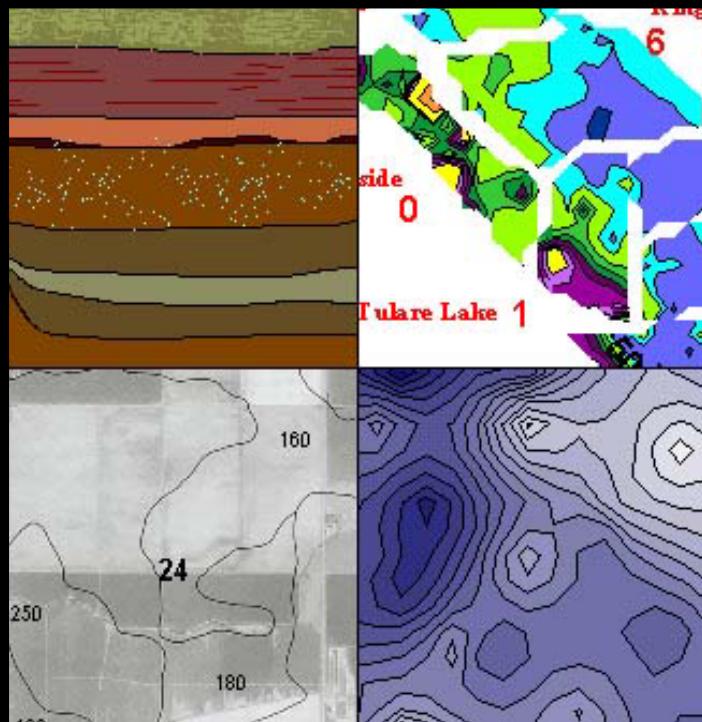


**THE HYDROGEOLOGIC SUITABILITY  
OF POTENTIAL GROUNDWATER BANKING SITES  
IN THE CENTRAL VALLEY OF CALIFORNIA**



**THE NATURAL HERITAGE INSTITUTE**

**David R. Purkey, Ph.D.  
Gregory A. Thomas, J.D.**

**with research by:**

**Shannon Byrne  
Ann M. Cheng  
Nathan E. Harrison**

This report is one of several technical studies prepared by the **Natural Heritage Institute** as part of a System-Wide Investigation of Conjunctive Water Management Opportunities in the Central Valley of California under a cooperative agreement (99FC200189) with the U.S. Bureau of Reclamation. That project, in turn, is part of a larger program of activities to Enable Water Transactions to Restore Landscapes and Aquatic Habitats in California's Central Valley with support from the David and Lucile Packard Foundation, the Dean Witter Foundation and the William and Flora Hewlett Foundation.

The methodology and results in this study benefited greatly from a peer review by the following panel of experts who graciously donated their time and knowledge to this effort:

- Sydney Coatsworth, EDAW, Inc.
- Mark Cowin, CALFED Bay-Delta Program
- Toccoy Dudley, California Department of Water Resources
- John Fielden, California Department of Water Resources
- Jan Fleckenstien, University of California at Davis
- Graham Fogg, University of California at Davis
- David Fullerton, Natural Heritage Institute
- Carl Hauge, California Department of Water Resources
- Karen Hoover, California State University at Chico
- John Jenkins, US Bureau of Reclamation
- George Mantanga, US Bureau of Reclamation
- Doug Osugi, California Department of Water Resources
- Steven Phillips, US Geological Survey
- Anthony Saracino, Saracino, Kirby & Snow
- Walter Swain, US Geological Survey
- John Woodling, California Department of Water Resources

This report and others from this project are available on-line from NHI's website at [www.n-h-i.org](http://www.n-h-i.org) or contact the Natural Heritage Institute at the address below.

**THE NATURAL HERITAGE INSTITUTE**  
2140 Shattuck Ave. 5<sup>th</sup> Floor  
Berkeley CA 94704  
510.644.2900 / phone  
[nhi@n-h-i.org](mailto:nhi@n-h-i.org)

**The Natural Heritage Institute is a non-profit natural resource conservation organization composed of technical and legal specialists and dedicated to the improvement of the laws and institutions that manage our natural heritage both domestically and internationally.**

Copyright © 2001 The Natural Heritage Institute  
All rights reserved.

<b>1.0 Introduction</b>	<b>1</b>
<b>2.0 Identification of Potential Groundwater Banking Sites</b>	<b>7</b>
<b>3.0 Description of the Sub-Index Parameters</b>	<b>11</b>
<b>3.1 Geology Sub-Index</b>	<b>12</b>
3.1.1 Geology Sub-Index Parameters	12
3.1.2 Geology Sub-Index Weighting Factors	13
<b>3.2 Water Quality Sub-Index</b>	<b>15</b>
3.2.1 Water Quality Sub-Index Parameters	15
3.2.2 Water Quality Sub-Index Weighting Factors	16
<b>3.3 Soils Sub-Index</b>	<b>18</b>
3.3.1 Soils Sub-Index Parameters	18
3.3.2 Soils Sub-Index Weighting Factors	20
<b>3.4 Application of the Core Hydrogeologic Suitability Index</b>	<b>21</b>
<b>4.0 Application of the Hydrogeologic Suitability Index in the Sacramento Valley</b>	<b>22</b>
<b>4.1 Sacramento Valley Geology Sub-Index</b>	<b>23</b>
4.1.1 Results of the Sacramento Valley Geology Sub-Index	23
4.1.2 Comments on the Geology Sub-Index	27
<b>4.2 Sacramento Valley Water Quality Sub-Index</b>	<b>29</b>
4.2.1 Results of the Sacramento Valley Water Quality Sub-Index	29
4.2.2 Comments on the Water Quality Sub-Index	31
<b>4.3 Sacramento Valley Soils Sub-Index</b>	<b>33</b>
4.3.1 Results for the Sacramento Valley Soils Sub-Index	33
4.3.2 Comments on the Soils Sub-Index	35
<b>4.4 Sacramento Valley Hydrogeologic Suitability Index</b>	<b>36</b>
4.4.1 Results for the Sacramento Valley Hydrogeologic Suitability Index	36
4.4.2 Comments on the Sacramento Valley Hydrogeologic Suitability Index	38
<b>5.0 Application of the Hydrogeologic Suitability Index in the San Joaquin Valley</b>	<b>39</b>
<b>5.1 San Joaquin Valley Geology Sub-Index</b>	<b>40</b>
5.1.1 Results of the San Joaquin Geology Sub-Index	40
5.1.2 Comments on the San Joaquin Geology Sub-Index	43
<b>5.2 San Joaquin Valley Water Quality Sub-Index</b>	<b>44</b>
5.2.1 Results of the San Joaquin Valley Water Quality Sub-Index	44
5.2.2 Comments on the Water Quality Sub-Index	47
<b>5.3 San Joaquin Valley Soils Sub-Index</b>	<b>48</b>
5.3.1 Results for the San Joaquin Valley Soils Sub-Index	48
5.3.2 Comments on the Soils Sub-Index	50
<b>5.4 San Joaquin Valley Hydrologic Connection Sub-Index</b>	<b>51</b>

**Table of Contents**

NATURAL HERITAGE INSTITUTE

5.4.1 San Joaquin Valley Hydrologic Sub-Index Parameters	51
5.4.2 San Joaquin Valley Hydrologic Connection Sub-Index Weighting Factors	54
5.4.3 Results for the San Joaquin Valley Hydrologic Connection Sub-Index	54
5.4.4 Comments on the Hydrogeologic Connectivity Index	56
<b>    5.5 San Joaquin Valley Hydrogeologic Suitability Index</b>	<b>57</b>
<b>6.0 Conclusions</b>	<b>60</b>
<b>7.0 References</b>	<b>62</b>
<b>APPENDICES</b>	
A Raw Water Quality Data	
B Raw Soil Data	
C Soil Area Data by Site	
D Water Storage Volumes	
E Basin Maps — San Joaquin Valley	
F Basin Maps — Sacramento Valley	
<b>FIGURES</b>	
2.0.1 Potential Groundwater Banking Sites in the Sacramento Valley	9
2.0.2 Potential Groundwater Banking Sites in the San Joaquin Valley	10
3.1.1 Influence of Geologic Structure on Geologic Suitability	13
3.2.1 Lead Contour Map for the Sacramento Valley	16
3.3.1 Soil Survey Map of Mormon Slough	18
4.0.1 Flow Chart of Parameters Analyzed...Sacramento Valley	22
4.1.1 Vertical Stratification of Formations Encountered...Sacramento Valley	24
4.1.2 Sacramento Valley Geology Sub-Index Values (500 Feet)	25
4.1.3 Sacramento Valley Geology Sub-Index Values (300 Feet)	26
4.1.4 Sacramento Valley Geology Sub-Index Values (100 Feet)	26
4.1.5 Spatial Distribution of 300 Ft. Depth Geology Sub-Index Values... Sacramento Valley	27
4.2.1 Spatial Distribution of Basin and Site Water Quality Scores	30
4.2.2 Water Quality Sub-Index Ranking...Sacramento Valley	32
4.2.3 Spatial Distribution of Water Quality Sub-Index Values...Sacramento Valley	32
4.3.1 Soils Sub-Index Ranking...Sacramento Valley	34
4.3.2 Spatial Distribution of Soils Sub-Index Values...Sacramento Valley	35
4.4.1 Hydrogeologic Suitability Index Ranking...Sacramento Valley	37
4.4.2 Spatial Distribution of the Hydrogeologic Suitability Index Values... Sacramento Valley	37
5.0.1 Flow Chart of Parameters Analyzed...San Joaquin Valley	39
5.1.1 Geology Sub-Index Ranking...San Joaquin Valley	42
5.1.2 Spatial Distribution of Geology Sub-Index Values...San Joaquin Valley	42

5.2.1	Spatial Distribution of Basin and Site Water Quality Scores	45
5.2.2	Water Quality Sub-Index Ranking	46
5.2.3	Spatial Distribution of Water Quality Sub-Index Values	47
5.3.1	Soils Sub-Index Rank	49
5.3.2	Spatial Distribution of Soils Sub-Index Values	49
5.4.1	Turlock Basin Fall 1977 WSE Contours	53
5.4.2	Hydrologic Connection Sub-Index Rank	55
5.4.3	Spatial Distribution of Hydrologic Connection Sub-Index Values	56
5.5.1	San Joaquin Valley Hydrogeologic Suitability Index Rank	58
5.5.2	Spatial Distribution of Hydrogeologic Suitability Index Values	59

## TABLES

3.1.1	Parameter Weighting Factors Used to Calculate the Geology Sub-Index	13
3.2.1	Parameter Weighting Factors Used to Calculate the Water Quality Sub-Index	16
3.3.1	pH Rating Scale	19
4.1.1	Scores for Formations Found in the Sacramento Valley	23
4.1.2	Geology Sub-Index Values...Sacramento Valley	25
4.2.1	Water Quality Scores for Basins in the Sacramento Valley	29
4.2.2	Water Quality Scores for Sites in the Sacramento Valley	30
4.2.3	Water Quality Sub-Index Values...Sacramento Valley	31
4.3.1	Soil Sites Lacking Available Soil Surveys	33
4.3.2	Soils Sub-Index Values...Sacramento Valley	33
4.4.1	Sacramento Valley Hydrogeologic Suitability Index	36
5.1.1	Parameter Weighting Factors Used to Calculate the Geology Sub-Index... San Joaquin Valley	40
5.1.2	Scores for Formations Found in the San Joaquin Valley	41
5.1.3	Geology Sub-Index Values...San Joaquin Valley	41
5.2.1	San Joaquin Valley Basin Scores	44
5.2.2	San Joaquin Valley Site Scores	45
5.2.3	Water Quality Sub-Index Values...San Joaquin Valley	46
5.3.1	Soils Sub-Index	48
5.4.1	Water Contour Data for Turlock Basin	52
5.4.2	Hydrologic Connectivity Sub-Index Table	55
5.5.1	San Joaquin Valley Hydrogeologic Suitability Index	57

# 1.0 Introduction

This report is one product of a technical investigation to design a **Central Valley System-Wide Conjunctive Water Management Program** under an emerging partnership that includes the U.S. Bureau of Reclamation and a consortium of other public water management agencies. As envisioned by this program, conjunctive use entails the integration of groundwater banking with reservoirs that would be reoperated to generate the source water. Other products of the investigation that are now available include:

- **Feasibility Study of a Maximal Program of Groundwater Banking in California** (January 1999), which includes an overview of the project and three pilot feasibility studies.
- **Designing Successful Groundwater Banking Programs In The Central Valley: Lessons From Experience** (August 2001), which includes extensive analysis of legal and institutional constraints and solutions.

These and other project documents can be viewed and downloaded from the Natural Heritage Institute's website at [www.n-h-i.org](http://www.n-h-i.org).

Subject to the availability of financial resources, forthcoming products will include reports on:

- “*In lieu*” groundwater banking site analysis
- Design specifications for local groundwater banking institutions
- The potential for reoperating reservoirs to generate source water for groundwater banking and to restore downstream fluvial processes
- Analysis of institutional, land use, infrastructure, environmental and other factors bearing upon siting decisions for groundwater banks
- Results of “gaming” analysis of a series of conjunctive use configurations in the Central Valley
- Economic optimization analysis
- A final feasibility report and strategic plan

This work is animated by the widespread realization that conjunctive water management will be a prominent feature of California’s water future because it is an environmentally acceptable (indeed, environment-enhancing) and cost-competitive way to improve the reliability of water supplies for all sectors. Thus, groundwater banking has emerged as a management concept that can garner broad-based support. As a storage enhancement strategy, groundwater banking is an attractive alternative to many who are reluctant to endorse an ambitious expansion of the state’s surface storage infrastructure. Storage increases associated with groundwater banking offer the potential to increase the yield of the California water system—an attractive prospect to the state’s water user community. Indeed, the CalFed Record of Decision assigns a larger role to groundwater

storage (500,000–1,000,000 acre-feet) than to any of the surface storage options in its plan to increase water supplies. Notably, however, the RoD gives priority to conjunctive use projects that are developed for local benefit and is silent regarding the source of the water to be banked. It is difficult to see how that vision would create new yield not otherwise available in the system. By contrast, the system-wide investigation, of which this report is a part, is oriented toward system-wide benefits (including benefits that accrue in the locale where groundwater banking occurs) and would generate new yield by integrating the water storage with existing reservoirs that would be reoperated so as to increase the space available to capture a larger fraction of annual runoff.

Groundwater banking must, as a practical necessity, be developed with the cooperation and consent of overlying landowners, groundwater appropriators, water districts and groundwater management authorities. Indeed, the recharge and recovery operations will generally be conducted by such local interests. Increasingly those communities that have historically relied on groundwater pumping to meet their needs realize that the best way to assure that local benefits flow from potential groundwater banking projects is to be involved in the project selection and design processes. The apparent convergence of interest between those charged with assuring California's future water supplies and those charged with managing local groundwater resources creates a climate where attempts are being made to identify the most promising groundwater banking opportunities in advance of the design and implementation of actual projects.

As with any water management initiative, the translation of a promising concept into a viable project relies upon a rigorous analysis of site-specific opportunities and constraints. To determine how best to link reservoirs that would provide the recharge water, with groundwater banking sites that would store it, with project beneficiaries who would use it, in a way that proves universally beneficial, it is of course necessary to investigate the most suitable groundwater banking sites. There are many dimensions to that puzzle. To itemize the most prominent factors, the most suitable sites will be those where:

- The target aquifer has the best physical characteristics for the storage and retrieval of banked groundwater;
- The aquifer does not interact with surface water bodies (unless such interaction is a desired characteristic);
- The overlying water districts or groundwater management authority is willing to operate the banks and where effects on unincorporated groundwater users can be avoided;
- The existing patterns of groundwater use in the vicinity of the project are compatible with groundwater banking;
- The legal and institutional setting governing groundwater management, use and export is most congenial;
- The recharge, extraction and conveyance facilities will not conflict with existing land uses;

- The manipulation of groundwater levels will not adversely affect important habitats, crops or structures;
- The project can be easily linked to a water distribution network;
- The project is located down gradient of river reaches through which it is feasible to re-establish geomorphically beneficial peak flows;
- The project is located within the same sub-basin as the demand center that it is intended to serve (so as to minimize the need to transfer the banked water across the delta); and
- The costs of storing and recovering water are relatively attractive.

This report focuses on the first factor only, namely the hydrogeologic suitability of potential groundwater banking sites in the Central Valley. In limiting the scope of the report to this factor, we fully recognize that hydrogeologic suitability may not be the ultimate arbiter of where groundwater banking projects will prosper. The full suite of opportunities and constraints that will bear on any final project selection, as itemized above, will be the subject of other reports emanating from this project. Perhaps most predominant of those is the local receptivity as shaped by the legal and institutional settings of current groundwater utilization—this is treated at length in the companion report, ***Designing Successful Groundwater Banking Programs in the Central Valley: Lessons from Experience***, published by the Natural Heritage Institute in 2001.

Also, in limiting our scope to the Central Valley, we acknowledge that promising groundwater banking opportunities exist both in the Bay Area and on the Southern California Coastal Plain. Our assumption is that these opportunities will be pursued by the water management agencies that overlie those sites as part of their own local resource planning efforts. Here we are attempting to focus on potential groundwater banking projects that through integration with the overall California water system could improve that system's performance, but which are less likely to be included in purely local resource planning initiatives. These sites are located primarily in the Central Valley.

We also need to be clear that the scope of this hydrogeologic suitability analysis is limited to one of several modes of recharging groundwater: active recharge through percolation of water from ponds at the land surface that overlie the aquifer in which water will be stored. Water introduced to these ponds will percolate under gravity through any intervening unsaturated material prior to entering into groundwater storage. Another strategy, which is not treated in this report, involves introducing banked water directly to groundwater storage via wells screened in the target aquifer material. A third approach to groundwater banking is called *in lieu* groundwater banking. Under this approach, historic users of groundwater are provided with a new or expanded supply of surface water that decreases their need to pump groundwater. Groundwater that goes unpumped is considered banked (site suitability analysis for this type of groundwater banking technique will be the subject of a forthcoming report from this investigation). A fourth emerging concept focuses on rivers that will undergo dramatic shifts in their flow regimes as part of ecosystem restoration efforts. In theory, any additional seepage through the bed of these rivers that percolates down to the underlying aquifer system could be considered banked.

Each of the approaches is characterized by technical considerations that define its suitability for a particular location. If, for example, the aquifer targeted for groundwater banking is located below layers of low permeability material, injection wells would represent a more viable option for conveying water to storage than recharge ponds. If such an area has already experienced substantial development of groundwater wells, it might be particularly well-suited for an *in lieu* banking arrangement. For instance, the Tuscan formation below Butte County is highly suitable for *in lieu* groundwater storage because it is overlain with a thick layer of tight geologic material and is already utilized for irrigation. This report focuses exclusively on groundwater banking via recharge ponds. We have limited the scope of our analysis in full recognition that other types of groundwater banking projects are possible, and potentially important, in California. However, we chose to focus on recharge ponds based on several factors:

- The largest existing groundwater banking projects in California, of which the Kern Water Bank is the best known, have generally employed recharge ponds.
- Soil assemblages in the Central Valley, derived largely from the deposition of alluvial fans, often contain soils coarse enough to support recharge ponds.
- While vertical stratification of thin water bearing and flow retarding aquifers does exist in parts of the Central Valley, deep alluvial aquifers receiving recharge from overlying percolation are fairly widespread.

Within this limitation in scope, however, this report provides a methodology to compare sites in the Central Valley in terms of their hydrogeologic suitability for groundwater banking via recharge ponds. Our methodology relies upon utilizing a core set of available data related to geology, groundwater quality, soils and hydrology to develop a Hydrogeologic Suitability Index, which like all indices is the product of both analysis and judgment. In developing this index we were driven by the desire to create a uniform template against which all potential groundwater banking sites could be compared—tempered by the recognition that site-specific factors and data limitations generally complicate the application of a uniform standard. We acknowledge these complications, and make appropriate assumptions in response, because waiting until the definitive information is available to complete our analysis, if ever, is unacceptable in the accelerated state of water planning initiated by the RoD.

One significant complication in applying a single index across the Central Valley stems from the fact that hydrogeologic conditions in the Sacramento and San Joaquin Valleys differ. While regions of prolonged groundwater overdraft characterize the San Joaquin Valley, resulting in the creation of substantial cones of depression, aquifers in the Sacramento Valley are not typically impacted by overdraft and large cones of depression are less common in this region. This difference has implications for the sequence of water storage and recovery that could be implemented as part of a program of groundwater banking. In general, dewatered aquifer space is available for immediate groundwater storage in portions of the San Joaquin Valley while aquifer storage in

the Sacramento Valley would generally have to follow the groundwater recovery required to create storage space. The hydrologic parameters useful in evaluating the hydrogeologic suitability of groundwater banking under these two conditions are not identical. As a result, we developed a core index that includes information on geology, groundwater quality and soils that can be applied in both the Sacramento and San Joaquin Valleys, and an extended index that draws upon hydrologic information for use solely in the San Joaquin Valley.

Even in applying the index within the Sacramento or the San Joaquin Valley, however, we confronted the challenge of assigning appropriate weighting factors for the parameters under consideration. These assignments are certainly open to alternative interpretations. To allow for that, we have crafted a methodology that allows others to insert weighting factors that reflect their own judgments or preferences. The result is a spreadsheet that can be manipulated based on any number of assumptions regarding appropriate weighting factors. If suitably disaggregated data is available, the index is also scalable so that it could be applied to the comparison of promising groundwater banking sites within a single county as easily as it has been applied across the Sacramento or San Joaquin Valleys in this report.

We hope this flexibility and scalability will make the index useful to a range of potential users in California. These could include: agency staff charged with prioritizing the range of potential groundwater banking sites across the Central Valley, researchers examining the interactions between groundwater banking and other water management objectives such as flood control and ecosystem restoration, local and private resource managers deciding whether or not a groundwater banking project they are contemplating offers strategic advantages to statewide water planners, and reservoir operators attempting to develop groundwater banking strategies that take into consideration all of the constraints and opportunities listed above. Thus, despite the limitations inherent in adopting an index approach, we trust that our study will provide information useful to all of these actors as they attempt to move the analysis of groundwater banking to a point where consideration of more refined site-specific details of promising sites becomes both necessary and appropriate.

This work is properly viewed as a first screen in identifying the most suitable groundwater banking sites. The scale of analysis is too coarse and the data uncertainties too significant to permit specific parcels of land to be specified as the best locations to construct groundwater recharge or extraction facilities. Nor would we presume so far without the assent of such landowners. Indeed, the uncertainties inherent in the analysis point out areas where additional research carried out with limited public resources would prove beneficial. Refinement of the information on the heterogeneity of geologic and associated aquifer hydraulic properties in the areas that appear most suitable for groundwater banking is a direct benefit that can flow from the development of the index. Continued investment in water quality data acquisition may also be warranted at promising sites as much of the information currently available is decades old. Finally the analysis can lend focus to more targeted analysis that includes the other factors, itemized above, that will necessarily bear upon the selection of optimal sites. With the funds earmarked for conjunctive use beginning to flow from the CalFed Program, Proposition 13 funding, and other federal and state resources, the analysis behind the development of the index can provide useful on where to utilize research dollars intended to facilitate the increasing adoption of conjunctive use as a viable water management strategy.

Two things are clear: 1) the potential for conjunctive water management to contribute to a more secure water supply in California is too large to ignore, and 2) one of the factors that most inhibits the realization of this potential is the lack of definitive information on hydrogeologic suitability. Uncertainties in this regard engender fear of unintended consequences within those communities currently most reliant upon groundwater. Fear creates resistance among those who have most to gain from this water management technique—those landowners who control the aquifers and could manage them as a local public good and those public officials charged with managing our limited water supplies. If we wait for the optimal list of conjunctive use projects, developed from unimpeachable information, to appear, we may miss the opportunity to realize the enormous potential of conjunctive water management. Imperfect as it is, we hope that this document, along with others published by the investigation, will assist as we push toward the realization of actual conjunctive use projects.

## 2.0 Identification of Potential Groundwater Banking Sites

As stated in Section 1.0, differences in the hydrologic conditions encountered in the Sacramento and San Joaquin Valleys militate in favor of applying the Hydrogeologic Suitability Index separately to these two regions. In both regions a core index, based on geology, groundwater quality and soils considerations, can be applied. An extended index that takes into account hydrologic information can be applied in the San Joaquin Valley. Before applying either index, however, a list of potential groundwater banking sites in both regions of the Central Valley must be developed.

A number of inventories of potential groundwater banking sites have been assembled in recent years. Many of these were synthesized in the list of potential sites reported in *A Feasibility Study of a Maximal Scale Program of Groundwater Banking in California* published by the Natural Heritage Institute in 1999. A less inclusive list of the sites judged to be most feasible from a technical and political vantage point were evaluated for recharge and recovery capacity in the February 2000 *Conjunctive Use Site Assessment* prepared by the Integrated Storage Investigation of the CALFED Bay-Delta Program. In general, these inventories have adopted a broad perspective, leading to the identification of rather large areas as potential banking sites (e.g., Yuba County or the Tuolumne/Merced Basin). A slightly more refined optic was adopted during the development of the Hydrogeologic Suitability Index. Here an attempt was made to identify the actual regions where measured groundwater levels reveal the opportunity to store water within dewatered aquifer material, or areas where in spite of the current high water table conditions, geologic conditions would favor an increase in aquifer management through more ambitious pumping and recharge.

The following steps were taken in the process of identifying potential groundwater banking sites in the Central Valley. Data from the Department of Water Resources semi-annual survey of wells was downloaded for Fall 1992. Using a contouring program, a groundwater head surface was developed for the entire Central Valley. Data from areas that exhibited groundwater head levels lower than that found in the surrounding area were examined in greater detail. Based primarily on the geometry of the mapped depressions, a qualitative assessment was made as to whether the depressions represented water table declines or comparatively low piezometric surfaces in deep water-bearing horizons. In general, water table declines were deemed to exhibit continuity with levels observed in the majority of nearby wells while low piezometric surface readings were associated with "bulls eye" type depressions that exhibited little correlation with nearby wells. Once depressions that appeared to be related to declines in the regional water table were identified, the second step in site identification involved examining soils maps to identify promising sites for recharge basins. This examination, which also relied upon qualitative analysis of existing data, sought to identify four-square-mile blocks of land with the most "promising" assemblage of soils. This involved looking for blocks dominated by sandy soils with a minimum of clay. While this step did not involve statistical analysis of soil assemblages, it was generally possible to visually distinguish sites with generally coarse soil from those dominated by fine-grained material. The four-square-mile blocks of land located over what were considered to be water table depressions were selected as the potential groundwater banking sites.

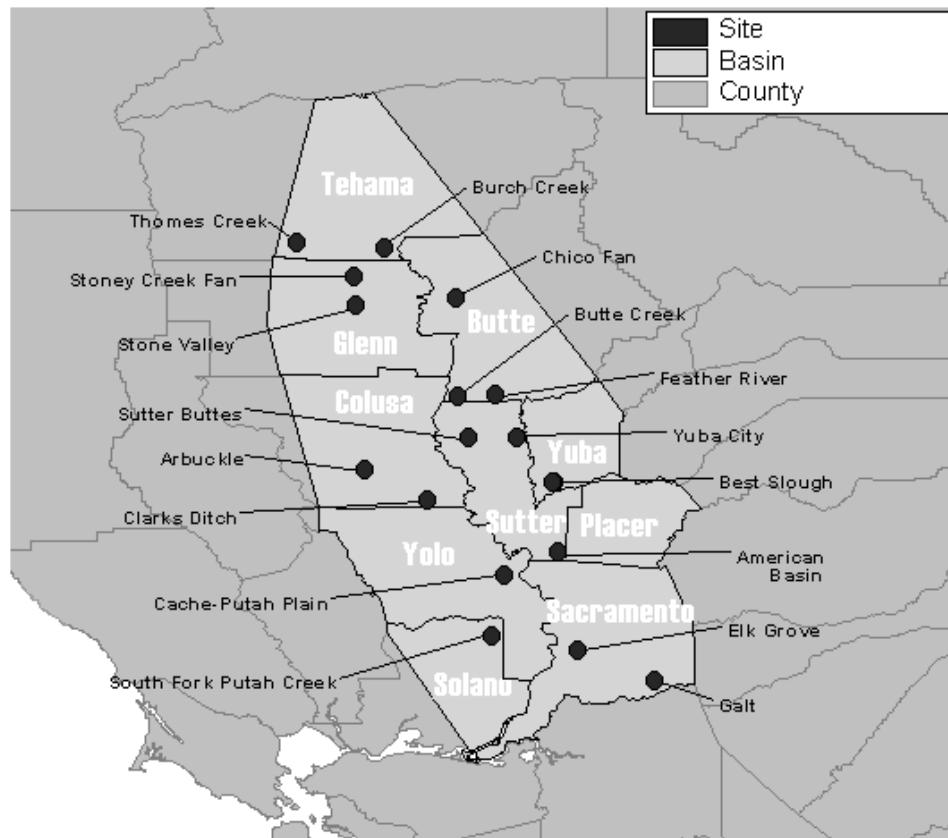
Viewed through this lens, several potential sites emerge within the broad regions previously defined. Figures 2.0.1 and 2.0.2 depict the locations of the sites that were ultimately selected for consideration in the Sacramento and San Joaquin Valleys, respectively. Information on the sites depicted in Figures 2.0.1 and 2.0.2 includes a site name, identifies the groundwater basin where the site is located and provides a reference to the site location based on the California State Land Survey system. The California Department of Water Resources delineated the groundwater basins.

The site names that appear in Figures 2.0.1 and 2.0.2 require some clarification. Information relevant to the Hydrogeologic Suitability Index is available at a variety of scales. In general, however, information on the characteristics of soils overlying potential groundwater banking sites is available at the finest scale (as fine as 1:20,000 in many soils surveys prepared by the United States Soil Conservation Service). In attempting to define important parameters associated with the soil characteristics at potential groundwater banking projects, four-square-mile land sections with the most attractive soil assemblages were identified in the region overlying targeted storage sites. The site names associated with each location are derived from prominent geographic features located near the selected land units. While these names may be less recognizable than Yuba County or the Tuolumne/Merced Basin, all information needed to locate the banking site selected for analysis are included in Figures 2.0.1 and 2.0.2.

