have on fish and wildlife**. Appendix IV includes our assessment of some potentially negative impacts of groundwater banking which must be resolved. Commonly, groundwater recharge sites are viewed as wetlands conducive to enhanced wildlife management opportunities. Wildlife experts[20] remind us that to be beneficial to wildlife, water must be provided to an environment, in the right amount, at the right time, in suitable quality; and, the supply must be reliable. It would seem that specific benefits to wildlife could be built-in to many recharge projects, to create and maintain wetlands, where needed, or to increase the base flow of small streams through raising ground water levels. Another, perhaps more far reaching, environmental benefit of groundwater banking goes beyond the local impact of a flooded recharge basin. This benefit goes to the aquatic eco-system restoration opportunities which would have otherwise been missed without the added water management flexibility associated with the potential yield increase from groundwater banking. An examples of this type of benefit include the potential to enhance Delta outflow by storing groundwater in San Joaquin County and to restore the anadramous fishery in the San Joaquin River by banking groundwater near the Gravelly Ford reach of the river.

Aquifer recharge, the first of two central operations in a groundwater bank, occurs primarily by spreading water on land and in stream beds, or, or by filling percolation ponds. In all cases, **the infiltration characteristics of soils and sediments** determine the rate at which surface water becomes ground water. Clayey soils and sediments tend to inhibit infiltration. Generally, suitable soils must overlie permeable sediments in order to provide the physical environment essential to recharge the water table. Soil surveys developed by the U.S. Natural Resources Conservation Service provide information adequate to evaluate the recharge potential of soils, but, information on underlying sediments usually does not extend beyond the description of parent material.[21] Work conducted by the USGS in the Tulare Lake Basin, for example, identified large areas in which shallow clays underlying surface soils[22], precluding the development of any effective program for recharging ground water reservoirs, even though surface soils accept water readily. Other USGS studies in eastern San Joaquin County and along the Gravelly Ford reach of the San Joaquin River reveled conditions conducive to groundwater banking. When aquifer recharge is accomplished via *in lieu* substitution the pre-existence of extensive groundwater pumping is required. By substituting surface water for this pumping, ground water storage can be increased. In order to estimate the potential for *in lieu* groundwater recharge, information must be developed on the amount of pumping which is likely to occur during years of normal or above normal precipitation. An inventory of agricultural pumping in Yolo County is an example of information required in this case[23].

The rate at which aquifers can be discharged by pumping wells, the second of the two central operations of a groundwater bank, is dependent on **the hydraulic properties of the aquifers**, the spatial extent of these aquifers, and the hydraulic head created by pumping.[24] Although specific investigations are required to quantify these properties, a history of groundwater use in target areas is a good indication that, under natural hydrologic conditions, these properties favor aquifer storage and recovery. In selecting a site, the presence of groundwater wells should be the minimum threshold for consideration. **The extent of well development and the long-term yield** of large volumes of ground water to wells suggests a favorable physical environment for recovery.

The magnitude of surface water/groundwater interaction at any given site may influence groundwater banking opportunities. In the San Joaquin Valley, where past overdrafts have dropped

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[20]Moore, S.B., and others, September 1990, "Fish and Wildlife Resources and Agricultural Drainage in the San Joaquin Valley, California: Technical Report of the San Joaquin Valley Drainage Program, Sacramento, California.
[21]Bullard, Gary, 1993, Senior Soil Scientist, U.S. Natural Resources Conservation Service, Davis, California, personal communication.
[22]San Joaquin Valley Drainage Program, September, 1990, "A Management Plan For Agricultural and Subsurface Drainage and Related Problems on the Westside San Joaquin Valley": Sacramento, California.
[23] Borcalli, Fran, 1992, "Yolo County Water Plan Update,"Report to Yolo County Board of Supervisors, Woodland, California; Jenkins, Mimi, Sept., 1992, "Yolo County, California's Water Supply System: Conjunctive Use Without Management," MS. Thesis, Dept. of Civil Engineering, University of California, Davis, California.
[24]Freeze, R.A. and Cherry, J.A., 1979, Groundwater, Prentice-Hill, Englewood Cliffs, NJ.

groundwater levels far below ground level, the degree to which adding groundwater storage may impact streamflow levels is relatively small. However, in many locations within the Sacramento Valley, groundwater storage may lead to increases in surface flows. Conversely, groundwater withdrawals could lead to reductions in surface flows. These kinds of interactions reduce the benefits of groundwater banking and increase the complexity of storage accounting. What is required is a thorough understanding of basin hydrogeology. Within California, there is a wide range in the certainty of knowledge of the hydraulic properties of specific aquifers.[25] Some water user organizations, such as the Turlock and Modesto Irrigation Districts, are well-armed with information to plan and operate an artificial recharge program as part of a conjunctive use strategy. Others, like the Butte Basin Water Users Association, are in the process of developing the quantitative models and monitoring devices useful for participation in such programs. This information is lacking in regions such as Tehama County.[26] Wherever groundwater banking ultimately occurs, detailed hydrogeologic analysis will be required.

A review of the history of irrigation and groundwater recharge in California[27] shows the importance of considering the **water quality effects of recharge**, whether that recharge is coincidental or planned. Positive or negative effects can be produced in soil water or in underlying ground water reservoirs through the introduction of surface water of a certain quality. For example, some of the soils of the eastside San Joaquin Valley (Fresno area) are too sodic to be recharged effectively with Sierra water, without the addition of gypsum to the soils.[28] Looking for a "win-win" situation, the San Joaquin Valley Drainage Program [29] analyzed the feasibility of exporting gypsiferous drainage water to irrigate these lands and recharge ground water. The concept was feasible, technically, but could not overcome political objections.

Most information on **land use effects of groundwater recharge** is anecdotal, obtained from discussions with various water experts. In San Bernadino County, artificial recharge was halted in one locale when rising groundwater levels caused clays to swell and threaten the structural integrity of piers in a highway overpass.[30] In highly urbanized Santa Clara County there have been chronic complaints, and lawsuits, from residents adjacent to percolation ponds.[31] Nearby residents have alleged the creation of mosquito problems, marshy soils, and dangerous nuisances from open water bodies. Because of these and associated cost factors, groundwater recharge in urban areas is most effectively conducted in natural or modified stream courses.

In light of resource limitations, NHI did not conduct detailed analysis of each of these attributes at all of the twenty potential sites in Figure 8. Our reconnaissance of the landscape, however, did lead us to three locations where a convergence of groundwater banking attributes seems to exist. While by no means claiming that these are the sites which must ultimately store yield generated through pre-delivery,[32] these are striking examples of the ability of groundwater banking to help meet: (1) water management objectives; (2) eco-system restoration objectives; and (3) a combination of both these objectives.

Cache-Putah Basin. Cache and Putah Creeks are significant westside tributaries of the Sacramento River. Historically, flows in these creeks recharged groundwater below Yolo County through instream hydraulic connections with the aquifers which provide much of the county's municipal and agricultural water supply. Recently the intensity of local reliance on groundwater has combined with the out-of-basin export of water from Putah Creek and the mining out of the instream gravel in Cache Creek to create nagging problems

[25]Durbin, Tim, 1993, Professional Engineer, vice-president, Hydrologic Consultants, Inc., Davis, California, personal communication.
[26]Durbin, Tim, 1993, Professional Engineer, vice-president, Hydrologic Consultants, Inc., Davis, California, personal communication.
[27]Prokopovich, Nikola P., April, 1989, "Irrigation History of the West-Central San Joaquin Valley" : U.S. Bureau of Reclamation Contract Report No. 7-PG-20-03920, Sacramento, California.
[28]Sposito, Garrison, and others, 1987, "Chemical Effects of Saline Drainage Waters on Irrigated San Joaquin Valley Soils": Calif. Water Resources Center, Univ. of Calif. Contribution No. 196.
[29]Hansen, B.R., and others, June, 1990, "An Assessment of Blending Westside Drainage Water with Friant-Kern Canal Water for Increasing Infiltration Rates": U.S. Bureau of Reclamation Contract Report No. 9-FC-20-08070.
[30]Fletcher, G. Louis, December, 1992, General Manager and Chief Engineer, San Bernadino Valley Municipal Water District, San Bernadino, California, personal communication.
[31]Wilson, Laurence, April, 1993, Ground Water Protection Supervisor, Santa Clara Valley Water District, San Jose, California.
[32] Tocay Dudley of the DWR Central District has been directing studies of groundwater storage opportunities in Yuba, East Placer, Yolo, and Sacramento counties. These may supplement the preliminary list outlined here.

with groundwater overdraft, land subsidence, and deteriorating groundwater quality.[33] Despite the high cost and political uncertainty, these challenges have prompted both agricultural and municipal water providers to initiate planning to secure a Sacramento River water right. Such a claim would certainly be facilitated by increasing the available yield through reservoir re-operation. This could be accomplished by developing new off-stream percolation ponds or negotiating *in lieu* arrangements with local farmers who would be supplied through an extension of the Tehama-Colusa Canal. In exchange for this introduction of water, the Yolo water users could continue to allow the Yolo County ground water reservoir to be used as part of the drought water bank which performed well during the heart of the 1987-92 drought. However, to garner local support for such a scenario, this approach needs to be compared with purely local opportunities to meet water management objectives.

<u>Gavelly Ford/Madera Ranch</u>. As mentioned in Section II, operation of the Friant Unit on the San Joaquin River has lead to the virtual de-watering of the river below Friant Dam. Besides occasional flood flows which spill from Millerton Lake, nearly all of the water in the San Joaquin in diverted to provide water for irrigation. Obviously this severe alteration of the hydrograph in the San Joaquin River has had a dramatic impact on fish. In particular, runs of anadramous fish were decimated. Enter the Anadramous Fish Recovery Act spawned by the CVPIA and its call for a doubling of the number of anadramous fish in the Central Valley, and restoration of the San Joaquin emerges as a promising management alternative. The challenge is to achieve this eco-system objective in a manner which minimizes negative impacts on existing water users. Groundwater banking opportunities in an expansive cone of depression below the Gravelly Ford reach of the San Joaquin and the adjacent Madera Ranch site could assist in removing political opposition to an environmental goal.

<u>East San Joaquin County</u>. Two associated groundwater basins in this area are overdrafted and the northernmost basin, which is used directly for water supply by the city of Stockton, is experiencing intrusion of brackish water from the Sacramento-San Joaquin Delta. There is an overall shortage of both groundwater and surface water, particularly surface water for environmental releases to the Stanislaus River Basin. Plans to extend the Folsom South Canal in order to use imported American River surface water for aquifer recharge have been discussed for many years although a consulting firm hire by local water districts[34] found that the structural modifications needed to facilitate large-scale groundwater banking would be formidable. Nevertheless, the strategic location of the groundwater basins with respect to the Delta make this a viable candidate area because water stored in this location would be well placed to help improve the export and environmental water management objectives in the Delta which may be compounded by certain Delta conveyance options under consideration by CalFed.

It is our hope that the detailed operational analysis of the Cache-Putah, east San Joaquin, and Gravelly Ford/Madera Ranch groundwater banking sites, which is found in Section VII, will motivate additional support to bring the remaining sites under similar scrutiny.

[33]Jenkins. Mimi, September 1992, "Yolo County, California's Water Supply System: Conjunctive Use Without Management," M.S. Thesis, Department of Civil Engineering, University of California, Davis.
[34] California Department of Water Resources, 1990, "Stanislaus and Calaveras Conjunctive Use Program," unpublished paper by Don Fisher, Senior Engineer, Sacramento, California.

VI. Workplan Step 4: Operational Analysis

In order to analyze both how any specific groundwater banking interventions might function and how they might interact with other features of the Central Valley water system, a simulation model is required. One of the key elements of an intentional program of groundwater banking will certainly be specific distribution and conveyance arrangements of both a structural and an institutional nature. An exploration of the ramifications of these arrangements is needed. In California, the type of exploration envisioned for this operational analysis has traditionally relied on the use of DWRSim, a simulation model of the State Water Project which has evolved into the standard reference for modeling the Central Valley water system.

In the current planning context, where the California water community is being encourage to pursue "fresh thinking rather than entrenched ideologies,"[35] DWRSim is somewhat constrained by its attention to the details and nuances of the current system. It is not easy to reprogram DWRSim to model radical departures from the current system such as reservoir re-operation and the integration of the groundwater banking sites in Table 14 into the Central Valley water system. To accomplish this exploratory analysis, NHI initiated a collaborative program with several California water partners to identify an appropriate screening level river basin simulation model. The goal of the effort was to develop a tool which could help identify water management arrangements that show promise and which merit further attention. The premise behind this search was that identifying a sub-set of promising arrangements could provide a sharper focus for subsequent refinement of the more cumbersome DWRSim model.

To develop this screening tool, NHI joined with the CalFed Bay-Delta Program, the US Bureau of Reclamation, the US Fish and Wildlife Service, and the Metropolitan Water District of Southern California to form the Joint Technical Unit (JTU). This group selected and guided the enhancement of the Water Evaluation and Planning system, or WEAP, developed by Tellus Institute. WEAP is a flexible water balance modeling tool conducive to the initial evaluation of management options at a system level. Unlike most river basin models, it effectively integrates supply, operation and demand. It is also highly flexible in that it can be easily reconfigured to screen emerging management options and to flesh out those which appear promising.

In order to make WEAP more appropriate for the Central Valley, the JTU funded two phases of model enhancement. Phase I included the development of a conjunctive use node to simulate the intentional transfer of water from the surface water system to a target groundwater banking site. The magnitude of the simulated transfer is the minimum of the excess surface supply during a given month, the available storage capacity in the aquifer, and the transmission capacity available to effectuate the transfer. A second Phase I modification involved the development of an active diversion feature. This feature mimics the operation of a single canal which services multiple points of demand, a common feature in the water management landscape of California. A second phase of modifications funded by the JTU fell into three categories: graphical output enhancements, water year type controls, and refinement of the conjunctive use node. The enhanced version of WEAP was delivered to the JTU in April 1998.

Since receiving the enhance software, NHI has carried out operational analysis on the three specific groundwater banking opportunities identified as the end of Section V: (1) the Cache-Putah Basin; (2)Gravelly Ford/Madera Ranch reach of the San Joaquin; and (3) east San Joaquin County. Respectively, these were selected as particularly strong examples of how groundwater banking can help meet: (1) local and regional water management objectives; (2) eco-system restoration objectives; and (3) a combination of both these objectives. It must be reiterated that NHI chose these examples only to demonstrate the far-reaching benefit which can be realized through the implementation of a maximal scale program of groundwater banking. The analysis presented in this section should not be interpreted as an endorsement of these particulate sites over the other contained in Table 14. In fact, NHI hopes that the following demonstration of WEAP's ability to screen potential groundwater banking sites will motivate the additional resources required to complete operational analysis on all potential storage sites.

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[35] Deep Water Thinking, Sacramento Bee Editorial, November 18, 1998.

VI.1 Meeting Water Management Objectives: The Cache-Putah Basin

Located in the southwestern Sacramento Valley between Cache and Putah Creeks, the Cache-Putah Basin (Figure 9) serves as an important source of water for both the agricultural and urban communities of Yolo County. Under current operating arrangements, surface water from Cache Creek, regulated by dams at the outlet of Clear Lake and at Indian Valley Reservoir and diverted at Capay, provides irrigation water for farms west of Davis and Woodland. The water in Putah Creek has been developed for use in Solano County and much of the flow is exported from the basin towards the south at a point east of Winters. In the extreme north of Yolo County, surface water is also available from the Tehama-Colusa Canal, and the Colusa Drain which convey Sacramento River water from points of diversion located in the Sacramento Valley to the north of the county. In the eastern portion of the Yolo County, water is taken directly from the Sacramento River for both irrigation and the municipal supply for the City of West Sacramento.

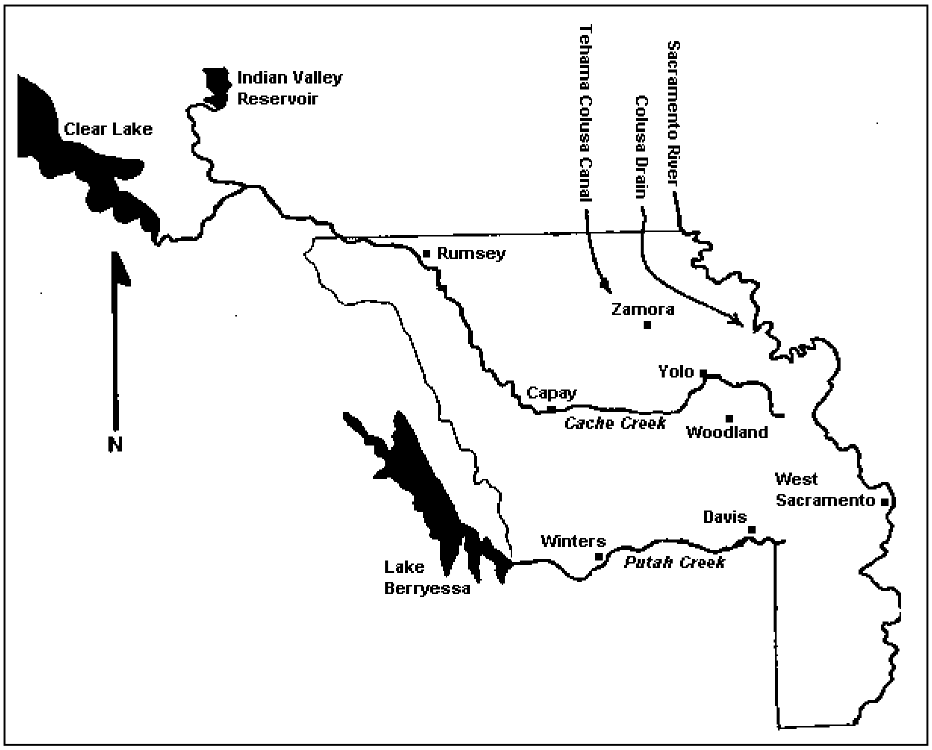

Figure 9: The Cache-Putah Basin

In spite of the availability of surface water from Cache Creek and the Sacramento River, there remain regions of Yolo County which rely exclusively on groundwater for supply. Overlying a map of the areas in which surface water is available with a map of the primary groundwater sub-basin of the Cache-Putah aquifer (Figure 10) reveals that a substantial portion of the land overlying the Lower Cache-Putah Sub-Basin has no access to surface water. This region includes Yolo County's principle cities, Davis and Woodland, as well as some of the most productive agricultural land in the Central Valley.

