additional details related to the plans to improve the monitoring network for GDEs and ISW within the subbasin.

   a. Issue: The GSP states that the ISW representative monitoring network will also be used to monitor GDEs. The GSP does not present any information or figures to support its assertion that the ISW monitoring sites are located sufficiently near to GDEs to assess shallow groundwater levels in those areas. While the Department appreciates the GSP's acknowledgement of data gaps related to the characterization of GDEs and ISW within the subbasin and the GSP's proposed plan to install up to an additional 10 shallow monitoring wells, the GSP does not provide details on planned locations or timelines for installation of these additional monitoring locations.
   b. Recommendation: The GSP should include additional detail related to the anticipated timeline for installation of additional wells to further refine ISW and GDE characterization and management. The Department recommends that the GSP assess the locations of special status species within the subbasin to determine which GDE areas likely provide priority habitat. GDE areas and ISW that support special status species or are most at risk of negative impacts due to groundwater pumping should be prioritized for monitoring to inform management actions (See Comment #2(v)).

4. **Comment #4** – **Sustainable Management Criteria** (5.3.6 Depletion of Interconnected Surface Water, 5.4.6 Depletions of Interconnected Surface Water; starting pages 5-15 and 5-30): Interconnected surface water sustainable management criteria (SMC) may not protect against undesirable results for fish and wildlife beneficial uses and users.
   a. Issues:
      i. Minimum Thresholds: Minimum thresholds (MTs) for ISW are set at 10 feet below the measured historical low for each representative monitoring well. The GSP states that establishing MTs below the historic lows is necessary to provide a sufficient margin of operational flexibility during GSP implementation, and that no undesirable results were observed at the historic low; however, the GSP does not include sufficient analysis or discussion to support this claim. In 2015, the second of back-to-back critically dry water years in the Sacramento Valley which resulted in recent historical low groundwater levels, vegetated and aquatic GDEs experienced adverse impacts including stressed or dying riparian vegetation, poor instream habitat availability, and increased water temperatures (DFW 2019). It is unclear what, if any, studies or

analyses were completed to assess whether environmental users within the subbasin experienced undesirable results at the historical low groundwater levels, or what metrics the GSP would evaluate to determine the presence of an undesirable result for GDEs or ISW in the event of additional groundwater decline beyond the historic low as the MTs allow. The ISW SMC are also referenced as protective of GDE beneficial users of groundwater according to the GSP, but the supporting discussion focuses on groundwater gradients and associated depletions. No analysis is presented that characterizes whether the established MTs are sufficient to maintain water levels that have historically been shallow enough to support GDEs, or if the MTs would permit groundwater levels to fall below root zones, removing groundwater as an available water source to some GDEs. If MTs are not protective of GDE access to groundwater supplies, significant impacts to environmental beneficial users of groundwater will likely be experienced before MTs are reached. Furthermore, the GSP reports annual net values for streamflow depletion from the modeled baseline conditions, baseline conditions with climate change, and baseline conditions with climate change and project scenarios. However, the annual analysis does not provide sufficient detail on the timing of depletions to adequately assess potential impacts to environmental users (See Comment #1). The GSP compares modeled annual depletions to *total* annual flow in these river systems, and uses this annual normalization to characterize groundwater contributions to ISW as nominal. This coarse annual comparison does not take into account how groundwater contributions to river base flows are often proportionately greater in dry years or during annual low-flow seasons, or how groundwater contributions play a key role in maintaining water quality and temperatures. Properly contextualizing groundwater contributions to surface water is especially important to understanding potential impacts of groundwater depletion on surface waters and their ecosystems, particularly when the GSP states that streamflow accretion is expected to decrease by 38.3% with climate change impacts (line 9, page 6-2).

ii. Undesirable Results: The GSP requires 25% of ISW representative monitoring wells in the subbasin to fall below their MTs for 24 consecutive months before identifying an undesirable result to GDEs or ISW. While environmental users are adapted to sustain short-term lowering of groundwater levels during dry periods, environmental users may not be able to sustain extended periods of reduced groundwater access that would result from allowing groundwater levels to fall to historic lows for 24 months. By the time an undesirable result is declared, and management actions are triggered in response to the undesirable result, environmental groundwater users will have already experienced significant stress and potentially irreversible mortality.

b. Recommendations:
    i. <u>Minimum Thresholds</u>: The Department recommends the GSP reselect minimum thresholds that would better protect environmental uses and users of groundwater, rather than enabling declines in groundwater levels over the implementation horizon beyond the historic low. Additional analyses of the specific impacts of the established thresholds on GDE and ISW beneficial users of groundwater should be included.
    ii. <u>Undesirable Results</u>: The Department recommends the GSP reconsider the 24-month duration of groundwater levels below MTs required to constitute an undesirable result, recognizing that extended durations of groundwater inaccessibility for environmental users will likely lead to adverse impacts that cannot be easily reversed when groundwater levels recover. At a minimum, the Department recommends identifying physical triggers (e.g., declining Normalized Difference Vegetation Index signals) and associated management actions (e.g., demand reduction) to enable the GSAs to identify and mitigate localized patterns of lowering groundwater or depleted ISW and associated negative impacts before the second year of MT exceedances yields more significant and undesirable impacts. These interim action triggers will help preempt irreversible losses and undesirable results for environmental users.

5. **Comment #5** – **Projects and Management Actions** (PMAs) (6.5.2.3 Long-term Demand Management Action, 6.5.2.4 Strategic Temporary Land Idling for Drought and Localized Short-Term Groundwater Management; starting page 6-84): The GSP should include additional metrics and timelines related to the implementation of demand management within the subbasin.
    a. Issue: The Department appreciates the GSP’s identification of both short- and long-term demand management actions that will serve as a “backstop” to the other identified PMAs. As the other PMAs focus largely on implementing recharge projects that may be costly, rely on securing additional surface water supplies, and/or require potentially lengthy

permitting processes, demand management may be necessary in instances where a quick response to undesirable results within the subbasin is needed. Though the GSP identifies various demand management strategies, the GSP states that these management actions are in the "early conceptual stage" and as such, no timelines have been determined.

b. Recommendation: The Department recommends detailing specific timelines and metrics that would trigger the implementation of the identified demand management scenarios should recharge projects encounter delays or fail to produce the anticipated groundwater benefits to the subbasin.

CONCLUSION

In conclusion, though the draft GSP provides detailed characterization of subbasin groundwater conditions, the GSP lacks a robust analysis of potential impacts to environmental beneficial users and should establish more protective management criteria. The Department recommends that the Colusa Subbasin GSAs address the above comments before GSP submission to DWR to best prepare for the following regulatory criteria for plan evaluation:

1. The assumptions, criteria, findings, and objectives, including the sustainability goal, undesirable results, minimum thresholds, measurable objectives, and interim milestones are not reasonable and/or not supported by the best available information and best available science (23 CCR § 355.4(b)(1)). (See Comment #1, 2, 4)
2. The GSP does not identify reasonable measures and schedules to eliminate data gaps. (23 CCR § 355.4(b)(2)) (See Comment #3)
3. The interests of the beneficial uses and users of groundwater in the basin, and the land uses and property interests potentially affected by the use of groundwater in the basin, have not been considered. (23 CCR § 355.4(b)(4)) (See Comment #1, 2, 4)
4. The projects and management actions are not feasible and/or not likely to prevent undesirable results and ensure that the basin is operated within its sustainable yield. (23 CCR § 355.4(b)(5)) (See Comment #4)

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Attachment B

LITERATURE CITED

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CITY COUNCIL
Bruce T. Roundy, Mayor
Jeffrey A. Tolley, Vice-Mayor
Dennis Hoffman
William "Billy" Irvin
Chris Dobbs

CITY OFFICIALS
Janet Wackerman
City Clerk

Leticia Espinosa
City Treasurer

CITY OF ORLAND

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CITY MANAGER
Peter R. Carr

Date: October 20, 2021

To: Lisa Hunter, Program Manager, Glenn Groundwater Authority

From: Orland City Council

Subject: Comments on Draft Colusa Subbasin Groundwater Sustainability Plan

On behalf of the residents of the City of Orland, the Orland City Council recognizes the admirable cooperation of various water users in developing a plan, the scientific data that went into development of the plan, and the inherent assumptions necessarily undergirding the plan. In the spirit of public comment on the plan, we offer the following observations:

1. Chapter 5 states that the subbasin is currently being managed sustainably without undesirable results despite over 150 domestic wells going dry this summer alone as 2021 data is not yet included in plan development. It is notable that a key partner in the draft plan explained at the October 13th public meeting, "The current actual drought is more compelling than modeled future sustainability challenges."

2. The plan's allowance for up to 20% of domestic wells going dry may be understandable in light of the age and depths of most of the wells. However, depletion of up to 5% of groundwater storage (over 5 years) and inelastic subsidence of up to ½ foot per year were also considered acceptable in the July version of the draft plan, apparently due to an estimate that we still have 26-140 million AF (acre feet) of water in the aquifer. Consultants to the GGA suggest that 26M AF is reliably established, but the estimate of upwards of 140M AF is more of a projection. We are concerned about any reliance on the 140M AF estimate, and suggest that the subbasin should be more conservatively managed to an assumption of 26M AF.

3. We welcome the recent consultant proposal, adopted by the Board October 11th, to revise the plan with an amendment tightening the measurable objectives (MO) and minimum thresholds (MT) for inelastic subsidence, as the draft plan's original allowance for excessive subsidence would have exposed municipal services like water, wastewater and storm drainage to unacceptable risk of severe disruption.

4. City of Orland observes that the draft plan as written does not appear to adequately protect the integrity of domestic and municipal drinking water wells. With most said wells being less

than 200' deep, more than 20% would be dry by the time well depth MO were reached and almost all would be dry by the point MT were reached. It would seem that the MO and MT for well depths should be reconsidered and revised to a more conservative and protective standard.

5. Finally, we commend the GGA Board for its many projects in progress, planned and contemplated, as laid forth in Chapter 6. However, there do not yet appear to be real "triggers" that would commit the GGA to certain substantive actions when passing MO and approaching MT. We hope the GGA works with the State and consultants in coming years to develop and specify such triggers as a backstop to recharge projects in order to truly protect the precious drinking water resources on which the people of Orland and Glenn County rely.

Thank you for your consideration of our comments.

For the Orland City Council:

Bruce T. Roundy

Bruce T. Roundy, Mayor

Janet Wackerman

Janet Wackerman, City Clerk

GCID
Glenn-Colusa Irrigation District
Serving Our Lands and Environment Sustainably
Water Rights Established in 1883

DATE: October 25, 2021

TO:
Colusa Groundwater Authority
Glenn Groundwater Authority
Corning Subbasin Groundwater Sustainability Agency
Tehama County Flood Control & Water Conservation District Groundwater Sustainability Agency
Butte Subbasin Groundwater Sustainability Agencies (all eleven)
Vina and Rock Creek Reclamation District Groundwater Sustainability Agencies

FROM: Holly Dawley, GCID Water Resources Manager

SUBJECT: Support for Groundwater Sustainability Plans and Concern about Groundwater Surface Water Interactions

---

Glenn-Colusa Irrigation District (GCID) is located in the heart of the Sacramento Valley; we are the largest and one of the oldest diverters of water from the Sacramento River. GCID diverts water from the Sacramento River through a 65-mile long irrigation canal into a complex system of nearly 500 miles of laterals. The water is delivered to more than 1,200 families who farm approximately 141,000 acres of valuable, productive agricultural land. More than $270 million of agricultural products are produced annually on Glenn-Colusa Irrigation District farms, helping to sustain an estimated 12,000 jobs in the region. GCID is also the sole source of surface water deliveries for three wildlife refuges – the Sacramento, Delevan and Colusa National Wildlife Refuges that comprise over 20,000 acres of critical wildlife habitat. Winter water supplied by GCID to thousands of acres of rice land also provides a rich oasis for migrating waterfowl.

GCID is an active member of the Colusa Groundwater Authority, the Glenn Groundwater Authority, and the Corning Subbasin Groundwater Sustainability Agency.

Support for Groundwater Sustainability Plans

GCID appreciates the opportunity to provide comment to your agency for Groundwater Sustainability Planning in the Sacramento Valley (Valley). As a member of three Groundwater Sustainability Agencies (GSAs) within the Valley, GCID staff have valued our participation in the development of two Draft Groundwater Sustainability Plans (GSPs) and support a collaborative approach to management across a shared resource. We support the adoption of the GSPs by each of the GSAs to meet the January 31, 2022, deadline and we look forward to continued participation during implementation.

Concern about Groundwater Surface Water Interactions

While we support the adoption of the GSPs, this communication serves as a formal written comment to highlight and express a particular area of concern that could lead to the development of an incomplete decision framework and compromise the stability afforded to groundwater users in the various Sacramento Valley subbasins and more specifically to surface water users and senior water right holders which includes our District. We are writing to express deep concern regarding the lack of consideration in the GSPs about stream-aquifer interactions and impacts from unrestricted groundwater pumping.

This year in response to historically dry conditions, GCID and our fellow Sacramento River Settlement Contractors (SRSCs) took a multitude of voluntary actions significantly reducing the supply to our water users. These actions collaboratively supported watershed objectives in the face of declining storage and identified environmental concerns. While GCID and its partners were working daily for months with Central Valley Project (CVP) operators and State resource agencies to reduce surface water use and stabilize flows in the Sacramento River to help with Delta outflows and environmental needs, groundwater pumpers accessed the resource unabated impacting the stream flows we were actively working to stabilize.

As a significant contributor to groundwater recharge within the Valley, we only utilize that resource in years of shortage. We contribute every year to over 100,000 acre-feet (*Colusa GSP Draft, Appendix 3D, pg. 27*) of groundwater recharge even in Shasta critically dry years. However, we only utilize the resource when our surface water supplies are diminished by drought. Even with all of our voluntary surface water reductions in 2021, we only utilized 20,000 ac-ft of groundwater, while taking over 20,000 acres of land out of production to balance our supply and demand.

According to the Draft GSPs for Vina, Butte, Corning, and Colusa Subbasins, current year estimates of groundwater pumping, summarized in the table below, are over 1 million acre-feet per year (ac-ft/yr) in the region that surrounds our District.

Table 1, Groundwater Pumping in Subbasins in and around GCID (TAF)

	Historical	Current	Future, No Climate Change	Future, 2030 Climate Change	Future, 2070 Climate Change
Butte[a]	142.2	162.8	162.6	189.4	210.5
Vina[b]	243.5	209.2	215.8	225.9	238
Colusa[c]	502	499	499	525	559
Corning[d]	132.3	153		159.3	167.3
Totals (TAF)	***1020***	***1024***	***877.4***	***1099.6***	***1174.8***

Notes

[a]Butte Groundwater Sustainability Plan, Public Review Draft, Section 2, pg. 2-65

[b]Vina Groundwater Sustainability Plan, Public Final Draft, Section 2, pg. 82

[c]Colusa Groundwater Sustainability Plan, Final Draft Report, Section 3, pg. 3-96

[d]Corning Groundwater Sustainability Plan, Public Review Draft, Section 4, pg. 4-69

This groundwater pumping impacts groundwater storage as evidenced by declining groundwater levels and impacts surface-groundwater interactions as evidenced by decreased streamflow and more reaches becoming losing streams. These numbers indicate a need to understand the origin of groundwater pumping and the potential impacts to the subbasins as water users pull from a shared resource. In looking at these pumping numbers, a particular concern that becomes palpable is that all the GSPs identify increased groundwater pumping which will result in groundwater storage impacts and will result in increased streamflow depletion.

After reviewing the documents, senior surface water rights holders and their operations seem to be a minor share of the use of the resource, but a significant contributor to the replenishment of the resource. We ask that as GSAs move from planning to implementation and continue to look for opportunities to leverage surface water over groundwater, you consider those members and partners with senior water rights and stable contracts that contribute to our shared aquifers and provide high quality environmental habitat. We look forward to better identifying and quantifying this benefit for the subbasins during implementation. Further, we ask that GSAs work with their County partners to consider land use planning and accountability.

Thank you for your consideration of these concerns. We urge you to consider language to address or at least acknowledge this issue in the GSPs. We look forward to working through this issue during implementation.

October 31, 2021

Colusa Groundwater Authority
1213 Market Street
Colusa, CA 95932

Submitted via email:lhunter@countyofglenn.net; mfahey@countyofcolusa.com

Re: Public Comment Letter for Colusa Subbasin Draft GSP

Dear Mary Fahey,

On behalf of the above-listed organizations, we appreciate the opportunity to comment on the Draft Groundwater Sustainability Plan (GSP) for the Colusa Subbasin being prepared under the Sustainable Groundwater Management Act (SGMA). Our organizations are deeply engaged in and committed to the successful implementation of SGMA because we understand that groundwater is critical for the resilience of California's water portfolio, particularly in light of changing climate. Under the requirements of SGMA, Groundwater Sustainability Agencies (GSAs) must consider the interests of all beneficial uses and users of groundwater, such as domestic well owners, environmental users, surface water users, federal government, California Native American tribes and disadvantaged communities (Water Code 10723.2).

As stakeholder representatives for beneficial users of groundwater, our GSP review focuses on how well disadvantaged communities, drinking water users, tribes, climate change, and the environment were addressed in the GSP. While we appreciate that some basins have consulted us directly via focus groups, workshops, and working groups, we are providing public comment letters to all GSAs as a means to engage in the development of 2022 GSPs across the state. Recognizing that GSPs are complicated and resource intensive to develop, the intention of this letter is to provide constructive stakeholder feedback that can improve the GSP prior to submission to the State.

Based on our review, we have significant concerns regarding the treatment of key beneficial users in the Draft GSP and consider the GSP to be **insufficient** under SGMA. We highlight the following findings:

1. Beneficial uses and users **are not sufficiently** considered in GSP development.
    a. Human Right to Water considerations **are not sufficiently** incorporated.
    b. Public trust resources **are not sufficiently** considered.
    c. Impacts of Minimum Thresholds, Measurable Objectives and Undesirable Results on beneficial uses and users **are not sufficiently** analyzed.
2. Climate change **is not sufficiently** considered.

3. Data gaps **are not sufficiently** identified and the GSP **does not have a plan** to eliminate them.
4. Projects and Management Actions **do not sufficiently consider** potential impacts or benefits to beneficial uses and users.

Our specific comments related to the deficiencies of the Colusa Subbasin Draft GSP along with recommendations on how to reconcile them, are provided in detail in **Attachment A.**

Please refer to the enclosed list of attachments for additional technical recommendations:

Attachment A	GSP Specific Comments
Attachment B	SGMA Tools to address DAC, drinking water, and environmental beneficial uses and users
Attachment C	Freshwater species located in the basin
Attachment D	The Nature Conservancy's "Identifying GDEs under SGMA: Best Practices for using the NC Dataset"
Attachment E	Maps of representative monitoring sites in relation to key beneficial users

Thank you for fully considering our comments as you finalize your GSP.

Best Regards,

Ngodoo Atume
Water Policy Analyst
Clean Water Action/Clean Water Fund

J. Pablo Ortiz-Partida, Ph.D.
Western States Climate and Water Scientist
Union of Concerned Scientists

Samantha Arthur
Working Lands Program Director
Audubon California

Danielle V. Dolan

Danielle V. Dolan
Water Program Director
Local Government Commission

E.J. Remson
Senior Project Director, California Water Program
The Nature Conservancy

Melissa M. Rohde

Melissa M. Rohde
Groundwater Scientist
The Nature Conservancy

Amy Merrill, Ph.D.
Acting Director, California Program
American Rivers

Kristen N Culbert

Kristan Culbert
Associate Director, California Central Valley River Conservation
American Rivers

Attachment A

Specific Comments on the Colusa Subbasin Draft Groundwater Sustainability Plan

1. Consideration of Beneficial Uses and Users in GSP development

Consideration of beneficial uses and users in GSP development is contingent upon adequate identification and engagement of the appropriate stakeholders. The (A) identification, (B) engagement, and (C) consideration of disadvantaged communities, drinking water users, tribes,[1] groundwater dependent ecosystems, streams, wetlands, and freshwater species are essential for ensuring the GSP integrates existing state policies on the Human Right to Water and the Public Trust Doctrine.

A. Identification of Key Beneficial Uses and Users

Disadvantaged Communities, Drinking Water Users, and Tribes

The identification of Disadvantaged Communities (DACs), drinking water users, and tribes is **incomplete**. The GSP provides a map of tribal lands in the subbasin (Figure 2-5), and provides information on DACs, including identification by name and location on a map (Figure 2-6). However, the plan fails to clearly document the population of each DAC and the population dependent on groundwater as their source of drinking water in the subbasin.

While the plan provides a density map of domestic wells in the subbasin (Figure 2-7), the GSP fails to provide depth of these wells (such as minimum well depth, average well depth, or depth range) within the subbasin.

These missing elements are required for the GSAs to fully understand the specific interests and water demands of these beneficial users, and to support the consideration of beneficial users in the development of sustainable management criteria and selection of projects and management actions.

RECOMMENDATIONS

- Provide the population of each identified DAC. Identify the sources of drinking water for DAC members, including an estimate of how many people rely on groundwater (e.g., domestic wells, state small water systems, and public water systems).
- Include a map showing domestic well locations and average well depth across the subbasin (i.e., a map similar to Figure 2-7 showing average well depth per square mile).

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[1] Our letter provides a review of the identification and consideration of federally recognized tribes (Data source: SGMA Data viewer) within the GSP from non-tribal members and NGOs. Based on the likely incomplete information available to our organizations for this review, we recommend that the GSA utilize the California Department of Water Resources' "Engagement with Tribal Governments" Guidance Document (https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents) to comprehensively address these important beneficial users in their GSP.

Interconnected Surface Waters

The identification of Interconnected Surface Waters (ISWs) is **insufficient**, due to lack of a comprehensive map of ISWs in the subbasin. Despite the lack of an ISW map, the GSP presents a thorough, comprehensive evaluation of ISWs in the subbasin as presented in Appendix 3G of the GSP (Evaluation of Depletions of Interconnected Surface Water in the Colusa Subbasin). Streamflow depletion in the Colusa Subbasin was evaluated using the C2VSimFG-Colusa model, an integrated hydrologic flow model for the subbasin. The model is described in Appendix 3D (Model Development and Calibration) and used groundwater and surface water data from 1990-2015. Appendix 3D describes the groundwater data used in the model, including spatial location of wells and screening depths. The ISW section of the GSP could be improved with the following recommendations.

RECOMMENDATIONS

- Provide a map showing all the stream reaches in the subbasin, with reaches clearly labeled as interconnected (gaining and losing) or disconnected. Consider any segments with data gaps as potential ISWs and clearly mark them as such on maps provided in the GSP.

- Discuss stream reaches in the interior of the subbasin. For example, discuss whether they were included in the groundwater model and discuss relevant depth to groundwater data. Clearly state that they are considered to be disconnected, if that is the case, and what data was utilized to support that conclusion.

- To confirm the results of the groundwater modeling analysis and support conclusions about the smaller interior stream reaches, overlay the stream reaches shown with depth-to-groundwater contour maps to illustrate groundwater depths and the groundwater gradient near the stream reaches. For the depth-to-groundwater contour maps, use the best practices presented in Attachment D. Specifically, ensure that the first step is contouring groundwater elevations, and then subtracting this layer from land surface elevations from a Digital Elevation Model (DEM) to estimate depth-to-groundwater contours across the landscape. This will provide accurate contours of depth to groundwater along streams and other land surface depressions where GDEs are commonly found.

Groundwater Dependent Ecosystems

The identification of Groundwater Dependent Ecosystems (GDEs) is **insufficient**. The GSP took initial steps to identify and map GDEs using the Natural Communities Commonly Associated with Groundwater dataset (NC dataset). However, we found that some mapped features in the NC dataset were improperly disregarded. NC dataset polygons were incorrectly removed in areas adjacent to irrigated fields or due to the presence of surface water supplies. However, this removal criteria is flawed since GDEs, in addition to groundwater, can rely on multiple water sources – including shallow groundwater receiving inputs from irrigation return flow from nearby irrigated fields – simultaneously and at different temporal/spatial scales. NC dataset polygons adjacent to irrigated land or surface water supplies can still potentially be reliant on shallow groundwater aquifers, and therefore should not be removed solely based on their proximity to irrigated fields or surface water supplies.

The GSP states (3-82): "*Average spring groundwater level data from 2014 to 2018 indicates that shallow groundwater levels (i.e., within 30 feet of ground surface) exists throughout most of the* *subbasin. A depth to water (DTW) of 30 feet based on the average DTW for 2014 to 2018 was used as one of the primary criteria in the initial screening of potential GDEs.*" While we recognize that the period 2014-2018 represents multiple water year types, we recommend that a longer baseline period (10 years from 2005 to 2015) be established to characterize groundwater conditions.

The GSP does not provide an inventory of the flora or fauna species present in the subbasin's GDEs, except to discuss the four most prevalent vegetation species. Furthermore, the GSP does not acknowledge endangered, threatened, or special status species in the subbasin.

RECOMMENDATIONS

- Provide a comprehensive set of maps for the subbasin's GDEs. For example, provide a map of the NC Dataset. On the map, label polygons retained, removed, or added to/from the NC dataset (include the removal reason if polygons are not considered potential GDEs, or include the data source if polygons are added). Discuss how local groundwater data was used to verify whether polygons in the NC Dataset are supported by groundwater in an aquifer. Refer to Attachment D of this letter for best practices for using local groundwater data to verify whether polygons in the NC Dataset are supported by groundwater in an aquifer.

- Use depth-to-groundwater data from multiple seasons and water year types (e.g., wet, dry, average, drought) to determine the range of depth to groundwater around NC dataset polygons. We recommend that a baseline period (10 years from 2005 to 2015) be established to characterize groundwater conditions over multiple water year types. Refer to Attachment D of this letter for best practices for using local groundwater data to verify whether polygons in the NC Dataset are supported by groundwater in an aquifer.

- Provide depth-to-groundwater contour maps, noting the best practices presented in Attachment D. Specifically, ensure that the first step is contouring groundwater elevations, and then subtracting this layer from land surface elevations from a DEM to estimate depth-to-groundwater contours across the landscape.

- If insufficient data are available to describe groundwater conditions within or near polygons from the NC dataset, include those polygons as "Potential GDEs" in the GSP until data gaps are reconciled in the monitoring network. It is not clear from the description in the GSP whether NC dataset polygons labeled with a 'GDE Likelihood Score' of 1 to 3 on Figure 3-36 are retained as potential GDEs.

- Include an inventory of the fauna and flora present within the subbasin's GDEs (see Attachment C of this letter for a list of freshwater species located in the Colusa Subbasin). Note any threatened or endangered species.

Native Vegetation and Managed Wetlands

Native vegetation and managed wetlands are water use sectors that are required to be included in the water budget.[2,3] The integration of these ecosystems into the water budget is **sufficient** because the GSP included the groundwater demands of native vegetation and managed wetlands in the historical, current, and projected water budgets.

B. Engaging Stakeholders

Stakeholder Engagement during GSP Development

Stakeholder engagement during GSP development is **insufficient**. SGMA's requirement for public notice and engagement of stakeholders is not fully met by the description in the Stakeholder Communication and Engagement Plan (Appendix 2E).[4]

We note the following deficiencies with the overall stakeholder engagement process:

- The opportunities for public involvement and engagement with DACs, drinking water users, tribes, and environmental stakeholders are described in very general terms. They include technical and informational workshops and meetings open to the public. No specific outreach targeted to DACs, drinking water users, tribes, or environmental stakeholders is described in the GSP.

- The plan does not include a plan for continual opportunities for engagement through the *implementation* phase of the GSP for DACs, domestic well owners, tribes, and environmental stakeholders.

RECOMMENDATIONS

- In the Stakeholder Communication and Engagement Plan, describe active and targeted outreach to engage DACs, drinking water users, tribes, and environmental stakeholders throughout the GSP development and implementation phases. Refer to Attachment B for specific recommendations on how to actively engage stakeholders during all phases of the GSP process.

- Describe efforts to consult and engage with DACs and domestic well owners within the subbasin.

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[2] "'Water use sector' refers to categories of water demand based on the general land uses to which the water is applied, including urban, industrial, agricultural, managed wetlands, managed recharge, and native vegetation." [23 CCR §351(al)]

[3] "The water budget shall quantify the following, either through direct measurements or estimates based on data: (3) Outflows from the groundwater system by water use sector, including evapotranspiration, groundwater extraction, groundwater discharge to surface water sources, and subsurface groundwater outflow." [23 CCR §354.18]

[4] "A communication section of the Plan shall include a requirement that the GSP identify how it encourages the active involvement of diverse social, cultural, and economic elements of the population within the basin." [23 CCR §354.10(d)(3)]

- Utilize DWR's tribal engagement guidance to comprehensively address all tribes and tribal interests in the subbasin within the GSP.[5]

- Describe efforts to consult and engage with environmental stakeholders within the subbasin.

C. Considering Beneficial Uses and Users When Establishing Sustainable Management Criteria and Analyzing Impacts on Beneficial Uses and Users

The consideration of beneficial uses and users when establishing sustainable management criteria (SMC) is **insufficient**. The consideration of potential impacts on all beneficial users of groundwater in the basin are required when defining undesirable results and establishing minimum thresholds.[6,7,8]

Disadvantaged Communities and Drinking Water Users

For chronic lowering of groundwater levels, the minimum threshold at representative monitoring wells is calculated by finding the deeper value of: (1) 20th percentile of shallowest domestic well depths in the monitoring well's Thiessen polygon, and (2) 50% of range below the historical low groundwater elevation. The GSP states (p. 5-20): *"The GSAs chose this methodology for calculating the minimum threshold to balance the needs of multiple beneficial uses and users of the groundwater by allowing for adequate flexibility to compensate for drought periods while potentially protecting up to 80 percent of nearby domestic wells, therefore avoiding undesirable results. Additionally, anecdotal evidence provided by the GSA member stakeholders suggest that groundwater levels seen in 2015 did not result in significant and unreasonable impacts to beneficial uses and users. Although some wells in that period were dewatered, those wells were generally replaced with deeper wells. The GSAs therefore consider the historical low groundwater elevation to be protective of current and future beneficial uses and users."* Despite this analysis, the GSP does not sufficiently describe whether minimum thresholds will avoid significant and unreasonable loss of drinking water to domestic well users in those 20% not protected by the minimum threshold, and whether the undesirable results are consistent with the Human Right to Water policy.[9]

In addition, the GSP does not sufficiently describe or analyze direct or indirect impacts on DACs or tribes when defining undesirable results, nor does it describe how the groundwater levels minimum threshold will avoid significant and unreasonable impacts on beneficial users beyond 2015 and be consistent with Human Right to Water policy.

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[5] Engagement with Tribal Governments Guidance Document. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Sustainable-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents/Files/Guidance-Doc-for-SGM-Engagement-with-Tribal-Govt_ay_19.pdf

[6] "The description of undesirable results shall include [...] potential effects on the beneficial uses and users of groundwater, on land uses and property interests, and other potential effects that may occur or are occurring from undesirable results." [23 CCR §354.26(b)(3)]

[7] "The description of minimum thresholds shall include [...] how minimum thresholds may affect the interests of beneficial uses and users of groundwater or land uses and property interests." [23 CCR §354.28(b)(4)]

[8] "The description of minimum thresholds shall include [...] how state, federal, or local standards relate to the relevant sustainability indicator. If the minimum threshold differs from other regulatory standards, the agency shall explain the nature of and the basis for the difference." [23 CCR §354.28(b)(5)]

[9] California Water Code §106.3. Available at: https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=WAT&sectionNum=106.3

The GSP states (3-67): *“Groundwater quality concerns within the Colusa Subbasin include locally elevated levels of salinity, TDS, adjusted sodium absorption ratio, arsenic, boron, hexavalent chromium, iron, manganese, and nitrate.”* However, for degraded water quality, salinity is the only constituent of concern (COC) for which SMC are established in the subbasin. The minimum threshold for salinity has been established for electrical conductivity (EC) as the higher of either the recommended California Secondary Maximum Contaminant Level (SMCL), or the pre-2015 historical maximum recorded EC value. The use of the latter term, with no values associated with it, is inappropriate; the Plan must provide actual historical data identifying what this minimum threshold would be. Furthermore, this value should not in any case exceed the salinity objective in the Basin Plan.

The GSP states (5-11): *“Existing regulatory programs address most water quality concerns, and the CGA and GGA will coordinate with these programs, the lead regulatory agencies, and the regulated community within the Colusa Subbasin during implementation of this GSP, including during development and implementation of projects and management actions.”* However, SMC should be established for all COCs in the subbasin impacted or exacerbated by groundwater use and/or management, in addition to coordinating with water quality regulatory programs.

RECOMMENDATIONS

Chronic Lowering of Groundwater Levels

- Describe direct and indirect impacts on drinking water users, DACs, and tribes when describing undesirable results and defining minimum thresholds for chronic lowering of groundwater levels.

Degraded Water Quality

- Describe direct and indirect impacts on drinking water users, DACs, and tribes when defining undesirable results for degraded water quality. For specific guidance on how to consider these users, refer to “Guide to Protecting Water Quality Under the Sustainable Groundwater Management Act.”[10]
- Evaluate the cumulative or indirect impacts of proposed minimum thresholds for degraded water quality on drinking water users, DACs, and tribes.
- For EC, provide a summary table that presents the pre-2015 historical maximums, the salinity objective from the Basin Plan, the SMCL, and the resulting minimum thresholds. Ensure that the minimum thresholds do not exceed the salinity objective in the Basin Plan.
- Set minimum thresholds and measurable objectives for all water quality constituents within the subbasin that can be impacted and/or exacerbated as a result of groundwater use or groundwater management. Ensure they align with drinking water standards.[11]

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[10] Guide to Protecting Water Quality under the Sustainable Groundwater Management Act https://d3n8a8pro7vhmx.cloudfront.net/communitywatercenter/pages/293/attachments/original/1559328858/Guide_to_Protecting_Drinking_Water_Quality_Under_the_Sustainable_Groundwater_Management_Act.pdf?1559328858.

[11] “Degraded Water Quality [...] collect sufficient spatial and temporal data from each applicable principal aquifer to determine groundwater quality trends for water quality indicators, as determined by the Agency, to address known water quality issues.” [23 CCR §354.34(c)(4)]

Groundwater Dependent Ecosystems and Interconnected Surface Waters

Sustainable management criteria for chronic lowering of groundwater levels provided in the GSP do not consider potential impacts to environmental beneficial users. The GSP neither describes nor analyzes direct or indirect impacts on environmental users of groundwater when defining undesirable results. This is problematic because without identifying potential impacts to GDEs, minimum thresholds may compromise, or even destroy, these environmental beneficial users. Since GDEs are present in the subbasin, they must be considered when developing SMC for chronic lowering of groundwater levels.

Sustainable management criteria for depletion of interconnected surface water are established by proxy using groundwater levels at existing monitoring wells with locations and depths considered appropriate for monitoring groundwater with potential to influence interconnected streams. Minimum thresholds were established at groundwater levels that are 10 feet deeper than the observed Fall 2015 water level. However, if minimum thresholds are set to levels lower than historic low groundwater levels and the subbasin is allowed to operate at or close to those levels over many years, there is a risk of causing catastrophic damage to ecosystems that are more adverse than what was occurring at the height of the 2012-2016 drought. This is because California ecosystems, which are adapted to our Mediterranean climate, have some drought strategies that they can utilize to deal with short-term water stress. However, if the drought conditions are prolonged, the ecosystem can collapse.

No analysis or discussion is presented to describe how the SMC will affect GDEs, or the impact of these minimum thresholds on GDEs in the subbasin. Furthermore, the GSP makes no attempt to evaluate the impacts of the proposed minimum threshold on environmental beneficial users of surface water. The GSP does not explain how the chosen minimum thresholds and measurable objectives avoid significant and unreasonable effects on surface water beneficial users in the subbasin, such as increased mortality and inability to perform key life processes (e.g., reproduction, migration).

RECOMMENDATIONS

- When defining undesirable results for chronic lowering of groundwater levels, provide specifics on what biological responses (e.g., extent of habitat, growth, recruitment rates) would best characterize a significant and unreasonable impact to GDEs. Undesirable results to environmental users occur when ‘significant and unreasonable’ effects on beneficial users are caused by one of the sustainability indicators (i.e., chronic lowering of groundwater levels, degraded water quality, or depletion of interconnected surface water). Thus, potential impacts on environmental beneficial uses and users need to be considered when defining undesirable results in the subbasin.[12] Defining undesirable results is the crucial first step before the minimum thresholds can be determined.[13]

- When establishing SMC for the subbasin, consider that the SGMA statute [Water Code §10727.4(l)] specifically calls out that GSPs shall include “impacts on groundwater dependent ecosystems”.

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[12] “The description of undesirable results shall include [...] potential effects on the beneficial uses and users of groundwater, on land uses and property interests, and other potential effects that may occur or are occurring from undesirable results”. [23 CCR §354.26(b)(3)]

[13] The description of minimum thresholds shall include [...] how minimum thresholds may affect the interests of beneficial uses and users of groundwater or land uses and property interests.” [23 CCR §354.28(b)(4)]

- When defining undesirable results for depletion of interconnected surface water, include a description of potential impacts on instream habitats within ISWs when minimum thresholds in the subbasin are reached.[14] The GSP should confirm that minimum thresholds for ISWs avoid adverse impacts to environmental beneficial users of interconnected surface waters as these environmental users could be left unprotected by the GSP. These recommendations apply especially to environmental beneficial users that are already protected under pre-existing state or federal law.[6,15]

2. Climate Change

The SGMA statute identifies climate change as a significant threat to groundwater resources and one that must be examined and incorporated in the GSPs. The GSP Regulations require integration of climate change into the projected water budget to ensure that projects and management actions sufficiently account for the range of potential climate futures.[16] The effects of climate change will intensify the impacts of water stress on GDEs, making available shallow groundwater resources especially critical to their survival. Condon *et al.* (2020) shows that GDEs are more likely to succumb to water stress and rely more on groundwater during times of drought.[17] When shallow groundwater is unavailable, riparian forests can die off and key life processes (e.g., migration and spawning) for aquatic organisms, such as steelhead, can be impeded.

The integration of climate change into the projected water budget is **insufficient**. The GSP incorporates climate change into the projected water budget using DWR change factors for 2030 and 2070. However, the plan does not consider multiple climate scenarios (e.g., the 2070 extremely wet and extremely dry climate scenarios) in the projected water budget. The GSP should clearly and transparently incorporate the extremely wet and dry scenarios provided by DWR into projected water budgets or select more appropriate extreme scenarios for the subbasin. While these extreme scenarios may have a lower likelihood of occurring, their consequences could be significant and their inclusion can help identify important vulnerabilities in the subbasin's approach to groundwater management.

The GSP incorporates climate change into key inputs of (e.g., precipitation and evapotranspiration) of the projected water budget. However, imported water should also be adjusted for climate change and incorporated into the surface water flow inputs of the projected water budget. The sustainable yield is calculated based on the projected water budget with climate change incorporated. However, if the water budgets are incomplete, including the omission of extremely wet and dry scenarios and the omission of projected climate change effects on imported water inputs, then there is increased uncertainty in virtually every subsequent calculation used to plan for projects, derive measurable objectives, and set minimum thresholds. Plans that do not adequately include climate change projections may underestimate future

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[14] “The minimum threshold for depletions of interconnected surface water shall be the rate or volume of surface water depletions caused by groundwater use that has adverse impacts on beneficial uses of the surface water and may lead to undesirable results.” [23 CCR §354.28(c)(6)]

[15] Rohde MM, Seapy B, Rogers R, Castañeda X, editors. 2019. Critical Species LookBook: A compendium of California’s threatened and endangered species for sustainable groundwater management. The Nature Conservancy, San Francisco, California. Available at: https://groundwaterresourcehub.org/public/uploads/pdfs/Critical_Species_LookBook_91819.pdf

[16] “Each Plan shall rely on the best available information and best available science to quantify the water budget for the basin in order to provide an understanding of historical and projected hydrology, water demand, water supply, land use, population, climate change, sea level rise, groundwater and surface water interaction, and subsurface groundwater flow.” [23 CCR §354.18(e)]

[17] Condon et al. 2020. Evapotranspiration depletes groundwater under warming over the contiguous United States. Nature Communications. Available at: https://www.nature.com/articles/s41467-020-14688-0

impacts on vulnerable beneficial users of groundwater such as ecosystems, DACs, domestic well owners, and tribes.

RECOMMENDATIONS

- Integrate climate change, including extremely wet and dry scenarios, into all elements of the projected water budget to form the basis for development of sustainable management criteria and projects and management actions.
- Incorporate climate change into surface water flow inputs, including imported water, for the projected water budget.
- Incorporate climate change scenarios into projects and management actions.

3. Data Gaps

The consideration of beneficial users when establishing monitoring networks is **insufficient**, due to lack of specific plans to increase the Representative Monitoring Sites (RMSs) in the monitoring network that represent water quality conditions and shallow groundwater elevations around DACs, domestic wells, tribes, GDEs, and ISWs in the subbasin.

Figure 4-6 (Representative Groundwater Level Monitoring Network) shows insufficient representation of drinking water users and tribal users for groundwater elevation monitoring. Figure 4-7 (Representative Groundwater Quality Monitoring Network) shows insufficient representation of DACs and tribal users for water quality monitoring. Refer to Attachment E for maps of these monitoring sites in relation to key beneficial users of groundwater. These beneficial users may remain unprotected by the GSP without adequate monitoring and identification of data gaps in the shallow aquifer. The Plan therefore fails to meet SGMA's requirements for the monitoring network.[18]

The GSP provides some discussion of data gaps for GDEs and ISWs in Sections 4.2.4.5 (Proposed Actions to Address Data Gaps) and Section 7.1.2.1 (Expand Shallow Groundwater Level Monitoring Network), but does not provide specific plans, such as locations or a timeline, to fill the data gaps.

RECOMMENDATIONS

- Provide maps that overlay current and proposed monitoring well locations with the locations of DACs, domestic wells, tribes, GDEs, and ISWs to clearly identify potentially impacted areas.
- Increase the number of RMSs in the shallow aquifer across the subbasin as needed to adequately monitor all groundwater condition indicators across the subbasin and at appropriate depths for *all* beneficial users. Prioritize proximity to DACs, domestic wells, tribes, and GDEs when identifying new RMSs.

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[18] "The monitoring network objectives shall be implemented to accomplish the following: [...] (2) Monitor impacts to the beneficial uses or users of groundwater." [23 CCR §354.34(b)(2)]

- Ensure groundwater elevation and water quality RMSs are monitoring groundwater conditions spatially and at the correct depth for *all* beneficial users - especially DACs, domestic wells, tribes, and GDEs.

- Describe biological monitoring that can be used to assess the potential for significant and unreasonable impacts to GDEs or ISWs due to groundwater conditions in the subbasin.

4. Addressing Beneficial Users in Projects and Management Actions

The consideration of beneficial users when developing projects and management actions is **insufficient** due to the failure to completely identify benefits or impacts of identified projects and management actions, including water quality impacts, to key beneficial users of groundwater such as GDEs, aquatic habitats, surface water users, DACs, drinking water users, and tribes. Therefore, potential project and management actions may not protect these beneficial users. Groundwater sustainability under SGMA is defined not just by sustainable yield, but by the avoidance of undesirable results for *all* beneficial users.

We commend the GSAs for including the Colusa Subbasin Multi-Benefit Groundwater Recharge project, developed in partnership with The Nature Conservancy. The GSP describes the multiple benefits of this project, including benefits to migratory shorebirds, DACs, private landowners, and groundwater conditions.

The GSP includes a domestic well mitigation program. However, the mitigation program is described as a potential project to be implemented on an as-needed basis instead of a proposed project that will be implemented within the GSP planning horizon.

RECOMMENDATIONS

- Clarify the planning horizon of the described domestic well mitigation program to ensure that it will proactively monitor and protect drinking water wells through GSP implementation. Refer to Attachment B for specific recommendations on how to implement a drinking water well mitigation program.

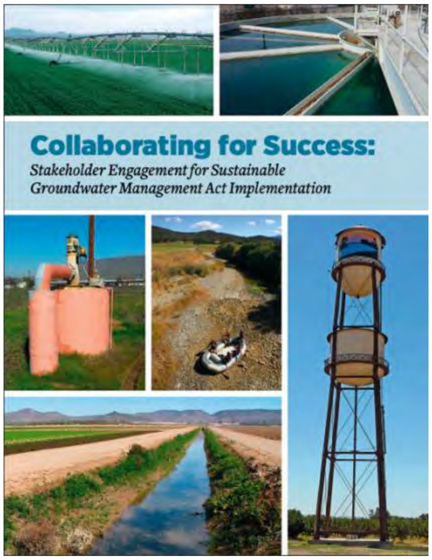
- For DACs and domestic well owners, include a discussion of whether potential impacts to water quality from projects and management actions could occur and how the GSAs plans to mitigate such impacts.

- Develop management actions that incorporate climate and water delivery uncertainties to address future water demand and prevent future undesirable results.

Attachment B

SGMA Tools to address DAC, drinking water, and environmental beneficial uses and users

Stakeholder Engagement and Outreach



Collaborating for Success:

Stakeholder Engagement for Sustainable Groundwater Management Act Implementation

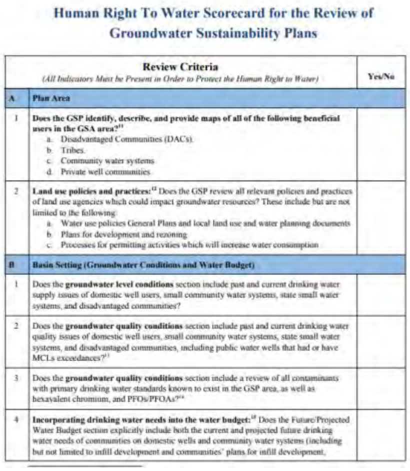
Clean Water Action, Community Water Center and Union of Concerned Scientists developed a guidance document called Collaborating for success: Stakeholder engagement for Sustainable Groundwater Management Act Implementation. It provides details on how to conduct targeted and broad outreach and engagement during Groundwater Sustainability Plan (GSP) development and implementation. Conducting a targeted outreach involves:

- Developing a robust Stakeholder Communication and Engagement plan that includes outreach at frequented locations (schools, farmers markets, religious settings, events) across the plan area to increase the involvement and participation of disadvantaged communities, drinking water users and the environmental stakeholders.

- Providing translation services during meetings and technical assistance to enable easy participation for non-English speaking stakeholders.

- GSP should adequately describe the process for requesting input from beneficial users and provide details on how input is incorporated into the GSP.

The Human Right to Water

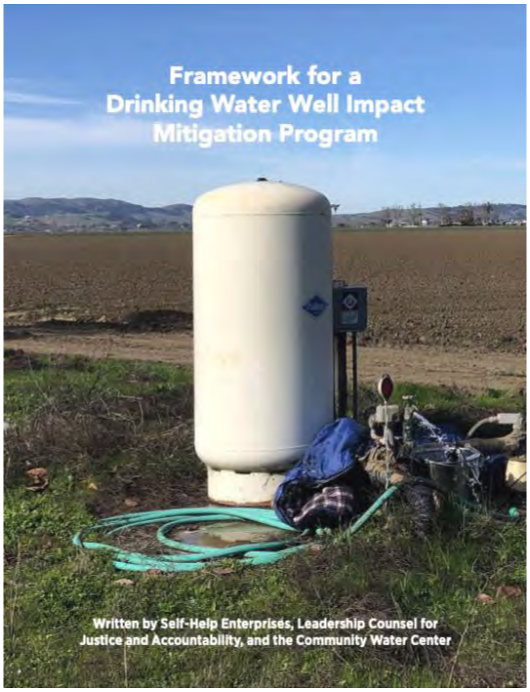


Human Right To Water Scorecard for the Review of Groundwater Sustainability Plans

	Review Criteria *(All Indicators Must be Present in Order to Protect the Human Right to Water)*	Yes/No
A	**Plan Area**	
1	**Does the GSP identify, describe, and provide maps of all of the following beneficial users in the GSA area?**[11] a. Disadvantaged Communities (DACs). b. Tribes. c. Community water systems. d. Private well communities.	
2	**Land use policies and practices:**[12] Does the GSP review all relevant policies and practices of land use agencies which could impact groundwater resources? These include but are not limited to the following: a. Water use policies General Plans and local land use and water planning documents b. Plans for development and rezoning c. Processes for permitting activities which will increase water consumption	
B	**Basin Setting (Groundwater Conditions and Water Budget)**	
1	Does the **groundwater level conditions** section include past and current drinking water supply issues of domestic well users, small community water systems, state small water systems, and disadvantaged communities?	
2	Does the **groundwater quality conditions** section include past and current drinking water quality issues of domestic well users, small community water systems, state small water systems, and disadvantaged communities, including public water wells that had or have MCLs exceedances?[13]	
3	Does the **groundwater quality conditions** section include a review of all contaminants with primary drinking water standards known to exist in the GSP area, as well as hexavalent chromium, and PFOs/PFOAs?[14]	
4	**Incorporating drinking water needs into the water budget:**[15] Does the Future/Projected Water Budget section explicitly include both the current and projected future drinking water needs of communities on domestic wells and community water systems (including but not limited to infill development and communities' plans for infill development,	

The Human Right to Water Scorecard was developed by Community Water Center, Leadership Counsel for Justice and Accountability and Self Help Enterprises to aid Groundwater Sustainability Agencies (GSAs) in prioritizing drinking water needs in SGMA. The scorecard identifies elements that must exist in GSPs to adequately protect the Human Right to Drinking water.