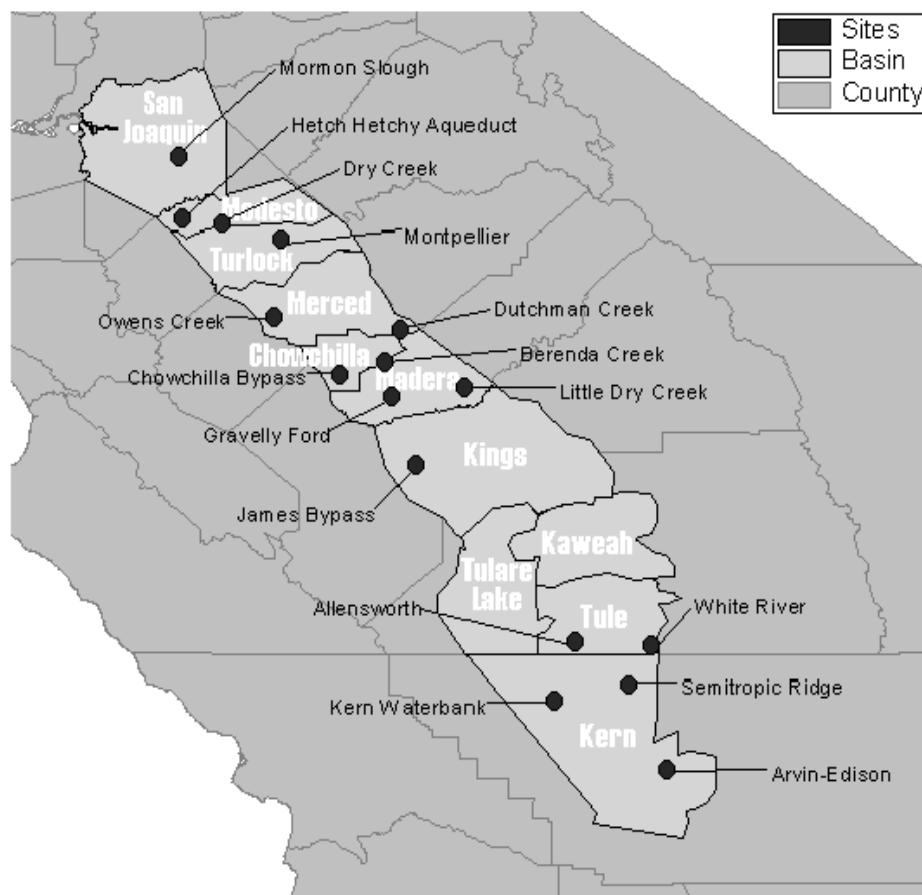
In selecting the sites depicted in Figures 2.0.1 and 2.0.2, we anticipate that many readers will find reasons to object to the inclusion of a particular site or the exclusion of another. We make no claim that the lists we developed are complete and comprehensive. We do feel, however, that we have created a sample that reasonably reflects the range of potential groundwater banking sites in the Central Valley. There are sites in the western Sacramento Valley that are associated with the flashy gravel-laden streams that emerge from the Coast Range Mountains. Sites on the east side of the Sacramento Valley are associated with large perennial streams that drain the granite-rich Sierra Nevada. In the San Joaquin Valley there are sites associated with rivers that issue to the Bay-Delta system and others that drain into the Tulare Lake Basin. The only region of the Central Valley not represented is the western San Joaquin Valley, a region plagued by poor groundwater quality that makes it less favorable to groundwater banking based on the use of recharge ponds.

In addition, if others feel that additional sites should be added to the list, it is easy to do so in the spreadsheet developed as part of this project. It is simply a matter of defining the required parameter values and adding the site to the database.

**Figure 2.0.1: Potential Groundwater Banking Sites in the Sacramento Valley**



Site	Basin	Township, Range	Sections
Thomas Creek	Tehama	T24N, R5W	9, 10, 15, 16
Burch Creek	Tehama	T23N, R2W	17, 18, 19, 20
Stony Creek Fan	Glenn	T22N, R3W	19, 20, 29, 30
Stone Valley	Glenn	T21N, R3W	28, 29, 32, 33
Chico Fan	Butte	T21N, R1E	15, 16, 21, 22
Butte Creek	Butte	T17N, R1E	15, 16, 21, 22
Feather River	Butte	T17N, R2E	14, 15, 22, 23
Sutter Buttes	Sutter	T15N, R1E	1, 2, 11, 12
Yuba City	Sutter	T15N, R3E	4, 5, 8, 9
Arbuckle	Colusa	T14N, R3W	15, 16, 21, 22
Best Slough	Placer-Yuba	T13N, R4E	3, 4
		T14N, R4E	33, 34
Clarks Ditch	Colusa	T13N, R1W	21, 22, 27, 28
American Basin	Sutter	T11N, R4E	26, 27, 34, 35
Cache-Putah Plain	Solano-Yolo	T10N, R2E	24, 25
		T10N, R3E	19, 30
South Fork Putah Creek	Solano-Yolo	T7N, R2E	2, 3, 10, 11
Elk Grove	Sacramento	T7N, R5E	27, 28, 33, 34
Galt	Sacramento	T5N, R7E	1, 12
		T5N, R8E	6, 7

**Figure 2.0.2: Potential Groundwater Banking Sites in the San Joaquin Valley**

Site	Basin	Township, Range	Sections
Mormon Slough	San Joaquin	T1N, R7E	13, 24
		T1N, R8E	18, 19
Hetch Hetchy Aqueduct	Modesto	T3S, R8E	19, 20, 29, 30
Dry Creek	Modesto	T3S, R9E	25, 26, 35, 36
Montpellier	Turlock	T4S, R12E	19, 20, 29, 30
Owens Creek	Merced	T8S, R11E	13, 14, 23, 24
Dutchman Creek	Merced	T8S, R17E	31, 32
		T9S, R17E	5, 6
Berenda Creek	Chowchilla	T10S, R16E	21, 22, 27, 28
Chowchilla Bypass	Chowchilla	T11S, R14E	2, 3, 10, 11
Gravelly Ford	Madera	T12S, R16E	11, 12, 13, 14
Little Dry Creek	Madera	T11S, R19E	25, 26, 35, 36
James Bypass	Kings	T15S, R17E	23, 24, 25, 26
White River	Tule	T24S, R27E	22, 23, 26, 27
Allensworth	Tule	T24S, R24E	15, 16, 21, 22
Semitropic Ridge	Kern	T26S, R26E	13, 14, 23, 24
Kern Waterbank	Kern	T27S, R23E	10, 11, 14, 15
Arvin-Edison	Kern	T30S, R28E	21, 22, 27, 28

## 3.0 Description of the Sub-Index Parameters

As mentioned in Section 1.0, conditions encountered in the Sacramento and San Joaquin Valleys are sufficiently distinct to warrant the application of different versions of the Hydrogeologic Suitability Index. One major difference is the degree to which aquifers in the two regions have been drawn down. While the San Joaquin Valley is characterized by substantial cones of depression, surface aquifers in the Sacramento Valley generally exhibit water tables that closely track the land surface profile. This makes it more difficult to speculate how these aquifers would respond to the more intensive management that would accompany groundwater banking. As such, a sub-index related to hydrologic conditions in the target aquifers has been applied only at sites in the San Joaquin Valley.

In both locations, however, a core set of data related to geology, groundwater quality and soils can be used to develop relevant sub-indices. This section describes the parameters included in the core index and a methodology for evaluating their impact on the overall hydrogeologic suitability of potential groundwater banking sites. One of the central challenges in developing these sub-indices was to assign values to their various components. In the geology sub-index, for example, we consider the permeability of water-bearing geologic formations below potential groundwater banking sites. In making this consideration we reviewed numerous reports describing the geology of the target basins. These reports often used terms such as the formation is “highly” or “moderately” permeable. In a few cases, ranges of permeability values were also given, many of which were quite broad.

We did not attempt to translate these observations into a rigorous geo-statistical representation of permeability across the Central Valley. Instead we sought to develop associations between what previous researchers called highly, moderately and non-permeable materials and the range of actual permeability values that were occasionally reported in the literature. While this qualitative approach did not allow us to distinguish between two formations that were deemed to be highly permeable to find the “most promising sites”, it did allow us to confidently sort the geologic formations into broad categories useful in defining the “most promising sites”. This level of refinement was in keeping with the fact that the hydrogeologic suitability of a potential site will be only one factor influencing its ultimate selection for a groundwater banking project. A similar qualitative approach was taken in defining values for certain components of other core sub-indices. While this approach may seem cursory to some, we feel it is in keeping with the intent of this effort, which is to provide insight useful in identifying a suite of potential sites that merit the type of closer consideration that will lead to more refined comparisons among potential groundwater banking project locations.

### 3.1 Geology Sub-Index

Perhaps the most important factor in evaluating the hydrogeologic suitability of potential groundwater banking sites is the nature of the underlying geologic formations. The characteristics of these formations will control the amount of water that can be stored within a given volume of aquifer material and the ease with which water can be recharged to and extracted from the water-bearing formations. Clearly, an unconsolidated, uncemented, coarse-grained alluvial formation would offer easier access to larger storage volumes than a consolidated, fine-grained, lacustrian formation.

#### 3.1.1 Geology Sub-Index Parameters

Having reviewed some of the voluminous geologic literature available for the Central Valley (see the Geology portion of Section 7.0: References), we decided to employ three parameters to characterize the geologic suitability of formations underlying potential sites for groundwater banking: permeability, the presence of paleosols, and the presence of geologic structures that could enhance or detract from aquifer storage potential. While many other parameters could have been used, we limited our selection based on the availability of data across most of the sites under consideration and on our desire to use parameters that were likely to be independent of one another. For example, we originally considered using both the percent coarse-grained material and the degree of cementation and consolidation of the target aquifer as parameters in the geology sub-index. These were ultimately discarded because they are likely correlated with the permeability of the aquifer formation. Details on the final set of parameters are presented in the following paragraphs.

##### *Permeability*

Permeability describes the ease with which water can flow through geologic material. Measured in units of length per time, permeability affects the rate at which water can percolate into the geologic material for storage and also the rate at which it can be pumped out in recovery. In general, the higher the estimated permeability, the better the yield of wells installed in a formation. Increases in well yield would facilitate the recovery of water stored in a potential groundwater banking site, enhancing that site's suitability. Permeability was scored based on textual descriptions of formations from the references cited in Section 7.0. Formations were described as being impermeable, moderately permeable, or highly permeable.

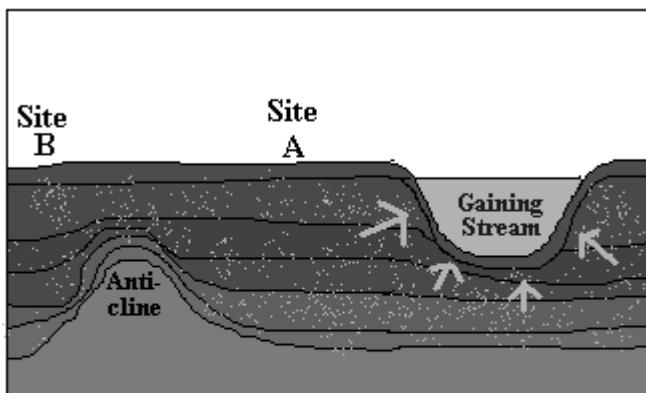
##### *Paleosols*

The deposition of sedimentary formations is not a continuous process. At certain periods the forces contributing to deposition are absent, resulting in long-term exposure of the material at the surface of the formation. During these periods, soil development can occur. Paleosols, or fossil soils, are old soil layers that are buried in a geologic formation when the forces contributing to deposition resume. As a high concentration of clay minerals and the potential for hardpan development exist in the paleosols, they can impede the vertical flow of water through a formation. Such an impediment could restrict the access to storage available in the geologic formations below the paleosol layer, thereby reducing the suitability of a potential groundwater banking site.

## Geologic Structure

Tectonic forces acting on sedimentary deposits can create structures within a formation. Depending on their location and orientation, folds and faults can serve to isolate stored groundwater from the surrounding aquifer. Figure 3.1.1 depicts a situation where the presence of an anticline in folded sedimentary deposits could isolate stored groundwater from a gaining stream that conveys water away from aquifer storage. By separating Site B from the stream's influence, the anticline structure increases the suitability of that site relative to Site A.

**Figure 3.1.1: Influence of Geologic Structure on Geologic Suitability**



Groundwater banked at Site A, which is in proximity to a gaining stream, would be subject to higher losses than water banked at Site B, which is isolated from the stream by an anticline structure within the formation.

## 3.1.2 Geology Sub-Index Weighting Factors

Having described these parameters for each of the formations found below potential groundwater banking sites, we gave them a score on a scale from 0 to 10, with a score of 10 representing characteristics that would make a particular formation a suitable target for groundwater banking. Our scoring system is described in Table 3.1.1.

Having scored each of the parameters, a composite formation score was calculated based on Equation 3.1.

**Table 3.1.1: Parameter Weighting Factors Used to Calculate the Geology Sub-Index**

Component	0	5	10
Permeability	Impermeable	Moderately permeable	Highly permeable
Paleosols	Contains resistant paleosols	Contains some slightly resistant paleosols	No paleosols
Geologic Structure	Contains structural features that direct stored groundwater toward gaining streams	Contains no structural features	Contains structural features that isolate stored groundwater from gaining streams

$$\text{Formation Score} = 2 * (\text{Permeability}) + 0.5 * (\text{Paleosols}) + (\text{Geological Structure}) \quad (3.1)$$

Given the relative importance of permeability in terms of evaluating the suitability of a formation for groundwater banking, it was assigned a weighting factor of 2. The existence of paleosols was assigned a weighting coefficient of 0.5 because, although they can act as barriers to the vertical movement of water, they tend to be described as thin and discontinuous in the Central Valley. The geology sub-index values are calculated as the sum of the scores for each of the formations underlying a particular groundwater banking site, weighted by the relative formation thickness within the top several hundred feet of the sub-surface (Equation 3.2). In the Sacramento Valley, several stratified formations were often encountered; in the San Joaquin Valley, undifferentiated alluvial deposits were the norm.

$$\text{Geology Sub-Index} = \sum_A (\text{Formation Score}_A * \text{Formation Thickness}_A) \quad (3.2)$$

The preceding equations point out the role that weighting factors play in the calculation of the Hydrogeologic Suitability Index. Scores for both the parameters and the formations rely upon somewhat arbitrary weighting factors. When a formation is ranked as highly permeable, it receives a score twice as high as a moderately permeable formation, and that difference in score is multiplied by 2 in calculating the formation score. It is here that another individual interested in groundwater banking could apply a different set of weighting factors in the spreadsheet developed for this project.

## 3.2 Water Quality Sub-Index

If water is stored at a potential groundwater banking site, it will commingle with the native groundwater. The quality of this native water will influence the ultimate quality of water stored in and recovered from the aquifer (the quality of stored water will also influence the quality of water available to existing groundwater users). This sub-index attempts to compare sites in terms of the quality of groundwater found at potential sites.

### 3.2.1 Water Quality Sub-Index Parameters

Four water quality components were selected based on their importance to both urban and agricultural water users and on the availability of data for the potential groundwater banking sites: arsenic, boron, lead and total dissolved solids. These parameters were defined using USGS National Water Information System (NWIS) data collected after 1/1/1970.

#### *Arsenic (As)*

Arsenic is a micronutrient for humans. However, long-term exposure to high concentrations of arsenic in drinking water can lead to many dangerous health problems including at least 8 different types of cancer (EPA website, 2001). Arsenic contained in groundwater generally comes from the natural weathering of the local geologic materials, although it can also result from anthropogenic sources such as industrial waste, arsenical pesticides and smelting operations (De Zuane, 1997). The maximum contaminant level for As enforced by the EPA is 50 ppb (or 50 mg/L), though this standard is currently under review and may be lowered to 10 ppb (or 10 mg/L) (EPA website, 2001).

#### *Boron (B)*

Boron is a micronutrient required in small amounts by both humans and plants. However, if the concentration of boron in groundwater is too high, it can be toxic for many commercially important crops in California. In general, water used for irrigation of boron-sensitive crops should contain less than 1.0 mg/L (or 1000 mg/L) to prevent toxicity.

#### *Lead (Pb)*

Lead is a metal that can be found in drinking water as a result of natural weathering of local ore deposits. Lead is extremely hazardous and can cause a multitude of health problems including stroke, kidney disease and cancer. It also disrupts normal physical and mental development in infants and children (EPA website, 2001). Due to these extreme effects, the EPA maximum contaminant level for lead is zero; however, the action level at which clean-up takes place is 15 ppb (or 15 mg/L) due to current technological and resource-oriented constraints (EPA website, 2001).

#### *Total Dissolved Solids (TDS)*

TDS is not a trace element like the other water quality parameters, but is a measure of the concentration of inorganic salts (primarily Ca, Mg, K, Na, bicarbonates, chlorides and sulfates) and organic material dissolved in water (WHO, 1993). Although there are no specific health problems or regulations associated with high TDS levels, the generally accepted limit for

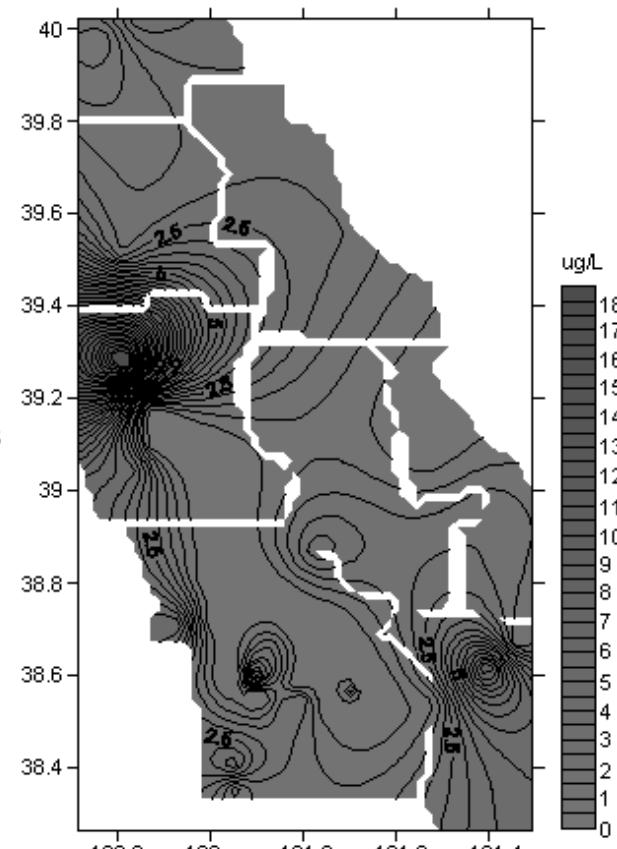
drinking water is 1000 mg/L (WHO, 1993). For TDS, the EPA sets the National Secondary Drinking Water Regulation, a non-enforceable guideline based on the cosmetic and aesthetic qualities of water, at 500 mg/l (EPA website, 2001).

Data gathered on each of these parameters (see the Water Quality portion of Section 7.0: References) reveal a fair amount of spatial variability across the Central Valley. As an example, measured lead concentrations in groundwater in the Sacramento Valley are shown in Figure 3.2.1. The most elevated levels were observed in Colusa and Sacramento Counties. Contour maps of the three other parameters reveal distinct patterns of spatial variability that could influence the selection of potential groundwater banking sites.

### 3.2.2 Water Quality Sub-Index Weighting Factors

The raw water quality data for the four parameters above is listed in Appendix A. In order to convert these raw parameter values into a water quality sub-index, a method for assigning parameter scores between 1 and 10 was developed. As with the geology sub-index parameters, a score of 10 corresponds with conditions most favorable to groundwater banking. Table 3.2.1 describes the scores assigned to distinct ranges of raw parameter values. In each case, a score of 5 corresponds with the EPA-recommended level.

**Figure 3.2.1: Lead Contour Map for the Sacramento Valley**



**Table 3.2.1: Parameter Weighting Factors Used to Calculate the Water Quality Sub-Index**

	Score	Arsenic µg/L		Boron µg/L		Lead µg/L		TDS mg/L					
Toxic	1	50.00	+	9000.00	+	15.00	+	1000.00	+				
	2	40.00	-	49.99	7000.00	-	8999.00	13.33	-	14.99	875.00	-	999.00
	3	30.00	-	39.99	5000.00	-	6999.00	11.67	-	13.32	750.00	-	874.00
	4	20.00	-	29.99	3000.00	-	4999.00	10.00	-	11.66	625.00	-	749.00
Recommended	5	10.00	-	19.99	1000.00	-	2999.00	8.33	-	9.99	500.00	-	624.00
	6	8.00	-	9.99	800.00	-	999.00	6.67	-	8.32	400.00	-	499.00
	7	6.00	-	7.99	600.00	-	799.00	5.00	-	6.66	300.00	-	399.00
	8	4.00	-	5.99	400.00	-	599.00	3.33	-	4.99	200.00	-	299.00
	9	2.00	-	3.99	200.00	-	399.00	1.67	-	3.32	100.00	-	199.00
	10	0.00	-	1.99	0.00	-	199.00	0.00	-	1.66	0.00	-	99.00

Scores for the individual parameters can be combined to calculate a composite water quality score, as in Equation 3.3. In this case no weighting factors have been employed, although

someone interested in a particular parameter could weight that constituent accordingly in the spreadsheet developed as part of this effort.

$$\text{Water Quality Score} = (\text{As Score}) + (\text{B Score}) + (\text{Pb Score}) + (\text{TDS Score}) \quad (3.3)$$

Below a particular groundwater banking site, two water quality scores may be of interest. The first corresponds with the water quality immediately below a potential groundwater banking site and reflects the short-term mixing between recharge water and native groundwater that occurs when they come into contact. Once a significant amount of recharge occurs and water is stored at a banking site for extended periods of time, the potential for longer-term mixing between stored water and the native groundwater extends over a much larger area. Over this time scale, it is the quality of the groundwater in the basin surrounding the potential banking site that is important. Using available data, basin groundwater quality scores were calculated by averaging all the data from the wells within the basin boundaries for a specific component. This same data was then used to create a contour map (similar to Figure 3.2.1) so the approximate water quality score at potential groundwater banking sites could be determined.

Our attempt to capture the full spectrum of potential mixing between banked water and native groundwater led us to define the two components of the water quality sub-index described in Equation 3.4.

$$\text{Water Quality Sub-Index} = 1.5 * (\text{Basin Score}) + (\text{Site Score}) \quad (3.4)$$

In this version of the water quality sub-index, the basin score was weighted more heavily than the site score. The heavier weighting on the basin score tends to stress the impact of long-term interactions between banked water and native groundwater. This is in keeping with the utility assigned to most banked groundwater in California—namely that it is to serve as a source of supplemental supply in the relatively infrequent dry and critical water years.

One final point that should be made regarding the water quality sub-index is that the data used to develop water quality contour maps come from wells screened at different depths. Ideally the vertical relationship between water quality observations should be considered along with their relative horizontal positions. We made an attempt to limit the vertical extent of water quality observations by excluding any samples that were noted as having been taken from below the Corcoran Clay in the San Joaquin Valley. As the screened interval in most sampled wells is neither known nor reported, it was difficult to introduce the vertical dimension into our water quality contour maps. Any attempt to screen the samples by depth would have proved much too expensive and time consuming to be undertaken in the current effort. This is another area where more specific analysis of potential sites will be required once the field of potential groundwater banking sites has been thinned.

### 3.3 Soils Sub-Index

Soil characteristics exert a potentially important control on the overall hydrogeologic suitability of potential groundwater banking projects employing recharge ponds, since the physical properties of the soil profile may limit the percolation rate. Sites with low percolation rates will require larger basins in order to recharge a given volume of water, thereby increasing the overall cost of the project. If the soil chemistry at a site is poor, the quality of banked water might be degraded as it percolates from the recharge basin. In the extreme, problematic soils could be removed from a potential site prior to the construction of recharge basins. However, this would greatly increase the overall cost of the project, potentially making it less attractive with respect to other alternatives.

#### 3.3.1 Soils Sub-Index Parameters

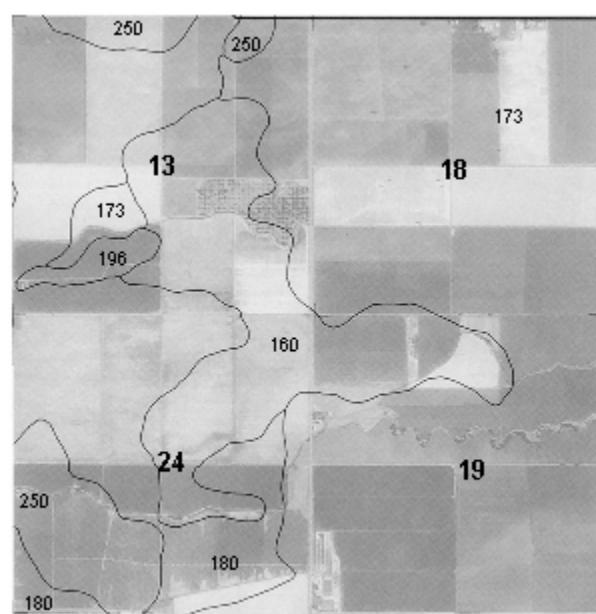
The main data source used to define parameters for this sub-index was the USDA soil survey series for California (see the Soils portion of Section 7.0: References). Each volume of the series covers an area of California (typically a single county) and is composed primarily of detailed maps showing aerial photographs overlaid by the delineation of soils found in the area. An example (Figure 3.3.1) is an excerpt from the [Soil Survey of San Joaquin County, California](#) (McElhiney, 1992). The large font numbers that appear on the figure (13, 18, 24, 19) are the township and range sections associated with the California Public Lands Survey. The small number found within each soil polygon correlates to a soil type and a series of soil parameters. For example, 180 represents an area covered by Jackstone clay.

From the extensive list of parameters reported for each soil type, we selected four that we feel capture the impacts that the physical and chemical properties of a soil can exert on groundwater banking via recharge ponds: soil thickness, soil permeability, soil pH and the presence or absence of hardpans. These parameters were evaluated for each soil type encountered at potential groundwater banking sites according to the approach described in the following paragraphs.

##### *Thickness*

Each soil's thickness was recorded in inches and normalized relative to the maximum soil thickness encountered at the full suite of potential groundwater banking sites to generate a soil thickness score between 0 and 1. A thick soil will magnify any negative effects on percolation or water quality encountered as water flows through the soil column to the underlying aquifer. Similarly, a thick soil will magnify positive soil characteristics.

**Figure 3.3.1: Soil Survey Map of Mormon Slough (McElhiney, 1992)**



### *Permeability*

Soil permeability is a measure of how easily and quickly water moves through a soil. The USDA soil surveys report permeability in a range in inches of water per hour. We took the average value of the range reported for each soil type encountered at the each of the potential groundwater banking sites and normalized it to arrive at a score between 0 and 1, where a value of 1 is desirable. In cases where no specific permeability value was provided, the permeability was estimated as a function of soil structure and clay content as per the National Soil Survey Handbook (USDA, 1999).

### *pH*

Soil pH is a measure of the acidity of a soil. The USDA assigns categories to pH levels, and we assigned numerical values to the categories in order to include them in the soils sub-index, as shown below in Table 3.3.1. In this case, a neutral pH of 7 corresponds with component score of 1. Increasingly acidic and alkaline soils are awarded decreasing parameter scores. While not a perfect predictor for the types of chemical transformation water percolating from a recharge pond will undergo, pH is a good proxy for a number of potential water quality problems in the soil.

**Table 3.3.1: pH Rating Scale**

pH reading	USDA category	Suitability Index
3.5 - 4.4	Extremely acid	0
4.5 - 5.0	Very strongly acid	0.2
5.1 - 5.5	Strongly acid	0.4
5.6 - 6.0	Moderately acid	0.6
6.1 - 6.5	Slightly acid	0.8
6.6 - 7.3	Neutral	1.0
7.4 - 7.8	Slightly alkaline	0.8
7.9 - 8.4	Moderately alkaline	0.6
8.5 - 9.0	Strongly alkaline	0.4
9.1 - 11.0	Very strongly alkaline	0.2

### *Hardpan*

Each soil description was checked to see if the presence of a hardpan was reported. A hardpan can impede the percolation of water below a recharge pond, limiting the suitability of a potential project site. If a hardpan was present, a parameter score of 0 was assigned. If there was no hardpan occurrence, then a value of 1 was assigned.

The raw soil data is available in Appendix B. As can be expected when gathering data from diverse sources, not all soil surveys reported the same soil parameters. When a particular piece of data, such as permeability, was not available for a soil type, we attempted to locate the value in a soil survey for an adjacent county before invoking any other approximation method. We will point out where we were forced to approximate a soil parameter in later sections dealing with specific potential groundwater banking sites.

### 3.3.2 Soils Sub-Index Weighting Factors

Once the parameter scores were developed for each of the soil types at the potential groundwater banking sites, a weighted average parameter score was calculated based on the area of each soil type overlying potential project sites. The area data is available in Appendix C. This produced a score for each site for each of the four soil parameters. The soils sub-index was calculated by applying the weighting factors shown in the following equation:

$$\text{Soils Sub-Index} = (\text{Thickness}) * (3 * [\text{Permeability}] + [\text{pH}] - 2 * [1 - \text{Hardpan}]) \quad (3.5)$$

In Equation 3.5, permeability was weighted by a factor of 3 and hardpan by a factor of 2 to stress the importance of these components on the ability of water to percolate below recharge basins. Since potentially constraining soil parameters are subtracted in Equation 3.5, it is possible to arrive at negative sub-index values. Once again, another individual interested in groundwater banking could apply a different set of weighting factors in the spreadsheet developed for this project.

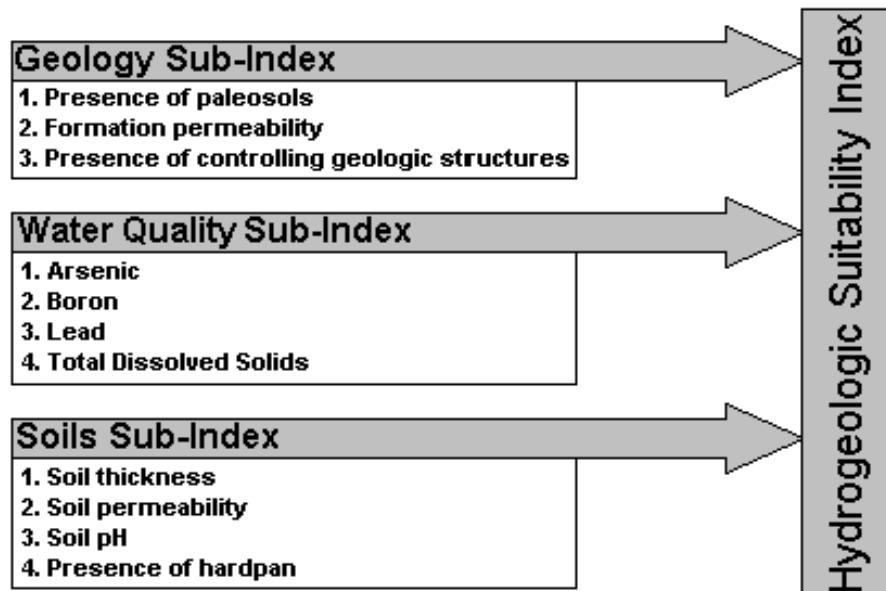
### 3.4 Application of the Core Hydrogeologic Suitability Index

The sub-indices presented in the previous sections constitute the core of the Hydrogeologic Suitability Index that will be applied to potential groundwater banking sites in both the Sacramento and San Joaquin Valleys. A separate sub-index based on the temporal evolution of the elevation of the water table is applied only in the San Joaquin Valley. Details of this sub-index are presented in Section 5.0 dealing with the application of the index in that region.