The result of this heavy reliance on pumped groundwater has been the development of a cone of depression in the water table of the Lower Cache-Putah Sub-Basin. The dimensions of this feature following the wet winter of 1993 are shown in Figure 11. Water table elevation data suggest that depending on hydrologic conditions, this cone of depression will vary in size and depth, although it remains persistent. This feature is a remnant of the much more extensive depression which plagued the county prior to the construction of Indian Valley Reservoir on the North Fork of Cache Creek in the 1975. The enhancement of surface supplies afforded by the reservoir has allowed for a reduction in groundwater pumping, improving the water balance in the county. Nonetheless, the nagging persistence of this overdraft feature continues to create concern over land subsidence, the initiation of groundwater flow patterns which threaten water quality, and increased pumping costs.

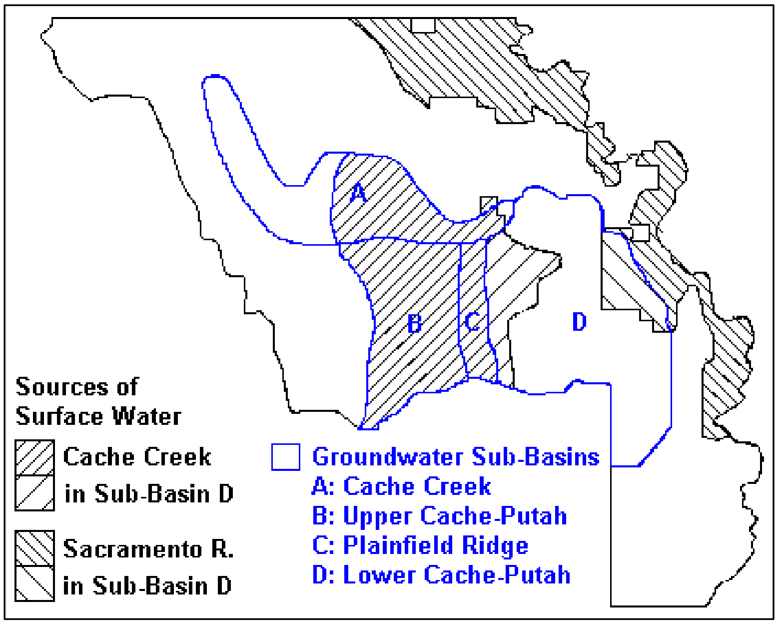

Figure 10: Composite Map of Groundwater Basins and Surface Water Service Areas

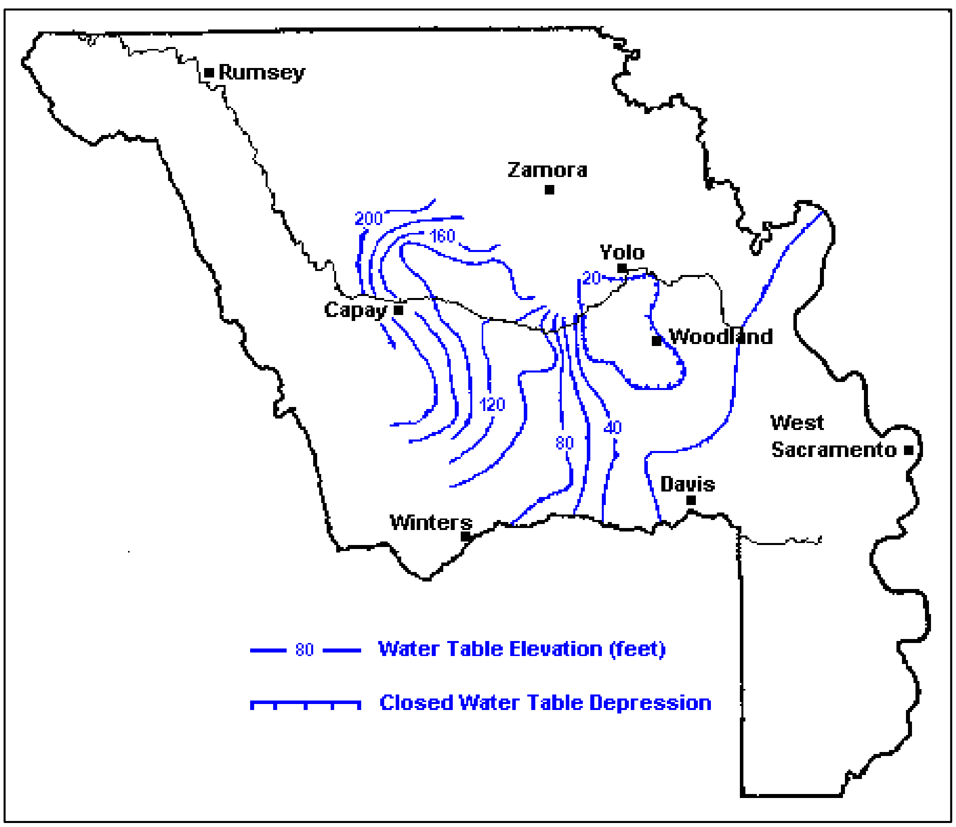

Figure 11: 1993 Cone of Depression in the Lower Cache-Putah Sub-Basin

In response to these threats, local water managers have proposed many alternatives. One is to expand the area receiving surface water from Cache Creek as part of a local *in lieu* substitution program.

An alternative to this purely local response might be integration of the aquifer storage resource in the Lower Cache-Putah Sub-Basin into the broader Central Valley water system. Such integration could potentially assist in capturing some of the yield which could be generated through re-operation of Shasta Dam. It could be accomplished by implementing the long-discussed extension of the Tehama-Colusa Canal into central Yolo County. With the connection in place, imported surface water could be used to implement *in lieu* transfers with farms overlying the dewatered portion of the Lower Cache-Putah Sub-Basin. Operational analysis using WEAP was conducted to explore the relative advantages and dis-advantages of these two water management strategies.

This was accomplished by configuring WEAP to represent the major features of the hydrologic system. Within the Cache-Putah Basin the essential features include the major sources of water supply, the principle points of demand, and the existing and proposed hydraulic infrastructure. These are depicted in the WEAP Network Configuration shown in Figure 12. The data used to define these nodes was gathered primarily from the pages of the detailed inventory of Yolo County water developed by Jenkins (1992)

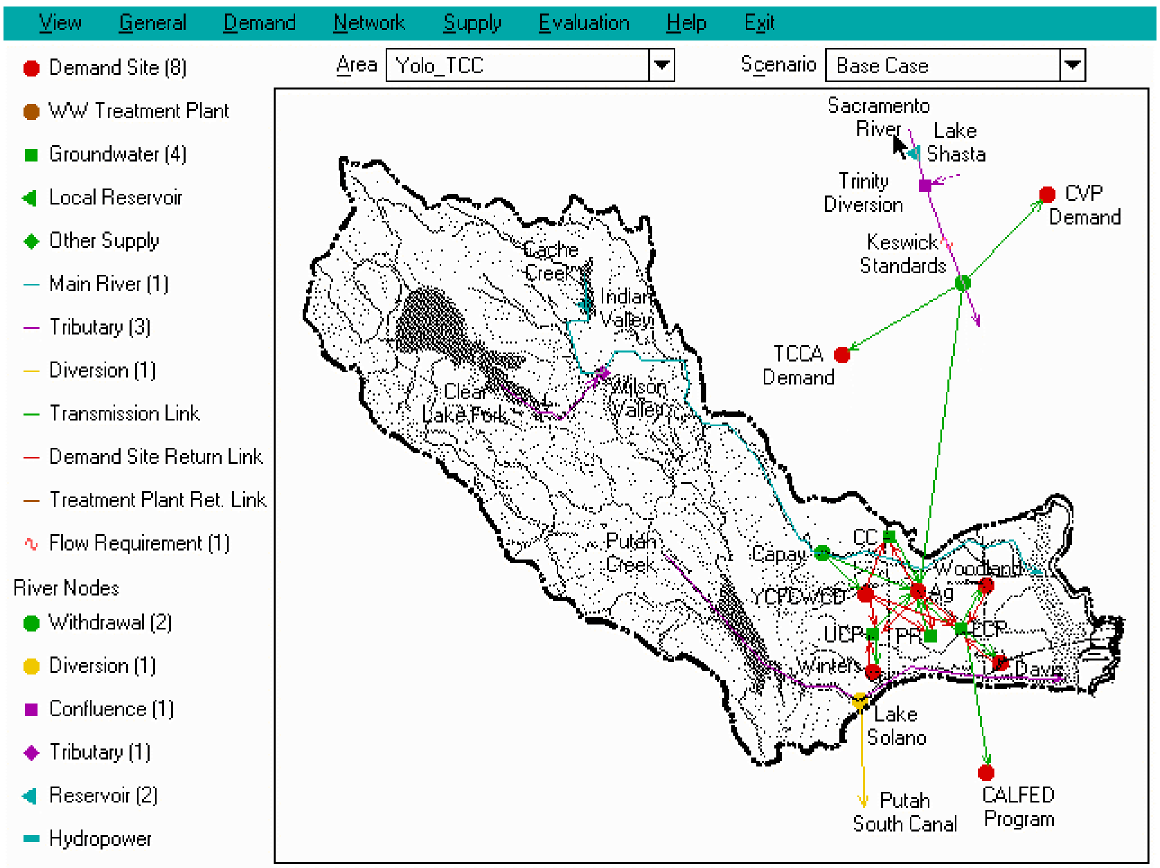

Figure 12: WEAP Cache-Putah Basin Network Configuration

The network configuration in Figure 12 includes all of the elements required to simulate three scenarios: the current base case; *in lieu* groundwater banking using surface water from Cache Creek; and *in lieu* groundwater banking using surface water from the Sacramento River. In the base case, the transmission links joining the Capay and T-C Canal withdraw nodes with the Ag demand node in Yolo County are inactive. For the Cache Creek *in lieu* scenario, the Capay link is activated and Indian Valley Reservoir is re-operated to pre-deliver water to the Ag node when surface water is available. In this scenario, the operation of Clear Lake Dam does not change as the YCFCWCD annually takes as much water as it can from that resource. By activating the transmission link between the T-C Canal and the Yolo County Ag demand node, Central Valley scale integration can be simulated. In this case Lake Shasta is re-operated to transfer available surface water to Yolo County for *in lieu* substitution. Broad water supply benefit can be achieved by activating the transmission link between the Lower Cache-Putah Sub-Basin and the CALFED Program demand node which calls for supplemental supplies during dry and critical water years.

Realization of either scenario will require the support of Yolo County water managers, stakeholders and politicians. From this perspective, there are two essential question in evaluating the relative merits of the various approaches. Does the water management intervention reduce the threats posed by the existence of a persistent aquifer draw down feature? How do existing stakeholders fare under the modified arrangements? Responses to both questions rely upon the establishment of a base reference.

Figure 13 is a simulated forecast of storage in the Lower Cache-Putah Sub-Basin under existing management arrangements and projected demand, assuming that the hydrologic record from 1972-1992 recurs between 1990 and 2010. The implication is that, absent management intervention, there will be a continued depletion of the groundwater resource in Yolo County. This change would likely strengthen the water quality and land subsidence threats faced by the county.
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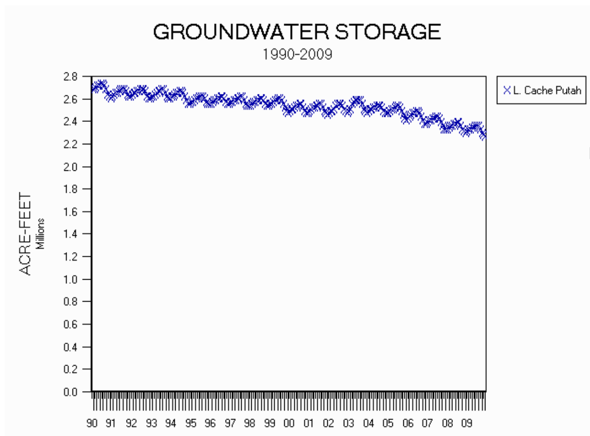


Figure 13: Simulated Groundwater Storage in the Lower Cache-Putah Sub-Basin Under Existing Arrangements

Recognizing this likely trend, local water managers have proposed the Cache Creek *in lieu* substitution scenario as a potentially beneficial strategy. In terms of the first essential question, by reducing groundwater pumping at the Ag demand node through the delivery of surface water, the simulated decline in aquifer storage substantially reduced (Figure 14). In this case, rather than demonstrating a steadily decreasing trend, aquifer storage appears to fluctuate within an acceptable management range. The decline in storage at the end of the simulation corresponds to the recurrence of the 1987-1992 drought.

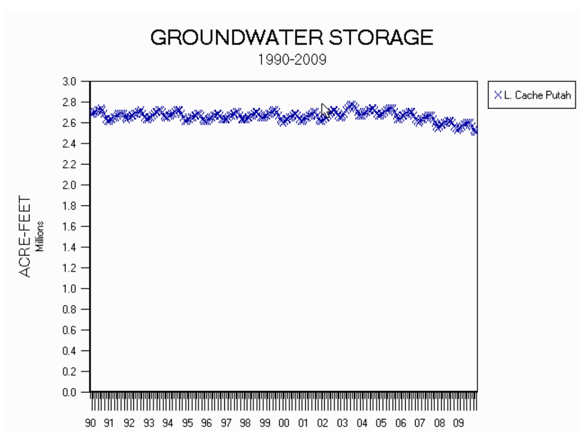


Figure 14: Simulated Groundwater Storage in the Lower Cache-Putah Sub-Basin Under Local *In Lieu* Arrangements

Increasing the area which receives water from Cache Creek, however, will presumably place a heavier burden on the surface water infrastructure on Clear Lake and Indian Valley Reservoir. In terms of the second essential question, this could make it more difficult to supply water to existing YCFCWCD customers. Figure 15 compares the difference in supply requirement coverage, or the extent to which demand is satisfied, under the proposed local *in lieu* substitution program as compared with the current arrangements. Relative to the base case, the heavier draw on the local surface water system would apparently cause the existing YCFCWCD customers to experience a decline in service relative to the level they would have received absent the program. Building a case for local *in lieu* substitution could be hampered by the decline in service experienced by an important group of stakeholders.

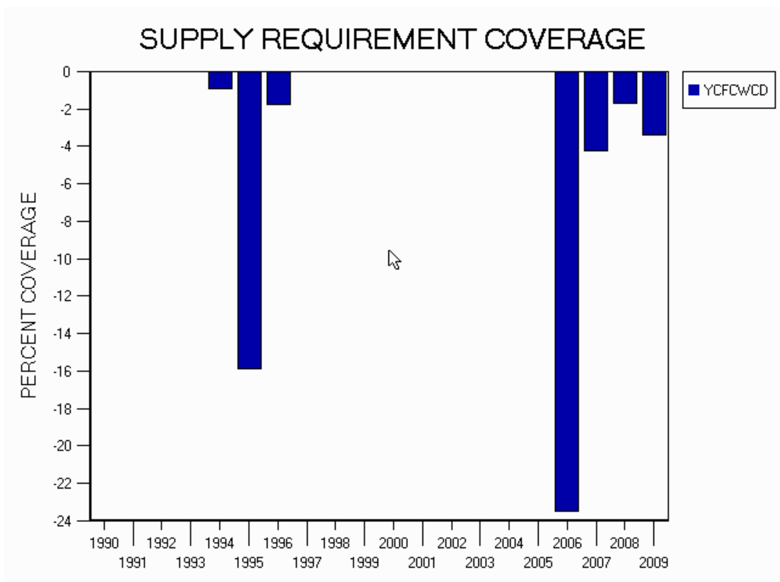


Figure 15: The Difference Between the Percent of the Supply Requirement (Demand) Coverage in the Base Case and the Local *In Lieu* Program Using Surface Water from Cache Creek

Carrying out *in lieu* arrangements with agricultural interests overlying the Lower Cache-Putah Sub-Basin using surface water made available through re-operation of Shasta Dam also mitigates the steady decline in aquifer storage predicted under the base case (Figure 16). The wider fluctuations in storage experienced under this arrangement relative to the local approach are the result of the more aggressive storage and recovery program carried out under integration into the Central Valley water system.

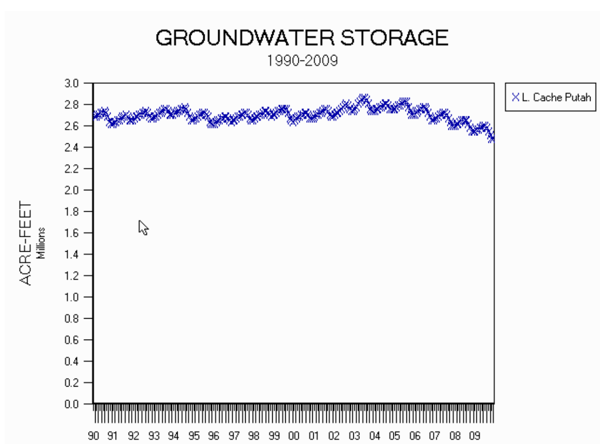


Figure 16: Simulated Groundwater Storage in the Lower Cache-Putah Sub-Basin Under Central Valley *In Lieu* Arrangements

Under this integration, no re-operation of the Cache Creek surface water system occurs and therefore existing YCFCWCD customers would experience no decline in service relative to the base case. Under this scenario, however, statewide water stakeholders would anticipate gaining some water supply advantage. In the simulation this is achieved by activating a 100 cfs transmission link between the Lower Cache Putah aquifer and the CALFED Program demand node. This node calls for 20 TAF of water during dry water years and 100 TAF during critical years. Under these arrangements the pattern of water supply enhancement which could be generated is shown in Figure 17.