Drinking Water Well Impact Mitigation Framework

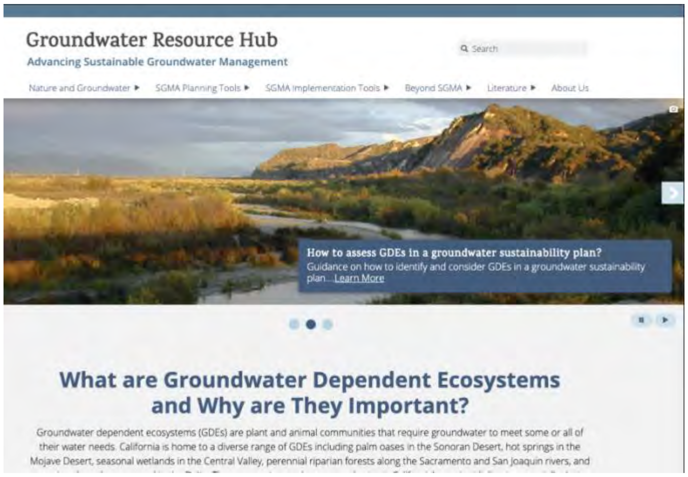


Framework for a Drinking Water Well Impact Mitigation Program

Written by Self-Help Enterprises, Leadership Counsel for Justice and Accountability, and the Community Water Center

The Drinking Water Well Impact Mitigation Framework was developed by Community Water Center, Leadership Counsel for Justice and Accountability and Self Help Enterprises to aid GSAs in the development and implementation of their GSPs. The framework provides a clear roadmap for how a GSA can best structure its data gathering, monitoring network and management actions to proactively monitor and protect drinking water wells and mitigate impacts should they occur.

Groundwater Resource Hub



How to assess GDEs in a groundwater sustainability plan?
Guidance on how to identify and consider GDEs in a groundwater sustainability plan... Learn More

What are Groundwater Dependent Ecosystems and Why are They Important?

Groundwater dependent ecosystems (GDEs) are plant and animal communities that require groundwater to meet some or all of their water needs. California is home to a diverse range of GDEs including palm oases in the Sonoran Desert, hot springs in the Mojave Desert, seasonal wetlands in the Central Valley, perennial riparian forests along the Sacramento and San Joaquin rivers, and

The Nature Conservancy has developed a suite of tools based on best available science to help GSAs, consultants, and stakeholders efficiently incorporate nature into GSPs. These tools and resources are available online at GroundwaterResourceHub.org. The Nature Conservancy's tools and resources are intended to reduce costs, shorten timelines, and increase benefits for both people and nature.

Rooting Depth Database

The Plant Rooting Depth Database provides information that can help assess whether groundwater-dependent vegetation are accessing groundwater. Actual rooting depths will depend on the plant species and site-specific conditions, such as soil type and availability of other water sources. Site-specific knowledge of depth to groundwater combined with rooting depths will help provide an understanding of the potential groundwater levels are needed to sustain GDEs.

How to use the database

The maximum rooting depth information in the Plant Rooting Depth Database is useful when verifying whether vegetation in the Natural Communities Commonly Associated with Groundwater (NC Dataset) are connected to groundwater. A 30 ft depth-to-groundwater threshold, which is based on averaged global rooting depth data for phreatophytes[1], is relevant for most plants identified in the NC Dataset since most plants have a max rooting depth of less than 30 feet. However, it is important to note that deeper thresholds are necessary for other plants that have reported maximum root depths that exceed the averaged 30 feet threshold, such as valley oak (*Quercus lobata*), Euphrates poplar (*Populus euphratica*), salt cedar (*Tamarix spp.*), and shadescale (*Atriplex confertifolia*). The Nature Conservancy advises that the reported max rooting depth for these deeper-rooted plants be used. For example, a depth-to groundwater threshold of 80 feet should be used instead of the 30 ft threshold, when verifying whether valley oak polygons from the NC Dataset are connected to groundwater. It is important to re-emphasize that actual rooting depth data are limited and will depend on the plant species and site-specific conditions such as soil and aquifer types, and availability to other water sources.

The Plant Rooting Depth Database is an Excel workbook composed of four worksheets:

1. California phreatophyte rooting depth data (included in the NC Dataset)
2. Global phreatophyte rooting depth data
3. Metadata
4. References

How the database was compiled

The Plant Rooting Depth Database is a compilation of rooting depth information for the groundwater-dependent plant species identified in the NC Dataset. Rooting depth data were compiled from published scientific literature and expert opinion through a crowdsourcing campaign. As more information becomes available, the database of rooting depths will be updated. Please Contact Us if you have additional rooting depth data for California phreatophytes.

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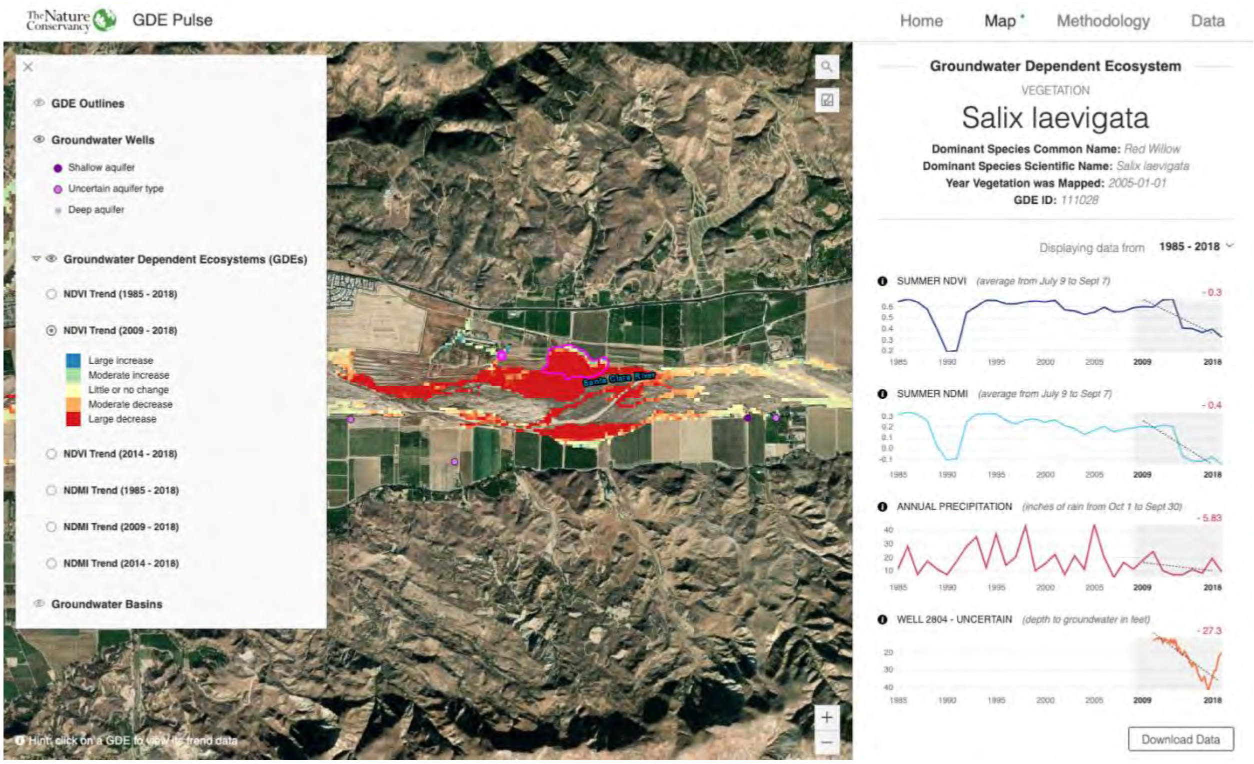
[1] Canadell, J., Jackson, R.B., Ehleringer, J.B. et al. 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108, 583–595. https://doi.org/10.1007/BF00329030

GDE Pulse



Groundwater Dependent Ecosystem

VEGETATION

Salix laevigata

Dominant Species Common Name: *Red Willow*
Dominant Species Scientific Name: *Salix laevigata*
Year Vegetation was Mapped: *2005-01-01*
GDE ID: *111028*

Displaying data from **1985 - 2018**

GDE Pulse is a free online tool that allows Groundwater Sustainability Agencies to assess changes in groundwater dependent ecosystem (GDE) health using satellite, rainfall, and groundwater data. Remote sensing data from satellites has been used to monitor the health of vegetation all over the planet. GDE pulse has compiled 35 years of satellite imagery from NASA's Landsat mission for every polygon in the Natural Communities Commonly Associated with Groundwater Dataset. The following datasets are available for downloading:

Normalized Difference Vegetation Index (NDVI) is a satellite-derived index that represents the greenness of vegetation. Healthy green vegetation tends to have a higher NDVI, while dead leaves have a lower NDVI. We calculated the average NDVI during the driest part of the year (July - Sept) to estimate vegetation health when the plants are most likely dependent on groundwater.

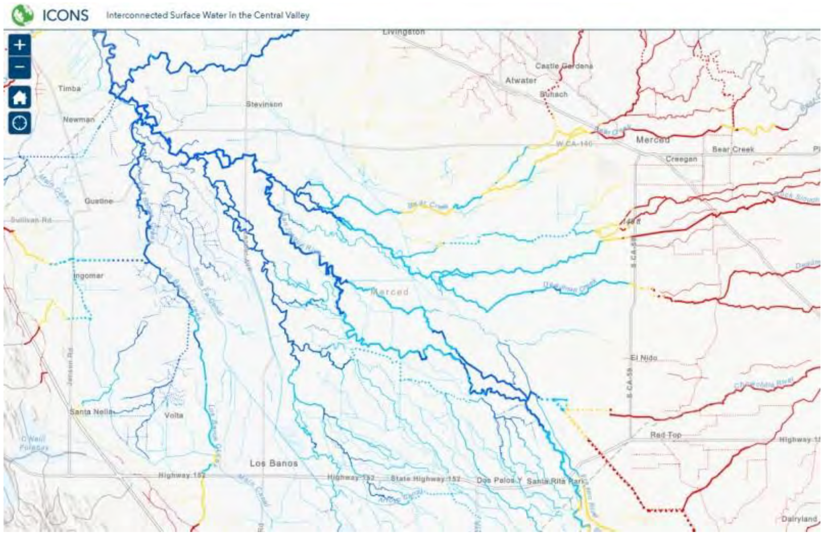
Normalized Difference Moisture Index (NDMI) is a satellite-derived index that represents water content in vegetation. NDMI is derived from the Near-Infrared (NIR) and Short-Wave Infrared (SWIR) channels. Vegetation with adequate access to water tends to have higher NDMI, while vegetation that is water stressed tends to have lower NDMI. We calculated the average NDVI during the driest part of the year (July–September) to estimate vegetation health when the plants are most likely dependent on groundwater.

Annual Precipitation is the total precipitation for the water year (October 1st – September 30th) from the PRISM dataset. The amount of local precipitation can affect vegetation with more precipitation generally leading to higher NDVI and NDMI.

Depth to Groundwater measurements provide an indication of the groundwater levels and changes over time for the surrounding area. We used groundwater well measurements from nearby (<1km) wells to estimate the depth to groundwater below the GDE based on the average elevation of the GDE (using a digital elevation model) minus the measured groundwater surface elevation.

ICONOS Mapper

Interconnected Surface Water in the Central Valley



ICONS maps the likely presence of interconnected surface water (ISW) in the Central Valley using depth to groundwater data. Using data from 2011-2018, the ISW dataset represents the likely connection between surface water and groundwater for rivers and streams in California's Central Valley. It includes information on the mean, maximum, and minimum depth to groundwater for each stream segment over the years with available data, as well as the likely presence of ISW based on the minimum depth to groundwater. The Nature Conservancy developed this database, with guidance and input from expert academics, consultants, and state agencies.

We developed this dataset using groundwater elevation data available online from the California Department of Water Resources (DWR). DWR only provides this data for the Central Valley. For GSAs outside of the valley, who have groundwater well measurements, we recommend following our methods to determine likely ISW in your region. The Nature Conservancy's ISW dataset should be used as a first step in reviewing ISW and should be supplemented with local or more recent groundwater depth data.

Attachment C

Freshwater Species Located in the Colusa Subbasin

To assist in identifying the beneficial users of surface water necessary to assess the undesirable result "depletion of interconnected surface waters", Attachment C provides a list of freshwater species located in the Colusa Subbasin. To produce the freshwater species list, we used ArcGIS to select features within the California Freshwater Species Database version 2.0.9 within the basin boundary. This database contains information on ~4,000 vertebrates, macroinvertebrates and vascular plants that depend on fresh water for at least one stage of their life cycle. The methods used to compile the California Freshwater Species Database can be found in Howard et al. 2015[1]. The spatial database contains locality observations and/or distribution information from ~400 data sources. The database is housed in the California Department of Fish and Wildlife's BIOS[2] as well as on The Nature Conservancy's science website[3].

Scientific Name	Common Name	Legal Protected Status		
		Federal	State	Other
BIRDS				
Agelaius tricolor	Tricolored Blackbird	Bird of Conservation Concern	Special Concern	BSSC - First priority
Coccyzus americanus occidentalis	Western Yellow-billed Cuckoo	Candidate - Threatened	Endangered	
Egretta thula	Snowy Egret			
Nycticorax nycticorax	Black-crowned Night-Heron			
Pandion haliaetus	Osprey		Watch list	
Riparia riparia	Bank Swallow		Threatened	
Actitis macularius	Spotted Sandpiper			
Aechmophorus clarkii	Clark's Grebe			
Aechmophorus occidentalis	Western Grebe			
Aix sponsa	Wood Duck			
Anas acuta	Northern Pintail			
Anas americana	American Wigeon			
Anas clypeata	Northern Shoveler			
Anas crecca	Green-winged Teal			
Anas cyanoptera	Cinnamon Teal			
Anas discors	Blue-winged Teal			
Anas platyrhynchos	Mallard			
Anas strepera	Gadwall			
Anser albifrons	Greater White-fronted Goose			
Ardea alba	Great Egret			
Ardea herodias	Great Blue Heron			

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[1] Howard, J.K. et al. 2015. Patterns of Freshwater Species Richness, Endemism, and Vulnerability in California. PLoSONE, 11(7). Available at: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0130710

[2] California Department of Fish and Wildlife BIOS: https://www.wildlife.ca.gov/data/BIOS

[3] Science for Conservation: https://www.scienceforconservation.org/products/california-freshwater-species-database

Aythya affinis	Lesser Scaup			
Aythya americana	Redhead		Special Concern	BSSC - Third priority
Aythya collaris	Ring-necked Duck			
Aythya marila	Greater Scaup			
Aythya valisineria	Canvasback		Special	
Botaurus lentiginosus	American Bittern			
Bucephala albeola	Bufflehead			
Bucephala clangula	Common Goldeneye			
Butorides virescens	Green Heron			
Calidris alpina	Dunlin			
Calidris mauri	Western Sandpiper			
Calidris minutilla	Least Sandpiper			
Chen caerulescens	Snow Goose			
Chen rossii	Ross's Goose			
Chlidonias niger	Black Tern		Special Concern	BSSC - Second priority
Chroicocephalus philadelphia	Bonaparte's Gull			
Cinclus mexicanus	American Dipper			
Cistothorus palustris palustris	Marsh Wren			
Cygnus columbianus	Tundra Swan			
Empidonax traillii	Willow Flycatcher	Bird of Conservation Concern	Endangered	
Fulica americana	American Coot			
Gallinago delicata	Wilson's Snipe			
Gallinula chloropus	Common Moorhen			
Geothlypis trichas trichas	Common Yellowthroat			
Grus canadensis	Sandhill Crane			
Haliaeetus leucocephalus	Bald Eagle	Bird of Conservation Concern	Endangered	
Himantopus mexicanus	Black-necked Stilt			
Icteria virens	Yellow-breasted Chat		Special Concern	BSSC - Third priority
Ixobrychus exilis hesperis	Western Least Bittern		Special Concern	BSSC - Second priority
Limnodromus scolopaceus	Long-billed Dowitcher			
Lophodytes cucullatus	Hooded Merganser			
Megaceryle alcyon	Belted Kingfisher			
Mergus merganser	Common Merganser			
Numenius americanus	Long-billed Curlew			
Numenius phaeopus	Whimbrel			
Oxyura jamaicensis	Ruddy Duck			

Pelecanus erythrorhynchos	American White Pelican		Special Concern	BSSC - First priority
Phalacrocorax auritus	Double-crested Cormorant			
Phalaropus tricolor	Wilson's Phalarope			
Plegadis chihi	White-faced Ibis		Watch list	
Pluvialis squatarola	Black-bellied Plover			
Podiceps nigricollis	Eared Grebe			
Podilymbus podiceps	Pied-billed Grebe			
Porzana carolina	Sora			
Rallus limicola	Virginia Rail			
Recurvirostra americana	American Avocet			
Setophaga petechia	Yellow Warbler			BSSC - Second priority
Tachycineta bicolor	Tree Swallow			
Tringa melanoleuca	Greater Yellowlegs			
Tringa semipalmata	Willet			
Tringa solitaria	Solitary Sandpiper			
Vireo bellii	Bell's Vireo			
Xanthocephalus xanthocephalus	Yellow-headed Blackbird		Special Concern	BSSC - Third priority
CRUSTACEANS				
Branchinecta conservatio	Conservancy Fairy Shrimp	Endangered	Special	IUCN - Endangered
Branchinecta lynchi	Vernal Pool Fairy Shrimp	Threatened	Special	IUCN - Vulnerable
Lepidurus packardi	Vernal Pool Tadpole Shrimp	Endangered	Special	IUCN - Endangered
Linderiella occidentalis	California Fairy Shrimp		Special	IUCN - Near Threatened
Hyalella spp.	Hyalella spp.			
FISH				
Oncorhynchus mykiss irideus	Coastal rainbow trout			Least Concern - Moyle 2013
Spirinchus thaleichthys	Longfin smelt	Candidate	Threatened	Vulnerable - Moyle 2013
Acipenser medirostris ssp. 1	Southern green sturgeon	Threatened	Special Concern	Endangered - Moyle 2013
Oncorhynchus mykiss - CV	Central Valley steelhead	Threatened	Special	Vulnerable - Moyle 2013
Oncorhynchus tshawytscha - CV spring	Central Valley spring Chinook salmon	Threatened	Threatened	Vulnerable - Moyle 2013
Oncorhynchus tshawytscha - CV winter	Central Valley winter Chinook salmon	Endangered	Endangered	Vulnerable - Moyle 2013
HERPS				
Actinemys marmorata marmorata	Western Pond Turtle		Special Concern	ARSSC

Ambystoma californiense californiense	California Tiger Salamander	Threatened	Threatened	ARSSC
Anaxyrus boreas boreas	Boreal Toad			
Dicamptodon ensatus	California Giant Salamander			ARSSC
Rana boylii	Foothill Yellow-legged Frog	Under Review in the Candidate or Petition Process	Special Concern	ARSSC
Rana draytonii	California Red-legged Frog	Threatened	Special Concern	ARSSC
Spea hammondii	Western Spadefoot	Under Review in the Candidate or Petition Process	Special Concern	ARSSC
Thamnophis gigas	Giant Gartersnake	Threatened	Threatened	
Thamnophis sirtalis sirtalis	Common Gartersnake			
Pseudacris regilla	Northern Pacific Chorus Frog			
INSECTS & OTHER INVERTS				
Ablabesmyia spp.	Ablabesmyia spp.			
Acentrella insignificans	A Mayfly			
Ambrysus amargosus	Ash Meadows Naucorid			
Ambrysus mormon				Not on any status lists
Ambrysus spp.	Ambrysus spp.			
Anax junius	Common Green Darner			
Apedilum spp.	Apedilum spp.			
Argia lugens	Sooty Dancer			
Baetidae fam.	Baetidae fam.			
Baetis spp.	Baetis spp.			
Baetis tricaudatus	A Mayfly			
Belostomatidae fam.	Belostomatidae fam.			
Caenis latipennis	A Mayfly			
Centroptilum album	A Mayfly			
Centroptilum spp.	Centroptilum spp.			
Chironomidae fam.	Chironomidae fam.			
Chironomus anonymus				Not on any status lists
Chironomus spp.	Chironomus spp.			
Cladotanytarsus marki				Not on any status lists
Cladotanytarsus spp.	Cladotanytarsus spp.			
Coenagrionidae fam.	Coenagrionidae fam.			
Corisella decolor				Not on any status lists
Corixidae fam.	Corixidae fam.			

Cricotopus annulator				Not on any status lists
Cricotopus spp.	Cricotopus spp.			
Cryptochironomus curryi				Not on any status lists
Cryptochironomus spp.	Cryptochironomus spp.			
Dicrotendipes adnilus				Not on any status lists
Dicrotendipes spp.	Dicrotendipes spp.			
Ecdyonurus criddlei	A Mayfly			
Enallagma boreale	Boreal Bluet			
Enallagma carunculatum	Tule Bluet			
Enallagma civile	Familiar Bluet			
Enochrus spp.	Enochrus spp.			
Ephydridae fam.	Ephydridae fam.			
Fallceon quilleri	A Mayfly			
Fallceon spp.	Fallceon spp.			
Gomphidae fam.	Gomphidae fam.			
Harnischia spp.	Harnischia spp.			
Heptagenia adaequata				Not on any status lists
Heptagenia spp.	Heptagenia spp.			
Heptageniidae fam.	Heptageniidae fam.			
Hydrophilidae fam.	Hydrophilidae fam.			
Hydropsyche alternans				Not on any status lists
Hydropsyche californica	A Caddisfly			
Hydropsyche spp.	Hydropsyche spp.			
Hydroptila ajax	A Caddisfly			
Hydroptila spp.	Hydroptila spp.			
Ischnura cervula	Pacific Forktail			
Ischnura perparva	Western Forktail			
Laccobius spp.	Laccobius spp.			
Leptoceridae fam.	Leptoceridae fam.			
Libellula forensis	Eight-spotted Skimmer			
Libellula luctuosa	Widow Skimmer			
Libellula pulchella	Twelve-spotted Skimmer			
Libellulidae fam.	Libellulidae fam.			
Micrasema spp.	Micrasema spp.			
Microchironomus nigrovittatus				Not on any status lists
Microchironomus spp.	Microchironomus spp.			
Mideopsis pumila				Not on any status lists
Mideopsis spp.	Mideopsis spp.			

Nanocladius anderseni				Not on any status lists
Nanocladius spp.	Nanocladius spp.			
Nectopsyche spp.	Nectopsyche spp.			
Oecetis spp.	Oecetis spp.			
Oreodytes abbreviatus				Not on any status lists
Oreodytes spp.	Oreodytes spp.			
Pachydiplax longipennis	Blue Dasher			
Paltothemis lineatipes	Red Rock Skimmer			
Pantala flavescens	Wandering Glider			
Pantala hymenaea	Spot-winged Glider			
Paracladopelma alphaeus				Not on any status lists
Paracladopelma spp.	Paracladopelma spp.			
Parakiefferiella spp.	Parakiefferiella spp.			
Paratanytarsus spp.	Paratanytarsus spp.			
Pentaneura spp.	Pentaneura spp.			
Phaenopsectra dyari				Not on any status lists
Phaenopsectra spp.	Phaenopsectra spp.			
Polypedilum albicorne				Not on any status lists
Polypedilum spp.	Polypedilum spp.			
Procladius barbatulus				Not on any status lists
Procladius spp.	Procladius spp.			
Protochauliodes minimus				Not on any status lists
Protoptila erotica				Not on any status lists
Pseudochironomus spp.	Pseudochironomus spp.			
Rheotanytarsus spp.	Rheotanytarsus spp.			
Rhionaeschna multicolor	Blue-eyed Darner			
Serratella micheneri	A Mayfly			
Sigara alternata				Not on any status lists
Sigara mckinstryi	A Water Boatman			Not on any status lists
Sigara spp.	Sigara spp.			
Simulium anduzei				Not on any status lists
Simulium spp.	Simulium spp.			
Sperchon spp.	Sperchon spp.			
Sperchon stellata				Not on any status lists
Sympetrum corruptum	Variegated Meadowhawk			

Sympetrum madidum	Red-veined Meadowhawk			
Tanytarsus angulatus				Not on any status lists
Tanytarsus spp.	Tanytarsus spp.			
Tinodes belisus	A Caddisfly			
Tipulidae fam.	Tipulidae fam.			
Tramea lacerata	Black Saddlebags			
Tricorythodes explicatus	A Mayfly			
Tricorythodes spp.	Tricorythodes spp.			
Unionicolidae fam.	Unionicolidae fam.			
MAMMALS				
Castor canadensis	American Beaver			Not on any status lists
Lontra canadensis canadensis	North American River Otter			Not on any status lists
Neovison vison	American Mink			Not on any status lists
Ondatra zibethicus	Common Muskrat			Not on any status lists
MOLLUSKS				
Anodonta californiensis	California Floater		Special	
Ferrissia spp.	Ferrissia spp.			
Gonidea angulata	Western Ridged Mussel		Special	
Gyraulus spp.	Gyraulus spp.			
Helisoma spp.	Helisoma spp.			
Lymnaea spp.	Lymnaea spp.			
Lymnaeidae fam.	Lymnaeidae fam.			
Margaritifera falcata	Western Pearlshell		Special	
Menetus opercularis	Button Sprite			CS
Menetus spp.	Menetus spp.			
Physa spp.	Physa spp.			
Planorbidae fam.	Planorbidae fam.			
PLANTS				
Chloropyron palmatum	NA	Endangered	Special	CRPR - 1B.1
Orcuttia pilosa	Hairy Orcutt Grass	Endangered	Endangered	CRPR - 1B.1
Puccinellia simplex	Little Alkali Grass			
Tuctoria greenei	Green's Awnless Orcutt Grass	Endangered	Rare	CRPR - 1B.1
Alnus rhombifolia	White Alder			
Alopecurus carolinianus	Tufted Foxtail			
Alopecurus pratensis	NA			
Alopecurus saccatus	Pacific Foxtail			
Ammannia coccinea	Scarlet Ammannia			
Ammannia robusta	Grand Redstem			
Anemopsis californica	Yerba Mansa			
Arundo donax	NA			

Azolla filiculoides	NA			
Azolla microphylla	Mexican mosquito fern		Special	CRPR - 4.3
Baccharis salicina				Not on any status lists
Bacopa eisenii	Gila River Water-hyssop			
Bacopa rotundifolia	NA			
Bergia texana	Texas Bergia			
Boehmeria cylindrica	NA			Not on any status lists
Bolboschoenus fluviatilis				Not on any status lists
Bolboschoenus glaucus	NA			Not on any status lists
Bolboschoenus maritimus paludosus	NA			Not on any status lists
Brasenia schreberi	Watershield		Special	CRPR - 2B.3
Brodiaea nana				Not on any status lists
Calamagrostis nutkaensis	Pacific Small-reedgrass			
Callitriche heterophylla bolanderi	Large Water-starwort			
Callitriche heterophylla heterophylla	Northern Water-starwort			
Callitriche longipedunculata	Longstock Water-starwort			
Callitriche marginata	Winged Water-starwort			
Callitriche trochlearis	Waste-water Water-starwort			
Calochortus uniflorus	Shortstem Mariposa Lily		Special	CRPR - 4.2
Carex densa	Dense Sedge			
Carex feta	Green-sheath Sedge			
Carex nudata	Torrent Sedge			
Carex obnupta	Slough Sedge			
Carex vulpinoidea	NA			
Castilleja minor minor	Alkali Indian-paintbrush			
Cephalanthus occidentalis	Common Buttonbush			
Cicendia quadrangularis	Oregon Microcala			
Cirsium douglasii breweri				Not on any status lists
Cotula coronopifolia	NA			
Crassula aquatica	Water Pygmyweed			
Crypsis vaginiflora	NA			
Cyperus acuminatus	Short-point Flatsedge			
Cyperus erythrorhizos	Red-root Flatsedge			

Cyperus fuscus	NA			
Cyperus iria	NA			Not on any status lists
Cyperus squarrosus	Awned Cyperus			
Damasonium californicum				Not on any status lists
Datisca glomerata	Durango Root			
Delphinium uliginosum	Swamp Larkspur		Special	CRPR - 4.2
Downingia bella	Hoover's Downingia			
Downingia bicornuta	NA			
Downingia concolor	NA			
Downingia cuspidata	Toothed Calicoflower			
Downingia insignis	Parti-color Downingia			
Downingia ornatissima	NA			
Downingia pulchella	Flat-face Downingia			
Downingia yina	NA			
Echinochloa oryzoides	NA			
Echinodorus berteroi	Upright Burhead			
Elatine californica	California Waterwort			
Elatine heterandra	Mosquito Waterwort			
Elatine rubella	Southwestern Waterwort			
Eleocharis acicularis acicularis	Least Spikerush			
Eleocharis atropurpurea	Purple Spikerush			
Eleocharis bella	Delicate Spikerush			
Eleocharis coloradoensis				Not on any status lists
Eleocharis engelmannii engelmannii	Engelmann's Spikerush			Not on any status lists
Eleocharis macrostachya	Creeping Spikerush			
Eleocharis montevidensis	Sand Spikerush			
Eleocharis obtusa	Blunt Spikerush			
Eleocharis parishii	Parish's Spikerush			
Eleocharis quadrangulata	NA			
Eleocharis quinqueflora	Few-flower Spikerush			
Epilobium campestre	NA			Not on any status lists
Epilobium cleistogamum	Cleistogamous Spike-primrose			
Eragrostis hypnoides	Teal Lovegrass			
Eryngium aristulatum aristulatum	California Eryngo			
Eryngium articulatum	Jointed Coyote-thistle			
Eryngium castrense	Great Valley Eryngo			
Eryngium jepsonii	NA			Not on any status lists

Eryngium vaseyi vallicola				Not on any status lists
Eryngium vaseyi vaseyi	Vasey's Coyote-thistle			Not on any status lists
Euphorbia hooveri	NA			Not on any status lists
Euthamia occidentalis	Western Fragrant Goldenrod			
Fimbristylis autumnalis	NA			
Gratiola ebracteata	Bractless Hedge-hyssop			
Hastingsia alba	White Rushlily			
Helenium bigelovii	Bigelow's Sneezeweed			
Helenium puberulum	Rosilla			
Heteranthera limosa	NA			
Hydrocotyle ranunculoides	Floating Marsh-pennywort			
Hydrocotyle umbellata	Many-flower Marsh-pennywort			
Isoetes howellii	NA			
Isoetes nuttallii	NA			
Isolepis cernua	Low Bulrush			
Juncus acuminatus	Sharp-fruit Rush			
Juncus articulatus articulatus				Not on any status lists
Juncus diffusissimus	NA			
Juncus effusus effusus	NA			
Juncus effusus pacificus				
Juncus uncialis	Inch-high Rush			
Juncus usitatus	NA			Not on any status lists
Juncus xiphioides	Iris-leaf Rush			
Lasthenia ferrisiae	Ferris' Goldfields		Special	CRPR - 4.2
Lasthenia fremontii	Fremont's Goldfields			
Leersia oryzoides	Rice Cutgrass			
Lemna aequinoctialis	Lesser Duckweed			
Lemna gibba	Inflated Duckweed			
Lemna minor	Lesser Duckweed			
Lemna minuta	Least Duckweed			
Lemna turionifera	Turion Duckweed			
Lepidium oxycarpum	Sharp-pod Pepper-grass			
Limnanthes alba alba	White Meadowfoam			
Limnanthes douglasii douglasii	Douglas' Meadowfoam			
Limnanthes douglasii nivea	Douglas' Meadowfoam			
Limnanthes douglasii rosea	Douglas' Meadowfoam			

Limnanthes floccosa californica	Shippee Meadowfoam	Endangered	Endangered	CRPR - 1B.1
Limosella acaulis	Southern Mudwort			
Limosella aquatica	Northern Mudwort			
Lipocarpha micrantha	Dwarf Bulrush			
Ludwigia grandiflora	NA			
Ludwigia hexapetala	NA			Not on any status lists
Ludwigia palustris	Marsh Seedbox			
Ludwigia peploides montevidensis	NA			Not on any status lists
Ludwigia peploides peploides	NA			Not on any status lists
Lycopus americanus	American Bugleweed			
Lythrum californicum	California Loosestrife			
Lythrum portula	NA			
Marsilea vestita vestita	NA			Not on any status lists
Mimulus tricolor	Tricolor Monkeyflower			
Myosurus minimus	NA			
Myosurus sessilis	Sessile Mousetail			
Myriophyllum aquaticum	NA			
Myriophyllum hippuroides	Western Water-milfoil			
Najas gracillima	NA			
Najas guadalupensis guadalupensis	Southern Naiad			
Navarretia cotulifolia	Cotula Navarretia			
Navarretia heterandra	Tehama Navarretia			
Navarretia intertexta	Needleleaf Navarretia			
Navarretia leucocephala bakeri	Baker's Navarretia		Special	CRPR - 1B.1
Navarretia leucocephala leucocephala	White-flower Navarretia			
Navarretia leucocephala minima	Least Navarretia			
Orcuttia tenuis	Slender Orcutt Grass	Threatened	Endangered	CRPR - 1B.1
Oxypolis occidentalis	Western Cowbane			
Panicum dichotomiflorum	NA			
Paspalum distichum	Joint Paspalum			
Perideridia bolanderi involucrata	Bolander's Yampah			
Perideridia kelloggii	Kellogg's Yampah			
Perideridia oregana	Oregon Yampah			
Persicaria hydropiper	NA			Not on any status lists
Persicaria hydropiperoides				Not on any status lists

Persicaria lapathifolia				Not on any status lists
Persicaria maculosa	NA			Not on any status lists
Persicaria punctata	NA			Not on any status lists
Phacelia distans	NA			
Phragmites australis australis	Common Reed			
Phyla lanceolata	Fog-fruit			
Phyla nodiflora	Common Frog-fruit			
Pilularia americana	NA			
Plagiobothrys austiniae	Austin's Popcorn-flower			
Plagiobothrys greenei	Greene's Popcorn-flower			
Plagiobothrys humistratus	Dwarf Popcorn-flower			
Plagiobothrys leptocladus	Alkali Popcorn-flower			
Plantago elongata elongata	Slender Plantain			
Platanus racemosa	California Sycamore			
Pogogyne douglasii	NA			
Pogogyne zizyphoroides				Not on any status lists
Potamogeton diversifolius	Water-thread Pondweed			
Potamogeton foliosus foliosus	Leafy Pondweed			
Potamogeton gramineus	Grassy Pondweed			
Potamogeton nodosus	Longleaf Pondweed			
Potamogeton pusillus pusillus	Slender Pondweed			
Psilocarphus brevissimus brevissimus	Dwarf Woolly-heads			
Psilocarphus brevissimus multiflorus	Delta Woolly Marbles		Special	CRPR - 4.2
Psilocarphus oregonus	Oregon Woolly-heads			
Psilocarphus tenellus	NA			
Puccinellia nuttalliana	Nuttall's Alkali Grass			
Ranunculus bonariensis	NA			
Ranunculus pusillus pusillus	Pursh's Buttercup			
Ranunculus sceleratus	NA			
Rhododendron occidentale occidentale	Western Azalea			
Rorippa curvisiliqua curvisiliqua	Curve-pod Yellowcress			

Rorippa palustris palustris	Bog Yellowcress			
Rotala ramosior	Toothcup			
Rumex conglomeratus	NA			
Rumex salicifolius salicifolius	Willow Dock			
Rumex stenophyllus	NA			
Sagittaria latifolia latifolia	Broadleaf Arrowhead			
Sagittaria longiloba	Longbarb Arrowhead			
Sagittaria montevidensis calycina				Not on any status lists
Sagittaria sanfordii	Sanford's Arrowhead		Special	CRPR - 1B.2
Salix babylonica	NA			
Salix breweri	Brewer's Willow			
Salix exigua exigua	Narrowleaf Willow			
Salix gooddingii	Goodding's Willow			
Salix laevigata	Polished Willow			
Salix lasiandra lasiandra				Not on any status lists
Salix lasiolepis lasiolepis	Arroyo Willow			
Salix lutea	Yellow Willow			
Salix melanopsis	Dusky Willow			
Schoenoplectus acutus occidentalis	Hardstem Bulrush			
Schoenoplectus americanus	Three-square Bulrush			
Schoenoplectus pungens pungens	NA			
Schoenoplectus tabernaemontani	Softstem Bulrush			
Sequoia sempervirens				
Sidalcea hirsuta	Hairy Checker-mallow			
Sidalcea oregana hydrophila	Water-loving Checker-mallow		Special	CRPR - 1B.2
Sinapis alba	NA			
Sparganium eurycarpum eurycarpum				
Spirodela polyrhiza	NA			
Stachys ajugoides	Bugle Hedge-nettle			
Stachys albens	White-stem Hedge-nettle			
Stachys pycnantha	Short-spike Hedge-nettle			
Stachys stricta	Sonoma Hedge-nettle			
Stuckenia pectinata				Not on any status lists
Suaeda calceoliformis	American Sea-blite			
Symphyotrichum lentum	Suisun Marsh Aster		Special	CRPR - 1B.2

Toxicoscordion micranthum	NA			Not on any status lists
Typha domingensis	Southern Cattail			
Typha latifolia	Broadleaf Cattail			
Utricularia gibba	Humped Bladderwort			
Veronica anagallis-aquatica	NA			
Veronica catenata	NA			Not on any status lists
Wolffia borealis	Dotted Watermeal			
Wolffia brasiliensis	Pointed Watermeal		Special	CRPR - 2B.3
Wolffia globosa	Asian Watermeal			
Wolffiella oblonga	Saber-shape Bogmat			
Zannichellia palustris	Horned Pondweed			
Zizania palustris palustris	NA			

Attachment D

The Nature Conservancy

July 2019

IDENTIFYING GDEs UNDER SGMA

Best Practices for using the NC Dataset

The Sustainable Groundwater Management Act (SGMA) requires that groundwater dependent ecosystems (GDEs) be identified in Groundwater Sustainability Plans (GSPs). As a starting point, the Department of Water Resources (DWR) is providing the Natural Communities Commonly Associated with Groundwater Dataset (NC Dataset) online[1] to help Groundwater Sustainability Agencies (GSAs), consultants, and stakeholders identify GDEs within individual groundwater basins. To apply information from the NC Dataset to local areas, GSAs should combine it with the best available science on local hydrology, geology, and groundwater levels to verify whether polygons in the NC dataset are likely supported by groundwater in an aquifer (Figure 1)[2]. This document highlights six best practices for using local groundwater data to confirm whether mapped features in the NC dataset are supported by groundwater.

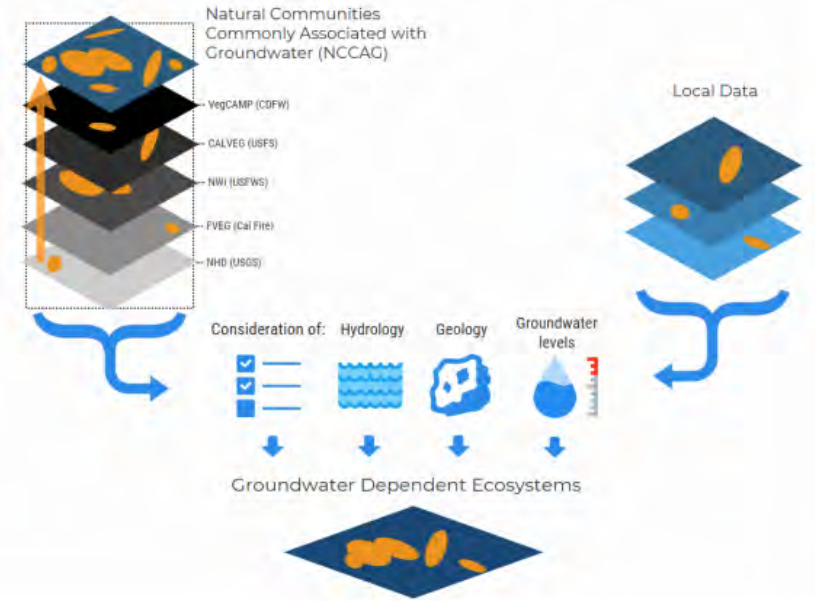

Figure 1. Considerations for GDE identification.
Source: DWR[2]

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[1] NC Dataset Online Viewer: https://gis.water.ca.gov/app/NCDatasetViewer/

[2] California Department of Water Resources (DWR). 2018. Summary of the "Natural Communities Commonly Associated with Groundwater" Dataset and Online Web Viewer. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Data-and-Tools/Files/Statewide-Reports/Natural-Communities-Dataset-Summary-Document.pdf

The NC Dataset identifies vegetation and wetland features that are good indicators of a GDE. The dataset is comprised of 48 publicly available state and federal datasets that map vegetation, wetlands, springs, and seeps commonly associated with groundwater in California[3]. It was developed through a collaboration between DWR, the Department of Fish and Wildlife, and The Nature Conservancy (TNC). TNC has also provided detailed guidance on identifying GDEs from the NC dataset[4] on the Groundwater Resource Hub[5], a website dedicated to GDEs.

BEST PRACTICE #1. Establishing a Connection to Groundwater

Groundwater basins can be comprised of one continuous aquifer (Figure 2a) or multiple aquifers stacked on top of each other (Figure 2b). In unconfined aquifers (Figure 2a), using the depth-to-groundwater and the rooting depth of the vegetation is a reasonable method to infer groundwater dependence for GDEs. If groundwater is well below the rooting (and capillary) zone of the plants and any wetland features, the ecosystem is considered disconnected and groundwater management is not likely to affect the ecosystem (Figure 2d). However, it is important to consider local conditions (e.g., soil type, groundwater flow gradients, and aquifer parameters) and to review groundwater depth data from multiple seasons and water year types (wet and dry) because intermittent periods of high groundwater levels can replenish perched clay lenses that serve as the water source for GDEs (Figure 2c). Maintaining these natural groundwater fluctuations are important to sustaining GDE health.

Basins with a stacked series of aquifers (Figure 2b) may have varying levels of pumping across aquifers in the basin, depending on the production capacity or water quality associated with each aquifer. If pumping is concentrated in deeper aquifers, SGMA still requires GSAs to sustainably manage groundwater resources in shallow aquifers, such as perched aquifers, that support springs, surface water, domestic wells, and GDEs (Figure 2). This is because vertical groundwater gradients across aquifers may result in pumping from deeper aquifers to cause adverse impacts onto beneficial users reliant on shallow aquifers or interconnected surface water. The goal of SGMA is to sustainably manage groundwater resources for current and future social, economic, and environmental benefits. While groundwater pumping may not be currently occurring in a shallower aquifer, use of this water may become more appealing and economically viable in future years as pumping restrictions are placed on the deeper production aquifers in the basin to meet the sustainable yield and criteria. Thus, identifying GDEs in the basin should done irrespective to the amount of current pumping occurring in a particular aquifer, so that future impacts on GDEs due to new production can be avoided. A good rule of thumb to follow is: *if groundwater can be pumped from a well - it's an aquifer*.

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[3] For more details on the mapping methods, refer to: Klausmeyer, K., J. Howard, T. Keeler-Wolf, K. Davis-Fadtke, R. Hull, A. Lyons. 2018. Mapping Indicators of Groundwater Dependent Ecosystems in California: Methods Report. San Francisco, California. Available at: https://groundwaterresourcehub.org/public/uploads/pdfs/iGDE_data_paper_20180423.pdf

[4] "Groundwater Dependent Ecosystems under the Sustainable Groundwater Management Act: Guidance for Preparing Groundwater Sustainability Plans" is available at: https://groundwaterresourcehub.org/gde-tools/gsp-guidance-document/

[5] The Groundwater Resource Hub: www.GroundwaterResourceHub.org

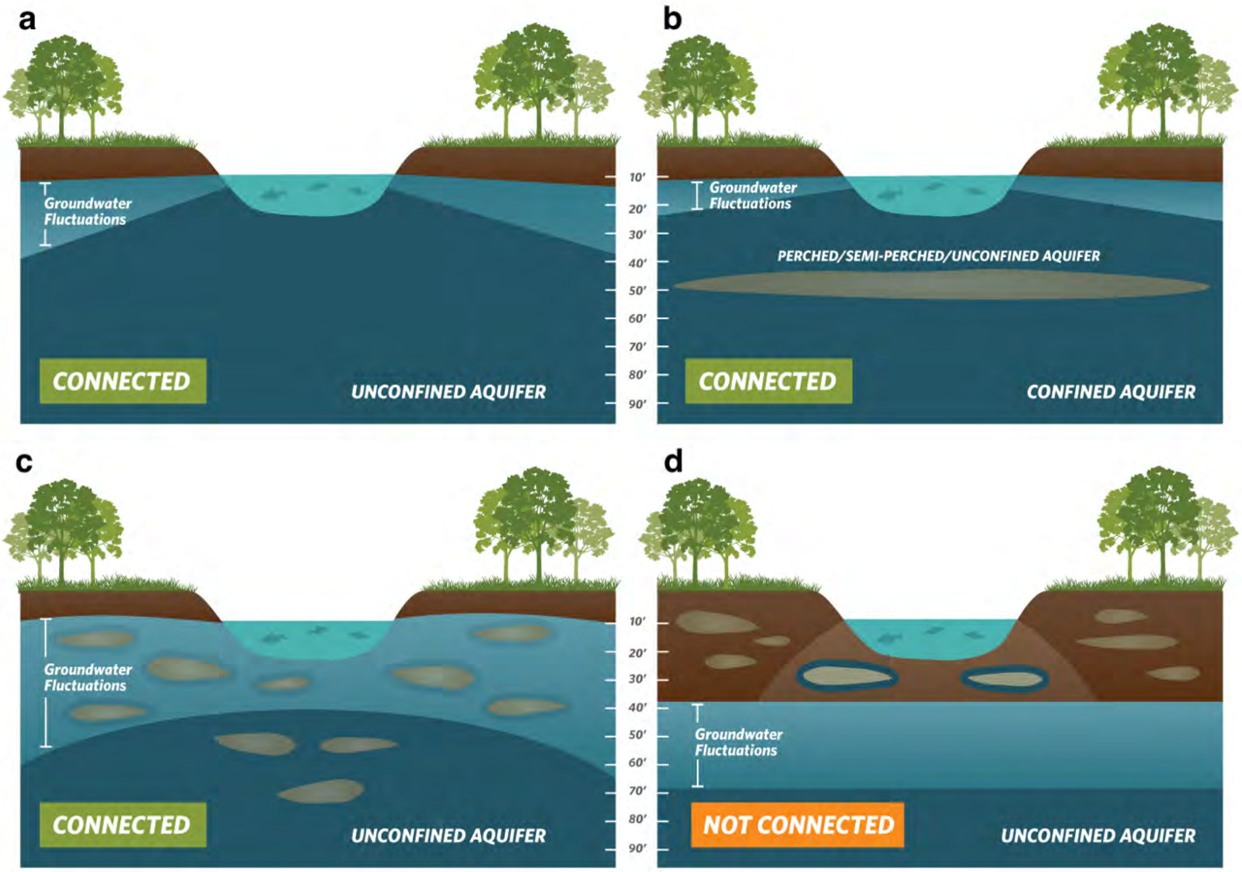

Figure 2. Confirming whether an ecosystem is connected to groundwater. Top: (a) Under the ecosystem is an unconfined aquifer with depth-to-groundwater fluctuating seasonally and interannually within 30 feet from land surface. **(b)** Depth-to-groundwater in the shallow aquifer is connected to overlying ecosystem. Pumping predominately occurs in the confined aquifer, but pumping is possible in the shallow aquifer. **Bottom: (c)** Depth-to-groundwater fluctuations are seasonally and interannually large, however, clay layers in the near surface prolong the ecosystem's connection to groundwater. **(d)** Groundwater is disconnected from surface water, and any water in the vadose (unsaturated) zone is due to direct recharge from precipitation and indirect recharge under the surface water feature. These areas are not connected to groundwater and typically support species that do not require access to groundwater to survive.

BEST PRACTICE #2. Characterize Seasonal and Interannual Groundwater Conditions

SGMA requires GSAs to describe current and historical groundwater conditions when identifying GDEs [23 CCR §354.16(g)]. Relying solely on the SGMA benchmark date (January 1, 2015) or any other single point in time to characterize groundwater conditions (e.g., depth-to-groundwater) is inadequate because managing groundwater conditions with data from one time point fails to capture the seasonal and interannual variability typical of California's climate. DWR's Best Management Practices document on water budgets[6] recommends using 10 years of water supply and water budget information to describe how historical conditions have impacted the operation of the basin within sustainable yield, implying that a baseline[7] could be determined based on data between 2005 and 2015. Using this or a similar time period, depending on data availability, is recommended for determining the depth-to-groundwater.

GDEs depend on groundwater levels being close enough to the land surface to interconnect with surface water systems or plant rooting networks. The most practical approach[8] for a GSA to assess whether polygons in the NC dataset are connected to groundwater is to rely on groundwater elevation data. As detailed in TNC's GDE guidance document[4], one of the key factors to consider when mapping GDEs is to contour depth-to-groundwater in the aquifer that is supporting the ecosystem (see Best Practice #5).

Groundwater levels fluctuate over time and space due to California's Mediterranean climate (dry summers and wet winters), climate change (flood and drought years), and subsurface heterogeneity in the subsurface (Figure 3). Many of California's GDEs have adapted to dealing with intermittent periods of water stress, however if these groundwater conditions are prolonged, adverse impacts to GDEs can result. While depth-to-groundwater levels within 30 feet[4] of the land surface are generally accepted as being a proxy for confirming that polygons in the NC dataset are supported by groundwater, it is highly advised that fluctuations in the groundwater regime be characterized to understand the seasonal and interannual groundwater variability in GDEs. Utilizing groundwater data from one point in time can misrepresent groundwater levels required by GDEs, and inadvertently result in adverse impacts to the GDEs. Time series data on groundwater elevations and depths are available on the SGMA Data Viewer[9]. However, if insufficient data are available to describe groundwater conditions within or near polygons from the NC dataset, include those polygons in the GSP <u>until</u> data gaps are reconciled in the monitoring network (see Best Practice #6).

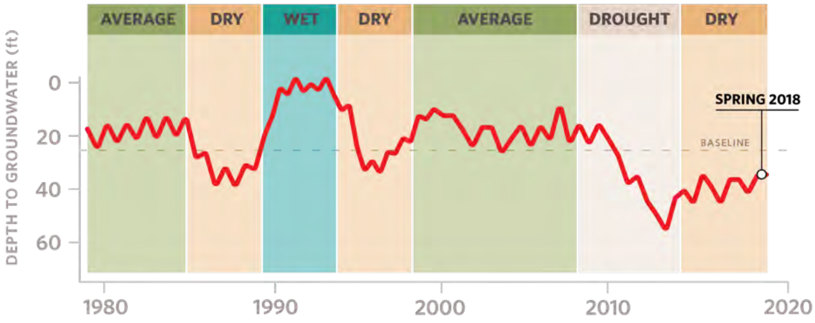

Figure 3. Example seasonality and interannual variability in depth-to-groundwater over time. Selecting one point in time, such as Spring 2018, to characterize groundwater conditions in GDEs fails to capture what groundwater conditions are necessary to maintain the ecosystem status into the future so adverse impacts are avoided.