## 4.0 Application of the Hydrogeologic Suitability Index in the Sacramento Valley

As mentioned previously, differences in the hydrologic conditions between the Sacramento and San Joaquin Valleys prompted our decision to apply the Hydrogeologic Suitability Index separately in the two regions. In the Sacramento Valley, a core index that includes sub-indices related to geology, groundwater quality and soils has been applied. Figure 4.0.1 provides a summary flow chart of the information used to develop each of the sub-indices and the overall Hydrogeologic Suitability Index. Descriptions of each of the parameters presented in Figure 4.0.1 are given in Section 3.0, along with a proposed methodology for assigning parameter scores. The following sections present the data used to calculate the sub-indices for each of the potential Sacramento Valley groundwater banking sites shown in Figure 2.0.1.

**Figure 4.0.1: Flow Chart of Parameters Analyzed in the Development of Relevant Sub-Indices and the Overall Hydrogeologic Suitability Index in the Sacramento Valley**



## 4.1 Sacramento Valley Geology Sub-Index

In Section 3.1.1, the geology sub-index parameters were discussed. These parameters are permeability, the presence of paleosols, and the presence of any controlling geologic structures. The methodology used to create a weighted average of parameter scores based on the thickness of the formations encountered at a given site was also presented in Equation 3.2. The influence of formation thickness is a particularly important issue in the Sacramento Valley because although there is a tendency to think of Sacramento Valley groundwater in terms of a homogeneous underground reservoir that fluctuates gradually with wet and dry cycles, the reality is more complex. While much of the Sacramento Valley groundwater basin is interconnected, aquifer structure is far from uniform (DWR, 1998). Considering the properties of only the uppermost formation would miss many important controls that this complex geology could exert on the groundwater banking operations using recharge ponds. The vertical sequence of formations must be taken into consideration along with their horizontal extent.

### Geology Sub-Index Equation Key

$$\text{Eq. 3.1: Formation Score} = 2 * (\text{Permeability}) + 0.5 * (\text{Paleosols}) + (\text{Geological Structure})$$

$$\text{Eq. 3.2: Geology Sub-Index} = \sum (\text{Formation Score}_A * \text{Formation Thickness}_A)$$

### 4.1.1 Results of the Sacramento Valley Geology Sub-Index

Table 4.1.1 contains a list of the geologic formations encountered below the potential groundwater banking sites identified for the Sacramento Valley. The table also includes the parameter scores assigned to the formations in terms of permeability, paleosols and geologic structures. The formation scores, as calculated using Equation 3.1, are listed in the Rank column. These scores are then normalized between 0 and 1 according to their relative position between the formation with the highest (Stony Creek Fan with a score of 32) and lowest (Mehrten, Flood Basin Deposits and South Fork Gravels with scores of 14) ranks. The normalized ranks are found in the % column.

**Table 4.1.1: Scores for Formations Found in the Sacramento Valley**

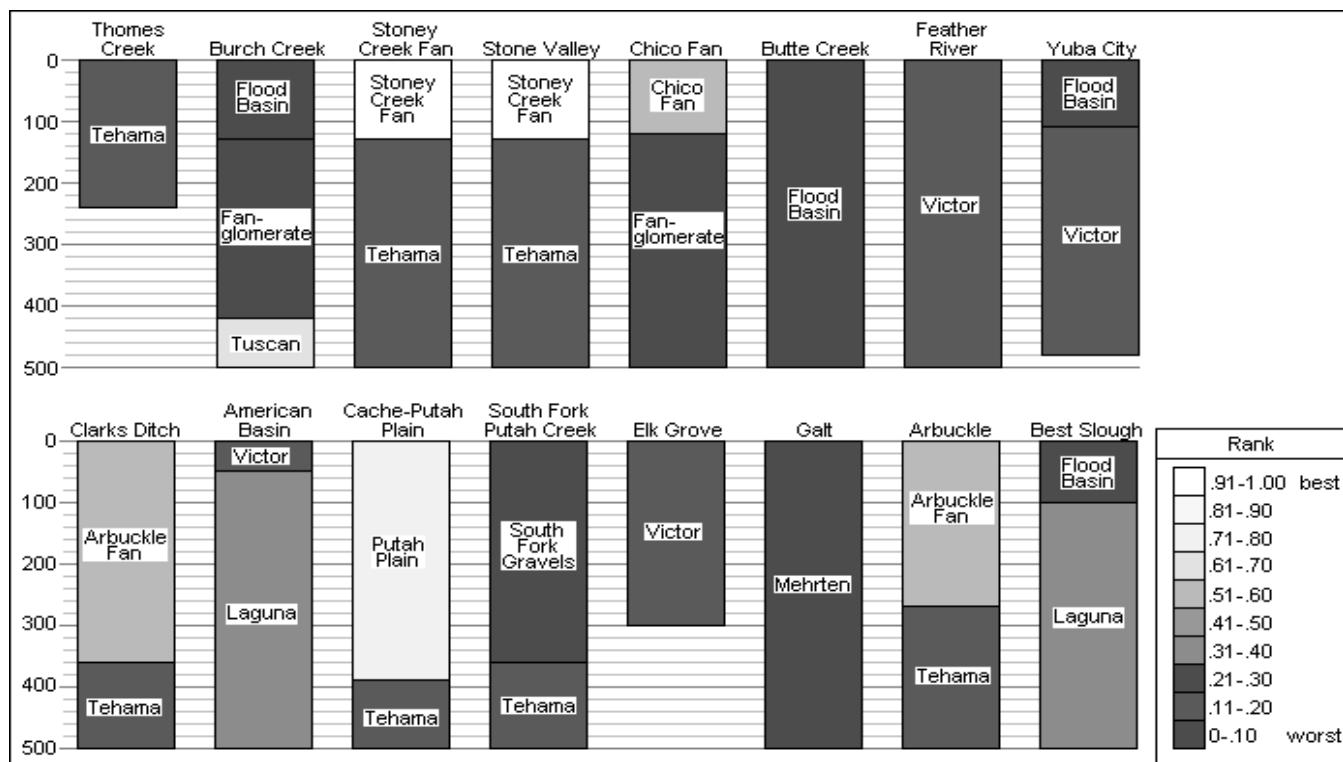
<b>Formation</b>	<b>Weighting Coefficient</b>	0.5	2	1	<b>Rank</b>	<b>%</b>
		<b>Paleosols</b>	<b>Permeability</b>	<b>Geo. Strct.</b>		
Stony Creek Fan	10	8.5		10	32	1.00
Putah Plain	10	6		10	27	0.72
Tuscan	0	10		5	25	0.61
Arbuckle Fan	10	7		5	24	0.56
Chico Fan	10	7		5	24	0.56
Laguna	10	5		5	20	0.33
Victor	0	6		5	17	0.17
Tehama	10	3		5	16	0.11
Fanglomerate	10	2.5		5	15	0.06
Mehrten	10	2		5	14	0.00
Flood Basin	10	2		5	14	0.00
South Fork Gravels	10	2		5	14	0.00

Having ranked the various formations encountered in the Sacramento Valley, we examined the vertical stratification of these units below each of the potential groundwater banking sites located in the Sacramento Valley (as shown in Figure 2.0.1). The formations encountered, which have been color coded according to their formation scores, are shown in Figure 4.1.1. If a program of groundwater banking is based on the use of recharge ponds, then the sequence of formations down from the ground surface at a potential site is critical. If a formation that is poorly suited to groundwater banking overlies one with attractive geologic properties, the opportunity for groundwater banking using recharge ponds is constrained by the poorly suited upper formation. In applying Equation 3.2, the formation sequence was taken into consideration.

Table 4.1.2 contains a list of the potential groundwater banking sites in the Sacramento Valley with the sequence of formations encountered down to a depth of 500 feet listed to the right, along with the formation score and local thickness. The geology sub-index is calculated by applying Equation 3.2 down to and including the first formation that overlies one with a higher score. For example, at the American Basin site, where the Victor Formation with a score of 0.17 overlies the Laguna Formation with a score of 0.33, only the properties and thickness of the overlying Victor Formation are considered in calculating the geology sub-index. This calculation has been carried out based on three assumed operational depths for the proposed groundwater banking projects: 100 ft., 300 ft. and 500 ft.

Figures 4.1.2 through 4.1.4 graphically present the rank associated with each potential site in terms of the geology sub-index under different assumptions regarding operational depth.

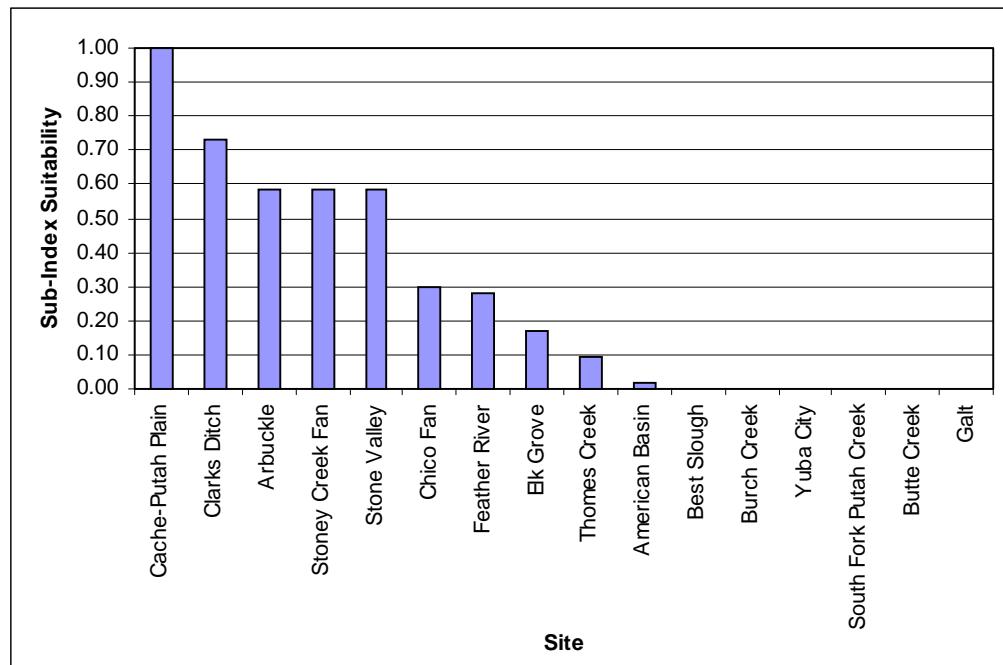
**Figure 4.1.1: Vertical Stratification of Formations Encountered at Potential Groundwater Banking Sites in the Sacramento Valley**



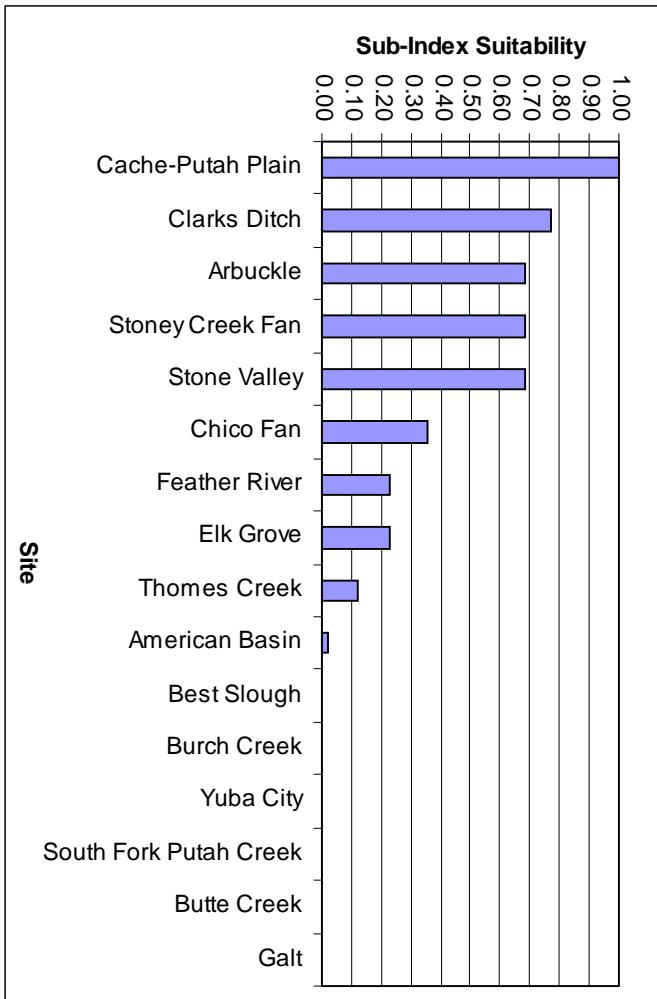
**Table 4.1.2: Geology Sub-Index Values Calculated for Potential Groundwater Banking Sites in the Sacramento Valley**

Site	Formation 1		Formation 2		Formation 1		Operational Depth								
	Formation	Score	Thickness	Formation	Score	Thickness	Formation	Score	Thickness	500 ft	300 ft	100 ft	Score	Normal	
										Score	Normal	Score	Normal	Score	Normal
Cache-Putah Plain	Putah Plain	0.72	390	Tehama	0.11	110				293.9	1.00	216.7	1.00	72.2	0.72
Clarks Ditch	Arbuckle Fan	0.56	360	Tehama	0.11	140				215.6	0.73	166.7	0.77	55.6	0.56
Arbuckle	Arbuckle Fan	0.56	260	Tehama	0.11	240				171.1	0.58	148.9	0.69	55.6	0.56
Stoney Creek Fan	Stony Creek Fan	1.00	130	Tehama	0.11	370				171.1	0.58	148.9	0.69	100.0	1.00
Stone Valley	Stony Creek Fan	1.00	130	Tehama	0.11	370				171.1	0.58	148.9	0.69	100.0	1.00
Chico Fan	Chico Fan	0.56	120	Fanglomerate	0.06	380				87.8	0.30	76.7	0.35	55.6	0.56
Feather River	Victor	0.17	500							83.3	0.28	50.0	0.23	16.7	0.17
Elk Grove	Victor	0.17	300							50.0	0.17	50.0	0.23	16.7	0.17
Thomes Creek	Tehama	0.11	240							26.7	0.09	26.7	0.12	11.1	0.11
American Basin	Victor	0.17	30	Laguna	0.33	470				5.0	0.02	5.0	0.02	5.0	0.05
Best Slough	Flood Basin	0.00	100	Laguna	0.33	400				0.0	0.00	0.0	0.00	0.0	0.00
Burch Creek	Flood Basin	0.00	130	Fanglomerate	0.06	280	Tuscan	0.61	90	0.0	0.00	0.0	0.00	0.0	0.00
Yuba City	Flood Basin	0.00	100	Victor	0.17	400				0.0	0.00	0.0	0.00	0.0	0.00
S. Fork Putah Creek	S. Fork Gravels	0.00	360	Tehama	0.11	140				0.0	0.00	0.0	0.00	0.0	0.00
Butte Creek	Flood Basin	0.00	500							0.0	0.00	0.0	0.00	0.0	0.00
Galt	Mehrten	0.00	500							0.0	0.00	0.0	0.00	0.0	0.00

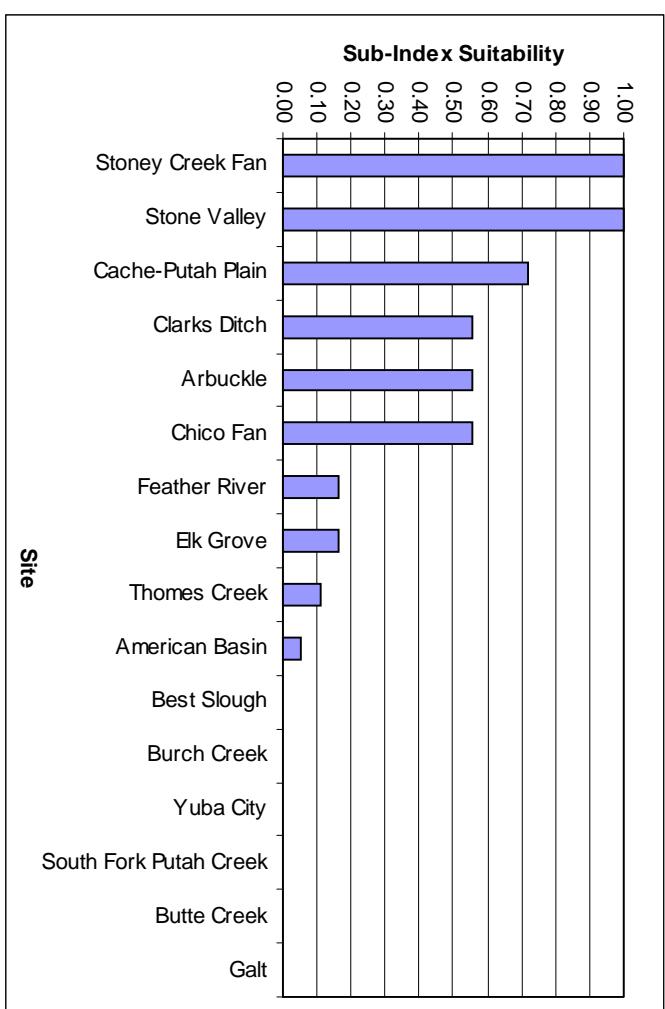
**Figure 4.1.2: Sacramento Valley Geology Sub-Index Values Assuming an Operational Depth of 500 Feet**



**Figure 4.1.3: Sacramento Valley Geology Sub-Index Values Assuming an Operational Depth of 300 Feet**

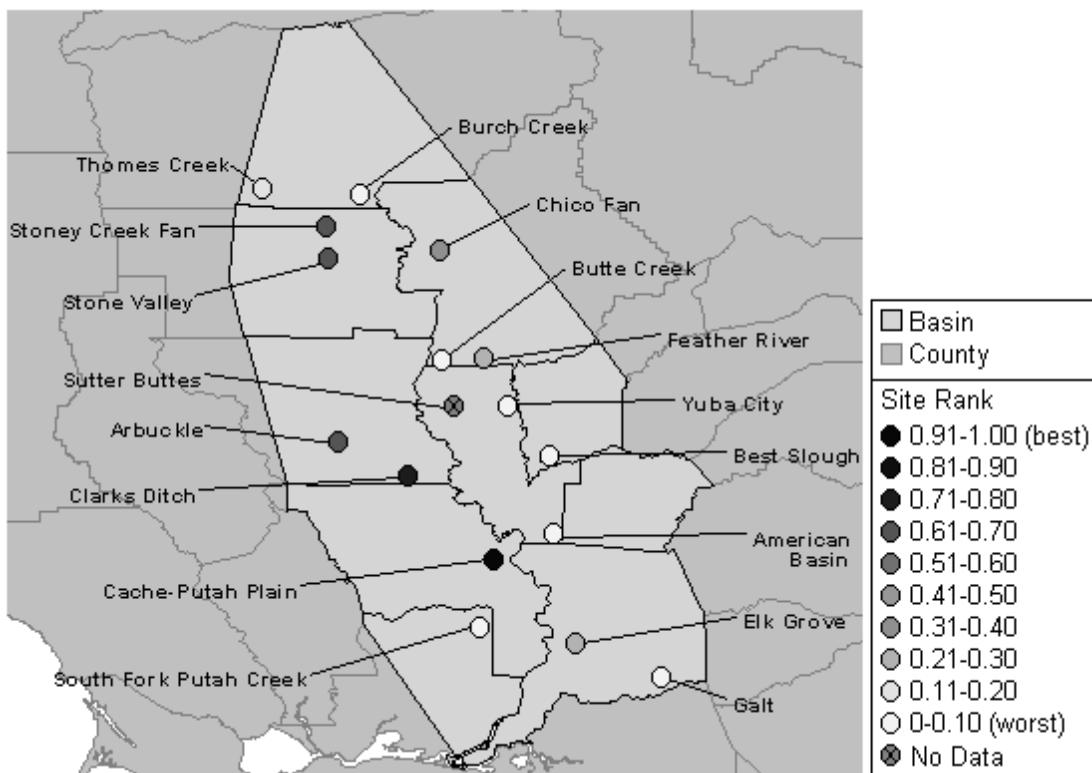


**Figure 4.1.4: Sacramento Valley Geology Sub-Index Values Assuming an Operational Depth of 100 Feet**



In calculating the overall Hydrogeologic Suitability Index for sites in the Sacramento Valley, geology sub-index values based on an assumed operational depth of 300 ft. are employed. Figure 4.1.5 displays the site comparison of the potential groundwater banking sites with respect to the 300 ft. depth rank.

**Figure 4.1.5: Spatial Distribution of 300 Ft. Depth Geology Sub-Index Values Across Potential Groundwater Banking Sites in the Sacramento Valley**



#### 4.1.2 Comments on the Geology Sub-Index

Several interesting observations emerge from the results of the geology sub-index. First, sites in the western Sacramento Valley (e.g., Stony Creek Fan, Arbuckle Fan, Cache-Putah Plain) provide excellent geologic settings for groundwater banking. This is an important discovery because the aquifers underlying these sites are generally full. As such, groundwater banking would require some level of enhanced groundwater pumping in order to create the space required for storing banked groundwater—a management sequence that raises legitimate concerns on the part of overlying groundwater users. The relative superiority of these sites in terms of the geology, however, suggest that it may be worth the effort to design the legal and institutional arrangements needed to make these sorts of projects viable.

Sites located in the central and eastern portions of the Sacramento Valley generally fare less well in terms of the geology sub-index. This is due to the prevalence of flood basin deposits and the Victor Formation in the upper portion of the stratigraphic column below these sites. While more

promising formations often lie below these units, access to them via recharge basins will be constrained by the less suitable overlying formations. These are areas where groundwater banking via injection wells or *in lieu* arrangements may be the preferred alternative.

## 4.2 Sacramento Valley Water Quality Sub-Index

As mentioned in Section 3.2, the water quality sub-index was based on the reported concentrations in groundwater of four parameters: arsenic, boron, lead and total dissolved solids.

### Water Quality Sub-Index Equation Key

**Eq. 3.3:** Water Quality Score = [As Score] + [B Score] + [Pb Score] + [TDS Score]

**Eq. 3.4:** Water Quality Sub-Index = 1.5\*[Basin Score] + [Site Score]

### 4.2.1 Results of the Sacramento Valley Water Quality Sub-Index

For each of the basins in the Sacramento Valley (see Figure 2.0.1), the average of all observations was used to assign a parameter score according to Table 3.2.1. The total water quality scores (in the Rank column), calculated using Equation 3.3, and normalized values between 0 and 1 (in the % column), are shown in Table 4.2.1.

**Table 4.2.1: Water Quality Scores for Basins in the Sacramento Valley**

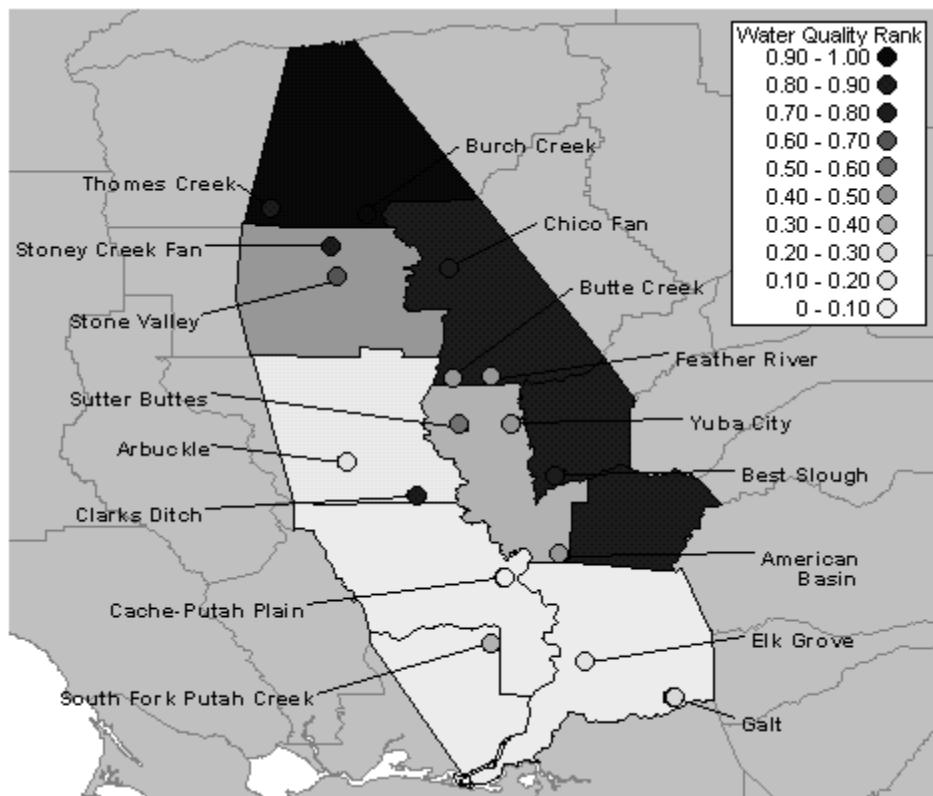
Weighting Coefficient	1	1	1	1	Rank	%
Basin Name	As	B	Pb	TDS		
Tehama	10	9	10	8	37	1.00
Yuba	9	10	10	8	37	1.00
Butte	9	10	9	8	36	0.86
Placer	9	8	10	8	35	0.71
Glenn	8	10	9	7	34	0.57
Sutter	7	10	9	7	33	0.43
Colusa	9	9	8	6	32	0.29
Solano	9	8	10	5	32	0.29
Sacramento	7	10	8	8	31	0.14
Yolo	9	5	10	6	30	0.00

Based on contour maps developed from the available data in each basin, estimated concentrations, parameter scores and normalized values between 0 and 1 were developed for each of the potential Sacramento Valley groundwater banking sites (Table 4.2.2).

The information in both Tables 4.2.1 and 4.2.2 is displayed spatially in Figure 4.2.1.

**Table 4.2.2: Water Quality Scores for Sites in the Sacramento Valley**

Weighting Coefficient	1	1	1	1	Rank	%
Site Name	As	B	Pb	TDS		
Burch Creek	10	10	10	9	39.00	1.00
Clarks Ditch	10	10	10	8	38.00	0.89
Stoney Creek Fan	10	10	10	8	38.00	0.89
Thomes Creek	10	10	10	8	38.00	0.89
Best Slough	9	10	10	8	37.00	0.78
Chico Fan	10	10	9	8	37.00	0.78
Stone Valley	9	10	9	8	36.00	0.67
Sutter Buttes	6	10	10	9	35.00	0.56
American Basin	7	10	9	8	34.00	0.44
Butte Creek	7	10	9	8	34.00	0.44
Feather River	7	10	10	7	34.00	0.44
Yuba City	6	10	10	8	34.00	0.44
South Fork Putah Creek	8	8	10	7	33.00	0.33
Galt	6	10	8	8	32.00	0.22
Arbuckle	9	6	8	8	31.00	0.11
Elk Grove	5	10	9	7	31.00	0.11
Cache-Putah Plain	8	5	10	7	30.00	0.00

**Figure 4.2.1: Spatial Distribution of Basin and Site Water Quality Scores**

Based on the water quality scores presented in Tables 4.2.1 and 4.2.2, the water quality sub-index for potential groundwater banking sites in the Sacramento Valley was calculated according to Equation 3.4. These scores were normalized between 0 (corresponding with the poorest groundwater quality at the Cache Putah Plain site) and 1 (corresponding with the best groundwater quality observed at the Burch Creek site). The results are shown in Table 4.2.3.

**Table 4.2.3: Water Quality Sub-Index Values for Potential Groundwater Banking Sites in the Sacramento Valley**

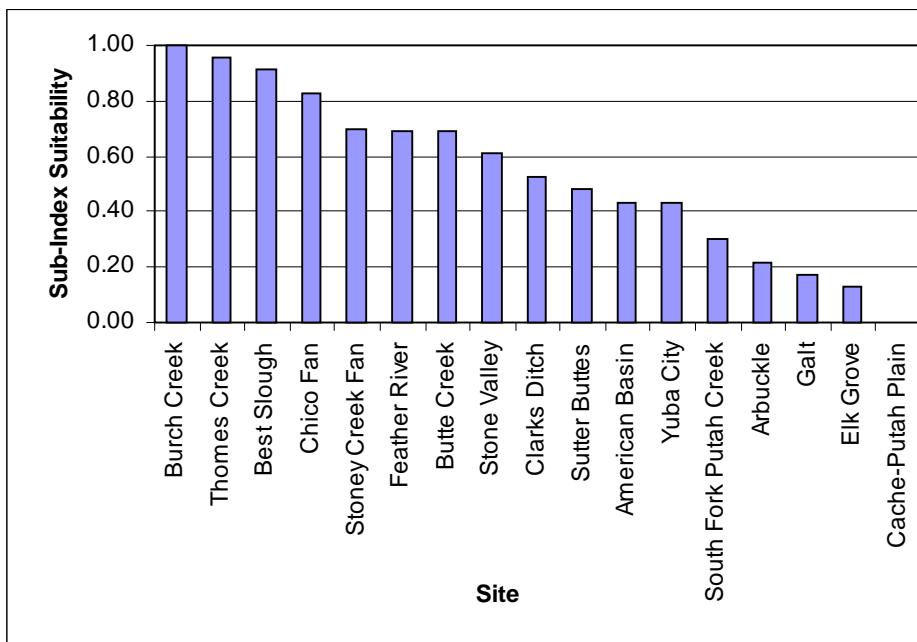
Site Name	Basin	1.5	1		
		Basin Wide	Site Specific	Rank	%
Thomes Creek	Tehama	1.00	0.89	2.39	0.96
Burch Creek	Tehama	1.00	1.00	2.50	1.00
Stoney Creek Fan	Glenn	0.57	0.89	1.75	0.70
Stone Valley	Glenn	0.57	0.67	1.52	0.61
Elk Grove	Sacramento	0.14	0.11	0.33	0.13
Butte Creek	Butte	0.86	0.44	1.73	0.69
Feather River	Butte	0.86	0.44	1.73	0.69
Chico Fan	Butte	0.86	0.78	2.06	0.83
American Basin	Sutter	0.43	0.44	1.09	0.43
Galt	Sacramento	0.14	0.22	0.44	0.17
Arbuckle	Colusa	0.29	0.11	0.54	0.22
Sutter Buttes	Sutter	0.43	0.56	1.20	0.48
Yuba City	Sutter	0.43	0.44	1.09	0.43
Clarks Ditch	Colusa	0.29	0.89	1.32	0.53
Cache-Putah Plain	Yolo	0.00	0.00	0.00	0.00
South Fork Putah Creek	Solano	0.29	0.33	0.76	0.30
Best Slough	Yuba	1.00	0.78	2.28	0.91

Figures 4.2.2 and 4.2.3 present the value of the water quality sub-index for potential banking sites in the Sacramento Valley derived from available data in terms of relative rank and spatial distribution, respectively.