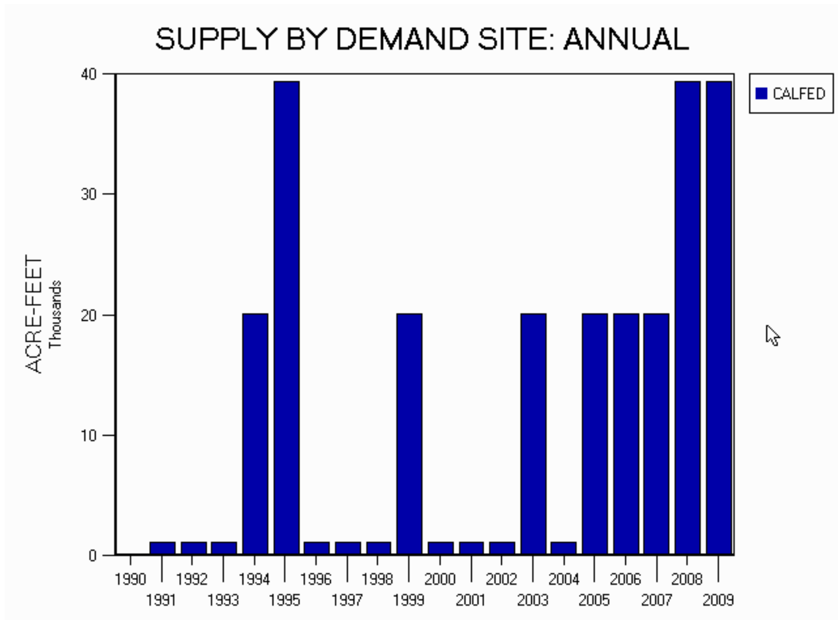


Figure 17: Simulated Water Supplies Enhancement for the CALFED Program Under a Central Valley *In Lieu* Substitution Program in the Lower Cache-Putah Sub-Basin

Increasing the capacity of the transmission link between the aquifer storage and the CALFED demand node could enable more complete coverage of the dry year demand, although potentially at the expense of stabilizing groundwater storage in the Lower Cache Putah Sub-Basin. As it is, there is a net transfer of water from the CVP storage system into the Yolo County groundwater system. Achieving a more balanced distribution could be achieved by fine-tuning the capacities of important transmission links. The important implication of these simulations is that without some sort of intervention, groundwater levels in Yolo County will likely continue to decline and that the opportunity to negotiate storage and recovery arrangements with the managers of the Central Valley water system could provide water supply benefits both locally and a broader scale.

VI.2 Meeting Environmental Objectives: Gravelly-Ford/ Madera Ranch

In addition to facilitating the achievement of water supply objectives, groundwater banking can also assist in achieving important eco-system restoration objectives. One particularly exciting opportunity would be the restoration of the anadramous fishery in the San Joaquin River below Friant Dam. This fishery was completely decimated when the U.S. Bureau of Reclamation impounded the San Joaquin River and diverted it for use outside the basin. The hydrologic impact of this manipulation is depicted in Figure 18 which presents measured flows at the USGS *San Joaquin R Bl Friant Ca* gauge. Once the Friant Unit of the Central Valley Project went on-line, base flows in the San Joaquin were drastically reduced, with only peak event spills from Millerton Lake passing downstream. This flow regime proved incapable of supporting spawning and rearing salmon and steelhead. Reversing the loss of this fishery could provide substantial momentum towards meeting the AFRP anadramous fish-doubling narrative standard. NHI believes this could be achieved by integrating the substantial groundwater banking opportunity at the Gravelly Ford/Madera Ranch into the surface water system in the San Joaquin Valley.

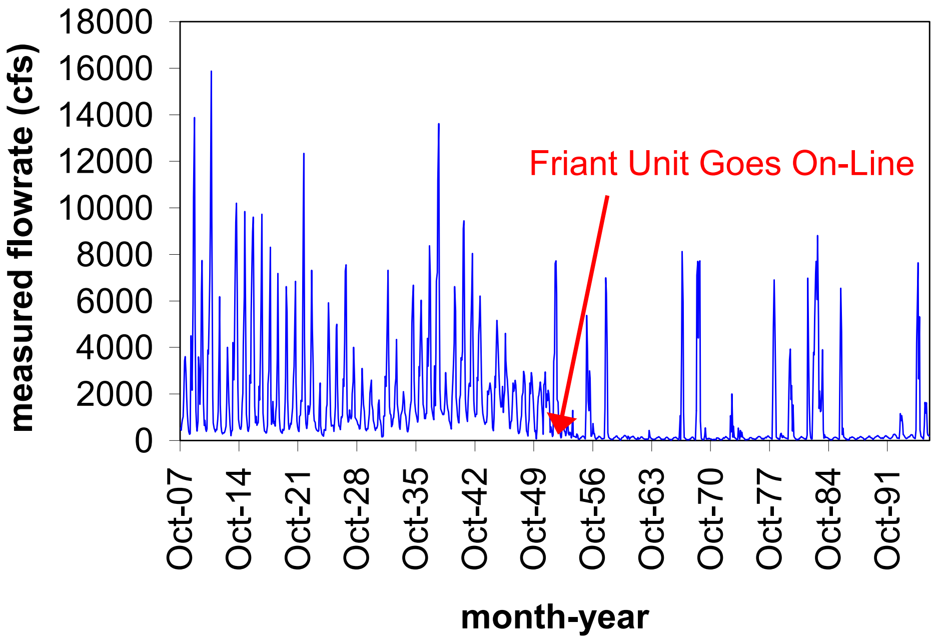


Figure 18: Measured Flows at the USGS *San Joaquin R Bl Friant Ca* Gauge Before and After the Construction of the Friant Unit of the Central Valley Project.

This system, depicted in Figure 19, includes the Delta-Mendota Canal which was constructed at the same time as the Friant Unit to provide roughly 800 TAF of replacement Delta water to exchange with contractors holding water rights on the de-watered San Joaquin River. Later, the California Aqueduct system, including the Delta pumps at Clifton Court, the regulating facility San Luis Reservoir, and various pumping plants, was constructed by the State of California to convey water to the southern San Joaquin Valley and then over the Tehachapi Mountains to Southern California. The Cross Valley Canal, financed by Kern County interests, was constructed to capitalize on the water management flexibility which could be achieved through exchanges between the Delta and San Joaquin River systems.

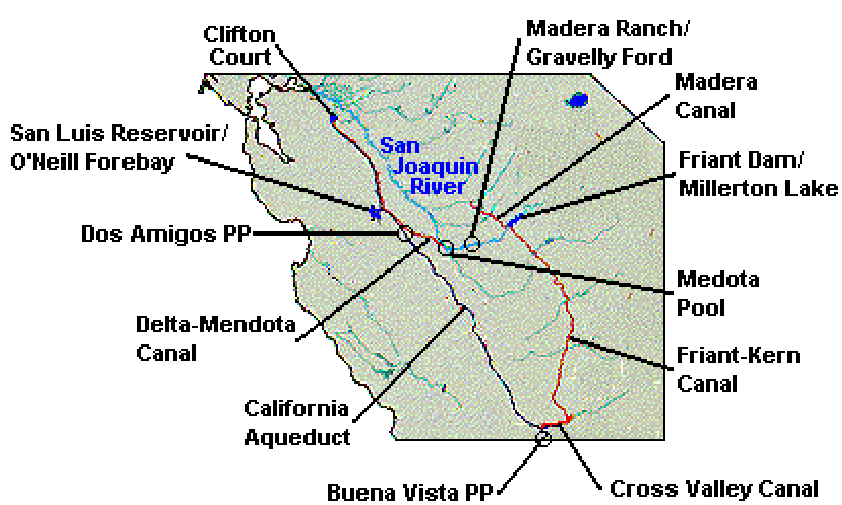


Figure 19: Important Elements of the San Joaquin Valley Water System

It is this type of flexibility which NHI would like to expand upon into order to profit from the substantial groundwater storage potential located below the de-watered Gravelly Ford reach of the San Joaquin. Figure 20 depicts the evolutions of the water table below the Central Valley over the first half of the 20th century based on simulations conducted by the USGS (Willamson et al. 1989). Where once groundwater flowed smoothly towards the valley outlet through the Carquinez Strait, by 1960 this surface was interrupted by numerous depressions related to the long-term imbalance between aquifer recharge and discharge. One of the most substantial depressions, located underneath the San Joaquin River downstream of metropolitan Fresno, developed in response to the elimination of seepage from the overlying San Joaquin River and the steady increase in groundwater pumping in this region. The decline was particularly acute given that the historically high seepage rate afforded by the coarse bed material in the Gravelly Ford reach was virtually eliminated by the closure of Friant Dam.

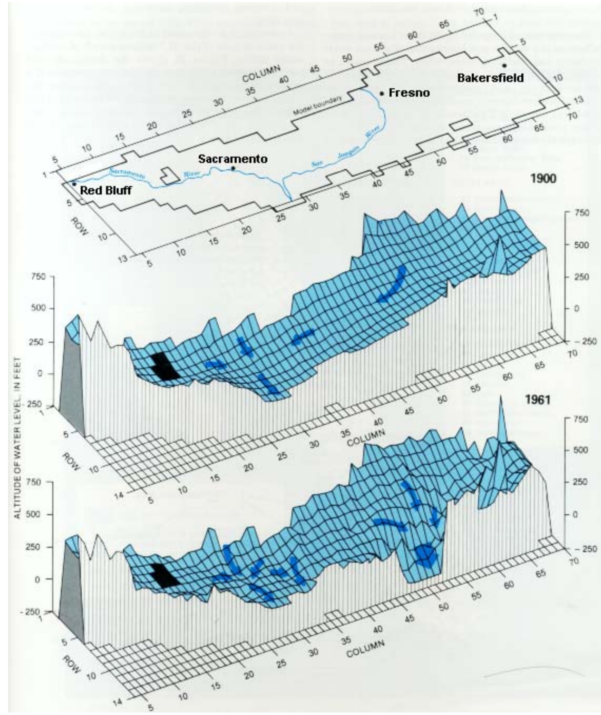


Figure 20: Water Table Evolution Below the Central Valley

There are those who discount any thought of restoring salmon to the San Joaquin precisely because of the heavy seepage losses at Gravelly Ford. They argue that the flows required to overcome these losses and to reconnect the Upper San Joaquin with the tributaries between Mendota Pool and the Delta would cripple the important agricultural economy in the southern San Joaquin Valley, which relies on the Friant Unit for irrigation water. Viewing the drawdown feature below Gravelly Ford as a groundwater banking site instead of as a hydrologic sink, however, provides the flexibility to restore the San Jaoquin with a minimum of disruption to the agricultural economy. This would be accomplished by re-routing water as depicted in Figure 21.

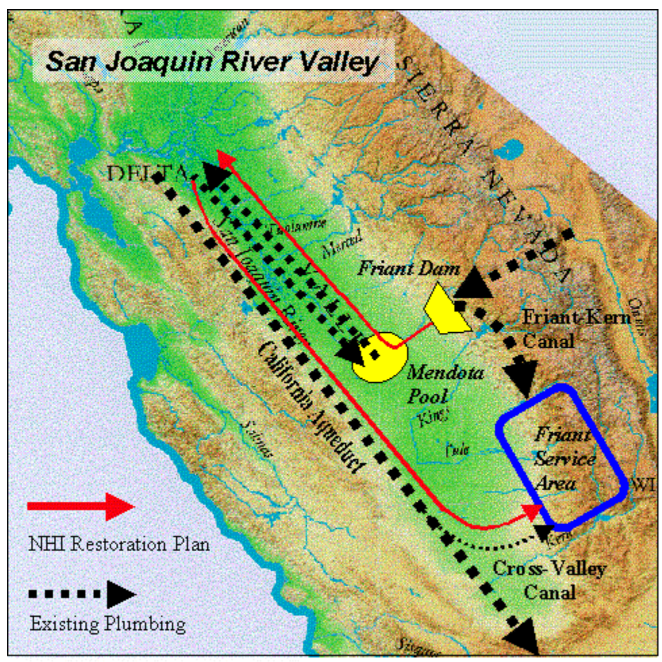


Figure 21: Proposed Arrangement for Restoring a Flow Regime in the San Joaquin River Suitable for Anadramous Fish

The basic premise of the arrangement involves wheeling Delta water currently delivered to the exchange contractors through the Delta-Mendota Canal to the southern Friant Unit via the California Aqueduct and an appropriate cross-valley link. Relieving some of the demand for San Joaquin water would allow the exchange contractors to compensate for lost Delta water with releases from Millerton Reservoir. During passage over the Gravelly Ford reach, a portion of these releases would seep through the river bed and become stored in the groundwater banking site. This storage could be reclaimed by the exchange contractors should the surface water system fail to meet their demand.

In order to avoid disrupting the use of the California Aqueduct facilities by its current beneficiaries, an analysis was conducted to determine what excess capacity was available in the system between 1975 and 1996. Using monthly reports of operation for the State Water Project, the minimum capacity available to move historical deliveries from the Delta-Mendota Canal to the California Aqueduct through the O'Neill Pumping Plant and to convey these transfers through the Dos Amigos Pumping Plant was calculated. Figure 22 depicts the time series of the wheeling through the California Aqueduct which could have been accomplished using available capacity alone. This is a conservative trace as future restrictions on Delta exports may limit pumping into the California Aqueduct at Clifton Court while the exchange contractors, by virtue of their superior export right, will likely continue to have access to their 800 TAF annual allotment of Delta water delivered though the Delta-Mendota Canal.

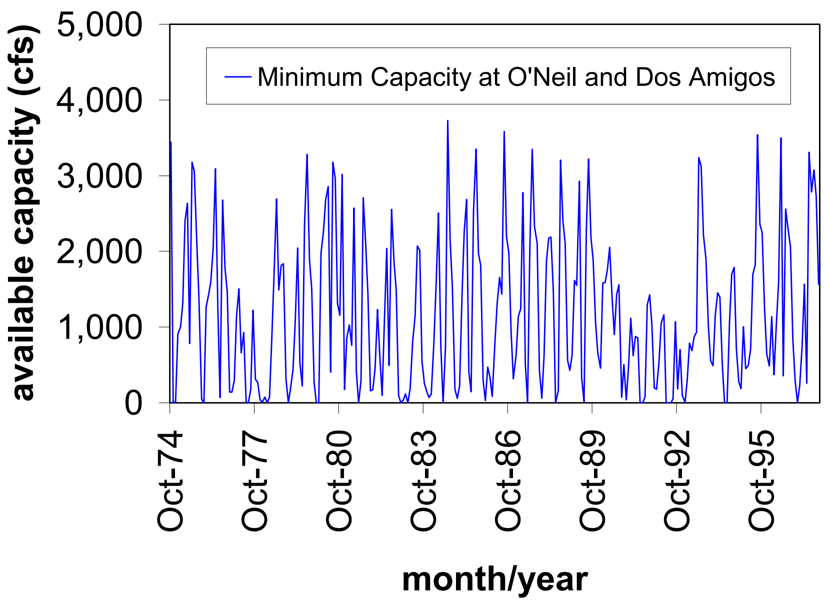


Figure 22: Historical Available Wheeling Capacity in the California Aqueduct System to a Point Below the Dos Amigos Pumping Plant.

Transfer of this Delta water into the Friant Unit could be accomplished through a variety of means. These could included the expansion of the Cross Valley Canal, the construction of some form of a Mid-Valley Canal, or institutional arrangements which would offer the wheeled water to agricultural interest in the Tulare Basin in exchange for the right to divert some of their Kings River water to the southern Friant Unit. In the context of this feasibility study, how the wheeling would be completed is of less interest then the opportunity which it would create to profit from the groundwater banking opportunity at Gravelly Ford.

The WEAP network configuration for this opportunity is presented in Figure 23. Three scenarios are simulated in this analysis. In a base case, which mimics the current arrangements, the exchange contractors receive water from the Act. DMC supply node while all other transmission links to the node are inactive. Transmission links emanating from the Wheel DMC supply node are also inactive under this scenario, as are those associated with Mendota Pool node and the Gravelly Ford groundwater banking site. In essence, the exchange contractors receive their water from the Delta while the irrigation districts serviced by the Friant Unit receive water from Millerton Lake on the San Joaquin. Under a salmon recovery scenario, a set of instream flows are imposed below the Mendota Pool. These standards, which were developed based on analysis by Cain (1997), are in keeping with the screening scope of this analysis.

As the analysis of this groundwater banking opportunity evolves these standards will be submitted to prominent fish biologists for review. Anticipating that the imposition of these standards will adversely impact the important agricultural interests in the Friant Unit, a final scenario integrates the Gravelly Ford groundwater banking site into the surface water system. Under these arrangements, those transmission links which were inactive during the base case become active, the exchange contractors receive a smaller supply of Delta water though the Adj. Wheel DMC tributary, with the wheeled water being sent into the southern Friant Unit trough the Wheel DMC node. Groundwater is stored in the groundwater banking site both by simulated seepage in the river reach between Gravelly Ford and Mendota Pool and through intentional transfers of water from Millerton Lake to the Gravelly Ford groundwater node through the Gravelly Ford withdraw node.