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[6] DWR. 2016. Water Budget Best Management Practice. Available at: https://water.ca.gov/LegacyFiles/groundwater/sgm/pdfs/BMP_Water_Budget_Final_2016-12-23.pdf

[7] Baseline is defined under the GSP regulations as "historic information used to project future conditions for hydrology, water demand, and availability of surface water and to evaluate potential sustainable management practices of a basin." [23 CCR §351(e)]

[8] Groundwater reliance can also be confirmed via stable isotope analysis and geophysical surveys. For more information see The GDE Assessment Toolbox (Appendix IV, GDE Guidance Document for GSPs[4]).

[9] SGMA Data Viewer: https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer

BEST PRACTICE #3. Ecosystems Often Rely on Both Groundwater and Surface Water

GDEs are plants and animals that rely on groundwater for all or some of its water needs, and thus can be supported by multiple water sources. The presence of non-groundwater sources (e.g., surface water, soil moisture in the vadose zone, applied water, treated wastewater effluent, urban stormwater, irrigated return flow) within and around a GDE does not preclude the possibility that it is supported by groundwater, too. SGMA defines GDEs as "ecological communities and species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface" [23 CCR §351(m)]. Hence, depth-to-groundwater data should be used to identify whether NC polygons are supported by groundwater and should be considered GDEs. In addition, SGMA requires that significant and undesirable adverse impacts to beneficial users of surface water be avoided. Beneficial users of surface water include environmental users such as plants or animals[10], which therefore must be considered when developing minimum thresholds for depletions of interconnected surface water.

GSAs are only responsible for impacts to GDEs resulting from groundwater conditions in the basin, so if adverse impacts to GDEs result from the diversion of applied water, treated wastewater, or irrigation return flow away from the GDE, then those impacts will be evaluated by other permitting requirements (e.g., CEQA) and may not be the responsibility of the GSA. However, if adverse impacts occur to the GDE due to changing groundwater conditions resulting from pumping or groundwater management activities, then the GSA would be responsible (Figure 4).

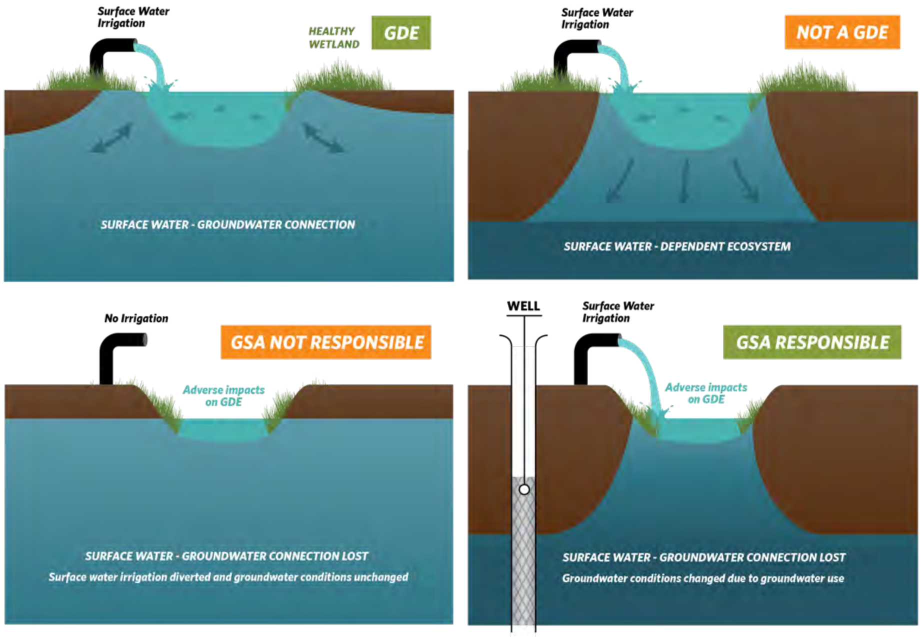

Figure 4. Ecosystems often depend on multiple sources of water. Top: (Left) Surface water and groundwater are interconnected, meaning that the GDE is supported by both groundwater and surface water. **(Right)** Ecosystems that are only reliant on non-groundwater sources are not groundwater-dependent. **Bottom: (Left)** An ecosystem that was once dependent on an interconnected surface water, but loses access to groundwater solely due to surface water diversions may not be the GSA's responsibility. **(Right)** Groundwater dependent ecosystems once dependent on an interconnected surface water system, but loses that access due to groundwater pumping is the GSA's responsibility.

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[10] For a list of environmental beneficial users of surface water by basin, visit: https://groundwaterresourcehub.org/gde-tools/environmental-surface-water-beneficiaries/

BEST PRACTICE #4. Select Representative Groundwater Wells

Identifying GDEs in a basin requires that groundwater conditions are characterized to confirm whether polygons in the NC dataset are supported by the underlying aquifer. To do this, proximate groundwater wells should be identified to characterize groundwater conditions (Figure 5). When selecting representative wells, it is particularly important to consider the subsurface heterogeneity around NC polygons, especially near surface water features where groundwater and surface water interactions occur around heterogeneous stratigraphic units or aquitards formed by fluvial deposits. The following selection criteria can help ensure groundwater levels are representative of conditions within the GDE area:

- Choose wells that are within 5 kilometers (3.1 miles) of each NC Dataset polygons because they are more likely to reflect the local conditions relevant to the ecosystem. If there are no wells within 5km of the center of a NC dataset polygon, then there is insufficient information to remove the polygon based on groundwater depth. Instead, it should be retained as a potential GDE until there are sufficient data to determine whether or not the NC Dataset polygon is supported by groundwater.

- Choose wells that are screened within the surficial unconfined aquifer and capable of measuring the true water table.

- Avoid relying on wells that have insufficient information on the screened well depth interval for excluding GDEs because they could be providing data on the wrong aquifer. This type of well data should not be used to remove any NC polygons.

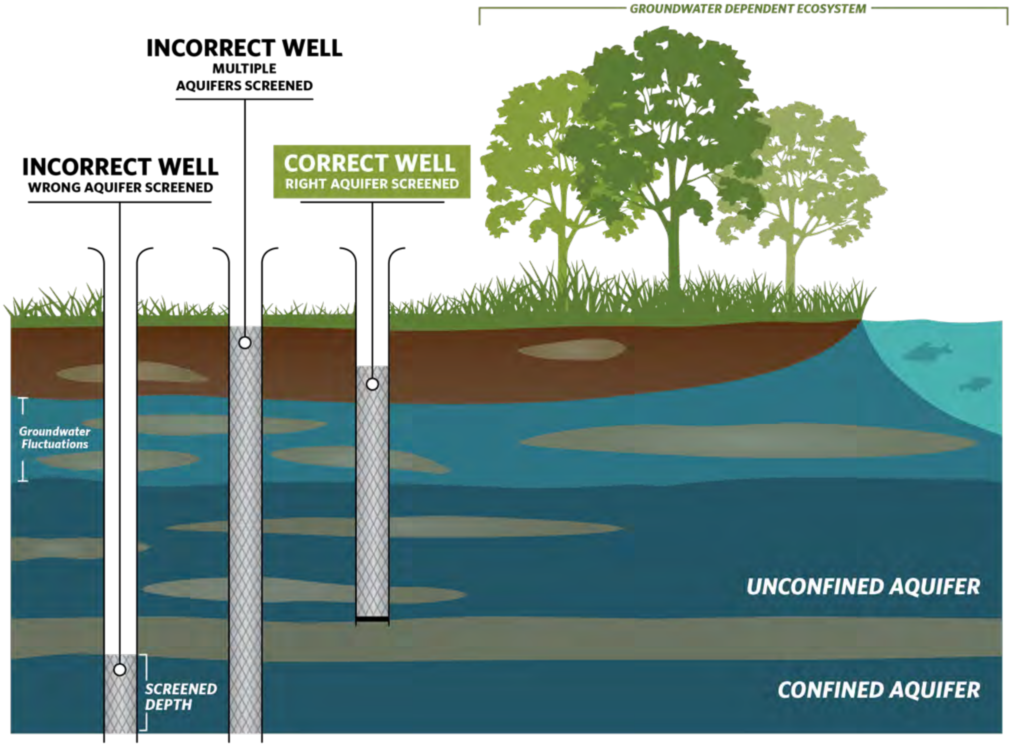

Figure 5. Selecting representative wells to characterize groundwater conditions near GDEs.

BEST PRACTICE #5. Contouring Groundwater Elevations

The common practice to contour depth-to-groundwater over a large area by interpolating measurements at monitoring wells is unsuitable for assessing whether an ecosystem is supported by groundwater. This practice causes errors when the land surface contains features like stream and wetland depressions because it assumes the land surface is constant across the landscape and depth-to-groundwater is constant below these low-lying areas (Figure 6a). A more accurate approach is to interpolate **groundwater elevations** at monitoring wells to get groundwater elevation contours across the landscape. This layer can then be subtracted from land surface elevations from a Digital Elevation Model (DEM)[11] to estimate depth-to-groundwater contours across the landscape (Figure b; Figure 7). This will provide a much more accurate contours of depth-to-groundwater along streams and other land surface depressions where GDEs are commonly found.

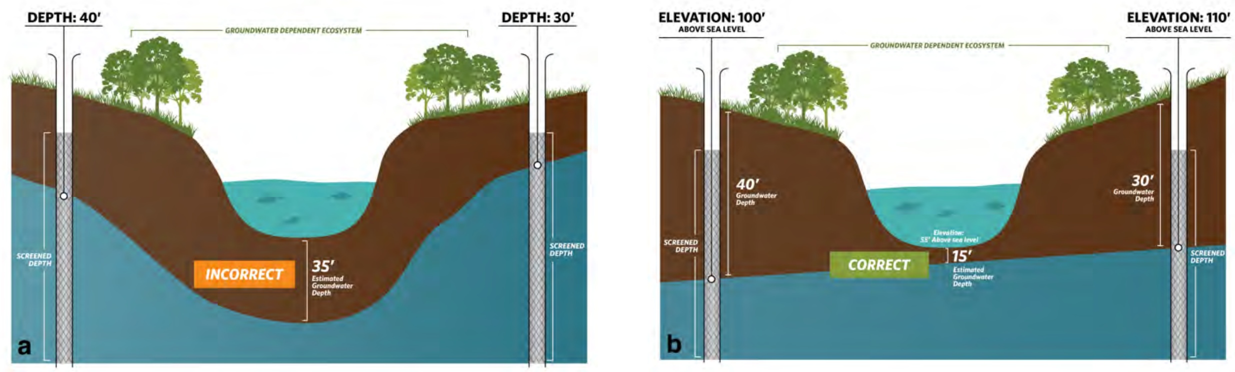

Figure 6. Contouring depth-to-groundwater around surface water features and GDEs. (a) Groundwater level interpolation using depth-to-groundwater data from monitoring wells. **(b)** Groundwater level interpolation using groundwater elevation data from monitoring wells and DEM data.

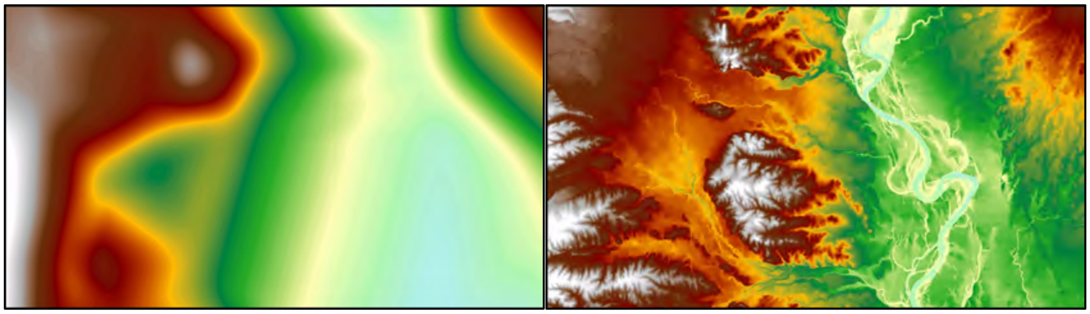

Figure 7. Depth-to-groundwater contours in Northern California. (Left) Contours were interpolated using depth-to-groundwater measurements determined at each well. **(Right)** Contours were determined by interpolating groundwater elevation measurements at each well and superimposing ground surface elevation from DEM spatial data to generate depth-to-groundwater contours. The image on the right shows a more accurate depth-to-groundwater estimate because it takes the local topography and elevation changes into account.

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[11] USGS Digital Elevation Model data products are described at: https://www.usgs.gov/core-science-systems/ngp/3dep/about-3dep-products-services and can be downloaded at: https://iewer.nationalmap.gov/basic/

BEST PRACTICE #6. Best Available Science

Adaptive management is embedded within SGMA and provides a process to work toward sustainability over time by beginning with the best available information to make initial decisions, monitoring the results of those decisions, and using the data collected through monitoring programs to revise decisions in the future. In many situations, the hydrologic connection of NC dataset polygons will not initially be clearly understood if site-specific groundwater monitoring data are not available. If sufficient data are not available in time for the 2020/2022 plan, **The Nature Conservancy strongly advises that questionable polygons from the NC dataset be included in the GSP until data gaps are reconciled in the monitoring network.** Erring on the side of caution will help minimize inadvertent impacts to GDEs as a result of groundwater use and management actions during SGMA implementation.

KEY DEFINITIONS

Groundwater basin is an aquifer or stacked series of aquifers with reasonably well-defined boundaries in a lateral direction, based on features that significantly impede groundwater flow, and a definable bottom. *23 CCR §341(g)(1)*

Groundwater dependent ecosystem (GDE) are ecological communities or species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface. *23 CCR §351(m)*

Interconnected surface water (ISW) surface water that is hydraulically connected at any point by a continuous saturated zone to the underlying aquifer and the overlying surface water is not completely depleted. *23 CCR §351(o)*

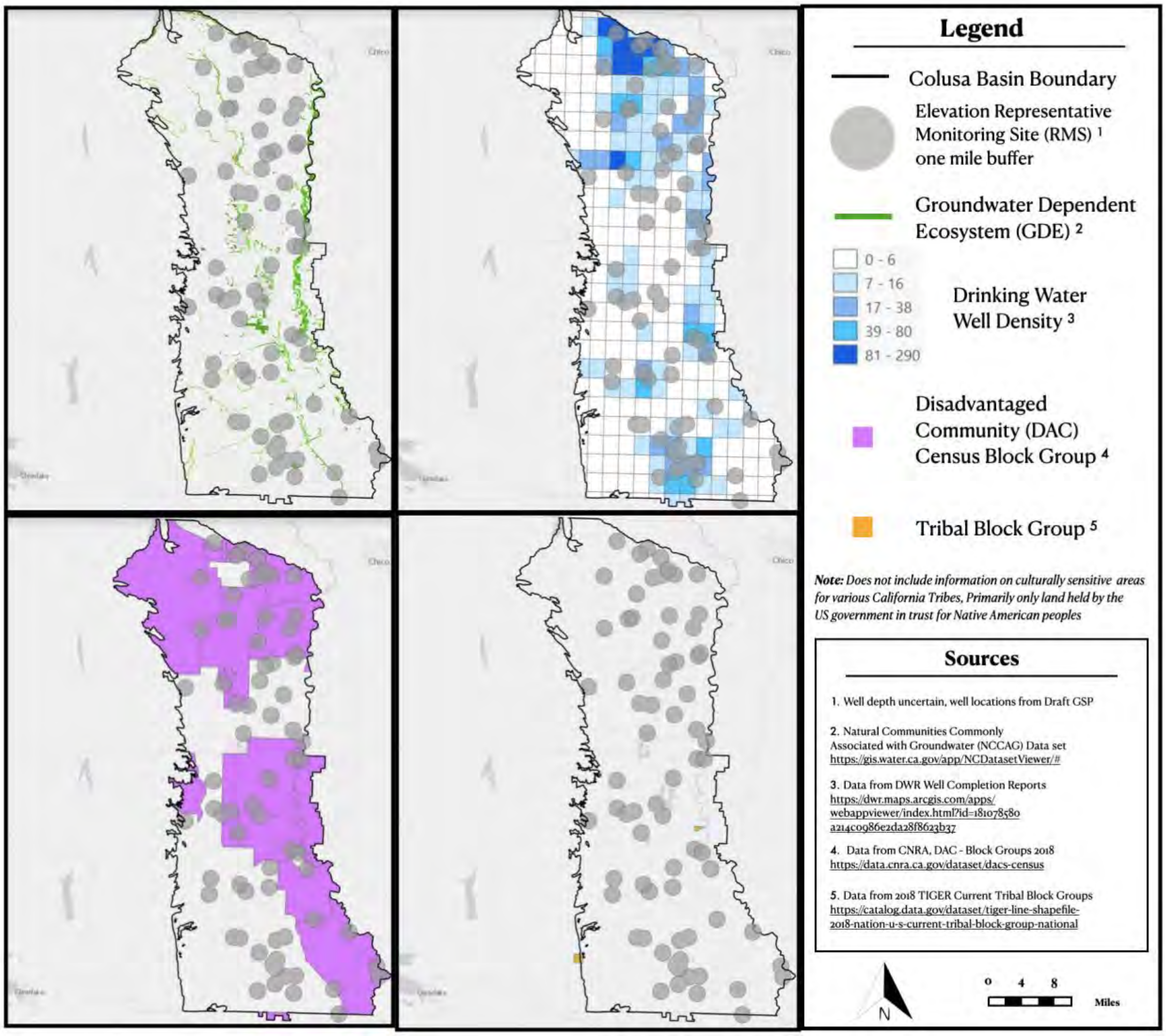
Principal aquifers are aquifers or aquifer systems that store, transmit, and yield significant or economic quantities of groundwater to wells, springs, or surface water systems. *23 CCR §351(aa)*

ABOUT US

The Nature Conservancy is a science-based nonprofit organization whose mission is *to conserve the lands and waters on which all life depends*. To support successful SGMA implementation that meets the future needs of people, the economy, and the environment, TNC has developed tools and resources (www.groundwaterresourcehub.org) intended to reduce costs, shorten timelines, and increase benefits for both people and nature.

Attachment E

Maps of representative monitoring sites in relation to key beneficial users

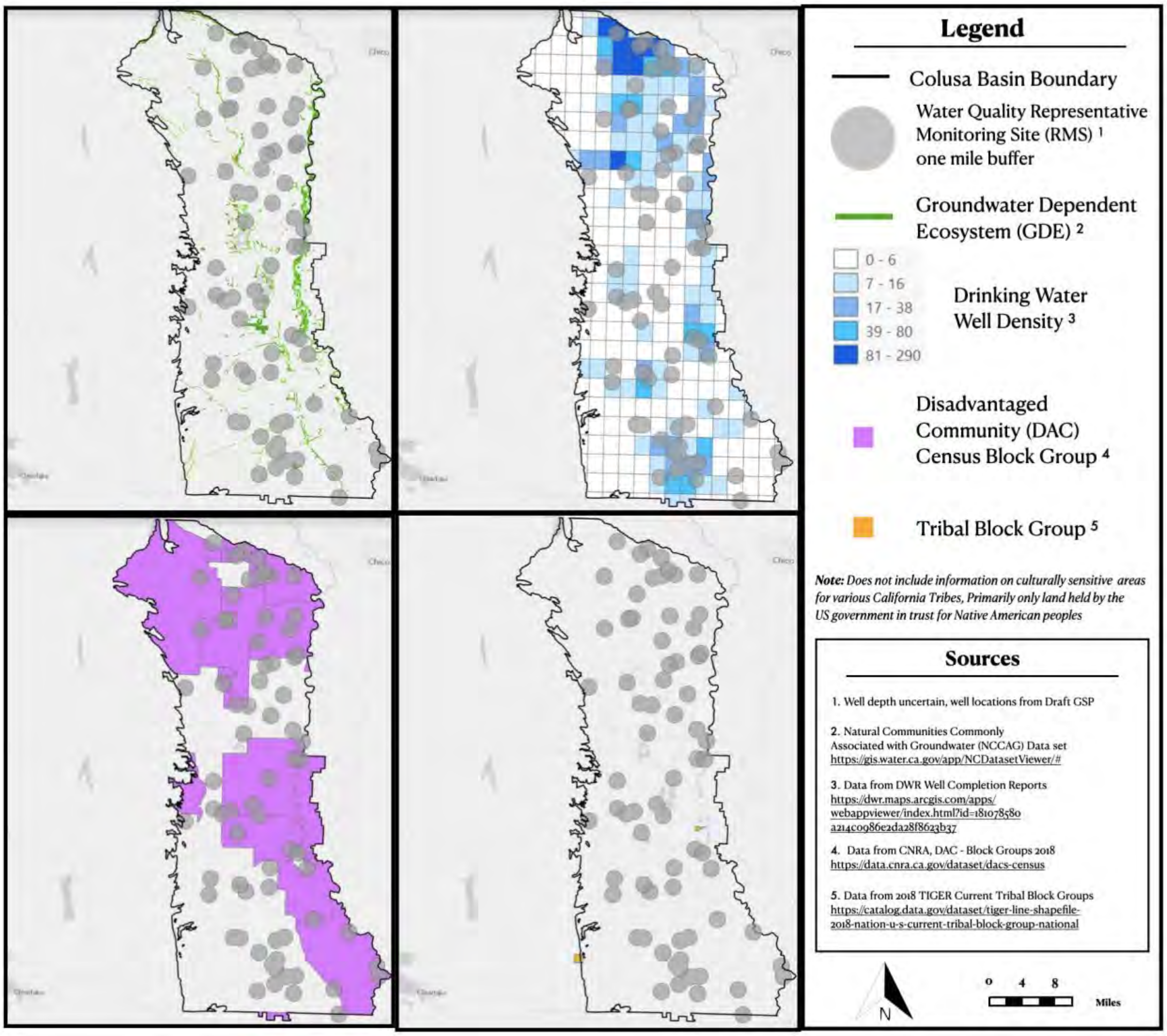


Note: *Does not include information on culturally sensitive areas for various California Tribes, Primarily only land held by the US government in trust for Native American peoples*

Sources

1. Well depth uncertain, well locations from Draft GSP
2. Natural Communities Commonly Associated with Groundwater (NCCAG) Data set https://gis.water.ca.gov/app/NCDatasetViewer/#
3. Data from DWR Well Completion Reports https://dwr.maps.arcgis.com/apps/webappviewer/index.html?id=181078580a214c0986e2da28f8623b37
4. Data from CNRA, DAC - Block Groups 2018 https://data.cnra.ca.gov/dataset/dacs-census
5. Data from 2018 TIGER Current Tribal Block Groups https://catalog.data.gov/dataset/tiger-line-shapefile-2018-nation-u-s-current-tribal-block-group-national

Figure 1. Groundwater elevation representative monitoring sites in relation to key beneficial users: a) Groundwater Dependent Ecosystems (GDEs), b) Drinking Water users, c) Disadvantaged Communities (DACs), and d) Tribes.



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3. Data from DWR Well Completion Reports https://dwr.maps.arcgis.com/apps/webappviewer/index.html?id=181078580a214c0986e2da28f8623b37

4. Data from CNRA, DAC - Block Groups 2018 https://data.cnra.ca.gov/dataset/dacs-census

5. Data from 2018 TIGER Current Tribal Block Groups https://catalog.data.gov/dataset/tiger-line-shapefile-2018-nation-u-s-current-tribal-block-group-national

Figure 2. Groundwater quality representative monitoring sites in relation to key beneficial users: a) Groundwater Dependent Ecosystems (GDEs), b) Drinking Water users, c) Disadvantaged Communities (DACs), and d) Tribes.

2B-3. Emails

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From: Ben King
To: Mary Fahey
Cc: Gosselin, Paul; Buck, Christina; Ben King
Subject: FW: Hydrogeology of the Sutter Basin, California 1971
Date: Monday, November 18, 2019 2:44:12 PM
Attachments: George Curtin Sutter Basin.pdf
USGS Sacramento Valley Tectonism.pdf

Hi Mary,

Here is the cite of the first paragraph of the Abstract for Hydrogeology of the Sutter Basin by George Curtin:

"***A mound of saline water exists in continental sediments between two fresh water rivers in the Sutter Basin of the Sacramento Valley, California. This saline water has moved from the marine sediments, at depth, upward along the Sutter Basin Fault and then through 2,000 feet of alluvium."***

I have also attached the USGS Sacramento Valley Tectonism Study published in 1987. This USGS report explains the faults surrounding the ancient Sutter Buttes volcano and the fact that the faults are still active.

As I mentioned, I am concerned about the potential for further later movement of the salt water northward towards the Butte Sink that may be cause by future groundwater substitution on east side of the Sacramento River near Colusa. As you know Colusa, Grimes, Sutter and Meridian use groundwater. The other issue that came to my mind was the potential for further deterioration due to future earthquake activity.

Perhaps – this area might be a good candidate for an Aerial mapping if the mapping could detect higher chloride levels in the groundwater?

Thanks again

Ben King

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Late Cenozoic Tectonism of the Sacramento Valley, California

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1359

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

REPRINTED PAGE FOR
GPO JACKET (FY 87) 785-048 (PRINT ORDER 77389)—
U.S. Geological Survey Professional Paper 1359

SUP. DOCS: This page is to be distributed according to the standard IGS mailing list for U.S. Geological Survey Professional Papers.

USER: This reprint of figure 5 should replace the present figure 5 of U.S. Geological Survey Professional Paper 1359. It was reprinted to correct the seismic reflection profile which was inadvertently printed backwards.

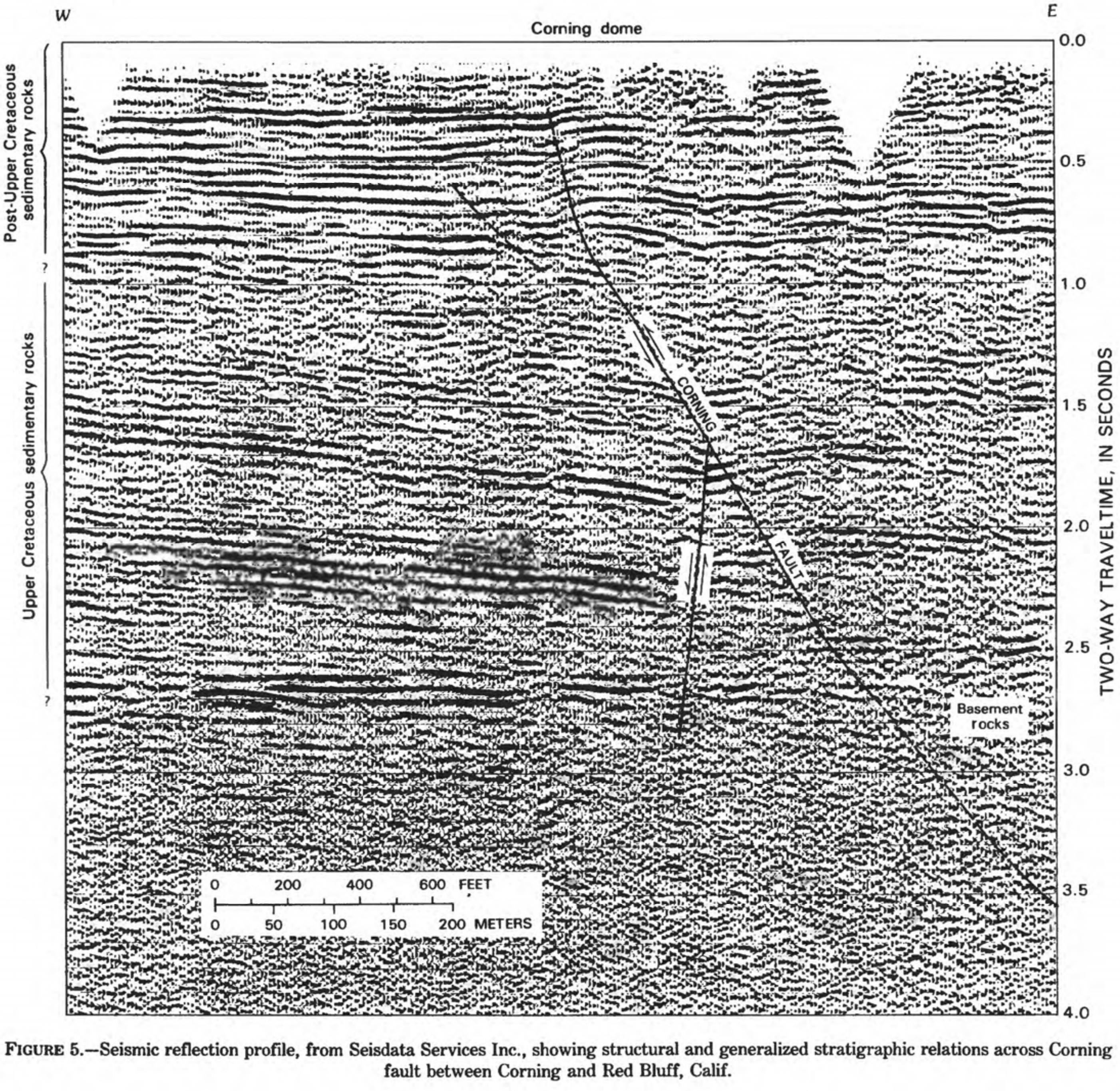

FIGURE 5.—Seismic reflection profile, from Seisdata Services Inc., showing structural and generalized stratigraphic relations across Corning fault between Corning and Red Bluff, Calif.

Late Cenozoic Tectonism of the Sacramento Valley, California

By DAVID S. HARWOOD *and* EDWARD J. HELLEY

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1359

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1987

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DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Harwood, David Smith, 1936–
Late Cenozoic tectonism of the Sacramento Valley, California.

(U.S. Geological Survey Professional Paper 1359)
Bibliography
Supt. of Docs. No.: I 19.16:1359
1. Geology, stratigraphic—Cenozoic. 2. Geology—California—Sacramento River valley. 3. Geology, structural. I. Helley, Edward John, 1939– . II. Title.
QE690.H37 1986 551.7'8'097945 85-600268

For sale by the Books and Open-File Reports Section,
U.S. Geological Survey, Federal Center, Box 25425, Denver, CO 80225

CONTENTS

Page
Structural features in the valley fill—Continued
  Structures southwest of the Willows fault—Continued

ILLUSTRATIONS

LATE CENOZOIC TECTONISM OF THE SACRAMENTO VALLEY, CALIFORNIA

By DAVID S. HARWOOD and EDWARD J. HELLEY

ABSTRACT

Structure contours drawn on top of the Cretaceous rocks in the Sacramento Valley define a large number of diversely oriented folds and faults that are expressed in topographic, hydrologic, and geologic features at the land surface. Although many of the structures in the valley have a protracted history of movement, some dating back to the late Mesozoic, a remarkable number of these structures show late Cenozoic deformation that can be accurately determined from folding and faulting of widespread, dated Pliocene and Pleistocene volcanic units. These time-stratigraphic units are used to define structural domains of essentially contemporaneous late Cenozoic deformation that was characterized by east-west compressive stress. The oldest structural domain is located in the southeastern part of the valley, where east-side-up reverse movement on the Willows fault ceased prior to deposition of continentally derived sediments of late Miocene and early Pliocene age. In the middle Pliocene to early Pleistocene, east-west compressive deformation progressed northward through the valley so that the youngest late Cenozoic deformation is recorded in east-northeast-trending folds and faults in the Battle Creek domain, at the northernmost part of the valley. The northward progression of east-west compressive deformation appears to be related to the northward eclipse of eastward subduction of the Juan de Fuca plate before the northwestward migration of the Mendocino triple junction along the continental margin west of the valley.

Much of the east-west compressive stress that affected the valley in the late Cenozoic was accommodated by east-side-up reverse movement on the steeply east-dipping, northwest-trending Willows fault and the north-trending Corning fault that splays off from the main stem of the Willows fault north of Sutter Buttes. Significant strain release also occurred on the northwest-trending fault beneath the Chico monocline and on the east-northeast-trending Red Bluff, Battle Creek, and Bear Creek faults in the past 2.0 m.y. Southeast of Sutter Buttes, the Willows fault follows the boundary between dense, magnetic, presumably ophiolitic basement to the west and Sierran basement to the east. The Chico monocline follows the same basement boundary north of Sutter Buttes, but that structure is stepped eastward from the trace of the Willows fault. It seems reasonably certain that the southeastern extension of the Willows fault and the Chico monocline fault are middle and late Cenozoic structures, respectively, that owe their existence and orientation, in part, to earlier, Mesozoic tectonic juxtapositioning of significantly different basement terranes.

INTRODUCTION

The Oroville earthquake ($M = 5.6$, August 1, 1975) added a new dimension to geologic studies of the Sacramento Valley. That event, more than any of the infrequent earthquakes that previously occurred in the area, awakened the geologic and engineering communities to the potential of active faulting in the valley and in the adjacent Sierran foothills. Because the Oroville earthquake occurred near the Lake Oroville dam (fig. 1) at a time when other large dams were being constructed along the Sierran foothills, several geologic studies, including this one, were conducted to specifically evaluate the late Cenozoic structural history of the region (Woodward-Clyde Consultants, 1977; Harwood and others, 1981; Helley and others, 1981; Helley and Harwood, 1985).

For about a half century prior to the Oroville earthquake, most geologic investigations of the Sacramento Valley (fig. 1) focused on locating natural gas in the deeper parts of the valley fill and water resources in the near-surface deposits. These investigations produced a wealth of stratigraphic and structural data that was gathered primarily from numerous gas fields scattered throughout the valley (map A, pl. 1). Several geologic syntheses resulted from these studies, but they were designed primarily to facilitate further exploration for these valuable resources and did not emphasize late Cenozoic tectonism (Bryan, 1923; Repenning, 1960; Olmsted and Davis, 1961; Safonov, 1968; Hackel, 1966; Redwine, 1972; California Department of Water Resources, 1978).

Recent developments in the concept of plate tectonics have given new emphasis and scope to regional geologic analyses by enabling integration of studies in the valley with those in the Coast Ranges to the west and the Sierra Nevada to the east (fig. 2). Within this concept, the Sacramento Valley was interpreted to be a late Mesozoic forearc basin (Dickinson, 1970; Ingersoll, 1976, 1978a, 1978b; Dickinson and Seely, 1979) that formed contemporaneously with and between the accretionary trench deposits of the Franciscan Complex to the west (Ernst, 1965, 1970; Blake and Jones, 1974; Blake and others, 1974) and an eastern magmatic arc complex, the roots of which are exposed in the Sierra Nevada (Hamilton, 1969). Although debate about the extent, geographic origin, and nature of the material accreted to the Mesozoic continental margin continues (Coney and others, 1980), the basic three-component model of an arc-trench system remains fundamental (Dickinson and Seely, 1979). Although the Sacramento Valley may be the most completely studied ancient forearc basin in the world (Ingersoll and others, 1977), the emphasis and scope of published paleogeo-

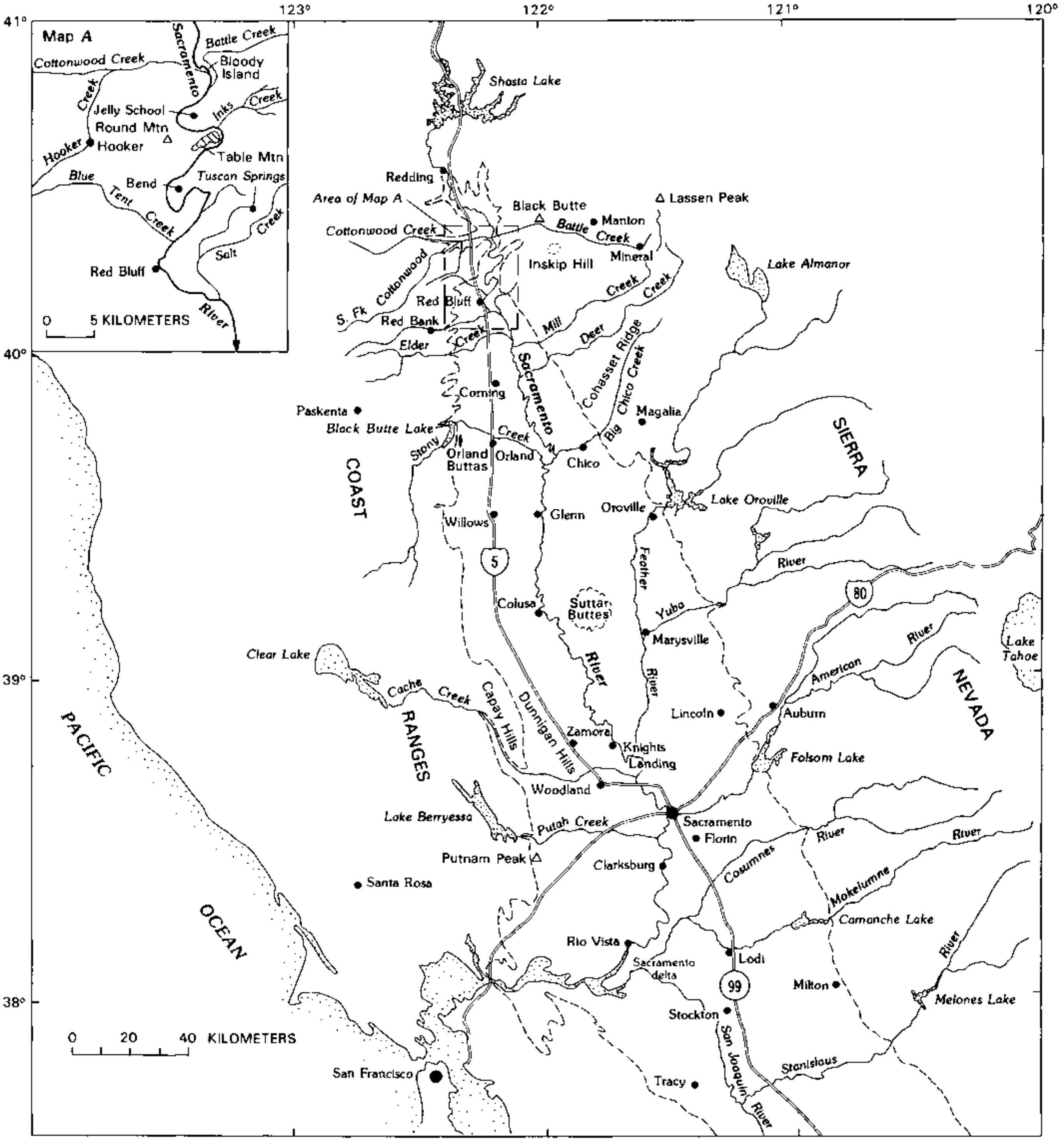


FIGURE 1.—Index map of northern California showing 500-foot topographic contour (dashed), which coincides approximately with boundary of Sacramento Valley.

graphic and paleotectonic studies generally precluded detailed analysis of late Cenozoic tectonism.

Structures discussed in this report are generally too young to provide new data for the late Mesozoic arc-trench model. In fact, a major objective of this report is to document that most of the folds and faults in the valley either formed in the late Cenozoic or are older structures that have undergone renewed deformation in the past few million years. In this respect, structures in the valley are more closely related to tectonic models of Cenozoic subduction, including subsequent lateral convergence along the San Andreas fault system and extension in the Basin and Range province to the east, than they are to the late Mesozoic tectonic models (Hamilton and Myers, 1966; Atwater, 1970; Christiansen and Lipman, 1972; Atwater and Molnar, 1973; Dickinson, 1979).

ACKNOWLEDGMENTS

The structure contour map presented in this report (pl. 1) integrates subsurface data from many summary reports of oil and gas operations published by the California Division of Oil and Gas. Credit is given to specific authors of gas field reports in the "Sources of Data" shown on plate 1, and we would like to express our appreciation to those authors, whose work contributed much of the basic data for our compilation. In addition to published reports, we analyzed well logs from a number of areas in the valley, and we acknowledge the courteous service provided by the staff of the Woodland office of the California Division of Oil and Gas.

Interpretation of the subsurface data was influenced to a great degree by exceptionally high-quality seismic-reflection profiles purchased from Seisdata Services Inc. We thank Seisdata Services Inc. for allowing us to reproduce a small segment of one of those profiles in this report.

We thank David Wagner of the California Division of Mines and Geology for sending us a preprint of his detailed map and discussion of the Capay Valley-Capay Hills area. Special thanks are given to the California Academy of Sciences for making available their collection of thin sections of basement rocks that were penetrated in wells in the Sacramento Valley.

We also acknowledge stimulating discussions with our colleagues J.A. Bartow, M.C. Blake, Jr., K.F. Fox, Jr., D.L. Jones, R.J. McLaughlin, T.H. Nilsen, A.M. Sarna-Wojcicki, and C.M. Wentworth. These discussions sharpened the focus of many points in this report, but responsibility for the analysis of subsurface structures and regional tectonism rests with Harwood, and the mapping of surficial deposits, which document the youthfulness of many structures, rests with Helley.

REGIONAL SETTING

The Sacramento Valley comprises the northern third of the Great Valley of California (fig. 2)—a broad, fertile lowland situated between mountainous terrains of the Coast Ranges to the west and the Sierra Nevada to the east. Marine sedimentary rocks, ranging in age from Late Jurassic to early Miocene, underlie the deeper parts of the Sacramento Valley. They are unconformably capped by a relatively thin cover of alluvial deposits and locally prominent volcanic rocks of early Miocene to Holocene age.

Marine sedimentary rocks exposed on the west flank of the Sacramento Valley record a nearly unbroken depositional sequence from Upper Jurassic through Upper Cretaceous (Lachenbruch, 1962; Ingersoll and others, 1977). On the east side of the valley, Upper Cretaceous sandstone and shale, described by Taft and others (1940) and Haggart and Ward (1984), rest unconformably on metamorphic and plutonic rocks of the Sierra Nevada basement and indicate a progressive eastward onlap of marine sedimentation during the late Mesozoic (Ingersoll and others, 1977). In a broad area south of Sutter Buttes, younger Upper Cretaceous sandstone and shale record a westward-prograding deltaic sequence and marine regression (Drummond and others, 1976; Garcia, 1981) during the Late Cretaceous, as the depositional basin was broadly uplifted and tilted to the south and west. Intermittent periods of uplift and subsidence, apparently caused by Paleogene subduction and possibly by lateral faulting to the west (Nilsen and Clarke, 1975; Nilsen and McKee, 1979), affected the depositional basin through the early Tertiary.

Four distinct submarine canyons developed during the uplift cycles, and they were subsequently filled with transgressive marine sequences during times of subsidence (fig. 2). Almgren (1978) has documented three ancient oscillatory tectonic-depositional cycles in the southern part of the Sacramento Valley. He concludes that the Martinez canyon was cut in the late early to middle Paleocene, the Meganos canyon was cut in early Oligocene and filled in late Oligocene and early Miocene, and the Markley canyon was cut in early Oligocene and filled in early Miocene time. Although the timing of the fourth submarine canyon is not as closely constrained by the sedimentary record as the other three, Redwine (1972) concluded that the Princeton canyon, located in the north-central part of the valley (fig. 2), was cut and filled between the late Paleocene and early Eocene, probably coincident with the formation of the Martinez canyon to the south (Almgren, 1978). Eocene marine deposits in the Princeton canyon apparently grade northward and eastward into alluvial deposits derived from the northern Sierra Nevada.

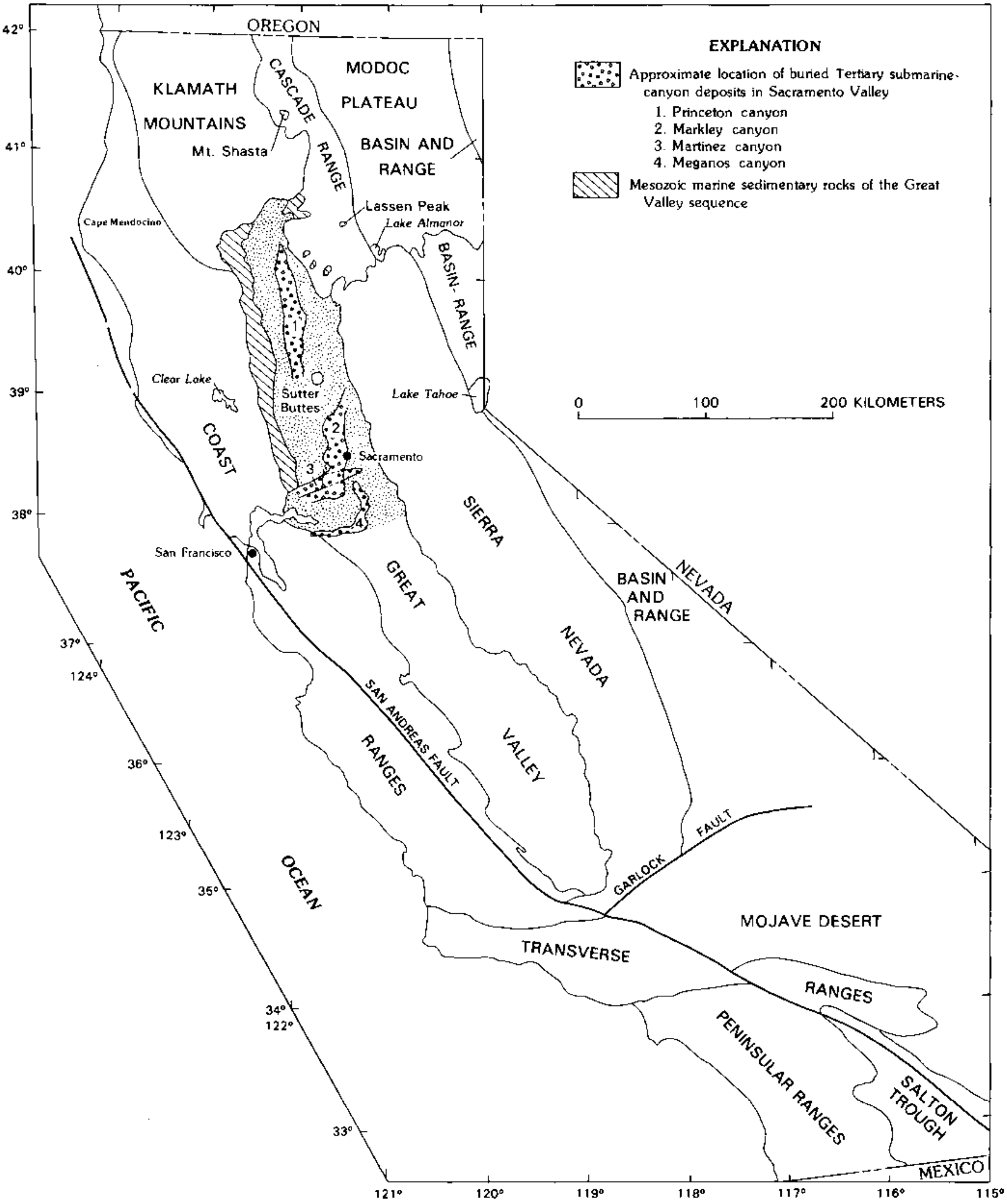


FIGURE 2.—Outline of geomorphic provinces in California and general location of buried Tertiary submarine canyon deposits in Sacramento Valley (stippled).

By the early Miocene, the northern part of the Sacramento Valley clearly was an emergent area, subjected to fluvial erosion and deposition. During this time, between 23.8 and 22.3 m.y. ago according to Dalrymple (1964), the Lovejoy Basalt was erupted from a vent or vents in the northern Sierra Nevada (Durrell, 1959) and flowed westward in a confined channel until it reached the Sacramento Valley near Oroville. Upon reaching the valley, the Lovejoy Basalt spread laterally, filling distributary alluvial channels (van den Berge, 1968) and flowed both westward, across the present axis of the valley now occupied by the Sacramento River at least to Orland Buttes, and southward at least to the vicinity of Putnam Peak (Weaver, 1949) (fig. 1), 260 km from the presumed source. Because of its distinctive characteristics, widespread distribution in both the surface and subsurface parts of the Sacramento Valley, and radiometrically determined age, the Lovejoy Basalt is an important marker unit (pl. 1) that places an age constraint on Cenozoic deformation in the valley.

After eruption of the Lovejoy Basalt, alluvial sediments of late middle Miocene to early Pliocene age accumulated in the central and southern part of the valley, capping marine sedimentary rocks deposited in the Princeton and Markley canyons (Redwine, 1972; Almgren, 1978). These alluvial deposits, however, are not present in surface exposures in the northern part of the valley, where Pliocene alluvium of the Tehama Formation in the northwest and coeval volcanic rocks of the Tuscan Formation in the northeast rest directly on the Lovejoy Basalt or on older rocks where the Lovejoy is missing.

A widespread felsic pumiceous tuff, the Nomlaki Tuff Member of the Tuscan and Tehama Formations, occurs at or near the base of the Pliocene rocks and serves as a second important time-stratigraphic marker in the valley, dated at 3.4 m.y. (Evernden and others, 1964). The Nomlaki, which was erupted from the vicinity of Lassen Peak, generally marks the beginning of volcanic activity that has occurred intermittently into historic time at the southern end of the Cascade Range (fig. 2). Pliocene and Pleistocene volcanic rocks, erupted from the Lassen area, flowed westward and interfingered with alluvial deposits of the ancestral Sacramento River system in the northern part of the valley (Anderson, 1933; Lydon, 1968; Harwood and others, 1981; Helley and others, 1981). Several of the volcanic units have been dated (Harwood and others, 1981), and they are important time indicators for the late Cenozoic depositional and tectonic evolution of the Sacramento Valley. Two informally designated volcanic units, the Rockland ash bed (referred to as the ash of Mount Maidu by Harwood and others, 1981) and the basalt of Deer Creek, dated at 0.45 and 1.09 m.y., respectively (Meyer and others, 1980; Harwood and others, 1981), are particularly significant because they bracket the age of the Red Bluff Formation. The Red Bluff forms a thin, widespread gravel pediment that unconformably caps the Pliocene rocks in the northern part of the valley. The fact that the Red Bluff Formation is faulted and folded clearly establishes the presence of late Cenozoic deformation, within the past million years, on most of the major features shown on the structure contour map (pl. 1).