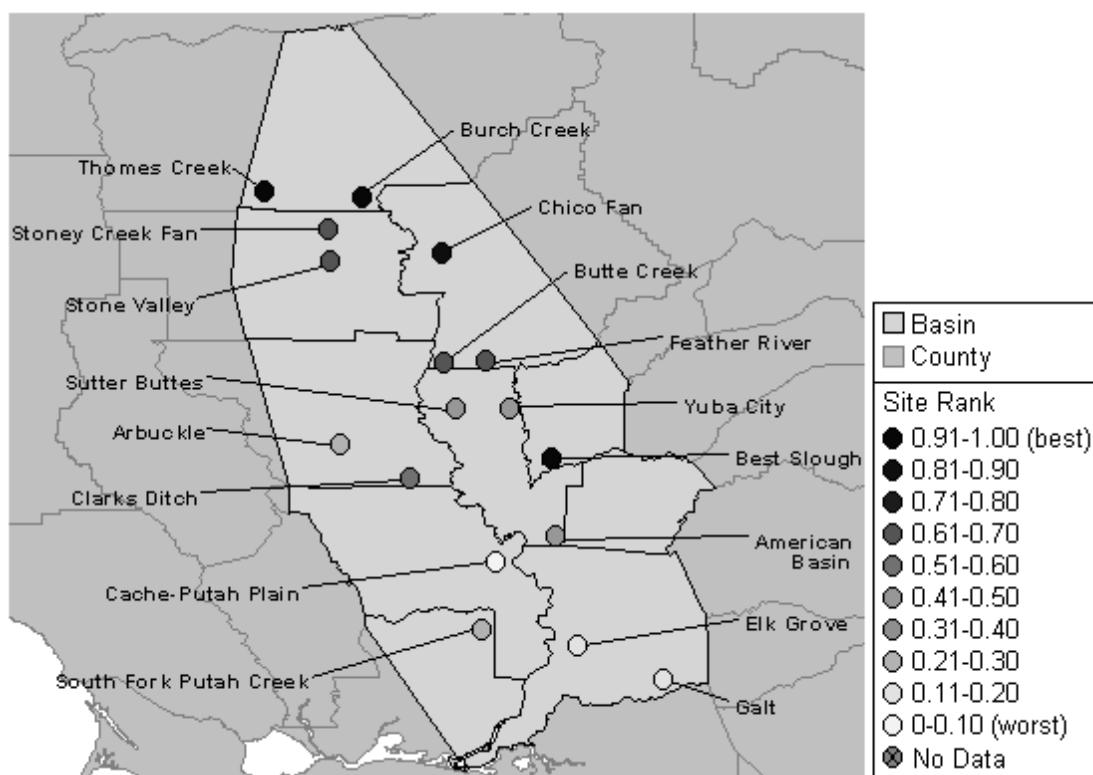
#### 4.2.2 Comments on the Water Quality Sub-Index

It is worth noting that the water quality of all sites in the Sacramento Valley is fairly good. However, boron does reach the recommended maximum level for boron-sensitive crops in the Cache-Putah Plain site and is also rather high in the Arbuckle region. There appears to be an area of increased arsenic levels in the northeast part of the valley, though these levels are still below the recommended levels and far below toxicity. Lead levels are very low in the Sacramento Valley, though anything over zero is considered too much by EPA standards. TDS is also very low, though levels seem to rise toward the south. While the Hydrogeologic Suitability Index is applied separately to sites in the Sacramento and San Joaquin Valleys, the relatively good quality of groundwater in the Sacramento Valley suggests that sites in this region are worthy of consideration despite the fact that little or no aquifer storage space currently exists in this region.

**Figure 4.2.2: Water Quality Sub-Index Ranking for Potential Groundwater Banking Sites in the Sacramento Valley**



**Figure 4.2.3: Spatial Distribution of Water Quality Sub-Index Values Across Potential Groundwater Banking Sites in the Sacramento Valley**



### 4.3 Sacramento Valley Soils Sub-Index

The soils sub-index was calculated as described in Section 3.3. The soil types under a site were identified, evaluated and scored based on the four soil parameters: thickness, pH, permeability and hardpan. The soils sub-index was not calculated directly for several of the sites in the Sacramento Valley owing to a lack of an available soil survey. These sites are listed in Table 4.3.1. For these sites, treatment of the soil sub-index in the calculation of the overall Hydrogeologic Suitability Index is discussed in Section 4.4.

**Table 4.3.1: Soil Sites Lacking Available Soil Surveys**

Site	Basin
Chico Fan	Butte
Butte Creek	Butte
Feather River	Butte
Arbuckle	Colusa
Clarks Ditch	Colusa

#### 4.3.1 Results for the Sacramento Valley Soils Sub-Index

The soils sub-index values that were calculated using Equation 3.5 are shown in Table 4.3.2, in the column entitled “Rank.” Normalized values between 1 (corresponding to the Sutter Buttes site) and 0 (corresponding with the Elk Grove site) are listed in the % column. These results are displayed graphically in terms of their rank and their spatial distribution in Figures 4.3.1 and 4.3.2, respectively.

#### Soil Sub-Index Equation Key

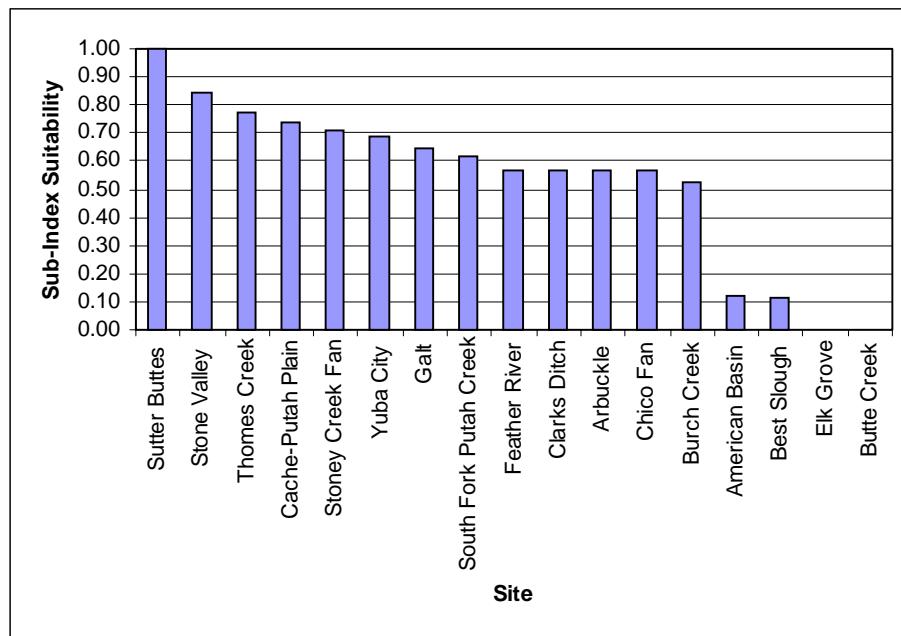
**Eq. 3.5:** Soils Sub-Index = (Thickness) [3(Permeability) + (pH) – 2(1 – Hardpan)]

**Table 4.3.2: Soils Sub-Index Values for Potential Groundwater Banking Sites in the Sacramento Valley**

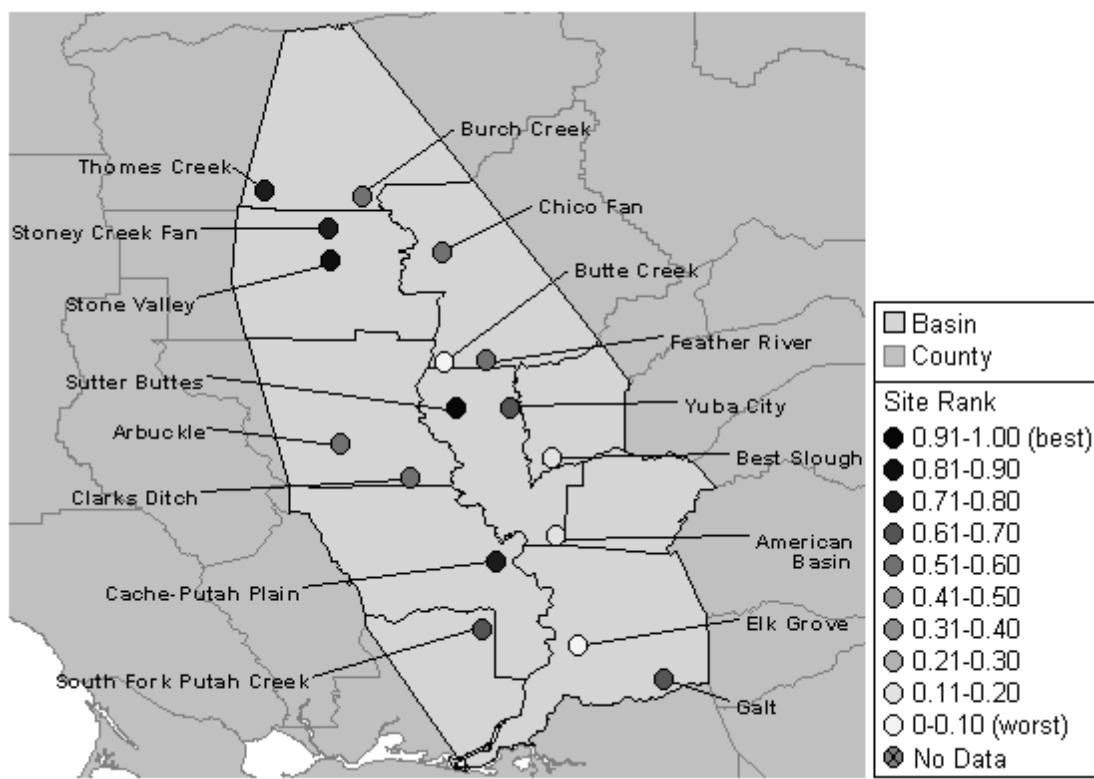
Site	Weighting Coefficient	1	3	2	1	Rank	%
		Thickness	Permeability	Hardpan	pH		
Thomes Creek	0.70	0.13	1.00	0.65	1.75	0.78	
Stoney Creek Fan	0.75	0.14	0.86	0.71	1.58	0.71	
Stone Valley	0.73	0.13	1.00	0.81	1.92	0.85	
Sutter Buttes	0.41	0.33	1.00	0.90	2.32	1.00	
Galt	0.78	0.08	0.95	0.51	1.41	0.64	
Cache-Putah Plain	0.40	0.22	0.96	0.65	1.64	0.73	
Yuba City	0.54	0.07	1.00	0.78	1.53	0.69	
South Fork Putah Creek	0.66	0.01	1.00	0.65	1.34	0.62	
American Basin	0.75	0.08	0.16	0.80	0.09	0.12	
Best Slough	0.50	0.06	0.31	0.77	0.07	0.11	
Elk Grove	0.75	0.08	0.00	0.79	-0.21	0.07	
Burch Creek	0.60	0.11	0.77	0.65	1.11	0.52	

To estimate the soils sub-index for the sites lacking the soil survey data needed for sub-index Equation 3.5, the agricultural crops grown on these sites were identified. Two types of crops were identified on the five sites in Table 4.3.1. The Butte Creek site cultivated rice, which requires clayey soils with extremely low permeabilities. These types of soils are not appropriate for groundwater banking, as discussed in Section 3.3.1, so Butte Creek was given a soils sub-index value of zero. The other four sites from Table 4.3.1 were mainly composed of orchards, which indicate a more average loamy soil with moderate permeability. The score for these sites was calculated by averaging the sub-index scores shown in Table 4.3.2, arriving at an estimated score of 0.56. Figure 4.3.1 shows these estimated values in relation to the values displayed in Table 4.3.2.

**Figure 4.3.1: Soils Sub-Index Ranking for Potential Groundwater Banking Sites in the Sacramento Valley**



**Figure 4.3.2: Spatial Distribution of Soils Sub-Index Values Across Potential Groundwater Banking Sites in the Sacramento Valley**



#### 4.3.2 Comments on the Soils Sub-Index

Areas with highly desirable soil characteristics are found primarily in the northern and western regions of the valley. Unfortunately, actual data were not available for much of Butte and Colusa Counties and had to be estimated. The Excel project that accompanies this report would be an appropriate place to input more specific soil data for these sites, should this information become available.

## 4.4 Sacramento Valley Hydrogeologic Suitability Index

Having evaluated the sites in terms of three relevant sub-indices, we combined the sub-indices to derive the overall Hydrogeologic Suitability Index. The overall index of suitability in the Rank column in Table 4.4.1 was arrived at by applying Equation 4.1.

$$\text{Hydrogeologic Suitability Index} = 2*(\text{Geology}) + 2*(\text{Water Quality}) + (\text{Soils}) \quad (4.1)$$

In this analysis, the geology and water quality sub-indices are weighted by 2 to stress their importance. The characteristics of the underlying formations determine whether water can be stored in an aquifer, and the water quality of the area is crucial if stored water is to be used for agriculture and urban uses. Soils are not weighted as high because problematic soils can be removed as part of project construction, although this would increase the overall cost of the project.

### 4.4.1 Results for the Sacramento Valley Hydrogeologic Suitability Index

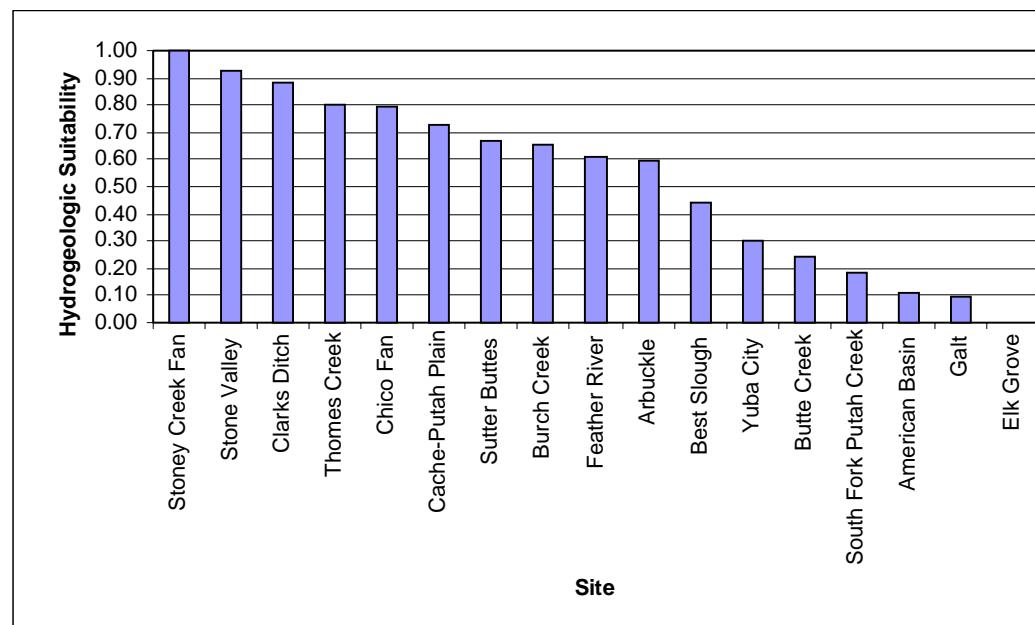
Table 4.4.1 shows the overall Hydrogeologic Suitability Index. Values were normalized between 1 (corresponding to the most suitable site at Stoney Creek Fan) and 0 (corresponding with Elk Grove) in the % column.

The overall Hydrogeologic Suitability Index values for sites in the Sacramento Valley are displayed graphically in terms of their rank and their spatial distribution in Figures 4.4.1 and 4.4.2, respectively.

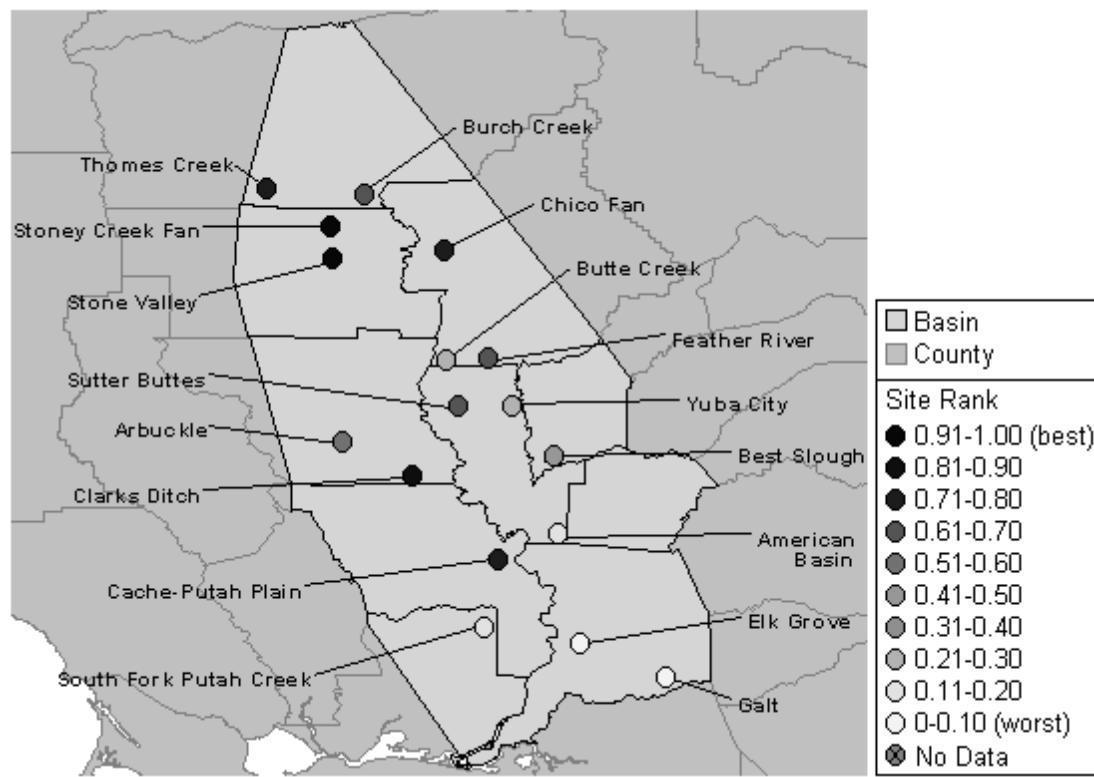
**Table 4.4.1: Sacramento Valley Hydrogeologic Suitability Index**

Weighting Coefficient <b>Site</b>	2 <b>Geology</b>	2 <b>Water Quality</b>	1 <b>Soils</b>	<b>Rank</b>	<b>%</b>
Stoney Creek Fan	0.69	0.70	0.71	3.48	1.00
Thomes Creek	0.12	0.96	0.78	2.93	0.80
Stone Valley	0.69	0.61	0.85	3.28	0.93
Chico Fan	0.35	0.83	0.56*	2.92	0.80
Arbuckle	0.69	0.22	0.56*	2.37	0.60
Cache-Putah Plain	1.00	0.00	0.73	2.73	0.73
Feather River	0.23	0.69	0.56*	2.41	0.61
Galt	0.00	0.17	0.64	0.99	0.10
Elk Grove	0.23	0.13	0.00	0.72	0.00
Clarks Ditch	0.77	0.53	0.56*	3.16	0.88
American Basin	0.02	0.43	0.12	1.03	0.11
Sutter Buttes	0.30*	0.48	1.00	2.56	0.67
Yuba City	0.00	0.43	0.69	1.56	0.30
Butte Creek	0.00	0.69	0.00*	1.38	0.24
South Fork Putah Creek	0.00	0.30	0.62	1.23	0.18
Best Slough	0.00	0.91	0.11	1.94	0.44
Burch Creek	0.00	1.00	0.52	2.52	0.65

**Figure 4.4.1: Hydrogeologic Suitability Index Ranking for Potential Groundwater Banking Sites in the Sacramento Valley**



**Figure 4.4.2: Spatial Distribution of the Hydrogeologic Suitability Index Values Across Potential Groundwater Banking Sites in the Sacramento Valley**



#### 4.4.2 Comments on the Sacramento Valley Hydrogeologic Suitability Index

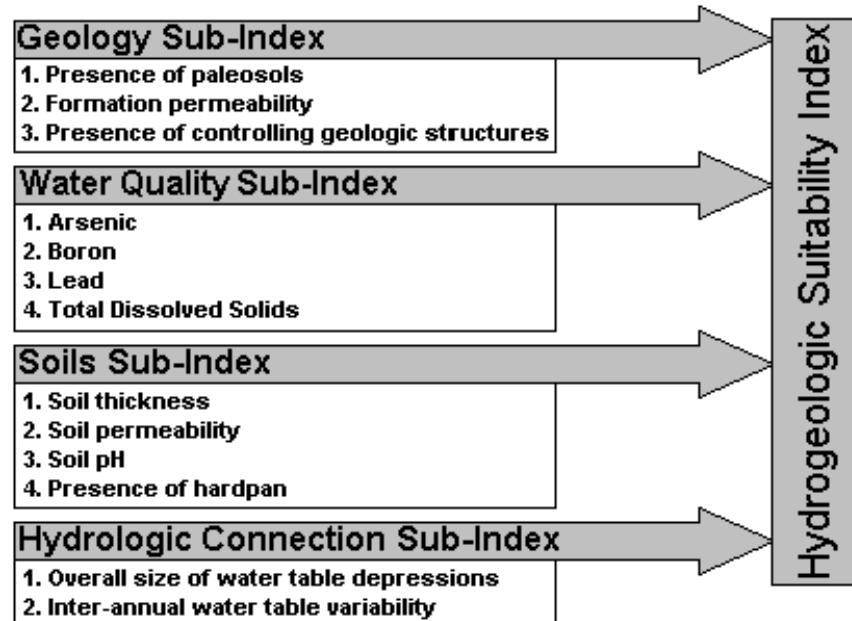
When all of the relevant sub-index values are taken into consideration, there appears to be a trend from the most suitable sites in the northern portion of the Sacramento Valley toward generally less suitable sites in the south. This has important implications in terms of integrating these sites into the state's surface water distribution network, as only Shasta Reservoir physically commands the most northern sites. While Shasta is a large facility, operational constraints associated with temperature control objectives may limit the ability to use Shasta as a direct source for groundwater banking. This suggests that a program of coordinated release from all of the Sacramento Valley reservoirs may be needed to "back" water up into Shasta Reservoir for eventual transfer to northern banking sites.

It should be pointed out that the ranking depicted in Figure 4.4.1 is purely a function of the numerical values assigned to each of the components and the weighting coefficients shown in Equation 4.1. It is possible that others interested in groundwater banking in the Central Valley would apply different component values and weighting coefficients. In order to allow for further exploration of geology, groundwater quality and soils on the suitability of potential groundwater banking sites in the Sacramento Valley, the information used to generate the ranking in Table 4.4.1 has been made available in the spreadsheet developed as part of this effort. In this spreadsheet, any of the values or weighting coefficients applied to the sub-indices may be changed and the new results can be viewed in tables and graphs similar to those in Table 4.4.1 and Figure 4.4.1.

## 5.0 Application of the Hydrogeologic Suitability Index in the San Joaquin Valley

The second application of the Hydrogeologic Suitability Report is in the San Joaquin Valley. Potential groundwater banking sites in this region are shown in Figure 2.0.2. As in the Sacramento Valley, each of the sites is evaluated in terms of the core index that covers relevant geology, groundwater quality and soils characteristics. In the case of the San Joaquin Valley, however, the index has been expanded to include a sub-index related to observed fluctuations in the water table below potential banking sites. As mentioned in Section 1.0, portions of the San Joaquin Valley have been exposed to prolonged periods of groundwater overdraft, resulting in the creation of significant and persistent cones of depression. These features will likely serve as the locus of groundwater storage in the San Joaquin Valley. The hydrologic connection sub-index is designed to assess the degree to which water deposited by groundwater banking at potential sites will remain available for eventual recovery. Details of this sub-index are presented in Section 5.4. Figure 5.0.1 provides a summary flow chart of the information used to develop and apply the Hydrogeologic Suitability Index in the San Joaquin Valley.

**Figure 5.0.1: Flow Chart of Parameters Analyzed in the Development of Relevant Sub-Indices and the Overall Hydrogeologic Suitability Index in the San Joaquin Valley**



## 5.1 San Joaquin Valley Geology Sub-Index

Deep, undifferentiated lacustrian and alluvial deposits characterize San Joaquin Valley geology. This contrasts with the Sacramento Valley, where various formations of differing thickness are encountered with depth below numerous sites. As such, in the San Joaquin Valley it is not generally possible to construct stratigraphic columns similar to those found in Figure 4.1.1. In fact, we assume that the formations encountered at each potential banking site are sufficiently thick to span the entire operational depth of a potential groundwater bank. In this case, the thickness of the single formation encountered at each potential banking site is treated as a parameter in the geology sub-index rather than as a weighting factor applied to the other geologic parameters (as in Equation 3.2). This thickness parameter is scaled as shown below (Table 5.1.1) in the adaptation to the Parameter Weighting Factors Table (Table 3.1.1).

### Geology Sub-Index Equation Key

$$\text{Eq. 3.2: Geology Sub-Index} = \Sigma (\text{Formation Score}_A * \text{Formation Thickness}_A)$$

**Table 5.1.1: Parameter Weighting Factors Used to Calculate the Geology Sub-Index, Adapted to Include Thickness as a Parameter for the San Joaquin Valley Hydrogeologic Suitability Index**

Component	0	5	10
Permeability	Impermeable	Moderately permeable	
Paleosols	Contains resistant paleosols	Contains some slightly resistant paleosols	Highly permeable No paleosols
Geologic Structure	Contains structural features that direct stored groundwater towards gaining streams	Contains no structural features	Contains structural features that isolate stored groundwater from gaining streams
Thickness	Less than 20 ft. thick	6 = 50 to 80 ft. 3 = 20 to 50 ft.	Equal to or exceeds 100 ft.

### 5.1.1 Results of the San Joaquin Geology Sub-Index

Parameter scores associated with the formations encountered at potential banking sites in the San Joaquin Valley are shown in Table 5.1.2. As in the Sacramento Valley, a score of 10 is associated with the most favorable characteristics of a given parameter. The geology sub-index (Table 5.1.3) was calculated from parameter scores based on Equation 5.1.

$$\text{Formation Score} = 2 * (\text{Permeability}) + 0.5 * (\text{Paleosols}) + (\text{Geological Structure}) + (\text{Thickness}) \quad (5.1)$$

In this equation, permeability was assigned a weighting coefficient of 2 due to its importance in the suitability of a formation for groundwater banking. The existence of paleosols was assigned a weighting coefficient of 0.5 because the extent to which paleosols are described varies between

**Table 5.1.2: Scores for Formations Found in the San Joaquin Valley**

Formation	Weighting Coefficient	0.5 Paleosols	2 Permeability	1 Thickness	1 Geo. Setting	Rank
Turlock Lake	4	6	10	5	29	
Tulare Formation	10	7	5	5	29	
Modesto	10	6	8	5	30	
N.W. Kern Fan	10	5	8	10	33	
Alluvial Fan Deposits	10	5	8	5	28	

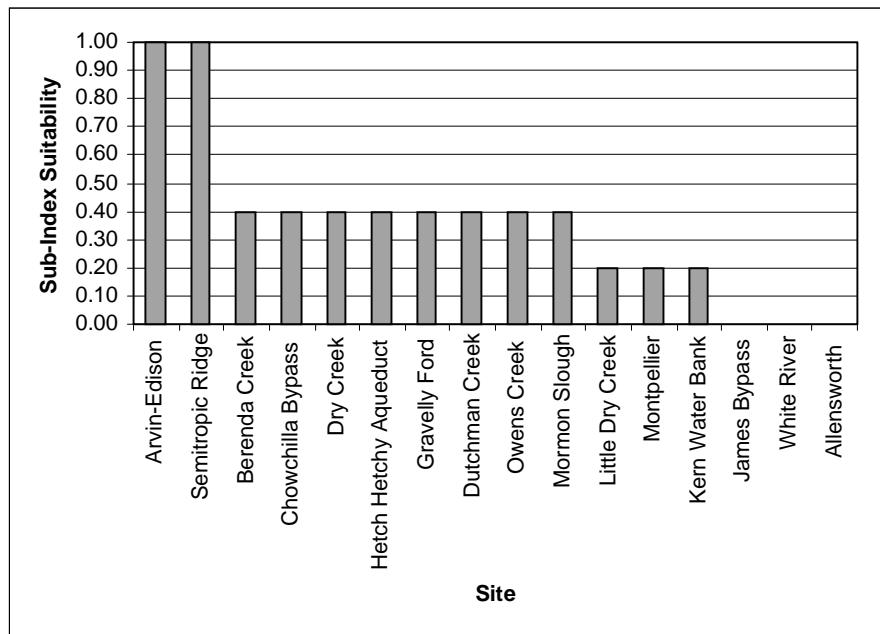
**Table 5.1.3: Geology Sub-Index Values for Potential Groundwater Banking Sites in the San Joaquin Valley**

Site ID	Basin	Geo Formation	Rank	%
Arvin-Edison	Kern	N.W. Kern Fan	33	1.00
Semitropic Ridge	Kern	N.W. Kern Fan	33	1.00
Berenda Creek	Madera	Modesto	30	0.40
Chowchilla Bypass	Chowchilla	Modesto	30	0.40
Dry Creek	Modesto	Modesto	30	0.40
Hetch Hetchy Aqueduct	Modesto	Modesto	30	0.40
Gravelly Ford	Madera	Modesto	30	0.40
Dutchman Creek	Merced	Modesto	30	0.40
Owens Creek	Merced	Modesto	30	0.40
Mormon Slough	Modesto	Modesto	30	0.40
Little Dry Creek	Madera	Turlock Lake	29	0.20
Montpellier	Turlock	Turlock Lake	29	0.20
Kern Water Bank	Kern	Tulare Formation	29	0.20
James Bypass	Kings	Alluvial Fan Deposits	28	0.00
White River	Tule	Alluvial Fan Deposits	28	0.00
Allensworth	Tule	Alluvial Fan Deposits	28	0.00

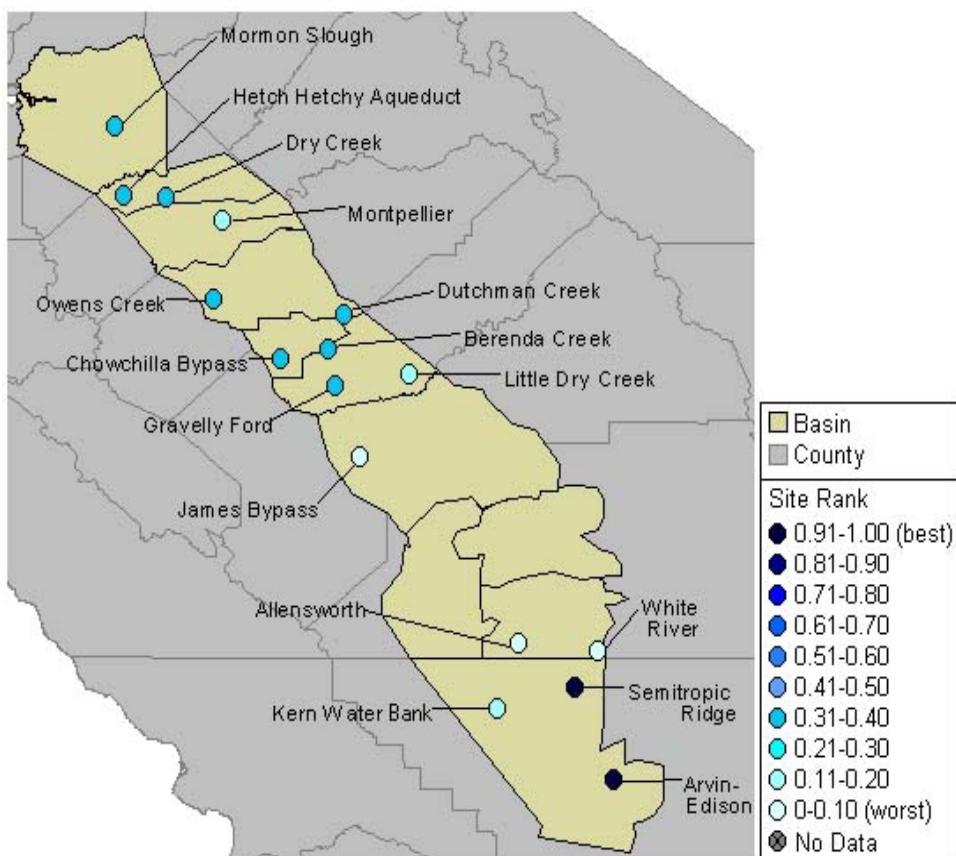
information sources, and when they are described they tend to be thin and discontinuous. The resulting score for each of the formations encountered at potential banking sites in the San Joaquin Valley is found in the Rank column in Table 5.1.2.