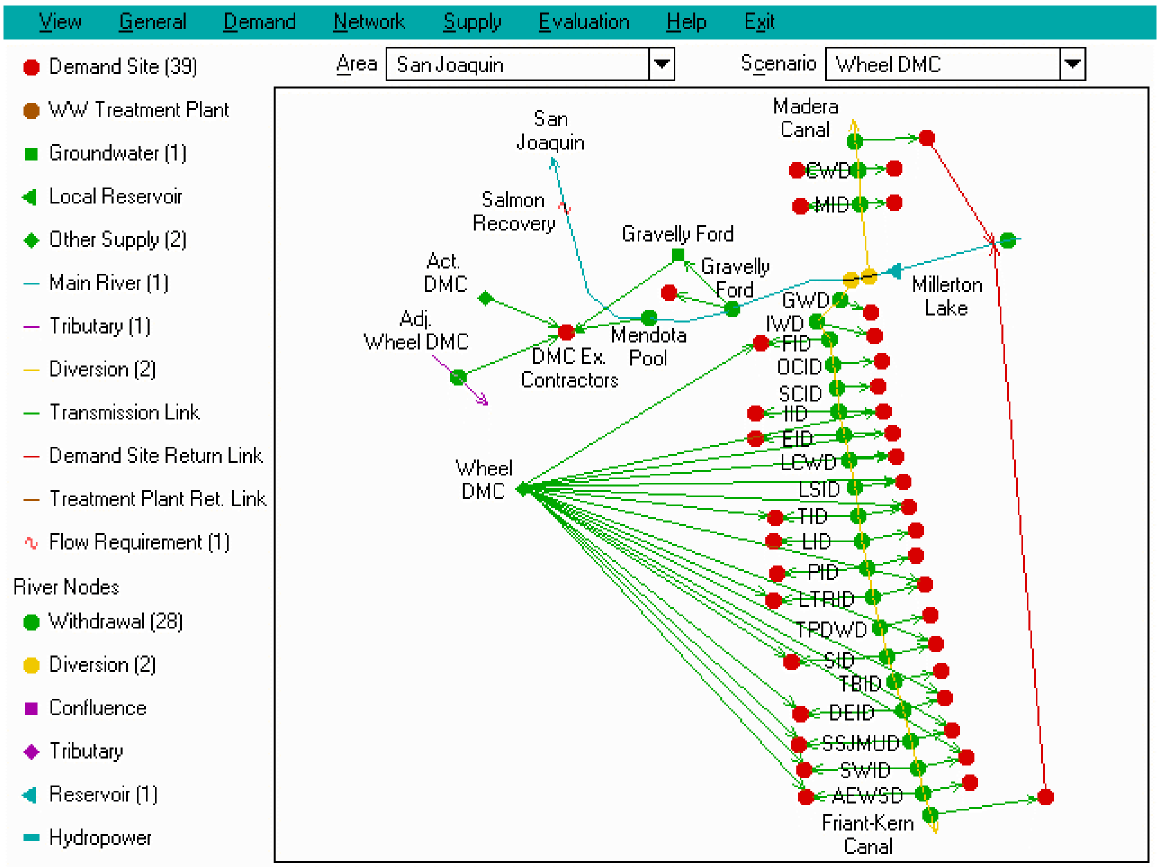


Figure 23: WEAP Gravelly Ford/Madera Ranch Network Configuration

In these simulations, an active salmon recovery standard is met prior to any San Joaquin River water being diverted for consumptive use. The implication of this logic is that the desired ecosystem objectives will be achieved under both the salmon recovery and wheeling scenarios. What is most relevant to this analysis is the degree to which groundwater banking can mitigate any impact which existing water users would experience by virtue of losing access to the San Joaquin River water released downstream to meet the standard. Figure 24 depicts the supply requirement coverage for the Class 1 contracts of two representative water districts in the Friant Unit - the Ivanhoe Irrigation District on the Friant-Kern Canal and the Chowchilla Water District on the Madera Canal. The negative economic impacts of imposing standards would apparently be most severe during drought periods. In 1977, for example, the degree to which demand was satisfied under the base case would have been reduced by nearly 14 % because of the reduction in Millerton storage associated with downstream releases. In this simulation, however, the Delta-Mendota Canal exchange contractors would have experienced no decline in their level of service as deliveries from the Delta do not change. On the other hand, under wheeling arrangements, Friant Unit districts experience less severe reductions in service relative to the base case, even with the imposition of the salmon recovery instream standard. The exchange contractors also fare well under these arrangements. In the simulation, the critically dry 1977 was difficult for both the exchange contractors, who suffered reduced Delta deliveries without being able to tap into a fully recharged groundwater bank, and the Chowchilla WD which did not have access to the wheeled DMC supply. With access to this Delta water, the Ivanhoe Irrigation District actually benefited from improved service.

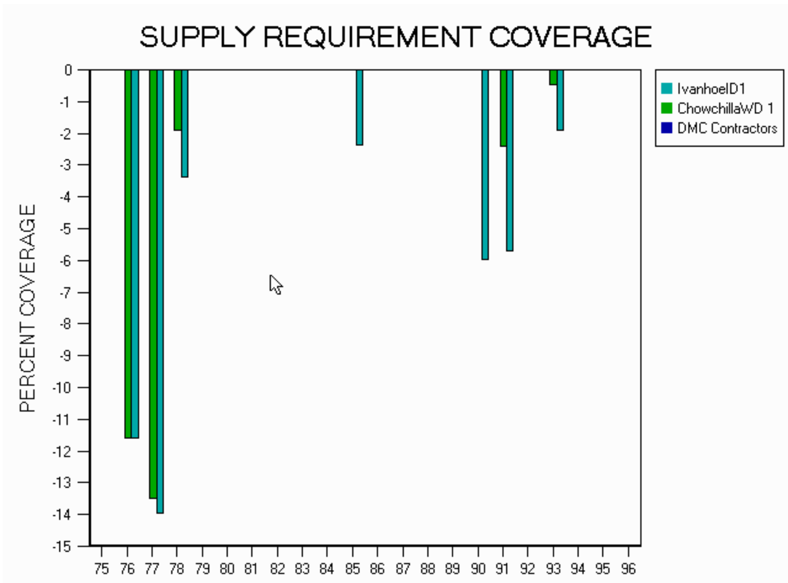


Figure 24: Change in Supply Requirement Coverage Between the Base Case and the Salmon Recovery Scenarios

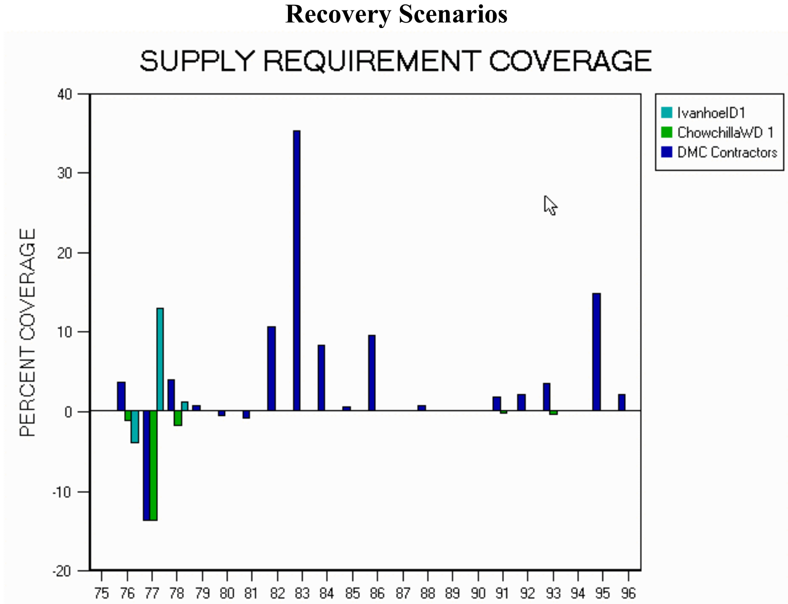


Figure 25: Change in Supply Requirement Coverage Between the Base Case and the Wheeling Scenarios

Figure 25 is a compelling example of how groundwater banking can transform potentially contentious environmental goals such as the restoration of the San Joaquin River into achievable objectives. Although water quality considerations, which could potentially prove problematic, have not been explicitly considered in this analysis, from a water supply perspective it appears that the salmon restoration releases can be made without overly taxing existing interests. This can occur because the extra storage available in

Gravelly Ford Groundwater Bank allows for greater flexibility in flood control operations at Millerton Lake, which reduces the magnitude of the peak spill events in the San Joaquin River (Figure 26).

A **B**

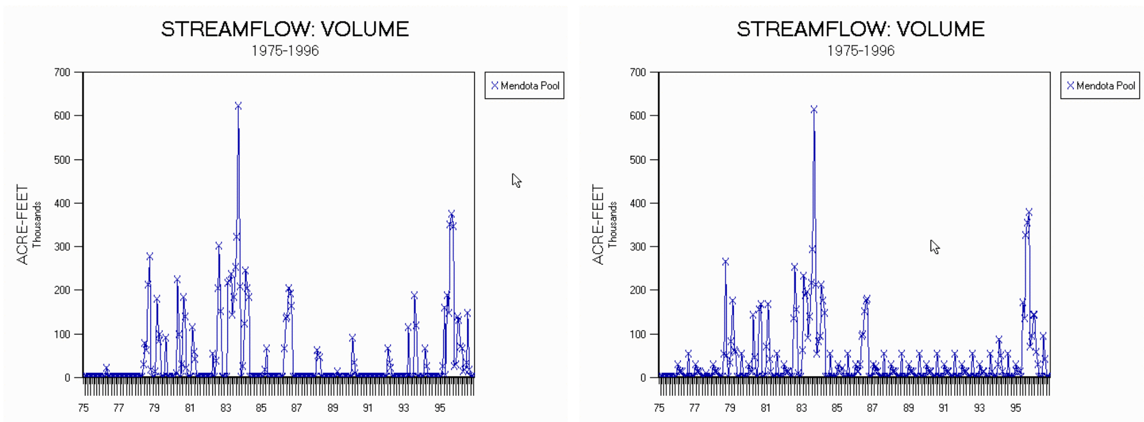


Figure 26: Simulated Streamflow Volumes in the San Joaquin River Below Mendota Pool Under the Base Case and Wheel DMC Sceanrios

The groundwater banking opportunity in Yolo County was framed as an approach for increasing both local and regional water management opportunities, while the Gravelly Ford opportunity was explored for its environmental restoration potential. By virtue of its strategic location relative to the Delta, the next suite of operational analysis highlights the real opportunity which maximal scale groundwater banking creates to achieve the full range of water supply and environmental benefits.

VI.3 Achieving Broad Benefits: East San Joaquin County

A WEAP network configuration which integrates the east San Joaquin County aquifer into the Central Valley water system is shown in Figure 27. A full description of each of the features in the network is contained in Table 17.

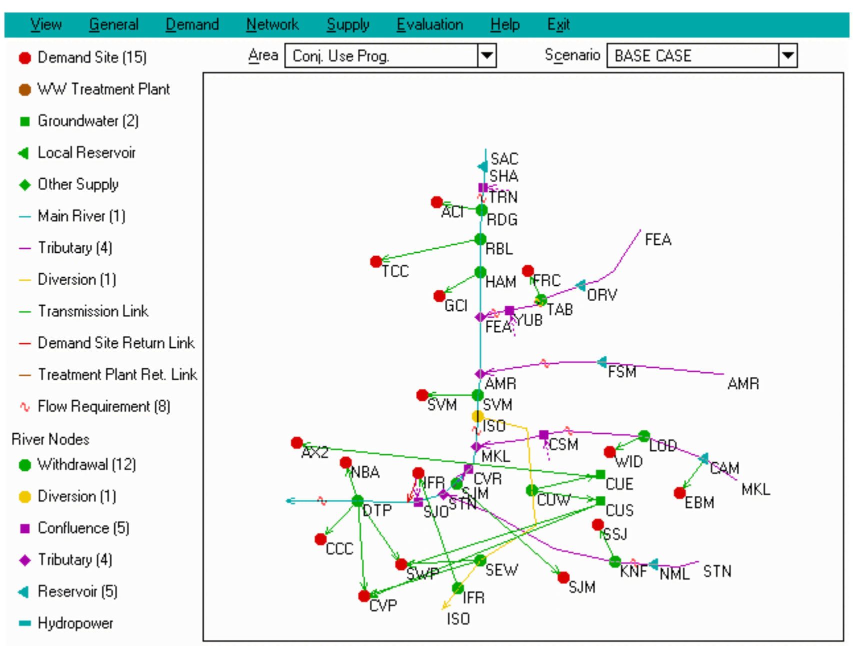


Figure 27: WEAP East San Joaquin County Network Configuration

Table 15: List of Features Included in the Case Study Network Configuration
(refers to Figure 27)

Feature Type	Name	Abbreviation
Main Stem	Sacramento River	SAC
Tributary	Feather River	FEA
	American River	AMR
	Mokelumne River	MKL
	Stanislaus River	STN
Reservoir	Lake Shasta	SHA
	Lake Oroville	ORV
	Folsom Lake	FSM
	Camanche/Pardee Reservoir System	CAM
	New Melones Reservoir	NML
Confluence	Trinity Diversions	TRN
	Yuba River	YUB
	Cosumnes River	CSM
	Calaveras River	CLV
	San Joaquin River	SJO
Active Diversion	Cross-Delta Isolated Faciity	ISO
Withdraw Node	Redding	RDG
	Red Bluff	RBL
	Hamilton City	HAM
	Thermalito Afterbay	TAB
	Sacramento Valley Municipal	SVM
	Lodi	LOD
	Knights Ferry	KNF
	Conjunctive Use	CUW
	Southern Export	SEW
	X2 from Isolated Facility	X2I
	Isolated Facility Return	IFR
	San Joaquin Valley Municipal	SJM
	Delta Pumps	DTM
	X2 from River	X2R
Conjunctive Use Node	Environmental Aquifer Storage	CUE
	Water Supply Aquifer Storage	CUS
Actual Demand Node[1]	Anderson-Cottonwood Irrigation District	ACI
	Tehama-Colusa Canal Authority	TCC
	Glenn-Colusa Irrigation District	GCI
	Feather River Canals	FRC
	Sacramento Valley Municipal	SVM
	East Bay MUD	EBM
	Woodbridge Irrigation District	WID
	South San Joaquin Irrigation District	SSJ
	San Joaquin Valley Municipal	SJM
	North Bay Aqueduct	NBA
	Contra Costa Canal	CCC
	Central Valley Project	CVP
	State Water Project	SWP
Fictitious Demand Node[2]	Isolated Facility Return Flow	IFR
	Additional X2 Water	AX2

Notes
1. An actual demand node refers to one meant to represent an actual off-stream demand site for which data on water consumption has been collected and evaluated
2. A fictitious demand site refers to a feature which has been added to "trick" the program into carrying out a water transfer not explicitly included in the allocation algorithm.

This configuration represents a large-scale view of the northern portion of the Central Valley which encapsulates two management scenarios: a base case and an enhanced Delta conveyance/ groundwater banking alternative. When the 8500 cfs ISO active diversion feature and the groundwater banking nodes are active, unallocated surface water in the Sacramento Valley is pre-delivered to a severely overdrafted groundwater banking site in eastern San Joaquin County. This water can be used to raise the level of the groundwater system during times of abundant water supply and to supplement local and south of Delta demand or enhance Delta outflow during times of shortage. When no unallocated water is available or when the groundwater banking site is full, the active diversion feature can be used to meet south of Delta demand. By shutting off the active diversion labeled ISO, all of the features which branch from the enhanced conveyance system, including the groundwater banking site and the links to the southern export demand sites are deactivated, leaving the system in roughly its current form.

The hydraulic infrastructure currently in place in California developed progressively over the course of the 20th century. By the 1970s, however, the current hydraulic infrastructure in California was largely built out. Therefore, the actual flow measurements made at various points around the State during this period already reflect the modifying influence of the fully developed water system. By limiting the simulated time horizon to the period between 1970 and 1992, historical hydrologic data can be used to drive the simulation. The proposed simulated time horizon contains some of the wettest years in the historical record, the 1974 water year for example, and the strongest, 1976-1997, and longest, 1987-1992, recorded droughts in the region. The placement of the protracted drought at the end of the simulated time horizon allows for direct comparison between the current arrangements and the proposed scenario.

The California Water Plan Update (DWR, 1994) estimated that 6.0 MAF of aquifer storage capacity exists in San Joaquin County. Rather than accept this extremely optimistic assessment, the derivation of which is not fully explained, our analysis adopted a very conservative view of the actual storage potential present in the field. A realistic available capacity of 600 TAF was derived following evaluation of the drawdown feature shown in Figure 28, and was allocated equally to water supply and environmental restoration storage.