A volcanic center, composed of andesitic fragmental deposits intruded by late-stage rhyolite domes, formed at Sutter Buttes in the central part of the valley between 2.4 and 1.4 m.y. ago (Williams, 1929; Williams and Curtis, 1977). This late Cenozoic volcanic center is located over a northwest-trending tectonic boundary that juxtaposes a basement of dense, magnetic, presumed oceanic crust (Cady, 1975; Griscom, 1973) on the west against metamorphic and plutonic rocks of the Sierran basement on the east. The boundary between the basement terranes is a Mesozoic tectonic feature that apparently has been reactivated by Cenozoic deformation (Harwood, 1984). Southeast of Sutter Buttes, the Willows fault approximately follows the contact between oceanic and Sierran basement terranes, and northeast of Sutter Buttes that basement boundary lies beneath the Chico monocline.

In the southeastern part of the valley, structure contours are drawn on the basement surface (pl. 1). In the rest of the valley, the datum is the top of the Cretaceous rocks. Contouring procedures are described on plate 1.

INTERPRETATION OF BASEMENT CONTOURS

The most pronounced deflection in basement contours is located beneath Sutter Buttes (pl. 1). This anomaly in basement topography was shown first by Smith (1964) and mentioned briefly by Williams and Curtis (1977, p. 6), who noted more than 395 m of local relief on the basement surface but offered no interpretation of the anomaly. Although some of the upwelling of the basement surface may be related to volcanic intrusion at Sutter Buttes, Harwood (1984) suggests that much of the basement uplift was related to east-side-up movement on the Willows fault, which passes just west and south of the Sutter Buttes.

Data from deep wells a few kilometers north of Sutter Buttes (pl. 1) indicate that the basement surface has a major deflection related to a northeast-trending fold or fault, or both. All of these possible structural configurations were investigated, and we conclude that the structure in the area is a northeast-trending fold, faulted along its southeast limb. The fault is interpreted to be a steeply dipping to vertical normal fault with southeast-side-down displacement. Both the fold and fault, however, appear to die out to the northeast.

In a zone southeast of Sutter Buttes that extends to the Stockton fault (pl. 1), variations in the slope of the basement surface are shown by northwest-trending zones of broadly spaced and relatively close-spaced contours. The basement surface may dip eastward locally in those areas marked by broadly spaced contours (see Jacobsen, 1981), but well data are too sparse to locate closed contours in this area, even if they would show at the chosen contour interval of 150 m.

From Sacramento south to the Stockton fault, the slope of the basement steepens significantly west of the −1,500-m contour. This change in basement slope lies near the eastern edge of the positive gravity and magnetic anomalies in the Great Valley that Cady (1975) interpreted to represent ophiolitic oceanic crust tectonically juxtaposed against Sierran basement rocks to the east. Reports of two wells south of Sacramento, however, show "granite" and "gneiss" at −1,954 m and −2,861 m, respectively, suggesting that the interpreted suture between oceanic and Sierran basements is not marked by the topographic break in the basement surface at the −1,500-m contour. It must be emphasized, however, that these identifications of basement rocks were made some time ago by the operators who drilled the wells, and it is possible that the "granite" may be a leucocratic rock associated with ophiolitic basement, such as plagiogranite, and the "gneiss" may be any dark-colored rock, even part of the ophiolitic basement. It seems reasonably certain, in any case, that the topographic break at the −1,500-m contour is controlled in some measure by a fault, possibly the extension of the Willows fault southeast of Sutter Buttes. It is interesting, and not altogether fruitless, to speculate that the Willows fault southeast of Sutter Buttes coincides with and represents the up-section propogation of the major fault between oceanic crust and the arc-massif basement of the Sierra Nevada. If such is the case, the Willows fault southeast of the Sutter Buttes may represent a structure inherited from the upper-slope discontinuity, a region of structural weakness over the boundary between forearc-basin and arc-massif basements, identified by Karig and Sharman (1975) in modern forearc basins.

From Sutter Buttes north to Chico, a number of wells penetrate basement rocks reported as diorite, gabbro, noritic gabbro, and serpentine. Not surprisingly, this part of the Sacramento Valley is characterized by large, positive gravity and magnetic anomalies that mark the northern part of the inferred Great Valley ophiolitic basement (Cady, 1975). Some thin sections of gabbro and diorite from wells in this area, contained in a collection of thin sections of basement rocks held by the California Academy of Sciences, reveal remarkably fresh coarse- and medium-grained clinopyroxene-plagioclase rocks that show pronounced cumulate textures. These textures, previously unrecognized, provide supporting evidence for the interpretation that the source rocks of the Great Valley anomaly are oceanic crust.

South and east of Sutter Buttes, several wells penetrate rocks reported as granite, granodiorite, metavolcanic rocks, and "gneiss" typical of rocks exposed in the Sierran foothills. The outline of granitic plutonic rocks, shown on plate 1, was determined from reported basement rocks, augmented by our interpretation of residual isostatic gravity data (Roberts and others, 1981). The boundary between the Sierran basement and mafic and ultramafic rocks of probable ophiolitic basement trends about N. 45° E. from Sutter Buttes to Oroville. It is clearly marked by significant changes in the gravity and magnetic patterns of the respective areas. The basement contours do not reflect this inferred lithologic change, and the northeast-trending fault north of Sutter Buttes is contained within the mafic-ultramafic basement terrane.

Sierran crystalline rocks are exposed in several deep canyons that cut through the Pliocene volcanic rocks of the Tuscan Formation east of Chico (Harwood and others, 1981). The mafic-ultramafic basement appears to abut against Sierran basement rocks along a major basement fault beneath the Chico monocline. This tectonic juxtaposition of basement terranes was proposed first by Griscom (1973), and the basement fault he proposed from geophysical data is confirmed by stratigraphic data. The basement fault beneath the Chico monocline shows east-side-up displacement with a minimum stratigraphic throw of 367 m on the basement surface. This fault represents late Cenozoic deformation superposed on a segment of the late Mesozoic boundary between the forearc-basin and arc-massif basements, and it is thus part of the upper-slope discontinuity (Karig and Sharman, 1975).

STRUCTURAL FEATURES IN THE VALLEY FILL

Structure contours drawn on top of the Cretaceous rocks outline a large number of diversely oriented folds and faults distributed throughout the valley. Some of these structures, such as the Corning domes, the Chico monocline, and the Dunnigan Hills anticline, have topographic expression and were recognized in the early ground-water studies of the valley by Kirk Bryan (1923). Most of the other structures do not have obvious surface expression, and they were discovered during exploration and development of the numerous small gas fields in the valley (pl. 1, map A). Although detailed reports have been published for many of the gas fields, few reports have synthesized the data from these studies into detailed structural analyses of the valley as a whole. Noteworthy exceptions to this generalization exist, however, and include the early stratigraphic and structural synthesis by Safonov (1968), the detailed study of the Princeton submarine channel system by Redwine (1972), and the continuing efforts of the California Division of Mines and

Geology to compile available data from the valley into small-scale maps of the entire state (Jennings, 1977).

The extent of many of the faults, particularly the complex pattern of the Willows fault and the relations between that fault system and many folds in the northern valley, has not been reported previously. Analyses of well logs, which are the basis for most reports of individual gas fields, do not provide sufficient data to interpret unequivocally the structure of each field. If recognizable stratigraphic units in the well logs are at different elevations in adjacent wells, it is generally impossible to determine if the units are offset by folding or faulting, or both, without additional data from surface exposures or seismic-reflection profiles. Our interpretation of the structural relations in the valley is based on data from well logs, augmented by detailed mapping of the surficial deposits by Helley, and exceedingly valuable seismic-reflection data obtained from Seisdata Services Inc.

WILLOWS FAULT SYSTEM

The main stem of the Willows fault was discovered in the subsurface rocks of the northern valley when it was penetrated by the Marathon Oil Company (formerly Ohio Oil Company) "Capital Company No. 1" well during development of the Willows-Beehive Bend gas field in the late 1950's (California Division of Oil and Gas, 1960; Alkire, 1962; 1968). From the discovery well, Redwine (1972) traced the Willows fault in the subsurface southeast to Sutter Buttes and suggested that it extended northwest of the discovery well, possibly connecting with the surface fault mapped west of the Orland Buttes (Anderson and Russell, 1939; Jennings and Strand, 1960). On the basis of the distribution of Quaternary units immediately south of Orland Buttes and of two seismic profiles north of the buttes, we have extended the Willows fault into northwestern Tehama County. At Orland Buttes, Upper Cretaceous rocks, the Lovejoy Basalt, and the Tehama Formation, on the up-thrown side of the Willows fault, are juxtaposed against the Tehama Formation on the down-thrown fault block to the west.

Redwine (1972) documented displacement on a 40-km segment of the main stem of the fault from east of Willows to Sutter Buttes and concluded that it dipped 74° or steeper to the east and showed reverse, east-side-up movement that decreased upward toward the surface. He found that the Princeton submarine channel was localized by movement on the fault and that vertical separation in the discovery well varied from about 488 m on top of the Cretaceous rocks to about 477 m on the top of the Eocene Capay Formation.

The pattern of deformation on the Willows fault and its effect on the thickness and facies patterns in the Capay Formation are clearly shown in figure 3. In this approximately east-trending cross section through the Marathon "Capital Company No. 1" well (No. 3, fig. 3), the thalweg of the Princeton channel, which is occupied by marine shale of the Capay, coincides with a syncline in the underlying Upper Cretaceous rocks. The west limb of the complementary anticline in the Upper Cretaceous rocks is broken by east-side-up movement on the Willows fault. The electric logs show that west of the fault the Capay is composed of shale, and east of the fault it is dominantly sandstone that interfingers with shale eastward toward the thalweg of the channel. Folding and faulting clearly postdated the deposition of Upper Cretaceous strata and preceded the deposition of the Capay and occurred between about 60 and 53 m.y. ago. During that time there was some erosion of the Upper Cretaceous rocks, particularly along the channel thalweg. The westward increase in sandstone and a complementary decrease in thickness of the Capay toward the fault suggest that the anticlinal welt of Upper Cretaceous rocks was a shoal area during Capay deposition. Because the shale-rich Capay west of the fault is about the same thickness as the sandstone-rich Capay east of the fault, there appears to have been little, if any, deformation on the Willows fault in this area during deposition of the Capay. The section shows about 475 m of post-Capay offset and possibly small offset on the base of the Tehama, but the amount of post-Pliocene offset is difficult to determine because there is no record for the upper part of well 2 (fig. 3).

CORNING FAULT

Data from a number of sources indicate that the Willows fault is far more extensive and complex than previously thought. The first clue that the Willows fault branched into a multistrand fault system was provided by an analysis of seismicity of the northern valley and Sierran foothills after the Oroville earthquake. Marks and Lindh (1978) located a number of small-magnitude earthquakes along a zone that originated near the Marathon "Capital Company No. 1" well in the Willows-Beehive Bend gas field and extended north about 30 km, rather than following the northwest trend of the Willows fault. These epicenters are shown relative to the trace of the Willows fault in figure 4. The trend of seismic events suggests that a north-trending fault splayed off from the main stem of the Willows fault and passed west of the Corning domes (pl. 1). In the Corning gas fields, analysis of well records by the Sacramento Petroleum Association (1962) showed an anticlinal fold in the area of the Corning domes, with about 121 m of maximum closure on the base of the Tehama Formation in the north dome and a steeply dipping southeast-trending fault located at the north end of south Corning dome, but it did not identify a fault west of them.

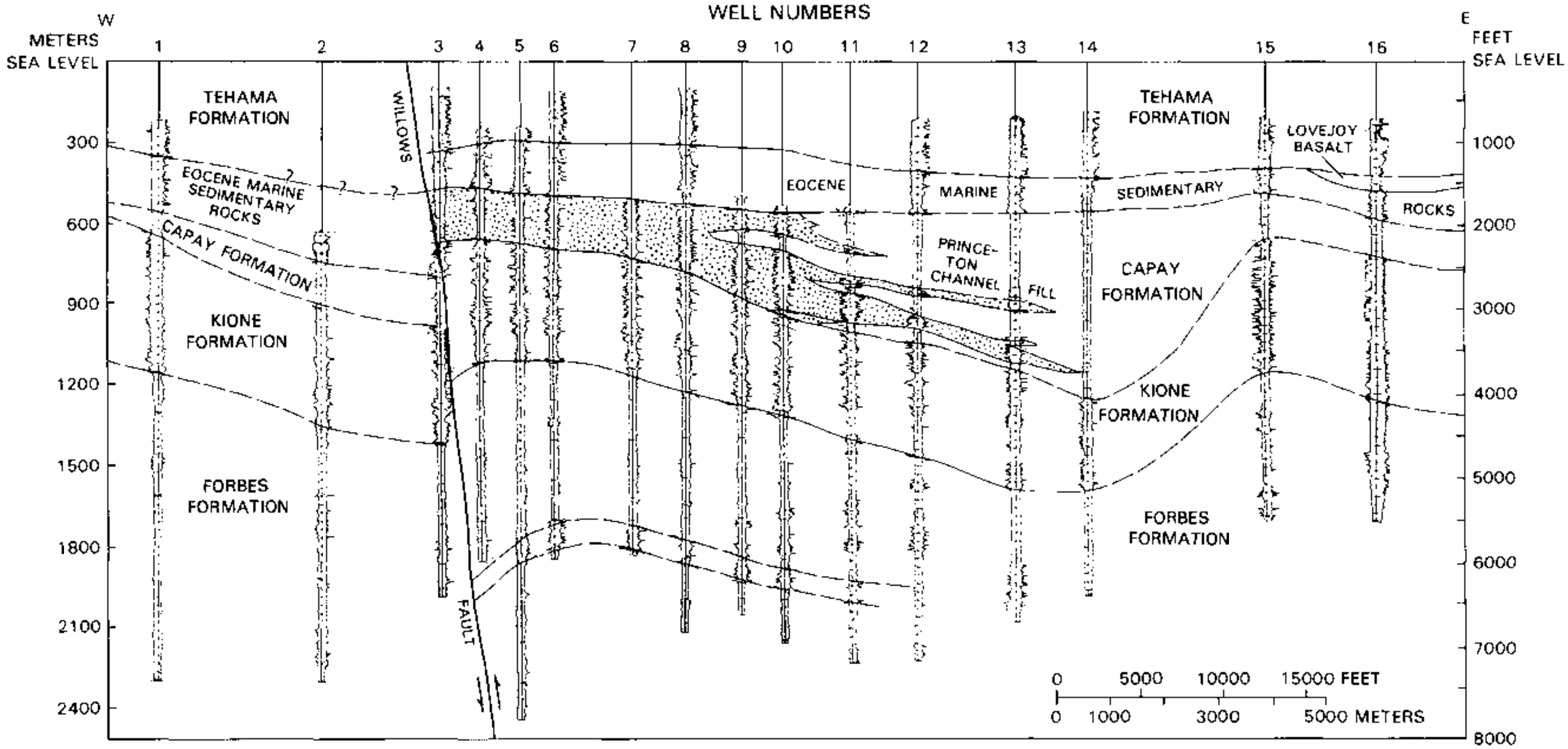


FIGURE 3.—Cross section showing electric logs and stratigraphic and structural relations across Willows-Beehive Bend gas field, Calif. Sandstone in Capay Formation indicated by stipple. Willows fault penetrated in well No. 3. Names of wells shown in appendix. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

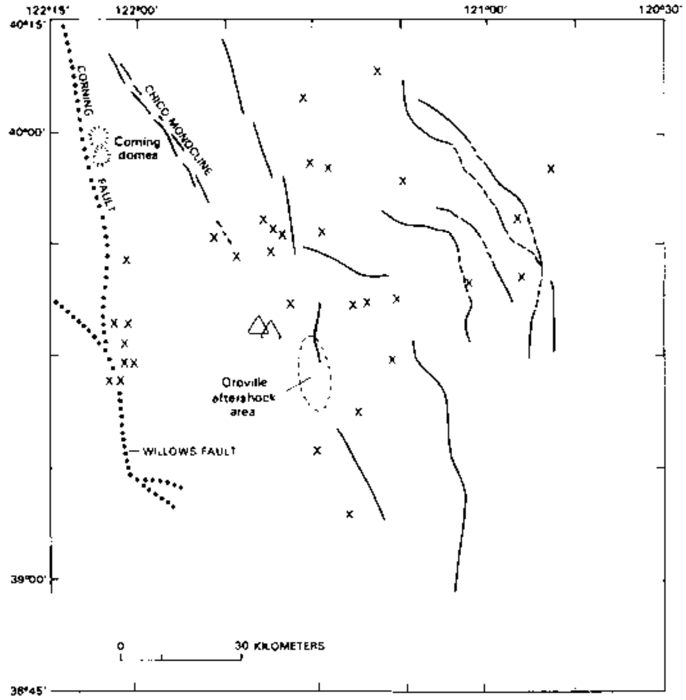


FIGURE 4.—Epicenters (X) of seismic events in area of Oroville, Calif., from June 1975 to August 1976 (modified from Marks and Lindh, 1978). Note north trend of epicenters extending from Willows fault approximately along trace of Corning fault. Unlabeled heavy lines indicate other faults. Triangles show epicenters of two unusually deep (40 km) earthquakes.

Seismic-reflection profiles in the area by Seisdata Services Inc. have identified a major north-trending, steeply east-dipping reverse fault that passes west of the Corning domes and the Greenwood anticline. We call this structure the Corning fault (pl. 1), and part of one of the profiles across it is shown in figure 5. The profile clearly shows that the shallow reflecting horizons in the eastern block are arched beneath the Corning dome by east-side-up drag on the Corning fault. It is also apparent in the profile that the vertical displacement increases with depth, indicating progressive deformation through time, similar to the deformation pattern on the main stem of the Willows fault in the Willows-Beehive Bend gas field (fig. 3). Curiously, however, the amount of vertical displacement of the Upper Cretaceous and younger strata shown on the profile is relatively small compared to the offset of the basement surface suggested by the few deep wells in the area shown on figure 6.

The deepest well east of the Corning fault is the Shell Oil Company "Victor Ranch No. 4" (sec. 7, T. 23 N., R. 2 W.), which bottomed in the Venado Sandstone of Late Cretaceous (Turonian) age at an elevation of −3,713 m (fig. 6). Lithologic information from this well helps interpret the seismic-reflection profile, and its total depth provides a minimum value for the basement elevation 8 km east of the Corning fault. Although local variations in the slope of the basement surface exist, the basement generally dips about 5° SW. between the Chico monocline and the Corning fault. The intersection of the basement surface and the Corning fault ranges in elevation from about −3,900 m in the north to about −4,600 m in the south. This south-southeast plunging line of intersection appears to lie significantly above the basement surface west of the Corning fault.

West of the Corning fault, only one well, the Shell Oil Company "Vilche No. 2" (sec. 5, T. 27 N., R. 4 W.), reached basement, which was serpentinite penetrated at an elevation of −5,978 m (fig. 6). Data from this well are not sufficient to determine the dip of the basement surface west of the Corning fault, but the dip immediately west of the fault may be the same as that just east of the fault, assuming that the basement surface was not chaotically tilted prior to deposition of the Great Valley sequence. If such is the case, the −6,000-m contour can be extrapolated south of the Shell Oil Company "Vilche No. 2" well parallel to the contours east of the Corning fault, as shown on figure 6. This extrapolation gives a vertical separation of about 1,500 m on the basement surface if one assumes no offset on the Red Bluff fault (fig. 6). Because the Red Bluff fault (discussed in a following section of this report) shows down-to-the-south displacement of the valley fill, similar basement offset on the Red Bluff fault would increase the basement separation on the Corning fault. Therefore, 1,500 m of vertical offset on the basement surface across the Corning fault is considered to be a minimum value.

The reason why the basement offset does not appear on the seismic reflection profile is not known. Perhaps the energy input was not sufficient to generate reflections from the deeper basement. Alternatively, the Venado Sandstone, which thickens westward, may have masked reflections from older rocks of the Great Valley sequence and the basement surface west of the Corning fault. Whatever the reason, geologic data strongly suggest that the basement was offset at least 1,500 m on the Corning fault prior to Turonian time and that pre-Turonian rocks of the Great Valley sequence, deposited on the down-dropped block of the fault were unconformably overlapped by the Venado Sandstone. Post-Turonian displacement on the Corning fault is a few hundred meters.

The youngest deposits deformed by the Corning fault are gravels of the Pleistocene Red Bluff Formation, the age of which is between 0.45 and 1.09 m.y. (Harwood and others, 1981).

NORTHWEST EXTENSION OF WILLOWS FAULT

The location of the Willows fault system north and northwest of Orland Buttes is not clearly indicated by direct evidence in either the surface or subsurface rocks.

Wells are sparse in this area of the valley, particularly west of the probable trace of the main stem of the Willows fault. For that reason, the structure contours are very generalized and of little value in locating even major structures.

Our projection of the Willows fault into the Cold Fork, Elder Creek, and Paskenta faults (pl. 1) mapped by Jones and others (1969) is based primarily on the outcrop pattern of the Tehama Formation. North of Elder Creek, the Tehama Formation dips gently east, and the Nomlaki Tuff Member is at the base of the Tehama or is, at most, a few tens of meters above its base. South of Elder Creek, however, the Tehama dips more steeply eastward into the valley, and the Nomlaki is a few hundred meters above the base of the Tehama. This outcrop pattern of the Tehama Formation suggests that the underlying Great Valley sequence was topographically higher and projected farther east into the valley north of the Willows fault prior to deposition of the Pliocene strata. The position of the Nomlaki Tuff Member, relative to the base of the Tehama on opposite sides of the Willows fault, indicates that the Tehama filled a topographic low southwest of the fault

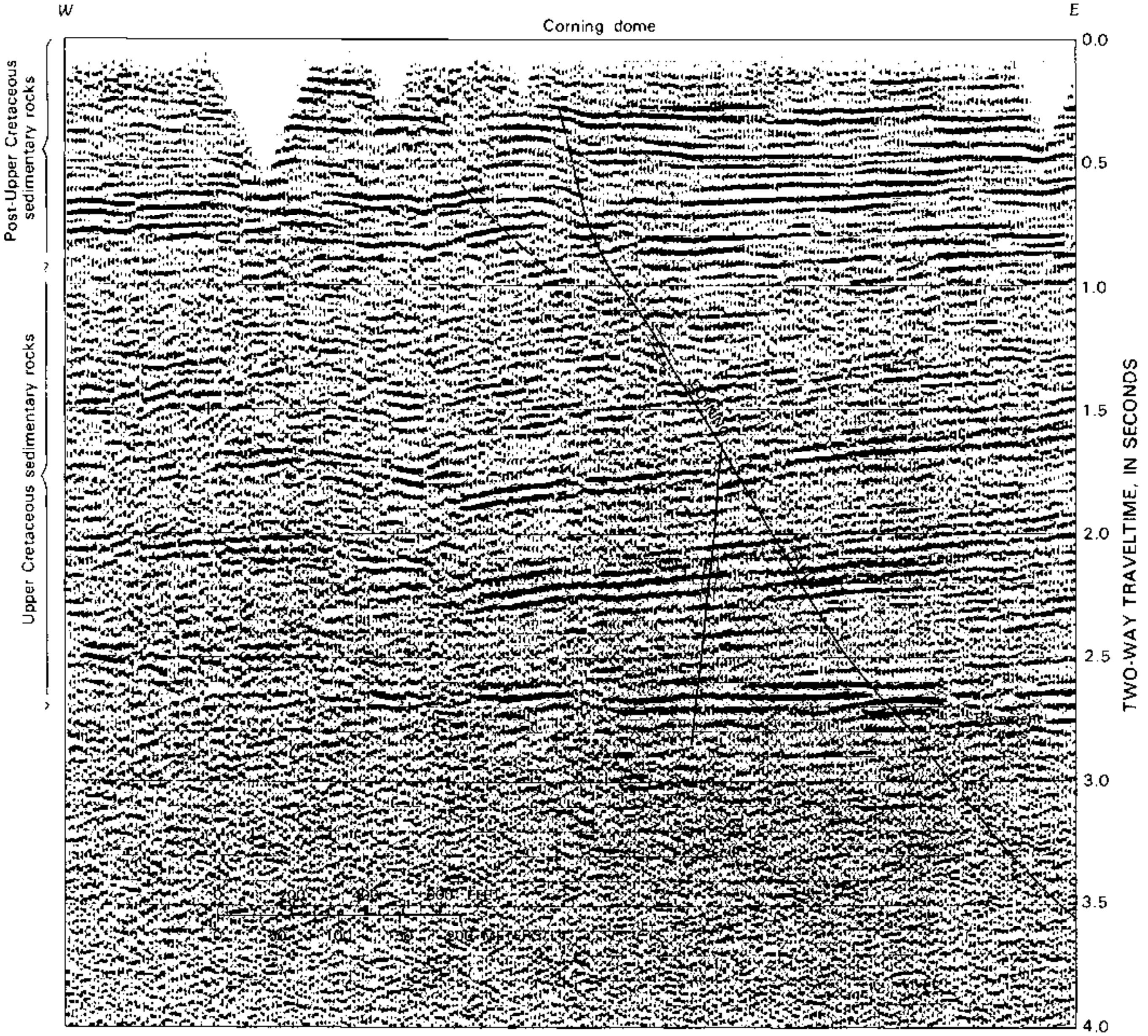


FIGURE 5.—Seismic-reflection profile, from Seisdata Services Inc., showing structural and generalized stratigraphic relations across Corning fault between Corning and Red Bluff, Calif.

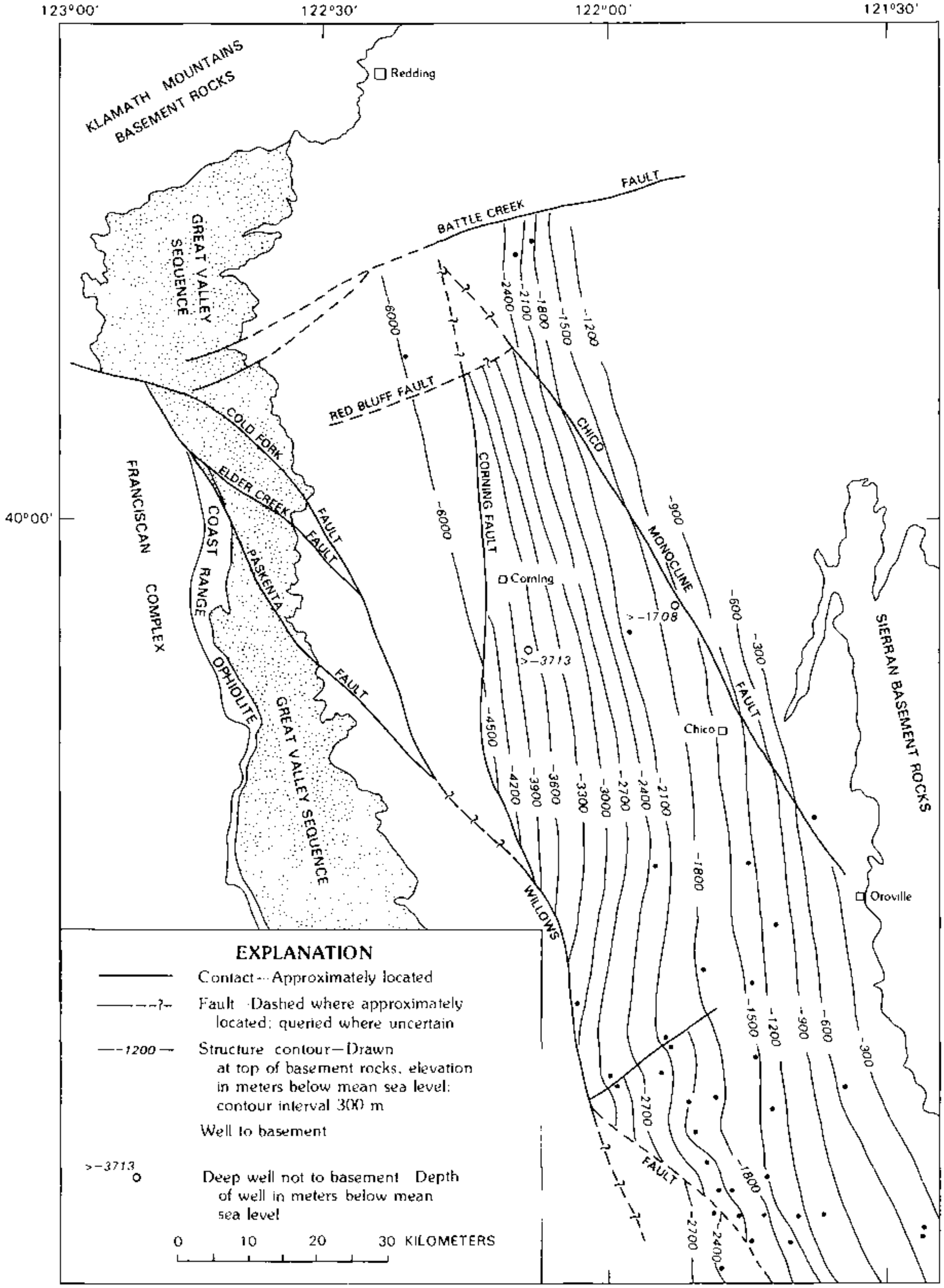


FIGURE 6.—Map of northern Sacramento Valley showing structure contours, drawn on top of basement rocks, used to estimate amount of vertical displacement of basement across Corning fault.

prior to eruption of the Nomlaki about 3.4 m.y. ago. We interpret the topographic low, reflected by the thicker basal part of the Tehama, to be the result of east-side-up movement on the Willows fault, prior to and possibly during, deposition of the lower part of the Tehama Formation. If this interpretation is correct, late Cenozoic movement on the Willows-Elder Creek fault system differs significantly, in style and amount of displacement, from the Cretaceous movement on the Elder Creek-Cold Fork-Paskenta fault system oulined by Jones and Irwin (1971).

Jones and Irwin (1971) inferred at least 96 km of left-lateral displacement of the Lower Cretaceous (Valanginian) strata along the combined Cold Fork-Elder Creek-Paskenta faults. They concluded that this deformation commenced shortly after deposition of the Valanginian strata and continued concurrently with deposition until at least the middle Late Cretaceous. Well-documented vertical displacement of Upper Cretaceous and overlying rocks on the Willows fault in the Willows-Beehive Bend gas field is not incompatible with left-lateral displacement on the Elder Creek fault system to the northwest, but it does indicate that the inferred lateral displacement was accompanied, or postdated by, a major component of east-side-up vertical movement. This vertical movement is consistent with the interpretation that the Elder Creek fault system represents tear faults in the upper plate of the Coast Range thrust (Jones and Irwin, 1971), along which the Klamath Mountains terrane moved upward and westward over the Coast Ranges province (fig. 2).

SOUTHEAST EXTENSION OF WILLOWS FAULT

Location of the Willows fault southeast of Sutter Buttes is not closely constrained by sparse well data along the eastern margin of the valley. No seismic-reflection profiles, that we are aware of, extend far enough east to cross the fault. However, wells in three widely spaced areas do extend far enough east from the deeper parts of the valley to cross the fault, and they provide the most direct evidence for the southeastern extension of the Willows fault. The first area we investigated extends southwest from near Marysville and passes through the Tisdale gas field (pl. 1, map A) just southeast of Sutter Buttes. A cross section (fig. 7) through wells in this area shows that the slope of the basement is significantly steeper east of the Willows fault (between wells 4 and 5, fig. 7), and we infer about 165 m of east-side-up displacement on the basement surface. Shale of the Eocene Capay Formation is recognizable in all of the electric logs in figure 7, and that unit shows about 100 m of displacement between wells 4 and 5. The base of continental deposits (nonmarine sedimentary rocks), which coincides generally with the base of fresh water in the valley, is difficult to identify in all the well logs of this section, but it does not appear to be offset between wells 3 and 5. The dip of the fault is not constrained in this section, and we have shown a steeply east-dipping reverse fault between wells 4 and 5, primarily because the pattern of offset in that area is so similar to that on the Willows fault to the northwest.

About 23 km southeast of the Tisdale gas field, a second line of wells extends from the Sacramento River near Knight's Landing northeastward toward Lincoln. Interest was directed initially to this line of wells because the outline of the Markley canyon, shown by Almgren (1978), is sharply deflected to the south in this area. A section through this line of wells is shown in figure 8. All of the sedimentary rocks in this part of the valley, except those in the Markley canyon, are offset up to the east between wells 3 and 4 (fig. 8). The amount of displacement appears to increase downward in the section from about 30 m at the base of the continental deposits to about 45 m in sandstone and shale sequences in the Upper Cretaceous rocks. Displacement of the basement is inferred to be about 150 m, but the depth to basement west of the Willows fault is not closely constrained by available well data. The most interesting aspect of the section is the marked asymmetry of the Markley canyon fill. Canyon development may have shifted progressively westward, to be localized immediately east of this part of the Willows fault, where the deepest part of the asymmetric canyon fill is located. This pattern of erosion and sedimentation suggests that late Oligocene and early Miocene movement on the Willows fault directly influenced the location and form of the Markley canyon.

The third line of wells we investigated extends from the Sacramento River near Clarksburg to the area east of Florin, where a series of low hills underlain by Pliocene continental deposits of the Laguna Formation rise above the surrounding Pleistocene alluvial deposits. A section through these wells is shown in figure 9. The electric log of the D. D. Feldman "Unit Plan No.1" well (sec. 8, T. 7 N., R. 6 E.); (No. 9, fig. 9) shows an obvious repeat in the Cretaceous rocks just above the basement. We interpret this repeat to represent east-side-up displacement on the Willows fault, which was intersected by the well at an elevation of −1,277 m. If this interpretation is correct, the basement surface is offset about 120 m. A similar offset is shown by Upper Cretaceous rocks.

West of the Willows fault (fig. 9), a steeply east-dipping normal fault, previously unreported, offsets the Capay Formation and older rocks down to the east about 153 m. This normal fault does not appear to offset the base of post-Eocene and younger nonmarine rocks, nor are these rocks offset by the Willows fault to the east. Offset of the basement between wells 5 and 6 (fig. 9) appears to be east side up and suggests early reverse movement on the east-dipping fault.

The location of the Willows fault southeast of Florin is

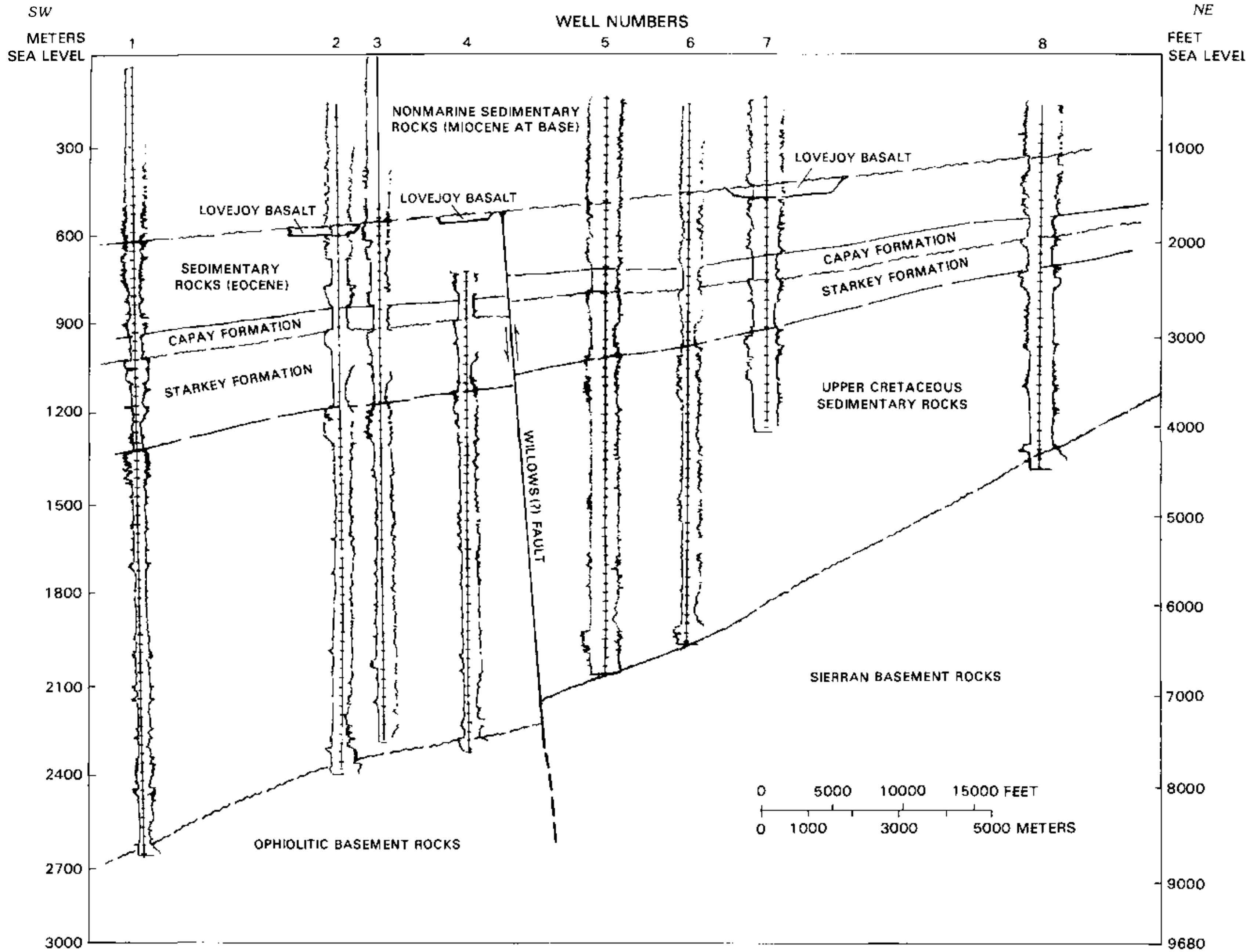


FIGURE 7.—Cross section showing electric logs and stratigraphic and structural relations across possible southeast extension of Willows fault near Tisdale gas field southeast of Sutter Buttes, Calif. Names of wells listed in appendix. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

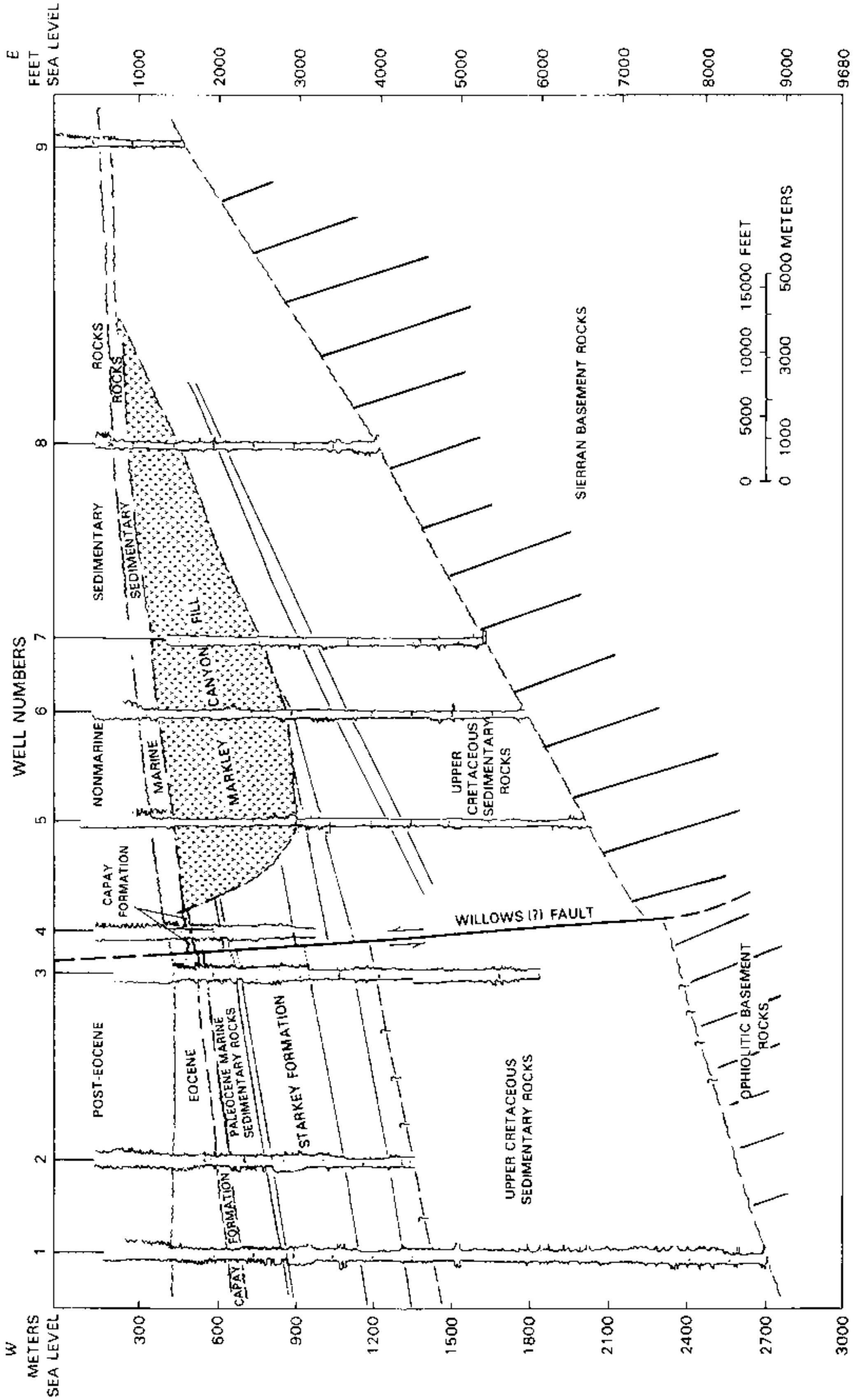


FIGURE 8.—Cross section showing electric logs and stratigraphic and structural relations across possible southeast extension of Willows fault near Catlett-Nicolaus gas fields, Calif. Names of wells listed in appendix. Note asymmetry of Markley canyon fill (patterned) and absence of offset in post-Eocene continental deposits. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

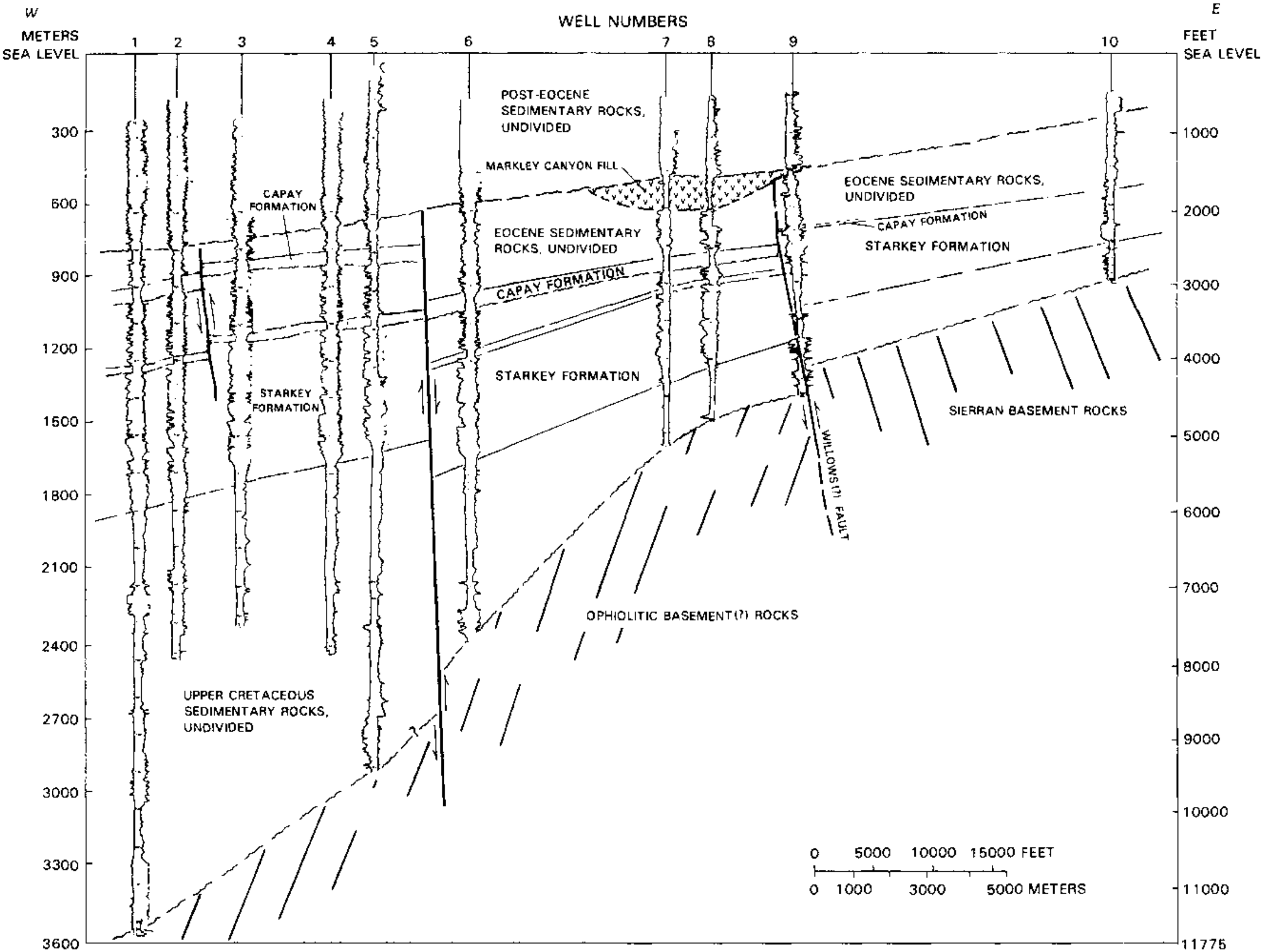


FIGURE 9.—Cross section showing electric logs and stratigraphic and structural relations across possible southeast extension of Willows fault southeast of Florin, Calif. Names of wells listed in appendix. Note repeated electric-log pattern near bottom of well 9 and apparent early east-side-up displacement of basement by unnamed fault between wells 5 and 6, followed by east-side-down offset of Cretaceous and early Tertiary rocks. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological

uncertain. A section through several wells east and west of the Lodi gas field, shown in figure 10, indicates a minor deflection in the Capay Formation between wells 6 and 7, but the underlying Cretaceous rocks and the basement surface are not significantly offset in that area. The general east-side-up flexure of the Capay between wells 6 and 7 is the type of deformation that would be expected adjacent to the Willows fault, but the absence of offset in underlying units argues against the existence of the fault. Deformation expressed as fault movement north of Lodi may be expressed as gentle warping to the south.

STRUCTURES NORTHEAST OF THE WILLOWS FAULT

The Willows fault diagonally transects the Sacramento Valley from northwest to southeast and divides the region into two late Cenozoic structural provinces. To the northeast, on the upthrown block of the Willows fault, the present axis of the Sacramento Valley is underlain by the Los Molinos and Glenn synclines (pl. 1). These narrow synclines, coupled with the Corning domes to the west and the Chico monocline to the east, have tightly controlled the course of the Sacramento River and influenced alluvial deposition during the late Quaternary. This tectonic control of alluvial deposition has profoundly influenced land use, particularly in the northeastern part of the valley, where a narrow strip of cultivated land, shown near the top of figure 11, flanks the river and lies directly over the trace of the Los Molinos syncline. South of the constricting influence of the Corning domes and the Chico monocline, late Quaternary alluvial deposits spread laterally across much of the valley over the Glenn syncline, the axial trace of which controls the present course of the Sacramento River as far south as Glenn, Calif. (pl. 1). From Glenn to Colusa, the course of the river lies along the trace of the Willows fault.

From the vicinity of Willows southeast to the Sacramento Delta, the downthrown southwest block of the Willows fault is capped by Holocene basin deposits that flooded over the broad Zamora syncline (pl. 1), burying older deposits, to rest unconformably on Upper Cretaceous rocks north of the Dunnigan Hills. The following part of the report discusses specific structural features on the northeast block of the Willows fault.

SUTTER BUTTES

Sutter Buttes (fig. 11) is a prominent set of hills composed of late Cenozoic volcanic rocks that rise about 635 m above the floor of the Sacramento Valley 15 km northwest of Marysville. According to Williams and Curtis (1977), volcanism and accompanying deformation of the surrounding sedimentary rocks occurred between 2.4 and 1.4 m.y. ago and consisted of two phases. During the early phase of magma injection, Upper Cretaceous and Tertiary rocks were arched into a dome 13 km across, broken by normal and high-angle reverse faults, and rapidly eroded so that the Tertiary rocks were stripped from the core of the dome before the explosive phase of volcanism. Explosive volcanism produced the rampart beds of tuff and tuff breccia that form the peripheral deposits of the buttes (fig. 11).

Extensive drilling for natural gas located an elongate dome in the subsurface about 10 km west of Sutter Buttes. Williams and Curtis (1977) referred to this structure as the buried Colusa buttes, but because it lacks surface expression, we refer to it as the buried Colusa dome (fig. 12). In the buried Colusa dome, several wells (fig. 12) penetrated volcanic rocks similar in composition and age to those in the Sutter Buttes. These data led Williams and Curtis (1977) to conclude that the buried Colusa dome formed solely by forceful magma injection contemporaneous with magmatism at Sutter Buttes. We suggest, however, that magmatism may have been localized by movement on the Willows fault and possibly by movement on the Mesozoic tectonic boundary between ophiolitic and Sierran basement terranes which passes beneath the eastern margin of Sutter Buttes (fig. 12).