Having established the formation scores, an association was made between each potential groundwater banking site and the formation encountered at the target location. These associations are shown in Table 5.1.3, along with the normalized value of the geology sub-index site found in the % column. In this case a value of 1 corresponds with sites overlying the northwestern Kern fan deposits, as these were deemed to be most geologically suitable. A value of 0 is assigned to the alluvial fan deposits associated with the James Bypass, White River and Allensworth sites. The results of the geology sub-index are shown graphically for each of the potential banking sites in Figures 5.1.1 and 5.1.2. Respectively, these figures show the results in terms of the relative rank and the spatial distribution.

**Figure 5.1.1: Geology Sub-Index Ranking for Potential Groundwater Banking Sites in the San Joaquin Valley**



**Figure 5.1.2: Spatial Distribution of Geology Sub-Index Values Across Potential Groundwater Banking Sites in the San Joaquin Valley**



### 5.1.2 Comments on the San Joaquin Geology Sub-Index

The eastern Kern Basin sites (Arvin-Edison and Semitropic Ridge) emerge as well-suited for a groundwater banking project owing to the favorable geologic properties of the underlying northwestern Kern fan formation laid down by the Kern River. By comparison, sites on Tule and Kings River alluvial fans rank low. A large part of this discrepancy is due to a relative lack of information in the published literature on the specific alluvial fans associated with the sites. This lack of information forced us to set parameter scores based on fairly coarse descriptions found in regional mapping studies. Given the quality of the data, we erred on the side of caution in assigning the parameter scores. If these sites prove to be extremely suitable based on other components of the index, further research and testing of these alluvial deposits might be warranted.

In general, however, sites in the San Joaquin Valley demonstrate much less geologic variability than those identified in the Sacramento Valley. The influence of the geology sub-index on the overall index, then, should be viewed in comparative rather than absolute terms.

## 5.2 San Joaquin Valley Water Quality Sub-Index

As in the Sacramento Valley, the water quality sub-index in the San Joaquin Valley comprises four parameters: groundwater concentrations of arsenic, boron, lead and total dissolved solids. The methodology employed to assign scores to each of these parameters and to calculate the sub-index value is found in Section 3.2.

### Water Quality Sub-Index Equation Key

**Eq. 3.3:** Water Quality Score = (As Score) + (B Score) + (Pb Score) + (TDS Score)

**Eq. 3.4:** Water Quality Sub-Index = 1.5\*(Basin Score) + (Site Score)

### 5.2.1 Results of the San Joaquin Valley Water Quality Sub-Index

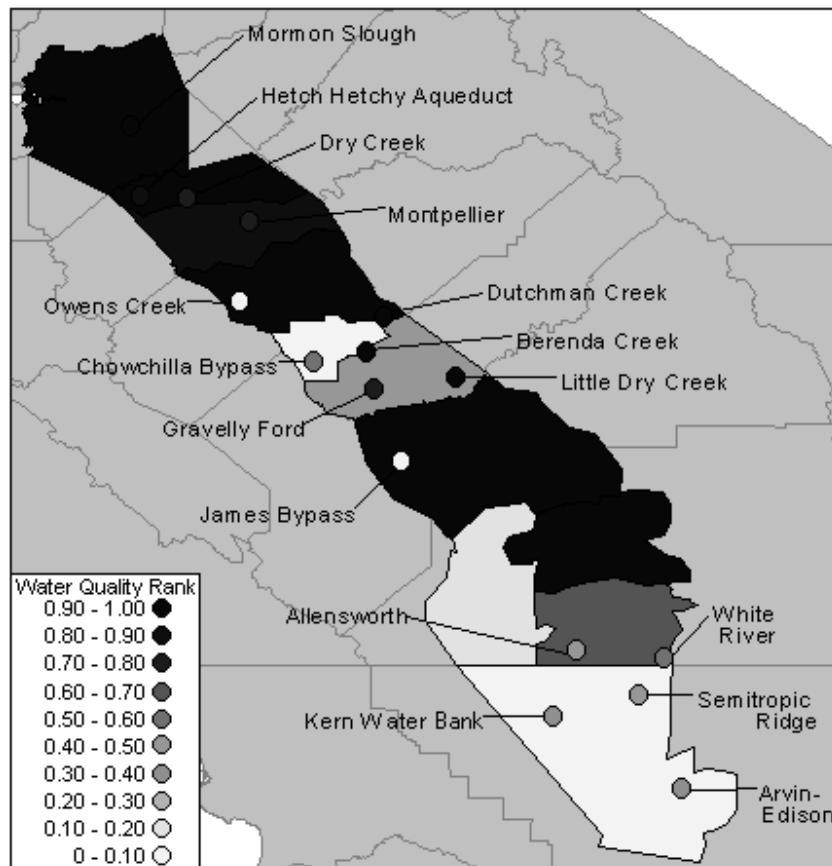
Groundwater quality parameter scores for both basins and sites in the San Joaquin Valley are given in Tables 5.2.1 and 5.2.2 respectively. Figure 5.2.1 illustrates these results spatially.

**Table 5.2.1: San Joaquin Valley Basin Scores**

Weighting Coefficient	1	1	1	1	Rank	%
<b>Basin Name</b>	<b>As</b>	<b>B</b>	<b>Pb</b>	<b>TDS</b>		
Modesto	9	9	7	9	34	1.00
Turlock	9	9	7	8	33	0.89
Merced	8	9	8	9	34	1.00
Chowchilla	6	10	3	6	25	0.00
Madera	7	10	5	7	29	0.44
Kings	9	10	7	8	34	1.00
Tule	5	10	7	9	31	0.67
Kaweah	9	10	7	8	34	1.00
Tulare Lake	5	4	8	9	26	0.11
Kern	3	10	5	7	25	0.00
San Joaquin	7	10	9	8	34	1.00

**Table 5.2.2: San Joaquin Valley Site Scores**

Weighting Coefficient	1 As	1 B	1 Pb	1 TDS	Rank	%
Site Name						
Dutchman Creek	9	10	8	9	36	1.00
Little Dry Creek	10	10	7	9	36	1.00
Mormon Slough	8	10	8	9	35	0.93
Berenda Creek	9	10	8	8	35	0.93
Hetch Hetchy Aqueduct	9	9	9	7	34	0.87
Dry Creek	9	9	9	6	33	0.80
Gravelly Ford	9	10	8	6	33	0.80
Montpellier	9	10	7	6	32	0.73
Chowchilla Bypass	6	10	7	6	29	0.53
White River	5	9	7	8	29	0.53
Allensworth	3	10	7	8	28	0.47
Semitropic Ridge	4	10	7	7	28	0.47
Kern Water Bank	3	10	8	6	27	0.40
Arvin-Edison	4	10	7	6	27	0.40
Owens Creek	5	5	9	3	22	0.07
James Bypass	8	2	7	4	21	0.00

**Figure 5.2.1: Spatial Distribution of Basin and Site Water Quality Scores**

These scores were used to calculate the water quality sub-index based on Equation 3.4. The results for potential banking sites in the San Joaquin Valley are found in Table 5.2.3.

In preparation for inclusion in the overall Hydrogeologic Suitability Index for the San Joaquin Valley, water quality sub-index values have been normalized between 1 (corresponding with best groundwater quality at the Dutchman Creek site) and 0 (corresponding with the poorest observed groundwater quality at the Kern Water Bank and Arvin-Edison sites) in the % column. These results are shown with reference to the overall rank and the spatial distribution in Figures 5.2.2 and 5.2.3.

**Table 5.2.3: Water Quality Sub-Index Values for Potential Banking Sites in the San Joaquin Valley**

Weighting Coefficient		1.5	1		
Site Name	Basin	Basin Wide	Site Specific	Rank	%
Dutchman Creek	Merced	1.00	1.00	2.50	1.00
Mormon Slough	San Joaquin	1.00	0.93	2.43	0.96
Hetch Hetchy Aqueduct	Modesto	0.87	1.00	2.30	0.89
Dry Creek	Modesto	0.80	1.00	2.20	0.84
Montpellier	Turlock	0.73	0.89	1.99	0.73
Little Dry Creek	Madera	1.00	0.44	1.94	0.71
Gravelly Ford	Madera	0.80	0.44	1.64	0.55
White River	Tule	0.53	0.67	1.47	0.46
Berenda Creek	Chowchilla	0.93	0.00	1.40	0.42
Allensworth	Tule	0.47	0.67	1.37	0.40
Owens Creek	Merced	0.07	1.00	1.10	0.26
James Bypass	Kings	0.00	1.00	1.00	0.21
Chowchilla Bypass	Chowchilla	0.53	0.00	0.80	0.11
Semitropic Ridge	Kern	0.47	0.00	0.70	0.05
Kern Water Bank	Kern	0.40	0.00	0.60	0.00
Arvin-Edison	Kern	0.40	0.00	0.60	0.00

**Figure 5.2.2: Water Quality Sub-Index Ranking**

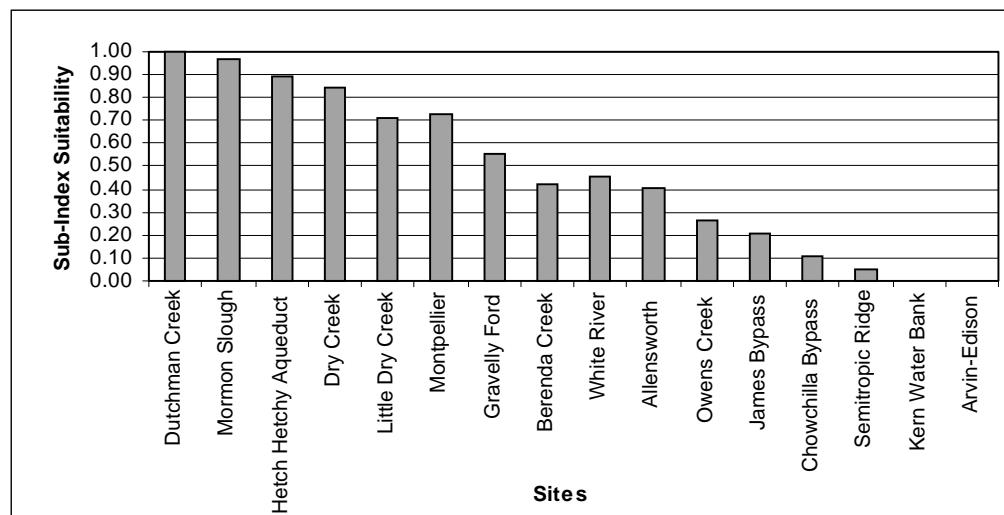
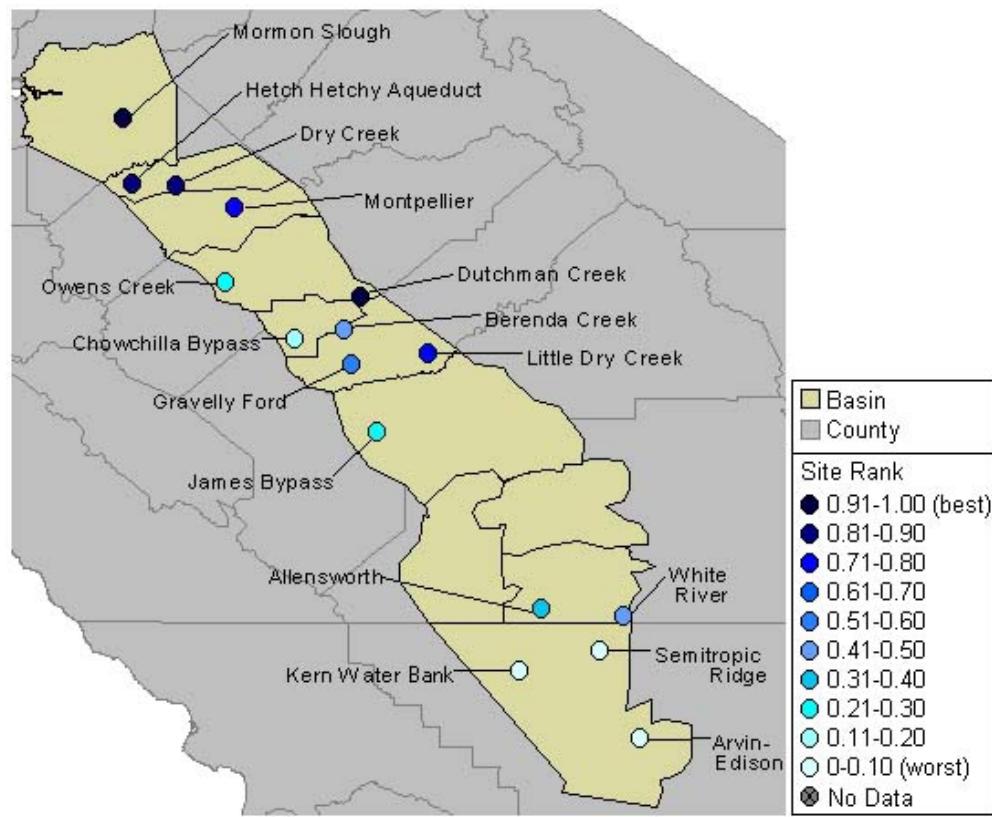


Figure 5.2.3: Spatial Distribution of Water Quality Sub-Index Values



### 5.2.2 Comments on the Water Quality Sub-Index

Excluding the western San Joaquin Valley, where groundwater quality is generally poor across wide areas and where no potential banking sites have been identified, groundwater in the San Joaquin Valley is characterized by the presence of spots of poor quality. Arsenic levels are particularly high in the southern part of the valley in Kern and Tulare Lake Basins. Boron levels peak in parts of Merced, Kings and Tulare Lake basins, a pattern that is mimicked by the distribution of elevated TDS measurements. Lead concentrations are fairly low throughout the valley.

This spatial pattern of groundwater quality points out the utility of the spreadsheet developed as part of this effort. In general, boron is of greatest concern to agricultural water users while arsenic is particularly problematic for municipal water providers. In calculating the water quality sub-index, equal weighting was given to each of these parameters. Someone interested in evaluating the implications of groundwater banking on either of these user communities may wish to weight the sub-index in favor of one of these parameters over the others.

## 5.3 San Joaquin Valley Soils Sub-Index

Parameters used to calculate the soils sub-index are described in Section 3.0.

### Soils Sub-Index Equation Key

$$\text{Eq. 3.5: Soils Sub-Index} = (\text{Thickness}) [3(\text{Permeability}) + (\text{pH}) - 2(1 - \text{Hardpan})]$$

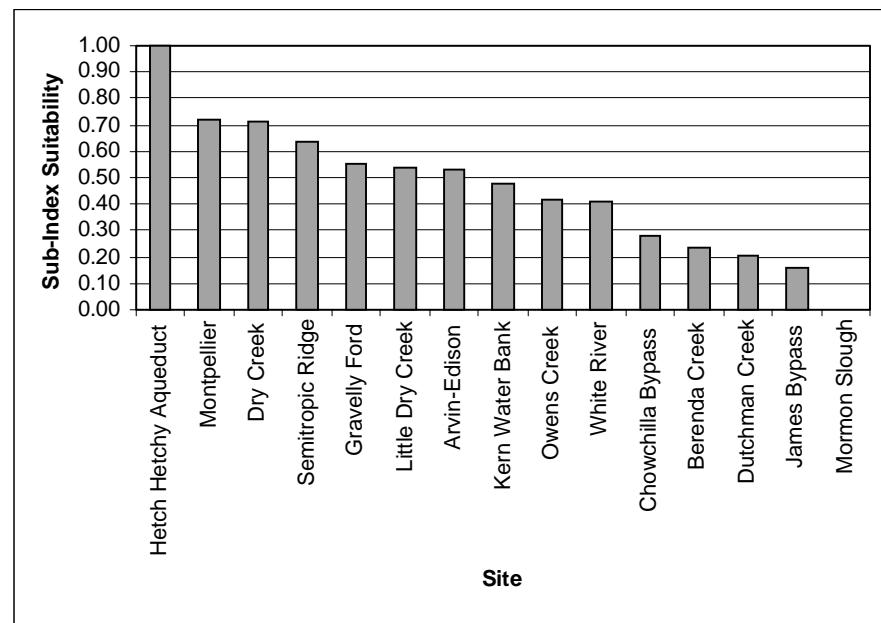
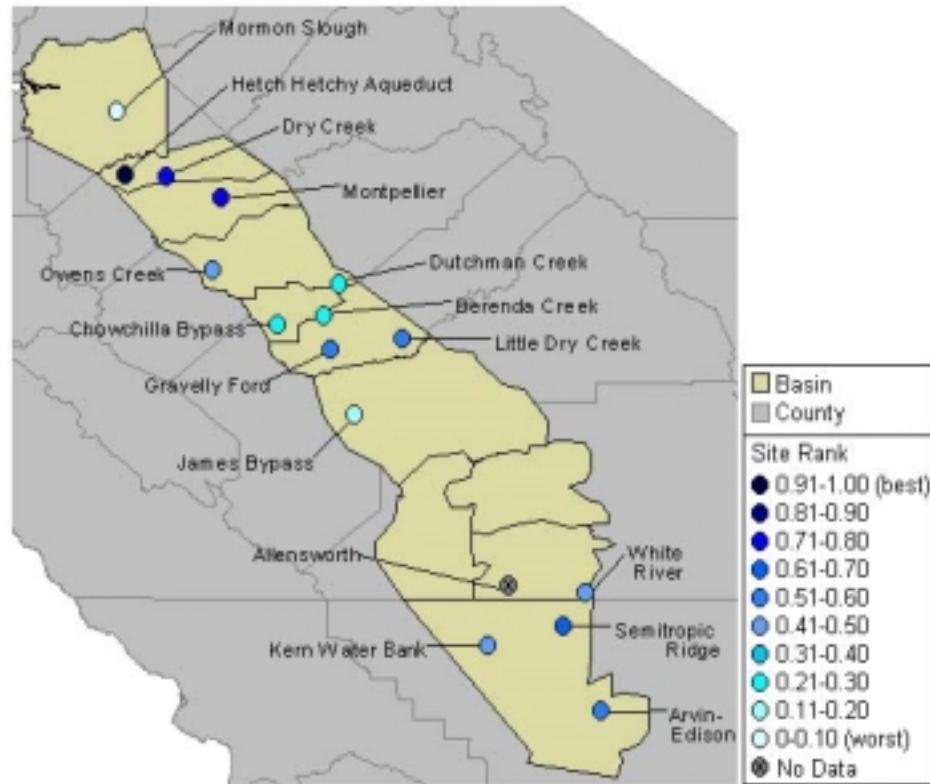
### 5.3.1 Results for the San Joaquin Valley Soils Sub-Index

Parameter scores and the soils sub-index values for selected sites in the San Joaquin Valley are shown below in Table 5.3.1.

**Table 5.3.1: Soils Sub-Index**

Site	Weighting Coefficient	1 Thickness	3 Permeability	2 Hardpan	1 pH	Rank	%
Hetch Hetchy Aqueduct	0.80	0.60	1.00	0.83	2.10	1.00	
Dry Creek	0.75	0.31	0.96	0.79	1.25	0.71	
Montpellier	0.48	0.75	0.85	0.74	1.28	0.72	
Semitropic Ridge	0.78	0.20	1.00	0.70	1.01	0.63	
Gravelly Ford	0.77	0.24	0.87	0.54	0.77	0.55	
Little Dry Creek	0.66	0.40	0.55	0.80	0.73	0.54	
Arvin-Edison	0.86	0.03	1.00	0.74	0.71	0.53	
Kern Water Bank	0.76	0.01	1.00	0.69	0.55	0.48	
Owens Creek	0.75	0.02	1.00	0.41	0.36	0.42	
White River	0.52	0.06	0.85	0.80	0.35	0.41	
Chowchilla Bypass	0.67	0.13	0.51	0.50	-0.05	0.28	
Berenda Creek	0.75	0.23	0.11	0.85	-0.17	0.24	
James Bypass	0.77	0.20	0.19	0.51	-0.40	0.16	
Dutchman Creek	0.64	0.14	0.23	0.68	-0.27	0.20	
Mormon Slough	0.75	0.02	0.00	0.76	-0.88	0.00	

The resulting values are normalized between 1 (corresponding with the most favorable soils at the Hetch Hetchy Aqueduct site) and 0 (corresponding with the Mormon Slough site) in the % column. These are presented graphically in Figures 5.3.1 and 5.3.2, which show the relative rank and spatial distribution of the results.

**Figure 5.3.1: Soils Sub-Index Rank****Figure 5.3.2: Spatial Distribution of Soils Sub-Index Values**

### 5.3.2 Comments on the Soils Sub-Index

Based on the selected parameters, the Turlock and Merced basins appear to possess the most suitable soils in the San Joaquin Valley. Soils in this region are derived from material of Sierran origin deposited by the high-energy Tuolumne and Merced Rivers. The result is a generally more coarse assemblage of soils as compared with material deposited by lower-energy streams to the north and south.

While more complete soil data was available for the San Joaquin Valley than in the Sacramento Valley, one site, Allensworth, lacked published soils information. Owing to a lack of data, in calculating the overall Hydrogeologic Suitability Index this site will be assigned a zero in terms of the soils sub-index.

## 5.4 San Joaquin Valley Hydrologic Connection Sub-Index

In the San Joaquin Valley, an additional sub-index has been added to the core Hydrogeology Suitability Index dealing with the hydrologic connection between potential storage space located within existing cones of depression and the surrounding hydrologic system. Groundwater basins are not surface reservoirs. While exposed to losses due to evaporation and seepage, water stored behind a dam is largely under the direct control of reservoir operators. When water is required, it need only be released from the storage pool. Storage in a groundwater bank does not benefit from the same level of control. Aquifers are open systems within which the existing level of use and conditions in surrounding groundwater basins and overlying surface water bodies influence flow patterns. In such a system, there is no guarantee that water recharged to a groundwater bank will remain within the pore space of the aquifer material immediately below the banking site. In assessing the hydrogeologic suitability of potential sites in the San Joaquin Valley, it is important to understand the way in which banked water would interact with the surrounding hydrologic system.

The most rigorous way to understand these potential interactions is through the use of groundwater models that describe flow patterns within an aquifer under various conditions. While the development of project-specific groundwater models will certainly occur once promising groundwater banking sites are identified and project design begins, it was beyond the scope of the current effort to develop such a tool for all of the potential sites in the San Joaquin Valley. In order to assess the potential for interaction between banked water and the surrounding aquifer, a simple method based on measured water level data was developed.

This methodology begins with the supposition that water banked in the San Joaquin Valley will ideally be stored within large, well-defined, stable drawdown features within an aquifer. This statement is based on two assumptions. First, it is assumed that where such features occur, the existing patterns of groundwater use and aquifer recharge leave a significant portion of the aquifer material perpetually unsaturated and available for long-term storage. Second, it is assumed that once recharge water joins the water table within such a large, well-defined, stable feature, it would be contained within the cone of depression and would not flow away from the recharge site. The methodology used to assess the degree of hydrologic connection between banked water and the surrounding aquifer relies upon analysis of the size and stability of target drawdown features.

### 5.4.1 San Joaquin Valley Hydrologic Connection Sub-Index Parameters

The components used in the hydrologic connection sub-index were all derived from data included in the semi-annual well survey conducted by the California Department of Water Resources. An example of the type of data contained in the survey is shown in Table 5.4.1.

**Table 5.4.1: Water Contour Data for Turlock Basin, 6/1/77 to 12/31/77**

UTM East	UTM North	WSE	GSWS	SWN	Meas. Date	UTM Zone
707008	4167178	118.0	82.0	03S12E33L01M	11/04/1977	10
672518	4159172	49.7	12.3	04S08E25D01M	11/01/1977	10
672572	4157724	48.6	9.4	04S08E25N01M	11/01/1977	10
670810	4158643	34.0	16.0	04S08E27H01M	11/01/1977	10
670808	4157564	44.4	8.6	04S08E34A01M	11/01/1977	10
669361	4157504	39.4	10.6	04S08E34D01M	11/01/1977	10
679642	4165707	33.4	24.6	04S09E03B01M	10/18/1977	10
677098	4165374	29.0	39.0	04S09E05H01M	10/14/1977	10

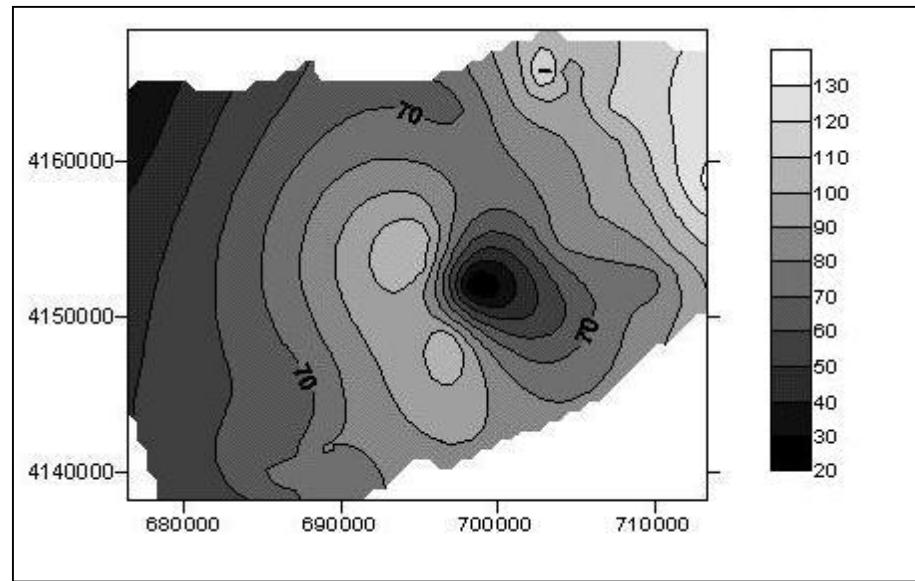
In the table, “UTM East”, “UTM North” and “UTM Zone” are used to specify the physical location of wells included in the survey. The column heading SWN denotes the state well number, which makes reference to the California Public Lands Survey. The date of the semi-annual measurement at a well is provided under the heading “Meas. Date”. We excluded from our analysis any data for which problems were encountered during measurement (as recorded during data collection). Hydrologic data related to the water surface elevation and the difference between the ground surface elevation and the water surface elevation are found under the “WSE” and “GSWS” headings, respectively (the sum of WSE and GSWS should yield the land surface elevation at the measurement site).

Data highlighted in Table 5.4.1 were used to define the parameters for the hydrologic connection sub-index. Water surface elevation data for the entire San Joaquin Valley were collected from Fall 1977 (selected to represent dry year conditions) and Fall 1997 (a wet water year) surveys. These data were used to develop approximate water table contour maps for each of the basins in the San Joaquin Valley. Figure 5.4.1 is an example of a map developed for the Turlock Basin based on the Fall 1977 survey. The large closed depression in the figure is located beneath the Montpellier site identified in Figure 2.0.2.

These maps should be considered approximate in that the wells included in the semi-annual survey were not specifically designed to track the position of the water table. Most are private wells that are screened across several hundred feet of aquifer material. As such, the water level observed in the well is an integrated sample of heads encountered both at the water table and at depth below the water table. In cases where significant flow-restricting horizons exist in the interval spanned by the well screen, these deeper heads may be quite different than the actual elevation of the water table surface. While an attempt was made to screen out problematic wells, some of the heads used to develop the contour maps most certainly did not reflect the true water table elevation at a given location.

Nonetheless, the contour maps developed as part of this analysis, found in Appendix E, capture the general location and scale of major cones of depression known to exist in the San Joaquin Valley. Lacking the resource to develop more accurate local water table maps, we used our

**Figure 5.4.1: Turlock Basin Fall 1977 WSE Contours  
(Elevation in feet above MSL)**



basin scale maps to estimate the storage volume located within a cone of depression using a standard specific yield estimate of 0.2. In the case of the depression below the Montpellier site, a horizontal plane set at 75 ft. capped approximately 208 TAF of available storage during Fall 1977. Based on the estimated basin scale water table contour maps developed during the fall surveys of 1977 and 1997, two parameters were defined for use in the hydrologic connection sub-index.