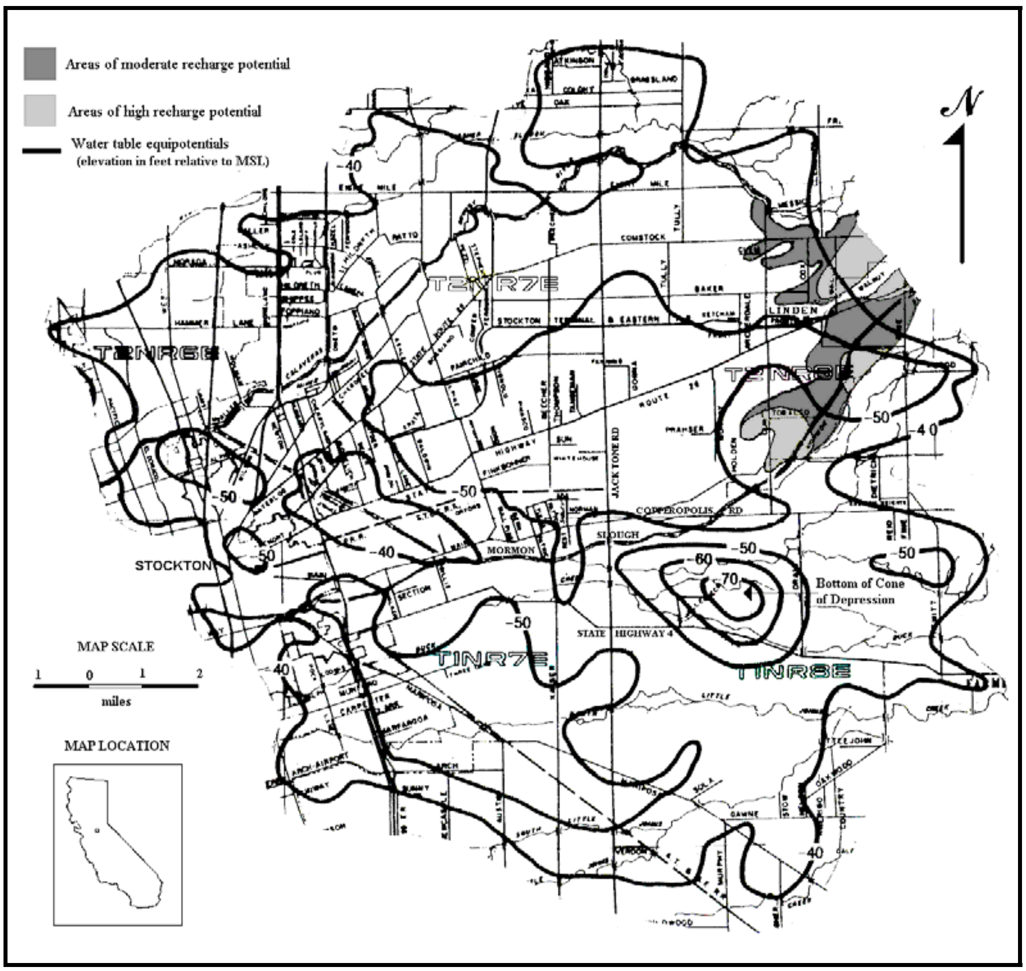


Figure 28: Spring 1995 Water Table Elevation Map East of Stockton, California

One basic result of the simulation has to do with the degree to which the enhanced Delta conveyance/groundwater banking alternative improves the ability to deliver water to points of demand which can be supplemented by tapping storage in the groundwater bank. These include the SWP and CVP actual demand sites which access water supply storage and the Additional X2 demand which accesses environmental storage. The water supply benefit is seen clearly in Figures 29 and 30 which depict the temporal pattern of deliveries to the SWP and CVP nodes respectively. Under the proposed alternative, during 1977, surface water deliveries through the Delta pumps under the Base Case are largely replaced by surface deliveries through the Isolated Facility with supplemental water being drawn from aquifer storage to help make up the simulated shortfall (Figures 29B and 30B). During 1988, the decrease in surface storage means that little or no deliveries of surface water take place under the proposed alternative, either through the Delta pumps of the Isolated Facility. In the extreme case, July 1988, the only water going to meet supply is from aquifer storage (Figures 29C and 30C). It seems likely that the generally poorer performance of the CVP relative to the SWP is related to the smaller amount of transmission capacity dedicated to the Federal project in the Isolated Facility and in the links issuing from the aquifer storage site. The results would have been different had the percent participation of the State and Federal projects been reversed. Adjusting the distribution of capacity is the type of screening exercise to which WEAP is ideally suited.

Figure 31A depicts the total Delta outflow in the Base Case and under the enhanced Delta conveyance/ groundwater banking alternative. Under the proposed alternative, Delta outflow is the sum of the simulated flow at the bottom of the river system and the transfer from aquifer storage to the Additional X2 node. The curves reveal that in extremely wet years, outflow in is higher in the Base Case, presumably because some of the excess water is being transferred to aquifer storage. In the driest years, on the other hand, the proposed alternative offers a small supplement over and above the minimum standards which have been imposed. This is a logical result. It also seems reasonable that the Export:Import regime in the Delta improves under the proposed scenario (Figure 31B). In dry years, water is delivered for southern export primarily through the Isolated Facility prior to entering the Delta. In this case, the ratio of southern export to Delta inflows drops to nearly zero.

On balance, the results of this simulation reinforce the notion that the proposed alternative could improve the performance of the Central Valley water system. What is particularly attractive about this specific opportunity is how it could help both local and regional water managers to respond to both water supply and environmental challenges. Located as it is at the nexus of the Central Valley water system, the east San Joaquin County groundwater banking site offers flexibility which may be unparalleled in California. The staggering effects of the dewatered local aquifer also provide enormous potential for collateral local benefit in terms of reducing energy expenditures for pumping and protecting the water quality of one of the state's important metropolitan centers. All of the actors, both locally and regionally, should be assembled to further investigate how the potential benefit of this site could be realized.

VI.4 Concluding Thoughts

The three preceding examples of operational analysis clearly demonstrate the array of issues which must be addressed in working out the operational details of a specific groundwater banking opportunity and the enormous benefit which can be gained from doing so. These examples also demonstrate the utility of the WEAP model for exploring the site-specific nuances of these opportunities. Developing WEAP network configurations for the other potential sites will be a major focus of future work on this project. These models will allow for an exploration, in concert with all interested actors, of the implications of site-specific management decisions. NHI is convinced that this dialogue will allow the most promising sites to emerge from the pack, so to speak, so that further requisite analysis using DRWSim and other suitable tools can proceed apace.

Figure 29: Deliveries to the SWP Demand Node for the Base Case (red) and Isolated Facility/1.2 MAF Conjunctive Use Alternative (green)
A: Over the Entire Simulated Time Horizon; B: During the 1977-1978 Drought; and C: During the 1987-1992 Drought
(heavy solid line: total deliveries; light solid line: Delta pumping; short dashed line: Isolated Facility; long dashed line: aquifer storage)

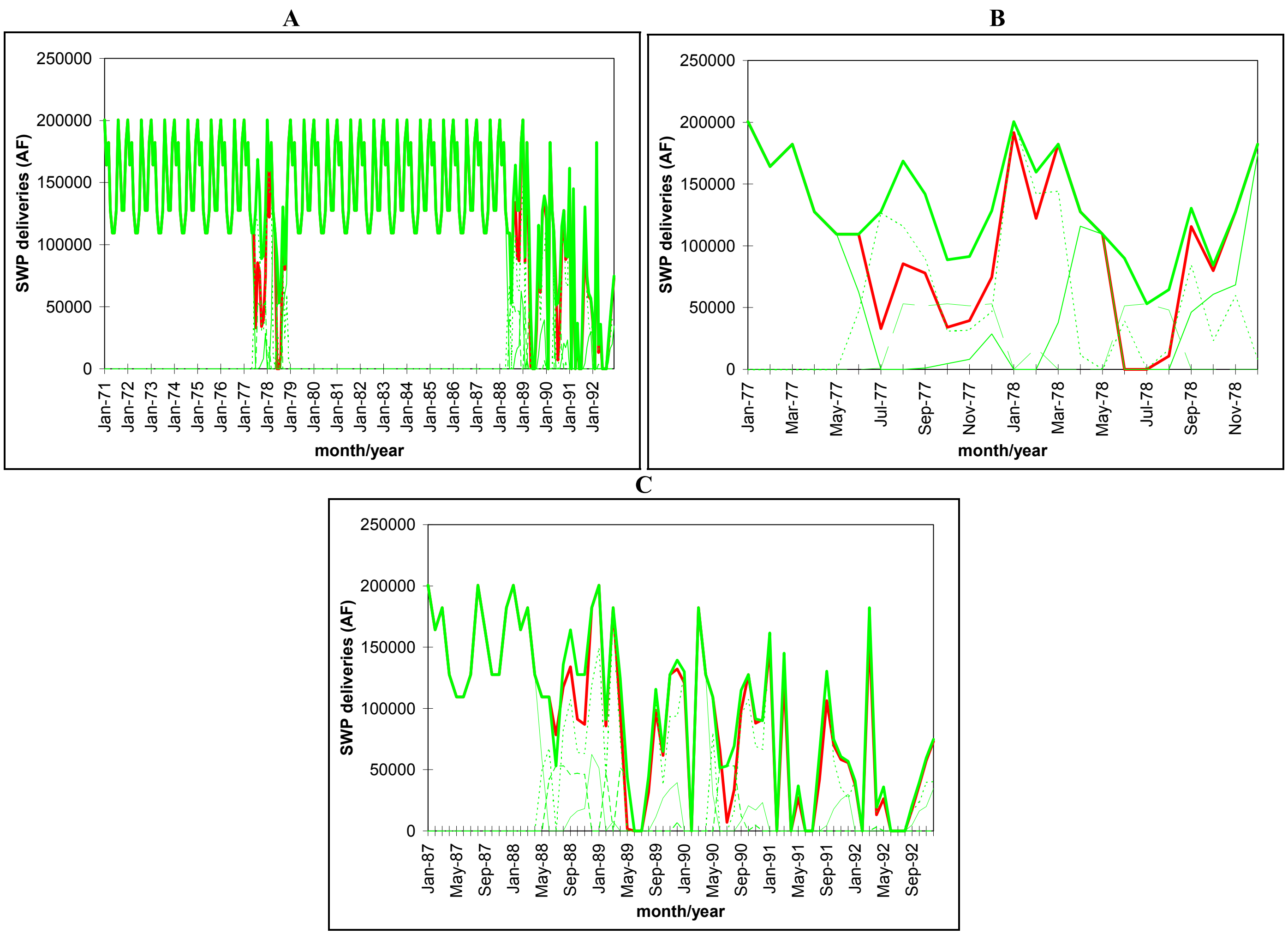


Figure 30: Deliveries to the CVP Demand Node for the Base Case (red) and Isolated Facility/1.2 MAF Conjunctive Use Alternative (green)
A: Over the Entire Simulated Time Horizon; B: During the 1977-1978 Drought; and C: During the 1987-1992 Drought
(heavy solid line: total deliveries; light solid line: Delta pumping; short dashed line: Isolated Facility; long dashed line: aquifer storage)

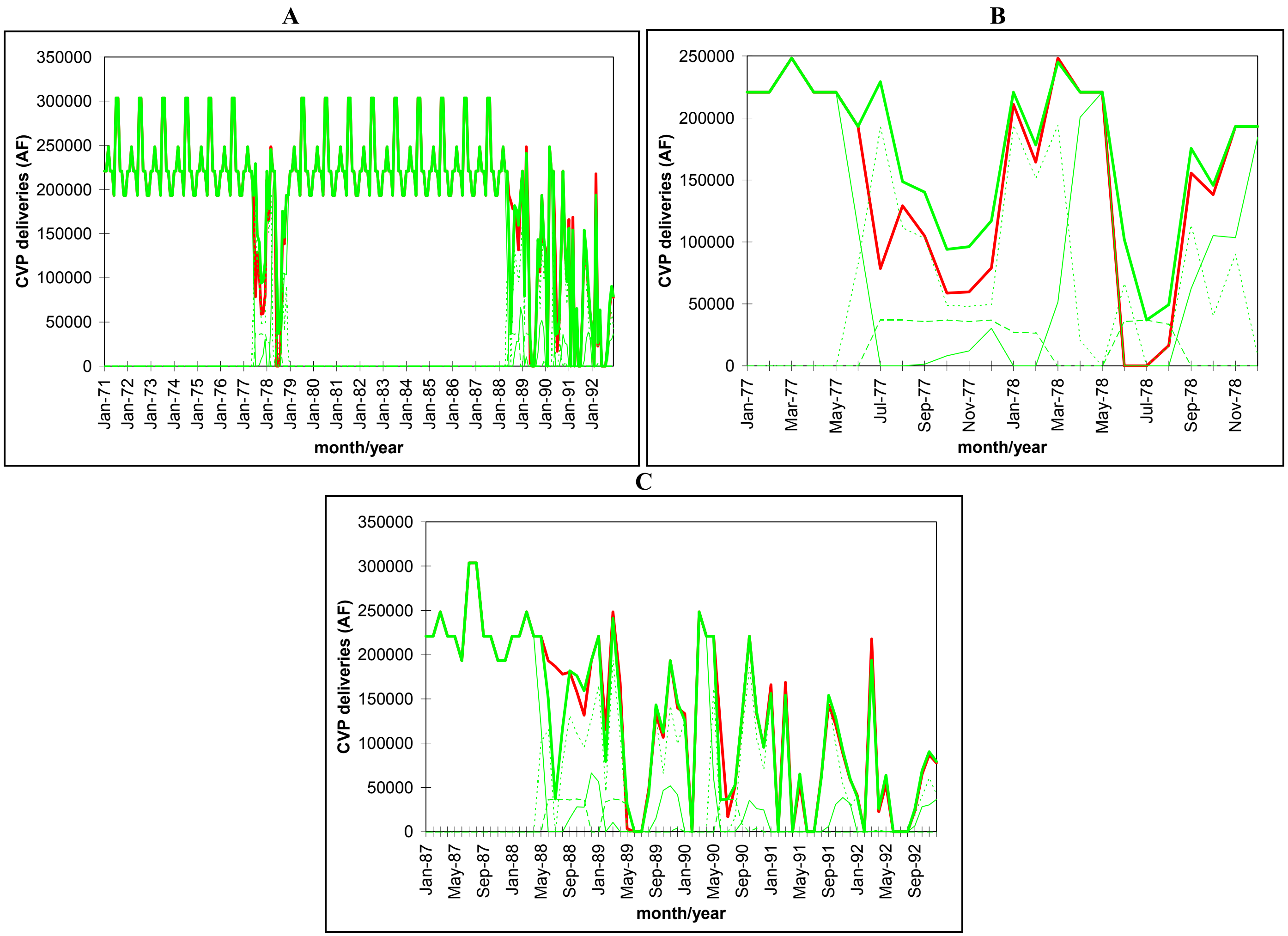
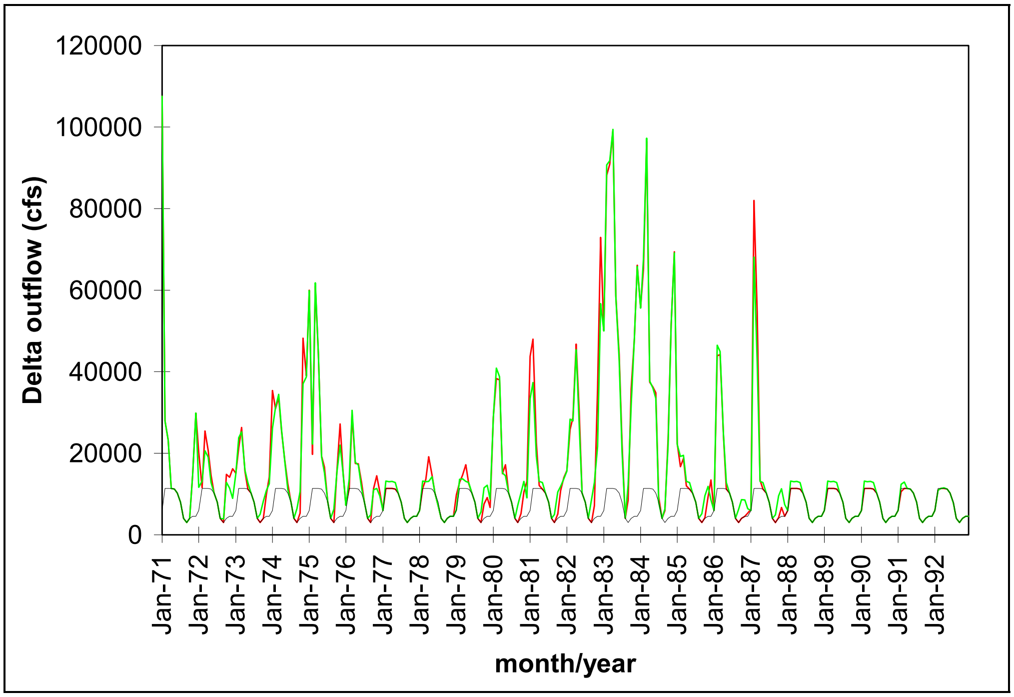
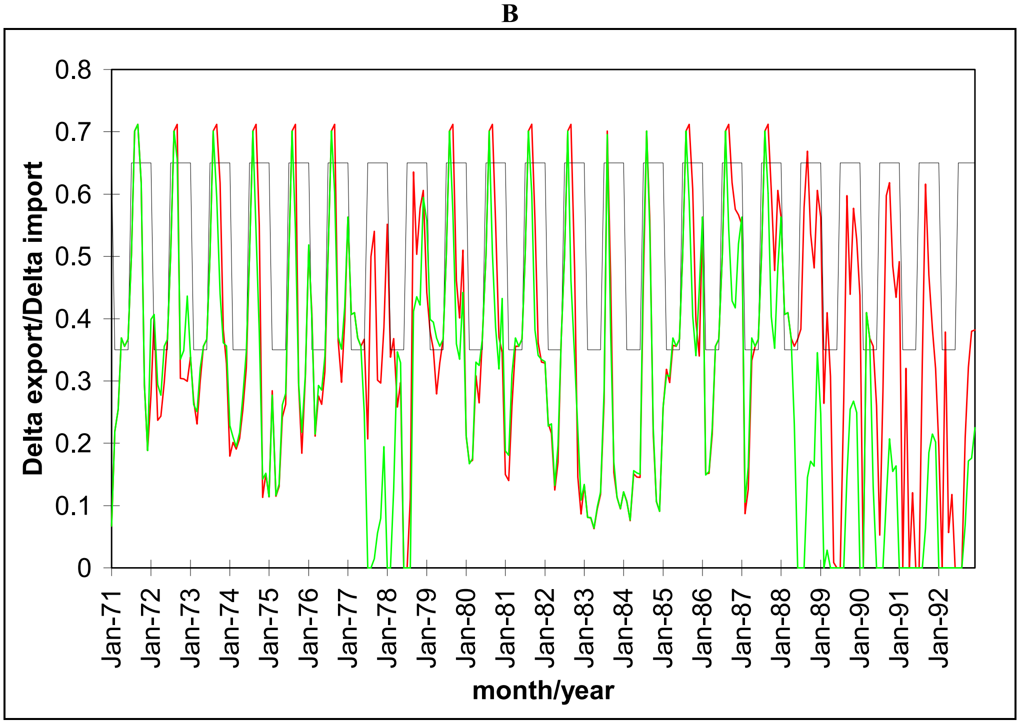


Figure 31: Simulated Delta Flow Regimes A: Delta Outflow and B: Export/Import Ratio for the Base Case (red) and the Isolated Facility/Conjunctive Use Alternative (green) as Compared to the Standard (black)

A



B



VII. Workplan Step 5: Economic Analysis

The economics of groundwater banking are often difficult to estimate and highly dependent on the specific characteristics of a given project. Recharge and extraction costs vary depending on aquifer characteristics and the nature of existing facilities. Greater uncertainties arise from the potential for unanticipated costs due to third party or environmental impacts. These can arise both in the source and recharge areas. Benefits are also variable. They range from the easily-quantified savings associated with lower pumping lifts to the less easily-quantified benefits associated with the insurance value of secure supplies. As with costs, many of these benefits depend on site characteristics.