The orientation and movement patterns of structures at Sutter Buttes and the buried Colusa dome suggest that deformation occurred in a regional east-west compressive stress field. The distribution of structural features at Sutter Buttes is distinctively asymmetrical. Beds in the Upper Cretaceous rocks on the south and southeast sides of the buttes dip steeply away from the core. Locally, they are overturned. Beds on the north and northwest sides of the buttes generally dip gently away from the core. As shown in figure 12, folds and faults are more abundant on the eastern half of the buttes and the wavelength of folds is tighter there than on the west. In addition to the small normal faults that surround the core of the dome, the eastern half of the dome is cut by a prominent set of steeply inward-dipping, arcuate high-angle reverse faults. This pattern of structural features indicates that the core of Sutter Buttes was thrust eastward as it moved upward.

The northward elongation of the buried Colusa dome strongly suggests that it too was formed in an east-west compressive stress regime. In fact, the amplitude, wavelength, and axial extent of the buried Colusa dome are remarkably similar to folds that occur just east of the Willows fault farther north (pl. 1; fig. 3). Although Redwine (1972) projected the Willows fault southeastward across the buried Colusa dome, our analysis of subsurface data suggests that a fault, possibly the Willows fault or a splay fault related to it, may lie just west of the buried Colusa dome. We conclude that the buried Colusa dome formed partly by east-side-up drag on a high-angle reverse fault along its western margin and partly by magma in-

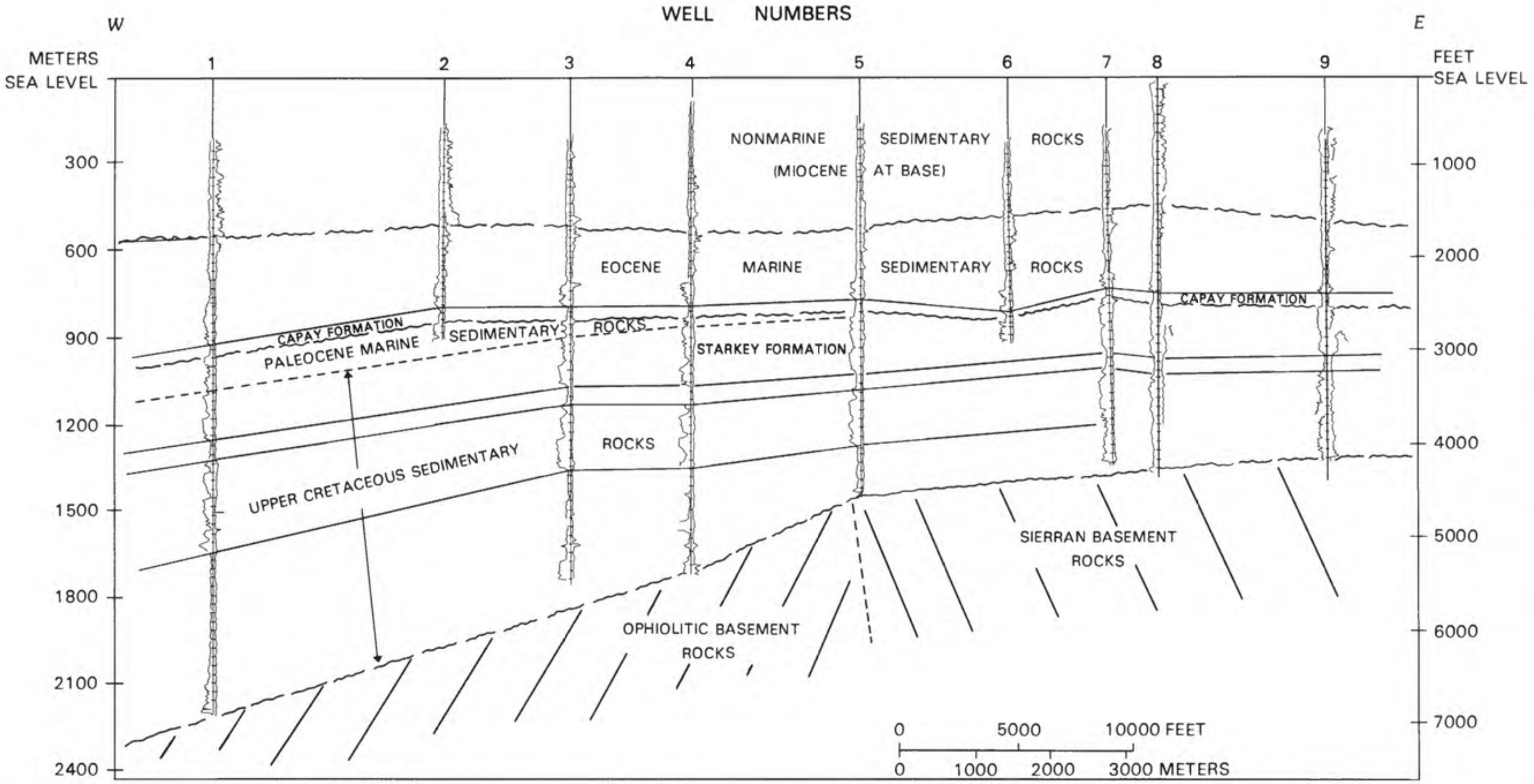


FIGURE 10.—Cross section showing electric logs and stratigraphic and structural relations across possible southeast extension of Willows fault (approximately follows trace of well 5) in area of the Lodi and Galt gas fields, Calif. Names of wells listed in appendix. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

jection that was localized by movement on that fault.

The pattern of radial normal faults around the core of Sutter Buttes, flanked by reverse faulting to the east and west, assuming that the Willows fault was involved in the tectonism, is the type of deformation found by Withjack and Scheiner (1982) in their modelling experiments of doming in a compressive stress field. Although it is difficult to unequivocally separate magmatic doming from regional compressive deformation in the Sutter Buttes area, supporting evidence for the regional east-west compressive stress field is found in the Chico monocline about 40 km to the north.

FIGURE 11.—U.S. Air Force high-altitude oblique aerial photograph showing northern Sacramento Valley viewed to the north from vicinity of Sutter Buttes (center foreground), a late Pliocene and early Pleistocene volcanic center, approximately 16 km in diameter. Dark core of buttes composed primarily of andesite surrounded by lighter colored volcaniclastic deposits that form peripheral rampart beds of Williams and Curtis (1977). Narrow strip of cultivated land (dark) along Sacramento River (SR) between Corning domes (CD) and Chico monocline (CM) is surface expression of Los Molinos syncline (pl. 1). Oroville dam (OD) located near north end of Cleveland Hills faults where ground rupture occurred during August 1, 1975, Oroville earthquake.

CHICO MONOCLINE

The Chico monocline (fig. 13) is a northwest-trending, southwest-facing flexure that bounds the northeast side of the Sacramento Valley between Chico and Red Bluff. East of the monocline, Pliocene volcanic rocks of the Tuscan Formation dip less than 5° SW., but bedding steepens to 20° or more along the monoclinal flexure where the Tuscan dips beneath Quaternary deposits of the valley. The trace of the monocline is characterized by a complex surface pattern of anastomosing fault strands

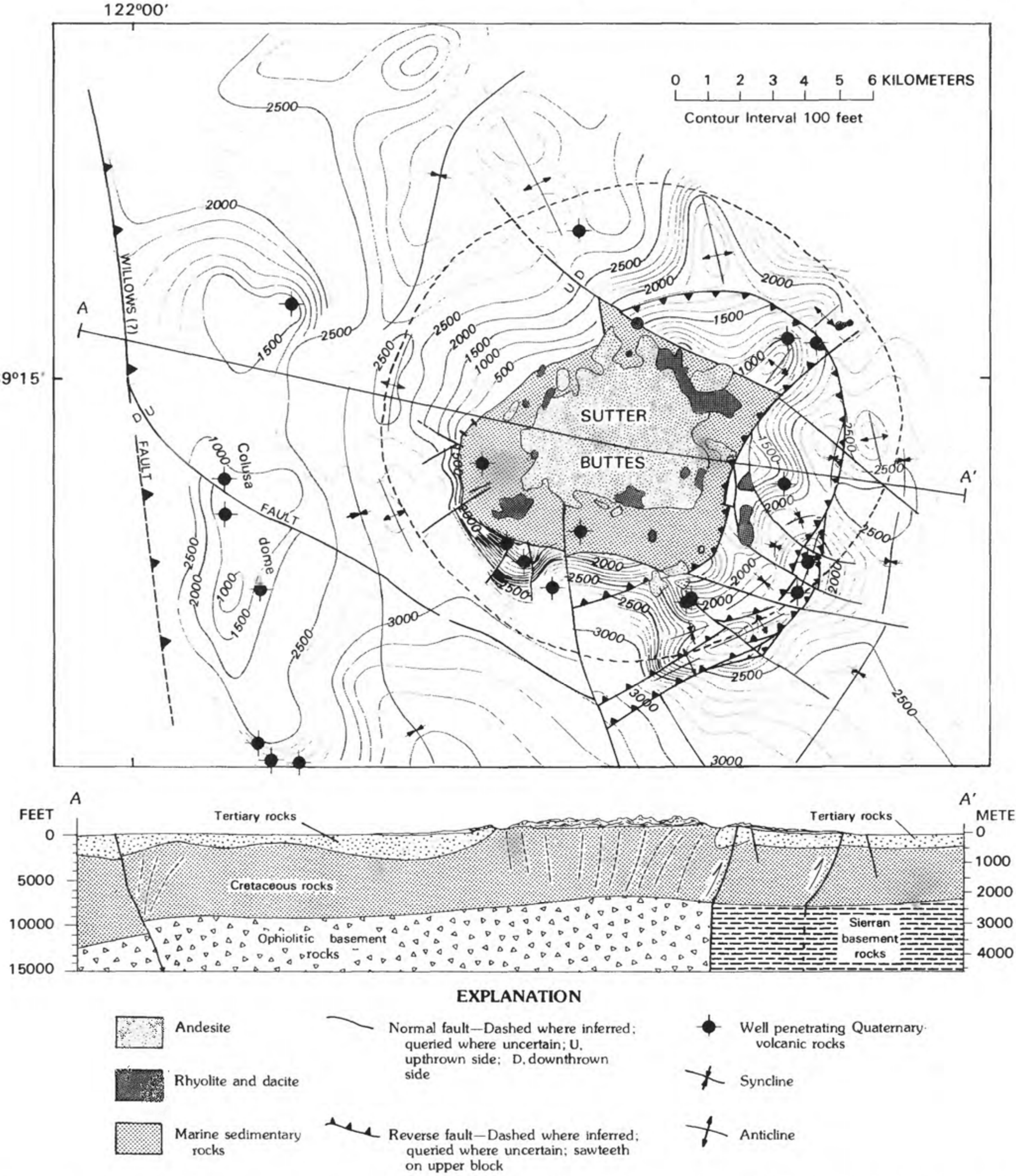


FIGURE 12.—Structure contour map of area around Sutter Buttes, modified from Williams and Curtis (1977, fig. 11) with data from Redwine (1972) and from our examination of electric logs in area of buried Colusa dome. Structure contours in feet; datum is top of the Kione sand of local usage (Williams and Curtis, 1977). Dashed circle on map marks approximate outer limit of rampart beds on valley floor; thin dashed lines on section represent schematic paths of magma injection.

FIGURE 13.—Composite of two U.S. Air Force high-altitude oblique aerial photographs showing pronounced linear trace of Chico monocline (CM, upper right to lower left), broad alluvial fan west of Chico monocline capped by Red Bluff Formation (RB, gray, uncultivated grazing land), and dissected topography of Tuscan Formation (TF) to east. DC, Deer Creek; CD, north Corning dome. Sacramento River (SR) follows trace of Los Molinos syncline (LMS) between north Corning dome and alluvial fan to east.

that show both west- and east-side-down displacements of small magnitude (Harwood and others, 1981).

Structure contours drawn on top of the Cretaceous rocks in the vicinity of the monocline indicate clearly that the Cretaceous strata are flexed and faulted by a major northwest-trending fault at depth beneath the surface trace of the monocline (pl. 1). The best control on the amount of displacement on the master fault beneath the Chico monocline comes from a line of wells that extends generally westward from the Exxon "C. C. Baccala No. 1" well (No. 4, fig. 14), which was drilled just west of the monocline about 18 km northwest of Chico. Although the Baccala well did not reach basement, it bottomed in Upper Cretaceous conglomerate at a depth of −1,700 m and provides a minimum elevation on the basement immediately west of the monocline when used in conjunction with the Pacific Western "Cana No. 1" well (No. 2, fig. 14) that reached serpentine at a depth of −2,100 m about 9 km to the west. Although no wells have been drilled east of the monocline, some control on the elevation and dip of the unconformities at the top and base of the Upper Cretaceous rocks is provided by exposures of these surfaces in several deep canyons to the east. When the trend of the basement surface at these exposures is projected westward, to pass beneath the bottom of the Baccala well, a minimum east-side-up offset of 365 m in the basement rocks is indicated on the fault beneath the monocline (fig. 14). The dip of this major fault cannot be determined directly from surface exposures or subsurface well data, but we show it as a steeply east-dipping reverse fault, because gravity and magnetic data (Griscom, 1973; Cady, 1975; Roberts and others, 1981) indicate that the relatively dense and magnetic basement beneath the northern part of valley extends eastward beneath the Sierran basement exposed east of the monocline. In the Sierran foothills southeast of Oroville, steep east dips are also commonly found in surface exposures of faults that may be the southeastward continuation of the fault beneath the monocline.

From available geophysical evidence, it appears that the fault beneath the monocline is a major tectonic boundary, with a long and complex tectonic history, along which the Sierran basement to the east was juxtaposed against highly magnetic, dense ophiolitic basement to the west (Cady, 1975; Griscom, 1973). These basement terranes were tectonically juxtaposed prior to deposition of the Upper Cretaceous strata. If this interpretation is correct, the fault beneath the Chico monocline may represent a part of the upper-slope discontinuity of Karig and Sharman (1975) that marks the boundary between basement of the late Mesozoic forearc basin to the west and that of the magmatic arc complex to the east. The Chico monocline, in that case, would be a structure inherited from the upper-slope discontinuity, possibly when that major tectonic break was reactivated by late Cenozoic subduction north of the migrating Mendocino triple junction.

The Chico monocline is clearly a late Cenozoic tectonic feature. It formed after deposition of the Ishi Tuff Member of the Tuscan Formation, about 2.6 m.y. ago and prior to the eruption of the olivine basalt of Deer Creek 1.09 m.y. ago (Harwood and others, 1981). Late Cenozoic displacement on the Chico monocline fault has been predominantly east side up, with an apparent component of left-lateral movement that may have contributed to the formation of the Salt Creek, Tuscan Springs and Sevenmile domes at the north end of the monocline and possibly influenced the northeast-trending Inks Creek fold system and Battle Creek fault zone farther northwest.

There is some indication that the Chico monocline fault may be active. The olivine basalt of Deer Creek is offset, but the amount of offset is small. Similarly, a few faults along the monocline show scarps about 1 m in height in the surface of the Tuscan Formation (Harwood and others, 1981). These observations indicate that movement has taken place on the monocline fault system within the past million years. In their study of regional seismicity after the Oroville earthquake, Marks and Lindh (1978)

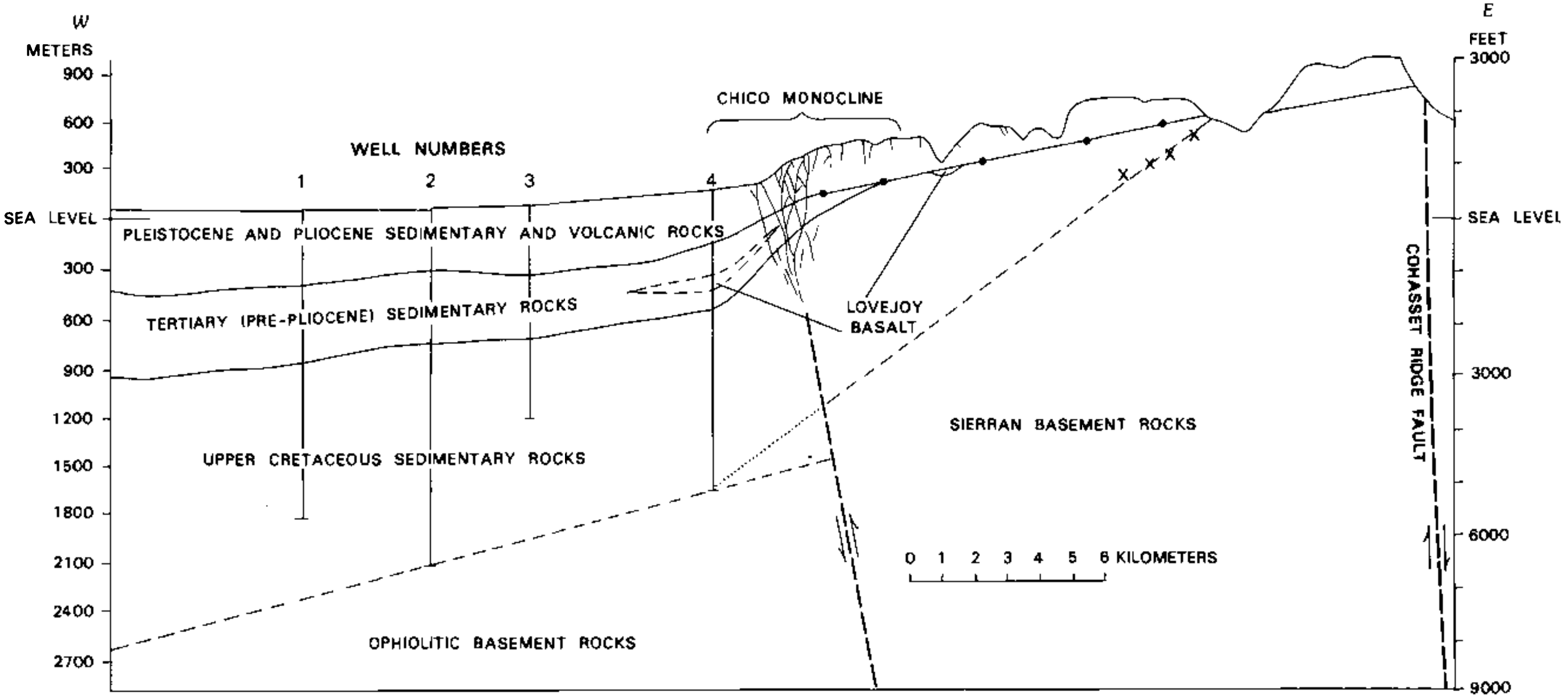


FIGURE 14.—Cross section across Chico monocline about half way between Chico and Red Bluff, Calif., showing offset of basement terranes. Dots indicate unconformity at base of Tuscan Formation, as projected into line of section; x's indicate unconformity at base of Upper Cretaceous rocks, as projected into line of section. Names of wells listed in appendix.

identified two events west of the Oroville aftershock zone at a depth of 40 km, significantly below the main cluster of aftershocks associated with the Oroville earthquake. We interpret those deep events to have occurred on the

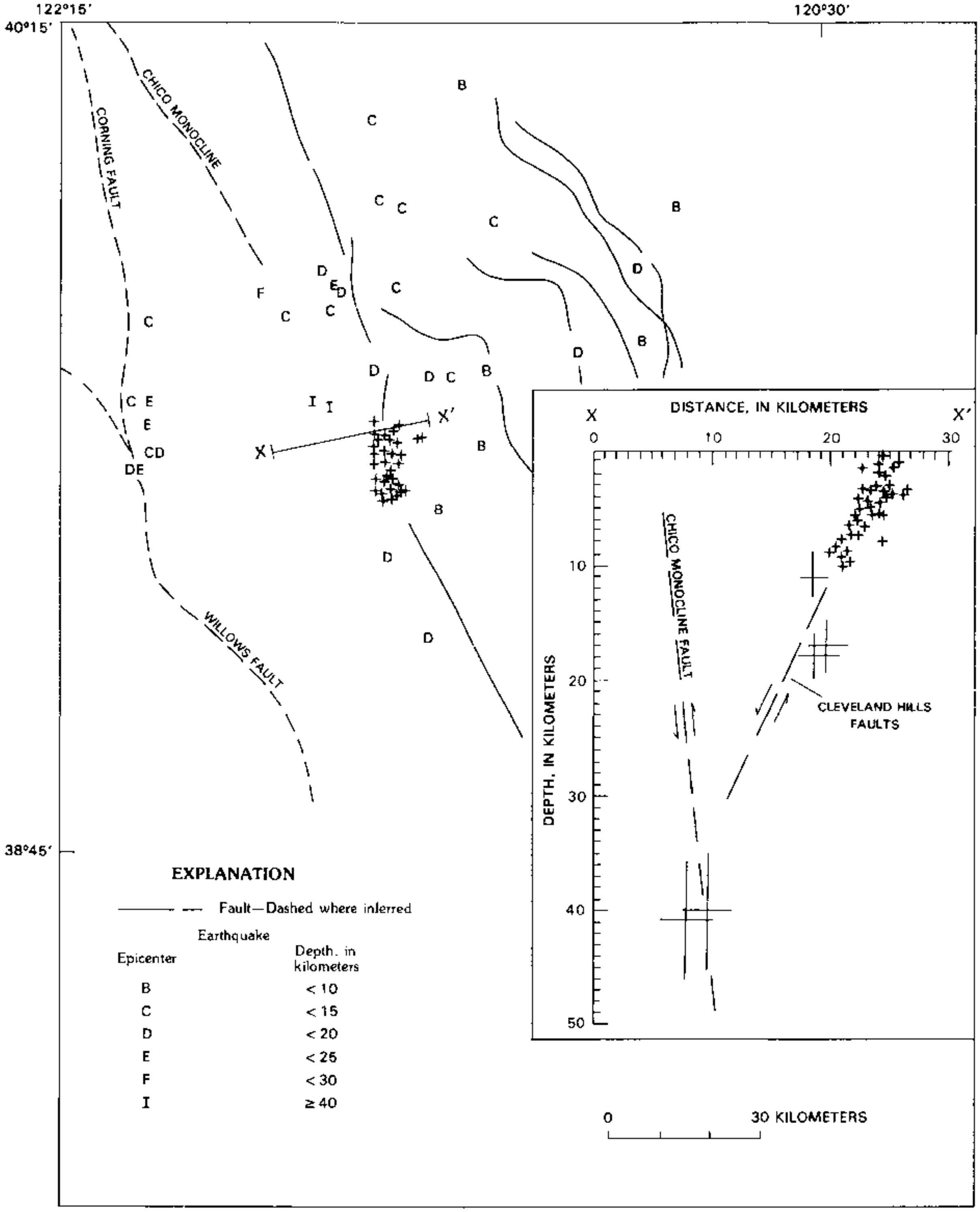


FIGURE 15.—Map and section showing locations of Oroville earthquake aftershocks (crosses on section) in relation to Cleveland Hills faults and Chico monocline (modified from Marks and Lindh, 1978). Earthquakes labeled I on map (largest crosses on section) at a depth of about 40 km are interpreted to have occurred on Chico monocline fault.

basement fault beneath the Chico monocline and not on the Cleveland Hills faults, where most of the aftershock events were located (fig.15). The steeply east-dipping normal fault, shown east of the Chico monocline on figure 15, is one of several short, north- and north-northwest-trending normal faults that extend along the northern foothills of the Sierra Nevada (pl. 1). This normal fault is probably part of the fault system on which the August 1, 1975, Oroville earthquake occurred.

BATTLE CREEK FAULT ZONE

The Battle Creek fault zone strikes east-northeast across the Sacramento Valley between Red Bluff and Redding, nearly at right angles to the trend of the Chico monocline. East of the Sacramento River, the Battle Creek fault zone is marked by a pronounced south-facing escarpment, shown in figure 16, that extends from the river northeastward toward Lassen Peak for a distance of 32 km. Fault strands within this part of the fault zone dip steeply southeast and show predominantly south-side-down, normal fault movement (Harwood and others, 1980; Helley and others, 1981). Vertical displacement on the fault zone increases from about 45 m just east of the Sacramento River to 330 m at Black Butte (fig. 1) and to about 440 m north of Manton. A small component of right-lateral strike-slip movement is suggested by fractures on some of the fault strands, but the exact amount of lateral displacement is not known.

West of the Sacramento River, the valleys of Cottonwood Creek and its south fork are probably controlled in part by the Battle Creek fault system, but modern stream activity and agricultural practices obscure any young traces of the faults east of the South Fork of Cottonwood Creek (pl. 1). At the South Fork of Cottonwood Creek and along Red Bank Creek, late Quaternary terraces show evidence of young faulting (Helley and others, 1981). To the west-southwest, the faults in the terrace deposits merge into previously mapped faults in the Red Bluff and Tehama Formations, and, on strike, they appear to merge with tear faults in the upper plate of the Coast Range thrust mapped by Bailey and Jones (1973).

FIGURE 16.—Photograph of Battle Creek fault scarp (BC) capped by basaltic cinder cone of Black Butte. View to northeast along Highway 36 and across rolling grassy plains underlain by volcanic fanglomerate correlated with the Red Bluff Formation.

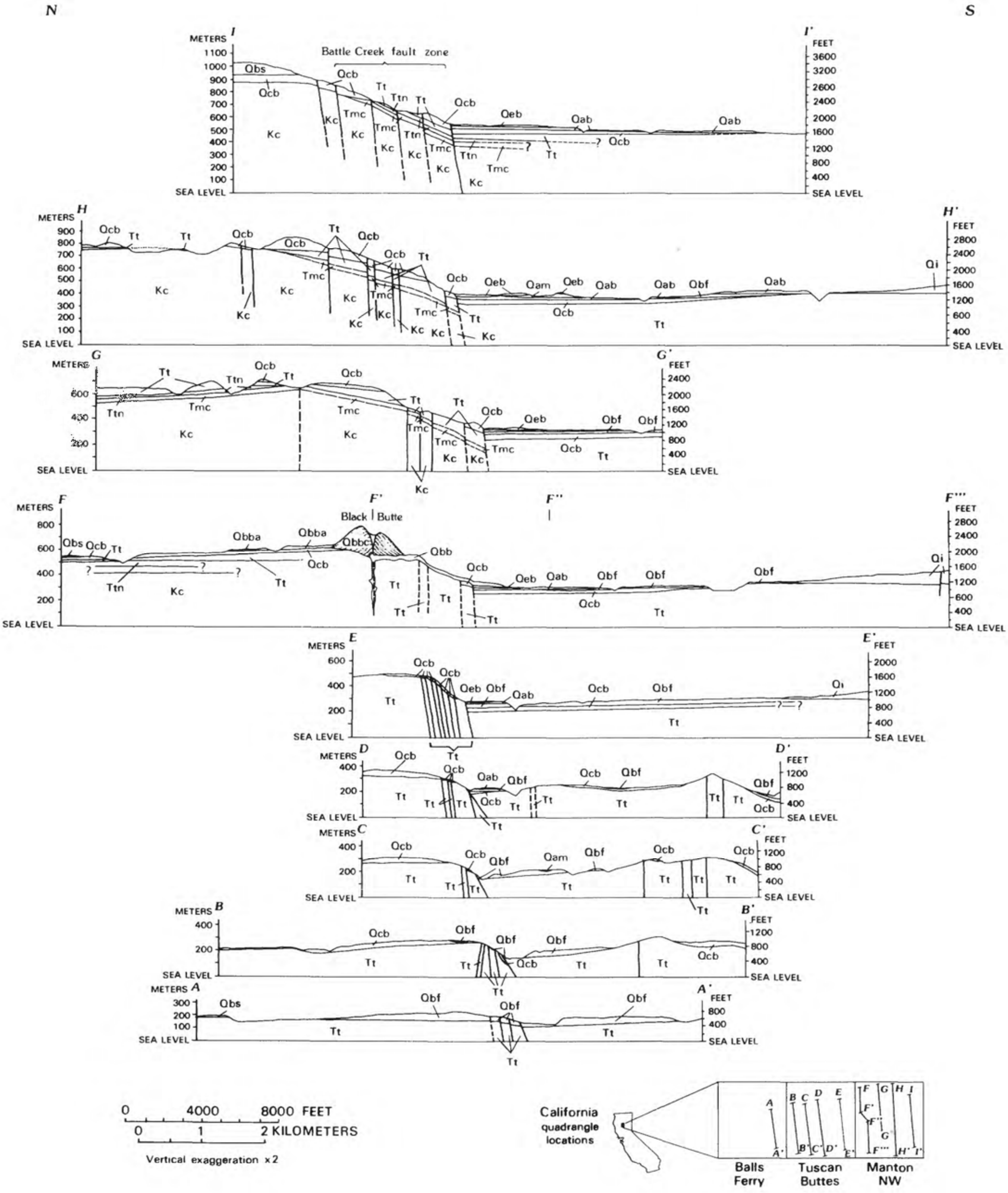
The orientation and distribution of faults in the Battle Creek fault zone east of the Sacramento River are shown in figure 17. Section *A-A′* is located 2.4 km east of the Sacramento River and shows relatively little offset of the fanglomerate that caps the Tuscan Formation. As the fault zone extends eastward, offset on the various Pliocene and Pleistocene units and the height of the fault scarp increases. From near the Sacramento River east to Black Butte (sections *A-A′* through *F-F′*, fig. 17), the fault strands are closely grouped along the fault scarp, but east of Black Butte (sections *G-G′* through *I-I′*, fig. 17) the fault strands are more widely spaced. In map view, the eastern fault strands veer northwestward and appear to die out a short distance north of the escarpment (Harwood and others, 1980).

Several clusters of small-magnitude earthquakes were reported along the eastern third of the Battle Creek fault zone, generally east of Black Butte (Bolt, 1979). Since 1980 the California seismic net of the U.S. Geological Survey has recorded several small-magnitude earthquakes (J. Eaton, oral commun., 1982) that lie approximately along the Battle Creek fault zone and extend west nearly to the Sacramento River.

Coarse volcanic fanglomerate, correlated here with the Red Bluff Formation by soil stratigraphy and geomorphic surface, is offset by the Battle Creek fault zone east of the Sacramento River and dates the major movement as younger than 1.09 m.y. The Rockland ash bed (referred to as the ash of Mount Maidu by Helley and others, 1981) appears to have been partly channeled by the Battle Creek fault scarp, suggesting that the faulting occurred prior to about 0.45 m.y. ago, the age of the Rockland ash bed (Meyer and others, 1980).

INKS CREEK FOLD SYSTEM

A set of northeast-trending folds, referred to as the Inks Creek fold system by Helley and others (1981), deforms the rocks south of the Battle Creek fault zone and structurally controls the major loops in the Sacramento River at Jelly School and the nearby Table Mountain (pl. 1; figs. 1, 18). The axial trace of the major syncline in the fold set passes through Table Mountain and extends northeastward, nearly coincident with Inks Creek. The complementary anticline to the north arches the volcanic fanglomerate, which is correlated with the Red Bluff Formation, and the underlying basalt of Coleman Forebay (Helley and others, 1981), exposing strata of the uppermost part of the Tuscan Formation northeast of Jelly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Battle Creek fault zone
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Vertical exaggeration x2
California quadrangle locations
Balls Ferry
Tuscan Buttes
Manton NW

School. Axial surfaces of the folds are vertical, and fold axes plunge 20°–35° SW. Axial traces of the folds change strike to the northeast so that the anticlinal trace merges with the trend of the Battle Creek fault zone and apparently dies out along the fault to the east-northeast.

West of the Sacramento River, the Inks Creek fold system is expressed as a broad area of uplift known as the Hooker dome (fig. 18). This structure, which has profoundly influenced drainage patterns in the area, particularly along Hooker Creek and Blue Tent Creek (fig. 18), is underlain by the Tehama Formation capped by a few scattered erosional remnants of the Red Bluff Formation.

The Inks Creek fold system is clearly reflected in the structure contours drawn on top of the Cretaceous rocks, which show a closure of about 485 m over the anticline (pl. 1). Although only a few wells in this area reach basement, the elevation of the basement in two wells drilled on the anticline of the Inks Creek fold system is higher than the total depth of some wells to the west that bottomed in Upper Cretaceous rocks. These data indicate that the basement was deformed, along with the cover rocks, during formation of the Inks Creek fold system. They also strongly suggest that the folds shown by the structure contours on plate 1 involve the basement of the valley rather than deformation on a decollement or a series of detachment thrusts in the cover rocks.

The fact that the anticlinal trace of the Inks Creek fold system merges with the Battle Creek fault zone suggests a genetic relation between these major structures. If this interpretation is correct, evidence for the age of the Inks Creek fold system provides data for the age of movement on the Battle Creek fault zone. At Round Mountain, about 3 km southwest of Jelly School, the Rockland ash bed rests unconformably on the eroded western contact of the Red Bluff Formation at an elevation of 160 m. We assume that the ash was deposited in an ancestral channel of the Sacramento River, which apparently formed a large westward bend at that time extending from Bloody Island on the north to the vicinity of Bend on the south (fig. 18). Uplift and erosion of the Red Bluff Formation, which was deposited between 0.45 and 1.09 m.y. ago, had begun

EXPLANATION

Qi	BASALTIC ROCKS OF INSKIP HILL VOLCANIC CENTER (QUATERNARY)--Undifferentiated basalt of Inskip Hill
	BASALTIC ROCKS OF BLACK BUTTE VOLCANIC CENTER (QUATERNARY)--Consist of:
Qbbc	Cinder-cone deposits
Qbba	Cinder-blanket deposits
Qbb	Basalt flow of Black Butte
Qbs	BASALT OF SHINGLETOWN RIDGE (QUATERNARY)
Qeb	BASALT OF EAGLE CANYON (QUATERNARY)
Qab	HYPERSTHENE ANDESITE OF BROKEOFF MOUNTAIN (QUATERNARY)
Qam	ASH OF MOUNT MAIDU (QUATERNARY)--Equivalent to the Rockland ash bed of Sarna-Wojcicki and others (1985)
Qbf	ALLUVIAL FAN DEPOSITS OF BATTLE CREEK (QUATERNARY)
Qcb	BASALT OF COLEMAN FOREBAY (QUATERNARY)
Tt	TUSCAN FORMATION, UNDIVIDED (PLIOCENE)--Locally divided into:
Ttn	Nomlaki Tuff Member
Tmc	MONTGOMERY CREEK FORMATION (EOCENE)
Kc	CHICO FORMATION (UPPER CRETACEOUS)

FIGURE 17.—Geologic cross sections showing statigraphic and structural relations along Battle Creek fault zone. Note eastward increase in height of fault scarp and amount of offset of geologic units from section A-A′ to section I-I′. Geologic units from Helley and others (1981).

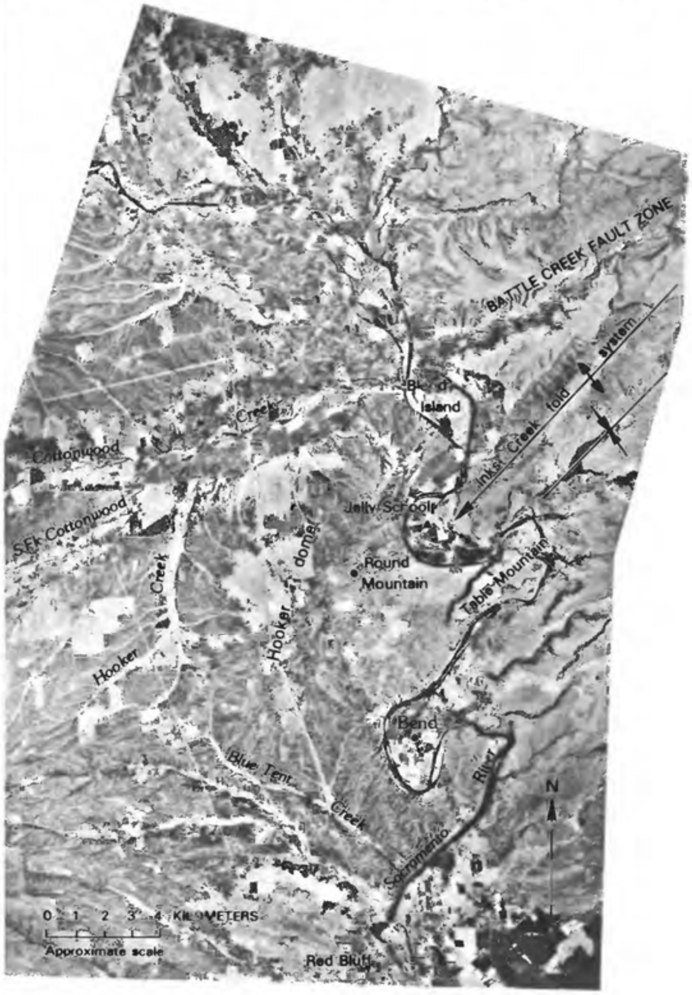


FIGURE 18.—Composite of two U.S. Air Force high-altitude vertical aerial photographs showing topographic expression of Inks Creek fold system (axial traces), Hooker dome, and Battle Creek fault zone.

prior to deposition of the ash. In contrast to the occurrence of the ash at Round Mountain, alluvial deposits of the lower part of the Riverbank Formation are found at an elevation of 120 m in this region, and they flank the present sinuous course of the Sacramento River through the structurally controlled loops of the river at Jelly School and Table Mountain. Clearly, the Sacramento River was forced into its tortuous course around the Inks Creek fold system by early Riverbank time. We conclude, therefore, that the Inks Creek fold system and at least some of the displacement on the Battle Creek fault zone developed in the timespan between 0.45 m.y., the age of the ash, and about 0.4 m.y. ago, the age of the lower part of the Riverbank Formation (Marchand and Allwardt, 1981).

SALT CREEK, TUSCAN SPRINGS, AND SEVENMILE DOMES

Small areas of Upper Cretaceous marine rocks are exposed beneath the Pliocene Tuscan Formation in Salt Creek, at Tuscan Springs, and in Sevenmile Creek between the north end of the Chico monocline and the Inks Creek fold system (pl. 1). In each area, beds in the Tuscan dip outward, away from the Upper Cretaceous rocks, and define three small domes, shown on plate 1 as the Salt Creek, Tuscan Springs, and Sevenmile domes.

The long axes of the domes trend north-northeast and plunge 15°–25° NE. and SW. Cold sulfurous springs are present in the Salt Creek and Tuscan Springs domes, and olivine basalt rests unconformably on steeply northwest-dipping Upper Cretaceous rocks in the core of Sevenmile dome. The olivine basalt was extruded from a north-trending fissure after the Tuscan Formation was domed and erosion had exposed the Upper Cretaceous rocks.

The age of the olivine basalt is unknown, but it probably is a few tens of thousands of years old, at most, and is roughly coeval with similar basalt flows and cinder cones found at Inskip Hill (pl. 1) and Black Butte along the Battle Creek fault zone. The domes probably formed during the same phase of late Quaternary deformation about 0.4–0.45 m.y. ago that produced the Inks Creek fold system and the Battle Creek fault zone, and they are thus younger than the Chico monocline.

RED BLUFF FAULT

The Red Bluff fault is a subsurface structure that extends southwest of Red Bluff for at least 25 km. West of Red Bluff, there is no surface feature associated unequivocally with the fault, and its location on plate 1 is taken from Jennings' (1977) geologic map of California. Apparently Jennings included the fault on that map on the basis of seismic-reflection data obtained from private industry (Oliver and Griscom, 1980). We have not seen that data or any other seismic profiles that might cross the fault. Griscom (1973) inferred the existence of a major northeast-trending fault in the area from magnetic data.

East of Red Bluff, structure contours on top of the Cretaceous rocks outline a major anticline, the broad crest of which lies beneath the Salt Creek, Tuscan Springs, and Sevenmile domes. The axial trace of this anticline roughly coincides with the east-northeast projection of the Red Bluff fault, but there is no indication that the Tuscan Formation is faulted at the surface along the N. 70° E. trend. The southeast limb of the anticline may be faulted at depth, but surface and subsurface data are too sparse to either prove or refute that structural possibility. Between Tuscan Springs and the Humble "Cone Ranch No. 1" well (sec. 20, T. 27 N., R. 2 W.) to the south, the top of the Cretaceous sequence drops about 1,433 m over a distance of less than 8 km. The lower elevation is due to warping and faulting on the Chico monocline fault, as well as to folding and possible faulting along the northeast projection of the Red Bluff fault.

From our reinterpretation of a north-south section along the Sacramento River near Red Bluff given by Redwine (1972, section *F-F′*), the base of the Tehama Formation could be offset, down to the south, by as much as 141 m across the Red Bluff fault just east of Red Bluff. Because of the lack of northeast-trending surface faulting in the Tuscan to the east, however, it seems unlikely that all of that differential elevation is due to fault displacement; much of it may be related to folding over a fault at depth.

FAULTS SOUTH OF INSKIP HILL

The northwest-trending arcuate faults that are shown south of Inskip Hill (pl. 1) are a gross simplification of the faults and fractures found in that area. In detail, the Tuscan Formation is laced with a dense network of short anastomosing faults along which thin lines of shrubs and trees grow (fig. 19). The amount of offset on a single fault is small, generally a few meters or less, and there appears to be no significant cumulative offset in the Tuscan Formation across the fractured area.

The arcuate pattern of faults is concave toward the area of Mineral, to the east, where Wilson (1961) identified a major volcanic center that he called Mount Maidu. It seems reasonably certain that the fracture pattern is related to volcanic-tectonic activity in the Lassen area, but whether it is associated with Mount Maidu or some other volcanic center is uncertain.

STRUCTURES SOUTHWEST OF THE WILLOWS FAULT

With the exception of the buried Colusa dome, the subsurface structure of the valley southeast of the Willows fault to the Sacramento Delta is dominated by the Zamora syncline. South of buried Colusa dome, the Zamora syncline is asymmetrical and has a broad, gently west-dipping east limb that extends to the Sierran foothills and a steeply dipping west limb that is warped by southeast-plunging folds. North of the buried Colusa dome, the axial trace of the Zamora syncline intersects the Willows fault, and the top of the Upper Cretaceous rocks defines a generally east-dipping homocline.The following sections discuss structural features west of the axial trace of the Zamora syncline.

CAPAY VALLEY-CAPAY HILLS AREA

Cache Creek drains east from Clear Lake and enters the Sacramento Valley west of Woodland, through the tectonically controlled depression of Capay Valley. On the west, Capay Valley is flanked by the eastern slope of the Coast Ranges that contain a remnant of Eocene marine sandstone and shale of the Capay Formation (Redwine, 1972) resting unconformably on Upper Cretaceous marine rocks (Kirby, 1943a). Beds in the Capay and underlying rocks dip 25°-55° E. The Capay Hills, previously known as the Rumsey Hills (Kirby, 1943b), lie immediately east of Capay Valley and are underlain by the same Upper Cretaceous rocks exposed to the west. Here, however, the Cretaceous rocks lie in the core of a faulted southeast-plunging anticline, shown by structure contours on plate 1. They are unconformably overlain by nonmarine sandstone and shale of the Pliocene Tehama Formation. The Eocene Capay Formation is not present in the Capay Hills or in the Capay Valley, where scattered subsurface and surface data indicate that the Tehama rests unconformably on Upper Cretaceous rocks.

FIGURE 19.—Low-altitude vertical aerial photograph (U.S. Geological Survey) showing arcuate fault pattern (dashes) and cinder cones (crosses) south of Inskip Hill. Gray incised plains are underlain by the Tuscan Formation; thin dark lines are concentrations of brush and trees growing along fault traces.

On the floor of Capay Valley, the Tehama and older rocks have been eroded, and old stream channels have been filled with a variety of Quaternary alluvial deposits. Alluvial deposits of the upper part of the Modesto Formation indicate that Cache Creek entered the Sacramento Valley through a channel cut in the Tehama Formation near the west boundary of Capay Valley in late Wisconsin time. During the past 12,000 years the course of Cache Creek has shifted eastward so that the creek now exits Capay Valley through a sharp gorge cut into the relatively resistant Upper Cretaceous rocks at the southern end of Capay Hills. The shift in the course of Cache Creek and the surface and subsurface data that show faulting in the Tehama Formation provide strong evidence for late Cenozoic tectonism in Capay Valley.

Along the west flank of the Capay Hills, Kirby (1943b) mapped a northwest-trending, east-dipping thrust, the Sweitzer fault, and a lower ancilliary thrust, the Eisner fault; both faults place Upper Cretaceous rocks in contact with the Tehama. Wagner and Saucedo (1984) have reinterpreted the Sweitzer and Eisner faults as west-dipping normal faults. Their interpretation of the Sweitzer fault is supported by subsurface data at the south end of Capay Hills, where the contact between the Forbes and Guinda Formations of Kirby (1943a) is downfaulted about 50 m on the west (fig. 20, wells 3 and 4). Compared to other faults in the area, the Sweitzer fault appears to have played a relatively minor part in the structural evolution of the Capay Valley and Capay Hills.

West of the Sweitzer fault, the contact between the Forbes and Guinda Formations was reported at an elevation of about 219 m beneath the Capay Valley (fig. 20, well 2). That contact is displaced about 610 m up to the west along the northwest-trending, steeply east-dipping East Valley fault (fig. 20). Along the west margin of Capay Valley, the contact between Upper Cretaceous rocks and the Tehama Formation is down faulted about

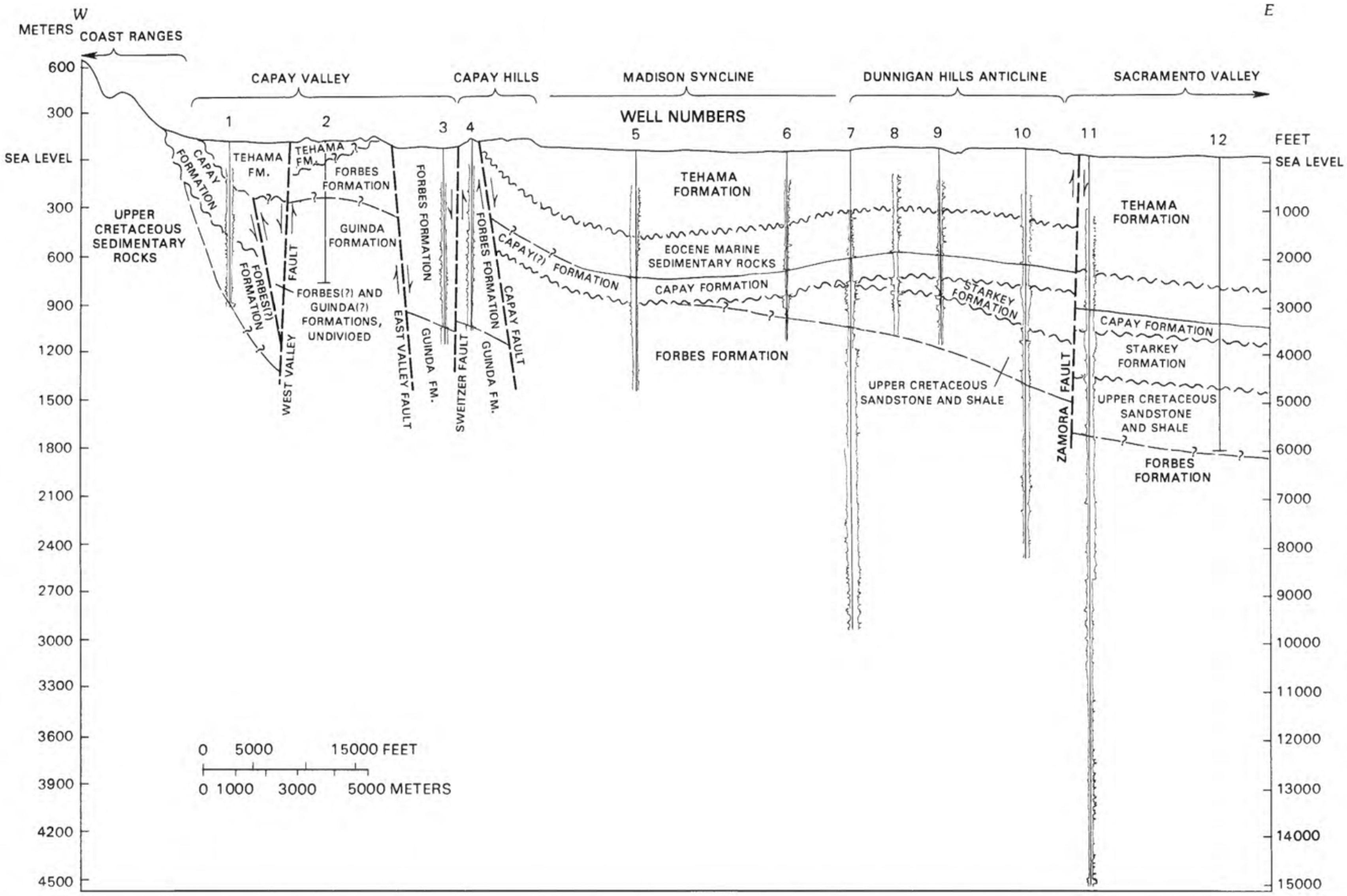


FIGURE 20.—Cross section showing electric logs and stratigraphic and structural relations in Capay Valley, Capay Hills, and Dunnigan Hills. Names of wells listed in appendix. Stratigraphic nomenclature used may not necessarily conform to that adopted by U.S. Geological Survey.

150 m to the west by the near-vertical West Valley fault (fig. 20). At the south end of Capay Valley, Upper Cretaceous rocks are thrust over the Eocene Capay Formation along a thrust or high-angle reverse fault that is exposed to the south along the east flank of the Coast Ranges (pl. 1). The location of this thrust or high-angle reverse fault is unknown east of the West Valley fault.