#### *Maximum Overall Size of Water Table Depressions*

The larger of the estimated available storage volumes calculated based on data from the Fall 1977 and Fall 1997 surveys was selected to represent the maximum overall size of water table depressions parameter. We anticipated the available storage volume would be larger during 1977 owing to the extremely dry conditions encountered at that time. We discovered, however, that some locations manifested larger available storage volumes during the wet 1997 water year. This is presumably due to the fact that groundwater overdraft during the 20 intervening years masked any water table recovery associated with higher levels of aquifer recharge.

#### *Inter-Annual Water Table Change*

Nonetheless, changing levels of aquifer recharge do contribute to fluctuations in the water table surface that can be observed between dry and wet periods. Groundwater basins that experience significant changes in water levels, and hence available storage volumes, generally benefit from a high degree of natural recharge during wet periods. If the storage of banked water would limit the ability to capture a portion of this natural recharge, then the project could create conflicts with historic groundwater users. Any such fluctuations can be described in the following equation used to define the inter-annual water table change parameter of the hydrologic connection sub-index.

$$\text{Inter-Annual Change} = (V_{77F} - V_{97F}) / \text{Max. Volume}$$

(5.2)

where  $V_{77F}$  = volume of a basin in Fall 1977  
 and  $V_{97F}$  = volume of a basin in Fall 1997

Because the effects of long-term overdraft can mask water table recovery associated with enhanced recharge during wet years, Equation 5.2 occasionally produces negative numbers. A site in overdraft provides a unique opportunity for a groundwater banking project because, not only would the site have a large depression available for storage, but the storage of water there could be used to provide benefits to overlying groundwater pumpers if some portion of the banked water could be used to slow down or reverse incipient water table declines.

#### 5.4.2 San Joaquin Valley Hydrologic Connection Sub-Index Weighting Factors

As in the case of the sub-indices included in the core index, calculation of the hydrologic connection sub-index can be influenced by the assignment of appropriate weighting factors. As the size of the cone of depression is the most important feature in determining what scale of a project could be pursued at a potential groundwater banking site, this parameter was weighted by a factor of two. In addition, the inter-annual change parameter should be subtracted from one so that a basin that experiences a small rise in the water table between wet and dry years (suggesting a small amount of hydrologic connection with the surrounding hydrology) would score higher than a basin where large fluctuations occur, presumably in response to significant interaction between the aquifer and the surrounding hydrologic features. In addition, for sites in overdraft (the inter-annual change parameter is negative), where banking could contribute to water table recovery, this subtraction would enhance the suitability of the site. Each of these assumptions is contained in the following equation used to calculate the hydrologic connection sub-index.

$$\text{Hydrologic Connection Sub-Index} = 2 * \text{Max. Volume} + (1 - \text{Inter-Annual Change})$$

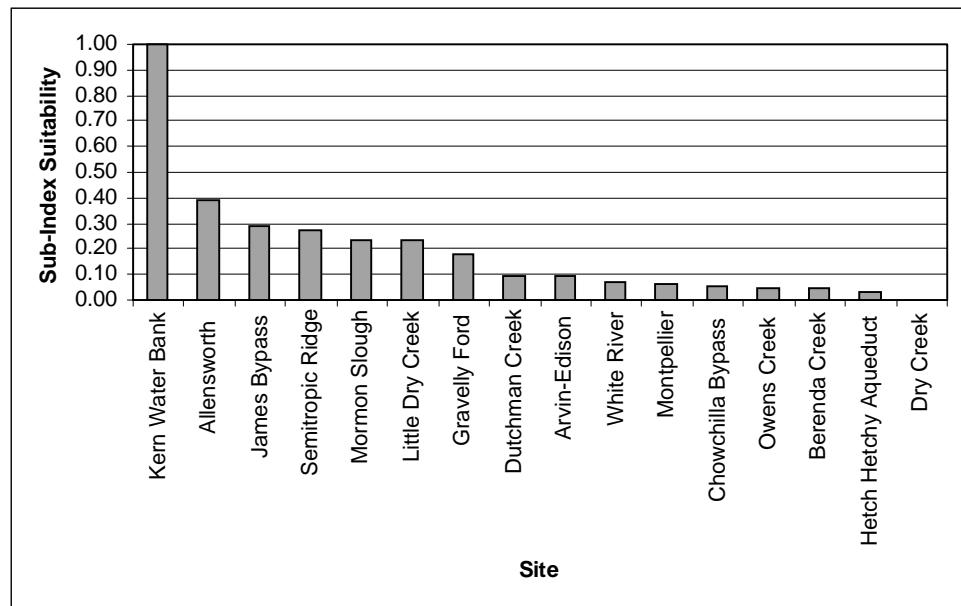
(5.3)

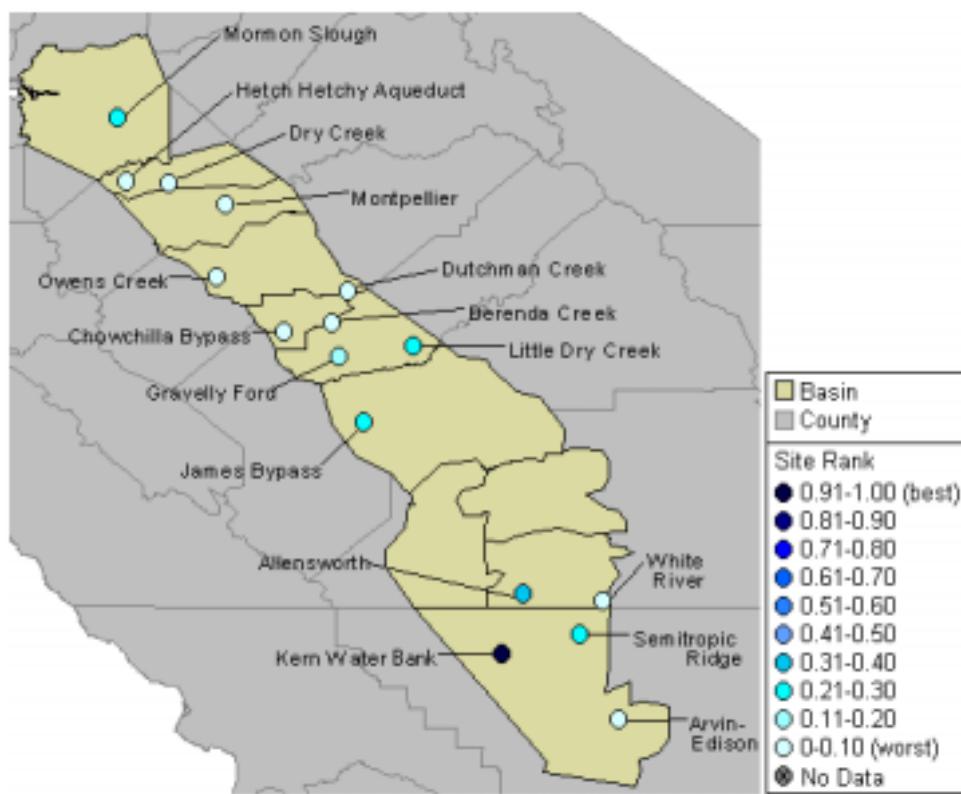
#### 5.4.3 Results for the San Joaquin Valley Hydrologic Connection Sub-Index

Applying Equation 5.3 to the estimated water table elevation data derived from the available data produces the hydrologic connection sub-index values shown in Table 5.4.2. These values have been normalized between 1 (corresponding with the Kern Water Bank site) and 0 (corresponding with the Dry Creek site) in the % column. Normalized results are shown in terms of relative rank in Figure 5.4.2 and spatial distribution in Figure 5.4.3.

**Table 5.4.2: Hydrologic Connectivity Sub-Index Table**

Site	Max. Vol.	Annual	Rank	%
Kern Water Bank	21.61	-0.40	44.62	1.00
Allensworth	7.77	-0.83	17.37	0.39
James Bypass	6.13	0.18	13.08	0.29
Semitropic Ridge	6.07	0.79	12.35	0.27
Mormon Slough	5.19	0.67	10.71	0.24
Little Dry Creek	4.37	-0.94	10.68	0.24
Gravelly Ford	3.61	0.06	8.15	0.18
Dutchman Creek	1.54	-0.41	4.49	0.10
Arvin-Edison	1.55	-0.35	4.45	0.10
White River	1.29	0.46	3.12	0.07
Montpellier	1.04	0.22	2.86	0.06
Chowchilla Bypass	0.32	-0.91	2.55	0.05
Owens Creek	0.79	0.25	2.33	0.05
Berenda Creek	0.06	-0.96	2.08	0.04
Hetch Hetchy	0.01	-0.67	1.69	0.03
Dry Creek	0.02	0.87	0.17	0.00

**Figure 5.4.2: Hydrologic Connection Sub-Index Rank**

**Figure 5.4.3: Spatial Distribution of Hydrologic Connection Sub-Index Values**

#### 5.4.4 Comments on the Hydrogeologic Connectivity Index

The Kern Water Bank dwarfs the rest of the potential groundwater banking sites in the San Joaquin Valley with respect to the hydrologic connection sub-index. This site overlies what was a large depression in 1977 and has been the locus of an active groundwater banking project for the past decade. While it no longer merits the label of a potential site, it was included in the analysis for comparative value.

Another cluster of relatively promising sites lies in the vicinity of the San Joaquin River. The Little Dry Creek, Gravelly Ford and James Bypass sites all score relatively high. The opportunity to manage these sites in conjunction with reoperation of Friant Dam on the San Joaquin likely merits additional evaluation.

## 5.5 San Joaquin Valley Hydrogeologic Suitability Index

Having developed the four relevant sub-indices, the overall Hydrogeologic Suitability Index for potential groundwater banking sites in the San Joaquin Valley was calculated based on the following equation.

$$\text{Hydrogeologic Suitability Index} = (\text{Geology}) + 2 * (\text{Water Quality}) + (\text{Soils}) + 0.5 * (\text{Hydrologic Connection}) \quad (5.4)$$

The results of this analysis are shown in Table 5.5.1 with the normalized values between 1 (corresponding with the Hetch Hetchy Aqueduct) and 0 (corresponding with James Bypass) shown in the % column. These results are shown graphically in Figures 5.5.1 and 5.5.2, which present the relative rank and spatial distribution, respectively.

**Table 5.5.1: San Joaquin Valley Hydrogeologic Suitability Index**

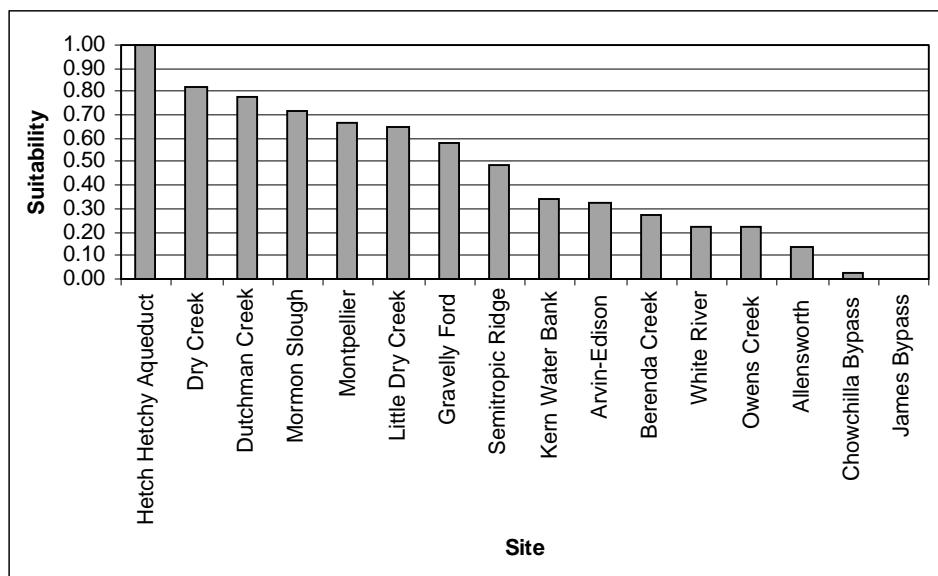
Weighting Coefficient Site	1 <b>Geology</b>	2 <b>Water Quality</b>	1 <b>Soils</b>	0.5 <b>Hydrologic Connectivity</b>	Rank	%
Hetch Hetchy Aqueduct	0.40	0.89	1.00	0.03	3.22	1.00
Dry Creek	0.40	0.84	0.71	0.00	2.80	0.82
Dutchman Creek	0.40	1.00	0.20	0.10	2.70	0.78
Mormon Slough	0.40	0.96	0.00	0.24	2.57	0.72
Montpellier	0.20	0.73	0.72	0.06	2.45	0.67
Little Dry Creek	0.20	0.71	0.54	0.24	2.39	0.65
Gravelly Ford	0.40	0.55	0.55	0.18	2.23	0.58
Semitropic Ridge	1.00	0.05	0.63	0.27	2.01	0.48
Kern Water Bank	0.20	0.00	0.48	1.00	1.68	0.34
Arvin-Edison	1.00	0.00	0.53	0.10	1.63	0.32
Berenda Creek	0.40	0.42	0.24	0.04	1.52	0.28
White River	0.00	0.46	0.41	0.07	1.39	0.22
Owens Creek	0.40	0.26	0.42	0.05	1.39	0.22
Allensworth	0.00	0.40	0.00*	0.39	1.19	0.14
Chowchilla Bypass	0.40	0.11	0.28	0.05	0.94	0.03
James Bypass	0.00	0.21	0.16	0.29	0.87	0.00

\* In cases where values were missing, the value zero was used.

In this analysis, the water quality sub-index was weighted by 2 to stress its importance to the ultimate users of banked groundwater. In the San Joaquin Valley, the geology sub-index only receives a weighting factor of 1 (as opposed to 2 in the Sacramento Valley) in order to reflect the fact that the data do not suggest as clear a differentiation between sites in terms of this important characteristic. Soils receive a weight of 1 to reflect the fact that while they can exert important

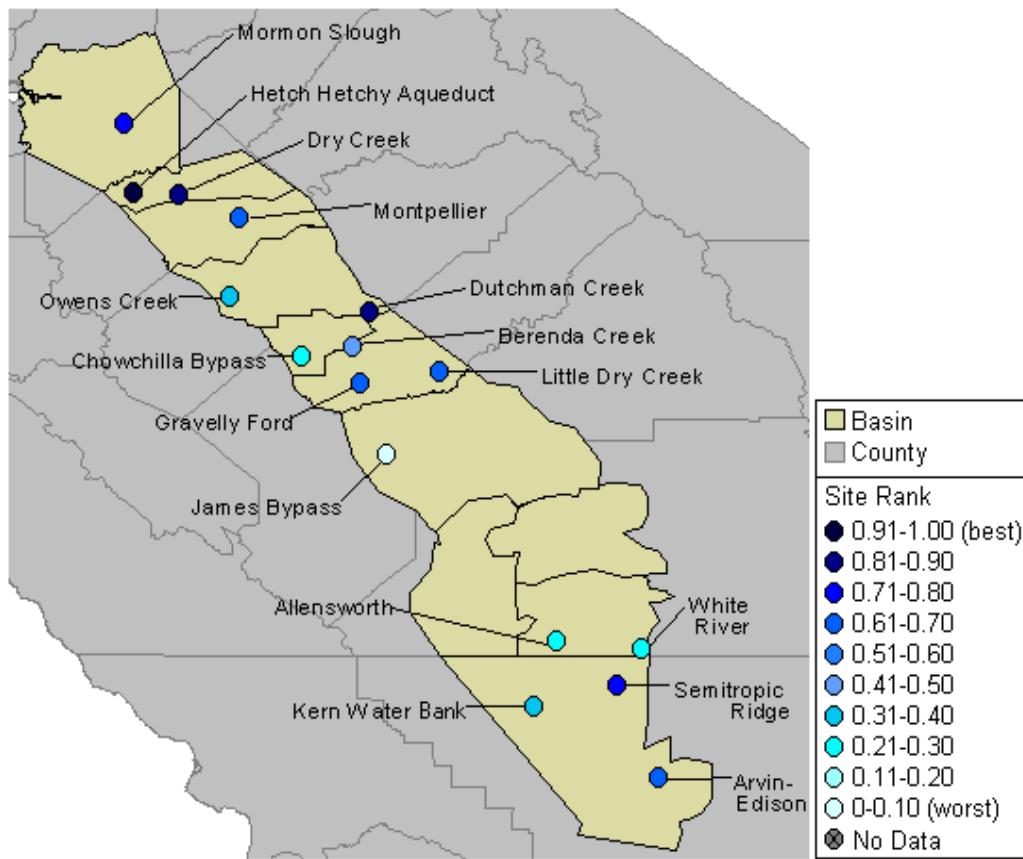
controls on the operation of recharge basins, problematic soils can be removed as part of project construction, although this would increase the overall cost of the project. The hydrologic connection sub-index receives a weight of 1 because, while the information on the water table depression size and stability is extremely important, the approach taken here is based on the hydrologic response of the system under existing management conditions. The initiation of storage and recovery operations at a potential site would substantially alter these conditions. As previously mentioned, the best way to evaluate this possibility is through the application of groundwater models—an exercise that was beyond the scope of the current investigation. In the event that modeling results become available, it would be possible to increase the weighting on this sub-index.

**Figure 5.5.1: San Joaquin Valley Hydrogeologic Suitability Index Rank**



It should be pointed out that the ranking depicted in Figure 5.5.1 is purely a function of the numerical values assigned to each of the components and the weighting coefficients shown in Equation 5.4. It is possible that others interested in groundwater banking in the San Joaquin Valley would apply different component values and weighting coefficients. In order to allow for further exploration of geology, groundwater quality, soils and the degree of hydrologic connection on the suitability of potential groundwater banking sites in the San Joaquin Valley, the information used to generate the ranking in Table 5.5.1 has been made available in the spreadsheet developed as part of this effort. In this spreadsheet, any of the values or weighting coefficients applied to the sub-indices may be changed and the new results can be viewed in tables and graphs similar to those in Table 5.5.1 and Figure 5.5.1.

Figure 5.5.2: Spatial Distribution of Hydrogeologic Suitability Index Values



## 6.0 Conclusions

A recent review of an attempt to develop an Environmental Sustainability Index (ESI) that could be applied to nations across the world (found in the 01/25/01 edition of *The Economist*) seized upon two major problems inherent to the development of comparative indices. First, “a tricky challenge...is to decide how to weigh each indicator”. Second, “another challenge remains the paucity of good data. By forging ahead anyway, the report risks lending a quantitative gravitas to conclusions that are based on still-sketchy data”.

The first critique stems from the fact that the ESI gives equal weight to all its 22 indicators. The authors of the ESI accepted this criticism, but explained that their database will soon be available on CD-ROM. Critics will then be able to use whatever weightings they prefer. The authors of the ESI responded to the second critique by arguing that they have created a framework that exposes the data deficiencies, and so spurs others to remedy them. Future versions of the report, they point out, can only get better. In fact, the authors conclude “the chief virtue of this index is that it begins the process of shifting environmental debates on to firmer foundations, underpinned by data and a greater degree of analytic rigor”.

While our development of a Hydrogeologic Suitability Index for potential groundwater banking sites in the Central Valley is a much less weighty endeavor than the development of the ESI, we anticipate that similar criticisms will be directed at this effort. Rather than weight each of our sub-indices equally, however, we made an attempt to highlight what we perceive to be the relative importance of the geologic setting and water quality sub-indices. By making the aforementioned Excel workbook available on the web, we encourage all those interested in groundwater banking in California to use whatever weightings they prefer. While the data used in this effort are likely better than those available to the authors of the ESI, we have pointed out that several compromises were made in order to assemble the minimum suite of data used to develop the Hydrogeologic Suitability Index. We encourage those with access to better information to improve upon our effort by bringing this information to bear on the on-line database. This process of refinement will only improve the quality of our effort.

As a starting point, however, we feel that the Hydrogeologic Suitability Index reveals several interesting findings in terms of potential projects that should be considered for more refined analysis. Notably, we found that the groundwater basins in the Sacramento Valley are generally more favorable in terms of their hydrogeologic suitability for groundwater banking. As has been mentioned on several occasions in this report, this finding raises a number of complicated legal and institutional issues related to the fact that these basins are not currently endowed with substantial volumes of unsaturated aquifer material ready to be used for storage. While these issues will by no means be simple to resolve, the quality of these basins from a purely hydrogeologic perspective suggests strongly that the effort should be made to resolve them.

In the Sacramento Valley, the best opportunities for groundwater banking seem to cluster near the northern end of the valley, with Stone Valley and Stoney Creek Fan leading the pack. The geology in particular under these sites is well-suited for a banking project.

In the San Joaquin Valley, there is no clear geographic gradient of favorable to poor sites. Clusters of favorable sites exist in Modesto, Madera and Kern basins. Both soils and hydrologic connection vary greatly in the San Joaquin Valley, which could account for the discontinuous distribution.

In concluding their review of the Environmental Sustainability Index, the commentators concluded that it “is a thoughtful step in the right direction”. While much work remains to be done in translating the promise of groundwater banking to actual yield-enhancing projects, we hope that the Hydrogeologic Suitability Index described in this report will ultimately be viewed in a similar light.

# 7.0 References

## Geology

- Bull, W.B. 1964. Alluvial Fans and Near-Surface Subsidence in Western Fresno County, California. USGS professional paper 1999-H. US Geological Survey in cooperation with Department of Water Resources.
- Croft, M.G. 1972. Subsurface Geology of the Late Tertiary and Quaternary Water-Bearing Deposits of the Southern Part of the San Joaquin Valley, California. US Geological Survey in cooperation with Department of Water Resources.
- Dale, R.H., J.J. French, and G.V. Gordon. 1966. Ground-Water Geology and Hydrology of the Kern River Alluvial-Fan Area, California. USGS Open-file report. US Geological Survey in Cooperation with Department of Water Resources.
- Davis, G.H., et al. 1959. Ground-Water Conditions and Storage Capacity in the San Joaquin Valley, California. USGS Water-Supply paper 1469. US Geological Survey in Cooperation with Department of Water Resources.
- Davis, S.N. and F.R. Hall. 1956. "Water Quality of Eastern Stanislaus and Northern Merced Counties, California." Stanford University Publications, Geological Sciences, v. 6, no. 1. Stanford University.
- Forbes, H. 1941. "Geology of the San Joaquin Valley as related to the Source and the Occurrence of the Ground-Water Supply". American Geophysical Union Transactions of 1941, Part 1-A p. 9-21. American Geophysical Union.
- Johnson, H.D., E.G. Brown, and R.B. Robie. 1978. Evaluation of Ground Water Resources: Sacramento Valley. Bulletin 118-6. Department of Water Resources in cooperation with the US Geological Survey.
- Lettis, W.R. 1988. "Quaternary Geology of the Northern San Joaquin Valley." Studies of the Geology of the San Joaquin Basin. Geomatrix Consultants Inc.
- Mitten, H.T. 1982. Preliminary Evaluation of the Potential for Artificial Ground-Water Recharge in Eastern San Joaquin County, California. USGS Open-file report 82-123. US Geological Survey in Cooperation with San Joaquin County Flood Control and Water Conservation Dist.
- Mitten, H.T. 1984. Ground Water in the Fresno Area, California: Preliminary Report. USGS Water-Resources Investigations Report 83-4246. US Geological Survey.
- Page, R.W. 1983. Geology of the Tulare Formation and Other Continental Deposits, Kettleman City Area, San Joaquin Valley, California, with a section on Ground-Water Management

## Water Quality

- Balding, G.O. and Page, R.W. 1971. Data for wells in the Modesto Merced Area, San Joaquin Valley California. Open File Report 72-11. USGS CDWR.
- De Zuane, J., P.E. 1997. Handbook of Drinking Water Quality. 2<sup>nd</sup> ed. Van Nostrand Reinhold: New York.
- Evenson, K.D. 1985. Chemical Quality of Ground Water in Yolo and Solano Counties, California. Water Resources Investigation Report 84-4244. USGS, CDWR.
- Fogelman, R.P. 1975. Descriptions and Chemical Analysis for Selected wells in the Tehama Colusa Canal Service Area. USGS, CDWR.
- Fogelman, R.P. 1976. Descriptions and Chemical Analysis for Selected wells in the Central Sacramento Valley, California. Open File Report 76-472. USGS, CDWR.
- Fogelman, R.P. 1977. Descriptions and Chemical Analysis for Selected wells in the Eastern Sacramento Valley, California. Open File Report 77-486. USGS, CDWR.
- Fogelman, R.P. 1982. Compilation of Selected Ground-Water Quality Data from the San Joaquin Valley, California. Open File Report 82-335. USGS.
- Hausenbuiller, R.L. 1985. Soil Science Principles and Practices. 3<sup>rd</sup> ed. Wm. C. Brown Publishers: Dubuque, Iowa.
- Hoffman, G.J. Water Quality Criteria for Irrigation. The Institute of Agriculture and Natural Resources web page: <http://ianr.unl.edu/pubs/irrigation/ec782.htm#toxicity>. 2001.
- Shelton, L. R. and Miller, L. K. 1988. Water-Quality Data, San Joaquin Valley California, March 1985- March 1987. Open-File Report 88-479. USGS, SJVDrainage Program.
- World Health Organization. 1993. Guidelines for Drinking-Water Quality. Vol. 1, 2nd ed. Geneva.
- The Environmental Protection Agency (EPA) website for drinking water quality and arsenic factsheet. 2001.  
<http://www.epa.gov/safewater/mcl.html>

[http://www.epa.gov/ars/ars\\_rule\\_factsheet.html](http://www.epa.gov/ars/ars_rule_factsheet.html)

The USGS National Water Information System (NWIS) web page  
<http://water.usgs.gov/ca/nwis/qwdata>. 2001.

## Soils

Andrews, W.F. 1972. Soil Survey of Yolo County, California. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station.

Arkley, R.J. 1962. Soil Survey of Eastern Stanislaus Area, California. US Department of Agriculture, Soil Conservation Service with California Agricultural Experiment Station.

Arkley, R.J. 1962. Soil Survey of Merced Area, California. US Department of Agriculture, Soil Conservation Service with California Agricultural Experiment Station.

Arroues, K.D. and C. H. Anderson, Jr. 1986. Soil Survey of Kings County, California. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station.

Bates, L.A. 1977. Soil Survey of Solano County, California. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station.

Begg, E.L. 1968. Soil Survey of Glenn County, California. US Department of Agriculture, Soil Conservation Service and Forest Service with UC Agricultural Experiment Station.

Chang, K.K. 1988. Soil Survey of Kern County, California, Northwestern Part. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station.

Cook, T.D. 1978. Soil Survey of Monterey County, California. US Department of Agriculture, Soil Conservation Service with the Forest Service, USDA and UC Agricultural Experiment Station.

Gowans, K.D. 1967. Soil Survey of Tehama County, California. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station.

Huntington, G.L. 1971. Soil Survey of Eastern Fresno Area, California. US Department of Agriculture with UC Agricultural Experiment Station.

Lytle, D.J. 1988. Soil Survey of Sutter County, California. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station.

Lytle, D.J. 1998. Soil Survey of Yuba County, California. US Department of Agriculture, Natural Resources Conservation Service with Regents of the University of California and the US Department of Agriculture, Forest Service.

- McElhiney, M.A. 1992. Soil Survey of San Joaquin County, California. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station and the California Department of Conservation.
- Rogers, J.H. 1980. Soil Survey of Placer County, California. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station.
- Schafer, W.M. and M.J. Singer. 1976. "Influence of physical and mineralogical properties on swelling of soils in Yolo County, California." Soil Science Society of America Journal 40(4): 557-562.
- Stephens, F.G. 1982. Soil Survey of Tulare County, California, Central Part. US Department of Agriculture, Soil Conservation Service and US Department of the Interior, Bureau of Indian Affairs, with the UC Agricultural Experiment Station.
- Tugel, A.J. 1993. Soil Survey of Sacramento County, California. US Department of Agriculture, Soil Conservation Service: in cooperation with Regents of the University of California.
- Ulrich, R. and Stromberg L. 1964. Soil Survey of Madera Area, California. US Department of Agriculture, Soil Conservation Service with California Agricultural Experiment Station.
- Woodruff, G.A., W.J. McCoy, and W.B. Sheldon. 1970. Soil Survey of Antelope Valley Area, California. US Department of Agriculture with UC Agricultural Experiment Station.
- Woodruff, G.A. 1980. Soil Survey of San Bernardino County, Southwestern Part, California. US Department of Agriculture, Soil Conservation Service with UC Agricultural Experiment Station.
- National Soil Survey Handbook, title 430-VI. September 1999. US Department of Agriculture, Natural Resources Conservation Service. Washington, D.C., U.S. Government Printing Office. Internet. 18 Oct. 2000. Available: <http://www.statlab.iastate.edu/soils/nssh/>.
- California Farm Bureau Federation web page  
<http://www.cfbf.com>. 2001.