VII.1 Direct Costs

Recharge and extraction costs in current projects range from a low $20 to over $300 per acre-foot (Appendix V). Typical cost ranges for new projects estimated in the context of the CVPIA are $90-120/acre-foot at the source (USDOI, USBR et al. 1995). These costs do not, however, include any charges for the water being supplied. Districts in MWD's service area would, for example, need to pay its charges for replenishment water on top of their actual costs for recharge and extraction. Where *in-lieu* methods of recharge are possible using existing facilities, recharge costs can be extremely low. On the Conway ranch in Yolo County and in parts of Kern county, they can be as little as $5/acre-foot.[36]

The direct costs indicated above and in Appendix V may, however, be misleading for conjunctive management activities in the future. As MWD notes in its recent IRP document: "A significant problem with groundwater conjunctive use storage is getting the water into the basin." (MWD 1996). This constraint is noted as a significant justification for their major Eastside Reservoir Project which could be used to temporarily store water during periods when existing recharge facilities are operating at capacity. The cost of this facility is estimated to be $1.9 billion.

VII.2 Benefits

Previous analyses of groundwater banking economics have focused primarily on the value of groundwater management activities within a limited agricultural area (e.g. Knapp and Olson 1995). Groundwater banking is modeled not as a way of creating "new" water supplies that would be available for any use, but more as a way of changing the cost structure of supplying a given amount of water to existing -- generally agricultural -- uses. As a result, the benefits are determined primarily by changes in the pumping costs versus management investments to supply that water. In contrast, this paper views the economics of groundwater banking from the perspective of storage creation. Groundwater banking use is a way of increasing the reliability of existing supplies and capturing new supplies that would otherwise be unavailable to the system as a whole through the creation of groundwater reservoir storage facilities. The economics of groundwater banking must therefore be analyzed in the same manner as surface storage reservoirs or other mechanisms for generating new or more reliable yield within an existing system.

While a full economic analysis of the benefits from groundwater banking is beyond the scope of this paper, it is important to note that the benefits associated with groundwater banking are not fully captured by analysis of new yield options on a least-cost of average annual supply basis. Three factors seem particularly important to note: (1) the stabilizing role of groundwater supplies; (2) the insurance value associated with ability to pre-deliver supplies; and (3) relative insensitivity of groundwater banking projects to changes in key economic assumptions.

In any situation where surface water supplies are variable, the presence of groundwater resources that can be tapped "as needed" for municipal, agricultural or other uses carries a stabilization value beyond that associated with increases in water supply alone. In an analysis of wheat cropping in the Negev desert,

[36] DWR, 1994, SWP Conjunctive Use--Eastern Yolo County; Kern County CA. April 1995. 1995 KFE Property Recharge Program.

Tsur estimated the stabilization value of groundwater development as "more than twice the benefit due to the increase in water supply"(Tsur 1990). In Southern California where surface water supplies are less variable than the Negev, the stabilization value in agriculture is, in some cases, as much as 50% of the total value of groundwater (Tsur 1993). Crop yield responses are often dependent on the timing of water application as well as on the volumes delivered. Since water stored in a groundwater banking site and dedicated for agricultural use will often be close to the point of end-use (e.g. on overlying lands), users will be far more able to fine tune extraction to meet their needs than they would be if they depended primarily on supplies stored in distant reservoirs. Groundwater banking operations will, thus, enhance the ability of groundwater resources to play a stabilization role. Furthermore, developing groundwater banking operations in areas currently dependent primarily on surface water would give those areas direct access to new "stabilization" benefits. In an analysis of groundwater banking in the South Platte system in Colorado, Bredehoeft and Young found that *installing sufficient groundwater pumping capacity to provide water to all areas irrigated by surface supplies made economic sense*. Doing this maximized expected net benefits and minimized annual income variation (Bredehoeft and Young 1983). As Tsur notes, ignoring the stabilization value of groundwater in economic comparisons with surface supplies can seriously bias policy-making based on cost-benefit considerations (Tsur 1993).

Municipal users also place a premium on supply stability. A recent contingent valuation survey found that: "on average, California residents are willing to pay $12 to $17 more per month per household on their water bills to avoid the kinds of water shortages which they or their regional neighbors have incurred in recent memory. The statewide magnitude of such additional consumer payments would be well over $1 billion per year" (Barakat & Chamberlin 1994). The lower figure represents a 20% shortage every 30 years while the higher applies to a 50% shortage every 20 years. Residents are also willing to pay between $11.67/month and $12.14/month to avoid shortages of 10% occurring with a frequency of 10 and 3 years respectively.

Insurance values associated with groundwater banking are closely related to stabilization. The distinction between stabilizing natural fluctuations in water availability and insurance against major disruptions is important. Elements of California's surface water supply system are highly vulnerable to earthquakes. Other sudden events -- for example, major pollution spills -- could also disrupt water supplies over short to medium term periods. The economic costs of these disruptions could be major for any of the industrial, agricultural, municipal or environmental users. Groundwater banking operations, by pre-delivering water to locations nearer to points of end-use and storing it in underground reservoirs that are relatively invulnerable to sudden disruption, will provide major insurance benefits.

Another economic benefit of conjunctive use in comparison to most water supply projects is relative insensitivity to discount rate and other development cost assumptions. Unlike surface supply, most conjunctive use projects can be completed rapidly or brought on-line sequentially as components are completed. They often do not have the long gestation periods and high up-front capital costs associated, for example, with the construction of a new reservoir. Furthermore, the benefits associated with individual components, such as spreading basins, can be realized even if a system is only partially completed. They do not depend on completion of an entire system. As a result, the economic viability of conjunctive use does not depend to the same degree as large surface projects on accurate projections of economic and other parameters (such as population growth) into the future. This benefit will, of course, only be true to the extent that groundwater banking projects are not dependent on the construction of major new surface facilities.

The stabilization and insurance values of water stored underground and the relative insensitivity to economic assumptions of conjunctive use projects are not captured in least-cost comparisons of yield generated. Estimating these and incorporating them into the economic evaluation will be important to evaluate the true costs and benefits of conjunctive use.

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Appendix I: Limnological Context for Reservoir Stratification

In a barotropic water body, the fluid density remains invariant with depth. This is somewhat of a hypothetical state which would be difficult to establish and maintain in a natural system. Many factors leading to the establishment of vertical density gradients, so called baroclinic conditions, act upon lakes in nature. In the context of a maximal groundwater banking program, the most important is the input of solar radiation at the water surface. Workplan Step I describes how reservoir re-operation would increase yield in the Central Valley water system via the transfer of surface water to aquifer storage in advance of winter storms. In the event of a wet winter, the excess reservoir capacity would be used to retain runoff normally released as part of flood control operations. A dry winter, on the other hand, might leave the reservoirs drawn down to a point where the input of solar radiation might subsequently make it difficult to maintain downstream temperature regimes suitable for aquatic resources, primarily anadromous fish.

As solar radiation penetrates into a lake or reservoir, it is absorbed at an exponential rate. Figure AI.1 shows how far into a body of distilled water two different wavelengths of visible light penetrate.

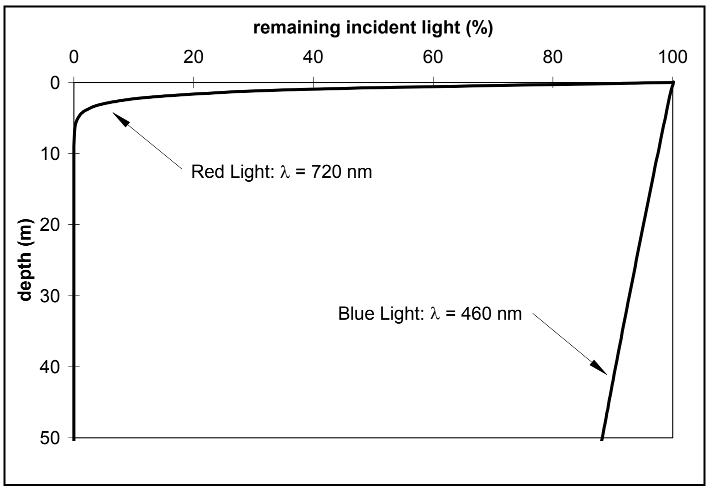
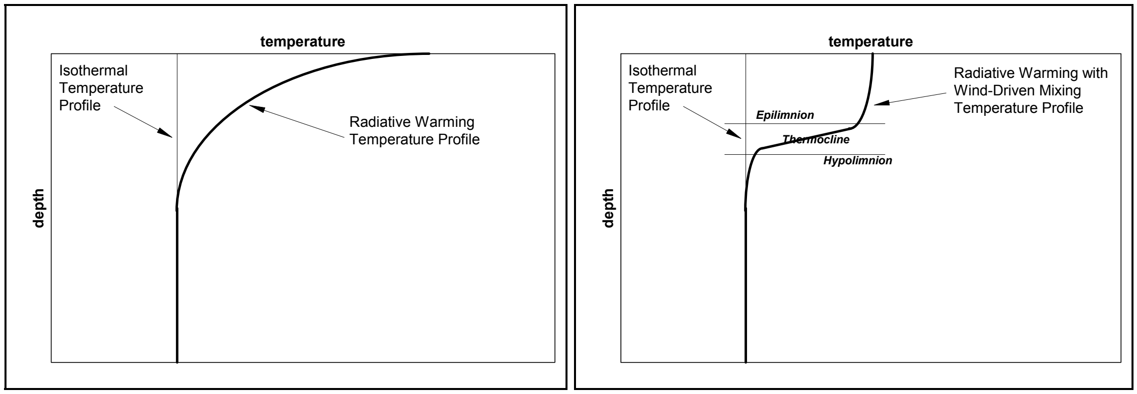


Figure AI.1: Light Penetration into Distilled Water for Red and Blue Regions of the Visible Light Spectrum
(source: Cole 1983)

According to these curves, by a depth of 5m, all but 1% percent of the incident red light (λ=720 nm) is absorbed by the water and converted to thermal energy. A similar pattern exists for infrared radiation which lies just outside of the visible portion of the spectrum. Shorter wavelength blue light (λ=460 nm), on the other hand, remains relatively unabsorbed even at depth of 50 m. Since it is the red/infrared wavelengths which convert much of their energy to heat when absorbed, the most intense warming takes place in top several meters of the water column.

If the input of solar radiation occurred in an initially isothermal lake, the resulting temperature profile would resemble the red/infrared penetration profile (Figure AI.2A). Under these conditions additional inputs of radiation would generate downward heat flow driven by temperature gradients. In addition to this driving force, however, the lake is exposed to winds passing over its surface. The wind serves to mix the water near the surface of the lake distributing the heat more evenly within the zone of mixing (Figure AI.2B). The end result is a layer of warmer, less dense water which overlies colder heavier water below. Additional inputs of solar energy and further wind-driven mixing will continue to warm the surface layer, making it increasing less dense relative to the cold layer below. The lake has become *stratified*, a common occurrence during the summer months in deep lakes located in temperate regions.



A **B**

Figure AI.2: Hypothetical Vertical Temperature Profiles Assuming
A: Simple Radiative Warming; and B: Combined Radiative Warming and Wind-Driven Mixing
(source: Laska 1981)

The thickness of the upper layer, or the *epilimnion*, is a function of the physio-chemical properties of the water in the lake and the dynamic interaction between the temporal pattern of incoming solar radiation and the local wind regime. It should be pointed out that the same amount of thermal energy can lead to the conditions shown in Figures AI.2A and AI.2B. If so, the integral of temperature with depth must be the same for both profiles. As the uniformly cold regions of each curve, referred to as the *hypolimnion* of the lake, are identical, the only way to preserve this equality is for a region of rapid temperature drop, or a *thermocline*, to become established between the two layers. The sharp temperature, and hence density, contrast means that in a *stratified* lake the epilimnion and the hypolimnion essentially act as separate bodies of fluid until sufficient work can be done on the system to remix them.

Actual temperature profiles taken at Lake Shasta during the month of September, Figure AI.3, reveal that stratified conditions do develop in the reservoir. Stratification seems to be most pronounced in years where the lake stage was relatively low in the late summer, as in 1961, 1964, and 1968. Data also suggest that the thermocline deteriorates with the advancing autumn. Figures AI.4A and AI.4B depict the evolution of the 1968 temperature profile in Shasta and Whiskeytown Lakes between September and November. Presumably the acceleration of radiative cooling and the inflow of cooler water with the onset of winter storms are responsible for the general cooling of these lakes late in the fall.

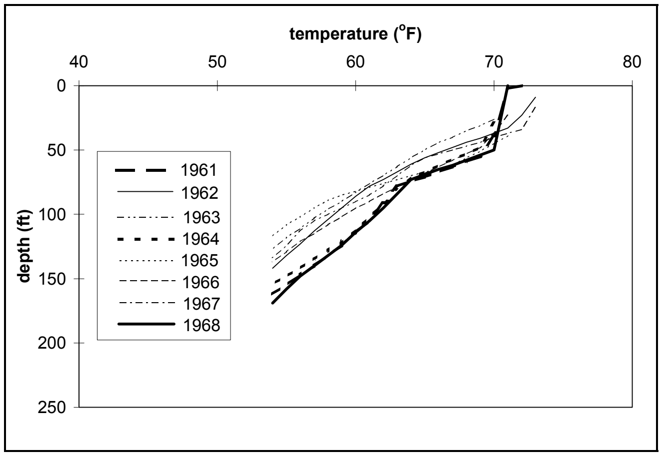
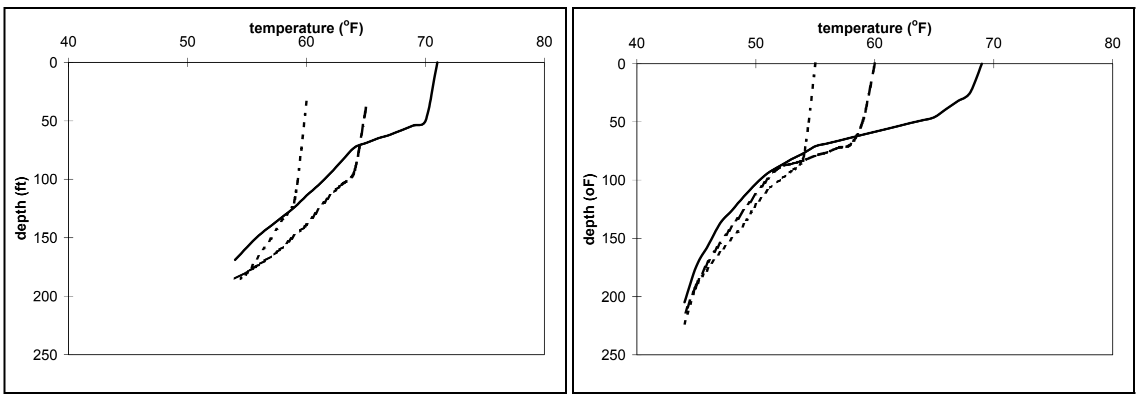


Figure AI.3: September Temperature Profiles in Lake Shasta
(bold curves represent years of low reservoir stage)
(source: Weidlein 1971)



A **B**

Figure AI.4: Evolution of Autumn, 1968 Water Temperature Profiles in A; Lake Shasta; and B: Wiskeytown Lake
(September: solid line; October: long dashed line; November: short dashed line)
(source: Weidlein 1971)

One conclusion which can be drawn from Figures AI.3 and AI.4 is that water temperatures in the epilimnion of these reservoirs are substantially higher than the 56°F recommended in the AFRP for the protection and restoration of anadromous fish in the Sacramento River, particularly in September. This has profound implication for the operation of reservoirs as part of the proposed groundwater banking program. To insure that only cold water from the hypolimnion will flow into the river downstream, reservoir releases must be made from depths below the thermocline. Unfortunately, under the worst case scenario of a critically dry winter following the ambitious pre-delivery of water to aquifer storage, the thermocline may be dangerously close to the level of the reservoir release works. In this case the flow hydraulics in the vicinity of the intake may lead to the release of warm water from the epilimnion. Of particular concern in this context are internal waves in the body of the reservoir, or *seiches*, which can cause the thermocline to oscillate and may, under drawn down conditions, result in periods of time when cold water is completely absent from the vicinity of the reservoir release works. The equations governing this phenomenon are presented in the following Appendix.

Appendix II: The Initiation and Magnitude of *Seiche* Oscillations

AII.1 Wind Driven Set-Up

As the wind passes over a reach of open water, it imposes a shear stress proportional to the square of the wind speed and the density of the atmosphere. This relationship is defined as:

$$\tau_S = C\rho_a W^2 \qquad \text{(AII.1)}$$

where τ_S is the shear stress; ρ_a is the density of the atmosphere immediately above the lake surface; W is the wind speed and C is an empirical parameter known as the drag coefficient. The imposition of this shear stress acts to pile up the lake surface at the offshore end, thereby generating a head gradient along a line parallel to the wind direction. Theory holds that, at steady state, this head gradient is balanced by the opposing shear stresses acting on the lake surface and along the lake bottom.

$$\tau_S - \tau_B = \rho g i H \qquad \text{(AII.2)}$$

where τ_B is the shear stress acting along the bottom of the lake; g is gravitational acceleration; i is the angle of denivelation of the lake surface; and H is the static depth of the lake. When lake currents are turbulent, the shear stress at the surface is generally considered to be significantly larger than those acting on the lake bottom so that the τ_B parameter can be ignored.