East of Capay Hills, the Capay Formation unconformably overlies east-dipping Upper Cretaceous rocks beneath the Madison syncline and the Dunnigan Hills anticline (pl. 1; fig. 20). The Capay Formation and overlying Eocene marine rocks are not exposed in the Capay Hills where the Pliocene Tehama Formation rests unconformably on Upper Cretaceous rocks. Because the Capay Formation is present west of Capay Valley, however, we assume that the Capay Formation once extended over the area of the Capay Hills but that it was eroded from the area after west-side-up movement on the Capay fault (fig. 20) and the other high-angle reverse faults to the west under Capay Valley. In this interpretation, the minimum displacement on the Capay fault would be about 700 m. Major west-side-up reverse movement occurred on the Capay fault, the East Valley fault, and the unnamed thrust or high-angle reverse fault to the west in post-Eocene time and before deposition of the Tehama Formation, which contains the 3.4-m.y. old Putah Tuff Member near its base (Sarna-Wojcicki, 1976). West-side-down movement occurred on the West Valley fault subsequent to deposition of the Tehama Formation, and east-side-down, post-Tehama displacement also may have occurred on the East Valley fault and the Capay fault.

DUNNIGAN HILLS ANTICLINE AND THE ZAMORA FAULT

Near Woodland, Bryan (1923) recognized accordant summit elevations capped by Red Bluff gravel on a series of northwest-trending dissected uplands that he called the Hungry Hollow Hills, but which are now known as the Dunnigan Hills. The northeast flank of the upland is bounded by a linear escarpment that Bryan called the Hungry Hollow fault, but which is referred to here as the Zamora fault ([illegible]; fig. 20). He recognized down-to-the-[illegible] displacement of at least 121 m at the north end of the fault scarp and offset of about 60 m near Cache Creek to the south (Bryan, 1923, p. 79).

Bryan's early work, combined with the topographic relief in the area, made the Dunnigan Hills a prime target for early seismic-reflection studies that resulted in the discovery of the Dunnigan Hills gas field in 1946 (Rofe, 1962). The gas-producing structure is a doubly plunging, northwest-trending anticline along which various Upper Cretaceous sandstone beds are unconformably capped by the Eocene Capay Formation (fig. 20). This major structure has topographic relief. Red Bluff gravel wraps around the northwest-plunging nose of the fold and occurs in scattered patches along the east flank, on the crest line, and at the southeast-plunging nose of the fold. Oat Creek (pl. 1) and Bird Creek to the southeast (not shown on pl. 1) are antecedent to the fold and change from southeast to northeast courses approximately at its axial trace.

Data from a recent well drilled near Zamora by the U.S. Geological Survey provide new information on the amount of late Cenozoic deformation in the area. A conspicuous volcanic ash bed, penetrated at a depth of −137 m (Page and Bertoldi, 1983), has been correlated tentatively by mineralogy and chemical composition of the glass with the Rockland ash bed by C. E. Meyer and A. M. Sarna-Wojcicki (oral commun., 1982). Because the ash occurs directly above Red Bluff gravels elsewhere in the valley (Harwood and others, 1981; Helley and others, 1981), it is assumed that the ash overlies the Red Bluff in the Zamora well and that there is a minimum of 220 m of vertical displacement of the Red Bluff Formation. This vertical separation is the result of folding on the Dunnigan Hills anticline and displacement on the Zamora fault (fig. 20).

MIDLAND FAULT

The Midland fault is a major subsurface structure that was discovered in the Sacramento Delta during development of the Rio Vista gas field between 1936 and 1943 (Frame, 1944). Through data from extensive drilling, the fault was extended about 25 km north of the Rio Vista field to the Maine Prairie gas field (Arleth, 1968). North of that field, the location of the Midland fault is uncertain. Redwine (1972) proposed that the Sweitzer fault, mapped by Kirby (1943b) in the Capay Hills, was the northwest continuation of the Midland fault. Although Jennings (1977) showed the Midland-Sweitzer fault connection, suitably queried, on his geologic map of California, that interpretation is no longer considered correct (C. Jennings, oral commun., 1981). The location of the Midland fault south of the Rio Vista gas field is uncertain.

In the Rio Vista gas field, the Midland fault is actually a north-trending, steeply west-dipping to vertical fault zone that offsets Paleocene and Eocene rocks down to the west in a series of fault blocks as shown in figure 21. Early in the development of the Rio Vista gas field, it became apparent that movement on the Midland fault had controlled local patterns of Tertiary sedimentation. Frame (1944) noted that the Capay Formation was significantly thicker west of the Midland fault, and he suggested that maximum movement occurred on the fault during or at the close of Capay deposition. Although the Capay Formation shows the greatest amount of syntectonic thickening across the fault, all of the Paleocene and Eocene units show some differential thickening west of the fault (Burroughs and others, 1968). In his detailed analysis of depositional and tectonic cycles in the southern Sacramento Valley, Almgren (1978) demonstrated approximately 610 m of episodic movement on the fault between the early Paleocene and early Oligocene. There is no indication that early Oligocene or younger deposits are offset by the Midland fault; therefore, it appears that the Midland fault was an active structural feature on the early Tertiary continental margin but that it has not been active in the late Cenozoic.

By combining data presented by Burroughs and others (1968) and Almgren (1978), it is possible to calculate approximate displacement rates on the Midland fault during the early Tertiary. Calculation of the displacement rates, shown in figure 22, assumes that displacement occurred on a single fault strand during the time deduced for various units by Almgren (1978) and that initial offset began in the Paleocene. Between 60 and 53 m.y. ago the slip rate was 3.8 cm/1,000 yr. The rate increased to a maximum of 7.2 cm/1,000 yr between 53 and 50 m.y., and it decreased significantly to 0.75 cm/1,000 yr between 49 and 42 m.y.

THORNTON ANTICLINE

The Thornton anticline, or the Thornton arch of Silcox (1968), is an east- to southeast-trending, west-plunging fold that is transected in part by closely spaced northwest-trending faults that generally show west-side-down displacements of less than 20 m. The fold extends from the east-central part of the Sacramento Delta to the vicinity of Lodi and provides structural control for several gas fields along its trace. Silcox (1968) provides the most detailed information on the structural development of the

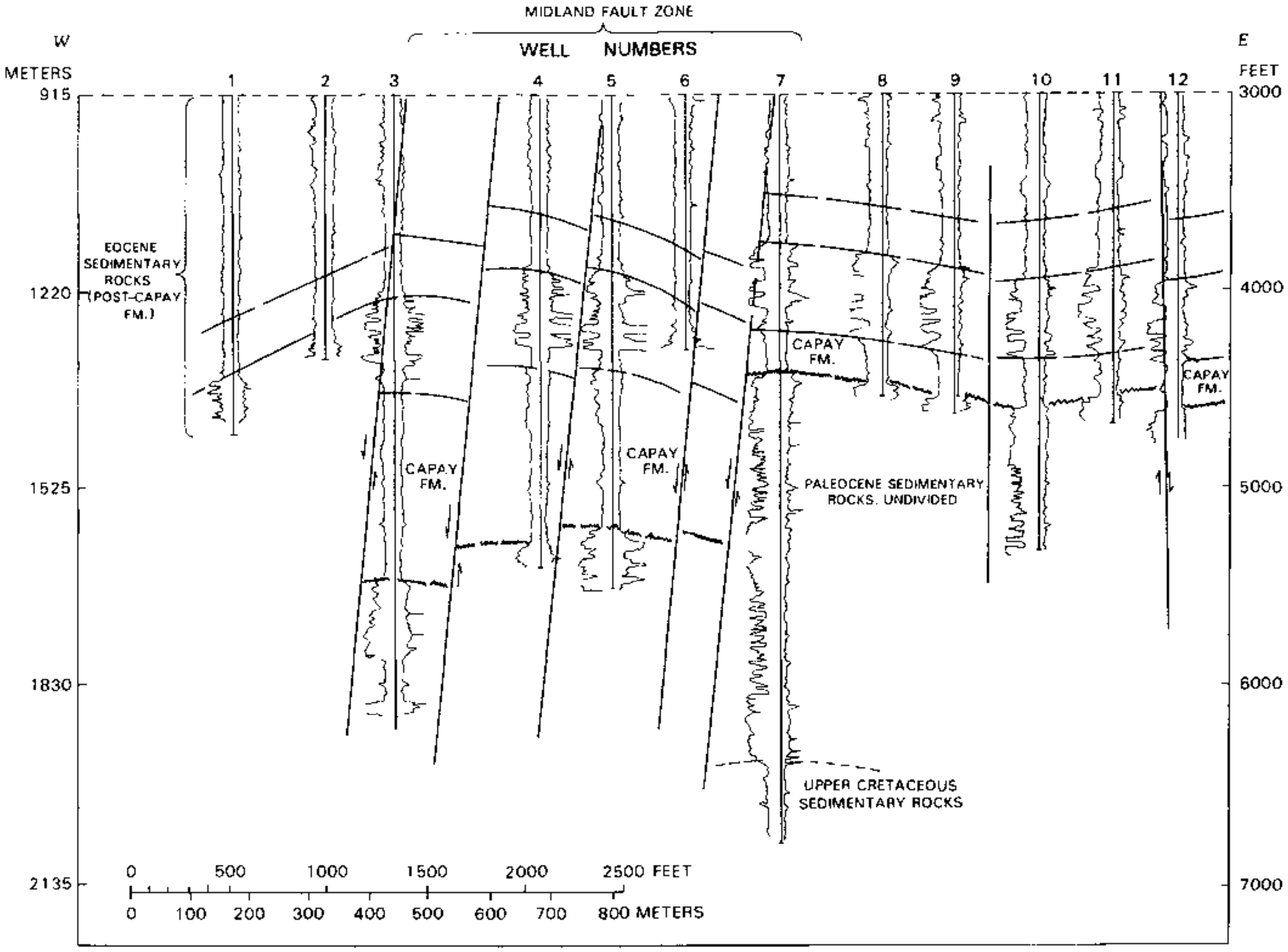


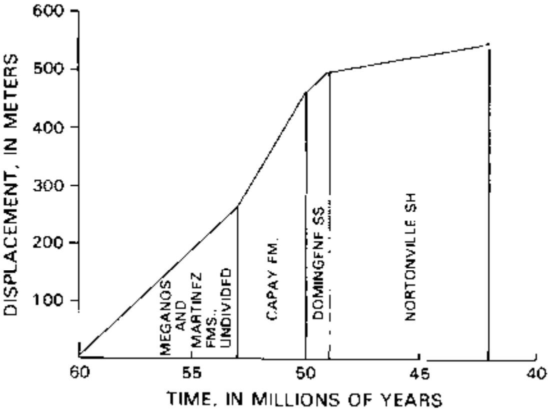
FIGURE 21.—Cross section showing electric logs and stratigraphic and structural relations across Midland fault zone in Rio Vista gas field (modified from Burroughs and others, 1968). Note significant thickening of the Eocene Capay Formation west of easternmost strand of Midland fault zone. Names of wells given by Burroughs and others (1968).

Thornton anticline in his description of the Thornton and Walnut Grove gas fields.

According to Silcox (1968) initial development of the Thornton anticline occurred prior to deposition of the basal Eocene rocks and may have been contemporaneous with Paleocene displacement on the Midland fault to the west. Maximum flexure of the structure apparently occurred in the late Eocene when lower and middle Eocene rocks were eroded and subsequently buried unconformably beneath deposits of the Markley submarine canyon. Miocene continental rocks, which were deposited unconformably on Markley canyon fill, do not show any significant folding over the Thornton anticline, nor are they offset by the northwest-trending faults that cut earlier deposits along the fold. Therefore, the structures are pre-Miocene.

STOCKTON FAULT

The Stockton fault is a northeast-trending, southeast-dipping subsurface fault that extends across the southern part of the Sacramento Valley between Tracy (south of pl. 1) on the west and the vicinity of Milton on the east. The fault lies north of a cross-valley, northeast-trending structural high in the basement, known as the Stockton arch, that apparently was discovered during some of the earliest seismic-reflection profiling done in the valley in the mid-1930's. Wells drilled near the Stockton fault during that time found only minor amounts of gas, and the relations between displacement on the Stockton fault and folding in the Upper Cretaceous marine rocks were not determined until development of the Lathrop gas field during the late 1940's. Teitsworth (1968), in his analysis of the Lathrop gas field, presents the most detailed study of the complex tectonic history of the Stockton fault. His work coupled with our analysis of wells to basement north of the Stockton fault, and Bartow's (1983) analysis of wells south of the fault provide the data for this discussion.



UNIT	DIFFERENTIAL THICKNESS (m)	POSTFORMATION OFFSET (m)	TOTAL OFFSET (m)	TIME (m.y. ago)	RATE (cm/10^3 yr)
Nortonville Sh	15	38	53	(49-42)	0.75
Domingene Ss.	26	23	49	(50-49)	4.9
Capay Fm	215	0	215	(53-50)	7.2
Meganos and Martinez Fms., undivided	260	5	265	(60-53)	3.8

FIGURE 22.—Graph showing amounts and rates of offset on Midland fault zone, assuming all displacement occurred on a single fault strand and that displacement began in the Paleocene. Amount of offset and syntectonic thickening of units taken from figure 21 (modified from Burroughs and others, 1968).

Near the city of Stockton, the −3,000-m basement contour is offset about 5 km in a left-lateral sense and depressed about 300 m down to the south, but the vertical component of movement is not closely controlled in that area. Eastward, near the −2,500-m contour, the basement surface is offset left-laterally about 6 km and depressed nearly 500 m south of the fault. The vertical component of displacement there is reasonably well controlled by wells north and south of the fault. Both the left-lateral and vertical components of displacement decrease eastward along the Stockton fault and appear to die out completely between the −500-m and 0 basement contours. No trace of the Stockton fault has been mapped in the exposed metamorphic rocks of the Sierran foothills between the north end of Gopher Ridge and the Mokelumne River (pl. 1) (Wagner and others, 1981).

Teitsworth's (1968) study of the Lathrop gas field (pl. 1, map A), which is located about 9 km southeast of Stockton, corroborates our analysis of the basement offset on the Stockton fault and adds valuable data about the amount and timing of deformation recorded in the Upper Cretaceous rocks. Teitsworth concluded that the Upper Cretaceous rocks were thicker south of the Stockton fault, indicating south-side-down vertical movement during early phases of deposition, and that they were subsequently offset about 3 km left-laterally during Late Cretaceous time. Deposition of Upper Cretaceous marine shale followed earlier strike-slip displacement on the Stockton fault, and these marine shale units also show left-lateral displacement. Following deposition and strike-slip displacement of the uppermost Upper Cretaceous unit in the area, but prior to deposition of Miocene continental strata that unconformably cap the Upper Cretaceous section, the Stockton fault experienced about 1,000 m of reverse, south-side-up movement (Teitsworth, 1968). During this period of reverse movement, west- and west-northwest-trending anticlines formed in the Upper Cretaceous rocks south of the fault, providing closure that trapped the gas in the Lathrop and East Stockton gas fields (pl. 1, map A). The trend of these folds and the northwest-trending anticlines in the Roberts Island and McDonald Island gas fields (pl. 1, map A) north of the Stockton fault indicate northeast-southwest compression in the area during the period of reverse movement on the Stockton fault. Teitsworth (1968) concluded that reverse movement probably occurred after the middle Eocene but before deposition of Miocene continental deposits. However, he shows a west-northwest-trending fold in contours drawn on the base of the Miocene rocks south of the Stockton fault, from which we conclude that the northeast-southwest compressive stress operated in the area into the middle Tertiary.

FAULTS IN THE SIERRAN FOOTHILLS

Clark (1960) combined data from a number of sources with his own field observations to produce the first regional structural synthesis of the Sierran foothills. He defined the Foothill fault system as a group of northwest-trending, steeply east-dipping to vertical faults that tectonically separate distinctive belts of Paleozoic and Mesozoic rocks for more than 320 km along strike in the western foothills of the Sierra Nevada. He recognized that the component faults in the system were actually complex fault zones marked by multiple fault strands and intensely sheared, cataclastic, and crumpled rocks, which were associated geographically, in many areas, with major bodies of sheared serpentinite. On the basis of limited paleontologic and radiometric data, he concluded that the major tectonic activity of the Foothill fault system occurred in the Late Jurassic.

Although displacement of Tertiary volcanic units was recognized locally along segments of the Foothill fault system after Clark's study (Bateman and Warhaftig, 1966), few investigations were made into the late Cenozoic deformational history of the fault system before the Oroville earthquake. That seismic event produced ground rupture on the Cleveland Hills faults (Clark and others, 1976) and opened the question of potential late Cenozoic deformation within the whole Foothill fault system.

In their earthquake evaluation studies of the Auburn Dam area, Woodward-Clyde Consultants (1977) made a regional analysis of potential late Cenozoic deformation along many linear features related to the Foothill fault system, and they trenched those linear features that had direct bearing on their Auburn Dam study. That study provided most of the data for our analysis of those strands of the fault system in the border zone between the Sierran foothills and the Sacramento Valley.

COHASSET RIDGE FAULT

Cohasset Ridge is a prominent south- to southwest-trending interfluve located northeast of Chico, between the major drainages of Big Chico Creek and Deer Creek. The ridge is capped by at least two essentially contemporaneous olivine basalt flows that appear to have originated in the Butte Mountain area (about 12 km east of pl. 1), on the southwest slope of a Pliocene volcano named Mount Yana by Lydon (1968). The olivine basalts flowed southwestward in channels eroded in the underlying Tuscan Formation, but subsequent erosion has inverted the topography so that the basalt now stands as the highest unit on the ridge. The olivine basalt of Cohasset Ridge represents the final phase of volcanism that reached the Sacramento Valley from Mount Yana. The upper basalt flow has been dated at 2.41 m.y. (Harwood and others, 1981).

East of Brushy Mountain (pl. 1), the olivine basalt of Cohasset Ridge is abruptly truncated on the east by a steeply east-dipping fault that strikes about N. 40° W., roughly parallel to the Chico monocline fault. Aune (cited in Woodward-Clyde Consultants, 1977) first recognized this fault, which he called the Cohasset Ridge fault, and concluded that the eastern equivalents of the olivine basalt of Cohasset Ridge were downfaulted to the east about 30 m along the normal fault. The Cohasset Ridge fault can be traced north of Deer Creek through an intensely fractured zone in the Tuscan Formation to the vicinity of Mill Creek, where it becomes obscured by a complex pattern of west- and northwest-trending arcuate faults (pl. 1; fig. 19). Although the area south of Deer Creek is heavily forested and the slopes are covered by a veneer of colluvium, the trace of the Cohasset Ridge fault is defined by a prominent topographic linear feature, observed by Rich and Steele (1974), that extends nearly to Magalia, where it apparently is intersected by the Magalia fault.

The Cohasset Ridge fault is a northwest-trending, steeply east-dipping fault that has experienced at least 30 m of east-side-down normal movement in the past 2.41 m.y.

MAGALIA FAULT

About 9 km north of Magalia, (pl. 1), the Cohasset Ridge fault is intersected by the N. 20° W.-trending Magalia fault. Extensive mine workings, which followed Tertiary auriferous gravel deposits at the base of the Tertiary volcanic sequence in the area, provide detailed data on the nature and local extent of the Magalia fault (Gassaway, 1899; Logan, 1930; Woodward-Clyde Consultants, 1977).

Although the Magalia fault is shown as a single fault on the map, detailed mine maps indicate that the fault is actually a complex fault zone consisting of numerous fault strands that have different orientations and amounts of displacement. In the Dix mine at the north end of the mining district, the gold-bearing gravels are offset 28 m down to the east. Southeastward along the trace of the Magalia fault at the Black Diamond mine, the gravel deposits are offset 68 m down to the east. Farther southeast at the Magalia mine, the channel deposits are offset down to the west from 2 to 11 m along three reverse faults that trend N. 60° W. and dip 58° NE.

From the mining records it appears that the various fault strands in the Magalia fault zone have experienced episodic and different movement through the Tertiary, with both normal east-side-down and reverse east-side-up displacement recorded. The relative ages of this disparate movement pattern along the Magalia fault are unknown, but the youngest movement appears to postdate movement on the Cohasset Ridge fault.

CLEVELAND HILLS FAULTS

The Cleveland Hills faults coincide with surface ruptures that occurred during the Oroville earthquake. During that seismic event, the ground surface failed in a 3.8-km long en echelon pattern of north- and north-northwest-trending normal faults that showed at least 55 mm of horizontal separation across the surface ruptures and as much as 180 mm of west-side-down vertical separation (Clark and others, 1976). Aftershocks of the Oroville earthquake defined a zone of seismic activity, assumed to coincide with the controlling fault, that dipped about 60° W. and trended nearly due north (fig. 15; also Bufe and others, 1976).

Trenches, dug across the zone of surface rupture by the California Department of Water Resources and logged by Akers and McQuilkin (1975), showed a gouge zone about 2 m wide in the bedrock below the surface ruptures that was flanked by 2-4 m of intensely fractured rock transitional into the country rock of foliated greenstone. The gouge zone contains anastomosing shear zones of deformed gouge that provide evidence of repeated earlier faulting along the zone of the ground failure. Earlier deformation in the area is also indicated by 30-60 m of apparent west-side-down offset of an erosion surface of probable Pleistocene age across the Cleveland Hills faults (Aune, 1975).

About 5.7 km northwest of the Cleveland Hills faults (pl. 1), Creely (1965) mapped a north-trending, steeply east-dipping fault that offset the base of Pleistocene or older gravel deposits about 2 m down to the west. Clark and others (1976) reported a second fault in the area that showed minor east-side-down offset of the gravel deposit.

FAULTS SOUTHEAST OF OROVILLE

In their earthquake evaluation of the Auburn Dam area, Woodward-Clyde Consultants (1977) identified a number of prominent linear features in the Sierran foothills southeast of the Cleveland Hills faults. With the exception of the northeast- and north-trending Highway 49 and Hancock Creek lineament zones (pl. 1), the linear features they investigated have northwest trends that coincide closely with the projected trace of the Chico monocline fault. The linear features were trenched extensively and logged in detail (Woodward-Clyde Consultants, 1977), and trench data were integrated with surficial geologic investigations in each area. Evidence of movement in the past 10 m.y. (Woodward-Clyde Consultants' definition of the "late Cenozoic") was detected in the trenches across the northwest-trending linear features, which are shown on plate 1 as the Swains Ravine, Spenceville, and Maidu fault zones and the Dewitt fault.

Deformation in the bedrock exposed in the trenches is remarkably similar to that shown in trenches across the Cleveland Hills faults. In most areas, bedrock beneath the surface lineaments contained one or more zones of slickensided clay-rich gouge a few meters wide or less. The gouge commonly contained anastomosing shear zones composed of polydeformed gouge and thin clay seams that indicated multiple phases of deformation. Rock adjacent to the gouge zones commonly was highly fractured, bleached, or manganese-stained and injected by thin quartz veins. In some trenches, a paleosol rested unconformably on bedrock and was offset locally along the faults marked by the gouge zones. That evidence led Woodward-Clyde Consultants (1977) to conclude that at least some of the faulting had occurred in the past 100,000 years. Based on the evidence presented by Woodward-Clyde Consultants (1977) and our observations in many of the trenches that they excavated during that study, we agree with their conclusions.

REGIONAL STRUCTURAL ANALYSIS

STRUCTURAL DOMAINS IN THE SACRAMENTO VALLEY

As we have shown in preceding sections of this report, late Cenozoic structural features in the valley have diverse orientations and displacement histories. In spite of this diversity, large areas of the valley are characterized by coeval structures that appear to have formed in a similar stress regime. To analyze the late Cenozoic structural evolution of the Sacramento Valley, we have grouped coeval structures that have similar displacement patterns into structural domains (fig. 23).

Delineating the various structural domains obviously depends on correctly identifying and correlating late Cenozoic deposits throughout the valley. Many of the late Cenozoic alluvial deposits are similar in outcrop characteristics, but fortunately they contain or are bracketed by distinctive tephra beds or volcanic flows that allow widespread correlation of alluvial units and provide absolute age control for the alluvial and tectonic histories of the region. In this regard, we have used the following time-stratigraphic units to define the late Cenozoic structural domains of the valley:

Unit	*Age/Age range* (*m.y.*)	*Reference*
Rockland ash bed	0.4-0.45	Sarna-Wojcicki and others (1985); Meyer and others (1980)
Red Bluff Formation	0.5-1.0	Harwood and others (1981)
Olivine basalt of Deer Creek	1.09	Harwood and others (1981)
Ishi Tuff Member of the Tuscan Formation	2.6	Harwood and others (1981; unpublished data, 1985)
Volcanic rocks of Sutter Buttes	1.4-2.4	Williams and Curtis (1977)
Nomlaki Tuff Member of the Tuscan and Tehama Formations	3.4	Evernden and others (1964)
Putah Tuff Member of the Tehama Formation	3.4	Sarna-Wojcicki (1976)

With the exception of the Dunnigan Hills, the structural domains shown in figure 23 become progressively younger northward through the valley. Late Cenozoic deformation in the Dunnigan Hills domain apparently overlapped that in the Corning domain, but the respective styles of deformation and the inferred stress regimes discussed in a later section differ significantly. This point emphasizes the fact that the structural domains include tectonic features that are homogeneous in time and style of deformation as far as we can determine. To a certain extent, the ages of the structural domains reflect the distribution of the time-stratigraphic units used to identify the major late Cenozoic deformation in a domain. It may be possible to subdivide some domains as more information on the distribution of the younger time-stratigraphic units becomes available. Furthermore, it is important to note that ascribing an age to the late Cenozoic deformation in a domain does not imply that all deformation necessarily began or ended within that time. Many late Cenozoic structural features in the valley formed over earlier structures in the upper Mesozoic or Tertiary rocks, and thus they owe their existence, in part, to tectonic heredity. In some areas, historic low-magnitude earthquakes can be identified with specific structural features such as the Battle Creek fault zone (Bolt, 1979) and Corning fault (Marks and Lindh, 1978), indicating that strain is currently being released on these structures.

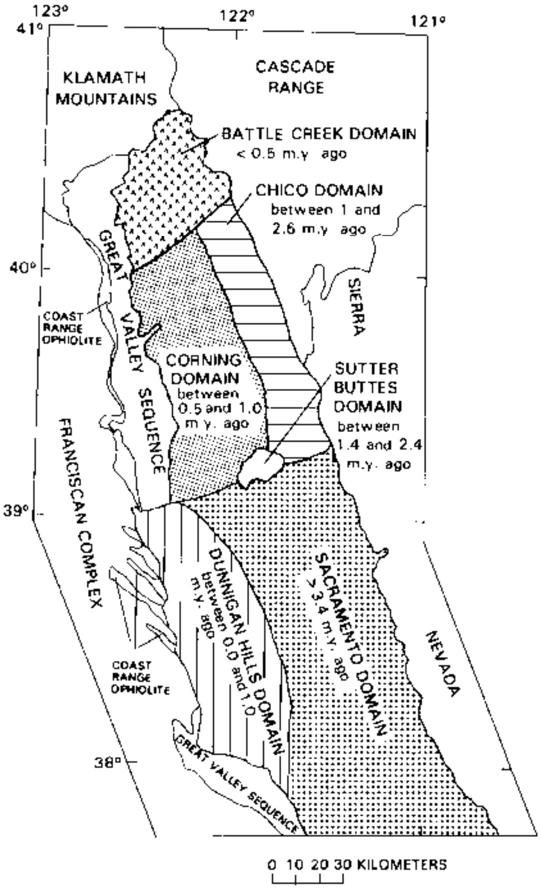


FIGURE 23.—Structural domains in Sacramento Valley. Numbers under domain names give duration or age of deformation that produced late Cenozoic structures in that domain.

SACRAMENTO DOMAIN

The Sacramento domain includes the Stockton fault, the Midland fault, the Thornton anticline, and the possible southeast extension of the Willows fault and other unnamed northwest-trending faults southeast of Sutter Buttes. None of these structures appear to offset or deform late Cenozoic alluvial deposits that are younger than the Nomlaki Tuff Member (figs. 7-10; Silcox, 1968; Teitsworth, 1968).

The minimum age of deformation is difficult to determine. If the Markley submarine canyon was localized, in part, by movement on the southeast extension of the Willows fault, as suggested by figures 8 and 9, then major deformation occurred in the domain in the middle Tertiary and could be as young as early Miocene, which is the upper age of the Markley canyon fill (Almgren, 1978). However, the Pliocene Laguna Formation, which contains the Nomlaki Tuff Member near its base just east of Marysville (Bussaca, 1982), does not appear to be offset in this domain; therefore, we conclude that deformation is older than 3.4 m.y. Upper Cretaceous rocks indicate syndepositional offset on the Stockton fault (Teitsworth, 1968) so the maximum age of deformation is Late Cretaceous.

The Willows fault north of Sutter Buttes (fig. 3) and the faults in Capay Valley (fig. 20) also show protracted deformation, ranging in age from Late Cretaceous to the middle Tertiary, that undoubtedly was contemporaneous with deformation in the Sacramento domain.

SUTTER BUTTES DOMAIN

The complex pattern of folds and faults at Sutter Buttes and the buried Colusa dome was interpreted by Williams

(1929) and Williams and Curtis (1977) to have formed by forceful intrusion of magma between 2.4 and 1.4 m.y. ago. Harwood (1984; this report) suggested that magmatism was localized at Sutter Buttes and the buried Colusa dome by movement on the Willows fault and possibly on the Mesozoic tectonic boundary between oceanic and Sierran basement terranes beneath Sutter Buttes. In this interpretation, deformation in the Sutter Buttes domain occurred through the combined effects of forceful intrusion of magma and east-west compression in a regional stress field.

Deformation in the Sutter Buttes domain may have overlapped in time with deformation in the Chico domain. However, the style of tectonism at Sutter Buttes is unique, and the area must be considered as a separate domain in a regional analysis.

Although Williams and Curtis (1977) suggested that Sutter Buttes formed in roughly half a million years, based on volume and morphology of volcanic deposits, their K/Ar ages for the volcanic complex range from about 1.4 to 2.4 m.y., and we have used that age range as the age of the structural domain.

CHICO DOMAIN

The Chico monocline is the dominant structure in the Chico domain (fig. 23). The monoclinal flexure and the controlling fault at depth (fig. 14) formed after the eruption of the Ishi Tuff Member of the Tuscan Formation, about 2.6 m.y. ago (Harwood, unpub. data, 1984), but before the eruption of the olivine basalt of Deer Creek, about 1.0 m.y. ago (Harwood and others, 1981). Formation of the monocline resulted directly from uplift of the northern Sierra Nevada and rupture along the controlling fault beneath the monocline. On the basis of geophysical evidence (Griscom, 1973; Cady, 1975), it seems reasonably certain that the controlling fault was a major late Mesozoic structure, separating oceanic from magmatic-arc crustal blocks, that was reactivated in the late Cenozoic.

Late Cenozoic tectonic uplift markedly increased erosion in streams antecedent to the monocline from Deer Creek northwest to Salt Creek just east of Red Bluff. Due to their tectonically steepened gradients, these streams deposited coarse, bouldery alluvial fanglomerate composed of volcanic material derived from the Tuscan Formation, extending from the monoclinal arch westward into the valley. The olivine basalt of Deer Creek filled the ancestral channel of Deer Creek east of the monocline and cascaded over the coarse fanglomerate, forming westward-overturned folds at the base of the flow west of the monoclinal flexure.

In Salt Creek and along nearby Hogback Road just east of Red Bluff, the fanglomerate (unit QTog of Harwood and others, 1981) rests unconformably on a partially stripped soil that developed on the Tuscan Formation. The soil indicates a significant period of nondeposition and weathering prior to flexing of the monocline and prior to rapid deposition of the alluvial fanglomerate. A period of erosion also followed deposition of the fanglomerate. The Red Bluff Formation was deposited unconformably on both the Tuscan and fanglomerate in Salt Creek. These stratigraphic relations, coupled with the fact that the Ishi Tuff Member is flexed, eroded, and unconformably overlain by the olivine basalt of Deer Creek along the monocline, establish deformation in the Chico domain between 1.0 and 2.6 m.y. This is clearly before deformation in the Corning domain to the west, where the Red Bluff is significantly folded and faulted.

The orientation of the horizontal compressive stress vector is not closely constrained in the Chico domain. Slickensides on some faults along the monocline flexure have a rake of 35° NW., suggesting some left-lateral oblique slip on the northwest-trending fault system. Whether the slickensides developed at the time the monocline formed or subsequently is unknown, but if they do record strain released during flexing of the monocline, the principal horizontal stress may have been oriented approximately east-west.

CORNING DOMAIN

West of the Chico monocline in an area extending to the Willows fault, late Cenozoic structures range in orientation from northwest to approximately north. The main stem of the Willows fault and the fault along the flank of South Corning dome nearly parallel the trend of the Chico monocline. On the other hand, the Corning fault, the Corning domes, and the Los Molinos and Glenn synclines trend more northerly than the monocline and converge on that structure near Red Bluff. All of these structures, within the Corning domain (fig. 23), deform the Red Bluff Formation and thus postdate the flexing of the Chico monocline. However, the subparallel orientation of structures in the Corning domain northeast of the Willows fault and of those in the Chico domain suggests that all may have formed in a common stress field.

The maximum horizontal compressive stress probably was oriented approximately east-west, normal to the trace of the Corning domes. The Corning fault might represent one shear diagonal of the strain ellipse, and the northwest-trending faults would indicate the other shear diagonal. In this model, strain release would have migrated westward with time, beginning along the Chico monocline and later moving to the Corning domes and Corning fault. Clearly, some offset may have occurred on the Corning fault and the northwest part of the Willows fault during formation of the monocline, and the small amount of offset in the olivine basalt of Deer Creek over the monocline may have occurred during the upwarping of the Red Bluff

Formation over the Corning domes.

The area of the Corning domain southwest of Sutter Buttes and the Willows fault is largely capped by Holocene basin deposits that lap westward onto Upper Cretaceous rocks along the western margin of the valley. These deposits could obscure many structures that might be recorded in the Red Bluff Formation in that area, indicating that the downthrown side of the Willows fault has been a structural basin throughout most of the late Quaternary.

DUNNIGAN HILLS DOMAIN

The Dunnigan Hills domain (fig. 23) includes the Zamora fault, the Dunnigan Hills anticline, the Madison syncline, and the tectonically complex area of Capay Valley and the Capay Hills. The Red Bluff Formation is folded by the Dunnigan Hills anticline and offset by the Zamora fault along the east margin of the Dunnigan Hills (fig. 20). Therefore, the late Cenozoic structures in that area are at least as young as the folds and faults in the vicinity of Corning domes, and they could be younger. Because there is no clear evidence for the minimum age of structures in the domain, we assume that late Cenozoic deformation ranges from 1.0 m.y. to the present.

Although the late Cenozoic deformation may overlap in time with that in the Corning and Battle Creek domains, the orientation and movement pattern of structures are significantly different. The northwest-trending axial surface of the Dunnigan Hills anticline and normal displacement on the northwest-trending Zamora fault suggest that these structures may have formed in a stress field in which the maximum horizontal compressive stress was oriented approximately north-south and the least horizontal compressive stress (maximum extension) was oriented approximately east-west. Because this is the present orientation of the stress field associated with the San Andreas fault in this area (Zoback and Zoback, 1980), late Cenozoic structures in the Dunnigan Hills domain may be related to right-slip wrench tectonism associated with movement on the San Andreas fault system (Allen, 1981).

BATTLE CREEK DOMAIN

The Battle Creek domain (fig. 23) is the youngest structural domain and occurs at the northern end of the valley. It is characterized by northeast-trending folds and faults oriented nearly perpendicular to the north- and northwest-trending structures of other domains to the south.

Late Cenozoic displacement on the northeast-trending, steeply south-dipping faults is invariably down to the south, with a suggestion of minor right-lateral slip on the Battle Creek fault system (Helley and others, 1981). The amount of horizontal separation on the Battle Creek fault is unknown, but it probably is on the order of a few tens of meters to a few hundred meters at the most. The Bear Creek and Red Bluff faults are not exposed well enough to establish or refute the occurrence of late Cenozoic horizontal slip on those structures. The amount of vertical displacement increases eastward along the Battle Creek fault zone, with about half of the vertical separation of units caused by broad anticlinal folding and half by fault displacement (fig. 17). Vertical separation of late Cenozoic units on the Bear Creek and Red Bluff faults is also accomplished partly by folding.

These observations, plus the fact that the Inks Creek fold system appears to be genetically related to folding and faulting on the Battle Creek fault zone, indicate that the structures in the Battle Creek domain formed either by northwest-southeast horizontal compressive stress or by right-lateral shear stress. Strain was released initially by folding, followed by rupture and predominantly normal fault displacement. Initial movement on the Battle Creek fault zone postdated deposition of fanglomerate, which is correlated with the Red Bluff Formation, and the fault scarp restricted movement of the proximal ash-flow part of the Rockland ash bed. Deformation younger than 0.45 m.y. is indicated by distribution of the early Riverbank-age alluvial deposits north of the Battle Creek fault zone and in the tectonically controlled loops of the Sacramento River around the Inks Creek fold system. The late Cenozoic structures in the Battle Creek domain formed in the past half million years.

Little surface evidence is available to document deformation before the late Cenozoic in the Battle Creek domain. A detailed analysis of paleomagnetic directions and lithofacies in the Upper Cretaceous marine rocks and Eocene continental rocks, which locally overlie the Cretaceous rocks, might provide data to resolve this question, but we did not pursue these studies. In the light of recent paleomagnetic studies (Simpson and Cox, 1980; Beck and Plumley, 1980; Magill and Cox, 1981), which suggest a two-phase, clockwise rotation of the Oregon Coast Ranges and possibly of the Klamath Mountains in Eocene and post-Oligocene times, we believe the Battle Creek domain may be a zone of decoupling between the Klamath Mountains and Oregon Coast Ranges provinces to the north and the Sacramento Valley-Sierra Nevada provinces to the south.

VALLEY STRUCTURES RELATED TO REGIONAL STRESS PATTERNS

With the exception of structures in the Dunnigan Hills domain and recent movement on the Cleveland Hills faults, late Cenozoic folds and faults in the Sacramento Valley appear to have formed in an east-west compressive stress regime. The north- and northwest-trending

Willows, Corning, and Chico monocline faults dip steeply east and show reverse displacements. The east-northeast-trending Red Bluff, Battle Creek, and Bear Creek faults dip steeply south and have normal offsets. The axial traces of many folds are parallel to the trends of adjacent faults, and the folding appears to be related to drag on those faults. The amount of lateral displacement on faults in the valley is difficult to determine, but the rake of slickensides and the orientation of ancilliary fractures suggest minor left-lateral movement on the northwest-trending Chico monocline fault and minor right-lateral slip on the east-northeast-trending Battle Creek fault zone. These kinematic patterns are consistent with a regional stress field in which the maximum horizontal component of compressive stress is oriented about N. 75° E. (Harwood, 1984).

The late Cenozoic kinematic pattern and inferred east-west compressive stress regime in the Sacramento Valley appear to be anomalous with respect to contemporary tectonism in adjacent regions. In the California Coast Ranges to the west and in the northern Basin and Range province to the east, north-trending faults generally show normal and right-lateral displacements, east-trending faults show reverse and left-lateral movement, and northwest- and northeast-trending faults show dominantly right-lateral and left-lateral displacement, respectively (Zoback and Zoback, 1980; Hill, 1982). From these kinematic patterns, as well as earthquake focal-plane solutions, and in-situ stress measurements, Zoback and Zoback (1980) and Hill (1982) inferred that the maximum horizontal compressive stress was oriented approximately north-south and the least horizontal compressive stress (maximum extension) was oriented approximately east-west. Hill (1982) related the contemporary stress patterns to movement between the North American and Pacific plates and visualized the western part of the North American plate as a continuous broad zone of deformation following the model first proposed by Atwater (1970).

East-west compressive deformation in the Sacramento Valley suggests that the late Cenozoic stress field was not homogeneous between the continental margin and the northern Basin and Range province. Instead, the Sacramento Valley apparently acted as an independent block where relatively small-scale compressive strain was periodically released in response to large-scale right-lateral transform tectonism in the San Andreas fault zone to the west and major east-west crustal extension in the northern Basin and Range province to the east.

Furthermore, the well-dated deformation patterns in the Sacramento Valley indicate that the compressive strain was not released randomly but, rather, that the late Cenozoic structural features formed in a sequential pattern that is progressively younger to the north. Northward progression of the compressive deformation implies a northward-migrating stress regime or a migrating energy source sufficient to initiate deformation in a regional compressive stress field. The interaction of lithospheric plates along the continental margin appears to provide a reasonable mechanism for generating the sequential compressive strain release observed in the valley.

Successive positions of the Mendocino transform, extrapolated backward in time to 4.0 m.y. at a rate of 5.5 cm/yr (Atwater and Molnar, 1973), are shown relative to the late Cenozoic structural domains in the Sacramento Valley in figure 24. Each domain is characterized by a particular set of late Cenozoic structural features that formed during a definite period of time. The time of deformation in the structural domains is linked to respective positions of the Mendocino transform by corresponding patterns on figure 24. Compressive deformation in the Sacramento domain occurred prior to eruption of the Nomlaki and Putah Tuff Members of the Tehama Formation about 3.4 m.y. ago, but we are unable to correlate movement on specific structures in that domain with relative plate motions shown by successive positions of the Mendocino transform. Beginning with magmatism and deformation in the Sutter Buttes domain about 2.4 m.y. ago, however, reasonable correlation exists between the position of the Mendocino transform and progressive east-west compressive deformation in the Sacramento Valley. This correlation clearly reflects the availability of geologic information that dates deformation in the northern part of the valley, but it may also reflect a greater degree of tectonism in the valley over the past 2.4 m.y. that was related to increased tectonism ahead of the advancing Mendocino triple junction (fig. 24).

According to Silver (1971), an episode of major bending and fracturing occurred in the Juan de Fuca plate (fig. 24) between 2.5 and 0.5 m.y. ago. This deformation apparently increased the north-south compressive stress ahead of the advancing Mendocino triple junction and caused underthrusting of oceanic crust in the Juan de Fuca plate beneath the Mendocino transform. Dickinson and Snyder (1979a) suggested that this type of instability at the Mendocino triple junction would increase the east-west extensional stress in the vicinity of the triple junction and possibly cause eastward migration of right-slip strain release along the San Andreas fault zone. Internal deformation of the Juan de Fuca plate also may have changed the rate and relative motion of the subducted part of that plate relative to the North American plate sufficiently to initiate magmatism at Sutter Buttes and at the Pliocene volcanic centers of Mount Yana and Mount Maidu (fig. 24) (Lydon, 1968) about 2.4 m.y. ago. Subsequent relative movement of the North American plate southwestward from its position above the subducted Juan de Fuca slab, over the eastern projection of the Mendocino transform and onto the area of the slab window of Dickinson and Snyder (1979b), may have initiated progressive deformation in the Sacramento Valley north of the Sutter Buttes domain.

According to Dickinson and Snyder (1979b), an expanding, triangular-shaped region, which they called the slab window, has developed east of the lengthening San Andreas transform since the rise-trench encounter about 20 m.y. ago. As the slab window expanded, upwelling asthenosphere came into contact with the base of the North American crust producing an expanding region of Neogene extensional tectonism. The northern boundary of the slab window, which is the eastern projection of the Mendocino transform, migrated northward as a consequence of the northward migration of the Mendocino triple junction and relative motion between the North American and Juan de Fuca plates. Successive positions of the northern boundary of the slab window beneath the Sacramento Valley for the past 2.5 m.y. are shown in figure 25.

About 2.5 m.y. ago, the northern boundary of the slab window was located approximately at the latitude of Sutter Buttes (fig. 25*A*). As the North American plate moved southwestward relative to the Juan de Fuca plate, the base of the valley crust near Sutter Buttes moved off the subducted ocean crust of the Juan de Fuca plate and encountered asthenophere in the slab window. This change in thermal regimes at the base of the valley crust possibly reactivated the Willows fault and the ancient tectonic boundary between ophiolitic basement rocks and the Sierran basement rocks, allowing magma to rise and differentiate below Sutter Buttes and the buried Colusa dome. Subsequent southwestward relative movement of the North American plate exposed an increasing area of the Sacramento Valley and northern Sierra Nevada crustal blocks to the higher thermal regime of the slab window. Basaltic volcanism erupted in the Tahoe-Almanor graben (fig. 25*A*) north of Lake Tahoe soon after magmatism began at Sutter Buttes (Dalrymple, 1964). Ac-

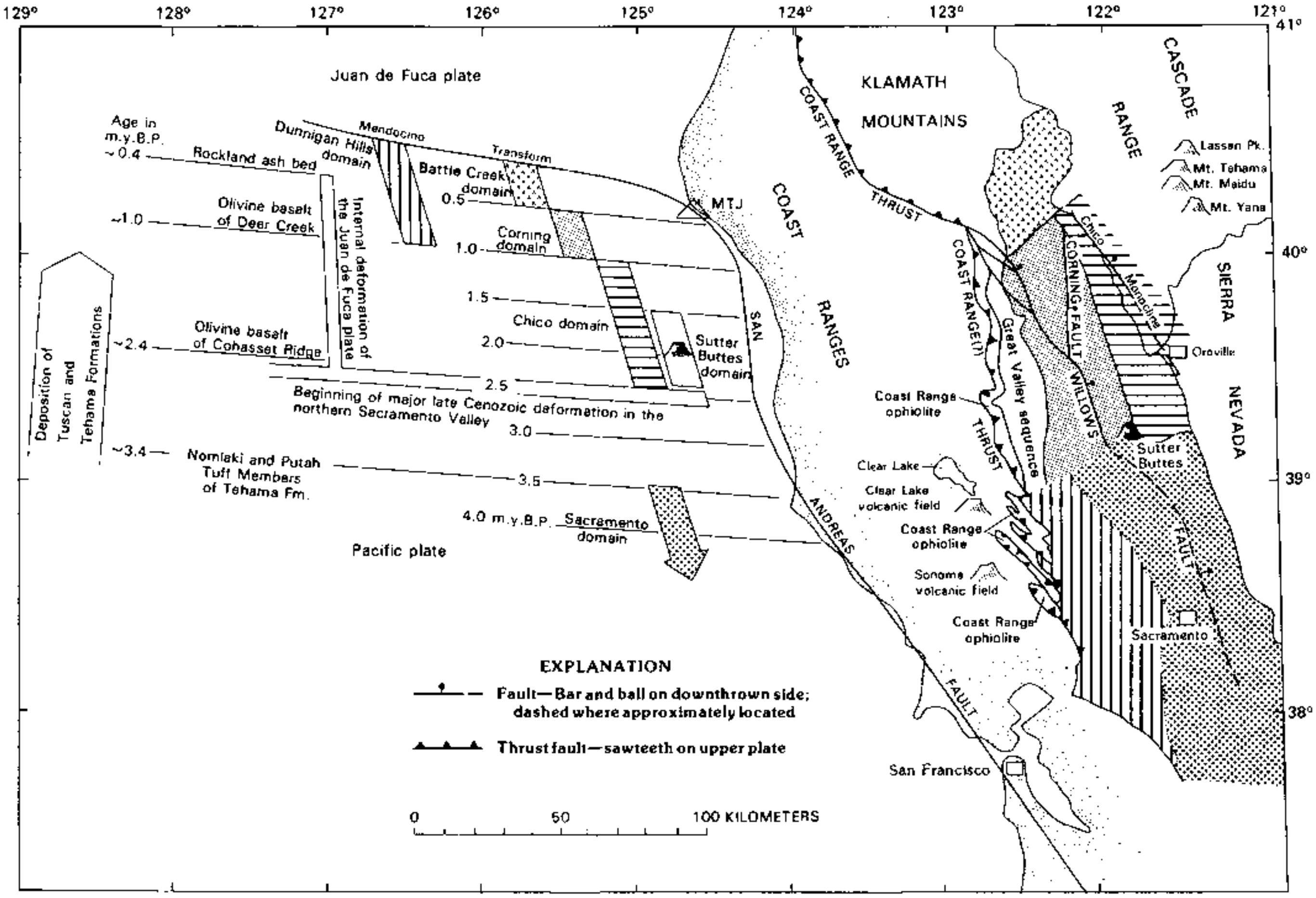


FIGURE 24.—Map of northwestern California relating late Cenozoic structural features and structural domains (patterned) to inferred position of the Mendocino triple junction (MTJ) during time structures formed. Position of Mendocino transform shown in 0.5-m.y. increments during past 4.0 m.y. Dated volcanic units used to bracket age of deformation in Sacramento Valley shown at left.

celerated uplift of the Sierra Nevada, which began about 3.0 m.y. ago in the central part of the range (Huber, 1981; Slemmons and others, 1979), eventually caused rupture between 2.5 and 1.0 m.y. ago along the Mesozoic fault that separates valley and Sierran blocks beneath the Chico monocline. Volcanism at Clear Lake (fig. 25), which began about 2.1 m.y. ago (Donnelly-Nolan and others, 1981), lagged behind passage of the northern boundary of the slab window and has continued nearly to the present.

Between 1.0 and 0.5 m.y. ago (fig. 25*B*), exposure of the base of the valley crust to the slab window may have reactivated the basement fault in the vicinity of the Corning domes, resulting in east-west compressional tectonism. Wrench tectonism and related east-west extension apparently started to affect the southwestern part of the valley after creating a zone of high shear strain in the Santa Rosa block (Fox, 1983), located in the eastern part of the Coast Ranges province. This is the earliest evidence of east-west extensional tectonism found in the valley and suggests a delay time of about 2.5 m.y. between passage of the slab-window boundary and production of recognizable extensional structures.