## Volume

Web Site for the California Department of Water Resources, Division of Planning and Local Assistance. Internet. 17 Nov. 2000. Available: <http://well.water.ca.gov/>.















































James Bypass	Cajon coarse sandy loam Calhi loamy sand Fresno clay loam Fresno fine sandy loam Fresno sandy loam Fresno-Traver complex Hesperia sandy loam Pond fine sandy loam Rossi fine sandy loam Traver fine sandy loam Traver sandy loam	3.4 5.8 23.4 31.6 19.4 5.3 0.5 3.7 0.3 0.4 4.6
White River	Centerville clay Exeter loam Havala loam	79.7 14.8 5.4
Semitropic Ridge	Chanac clay loam Delano sandy loam Wasco sandy loam Zerker loam	16.6 69 2.9 11.5
Arvin-Edison	Kimberlina fine sandy loam Panoche clay loam	81 19

## **Appendix D: Water storage volumes used in the San Joaquin Valley hydrologic connectivity sub-index**

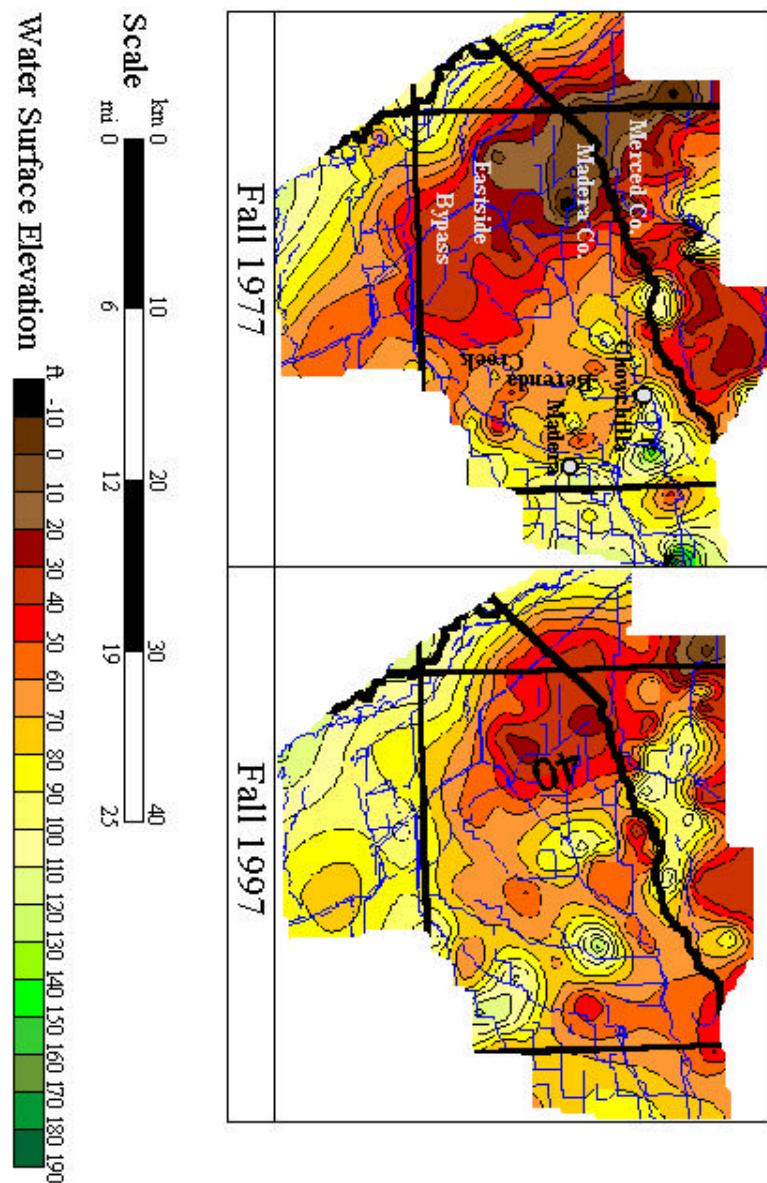
All values reported in million acre-feet

<b>Site</b>	<b>Fall 1977</b>	<b>Spring 1997</b>	<b>Fall 1997</b>
Allensworth	1.30	5.96	7.77
Arvin-Edison	1.01	1.11	1.55
Berenda Creek	0.00	0.19	0.06
Chowchilla Bypass	0.03	0.53	0.32
Dry Creek	0.02	0.00	0.00
Dutchman Creek	0.91	1.41	1.54
Gravelly Ford	3.61	3.38	2.04
Hetch Hetchy Aqueduct	0.00	0.01	0.01
James Bypass	6.13	2.50	5.01
Kern Water Bank	13.05	14.45	21.61
Little Dry Creek	0.28	1.29	4.37
Montpellier	1.04	0.31	0.81
Mormon Slough	5.19	0.79	1.71
Owens Creek	0.79	0.44	0.59
Semitropic Ridge	6.07	0.89	1.30
White River	1.29	0.15	0.70

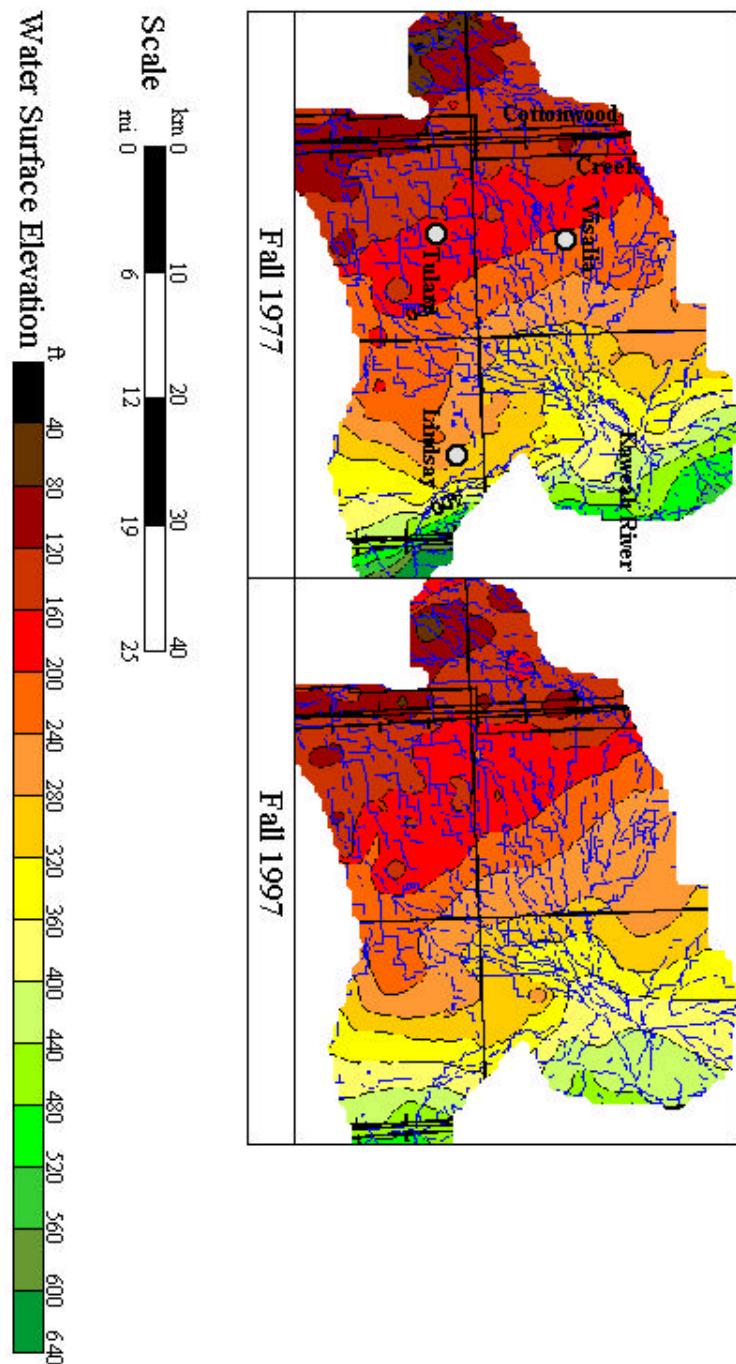
## **Appendix E: Basin Maps**

The following maps show water surface contours for each of the basins in the San Joaquin Valley in Fall 1977 and in Fall 1997.

## Chowchilla Basin

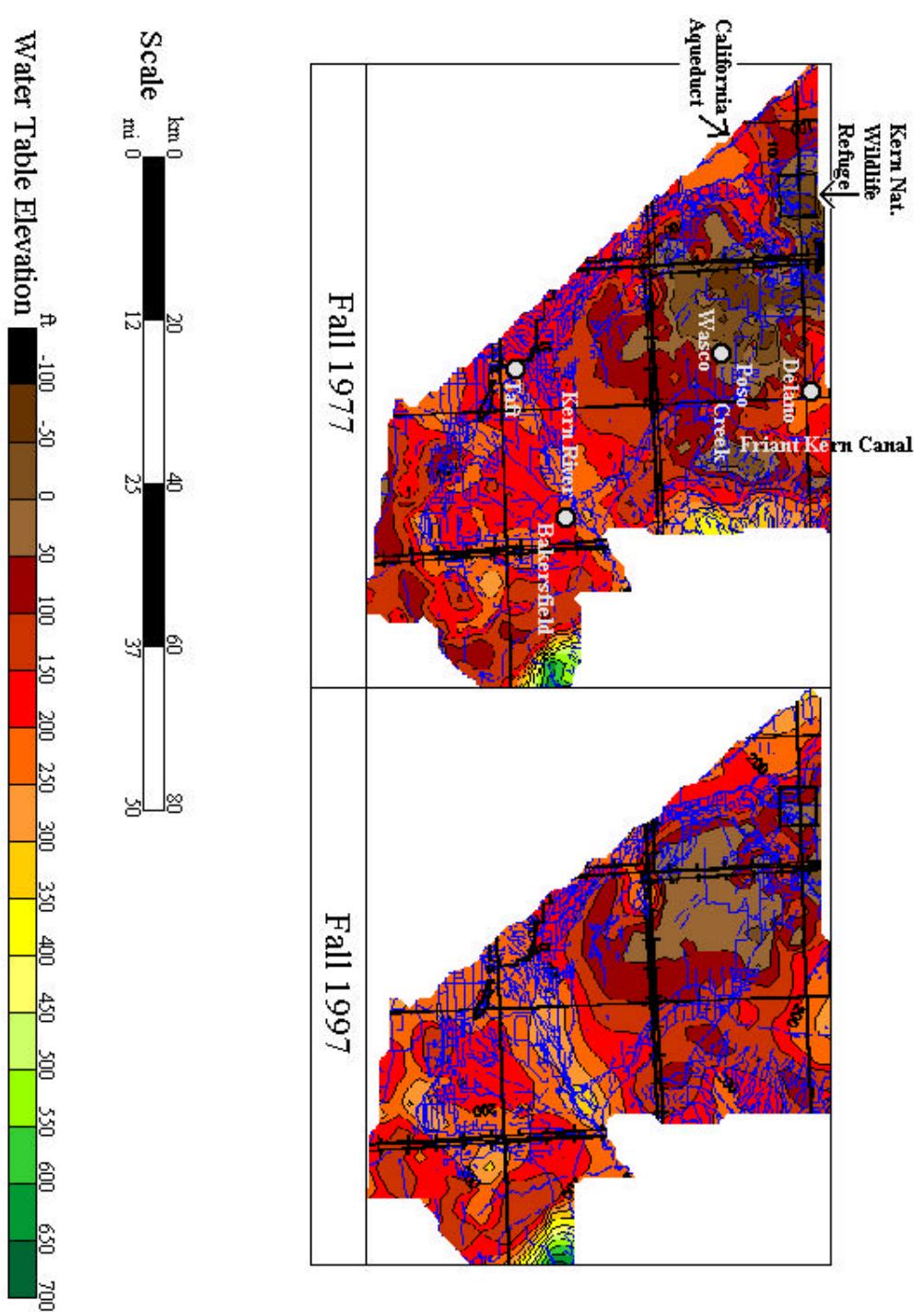


## Kaweah Basin

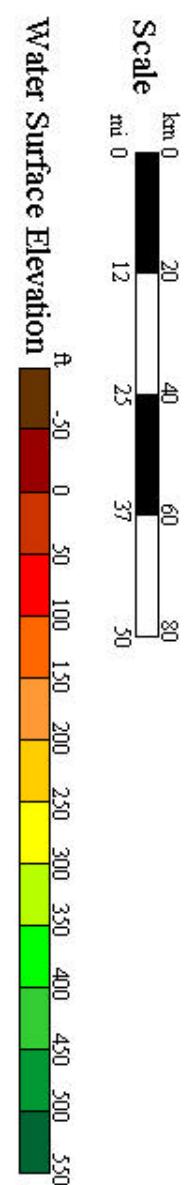
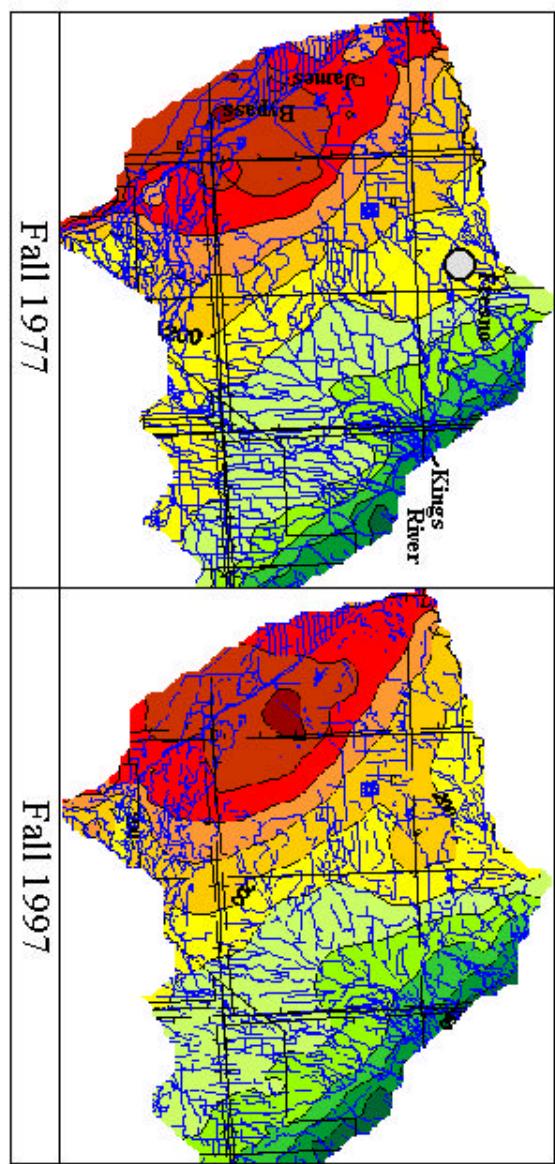


## Kern Basin

E-4

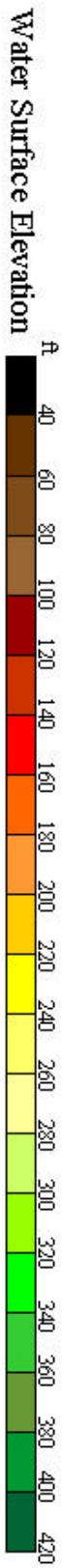
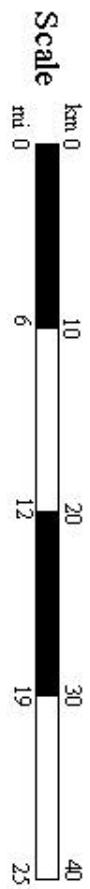
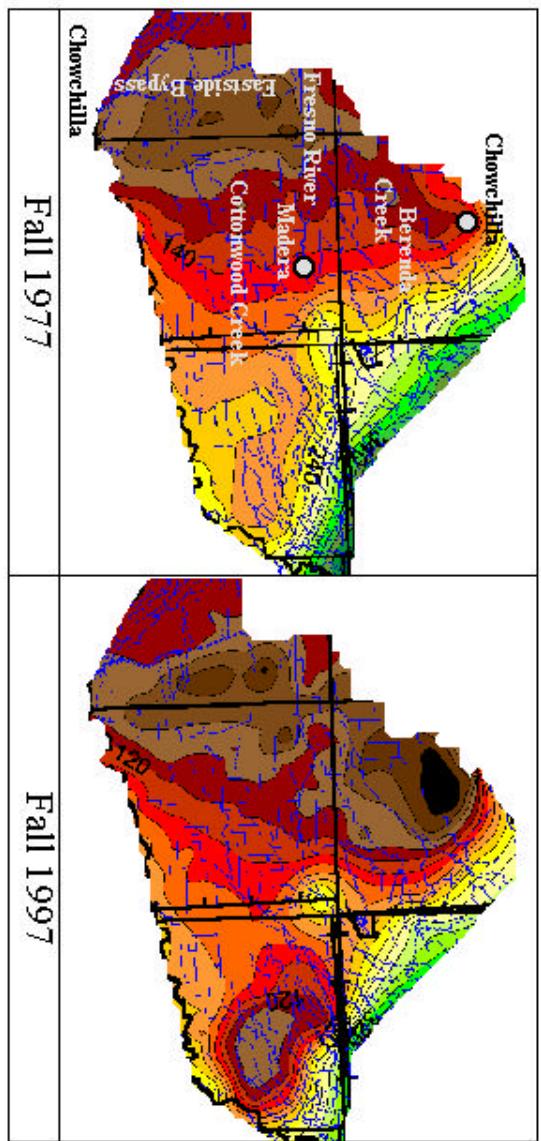