Making this assumption, one can equate equations AII.1 and AII.2 and solve for the angle of denivelation under a given wind regime:

$$i = C\frac{\rho_a}{\rho}\frac{W^2}{gH} \qquad \text{(AII.3)}$$

When combined with a parameter describing the length of the lake, equation AII.3 can be used to determine the magnitude of the wind driven set-up:

$$\zeta' = \frac{iL}{2} \qquad \text{(AII.4)}$$

where ζ' is the set-up, or lake surface displacement, at the off-shore end; and L is the length of the lake. During this investigation, to solve equation AII.4, the drag coefficient was set equal to 2.3×10^{-3} and the density of the atmosphere to 1.25×10^{-3} gm/cm^3.

AII.2 *Seiche* Oscillation

Stratified lakes are not static features in which a warm layer rest motionless upon a static pool of cold water. It has long been recognized that the interface between the two bodies of water in stratified lakes, the thermocline, oscillates (Wedderburn, 1909). This oscillation is often uninodal around some central point in the lake with the end effect being that when the thermocline is elevated relative to it static level at one end of the lake, it is depressed at the other.

When a dry rainy season follows pre-delivery to aquifer storage, there is an increased risk that these oscillations, or *seiches*, will periodically place warm water in close proximity to the reservoir release works, thereby displacing the cold water which would have been present under static conditions. This displacement could compromise the ability to maintain suitable temperature regimes downstream. Obviously *seiches* are complex hydrodynamic features whose properties depend on multiple variables. Nonetheless, by making some simple assumptions about the system, it is possible to develop some rules of thumb about the amplitude of these oscillations which might guide the establishment of suitable reservoir carryover storage parameters for the Central Valley reservoirs.

Consider a lake of length L and width W, where L>>W. Assume the lake is stratified into an upper warm layer of thickness h' and density ρ' and a lower cold layer of thickness h and density ρ. Once oscillation is initiated, the divergence of the lake surface and the thermocline from their static levels are represented by ζ' (the wind driven set-up in equation AII.4) and ζ respectively. As the lake is much longer than it is wide, one can assume that the oscillation is largely confined to the long, or x axis, of the lake. Manipulation of the equations of continuity and momentum for this simplified system lead to the following definition of the amplitude of the internal oscillation:

$$\zeta = -\zeta' \frac{\rho}{\rho - \rho'} \left(1 + \frac{h'}{h}\right) \qquad \text{(AII.5)}$$

Equation AII.5 suggests the following interactions between the displacement of the water surface and the displacement of the thermocline at depth:

- For a given water surface displacement, ζ', and for a given set of static eplimnoin and hypolimnion thickness values, h' and h, the internal displacement of the thermocline is inversely proportional to the density contrast between the warm and cold water pools; and
- For a given water surface displacement, ζ', and for a given density contrast between the warm and cold water pools, the internal displacement of the thermocline is proportional to the relative thickness of the epilimnion.

The combined effect of these interactions is that, in stratified lakes, a set-up on the order of centimeters can generate *seiche* displacements on the order of meters.

AII.3 Juxtaposition of Warm Water and Reservoir Release Works

Using the data presented in the previous sections, it is possible to approximate the magnitude of the wind driven set-up in each of the major foothill reservoirs (equation A.II.4) and the maximum displacement of warm water in the epilimnion below the static thermocline elevation during seiche-like oscillations (equation A.II.5). Having estimated the potential magnitude of displacement, the difference between the minimum elevation of the warm water in the reservoir and the elevation of the intake to the reservoir release works can be established for a given reservoir storage condition according to:

$$HT = \left(E_{surf} - D_{thermo} - \zeta\right) - E_{releases} \qquad \text{(AII.6)}$$

where: HT is the minimum hypolimnion thickness lying above the release works; E_{surf} is the lake surface elevation associate with the assumed reservoir storage level; D_{thermo} is the observed depth of the thermocline below the lake surface; and $E_{release}$ is the elevation of the release works.

Appendix III: Survey of District Recharge Activities

District	Storage Potentially Available	Current annual operating potential	Average current recharge volume
Arcade WD[37]			17,960 AF
Yuba Co. WA[38]	1,710,000		
DWR - M&T Chico Ranch[39]			12,000 AF
Western Canal Water District[40]	4,000,000 AF - total groundwater basin storage		
DWR - American Basin[41]			
DWR - Eastern Yolo County[42]			19,000 AF[43]
Alameda County WD[44]	20-32,000 AF		28,900 AF
Alameda Co. Flood Control District #7[45]	250,000 AF		10,000 AF
East Bay MUD[46]	600,000-700,000 AF	200,000 AF[47]	feasibility stage
Santa Clara Valley WD[48]		400,000 AF[49]	150,000 - 210,000 AF max Average year 100,000
Stockton-East WD[50]			5,800 AF
Chowchilla WD[51]	75,000 AF		30,000 AF

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37 CH2MHILL prepared for Arcade Water District. November 1993. Groundwater Recharge Project Feasibility Report. Arcade WD is in the process of implementing a combination injection and in-lieu recharge program. Figures were calculated using Arcade's recommended project which injects 9896 AF/yr and purchases 7.2 mgd of surface water from the City of Sacramento and delivered as in-lieu recharge. 7.2 mgd * 365 = 2,628 g/year. 2,628 g/year = 8,064 AF/yr in-lieu (1 AF = 325,900 g). 9,896 injection + 8,064 in-lieu = 17,960 AF/yr. This program, however, has not yet been implemented.

38 Yuba County WA. September 1992. Ground Water Resources and Management in Yuba County. Figure is total storage capacity, it would not be feasible to include this amount of water in a conjunctive use program. Calaculated within the Yuba Co. groundwater study area which includes 49,800 acres in Yuba-North subarea and 88,700 acres in Yuba-South subarea to a depth of 200 feet.

39 CH2MHILL. November 1994. DRAFT Conjunctive Use Working Paper Water Augmentation Program.

40 Brown, G., Western Canal Water District. June 19,1995. Personal Communication.

41 DWR, 1995, American Basin Conjunctive Use Project, Pre-Feasibility Report, California Department of Water Resources, Sacramento, pp 138.

42 DWR, 1994, SWP Conjunctive Use--Eastern Yolo County, Draft Pre-Feasibility Report, California Department of Water Resources, Sacramento.

43 In-delivery occurs during wet years, therefore, pre-feasibility report estimate indicates this amount of recharge would occur every other year.

44 Halliwell, M., Alameda County WD. August 15, 1995. Personal Communication. 28,900 AF were recharged in 1993-94 water year due to an excess amount of water being discharged, forecasted recharge volume 1994-95 is 21,100 AF. Alameda County Water District. February 1995. Survey Report on Groundwater Conditions.

45 Chahal, J., Alameda Co. FCD and WCD #7. July 17, 1995. Personal Communication.

46 EDAW, Inc. December 1992. Draft EIS/EIR for the Updated Water Supply Management Program. Prepared for East Bay Municipal Utility District, Oakland, California.

47 Potential annual withdrawal for conjunctive use if the program incorporated 100 wells with an average production capacity of 1200 gpm

48 CH2MHILL draft report. estimate pending information from district.

49 Personal Communication, William Molnar, Water Resource Development Division

50 Thomas, J., Stockton-East WD. July 1995. Personal communication. District is currently searching for additional percolation sites to increase their annual recharge rate, and reduce overdraft.

51 CH2M HILL. 1994. DRAFT Conjunctive Use Working Paper.

Rosedale RioBravo WD		209,950 AF[52]	89,385 AF[53]
Kern Delta WD		76,740 AF[54]	3,874 AF[55]
Buena Vista WSD		372,843 AF[56]	30,732 AF[57]
Tranquility WD[58]			At reconnaissance level which may evolve into a project (2-3 years) storage account 5,000 AF
Kern Water Bank[59]			Project on hold pending habitat conservation plan - previously recharging 100,000 AF annually
City of Fresno[60]			> 50,000 AF
Fresno ID[61]			60,000 AF
Laton CSD[62]			117 AF
Liberty WD[63]			15,000 AF
Westlands[64]			No formal recharge project, individual growers bank water
Arvin-Edison WSD		108,595 AF[65]	122,917 AF[66]
City of Bakersfield		180,992 AF[67]	7,881 AF[68]
Semitropic WSD, Groundwater Banking Project with MWD[69]	Roughly 1,000,000 acre-feet total available.	"put" max 315,000 AF/yr, "Take" max 224,000; guaranteed put of 91,000; guaranteed take of 90,000.	
Semitropic/MWDSC Water Storage and Exchange Program		31,500 - 170,000 AF[70]	

52 Figure is calculated using the recharge rate (cfs) for facilities within the district, therefore it is the highest possible number using existing facilities and assuming water is available year round. Kern County Water Agency.

53 Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

54 Figure is calculated using the recharge rate (cfs) for facilities within the district, therefore it is the highest possible number using existing facilities and assuming water is available year round. Kern County Water Agency.

55 Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

56 Figure is calculated using the recharge rate (cfs) for facilities within the district, therefore it is the highest possible number using existing facilities and assuming water is available year round. Kern County Water Agency.

57 Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

58 Brian Ehlers of Provost and Pritchers. June 16, 1995. Personal Communication.

59 Arvey Swanson, DWR. July 21, 1995. Personal Communication. CH2MHILL 1994. DRAFT Conjunctive Use Working Paper.

60 Integrated Water Technologies, Inc. June 1995. Presented at ACWA Groundwater Mini-Conference.

61 Bettner, T., Fresno ID. July 1995. Personal Communication.

62 Buttle, R., Laton CSD. July 1995. Natural Heritage Institute survey results. Substantial annual variation, depending on hydrologic conditions in the Sierras, range is from 0 - 15,000 AF.

63 Liberty WD. July 1995. Natural Heritage Institute survey results.

64 Dave Sunding. August 15, 1995. Personal Communication.

65 Figure is calculated using the recharge rate (cfs) for facilities within the district, therefore it is the highest possible number using existing facilities and assuming water is available year round. Kern County Water Agency. Kern County Water Agency.

66 Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

67 Figure is calculated using the recharge rate (cfs) for facilities within the district, therefore it is the highest possible number using existing facilities and assuming water is available year round. Kern County Water Agency. Kern County Water Agency.

68 Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

69 Semitropic Water Storage District and Metropolitan Water District of Southern California (1994) Semitropic Groundwater Banking Project, Final EIR, July 1994, p. 5-197.

70 Metropolitan Water District of Southern California. July 1995. Regional Urban Water Management Plan for MWDSC, p. 109. Under the joint program, MWDSC will have the right to store up to 350,000 AF. Semitropic provides Metropolitan with access to existing and new facilities and provides other necessary services for storage and recovery of SWP or other water supplies. MWDSC pays Semitropic for water management services.

I.D. No. 4 (Kern County)		296,102 AF[71]	82,960 AF[72]
Wheeler Ridge-Maricopa WSD			6,882 AF[73]
North Kern WSD		340,264 AF[74]	107,060 AF[75]
Kern County WA		1,400,000 AF[76]	176,272 AF[77]
Antelope Valley - East Kern WA[78]			18,467 AF
Kern-Tulare WD and Rag Gulch WD[79]			26,000 - 27,000 AF
Joint Powers Authority – Terra Bella ID, Lower Tule River ID, Saucelito ID, Pixley ID, and Porterville ID[80]			300,000 AF
Golden Hills CSD[81]			200 AF
Tehachapi-Cummings			
City of Santa Barbara – Goleta[82]		500 AF	
City of Oxnard[83]			3800 AF in two years
City of Santa Barbara – Foothill basin[84]	3,000 AF	1200-1500 AF	
Calleguas (In conjunction with MWDSC)[85]			10,000 AF
United WCD			
Chino Basin Watermaster[86]	Several hundred thousand AF	25,000 - 30,000 AF + 50 - 60,000 in-lieu	20,000 AF
Chino Basin WCD[87]			17,000 AF
MWDSC and			4,800 AF

[71] Figure is calculated using the recharge rate (cfs) for facilities within the district, therefore it is the highest possible number using existing facilities and assuming water is available year round. Kern County Water Agency. Kern County Water Agency.

[72] Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

[73] Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

[74] Figure is calculated using the recharge rate (cfs) for facilities within the district, therefore it is the highest possible number using existing facilities and assuming water is available year round. Kern County Water Agency. Kern County Water Agency.

[75] Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

[76] Calculated from potential recharge facilities assuming 100% efficiency of recharge. Kern County Long Term Storage Supply Project Report.

[77] Kern County Water Agency. 1995. Water Supply Report. Figures are for 1993.

[78] Fuller, R., Antelope Valley - East Kern WA. July 18, 1995. Personal Communication. Through the district's in-lieu incentive program, where well owners received a discounted price for surface water. From 1976-1994, 332,409 AF of in-lieu water was provided, giving an annual average of 18,467 AF. More water is expected to be recharge due to their new incremental incentive program.

[79] Bowers, B., Kern-Tulare WD. July 1995. Personal Communication. Amount of water recharged since 1993.

[80] Robb, R., Lower Tule River ID. July 1995. Personal Communication. Estimated recharge in first year of Joint Powers Authority. Previously each of the five districts had conjunctive use programs, they are in the process of combining their projects and adopting a joint management groundwater plan.

[81] Golden Hills CSD. July 1995. Natural Heritage Institute survey results.

[82] Integrated Water Technologies, Inc. June 1995. Presented at ACWA Groundwater Mini-Conference. Program uses existing facilities, and recharging during only 4 months of the year (when water is available)

[83] Integrated Water Technologies, Inc. June 1995. Presented at ACWA Groundwater Mini-Conference.

[84] Integrated Water Technologies, Inc. June 1995. Presented at ACWA Groundwater Mini-Conference.

[85] Horne, W.June, 8, 1995. General Methods & Facilities to Expand Conjunctive Use. Presented at the ACWA 1995 Ground Water Mini-Conference Conjunctive Use

[86] Stewart, T., Chino Basin Watermaster. August 1995. Personal Communication.

[87] Gumina, Sal, Chino Basin WCD. July 1995 Natural Heritage Institute survey results.

Cucamonga CCWD[88]			
Mojave WA[89]			360,000 AF
San Fernando Basin – includes Los Angeles, Glendale, and Burbank's water rights[90]	3,200,000 AF is the size of the basin, however 200,000 AF safe storage capacity	100,000 AF	152,000 AF
Orange County WD[91]		115,000 AF more than current recharge due to new facilities	300,000 - 400,000 AF
Water Replenishment District of southern California[92]			155,000 AF + 20 - 30,000 AF from injection
Los Angeles County[93]			220,000 AF local storm 68,000 AF imported 50,000 AF reclaimed
Central and West Coast Basins[94]		450,000 AF	145,000 AF
Eastern MWD - San Jacinto Basin[95]		7,641 - 9,526	
Elsinore Valley MWD[96]			13,000 AF
Three Valleys MWD[97]		75,000 AF	
San Bernadino Valley MWD[98]	500,000 AF		
City of Oxnard[99]			2,000 AF, but with improvements will recharge 6,000 AF
Calleguas and MWD in North Las Posas Basin	300,000 AF[100]	100,000 AF[101]	
Main San Gabriel Basin[102]	8,000,000 AF total storage potential		

88 Metropolitan Water District of Southern California. July 1995. Regional Urban Management Plan for MWDSC.

89 Rowe, L. July 26, 1995. Personal Communication.

90 Blevins, M., San Fernando Basin Watermaster. June 1995. Outline of presentation at ACWA Groundwater Mini-Conference. Average annual groundwater pumping (1968 through 1993) is 86,300.

91 Orange County Water District, 1994, Groundwater Management Plan.

92 Water Replenishment District of Southern California. 1995. Water supply report. Garcia, Mario. July 1995. Personal Communication.

93 Survey Response, Robert D. Pedigio, Hydraulic/Water Conservation Division, LAPWD. Figure includes amount recharged in LAPWD operated facilities for other organizations.

94 John Norman, General Manager, WRD. Letter to Dirk Reed, MWDSC. 300,000 AF of operating storage capacity is currently being operated by WRD. Includes barrier injection, spreading of imported and reclaimed water, and in-lieur deliveries.

95 Wang, C., B. Mortazavi., W. Liang, N. Sun, and W. Yeh. April 1995. Model Development for Conjunctive Use Study of the San Jacinto Basin, California. Water Resources Bulletin **31:** (2). p. Figure based on artificial recharge model for San Jacinto Basin.

96 Elsinore Valley MWD. February 28, 1994. Ground Water Recharge Feasibility Study. Feasibility stage, not yet implemented.

97 Stetson, T. June 1995. Case Studies on Implementing Conjunctive Use. Presented at ACWA Groundwater Mini-Conference on Conjunctive Use.

98 Tincher, Bob, San Bernadino Valley MWD. August 3, 1995. Personal Communication.

99 Arora, S., and S.Darabzand. 1990. Conjunctive Use of Surface and Groundwater Resources in the Central Valley of California, in Hydraulics/Hydrology of Arid Lands, Proceedings of the International Symposium, (ed. by R. H. French), ASCE, New York. p. 373-378.

100 Atwater, R., The Use of Wholesale Water Rates to Encourage the Groundwater Conjunctive Use. 1990. in Hydraulics/Hydrology of Arid Lands, Proceedings of the International Symposium, (ed. by R. H. French), ASCE, New York. pp. 46-48.

101 Horne, W.June, 8, 1995. General Methods & Facilities to Expand Conjunctive Use. Presented at the ACWA 1995 Ground Water Mini-Conference Conjunctive Use

Raymond Basin	100,000 AF[103]	23,600 - 31,300[104]	10,798.8 AF[105]
Sweetwater Authority[106]	120,000 - 240,000 AF		3,500 AF
San Diego River Groundwater Basin Task Force[107]			5,000 AF
City of San Diego and the San Pasqual Basin[108]			7,000 AF

Disclaimer: these figures cannot be added for a total volume of recharge because some districts are double counted, i.e. the districts report recharge, but recharge is done by another entity.

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102 Stetson, T. June 9, 1995. Presentation at ACWA's 1995 Groundwater Mini-Conference.

103 Man, D. June 8, 1995. Current Practices of Conjunctive Use in the State. Presented at ACWA 1995 Ground Water Mini-Conference Conjunctive Use.