In the past 0.5 m.y., the northern boundary of the slab window has passed beneath about half of the Battle Creek domain (figs. 24, 25*C*). The morphology of the valley in the Battle Creek domain, therefore, may reflect recent,

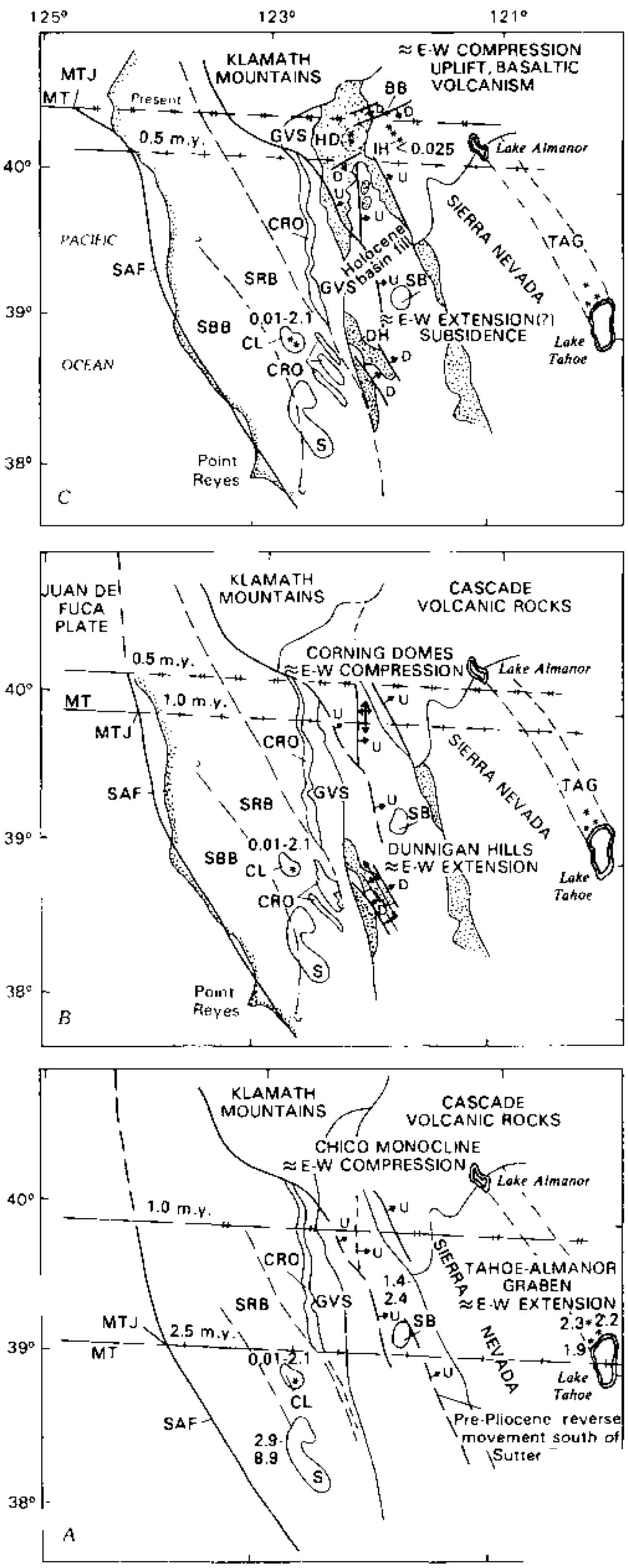


FIGURE 25.—Sketch maps of northwestern California showing inferred positions of northern boundary (barbed dashed lines) of slab window of Dickinson and Snyder (1979b) at about 2.5 and 1.0 m.y. (*A*), 1.0 and 0.5 m.y. (*B*) and 0.5 m.y. and present (*C*).

and possibly on-going, structural changes in the deeper parts of the valley fill and basement caused in part by changes in the thermal regime beneath the thick valley crust. This hypothesis was investigated by Helley and Jaworowski (1983), who used the distribution of the Red Bluff pediment as a surface indicator of deeper valley structures. The elevation of the floor rises abruptly north of Red Bluff, and the dissected uplands expose the Pliocene Tehama Formation that is unconformably capped by remnants of the Red Bluff Formation. Drainage patterns reflect local structures, such as Hooker dome (fig. 18), and major creeks locally follow the dominant northeast structural trends. The gradient of the Sacramento River steepens significantly across the Battle Creek domain, and its incised meanders are structurally controlled. Many of these geomorphic features are preserved, in somewhat more subdued form, around Corning domes and elsewhere in the valley south of Red Bluff (Helley and Jaworowski, 1985).

The northeast-trending Inks Creek fold system and the folding associated with the Battle Creek and Red Bluff faults suggest a northwest-southeast compressive stress system. If such is the case, however, normal displacement on the Bear Creek, Battle Creek, and Red Bluff faults are anomalous. The structural features in the Battle Creek domain may reflect a stress regime in which the maximum horizontal compressive stress (east-west) and the least horizontal compressive stress (north-south) vectors are more nearly equal. This inferred change in the stress pattern may be caused by oblique subduction of the Juan de Fuca plate and the possible buttressing effect of the Klamath Mountains on deformation in the northernmost part of the Sacramento Valley.

CONCLUSIONS

Kinematic patterns of late Cenozoic structural features in the Sacramento Valley differ significantly from those in the Coast Ranges province to the west and the northern Basin and Range province to the east. Certainly for the past 2.5 m.y., and probably much longer, deformation in the valley has occurred in a regional stress field in which the maximum horizontal component of compressive stress was oriented approximately east-west and the minimum component of compressive stress (maximum extension) was oriented approximately north-south. Within this stress regime, strain has been released primarily by reverse movement on north- and northwest-trending high-angle faults and associated folding in the sedimentary rocks of the valley fill. This style of deformation contrasts sharply with the pattern of northwest-trending en echelon folds and pull-apart basins, and east-west oriented thrust faults associated with large-scale right-lateral displacements on the San Andreas fault system (Blake and others, 1978; Graham, 1978; Harding, 1976; McLaughlin, 1981; Page, 1981) and the pattern of pervasive normal faulting, widespread volcanism, and large-scale east-west extension in the Basin and Range province (Christiansen and Lipman, 1972; Lipman and others, 1972; Zoback and others, 1981). During the late Cenozoic, the Sacramento Valley appears to have acted as an independent block on which relatively small-scale compressive deformation was imposed by eastward-directed subduction that was followed by large-scale transform tectonism along the continental margin and major east-west crustal extension in the Basin and Range. Early Tertiary deformation on the Willows fault and in the area of Capay Valley may be related to eastward tectonic wedging of the Franciscan Complex described by Wentworth and others (1984).

Tectonic heredity appears to have played a significant role in late Cenozoic deformation in the Sacramento Valley. Many of the faults that break or drape the upper Cenozoic deposits are located over pre-existing structures within and at the boundaries of basement blocks that were tectonically juxtaposed and broken during the Mesozoic and early Tertiary. The tectonic boundary between ophiolitic and Sierran basement rocks apparently has been reactivated beneath the Chico monocline and the possible southeast extension of the Willows fault. The Corning fault occurs over a Mesozoic fault within the ophiolitic basement terrane.

Within the past 2.5 m.y., at least, late Cenozoic east-west compressive deformation has progressed northward so that structures observed in the Battle Creek domain are a million years younger than those around Sutter Buttes. The northward progress of late Cenozoic deformation correlates with extrapolated positions of the Mendocino transform. Deformation may have been initiated by thermal changes in the valley basement as the North American plate moved relatively southwestward off the subducted oceanic crust of the Juan de Fuca plate and over asthenosphere in the slab window proposed by Dickinson and Snyder (1979b). During this sequential deformation, the relative magnitude of the horizontal compressive stress vectors appears to have changed. The kinematic pattern of structures south of Red Bluff suggests that east-west compression was dominant ($S_{\mathrm{maxEW}} >> S_{\mathrm{minNS}}$) and resulted in high-angle reverse faulting. However, the horizontal compressive stresses appear to have been more nearly equal ($S_{\mathrm{maxEW}} \cong S_{\mathrm{minNS}}$) in the Battle Creek domain causing northeast-trending folds and normal displacements on east-northeast-trending faults.

Northwest-trending folds and normal displacement on the Zamora fault suggest that east-west extension may have affected the southwestern part of the valley during the past million years, when east-west compressive deformation was occurring in the Corning domain. Focal-plane solutions constrained by geologic data in the Clear

Lake area indicate that the maximum compressive stress in the Coast Ranges is presently oriented approximately north-south (Bufe and others, 1981). These data, coupled with the observation that right-lateral tectonism is more intense in the Coast Ranges adjacent to the Dunnigan Hills domain than it is to the west or north (Fox, 1983), suggest that late Cenozoic deformation in the Dunnigan Hills domain was related to wrench tectonism on the San Andreas fault system. If such is the case, the beginning of right-lateral wrench tectonism in the valley appears to have lagged behind the northward migration of the Mendocino triple junction by about 2.5 m.y. A similar delay was noted between the migration of the triple junction and the build-up of maximum heat flow in the Coast Ranges by Lachenbruch and Sass (1980).

The well-dated and diverse deformation patterns in the Sacramento Valley indicate that late Cenozoic tectonism evolved through the region in response to major crustal movements outside the valley's physiographic boundaries. East-west compressive tectonism may have been imposed on the valley by eastward subduction of the Juan de Fuca plate, and consequent tectonic wedging of the Franciscan Complex coupled with a major component of westward stress due to east-west extension in the Basin and Range province.

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APPENDIX—*Wells with electric well-log data shown in cross sections*

Well no.	Operator	Well name	Sec.-T.-R.
		Wells on figure 3	
1.	Texaco	Cross No. 1	27-20N.-3W.
2.	Franco Western Oil Co.	Dunlap 36-1	36-20N.-3W.
3.	Marathon Oil Co.	Capital Co. No. 1	30-20N.-2W.
4.	R. W. McBurney	Westpet Sunray McBurney Capitol No. 1	30-20N.-2W.
5.	Mobil Oil Corp.	Capital Co. No. 30-1	30-20N.-2W.
6.	Mobil Oil Corp.	Section 29 Unit No. 4	29-20N.-2W.
7.	R. W. McBurney	Section 29 Unit No. 2	29-20N.-2W.
8.	Mobil Oil Corp.	Section 48 Unit No. 4	21-20N.-2W.
9.	Mobil Oil Corp.	Section 48 Unit No. 1	21-20N.-2W.
10.	Standard Oil Co.	Doheny N. G. Unit No. 1	22-20N.-2W.
11.	Mobil Oil Corp.	Section 46 Unit No. 2	27-20N.-2W.
12.	Bettie A. McBurney	Reserve McBurney Unit 51 No. 1	26-20N.-2W.
13.	Bettie A. McBurney	Section 52 Unit No. 3	25-20N.-2W.
14.	Neaves Pet. Devel. Co.	Neaves Capital 53-1	32-20N.-1W.
15.	Mobil Oil Corp.	Dano Seco No. 1	33-20N.-1W.
16.	Calif. Time Pet. Inc.	Butte Dano Seco No. 4	34-20N.-1W.
		Wells on figure 7	
1.	Occidental	Zumwalt K-2	12-13N.-1E.
2.	Shell	Strat. test well	31-14N.-2E.
3.	G. E. Kadane & Sons	Lamb No. 1	30-14N.-2E.
4.	Atlantic	AMKH et al	28-14N.-2E.
5.	Atlantic	Continental Stent No. 1	15-14N.-2E.
6.	Kenneth L. Sperry	Shannon No. 1	10-14N.-2E.
7.	Exxon	Shannon No. 1	14-14N.-2E.
8.	Pearson Sibert	Tom No. 1	5-14N.-3E.
		Wells on figure 8	
1.	Sun Oil Co.	SMC Cameron Dougherty No. 1	31-12N.-3E.
2.	McCulloch Oil & Gas Corp.	McCulloch-Magoon et al. No. 1	32-12N.-3E.
3.	Davis Oil Co.	Aileen Marty No. 1	35-12N.-3E.
4.	Davis Oil Co.	Van Dyke No. 1	35-12N.-3E.
5.	Decalta Int. Corp.	Osterli No. 3	31-12N.-4E.
6.	Sun Oil Co.	Lenert No. 55-29	29-12N.-4E.
7.	Kenneth L. Sperry	Davis No. 1	21-12N.-4E.
8.	Plateau Oil & Gas Co.	Van Dyke No. 1	24-12N.-4E.
9.	Exxon	Bonnefeld No. 1	10-12N.-5E.
		Wells on figure 9	
1.	Rocky Mtn. Drilling Co.	Murdoch No. 1	27-7N.-4E.
2.	McCulloch Oil & Gas Corp.	Scribner No. 1	27-7N.-4E.
3.	Chevron	Correa No. 1	24-7N.-4E
4.	Neaves Pet. Devel. Co.	Neaves-Standard Oil Sims No. 3	18-7N.-5E.
5.	Chevron	Sims Comm. No. 2	18-7N.-5E.
6.	Calif. Expln. Co.	Sacramento Unit A	16-7N.-5E.
7.	Union Oil Co. of Calif.	Union Dow Attorney General No. 1	13-7N.-5E.
8.	Intex Oil Co.	Unit plan No. 1	19-7N.-6E.
9.	D. D. Feldman	Unit plan No. 1	8-7N.-6E.
10.	Norris Oil Co.	Waegell No. 1	6-7N.-7E.
		Wells on figure 10	
1.	Shell Oil Co.	Shell-Brevelli No. 1	4-4N.-6E.
2.	Amerada Hess Corp.	Comm. 1-2	2-4N.-6E.
3.	Amerada Hess Corp.	Comm. 1-1	1-4N.-6E.
4.	Aminoil USA, Inc.	Comm. 2-1	12-4N.-6E.
5.	Union Oil Co. of Calif.	V-B-G No. 1	7-4N.-7E.
6.	Amerada Hess Corp.	Lodi Comm. 8-1	8-4N.-7E.
7.	Amerada Hess Corp.	Lodi Comm. 9-1	9-4N.-7E.
8.	Shell Oil Co.	Ferrera No. 1-10	10-4N.-7E.
9.	Ben Owens Drilling Co.	Thompson No. 1	11-4N.-7E.
		Wells on figure 14	
1.	Solar Drilling Co.	Solar-McElroy-Crawford No. 1	5-23N.-1W.
2.	Pacific Western	Cana No. 1	11-23N.-1W.
3.	Exxon	C. U. Roney No. 1	1-23N.-1W.
4.	Exxon	C. C. Baccala No. 1	28-24N.-1E.
		Wells on figure 20	
1.	Neaves Pet. Devel. Co.	Neaves-Cobb No. 1	11-10N.-3W.
2.	Empire Oil and Gas Co.	Porterfield No. 1	18-10N.-2W.
3.	Texaco, Inc.	Esparto c.h. No. 2	17-10N.-2W.
4.	Dow Chemical Co.	Duncan No. 1	9-10N.-2W.
5.	Gulf Oil Corp.	A. B. Stevens No. 1	7-10N.-1W.
6.	Atlantic Oil Co.	Irrigated Valley Land No. 1	4-10N.-1W.
7.	A. A. Hopkins, Jr.	Manler No. 62-3	3-10N.-1W.
8.	C. K. M. Oil Co.	Mast No. 1	35-11N.-1W.
9.	Gulf Oil Corp.	L. M. Bemmerley No. 1	36-11N.-1W.
10.	E. B. Towne	Slaven No. 1	30-11N.-1W.
11.	Arco	Reiff No. 1	29-11N.-1W.
12.	Arco	Hermle No. 1	15-11N.-1E.

GEOCHEMISTRY OF GROUND WATER IN THE SACRAMENTO VALLEY, CALIFORNIA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1401–B

Geochemistry of Ground Water in the Sacramento Valley, California

By LAURENCE C. HULL

CENTRAL VALLEY OF CALIFORNIA RASA PROJECT

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CONVERSION FACTORS

Factors for converting inch-pound units to the International System (SI) of units are given below:

Multiply	*By*	*To obtain*
acres	0.004047	km^2 (square kilometers)
acre-ft (acre-feet)	0.001233	hm^3 (cubic hectometers)
ft (feet)	0.3048	m (meters)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

Degrees Fahrenheit are converted to degrees Celsius by using the formula: °C=(°F-32)/1.8

Additional abbreviations:

µg/L	(micrograms per liter)
mm	(millimeters)
mg/L	(milligrams per liter)
(mg/L)/yr	(milligrams per liter per year)

National Geodetic Vertical Datum of 1929 (NGVD of 1929). A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is sometimes referred to as sea level in this report.

GEOCHEMISTRY OF GROUND WATER IN THE SACRAMENTO VALLEY, CALIFORNIA

By LAURENCE C. HULL

ABSTRACT

A geochemical investigation was done to evaluate temporal changes in water quality and to determine the processes that control water chemistry in shallow ground water of the Sacramento Valley, California. A total of 671 chemical analyses from 651 wells were used to study the processes controlling water chemistry. Temporal variations in dissolved-solids and nitrate concentrations were studied in 140 and 62 wells, respectively, having multiple observations with time.

The Sacramento Valley can be divided into six hydrochemical facies having distinctive chemical compositions. Waters from the Tuscan volcanic rocks and Victor Plain facies, along the eastern margin, have lower concentrations of dissolved solids and higher concentrations of silica than the waters from other areas of the Sacramento Valley. Ground waters in the basin hydrochemical facies (Butte Basin and Sutter Basin) along the valley axis are higher in iron, manganese, arsenic, and potassium. West side facies, the north alluvial fans and south alluvial fans, are low in silica. The south alluvial fans facies is higher in dissolved solids and has very high boron concentrations.

Significant increases have occurred in dissolved-solids and nitrate concentrations since the mid-1950's. Dissolved solids increased in five of the six hydrochemical facies, with rates ranging from 0.95 milligrams per liter per year in the Tuscan volcanic rocks facies to 4.75 milligrams per liter per year in the south alluvial fans facies. Nitrate-nitrogen did not significantly increase in the Tuscan volcanic rocks, Butte Basin, or Sutter Basin hydrochemical facies. Rates of increase of 0.036, 0.036, and 0.099 milligrams per liter per year occurred in the Victor Plain, south alluvial fans, and north alluvial fans, respectively.

Two processes control over 50 percent of the spatial variation in ground-water chemistry. Thirty-six percent of the variation in the data is explained by the effects of recharge water chemistry on the chemistry of ground water. Low dissolved solids and high silica from east-side recharge produces fairly uniform conditions in east-side ground waters. Recharge from the northwest is intermediate in dissolved solids and silica. Southwest recharge is high in dissolved solids, boron, and fluoride. High boron concentrations in the ground water originate in thermal springs in the Coast Ranges. A second important process consists of reactions occurring in the fine-grained sediments of the flood basin in the central part of the Sacramento Valley. Reducing conditions here produce higher concentrations of manganese, iron, and arsenic. Nitrate concentrations are low, probably reflecting denitrification reactions.

Precipitation and dissolution of aluminosilicates appear to control the relation between silica and aluminum in parts of the valley. Silica and aluminum in ground waters of the Sutter Basin hydrochemical facies show parallel behavior and have a ratio of 3 to 1. In the Tuscan volcanic rocks facies silica and aluminum are inversely related and are controlled by the solubility of halloysite. The clay minerals halloysite and illite were identified in the sediments. The clay mineral predicted to be the most stable in equilibrium with valley ground water is montmorillonite. Halloysite represents an intermediate step in the weathering of primary minerals to more stable secondary phases.

INTRODUCTION

GEOGRAPHY

The Sacramento Valley comprises the northern third of the Central Valley of California in the north-central part of the State (fig. 1). It is a sedimentary basin bounded by mountains to the east (Sierra Nevada), northeast (Cascade Range), and west (Coast Ranges). To the south, the valley merges with the delta of the Sacramento and San Joaquin Rivers. The area lies between 38°30′ and 40°15′ N. latitude, and 121°15′ and 122°30′ W. longitude. The valley covers about 4,400 square miles, is 150 miles in length from Red Bluff to the delta, and ranges in width from about 8 miles at Red Bluff to about 50 miles near the southern end. The topography consists of generally flat plains, with low dissected hills near the margins. The elevation of the valley at the southern end is near sea level, increasing northward and reaching 300 feet above sea level near Red Bluff. The relatively flat topography of the valley is interrupted near the center, where a volcanic neck of late Tertiary age, Sutter Buttes, rises 2,100 feet above the valley floor.

The Sacramento River enters the valley from the north and flows along the entire length of the valley before entering the delta region to the south. The Feather River is the only other principal stream that flows through the valley. The Sacramento and Feather Rivers are fed by tributaries draining the surrounding mountain areas. From the Sierra Nevada come the American, Bear, Yuba, and Feather Rivers. The Cascade Range is drained primarily by Big Chico, Butte, Mill, and Deer Creeks in the area adjacent to the Sacramento Valley. The streams entering the valley from the west rise in the Coast Ranges and are much smaller than the streams from the east. Thomes, Stony, Cache, and Putah Creeks are the only sizable streams entering

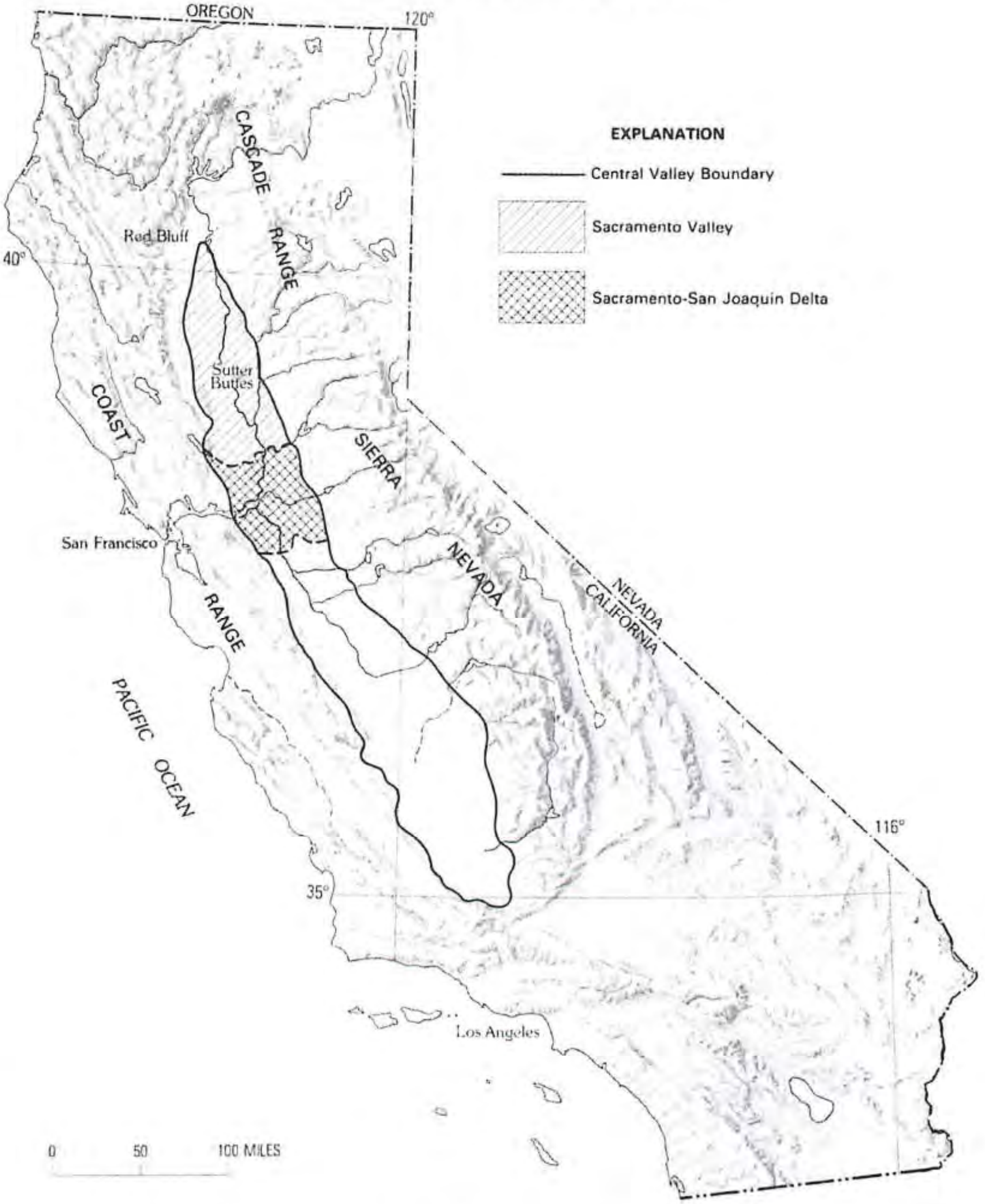

FIGURE 1.—Location map showing Sacramento Valley of California.

the west side of the valley. (See pl. 1*B* for stream locations.)

Little precipitation falls in the valley during the summer growing season, and irrigation is necessary to support extensive agricultural development. Early irrigated farming began in the mid-1800's as the gold miners moving to California created a demand for foodstuffs. Development of irrigation was slow, however, until the drought of 1864 stimulated the construction of new irrigation projects. During both world wars, heavy demand for agricultural products spurred periods of rapid development. Ground water has always lagged behind surface water as a source of irrigation water, amounting to only about 10 percent of the total use in the late 1910's. Since the late 1950's, however, the use of ground water has been increasing, and in 1970, it accounted for about 40 percent of all irrigation water used in the Sacramento Valley.

PURPOSE AND SCOPE

The U.S. Geological Survey began a series of hydrologic investigations—the regional aquifer systems analysis (RASA) program—to aid effective management of the Nation's ground-water resources by providing information on the hydrology and geochemistry of regional aquifer systems (Bennett, 1979). The Central Valley aquifer project, covering the Central Valley of California, is one of 29 such projects throughout the country and was started because of the long history of ground-water development and the importance of the area's agricultural production to the national economy (Bertoldi, 1979). Specific water-quality information needed for effective management in the future includes (1) the general inorganic chemical character of water from aquifers currently in use, (2) delineation of areas where degradation is occurring and where degradation may occur in the future, (3) the changes that have occurred in ground-water quality with time, and (4) the processes that control ground-water chemistry. This report evaluates temporal changes and geochemical processes as they influence the chemical quality of shallow ground water in the Sacramento Valley, the northern third of California's Central Valley. A companion report (Fogelman, 1983) deals with spatial variations in the chemical character of ground water and the delineation of areas of potential water-quality problems for this same study region.

DATA COMPILATION

Collection of additional water-quality samples was unnecessary because of the extensive data base of the U.S. Geological Survey and California Department of Water Resources. Chemical analyses from 653 wells throughout the Sacramento Valley sampled by the Geological Survey between 1974 and 1976 were already in the Survey's water-quality file (Fogelman, 1975, 1976; Fogelman and Rockwell, 1977). From the unpublished files of the California Department of Water Resources, an additional 2,136 analyses from 281 wells were added to the water-quality file. During the summer of 1979, 63 additional samples were collected by the Geological Survey in Yolo County to extend coverage into an area where high boron concentrations suggested a need for water-quality evaluation. All wells from which chemical analyses were used in this study have driller's logs on file with the California Department of Water Resources. Thus, reasonably reliable information is available about depths and perforated intervals for these wells. Some of the samples represented multiple observations over time from single wells, and these were used for the temporal studies. Samples for the period 1974–79 were examined, and complete analyses with less than 5 percent error in the electrical balance between cations and anions were used to study the spatial variation in the valley. These latter data consisted of 671 analyses from 651 wells.

Manipulation of data files and the statistical analyses used in this report were accomplished using the Statistical Analysis System (SAS)[1] programs on the U.S. Geological Survey's Reston computer system.

WELL-NUMBERING SYSTEM

Wells are identified according to their location in the rectangular system used for the subdivision of public lands. The identification consists of the township number, north or south; the range number, east or west; and the section number. A section is further divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with A in the northeast corner of the section and progressing in a sinusoidal manner to R in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian relative to which the townships and ranges are numbered. For the Sacramento Valley, this is the Mount Diablo base line and meridian (M). Figure 2 shows how the well number 11N/02E–23N01M is derived.

ACKNOWLEDGMENTS

The California Department of Water Resources has cooperated with the U.S. Geological Survey in past studies during which much of the data analyzed in this report were collected. The Department also provided additional unpublished chemical-quality data from their files. The author would like to thank J. R. Slack of the Geological Survey for his helpful suggestions on trend analysis. The cooperation of the residents of the Central Valley who have permitted the Geological Survey to collect water samples from their wells is also appreciated.

DESCRIPTION OF THE STUDY AREA

GEOLOGY AND GEOMORPHOLOGY

The Geology and geomorphology of the Sacramento Valley have been covered in detail by Olmsted and Davis (1961), the California Division of Mines and Geol-

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[1] Use of trade names does not imply endorsement and is used for information only.

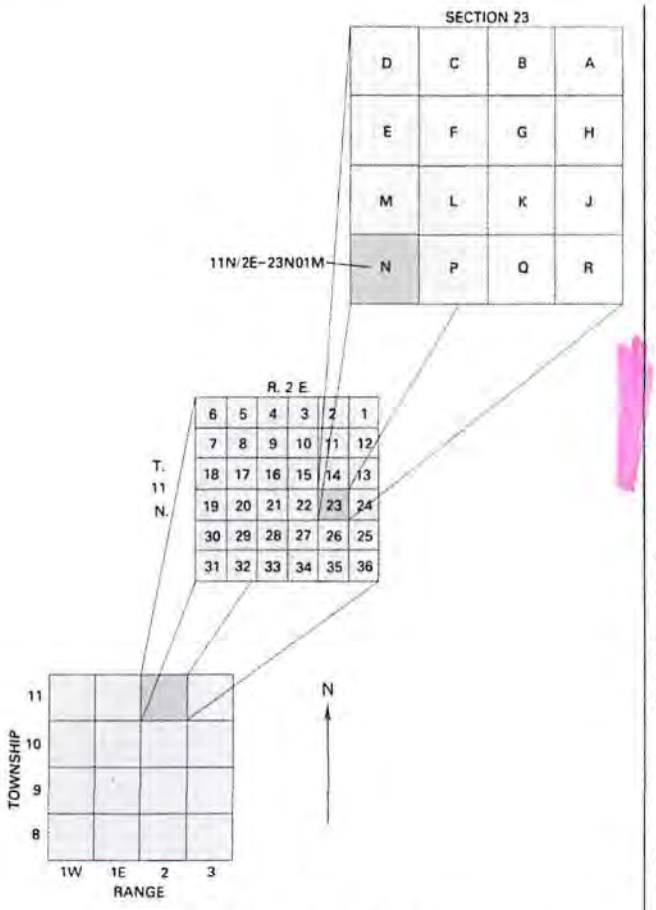

FIGURE 2.—Well-numbering system.

ogy (1966), and the California Department of Water Resources (1978a). Detailed maps and complete descriptions of the geology can be found in these publications. In this section, the geology and geomorphology are only briefly reviewed, with particular attention given to water-bearing characteristics and importance for water quality.

GEOLOGIC SYNOPSIS

The Sacramento Valley is an elongated structural trough trending to the northwest through central California. The trough is filled with a thick accumulation of sediments, perhaps as much as 50,000 feet in the deepest parts. Deposition has been occurring since early in the Cretaceous Period, with the bulk of the deposition occurring in a marine environment. A maximum of only 3,000 feet of continental deposits has been laid down as a veneer over the marine sediments. During early Tertiary time, the Cretaceous sediments west of the valley were folded and uplifted, forming the Coast Ranges and isolating the Sacramento Valley from the ocean to the west.

Early- and middle-Tertiary sedimentation was primarily confined to the southern and eastern parts of the valley, with only those sediments adjacent to the Sierra Nevada being continental deposits. During late Tertiary time, continental deposits were laid down throughout the valley, and deposition continued into Quaternary time. These continental deposits include the Tehama, Tuscan, Laguna, and Mehrten Formations and form some of the most important aquifers in the valley. Also, near the end of the Tertiary Period, andesitic lava was extruded through the older marine sediments to form Sutter Buttes, a prominent volcanic neck in the middle of the Sacramento Valley.

During Pleistocene time, continental deposition continued throughout the valley. Alluvial fans and plains developed from sediments eroded from the Sierra Nevada to the east and the Coast Ranges to the west. Continued action of rivers flowing through the valley produced alluvial channel deposits and natural levees along the axis of the valley and produced flood basins adjacent to the rivers.

GEOMORPHIC UNITS

The Sacramento Valley is generally characterized by alluvial plains and fans bounded by rugged mountains. The geomorphic units described by Olmsted and Davis (1961) are (1) Sierra Nevada, (2) Coast Ranges, (3) Cascade Range, (4) low hills and dissected uplands, (5) alluvial plains and fans, (6) flood basins, (7) stream channels and natural levees, and (8) Sutter Buttes. In this section, the location and extent of the geomorphic units are described, and the geologic formations composing each unit discussed. Attention will be given to the lithology, mineralogy, and water-bearing characteristics of the geologic units where information is avaliable. The location of the geomorphic units are illustrated on plate 1A.

(1) *Sierra Nevada.* The Sacramento Valley is bounded on the east by the mountainous Sierra Nevada, a massive block of the Earth's crust that has been uplifted and tilted westward. The block extends under the sediments of the valley and underlies the eastern part at depth. The Sierra Nevada is composed of intrusive igneous rocks, metamorphosed volcanic rocks, and Paleozoic sedimentary rocks. The intrusive rocks are mainly granodiorite and quartz diorite with andesitic and rhyolitic extrusive rocks. In addition to the feldspars, quartz, and biotite of the igneous rocks, a wide variety of other minerals is present. These include cal-

cite, magnesite, barite, serpentine, metal sulfides, and others. The massive rocks of the Sierra Nevada contain little water, with the little that is available occurring in joints and fractures. The water quality of streams draining the Sierra Nevada is generally very good.

(2) *Coast Ranges*. The Coast Ranges, adjacent to the west of the valley, consist of Cretaceous marine sedimentary rocks folded and uplifted into ridges trending northwest-southeast, parallel to the valley. The Cretaceous rocks dip eastward and underlie much of the Sacramento Valley at depth. Also present in the Coast Ranges is the Franciscan Complex, which consists of highly metamorphosed marine sedimentary rocks of late Mesozoic age. The major rock type is this geologic unit is greywacke, interbedded with shales and minor limestone units. The primary minerals of the sedimentary rocks are plagioclase and quartz. Many lithic fragments present contain chert, chlorite, and mica. Ultramafic minerals have been metamorphosed to serpentine and magnesite. The marine sedimentary rocks are mostly consolidated and contain little water. Some units retain connate saline water, and streams draining the Coast Ranges may be contaminated by saline springs.

(3) *Cascade Range*. Between Oroville and Red Bluff, the northeastern part of the Sacramento Valley is bounded by the Cascade Range geomorphic unit. Adjacent to the valley, this unit is composed of the gently southwestward dipping Tuscan Formation of Pliocene age. On the surface, the Tuscan Formation is extensively eroded, and southwestward flowing streams have incised deep canyons. Beneath the valley, the Tuscan extends westward under younger valley sediments as far as the Sacramento River, and there the Tuscan interfingers with the Tehama Formation. The Tuscan is composed of volcanic breccia, coarse- to fine-grained tuffs, and volcanic sands, all of primarily andesitic composition. The most abundant mineral in the black sands found in wells drilled into this unit is plagioclase, and accessory quartz and pyroxenes. Volcanic glass is also abundant from the mudflow and tuff deposits. The Tuscan is an important aquifer in the northeastern part of the valley, and it contains fresh water at all depths.

(4a) *Low hills and dissected uplands, east side*. The dissected alluvial uplands leading up to the Sierra Nevada on the east side of the valley are composed of Tertiary and lower Quaternary sediments. This gently rolling terrain merges with the foothills of the Sierra Nevada to the east and the low alluvial plains to the west. The oldest rocks here are of the Eocene Ione Formation, overlain by the Oligocene, Miocene, and Pliocene volcanic deposits of the Valley Springs and Mehrten Formations. These units extend westward to the trough of the valley, but they are generally too deep to be tapped as aquifers except in the foothills area. Overlying the volcanic sediments are upper Tertiary and Quarternary continental deposits eroded from the Sierra Nevada. The older Tertiary volcanic sediments are composites of volcanic sands, ash and mudflows, and tuff layers of rhyolitic and andesitic composition. Particular minerals noted in these units include biotite, hornblende, orthoclase, plagioclase, and quartz. The Ione Formation contains kaolinitic clay layers. The younger deposits, the Laguna Formation and Fair Oaks Formation of Shlemon (1967), are sand, gravel, and silt deposits intercalated by clay layers. The Quaternary deposits are poorly sorted, and wells finished in these units produce only moderate quantities of water.

(4b) *Low hills and dissected uplands, northeast*. The low hills on the northeast margin of the valley consist of reworked sediments eroded from the underlying Tuscan Formation. The hills show the characteristic form of alluvial fans but are deeply trenched by the streams draining the Cascade Range. These fanglomerate deposits, as they are called, are mainly cemented sands, gravels, and silts, and have a mineral composition similar to that of the Tuscan Formation from which they are derived. The fanglomerate is also an important source of water in this area.

(4c) *Low hills and dissected uplands, west side*. The low hills on the west side of the valley are composed of the Tehama Formation of Pliocene age. These deposits extend from Red Bluff on the north almost as far south as Fairfield. The Tehama is made up of poorly sorted fluviatile sediments, primarily beds of sandy silt and silty clay with some lenses of crossbedded sands and gravels. Many of the coarser layers are cemented by calcium carbonate that reduces their permeability. The Tehama extends eastward to about the middle of the valley and is generally within 150 to 200 feet of land surface. Tectonic activity since deposition has folded the Tehama into a number of structures such as the Dunnigan Hills, Corning Ridge, and Plainfield Ridge along the valley margin. Sediments originated in the Coast Ranges and are rich in plagioclase and magnesium silicates, such as chlorite and serpentine. The Tehama is an important potential aquifer, although currently most water is the area is being pumped from more permeable alluvial fan deposits nearer the surface.

(5a) *Alluvial plains and fans, east side*. The alluvial plain on the east side of the valley is referred to as the Victor Plain by Olmsted and Davis (1961). The Victor Formation[2] of Olmsted and Davis (1961), which

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[2] Recent work of Marchand and Allwardt (1981, p. 207) virtually eliminates the use of the Victor Formation for the northeastern part of the San Joaquin Valley. However, because no similar recent work has been done in the Sacramento Valley, the Victor Formation as defined and mapped by Olmsted and Davis (1961, p. 93) is used in this report.

ranges in thickness from 50 to 100 feet, covers the surface throughout the area and overlies the Laguna Formation, a Pleistocene continental deposit. The plain extends from the northern San Joaquin Valley to north of Chico, where it pinches out between the fanglomerate of the Cascade Range and the Sacramento River flood plain. The Victor Formation is composed of alluvial sediments carried down from the Sierra Nevada and contains numerous channel deposits. The sediments become generally finer grained towards the west with bluish- and greenish-gray clays indicating reducing deposition environments near the center of the valley. Opposite the Sierra Nevada, the material contains extensively weathered feldspars, quartz, mica, biotite, and layers of arkosic sandstones. Opposite the Cascade Range, the Victor Formation is composed of reworked volcanic detritus from the Tuscan Formation. Water is generally available throughout the Victor Formation, though many high-capacity irrigation wells also tap the underlying Laguna Formation.

(5b) *Alluvial plains and fans, west side.* The low alluvial fans on the west side of the valley have been laid down by streams draining the Coast Ranges. The fans are aggrading and have poorly developed soil horizons. The northernmost fan is that of Stony Creek, which extends from the valley margin to the Sacramento River. South of this fan, a series of small fans built up by ephemeral streams extends only a short distance away from the Coast Ranges. Cache Creek and Putah Creek, south of the Dunnigan Hills, also have developed rather large fans which coalesce to form Putah Plain. The lithology of these fans is varied but generally is coarse-grained and poorly sorted. The mineralogy reflects the source areas in the Coast Ranges. The alluvial fans are generally good aquifers, especially where old stream channel deposits are penetrated.

(6) *Flood basins.* Low areas adjacent to the Sacramento River were subject to frequent flooding before extensive construction of levees in modern times. In these basins, fine-grained sediments have settled out of flood waters to form poorly permeable deposits. Deposits between 50 and 170 feet thick of yellow clay, indicating oxidizing conditions, overlie blue clays reflecting reducing conditions at depth. Few wells are drilled in these areas, and the only water generally available is in tongues of sand and gravel from old channel deposits.

In Sutter Basin, ground water contains high chloride concentrations and is unsuitable for irrigation purposes. The origin of this high chloride water is thought to be from Cretaceous marine sedimentary rocks brought closer to the surface by faulting associated with the formation of Sutter Buttes.

(7) *Stream channels and natural levees.* Along the major rivers and streams throughout the valley, Holocene alluvial deposits form flood plains and natural levees. The levees slope gently away from the channels and merge into the surrounding flood basin deposits. The deposits are generally coarse grained and poorly sorted. The varied mineralogy reflects the many sources from which these sediments are derived. Wells drilled in these deposits are hydraulically connected to the adjacent rivers and can produce large quantities of water.

(8) *Sutter Buttes.* Sutter Buttes, a volcanic neck of late Tertiary age, rises abruptly 2,100 feet above the surrounding plains. The core of the buttes is andesite, surrounded by alluvial fans created from the erosion of the igneous rocks. The deposits are poorly sorted and contain tuff, volcanic breccia, and sands. Some Cretaceous marine sedimentary rocks exposed at the buttes were forced upwards by the rising lava. The volcanic rocks yield little water, but the adjoining alluvium produces moderate amounts.

HYDROGEOLOGY

The direction of ground-water movement can be determined from the configuration of the water table where ground water occurs in saturated sediments and is not confined. Ground-water movement is influenced by gravity, and so is downhill as determined by the altitude of the water table. Plate 1*B* is a map showing lines of equal altitude of the water table for the Sacramento Valley in the spring of 1975. Although extensive changes occurred in some areas during the drought of 1976 and 1977, the 1975 map reflects the general conditions throughout the valley as they existed when most of the water-quality samples were collected during the mid-1970's.

In the north part of the valley, ground waters flow to the south and away from the valley walls. The Sacramento River is a gaining stream north of Colusa and is a major ground-water discharge zone in the north part of the valley. Stony Creek alluvial fan is a particularly important area for recharge. South of Colusa, the Sacramento River becomes a losing stream, contributing water to the adjacent sediments. In the west-central part of the valley, between Colusa and Woodland, recharge from the west infiltrates the valley sediments and moves toward pumping depressions east of the Dunnigan Hills. In the east-central part of the valley, from Oroville to Marysville, the Feather, Yuba, and Bear Rivers recharge the ground water near the valley margin. Once on the valley floor, the Feather River becomes a gaining stream east of Sutter Buttes, but below Marysville it begins to lose water to pumping depressions to the east and west. A large pumping depression in the southeast draws water from the American and Sacramento Rivers in the vicinity of Sacramento. In the southwest, much ground-water recharge occurs in the Cache and Putah Creek alluvial fans. This water moves eastward toward pumping depressions near Woodland and Davis. Some recharge from Cache Creek flows around the end of the Dunnigan Hills to pumping depressions north of Woodland.

The water table in the Sacramento Valley is generally close to the surface, and in only a few places is it more than 80 feet below the surface. Depth to water in the flood basins and alluvium along the Sacramento and Feather Rivers ranges from 10 to 20 feet. This very shallow water table extends eastward to include much of the western part of the Victor Plain. In the alluvial fans along the west side of the valley, the depth to water is between 10 and 40 feet. Lowering of water levels in pumping depressions north of Woodland and south of Davis, however, has increased the depth to water in those places. Along the southeast margin of the valley, the depth to water increases from less than 10 feet, near the flood basins, to more than 80 feet in the foothills. In the fanglomerate of the Cascade Range around Chico, the depth to water is generally 10 to 40 feet.

The valley boundary illustrated on plate 1*B* is the approximate boundary of the principal alluvial aquifers currently used in the Sacramento Valley. There is no single definition of the Sacramento Valley, and different boundaries are drawn for different purposes. The boundary shown is approximately that used in a ground-water-flow model of the Sacramento Valley (California Department of Water Resources, 1978a, Appendix A). However, the definition of the Sacramento Valley ground-water basin by the State of California encompasses a much larger area. The boundary is a reference shape to show continuity among illustrations.

On the east side of the valley, the margin coincides with the contact between the alluvium of the low hills and dissected uplands geomorphic province, and the older rocks of the Sierra Nevada and Cascade Range provinces. On the west side, the division is at the contact between the younger alluvium of the alluvial fans and plains, and the older alluvium of the low hills and dissected uplands geomorphic province. This allows delineation of the Dunnigan Hills, and excludes a large, undeveloped and sparsely populated area to the northwest of the valley.

Some wells outside the principal alluvial aquifers were included in the data analysis, as the boundary of those aquifers is somewhat arbitrary. Because these wells lie in recharge zones, their characteristics are important to an understanding of ground-water chemistry in the rest of the valley, even though they are outside the area of the principal alluvial aquifers.

HYDROCHEMICAL FACIES

The concept of hydrochemical facies as described by Back (1966) is used to designate zones or areas in which ground waters share unique chemical characteristics. The differences between facies reflect different controls on water chemistry from the lithology and mineralogy of, flow patterns in, and sources of recharge to an aquifer. The prefix "hydro" is used as a modifier of "chemical" to emphasize the interdependence of chemistry and hydrology. The ground water in the Sacramento Valley shows a great diversity in chemical compositions. By dividing the valley into hydrochemical facies, the differences can be better related to differences in the sedimentary matrix holding the water and the sources of ground-water recharge.

CRITERIA AND PROCEDURE FOR DIVISION

While hydrochemical facies have commonly been defined in terms of water types (as determined by the predominance of ions in terms of equivalents per million; Back, 1966), the definition of hydrochemical facies can be based on any unique chemical signature. For the Sacramento Valley, this division was accomplished using differences in the concentrations of some of the dissolved chemical constituents.

An initial division of the valley was attempted by studying maps showing the geomorphic units, the water table, and the distribution of individual chemical constituents. Outlines of these areas were drawn up to the nearest quarter township, and a tentative hydrochemical facies was determined for each well. This initial division broke the valley into three areas extending northwest-southeast, parallel to the axes of the valley—along the west side, the east side, and in the central basins. Each of these areas was divided into a northern and southern part resulting in six tentative divisions.

After this initial division, these six areas were tested to determine if they could be successfully differentiated on the basis of their chemistries. Linear discriminant function analysis (Davis, 1973; Drake and Harmon, 1973) was used for this purpose. In linear discriminant function analysis, a linear combination of variables is used to distinguish between previously defined groups. After the function is defined, it can be used to classify new samples of unknown origin into one of the original groups.

To determine which chemical constituents would be the best to use in the discriminant analysis, the amount of variation in the major chemical species associated with the differences between hydrochemical facies was determined. The results of this analysis of variance are shown in table 1. The first five species in this table

TABLE 1.—*Variation in chemical constituents explained by variations between hydrochemical facies*

Constituent	Percent variation explained
Silica	62.7
Boron	48.5
Sodium	44.7
Bicarbonate	39.4
Nitrate	36.8
Chloride	30.1
Magnesium	27.2
Calcium	15.1
Sulfate	9.6

were picked for the analysis. Because chloride is closely associated with sodium in the valley, it was passed over and magnesium added to give a total of six chemical constituents to use in the discriminant analysis.

Of the 671 chemical analyses available, only 340 had measurements for all the species and could therefore be used in the analysis. Most of the reduction in sample size was due to the much smaller number (358) of silica analyses. However, because silica showed by far the greatest amount of variation between the tentative hydrochemical facies, it was decided to use silica at the cost of reducing the number of samples that could be classified using the discriminant function. Samples, which lack measurements of all six of the chemical species used, were subsequently classified on the basis of nearby wells.

About one-fifth of the eligible samples were used to define the discriminant functions for the six hydrochemical facies. Using these functions, the remaining eligible samples were classified using the chemistry, and this classification was compared to the prior classification from the map data. Misclassified observations were of two types. Type 1 misclassifications were scattered throughout other facies and showed no pattern nor were particularly close to the boundary between two areas.Type 2 misclassifications were clustered in an adjacent hydrochemical facies near the boundary. In the latter case, the boundaries were redrawn and the chemical analyses reclassified.

The discriminant functions were recalculated several times with adjustments in boundaries between each calculation. The final analysis showed that 76 percent of the samples could be correctly classified by hydrochemical unit using the six chemical species. Thirteen percent of the samples were misclassified into the adjacent northern or southern portion in the same part of the valley, indicating an association between west side, east side, and basin pairs. On the basis of the classification of wells in a quarter township, each quarter township was assigned to its final hydrochemical facies. Other wells missing some of the chemical species used for the classification were classified by their quarter township location.

The discriminant analysis showed that enough chemical variation existed among the six hydrochemical facies to consider them chemically distinct. The final boundaries of the hydrochemical facies are shown on plate 1*B*. On the east side of the valley, one of the facies lies opposite the Cascade Range, and one opposite the Sierra Nevada. The flood basins along the axis of the valley are divided into two more facies, one in Butte Basin and including Sutter Buttes, the second in the Colusa, Sutter, and American Basins. The final two hydrochemical facies are opposite the Coast Ranges and are divided north and south near Colusa. In the next section, the chemical characteristics of the six hydrochemical facies are presented and compared, and differences in chemistry are discussed.

DESCRIPTIONS OF HYDROCHEMICAL FACIES

Table 2 shows the geometric mean, minimum, and maximum of chemical concentrations for each of the hydrochemical facies. To determine if the average concentrations of chemical species in the hydrochemical facies are significantly different, the differences between geometric means were tested using a *t* test. The results of these comparisons are illustrated quantitatively in the same table.

TUSCAN VOLCANIC ROCKS

The Tuscan volcanic rocks hydrochemical facies is along the northeastern margin of the Sacramento Valley (pl. 1*B*) adjacent to the Cascade Range. The geologic formations in this area are the Tuscan Formation and more recent alluvial sediments derived from erosion of the Tuscan. Recharge is from the Cascade Range geomorphic province, and ground water is either discharged to the Sacramento River or moves into Butte Basin south of Chico. The Tuscan and its derivatives contain andesitic sands and extensive tuff deposits. Volcanic glass and plagioclase are abundant in these sediments.

The chemistry of ground water in the area reflects the low concentrations of dissolved solids carried by recharge from the Cascade Range, having low mean concentrations of magnesium, sodium, bicarbonate, sulfate, and chloride. Silica concentrations are high due to solution of volcanic glass, and the facies has the highest average nitrate-nitrogen concentration of the six. The maximum boron concentration is rather high, although the mean concentration is only moderate. Boron in excess of 1.0 mg/L occurs in only three wells, all to the east of the Sacramento River northeast of Red Bluff.