## Kings Basin

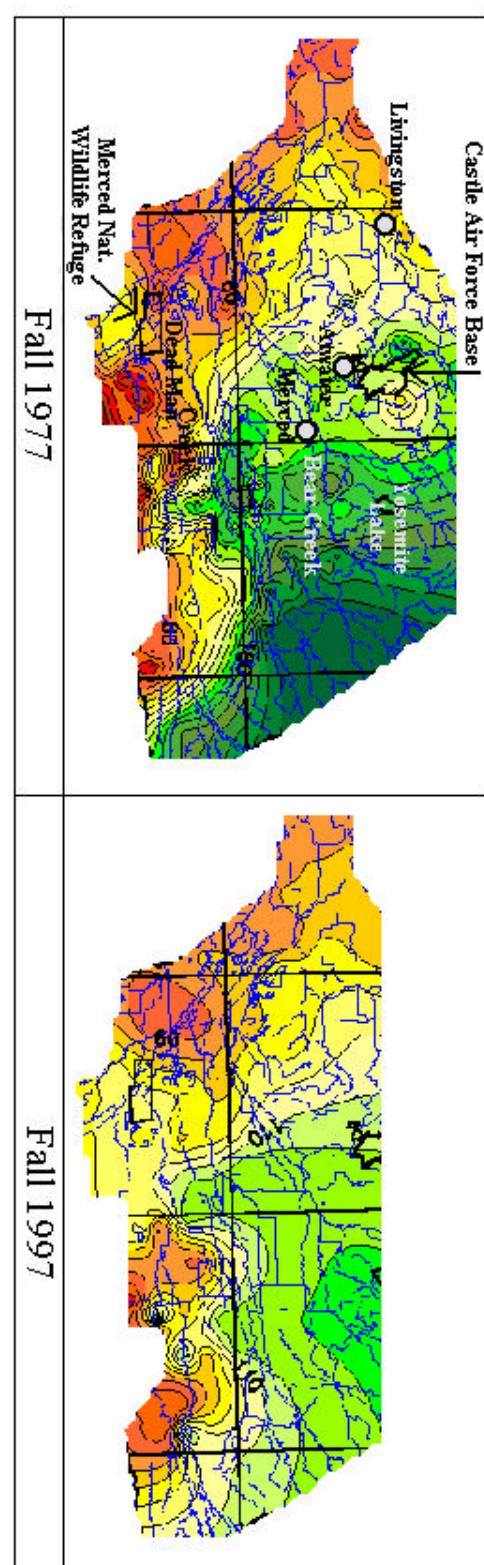


## Madera Basin

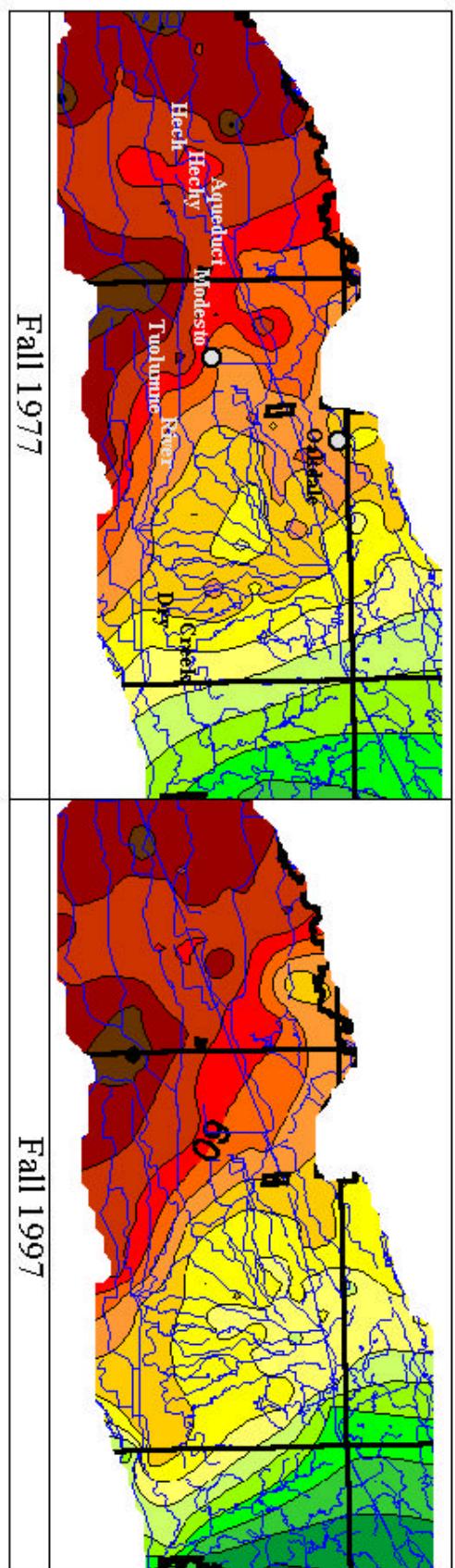
E-6



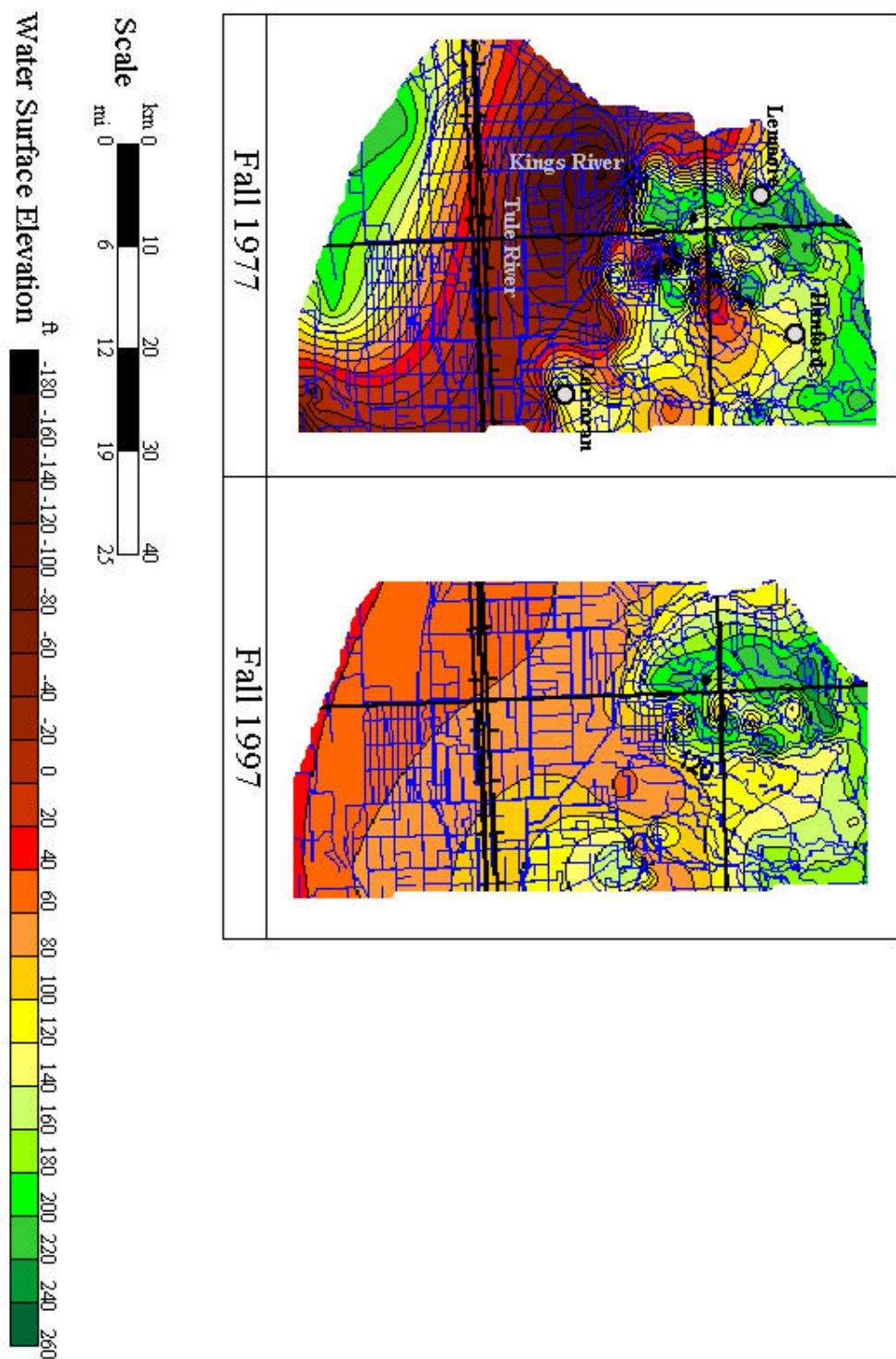
## Merced Basin



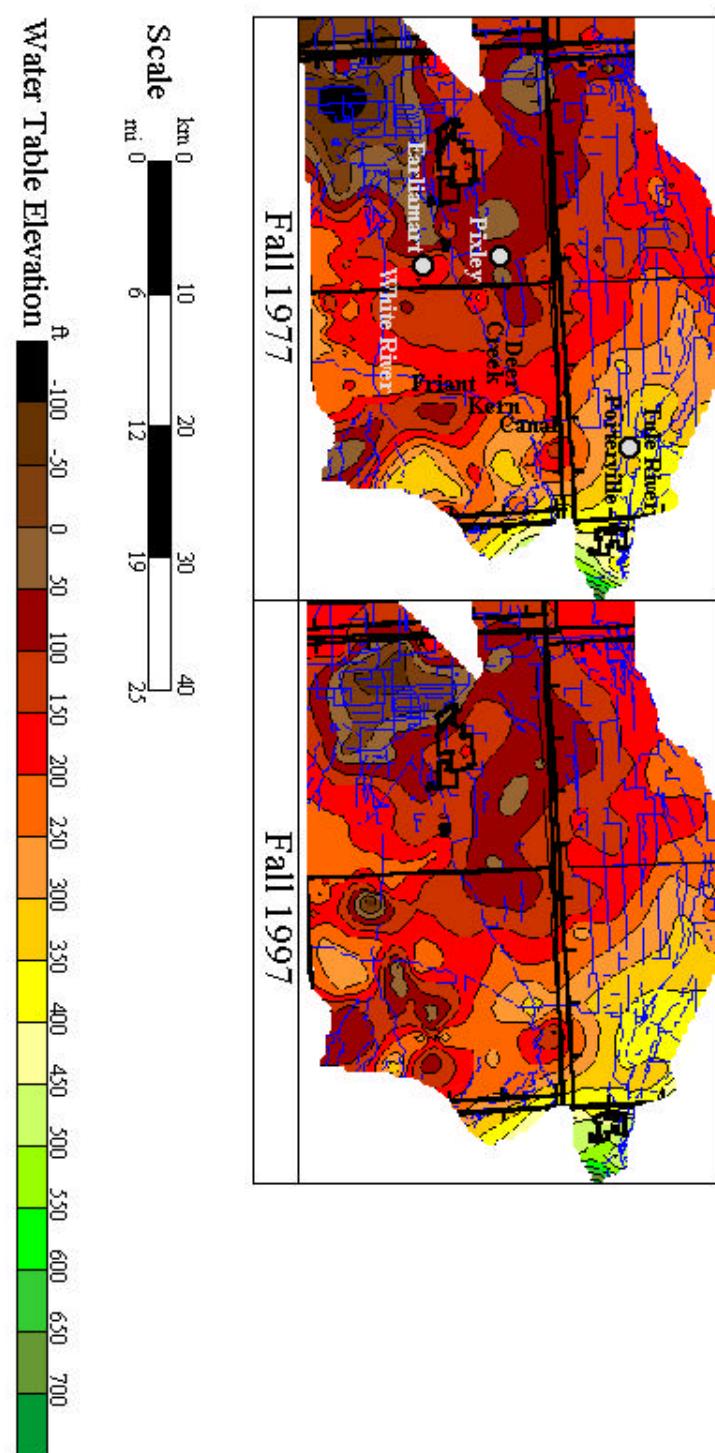
## Modesto Basin



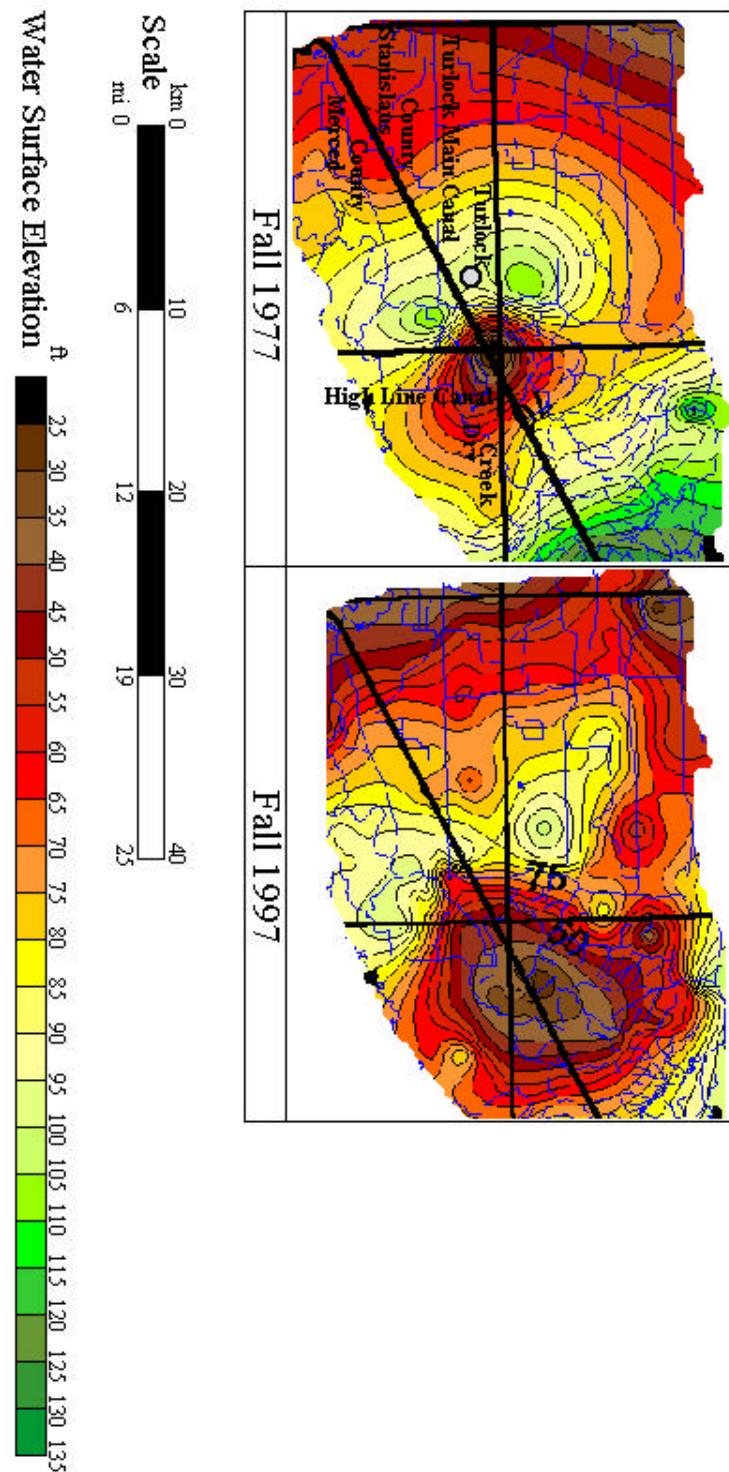
## Tulare Lake Basin



## Tule Basin



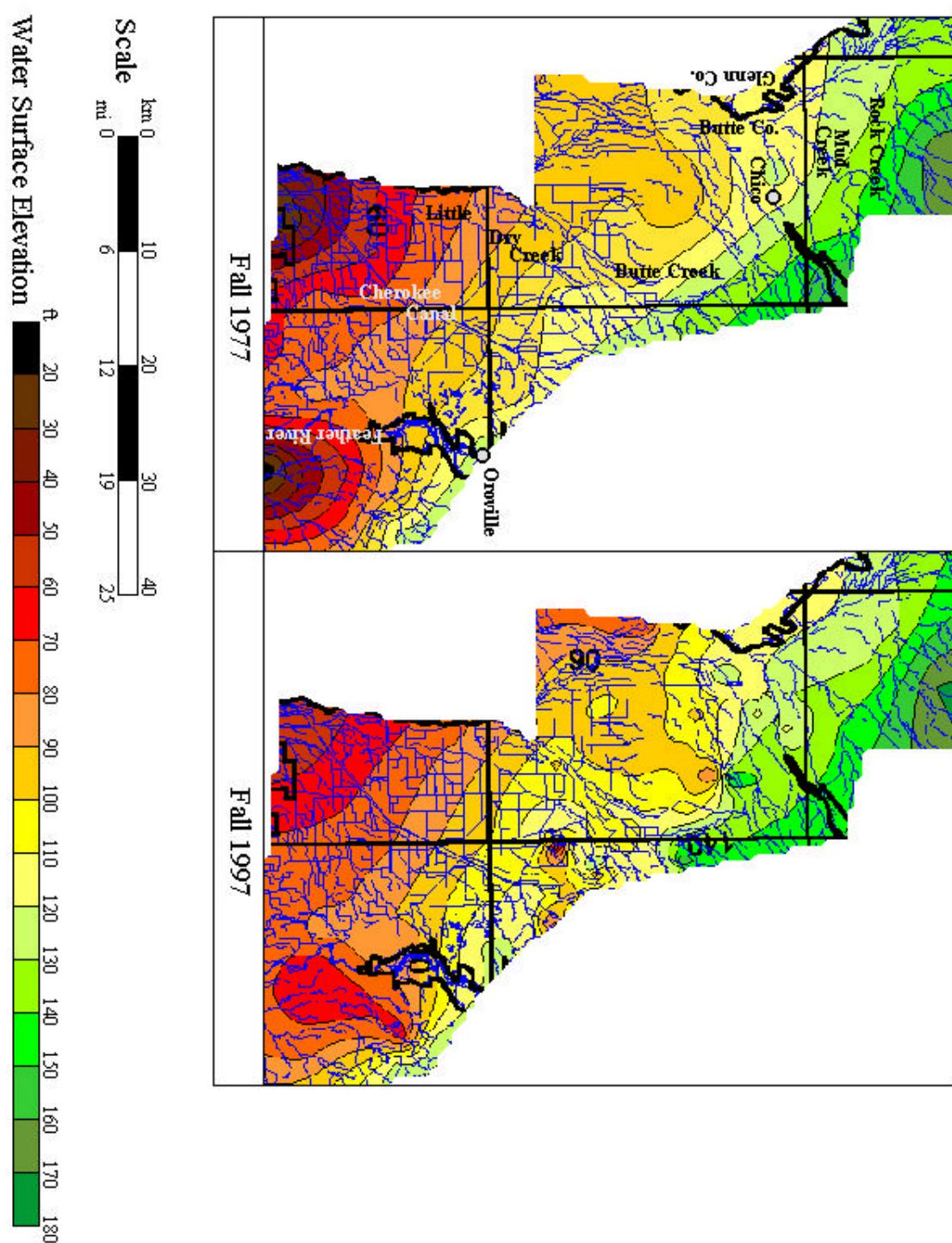
## Turlock Basin



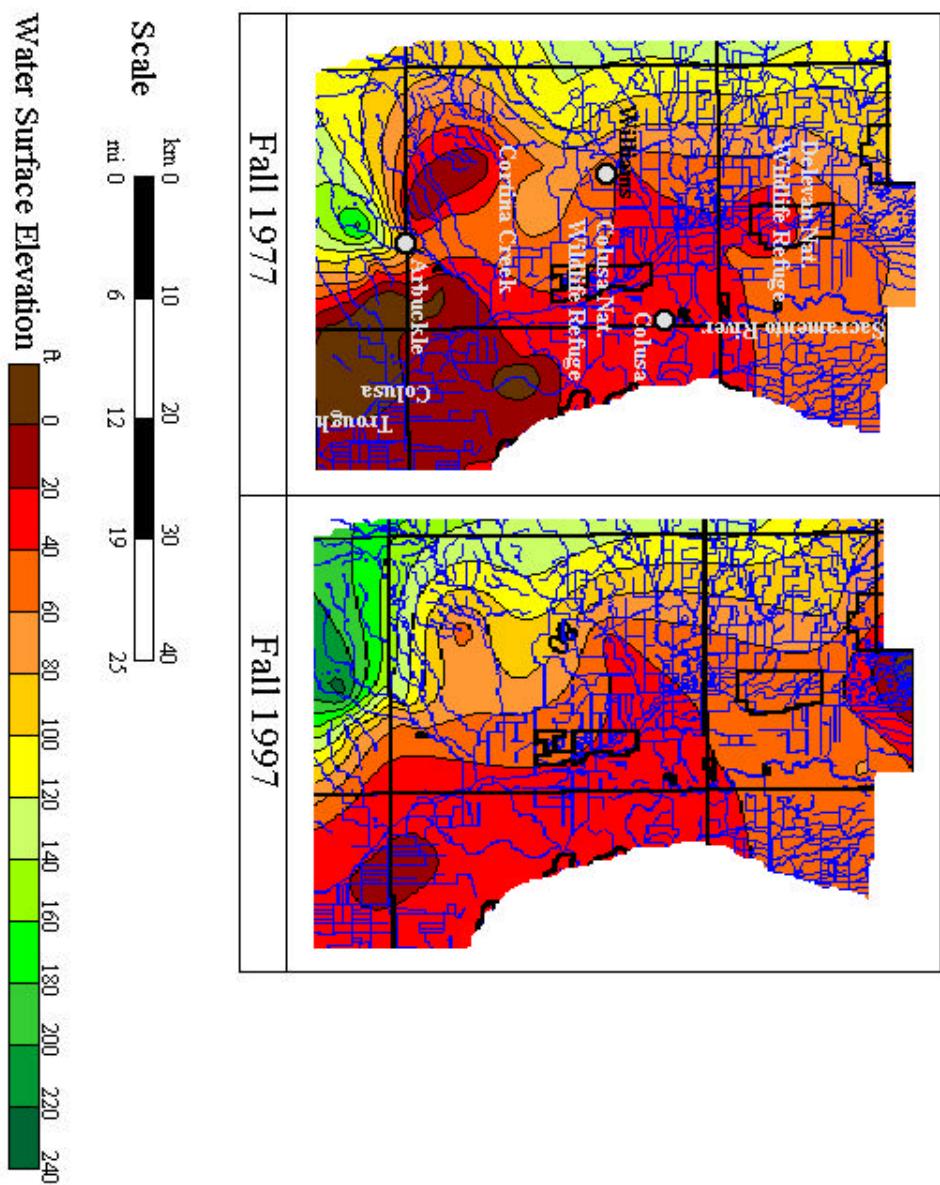
## **Appendix F: Basin Maps**

Even though the Sacramento Valley index did not include a Hydrologic Conductivity Sub-Index, we have included the water basin maps for Fall 1977 and Fall 1997 for comparative purposes.

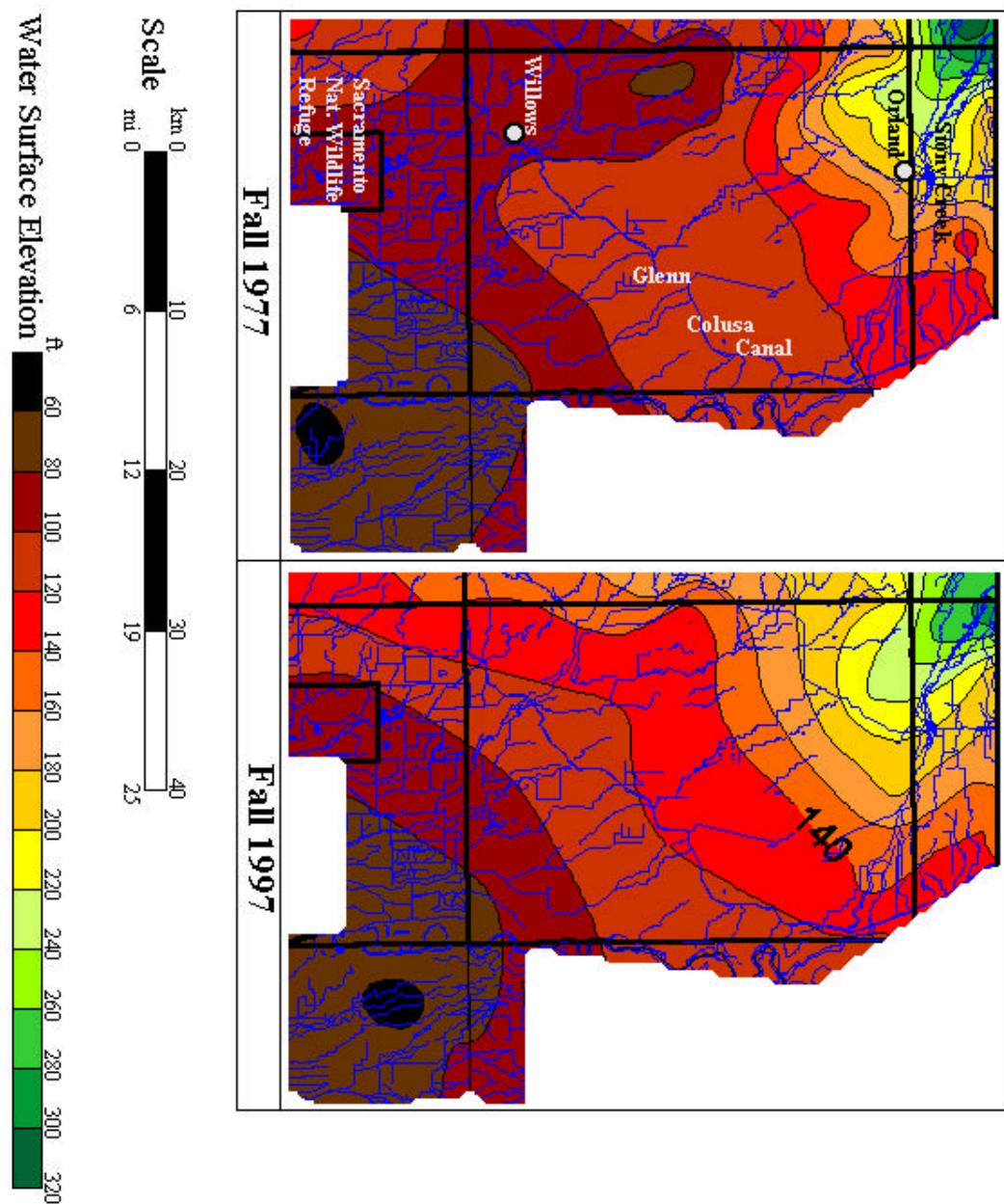
## Butte Basin



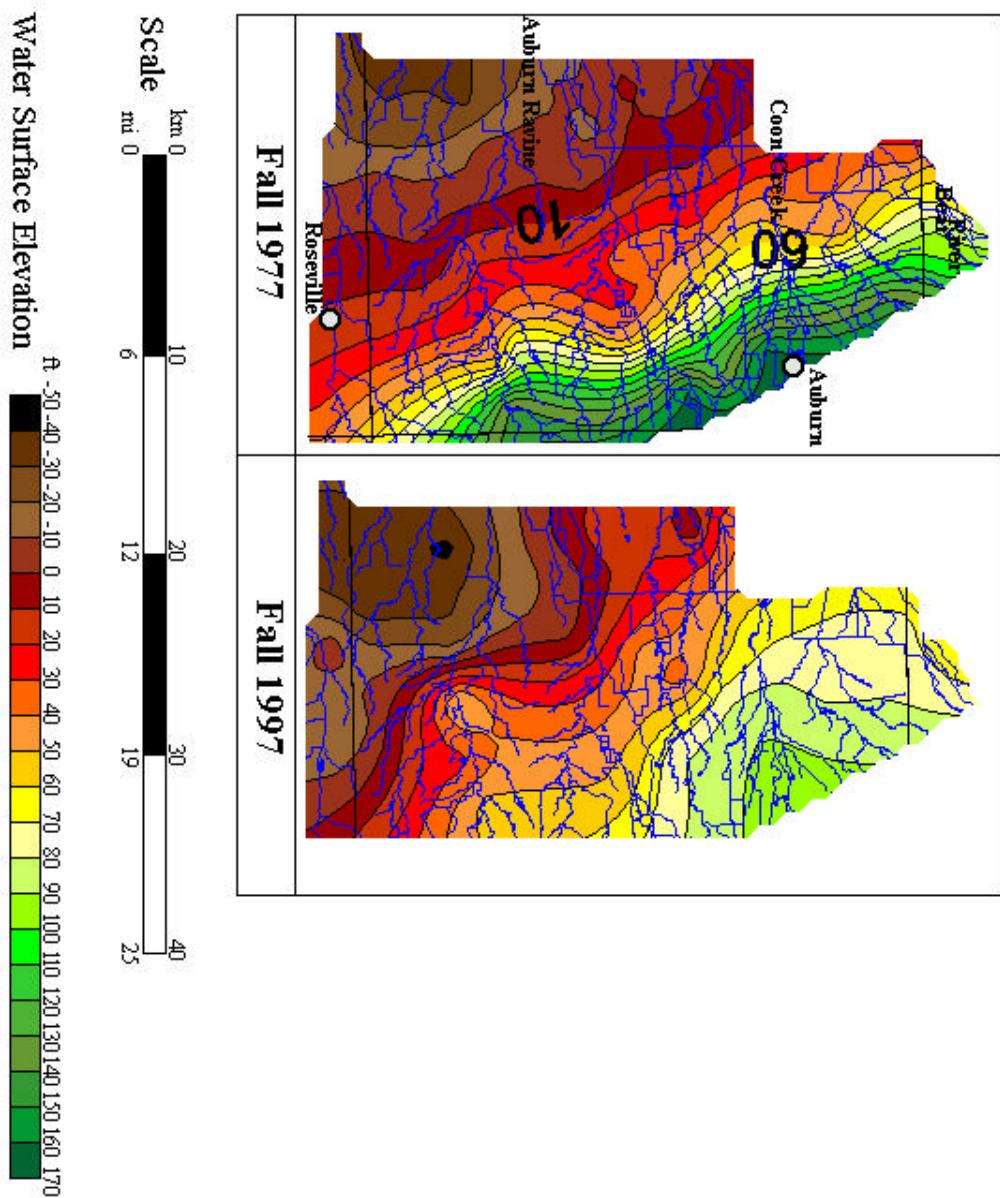
## Colusa Basin



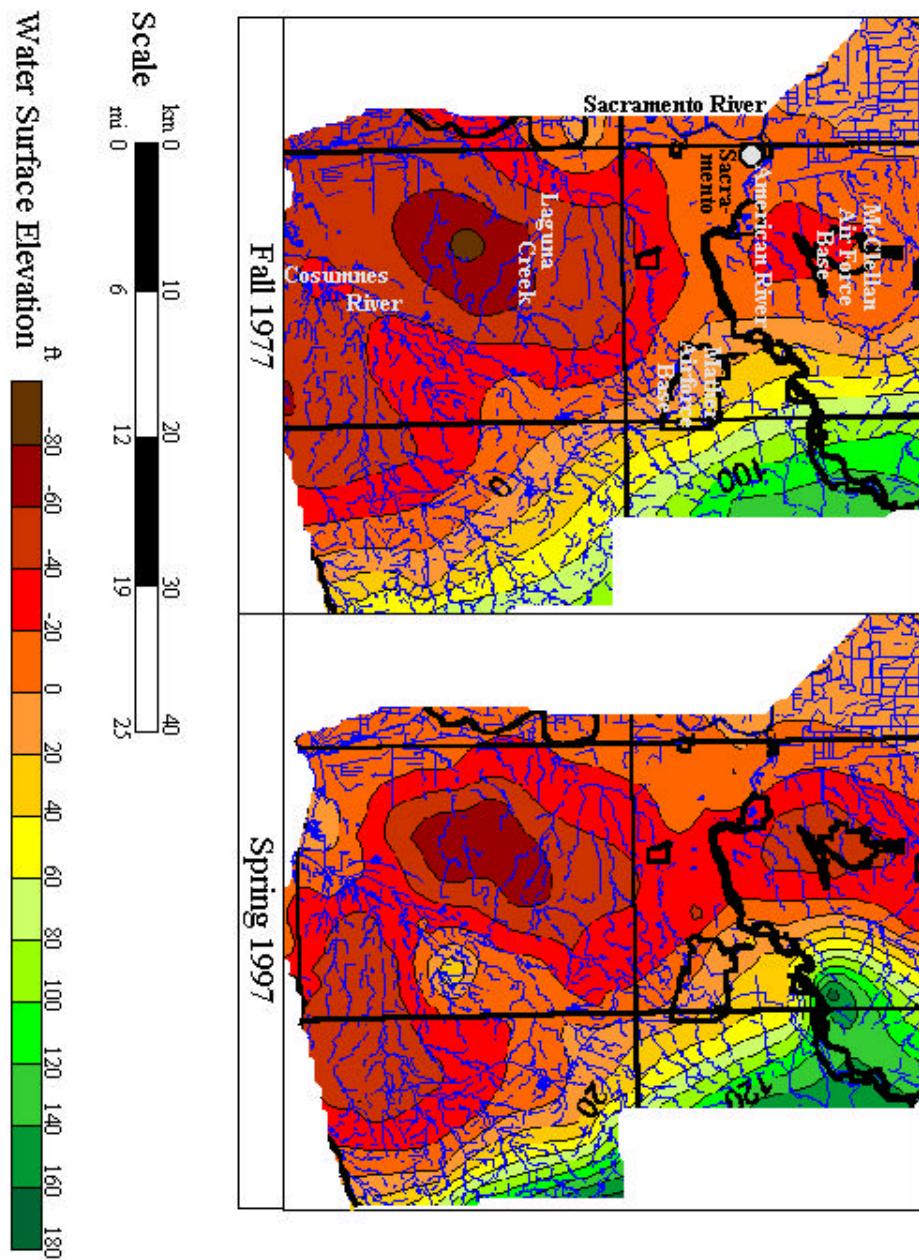
## Glenn Basin



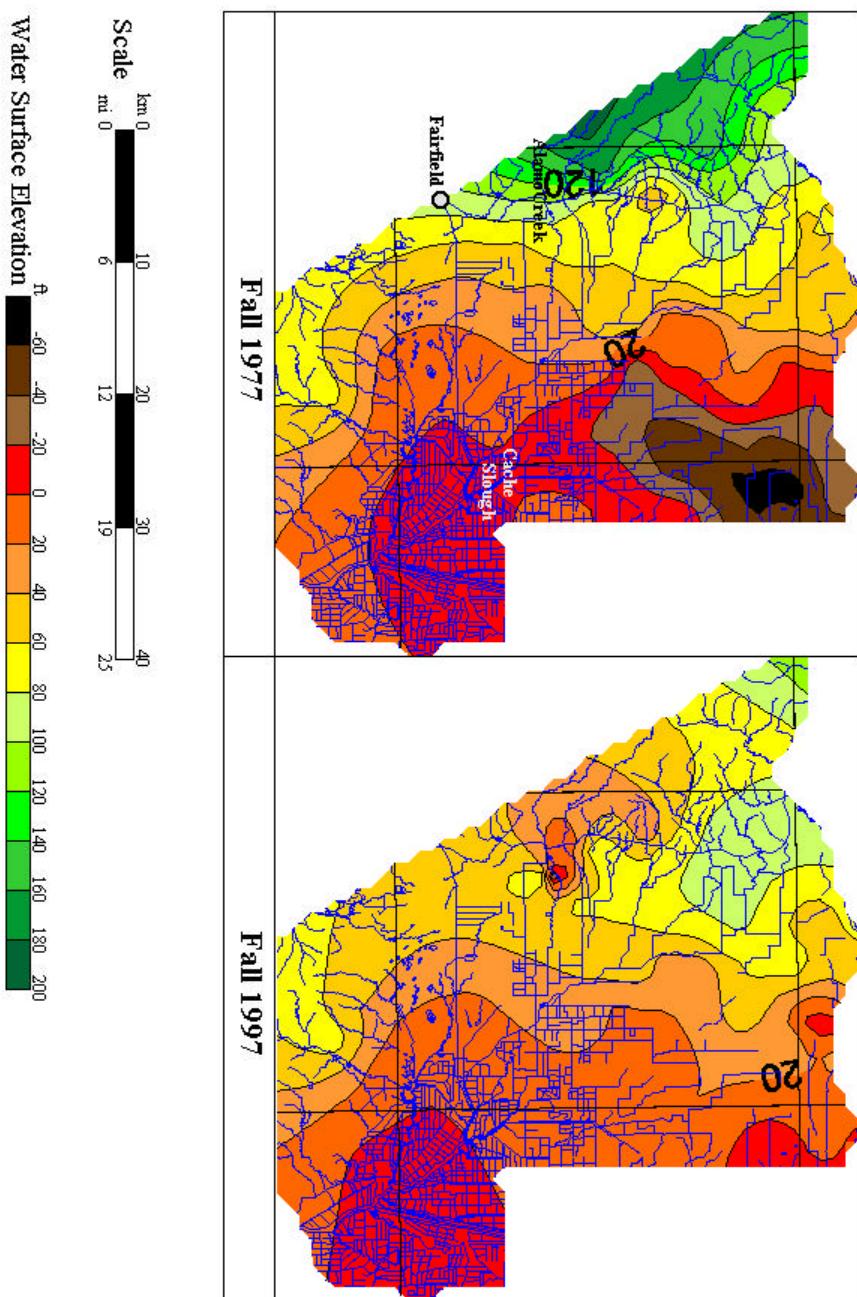
## Placer Basin



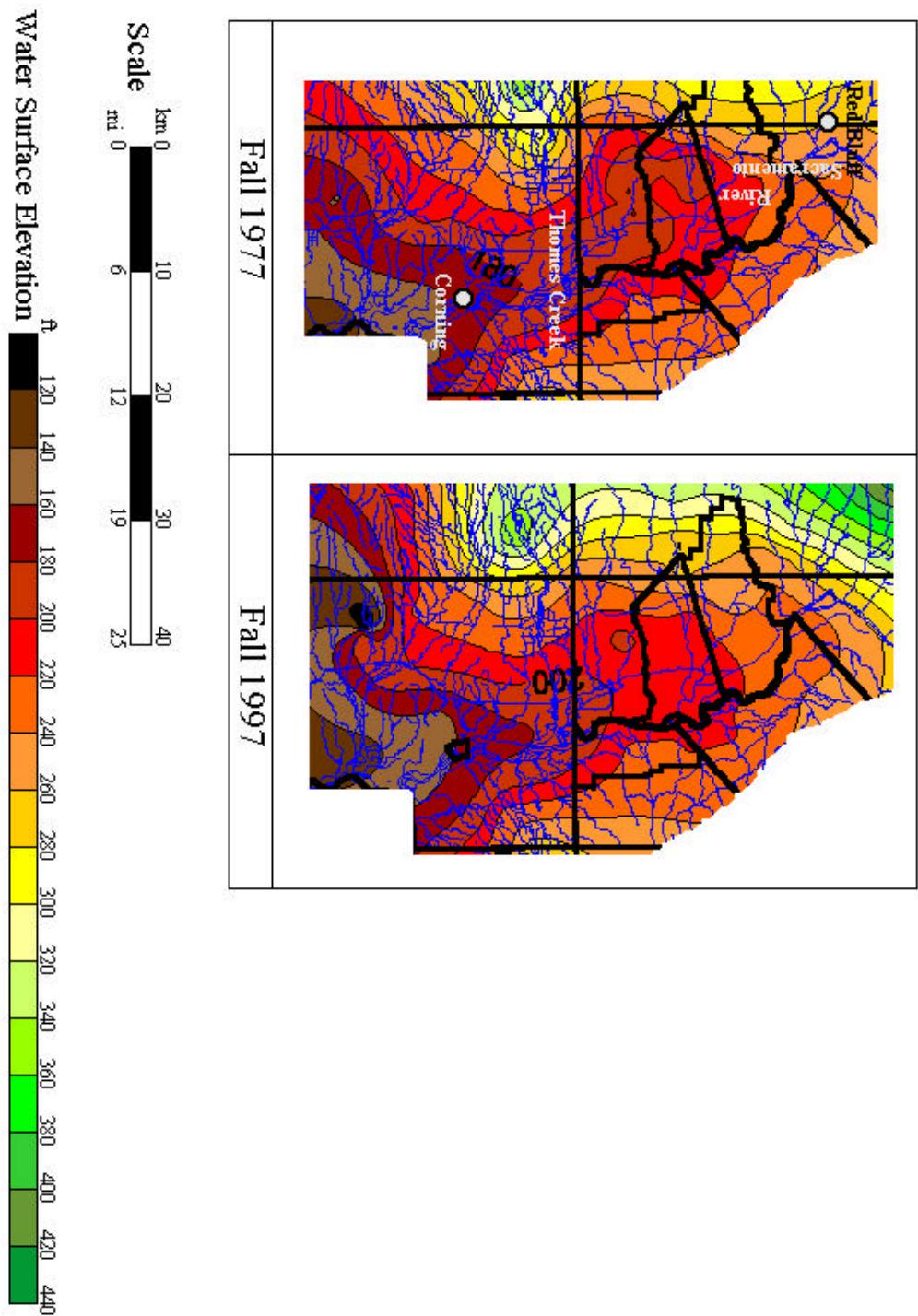
## Sacramento Basin



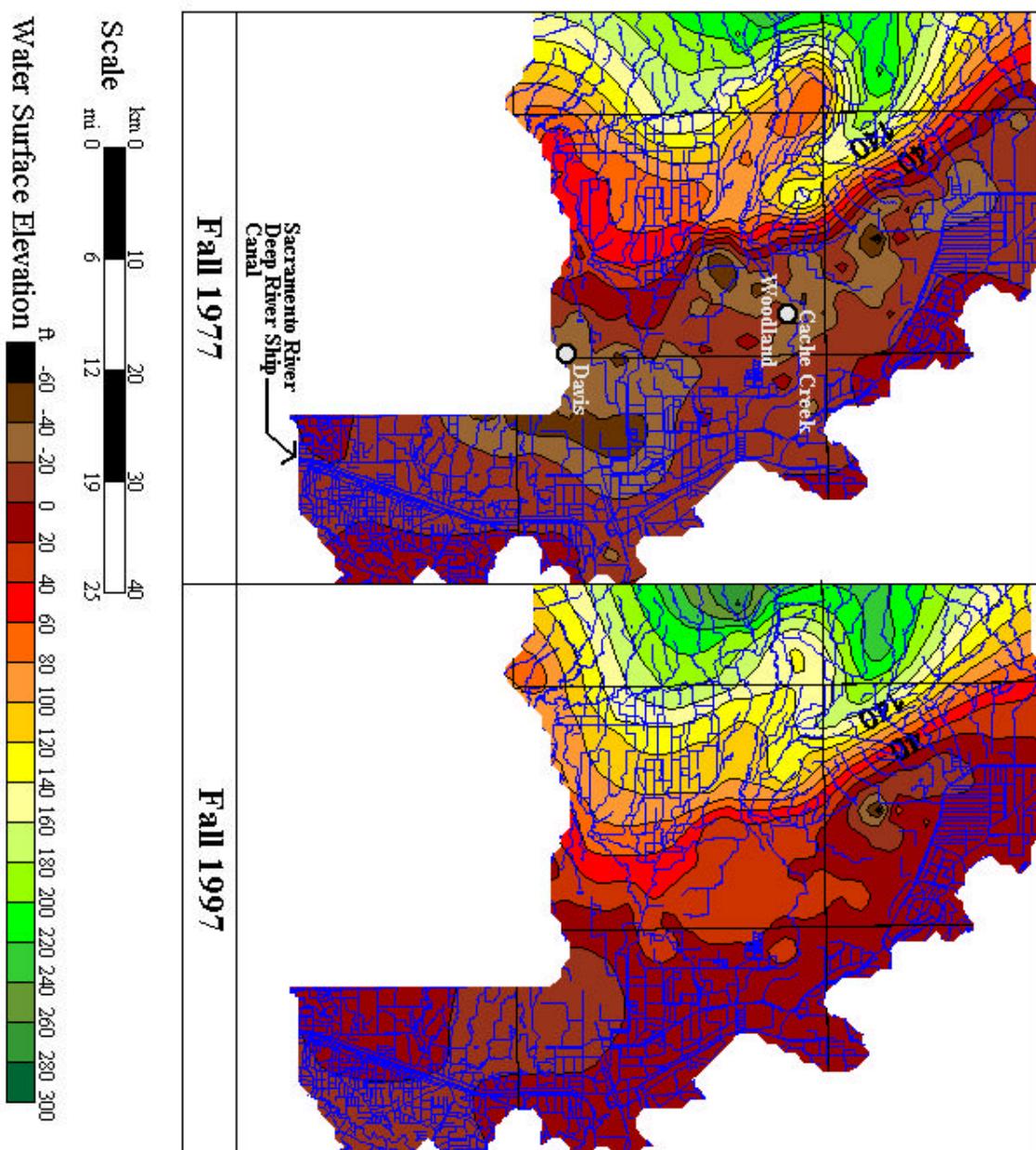
Solano Basin



## Tehama Basin



Yolo Basin



## Yuba Basin