104 Palmer, R., Raymond Basin Management Board. July 1995. Personal Communication.

105 Raymond Basin. 1995. Management Board Report, p. 18.

106 Daniel Diehr, San Diego County Water Authority. July 25, 1995. Facsimile communication. Preliminary results of agency's investigation. Planned project expected to begin by 1997-98.

107 Daniel Diehr, San Diego County Water Authority. July 25, 1995. Facsimile communication. Figure is an estimate, potential production is unknown at this time.

108 Daniel Diehr, San Diego County Water Authority. July 25, 1995. Facsimile communication. Production figure is from an earlier study, potential production is unknown at this time.

Appendix IV: Environmental Risks

AVI.1 Risks in Changing Surface Operations

One approach to increasing system yield analyzed in this paper involves transferring water from surface storage to underground storage in advance of periods when precipitation can be anticipated. This mode of operation may lead to two kinds of negative impacts. First, since the surface reservoirs will in general have greater empty space going into the winter, pulse flows that would normally pass through the reservoir will now be captured. This may have negative consequences downstream. Second, if reservoir levels are lowered before the winter and the winter is dry, it may be more difficult to maintain instream flows and temperature control below the dam .

The environmental benefits of pulse flows are a high-priority topic for additional work. Benefits may be derived from the effect of the water in transporting organisms downstream. Perhaps more significantly, occasional high flows are important for maintaining the natural morphology in downstream streambeds. Central Valley rivers are already highly regulated, though very high flow peaks still cannot be captured by storage. The use of groundwater storage to enhance yield would continue the historical reduction in pulse flows. The working hypothesis is that the benefits of enhanced environmental flows during critical seasons and dry years outweighs this negative effect, but more work is needed to determine whether this assumption is warranted.

As previously noted, many in-stream environmental uses depend on water temperature. Anadromous fish migration and spawning are affected by stream temperatures. Major streams such as the Sacramento and Mokelumne have temperature standards. Supplying water at these temperatures depends on maintaining thermal stratification in water supply reservoirs. Temperatures in upper levels increase during the summer but water at lower levels maintains stable temperatures and can be used to meet instream flow needs. If buffer storage levels are drawn down too far, water in the reservoirs will turn over and thermal stratification will be lost.

Risks of losing thermal stratification may increase with groundwater banking operations. Since conjunctive management necessitates partial evacuation of reservoirs in advance of precipitation, storage will inevitably be lower if the anticipated precipitation does not occur. As previously noted, California has historically faced drought periods extending for six or more years. The adequacy of groundwater banking to maintain sufficient surface storage will be most critical when this happens. Anadromous fish species have a migration cycle that spans a number of years. If spawning and other conditions are sub-optimal for individual years, overall population impacts may be minor. If sub-optimal conditions extend over consecutive years, net impacts will be substantially greater.

With groundwater banking, reservoir storage levels going into droughts will be lower than they would be under current operating procedures. Risks to in-stream flows and temperatures during this type of event depend critically on how rapidly the likelihood of a long-term deficit can be identified and how completely non-environmental users can be shifted to banked groundwater. If non-environmental demands on surface supplies can be reduced greatly before surface storage reaches critical levels, conjunctive management may increase the ability to maintain temperature stratification and surface supplies for in-stream uses. On the other hand, if operating mechanisms do not allow adequate shifts of high priority non-environmental demands from surface storage, if warning systems are insufficient to identify the probability of long-term deficits or if aggressive operating procedures result in inadequate surface reserves, temperature and in-stream flow impacts could be substantial. Current in-stream flow standards are often set just below dams. It is likely to be physically impossible (or at least economically impossible) to shift water from aquifer storage sites to these locations if buffer supplies prove inadequate. If buffer storage is too low, additional supplies could, potentially, be purchased from utility or district reservoirs upstream. How this might work, what it would cost and the availability of water for purchase during long-term droughts have yet to be investigated.

Beyond the environmental costs associated with conjunctive management, it is important to note that realizing many of the environmental benefits depends very heavily on operations procedures and hydraulic system configuration. The ability to shift non-environmental users onto groundwater during drought years depends on their location in relation to groundwater basins having appropriate storage characteristics. Banked water often cannot be directly applied to meet in-stream environmental needs. Aquifers are often located substantially downstream from critical environmental needs – such as spawning sites. In addition, groundwater is often warmer than water in surface streams. Since many habitat characteristics are temperature dependent, this can greatly affect the usability of banked groundwater for environmental purposes. As a result, generation of environmental benefits may depend critically on the degree to which banked water can be used to displace non-environmental demands on surface water supplies, particularly during intense drought periods. Similarly, the ability to create wetland habitat benefits depends on the match between the timing of water availability for recharge in relation to waterfowl wetland needs.[109] Overall, the environmental benefits of conjunctive management could be major – but the devil lies in specific details.

AIV.2 Recharge and Extraction Associated Risks

There is an array of potential environmental risks associated with the extraction and recharge component of any conjunctive management operation. In a broad sense these can be divided into two categories: (1) those associated with basin hydrology such as the potential for subsidence or interaction with surface stream flows; and (2) those related to water quality and pollution considerations. The first class of risks heavily depends on the degree to which the regional hydrology is accurately understood and the magnitude of flows related to storage and extraction in comparison to other flows. The second class may depend more on recharge and extraction mechanisms and agricultural chemical use patterns.

AIV.2.1 Hydrologic Uncertainty

The degree to which basin hydrologic characteristics are understood is a major factor influencing the risk of unanticipated environmental impacts. In addition, the accuracy with which the regional hydrology is understood greatly influences the degree of assurance the program has regarding ability to store and extract water in the amounts anticipated – and, thus, the overall benefits of conjunctive management.

Information on basin hydrology in the Sacramento-San Joaquin systems varies greatly depending on location. In general, the hydrology of the adjudicated basins in southern California has been quantified to a much greater degree than basins further north. This reflects the much longer history of water shortage and attempts to address it in the south compared to the north.

Characterization of the aquifer system underlying the Sacramento-San Joaquin has changed significantly over time. Early reports viewed the Sacramento basin essentially as a single unconfined aquifer and the San Joaquin essentially a two or multi-layered system in which confined and unconfined aquifers were separated by the dense and regionally extensive Corcoran Clay, or e-clay, member of the Tulare formation (Bertoldi, Johnston et al. 1991). More recently, the intensive Regional Aquifer System Analysis (RASA) study undertaken by the USGS has changed that image fundamentally. This detailed modeling effort characterized both the Sacramento and San Joaquin systems as essentially a single aquifer with multiple, discontinuous layers of low permeability clays creating semi-confined conditions in many locations (Bertoldi, Johnston et al. 1991). Study authors viewed flow within the system as linked throughout with substantial changes due to development. In some areas, vertical permeability of confining layers such as the Corcoran Clay has been reduced by 1.5 to 6 times (Bertoldi, Johnston et al. 1991, p. A26). Overall vertical flow has, however, increased by roughly an order of magnitude from conditions prior to development up to the 1970s. This was caused by leakage through wells with long perforated

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[109]. It would, for example, be important to evacuate reservoirs in the fall in advance of major precipitation periods in order to increase capture. Much of the recharge might, for this reason, need to be done in the late fall and early winter. Wetland habitat needs may, however, be particularly important in the spring and early summer.

sections (Bertoldi, Johnston et al. 1991). Most recently, work by the California DWR suggests that much of the Sacramento Valley might best be conceived as a two layer aquifer system in which extraction from or recharge to lower layers is essentially isolated from river flows.[110]

The above uncertainties have potentially great implications for conjunctive use activities. First, in parts of the Central Valley, the hydrologic system is not well enough understood at present to predict potential recharge and extraction effects on stream flows, wetlands and other associated environmental resources. This is particularly true in the Sacramento basin. Second, the same uncertainty limits the assurance a program could have regarding how much of the water it recharges will actually be available for extraction when needed and what liabilities the program might incur due to impacts on third parties. Vertical flow rates might be particularly important to this. In the Sacramento valley, for example, much would depend on whether or not recharge to deeper aquifer levels could be tapped during drought years without affecting levels in the upper unconfined aquifer or surface streams.

The above uncertainties are unlikely to represent as much of a concern in parts of the Central Valley (such as much of the San Joaquin and other groundwater basins in Southern California) where hydrological conditions are better known and where aquifers have been historically drawn down substantially or major pumping depressions currently exist. In these areas, surface-groundwater interactions are often minimal because streams are not in direct hydraulic connection with aquifers. Subsidence, while a concern, has often already occurred and, if fluctuations are kept within historical ranges, is unlikely to increase. Furthermore, because of overdraft, subsidence and other concerns, these areas have often been subject to extensive study. There is, therefore, a much larger body of information on aquifer characteristics and probable responses to the types of operations involved in a conjunctive management program. This substantially increases the degree of assurance a program would face with regard to environmental and third party impacts and the probability of stored water being available when needed.

AIV.2.2 Water Quality

A groundwater banking project of the type envisioned here should not encounter major water quality related problems in the short run. Longer term impacts are, however, much more difficult to predict. During the initial phases of a state-level conjunctive use program, water quality related problems are likely to be limited primarily to monitoring residues from agricultural operations (fertilizers and pesticides) and potential micro-element concerns in source water.[111] If direct percolation of water conveyed without intervening uses in dedicated recharge facilities is the primary recharge mechanism, source water quality should be high and problems relatively straightforward to monitor and control. Contamination is a point of concern primarily with spreading. It is also a concern if extraction causes major changes in hydraulic gradients and results in the mobilization of polluted or otherwise low quality water. This could emerge as a particular concern during long duration droughts when irrigators would be depending on groundwater as their primary source of supply over extended periods. There are two points it is important to make in this context:

1) Substantial contaminant loads including pesticides, fertilizers, salts and micro-elements such as selenium are currently isolated in the soil column. Increased flushing of the soil column due to intentional recharge (spreading) could mobilize large amounts of these contaminants. This would add to the contaminants picked up from current agricultural operations. Flushing from increased recharge could, on the other hand, have the opposite effect. Some suggest that the increased flow through aquifers resulting from conjunctive use operations could be used as a technique to reduce existing nitrate and other contamination.[112]

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110. Discussion with Glen Pearson, DWR on 8/17/95. In rice growing areas of the Sacramento Valley, shallow wells are observed to maintain steady water levels (lots of recharge) but deeper wells fluctuate substantially as pumping levels change. This suggests at least partial isolation of lower aquifers from upper levels.

111. Many conjunctive use projects envision recharge of reclaimed water. In this situation, treatment prior to injection is a major source of cost.

112. Personal communication, Walter Swain, U.S. Geological Survey

2) Changes in hydraulic gradients associated with extraction of stored groundwater are a major potential cause of contamination. In many locations, fresh water aquifers are in hydrologic contact with low quality water. Pumping fresh aquifers can cause intrusion of the low quality water, essentially ruining them as a source or storage location. This is a common problem in coastal areas but is also of potential concern in many inland locations as well. On the western side of the Sacramento valley, there are large areas of shallow saline groundwater that could be mobilized if hydraulic gradients change due to pumping associated with a conjunctive use program. Similar issues are present where high levels of Boron exist in groundwater, making it unusable for many agricultural operations.[113]

Groundwater banking will inherently increase fluctuations in aquifer levels. This will increase both lateral and vertical flow within the groundwater system. This will, in turn, have a tendency to mobilize pollutants and naturally occurring contaminants. The net effects are, on a broad scale, difficult to predict. In some areas, increased flushing could cause net water quality improvements. In others, mobilization could have the opposite impact.

The degree to which water quality concerns are likely to emerge if conjunctive use operations are implemented is unknown. Clearly, care would be needed to avoid regions where quality problems already exist that could be exacerbated by program operations. Program exposure to potential quality problems is likely, however, to be greatest with spreading methods. These techniques are otherwise often the least costly. This suggests that direct recharge using percolation or injection techniques may, over the long term, prove less expensive because it is possible to avoid non-point sources of contamination to a much greater extent. Overall, monitoring of groundwater quality trends is particularly essential in any conjunctive management program using spreading for recharge or one that causes significant water table fluctuations to ensure that contamination from agricultural residues or other sources does not occur.

[113]. Personal Communication, Tocay Dudley, DWR, 8/21/95

Appendix V: Groundwater Banking Cost in California

Site	Cost per Acre-Foot (1994-95)	Method
Eastern Yolo County [1]	54	In lieu of irrigation
Natomas Central Mutual Water Company [2]	150	In lieu of irrigation
Pleasant Grove-Verona Mutual Water Company [2]	71	In lieu of irrigation
South Sutter Water District [2]	83	In lieu of irrigation
WID [3]	110-208	In-lieu and off season irrigation, price range depends on scale, small scale=low price. Most of difference related to additional wells and reconfiguring existing surface storage for recharge.
Antelope Valley-East Kern WA [4]	90	In lieu deliveries
Water Replenishment District of Southern California [5]	112	In lieu deliveries
Yuba County Water Agency [6]	30-35	In lieu deliveries
Leach Canyon in Riverside County [7]	141	Spreading Basins
McVicker Canyon in Riverside County [7]	176	Spreading Basins
Kern-Tulare WD and Rag Gulch WD [8]	30	Spreading Basins outside of district
Rosedale-Rio Bravo WSD [9]	10-12	Spreading Basins using excess river flow
Water Replenishment District of Southern California[10]	20	Spreading Basins using imported water. Cost/AF of imported water, depending on source can be $263, $480, or $501 11
Water Replenishment District of Southern California[10]	20	Spreading Basins using recycled water. Cost/AF of recycled water can be $15 or $380 11
Rosedale-Rio Bravo WSD [9]	50-62	Spreading Basins using SWP water
San Bernadino Valley MWD [12]	60-120	Spreading Basins
Mojave WA [13]	200	Spreading basins using SWP water
Kern County WA [14]	5-35	Spreading Basins, depending on source of water, cost for recharge alone.
Joint Management Board - Terra Bella ID, Lower Tule River ID, Saucelito ID, Pixley ID, and Porterville ID[15]	25	Spreading Basins
Average for various sites in Central Valley 16	90-120	Active percolation
Orange County WD [17]	20	Active percolation
WID & SJCID [3]	110-337	Active percolation combined with in-lieu and off-season irrigation. Price range depends on scale. Most of difference related to conveyance facilities for withdrawal.
Alameda Co. WD [18]	189	Active percolation in recharge pits and along creek bed
Raymond Basin Management Board[19]	10	Active percolation of natural run-off

Chino Basin Watermaster[20]	249	Active percolation with MWDSC SSP water
Chino Basin WCD[21]	102	Active percolation recharge
Dudley Ridge WD[22]	65-110	Active percolation recharge outside of district
Wetlands east of Lake Elsinore in Riverside County[7]	186	Injection
MWDSC with Calleguas WD in Las Posas Basin[23]	130	Injection and extraction
Raymond Basin Management Board[19]	50	Injection using discounted water from MWDSC
Arcade WD[24]	80	Combination of injection and in-lieu deliveries

1 DWR, 1994, SWP Conjunctive Use--Eastern Yolo County
2 DWR, 1995, American Basin Conjunctive Use Project, Pre-Feasibility Report, P. 125
3 EDAW, Inc. December, 1992. Draft EIS/EIR for the Updated Water Supply ManagementProgram, Volume V, Technical Appendices D1-D3 and E1-E3. Prepared for East Bay Municipal Utility District, Oakland, California.
4 Fuller, R., Antelope Valley-East Kern WA. July 18, 1995. Personal Communication.
5 Water Replenishment District of Southern California. 1995. Annual Survey and Report on Groundwater Replenishment, p. 30. In-lieu reimbursement is $112, the District uses the same rate to determine expenditures for in-lieu replenishment.
6 Wilson, D., Yuba County WA. June 1995. Personal Communication.
7 Elsinore Valley Municipal Water District, 1994, Ground Water Recharge Feasibility Study Final Report, prepared by GEOSCIENCE Support Services Inc., p. 46
8 Bowers, B., Kern-Tulare and Rag Gulch WD. July 1995. Personal Communication. $30/AF is an average estimate
9 Crossley, H., Rosedale-Riobravo WSD. June 1995. Personal Communication. Cost includes variable costs only.
10 Garcia, M., Water Replenishment District of Southern California. August 18, 1995. Personal Communication. Cost of recharge is roughly estimated to be $20/AF. Currently, the Los Angeles Department of Public Works operates and funds recharge activities, and has not calculated the cost per AF for recharge.
11 Water Replenishment District of Southern California. 1995. Annual Survey and Report on Groundwater Replenishment., p. 5.
12 Tincher, Bob, San Bernadino Valley MWD. August 3, 1995. Personal Communication. Cost figures include amount paid for recharge facilities, does not include pumping costs. Price is subsidized
13 Mojave Water Agency. May 1993. Regional Water Management Plan. Prepared by Boyle Engineering Corporation
14 Kern County WA. April 1995. 1995 KFE Property Recharge Program.
15 Robb, R., Lower Tule River ID. July 1995. Personal Communication.
16 U.S. Bureau of Reclamation and Fish and Wildlife Service, July 1995, DRAFT Conjunctive Use Technical appendix #4 to the Least-Cost CVP Yield Increase Plan, p. 6-1
17 Van Haun, J., Orange County WD. June 1995. Personal Communication.
18 Alameda County WD. February 1995. Survey Report on Groundwater Conditions. p. 21.
19 Ron Palmer, Raymond Basin Management Board. July 1995. Personal Communication.
20 Stewart, T., Chino Basin Watermaster. August 1995. Personal Communication.
21 Gumina, S., Chino Basin WCD. July 1995. Survey results.
22 Melville, D., Dudley Ridge WD., July 1995. Survey results. Cost does not include cost of water which can be highly variable.
23 Horne, W.. June, 8, 1995. General Methods & Facilities to Expand Conjunctive Use. Presents at the ACWA 1995 Ground Water Mini-Conference Conjunctive Use
24 CH2M Hill,. November 1993. Groundwater Recharge Project Feasibility Report. Prepared for Arcade Water District. Cost/AF calculated using present worth of project (20-year project life, 4% annual inflation, and 8.25% discount rate) of $28.65 million / 17,960 AF/yr * 20 years (359,200 AF) = $80/AF