TABLE 2.—*Geometric mean, minimum, and maximum of chemical concentrations for each of the hydrochemical facies, Sacramento Valley*

[Figure above line refers to geometric mean; figures below line refer to minimum-maximum range. H, high; L, low; VH, very high; VL, very low. NOTE.—These comparisons are relative to the other hydrochemical facies and do not necessarily describe the absolute values. Labels were assigned only where the difference between two geometric means tested significant at the 95 percent level]

Chemical species	Tuscan volcanic rocks	Victor Plain	Butte Basin	Sutter Basin	North alluvial fans	South alluvial fans
Dissolved solids (mg/L)	L 231 137–571	L 220 137–1100	290 129–723	H 400 97–2040	280 108–1170	H 400 175–1420
Calcium (mg/L)	26 14–75	L 21 5.7–170	32 5.5–98	32 6.9–220	H 39 8.2–99	H 39 13–140
Magnesium (mg/L)	L 19 9.1–60	VL 12 3.6–120	24 5.0–93	24 2.2–160	24 7.6–70	H 33 3.5–140
Sodium (mg/L)	L 14 3.9–68	19 7.2–180	20 6.3–93	H 55 5.9–360	22 7.5–240	H 52 15–320
Potassium (mg/L)	1.3 0.3–5.9	1.3 0.4–4.5	H 1.9 0.6–5.0	H 1.7 0.3–5.4	L 0.8 0.4–2.1	1.2 0.2–7.0
Bicarbonate (mg/L)	L 170 98–400	VL 130 68–504	230 44–522	H 270 70–897	240 83–560	VH 310 130–1060
Sulfate (mg/L)	L 8.1 0.0–71	L 8.0 0.2–140	12 0.5–150	17 0.3–590	18 1.6–400	21 1.8–180
Chloride (mg/L)	VL 6.5 0.9–97	15 2.0–380	L 11 1.0–210	H 31 2.4–920	15 2.7–170	H 37 2.2–580
Fluoride (mg/L)	0.11 0.1–0.3	0.18 0.1–10.0	0.12 0.1–0.3	0.11 0.0–0.4	0.16 0.0–0.6	H 0.29 0.1–1.0
Nitrate - N (mg/L)	H 2.7 0.2–27	0.81 0–61	1.0 0–20	L 0.12 0–14	1.7 0.01–11	1.8 0–12
Phosphate - P (mg/L)	0.05 0.0–0.31	0.11 0.01–0.39	0.11 0.01–0.45	0.15 0.01–0.50	0.06 0.02–0.30	0.07 0.01–0.42
Silica (mg/L)	H 51 35–67	H 55 25–74	H 51 31–75	39 23–73	L 26 8.5–52	L 28 12–54
Iron (μg/L)	4.8 0–170	5.2 0–600	8.0 0–1900	H 11 0–520	9.7 0–280	8.0 0–180
Manganese (μg/L)	3.4 0–10	5.6 0–280	9.1 0–1700	H 75 0–2300	8.0 0–70	2.8 0–2000
Arsenic (μg/L)	1.2 0–4	2.2 0–20	H 5.5 0–50	H 5.8 0–100	1.7 0–6	2.3 0–31
Boron (mg/L)	0.066 0–1.50	L 0.023 0–0.60	L 0.034 0–0.37	H 0.140 0–1.10	0.068 0–0.58	VH 0.400 0–8.10

The source of the high boron water is Tuscan Spring, located along Salt Creek in Tehama County in section 32 of township 28 N., range 2 W. (Waring, 1965).

VICTOR PLAIN

The Victor Plain hydrochemical facies is along the east and southeast margin of the valley, and extends westward to near the Feather and Sacramento Rivers. Recharge is primarily from the Sierra Nevada to the east, although pumping depressions southeast of Marysville and north of Sacramento induce recharge from the rivers. North of Marysville, water is discharged into the Feather River or passed into Butte Basin. South of Marysville, most of the ground-water discharge seems to be by pumping. Along the valley margin, the aquifers are volcanic sands with associated tuffaceous deposits. In the central and western parts of this facies, the volcanic units dip under the Victor Formation composed of alluvium from the Sierra Nevada.

The Victor Plain facies has a low average dissolved-solids content reflecting recharge from the Sierra Nevada. Concentrations of calcium, magnesium, bicarbonate, boron, and sulfate are all low in this area. Silica is high, reflecting the volcanic material present in the sediments.

BUTTE BASIN

The Butte Basin hydrochemical facies roughly coincides with the Butte flood basin east of the Sacramento River. The basin extends from Chico on the north to Yuba City on the south and lies between the Feather and Sacramento Rivers. Sutter Buttes is included in this facies as too few chemical analyses were available from this area to justify a separate facies. The basin receives recharge from the Tuscan volcanic rocks facies and from Victor Plain to the east. A small amount of recharge also occurs in the vicinity of Sutter Buttes. Ground water leaves the Butte Basin facies to enter the Sacramento River and to enter the Sutter Basin facies east of Sutter Buttes. In the flood basins the sediments are fine grained and reducing.

Ground water in the Butte Basin facies has a somewhat higher average dissolved-solids concentration than the two eastern margin facies possibly reflecting longer subsurface residence times or a change in sediment lithology. Chloride and boron are the only two species that have low average concentrations in this facies. The high silica concentrations may be a result of recharge from the Tuscan volcanic rocks facies and from volcanic material around Sutter Buttes. High arsenic concentrations imply deposition in a reducing environment (Garrels and Christ, 1965). This facies has the highest average potassium concentration, which may reflect the longer residence times or a change in mineralogy of the sediments.

Information on the variation in water chemistry with depth was obtained from a U.S. Geological Survey test well drilled in section 32 of township 19 N., range 1 W. Three piezometer tubes were installed at different depths and isolated by cement packers. Data on the shallow water at the site are available from a previous study (Fogelman, 1976).

Analyses from the three piezometers and from the shallow water are shown in table 3. The percent composition of the major ionic species in terms of milliequivalents per liter are provided in figure 3. Between 80 and 595 feet, a decrease in magnesium is balanced by an increase in sodium, with calcium remaining about the same. There is a slight increase in the percent of chloride in the ground water over this same interval, but the net change in anion composition is very small. Below 595 feet, however, calcium and magnesium decrease, both in percent composition and concentration, and sodium increases. Chloride also increases, becoming the dominant anion by a depth of 968 feet. Even at 1,333 feet, however, the dissolved-solids concentration of the water is only moderate, at 526 mg/L, and the boron concentration remains low.

SUTTER BASIN

The Sutter Basin hydrochemical facies is between the Sacramento and Feather Rivers south of Sutter Buttes. This facies extends west of the Sacramento River near Colusa to include part of Colusa Basin and includes some of the American Basin east of the Feather River. Recharge comes from Sutter Buttes, from the Butte Basin hydrochemical facies east of Sutter Buttes, and from both the Sacramento and Feather Rivers. Sediments in the flood basins are generally fine grained and reducing at depth.

The Sutter Basin facies is tied with the south alluvial fans facies for the highest average dissolved-solids concentration. This facies is also high in sodium, chloride, bicarbonate, potassium, and boron. The effects of reducing conditions are evident in the relatively higher concentrations of iron, manganese, and arsenic in this area, all of which are more soluble in reducing environments (Garrels and Christ, 1965). The very low average nitrate concentration in this facies is also indicative of reducing conditions, where nitrate can be removed by denitrification reactions.

The origin of the high dissolved-solids water is thought to be connate marine water moving upward along fault zones created when Sutter Buttes was emplaced (Curtin, 1971). Throughout much of the southern part of Sutter Basin, water of very high salinity (specific conductance greater than 3,000 micromhos) is located within 400 feet of the surface.

TABLE 3.—*Chemical composition of water from wells of various depths, section 32 of township 19 N., range 1 W.*

Sample No. (fig. 3)	Site identification	Depth of well (feet)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Nitrate-N (mg/L)	Boron (mg/L)	Dissolved solids (mg/L)
1	19N/01W–32A01M	80	28	24	34	260	12	12	0.59	0.12	276
2	19N/01W–32G03M	595	25	4.4	62	210	12	22	.03	.15	276
3	19N/01W–32G02M	968	12	2.6	110	150	3.6	110	.02	.18	340
4	19N/01W–32G01M	1,333	15	2.8	160	110	3.4	230	.12	.24	526

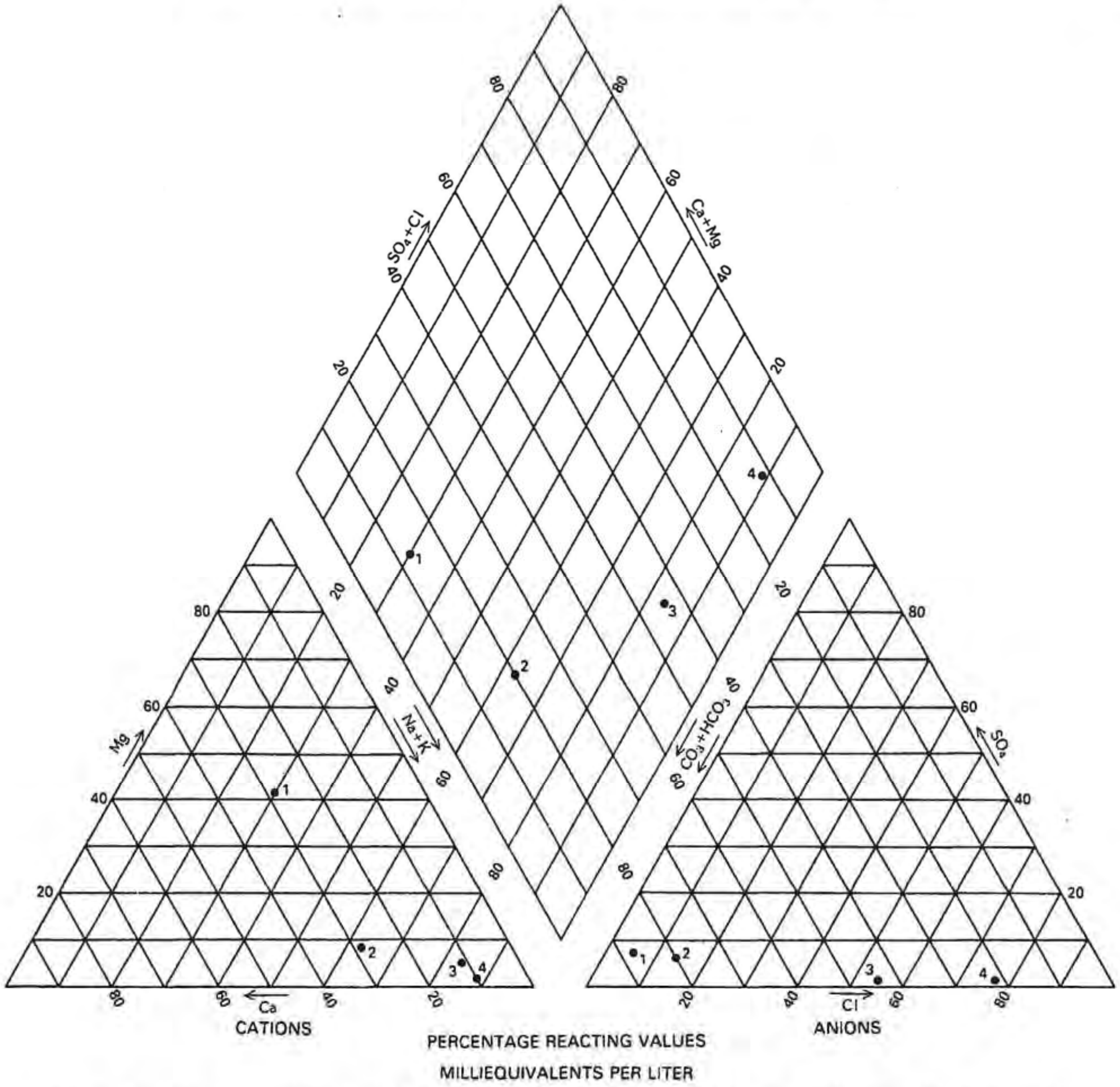

FIGURE 3.—Major-ion composition of water from wells of various depths in section 32 of township 19 N., range 1 W. Numbers refer to sample numbers in table 3.

NORTH ALLUVIAL FANS

The north alluvial fans hydrochemical facies is along the northwestern margin of the valley. Ground water occurs primarily in alluvial fan deposits and is recharged by streams draining the Coast Ranges. The alluvial fan of Stony Creek is a major source of recharge in this area, with flow radiating away from the fan to the north, east, and south. Ground-water flow in this facies is generally east and south. Most of the water is discharged to the Sacramento River along the eastern margin of the facies, although some moves into Colusa Basin along the southern boundary. Sediments in the alluvial fans are primarily derived from Mesozoic marine rocks of the Coast Ranges with sediments derived from Franciscan metamorphic rocks carried down by some of the larger streams.

The average dissolved-solids concentration in the north alluvial fans facies is moderate, and most of the chemical-constituent averages fall between those of the other facies. Calcium is the only species with a high average concentration in this facies; this is from the waters of Stony Creek, which are high in calcium. Silica is much lower in waters on the west side of the valley, and this is shown by the low average silica concentration.

SOUTH ALLUVIAL FANS

Located along the southwestern margin of the valley in alluvial fans adjacent to the Coast Ranges, the south alluvial fans hydrochemical facies extends from Putah Creek north to township 15 N. Recharge from the Coast Ranges is provided by numerous ephemeral streams north of township 10 N., and by Cache and Putah Creeks in townships south of 11 N. Recharge from Cache Creek moves around the end of the Dunnigan Hills to pumping depressions north of Woodland. Some recharge is also drawn from the Sacramento River to these same pumping depressions.

The south alluvial fans hydrochemical facies is distinguished by having high average concentrations for many of the chemical species measured. Dissolved solids, calcium, magnesium, sodium, chloride, and fluoride all have high average concentrations here. Boron and bicarbonate concentrations in this facies average very high. With little volcanic material to provide silica, its average concentration is low, as in the north alluvial fans.

Boron and chloride concentrations in the ground water of this facies average the highest in the valley, and boron concentrations as high as 8.1 mg/L have been measured in township 11 N., range 2 E. The source of the chloride and boron has been attributed to the streams draining the Coast Ranges (Bertoldi, 1976). Information obtained from a deep test well drilled by the U.S. Geological Survey in section 34 of township 12 N., range 1 E., indicated another possible source. The test well 12N/01E–34Q was drilled to a total depth of 2,400 feet and piezometers tubes installed at 942 feet, 1,396 feet, and 2,120 feet. No sample was obtained from the 942-foot depth, but analyses from the two deeper piezometers are shown in table 4. At a depth of 2,120 feet, water containing 12 mg/L boron and 660 mg/L chloride was encountered. Piezometric heads in the test well indicate upward movement of water, which may be contaminating the shallow water.

The source of boron and chloride in the streams draining the Coast Ranges is warm saline springs, a number of which occur in the Clear Lake area. Partial chemical analyses from these springs are also shown in table 4. Boron concentrations are as high as 310 mg/L in these springs. To determine the source of the high boron concentrations in the ground water in township 11 N., range 2 E., the percent composition in milliequivalents per liter of the wells in this township were plotted along with the deep well water and the warm spring water (fig. 4). The Wilbur Oil Test is a wildcat oil well that produces cold water also high in boron and chloride.

TABLE 4.—*Data for wells and springs plotted in figures 4 and 5*

[Samples 1–2 from U.S. Geological Survey test well; 3–9, reported by Fogelman (1976); 10, average for 1960–76; 11–15, reported by White and others (1973), with locations as indicated therein]

Sample No. (fig. 4)	Site identification	Depth to first opening (feet)	Dissolved solids (mg/L)	Chloride (mg/L)	Boron (mg/L)	Temperature (°C)
1	12N/01E–34Q01M	2,120	1,310	660	12	21.0
2	12N/01E–34Q02M	1,396	482	95	1.1	21.5
3	11N/02E–20K06M	387	1,060	210	3.7	20.0
4	11N/02E–18R01M	264	321	39	1.4	18.5
5	11N/02E–18C02M	205	1,470	210	8.1	18.0
6	11N/02E–23N02M	200	746	66	2.5	21.0
7	11N/02E–14B03M	198	307	37	1.1	17.5
8	11N/02E–30C01M	184	741	96	3.3	18.0
9	11N/02E–29A02M	151	816	140	4.8	18.0
10	Cache Creek at Capay	---	268	36	1.5	---
11	Wilbur Springs	---	27,134	9,700	310	55.0
12	Elgin Mine Spring	---	28,872	11,000	240	68.5
13	Abbott Mine Spring	---	7,250	1,900	56	≈30
14	Grizzly Spring	---	12,400	3,940	178	17.5
15	Wilbur Oil Test	---	19,080	11,400	23	21.3

From figure 4 there is no clear indication of whether the water in the wells (sample Nos. 3–9) is derived from the thermal springs (sample Nos. 11–14) or from deep ground water in the area (sample No. 1). Two of the thermal springs, Wilbur Oil Test well and the deep well, are very high in percent sodium. Two of the thermal springs show an increase in percent magnesium, but the percent calcium remains very low.

The deep ground water and the Wilbur Oil Test well have a much higher percentage of chloride than the thermal springs, which are enriched in carbon dioxide from metamorphism at depth (Barnes and others, 1973). As no clear trends emerged in the plot of the percent compositions in milliequivalents per liter, a second plot of chloride versus boron concentrations was made (fig. 5). The dashed diagonal line in figure 5 represents the dilution of Wilbur Springs water with water containing no boron or chloride. The thermal springs all plot very close to this line, having both high chloride and boron concentrations. The shallow wells in township 11 N., range 2 E., all plot very close to the the line representing dilution of Wilbur Springs water, as does the average composition of Cache Creek. Wilbur Oil Test well and the deep wells in the valley plot to the right of the dilution line, which indicates more chloride relative to boron in these waters. From figure 5 the source of the high chloride and boron concentrations is confirmed as water from the thermal springs in the Coast Ranges carried into the valley by streams, such as Cache Creek. Distinct differences between the cold waters,

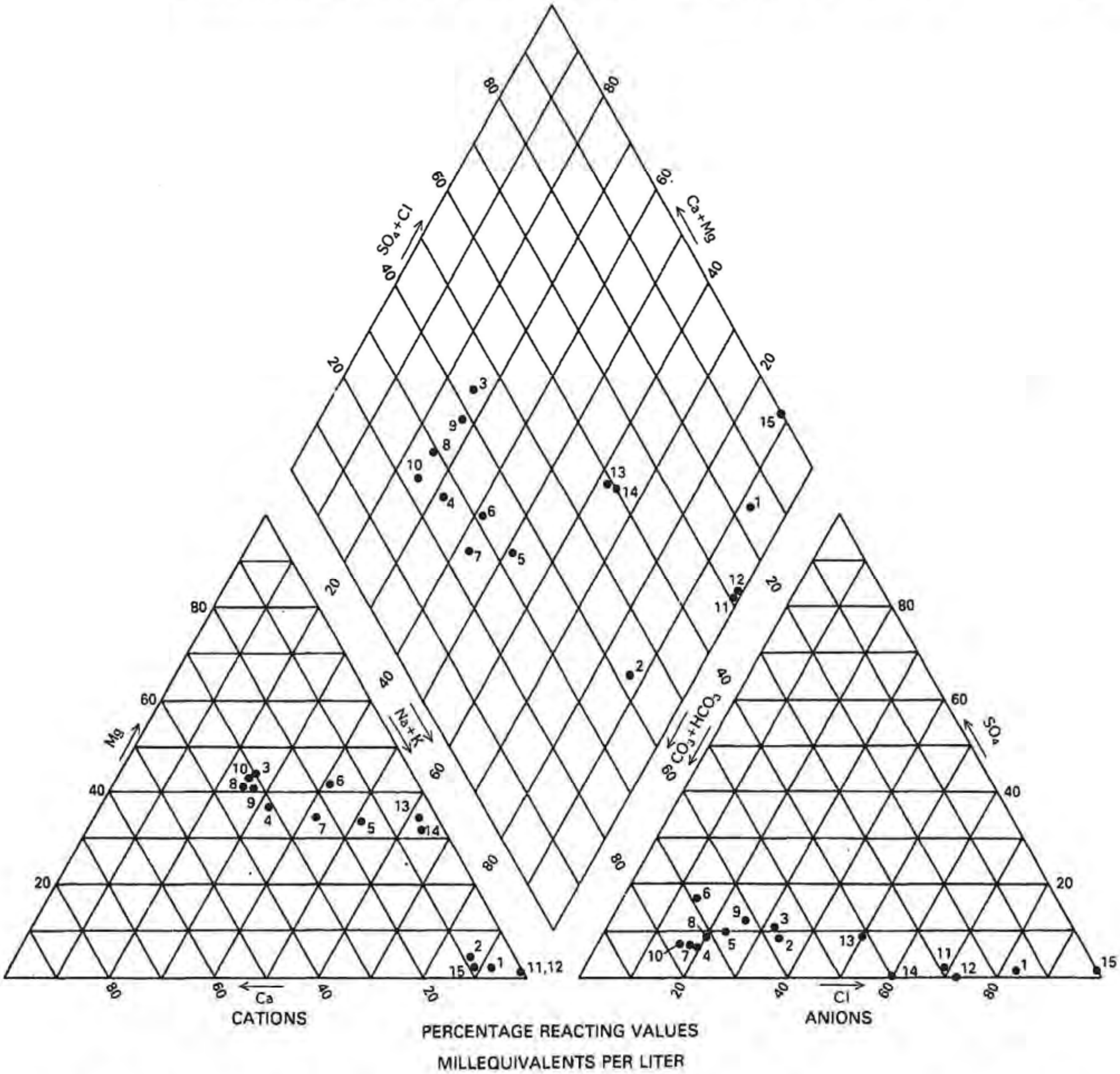

FIGURE 4.—Major-ion composition of water from springs in the Clear Lake area and from wells in a high boron area northwest of Woodland. Numbers refer to sample numbers in table 4.

such as Wilbur Oil Test and well 12N/01E-34Q01, and the thermal waters can be found in the boron-to-chloride ratio and the percent of bicarbonate ion in the waters. The hot waters probably receive inputs of carbon dioxide and boron from a gas phase produced during metamorphism of the marine sediments at depth. Cold waters are not enriched in volatile components and therefore have lower boron-to-chloride ratios and lower percent bicarbonate contents. The shallow wells in township 11 N., range 2 E., have the higher boron-to-chloride ratios indicative of a thermal water source.

TEMPORAL CHANGES

Ground-water-quality degradation may be occurring in the Sacramento Valley because of increasing development accompanied by more intensive agriculture and denser habitation. Such effects have been noted in the

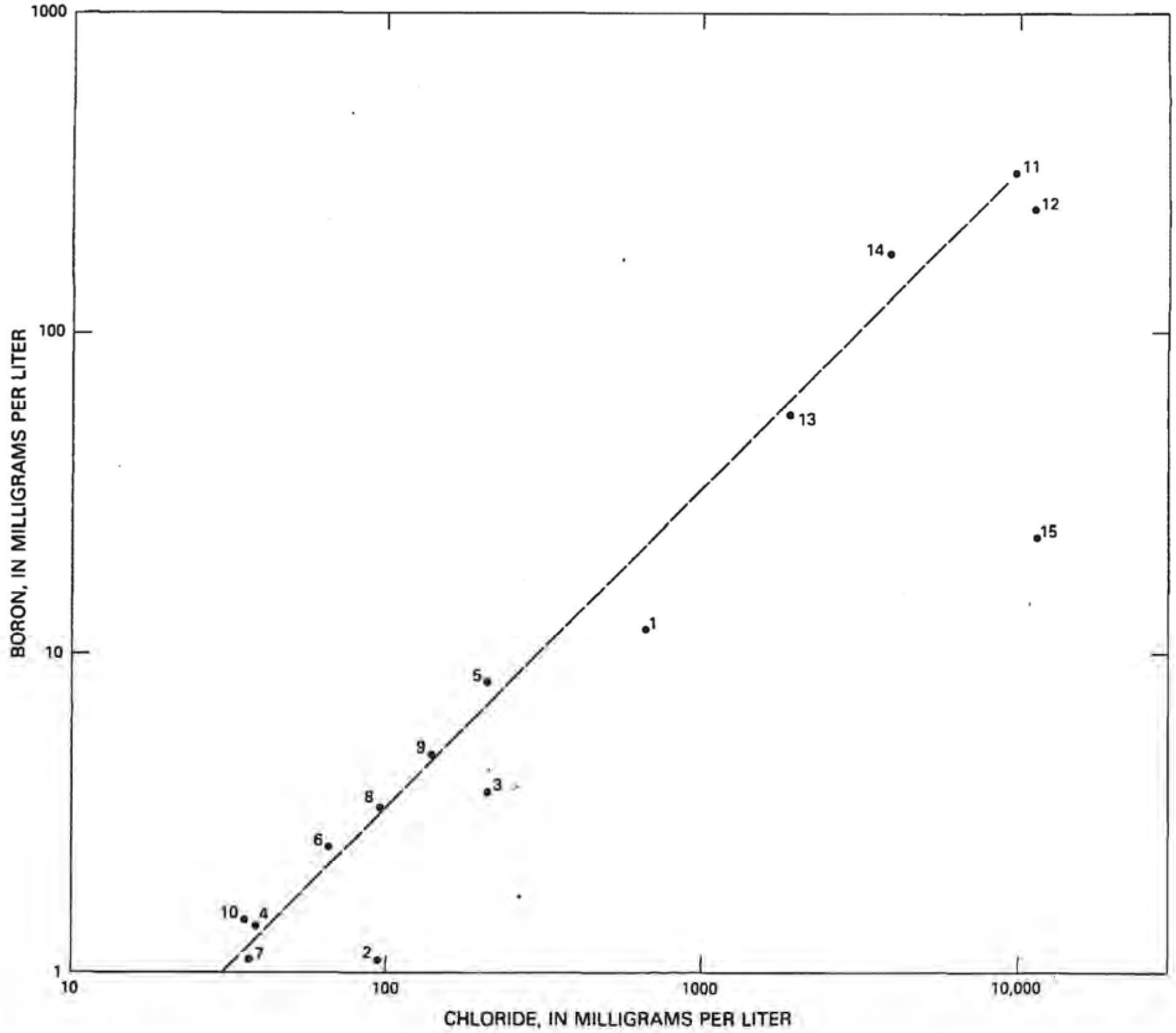

FIGURE 5.—Plot of chloride versus boron for springs in the Clear Lake area and for wells in a high boron area northwest of Woodland. Numbers refer to sample numbers in table 4. Dashed line indicates dilution of Wilbur Springs water with water containing no boron or chloride.

San Joaquin Valley (Kern County Water Agency, 1979), in San Bernardino County (Klein and Bradford, 1979), and in the Colorado River Basin (El-Ashry, 1980). Much of the problem is related to infiltrating irrigation water that (1) has been concentrated by evapotranspiration, (2) has dissolved salts added as fertilizers and soil conditioners, and (3) has leached natural salts from the unsaturated zone. Additional degradation can occur from nonagricultural activities, such as the disposal of sewage and industrial wastes.

In this section, water-quality data from the Sacramento Valley are examined for linear trends with time. Data in each of the hydrochemical facies are combined to derive an average trend for each of the areas. Individual wells are also examined for temporal changes to show more localized variations. The locations of wells used to study the temporal changes are plotted on a map of the valley, and those wells showing significant changes are labeled with symbols indicating the direction of change (pl. 2).

Two variables are used in this study, dissolved-solids and nitrate concentrations. Dissolved solids measures the total amount of dissolved chemicals in a water, and it gives a general indication of overall water quality. Nitrate is derived from a number of potential pollution sources, such as fertilizers and sewage. Increases in nitrate would indicate specific influences of man's activities. These two variables will give a fairly comprehensive evaluation of any temporal changes that may be occurring.

METHODS OF DATA ANALYSIS

To determine the average changes occurring in a hydrochemical facies, some technique was needed so that wells with different average dissolved-solids or nitrate concentrations could be compared. This was accomplished by standardizing the data for each well to have a mean of zero and a standard deviation of one. Data from all the wells for each year could then be averaged with equal weight being given to each well. This data manipulation procedure produced a data set with one observation per year for the period of record in each hydrochemical facies. The yearly observations represented the average for all the wells for which data were available in each hydrochemical facies.

Trends in the chemistry of the facies were then studied using a linear regression of the standardized and averaged dissolved-solids or nitrate concentrations versus time. One of the fundamental assumptions of regression analysis is that the observations are independently distributed. For sequences of data collected over time, this requirement is sometimes violated because the data are autocorrelated. Because of memory effects in natural processes, measurements taken at one time may be correlated to measurements taken at previous times.

To test the extent to which the dissolved solids and nitrate data suffered from autocorrelation problems, lag one serial correlations were calculated, and cumulative frequency histograms of these autocorrelations compiled. Matalas, Slack, and Wallis (1975) have generated a series of empirical cumulative frequency histograms for data sequences having a range of serial correlations. By comparing the cumulative frequency histograms for dissolved solids and nitrate in the Sacramento Valley to these empirical histograms, the probable population autocorrelations were determined to be about 0.3 for dissolved solids and between 0.3 and 0.5 for nitrate.

Serial correlations of this magnitude indicate a tendency for subsequent values to be positively correlated to previous values. As a result, the trends determined from the regression analyses may not be as strong as indicated. Positive autocorrelations of this magnitude, however, will not significantly affect the conclusions of the temporal study.

The equations describing the average temporal changes for the hydrochemical facies were transformed back to concentrations by destandardizing the regression equations. For each hydrochemical facies, the average of the means and standard deviations of the individual wells was calculated. By multiplying the regression equations by these average standard deviations and adding the average means, equations were obtained that give the average trend in a facies in terms of concentrations. This equation describes what might be observed in a typical well in each facies, and no individual well can be expected to show the same relation.

The equations produced by this analysis are not predictive equations, but merely reflect the average rate of change over the period of record, from about 1955 to 1977. An example of the problems that can arise if they are used as predictive equations is demonstrated by considering what happens if some of the equations are used to estimate past concentrations. The equation describing the average changes in nitrate-nitrogen concentrations for the Victor Plain hydrochemical facies indicates negative concentrations in the ground water prior to 1939. This is a physical impossibility and arises because the equation was used for a purpose for which it was not intended. While predictions of future concentrations of dissolved solids and nitrate-nitrogen may not produce negative results, the values obtained could be just as meaningless.

In addition to testing for average trends throughout a hydrochemical facies, individual wells were examined for temporal variations. Where a significant trend was noted for an individual well, the equation was recorded and the well's location plotted on a map of the valley with a symbol indicating the direction of the trend (pl. 2).

Few wells in the valley have multiple observations over time. To minimize the effects of random fluctuations, only wells with seven or more observations for dissolved solids and six or more observations for nitrate were used. There was no attempt to assure a random distribution of wells throughout the valley, and all wells in the valley or along the margins having a sufficient number of observations were used. Time is measured as the year minus 1900. For example, for the year 1975, time is equal to 1975–1900 or 75.

DISSOLVED SOLIDS

Dissolved solids is a measure of the total amount of dissolved chemicals in water. An increase in any of the individual constituents will be reflected by an increase in the dissolved solids. While not many historical dissolved-solids measurements are available, many specific-conductance measurements have been made. Specific conductance is proportional to the quantity and valence of ionized chemicals in a water. Because almost all the major dissolved chemical constituents in a water are ionized, dissolved solids and specific conductance are closely related.

It was felt that dissolved solids would have more meaning for most users of this report; therefore, specific conductivities were transformed to dissolved-solids concentrations. The relation between dissolved solids and specific conductance will depend on the specific ionized species present and the amount of uncharged species, mainly silica, present in the water. For this reason, separate equations were derived for different parts of the valley. These areas do not exactly coincide with the hydrochemical facies as they were finally defined, but the division follows the same basic pattern. Thus, the effects of different water chemistries on the relation between dissolved solids and conductance were taken into account during the transformation.

Equations that describe the relation between dissolved solids and specific conductance were derived from a linear regression on data from about 650 wells having measurements of both dissolved solids and conductance. A linear equation with both slope and intercept terms was used rather than a ratio. The intercept terms of all the linear equations were significantly different from zero, which indicates that the linear equations better fit the data than ratios.

Because the calculation of dissolved solids from conductance is a simple linear transformation, the calculation in no way affects the presence of trends in the data. All dissolved-solids values for a well were estimated from conductance measurements even if some measured dissolved-solids concentrations were available. This prevented any changes that might be induced by using dissolved-solids data from different sources.

Locations of wells examined for trends in dissolved solids are shown on plate 2*A*. The changes for each hydrochemical facies are discussed in the next section and coefficients for the equations describing the average temporal changes are given in table 5. Coefficients for individual wells are summarized in table 6.

HYDROCHEMICAL FACIES

Dissolved solids in the Tuscan volcanic rocks hydrochemical facies show an average annual increase of 0.95 mg/L. The trend line accounts for 31 percent of the variation in the standardized dissolved-solids data averaged over all wells by year. A plot of the trend line is shown in figure 6. Temporal variations are significant in five of the 19 wells for which historical data are available (table 6). Two of these wells show rising trends and three show decreasing trends.

TABLE 5.—*Analyses of variance and coefficients for the regression of average yearly dissolved solids with time for the six hydrochemical facies in the Sacramento Valley*

[t=(year–1900); for example, t=(1980–1900)=80. NS, linear trend not significant at the 90 percent confidence level]

								MODEL Dissolved solids=A+Bt			
Hydrochemical facies	Number of wells	Source	Degrees of freedom	Sum of squares	F ratio	Probability of exceeding F ratio	r^2	A	90 percent confidence limit	B	90 percent confidence limit
Tuscan volcanic rocks	19	Model	1	1.52	8.89	0.01	0.31	194	±36	0.95	±0.55
		Error	20	3.43							
		Total	21	4.95							
Victor Plain	20	Model	1	2.50	13.91	<0.01	.38	236	±48	1.61	±0.74
		Error	23	4.13							
		Total	24	6.63							
Butte Basin	12	Model	1	1.17	12.55	<0.01	.41	197	±45	1.37	±0.67
		Error	18	1.68							
		Total	19	2.85							
Sutter Basin Basin	10	Model	1	.03	.05	.83	.00	---	---	NS	---
		Error	23	15.21							
		Total	24	15.24							
North alluvial fans	62	Model	1	1.05	14.11	<0.01	.43	222	±31	1.02	±.46
		Error	19	1.41							
		Total	20	2.46							
South alluvial fans	18	Model	1	7.41	65.16	<0.01	.76	184	±67	4.75	±1.01
		Error	21	2.39							
		Total	22	9.80							

TABLE 6.—*Wells showing significant trends in dissolved-solids concentration*

[For the model: Dissolved solids=A+Bt, where t is the year minus 1900]

Well	A	Standard error	Student's *t*	B	Standard error	Student's *t*	Probability of exceeding t for B
TUSCAN VOLCANIC ROCKS							
23N/01W–09L01M	–24.6	73.2	0.34	5.72	1.12	5.12	<0.01
25N/02W–16P01M	666.4	174.5	3.82	–6.09	2.42	2.52	.01
26N/02W–09E01M	909.5	257.0	3.54	–7.44	3.56	2.09	.04
27N/03W–15N01M	1055.6	288.1	3.66	–9.56	3.92	2.44	.02
27N/03W–22B01M	–122.4	223.1	.55	6.30	3.06	2.06	.04
VICTOR PLAIN							
06N/07E–23A01M	892.6	373.4	2.39	–10.32	5.61	1.84	0.07
18N/04E–28M01M	325.8	209.4	1.56	22.03	3.02	7.29	.01
BUTTE BASIN							
16N/04E–09D01M	–389.3	181.4	2.15	8.57	2.80	3.06	<0.01
17N/01W–30K03M	1833.2	515.4	3.56	–21.27	7.04	3.02	<0.01
SUTTER BASIN							
15N/03E–15H04M	–910.0	485.4	1.87	20.92	6.82	3.07	<0.01
16N/02W–25B02M	2428.1	395.1	6.15	–24.98	5.56	4.49	<0.01
NORTH ALLUVIAL FANS							
17N/03W–33R01M	383.2	76.6	5.01	3.24	1.13	2.87	<0.01
18N/02W–01E01M	–716.6	77.8	9.21	16.37	1.16	14.16	<0.01
18N/04W–02F01M	–817.1	112.5	7.26	22.73	1.74	13.07	<0.01
19N/02W–23N01M	–464.2	77.8	5.97	14.03	1.16	12.14	<0.01
20N/02W–22E01M	–618.4	442.7	1.40	11.31	5.97	1.89	.06
21N/02W–15C01M	–241.0	84.5	2.85	8.77	1.25	7.04	<0.01
21N/03W–02Q01M	–121.4	84.6	1.43	7.41	1.25	5.95	<0.01
22N/01W–29C01M	40.2	87.8	.46	3.98	1.30	3.06	<0.01
22N/02W–03A01M	125.3	77.8	1.61	3.37	1.16	2.91	<0.01
22N/02W–04C02M	–459.7	376.8	1.22	10.53	5.11	2.06	.04
22N/03W–06H01M	–922.3	553.3	1.67	20.71	7.62	2.72	<0.01
22N/03W–22Q01M	20.0	77.8	.26	3.88	1.16	3.35	<0.01
23N/03W–35B01M	–69.5	84.3	.82	3.40	1.25	2.73	<0.01
24N/03W–24P01M	–724.6	364.0	1.99	16.36	4.95	3.30	<0.01
25N/03W–31R01M	89.9	77.8	1.16	3.49	1.16	3.02	<0.01
SOUTH ALLUVIAL FANS							
06N/01E–19L02M	–661.9	209.8	3.15	18.11	3.15	5.76	<0.01
06N/01E–19Q01M	101.0	207.1	.49	5.94	3.05	1.95	.05
06N/01W–01B04M	–166.4	280.1	.59	7.48	4.04	1.85	.07
07N/02E–34C02M	–152.3	185.0	.82	10.56	2.81	3.75	<0.01
09N/04E–33L01M	–740.0	169.8	4.36	28.96	2.75	10.55	<0.01
13N/01W–07A01M	335.8	139.7	2.40	7.43	2.04	3.64	<0.01
13N/01W–36Q02M	–32.3	117.0	.28	4.67	1.74	2.68	<0.01
14N/03W–11H01M	7.9	166.3	.05	4.45	2.46	1.81	.07

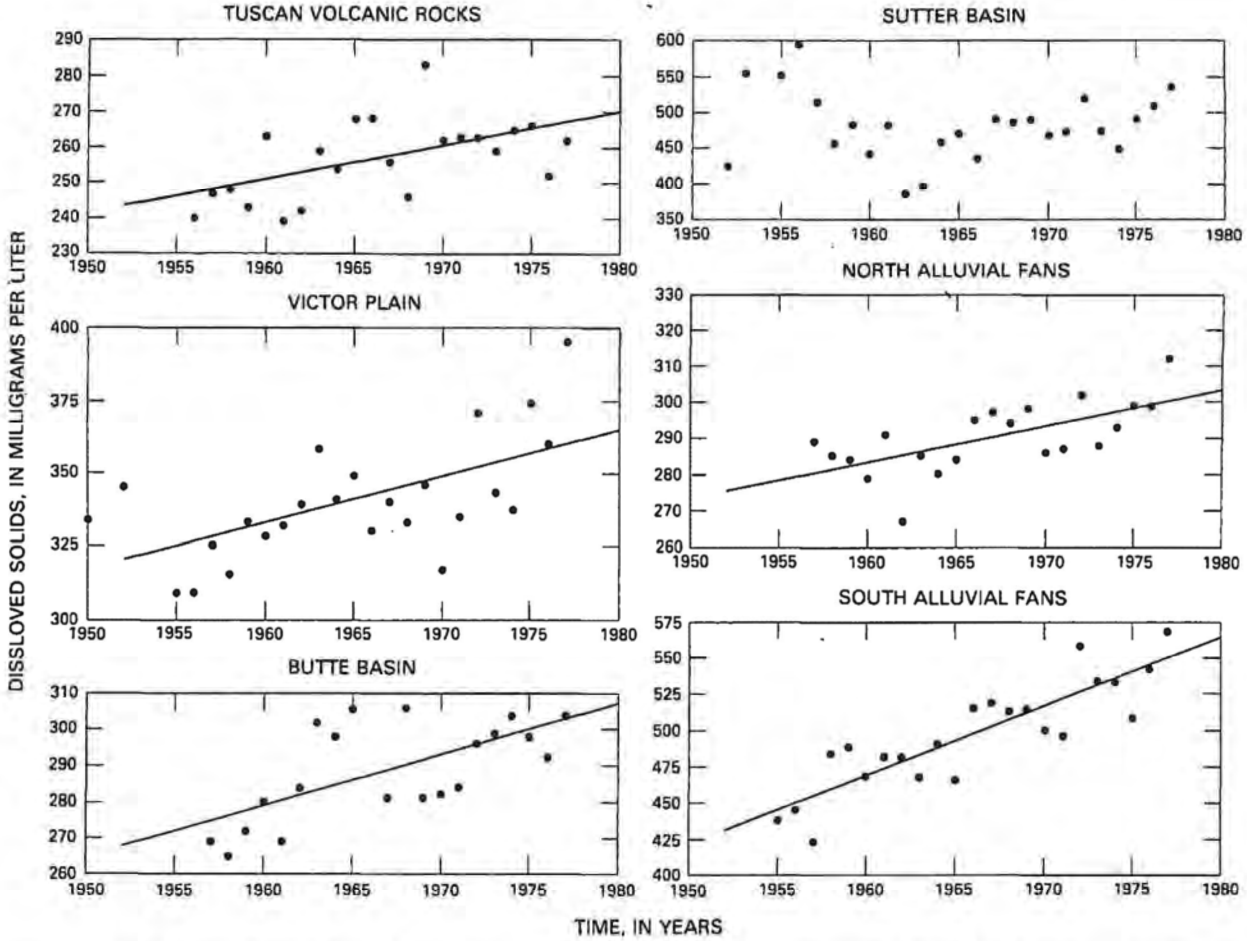

FIGURE 6.—Average yearly dissolved-solids concentrations versus time for the six hydrochemical facies in the Sacramento Valley. The coefficients and significance tests for the trend lines are given in table 5. If no line is shown, then the slope of the trend line is not significantly different from zero at the 90 percent confidence level. The technique by which the average yearly dissolved-solids values were derived is explained in the text.

The average yearly increase in dissolved solids for the Victor Plain facies is 1.61 mg/L. The trend line, which explains 38 percent of the variation in the standardized data, is shown in figure 6. Only two of the 20 wells studied in this facies showed significant changes, one of which showed an increase, and the other a decrease with time.

For Butte Basin, a temporal trend having a slope of 1.37 (mg/L)/yr explains 41 percent of the variation in the averaged data. In this facies also, two wells showed significant trends. One well demonstrated an increase and the other a decrease in dissolved solids with time.

Sutter Basin is the only hydrochemical facies to show no significant temporal change in average dissolved-solids concentration. Two of the 10 wells did show significant trends, but in opposite directions.

An increase in the average dissolved-solids concentration of the north alluvial fans facies of 1.02 (mg/L)/yr explains 43 percent of the variation in the yearly average data. A plot of the trend line is shown in figure 6. Of 62 wells that have seven or more observations in this area, 15 show significant upward trends, and none decrease.

Seventy-six percent of the variation in the average yearly dissolved-solids data are explained by a linear trend in the south alluvial fans facies. The slope is very steep 4.75 (mg/L)/yr and indicates a very rapid increase in dissolved solids (fig. 6). Of the 18 wells examined in this facies, 8 had significant increases in dissolved solids. There were no wells that showed decreases.

NITRATE

A certain amount of nitrate is present in precipitation, and chemical reactions in the soil zone may add to this amount. Thus, even under natural conditions, a finite amount of nitrate will exist in ground water. An estimate of natural nitrate concentrations in the Sacramento Valley can be made from data gathered during the period 1912–13 (Bryan, 1923). The median nitrate-nitrogen concentration in these 43 samples is 0.67 mg/L. The highest nitrate-nitrogen concentration measured was 14 mg/L, which suggests some wells were polluted as long as 70 years ago. From the frequency histogram of the 1912–13 nitrate data (fig. 7), it is estimated that under natural conditions, no more than about 3 mg/L nitrate-nitrogen would be expected in the ground water.

By the period 1974–78, the median nitrate-nitrogen concentration had more than doubled to 1.6 mg/L. The maximum observed nitrate-nitrogen concentration also increased, with two wells containing 27 mg/L and one well 61 mg/L. These increases likely reflect the influences of man's activities, and the extent of temporal changes was, therefore, investigated to determine the magnitude of the problem.

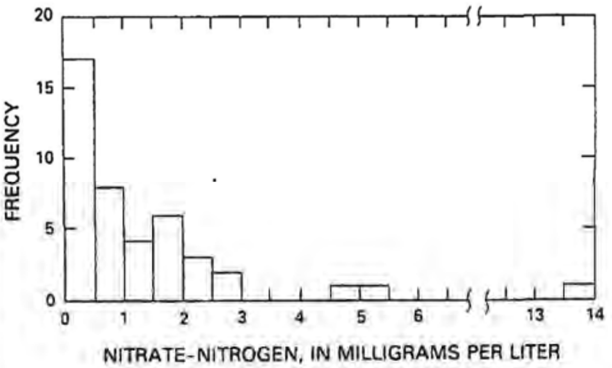

FIGURE 7.—Frequency histogram of dissolved nitrate-nitrogen concentrations in wells, 1912–13. Data from Bryan (1923).

Locations of wells examined for trends in nitrate are shown on plate 2*B*. The changes for each hydrochemical facies are discussed further and coefficients for the equations describing the average temporal changes are given in table 7. Coefficients for individual wells are summarized in table 8.

TABLE 7.—*Analyses of variance and coefficients for the regression of average yearly nitrate-nitrogen concentrations with time for the six hydrochemical facies in the Sacramento Valley*

[t=(year–1900); for example, t=(1980–1900)=80. NS, linear trend not significant at the 90 percent confidence level]

								MODEL Nitrate nitrogen=A+Bt			
Hydrochemical facies	Number of wells	Source	Degrees of freedom	Sum of squares	F ratio	Probability of exceeding F ratio	r^2	A	90 percent confidence limit	B	90 percent confidence limit
Tuscan volcanic rocks	5	Model	1	0.88	1.25	0.28	0.08	---	---	NS	---
		Error	15	10.57							
		Total	16	11.45							
Victor Plain	13	Model	1	6.05	29.31	<0.01	.63	−1.402	±0.751	0.036	±0.012
		Error	17	3.51							
		Total	18	9.56							
Butte Basin	3	Model	1	.69	1.85	.20	.12	---	---	NS	---
		Error	14	5.26							
		Total	15	5.95							
Sutter Basin	2	Model	1	.65	.84	.38	.08	---	---	NS	---
		Error	10	7.77							
		Total	11	8.42							
North alluvial fans	26	Model	1	5.02	49.67	<0.01	.73	−3.786	±1.625	.099	±0.024
		Error	18	1.82							
		Total	19	6.84							
South alluvial fans	13	Model	1	2.03	7.72	.01	.30	−0.506	±1.514	.036	±0.023
		Error	18	4.73							
		Total	19	6.76							

TABLE 8.—*Wells showing significant trends in nitrate-nitrogen concentration*

[For the model: Nitrate-nitrogen = A + Bt, where t is the year minus 1900]

Well	A	Standard error	Student's t	B	Standard error	Student's t	Probability of exceeding t for B
TUSCAN VOLCANIC ROCKS							
23N/01W–09L01M	–25.33	3.82	6.63	0.53	0.06	8.78	<0.01
25N/02W–07K01M	–7.96	3.74	2.13	.17	.06	2.89	<0.01
VICTOR PLAIN							
10N/05E–06M02M	–6.58	1.62	4.06	0.12	0.03	4.85	<0.01
11N/06E–16M01M	–9.38	1.35	6.96	.18	.02	8.56	<0.01
13N/05E–13D01M	–3.98	2.09	1.90	.08	.03	2.31	.02
14N/05E–32R03M	–14.48	2.19	6.60	.23	.03	7.38	<0.01
18N/04E–07A01M	–0.81	1.09	.75	.03	.02	1.87	.06
BUTTE BASIN							
None							
SUTTER BASIN							
None							
NORTH ALLUVIAL FANS							
18N/04W–02F01M	–73.57	6.37	11.54	1.38	0.10	13.96	<0.01
20N/03W–02D01M	–11.39	7.49	1.52	.23	.12	1.95	.05
21N/02W–15C01M	–15.47	5.62	2.75	.29	.08	3.43	<0.01
21N/03W–02Q01M	–33.53	7.80	4.30	.58	.12	4.89	<0.01
22N/01W–29C01M	–8.35	6.41	1.30	.17	.10	1.70	.09
22N/02W–03A01M	–10.26	6.16	1.67	.28	.10	2.92	<0.01
25N/03W–31R01M	–10.34	6.88	1.50	.24	.10	2.30	.02
SOUTH ALLUVIAL FANS							
09N/02E–10D01M	26.38	6.93	3.81	–0.38	0.11	3.44	<0.01
18N/01W–07A01M	–10.19	2.66	3.84	.21	.04	5.26	<.01
13N/01W–08B01M	–11.80	2.36	5.00	.22	.04	6.13	<.01
14N/03W–11H01M	–4.40	2.75	1.60	.10	.04	2.33	.02
14N/03W–14Q02M	–25.22	5.95	4.24	.38	.08	4.55	<.01

HYDROCHEMICAL FACIES

No significant average trend was found for the Tuscan volcanic rocks hydrochemical facies. However, two of the five wells examined did show significant upward trends in nitrate concentrations.

A linear trend with a slope of 0.036 (mg/L)/yr explains 63 percent of the temporal variation in the average yearly nitrate-nitrogen concentrations in the Victor Plain facies. A plot of this trend line is shown in figure 8. Of 13 wells in this area that had 6 or more observations, 5 showed signifiicant upward trends. None of the wells showed a significant decrease.

Neither Butte nor Sutter Basin had a significant average trend in nitrate. Also, there were no individual wells in either that showed any significant changes. However, with only three wells in Butte Basin and two in Sutter Basin having six or more observations, there are too few samples for the results of the test to be conclusive.

The nitrate-nitrogen concentrations in the north alluvial fans hydrochemical facies show a distinct upwards

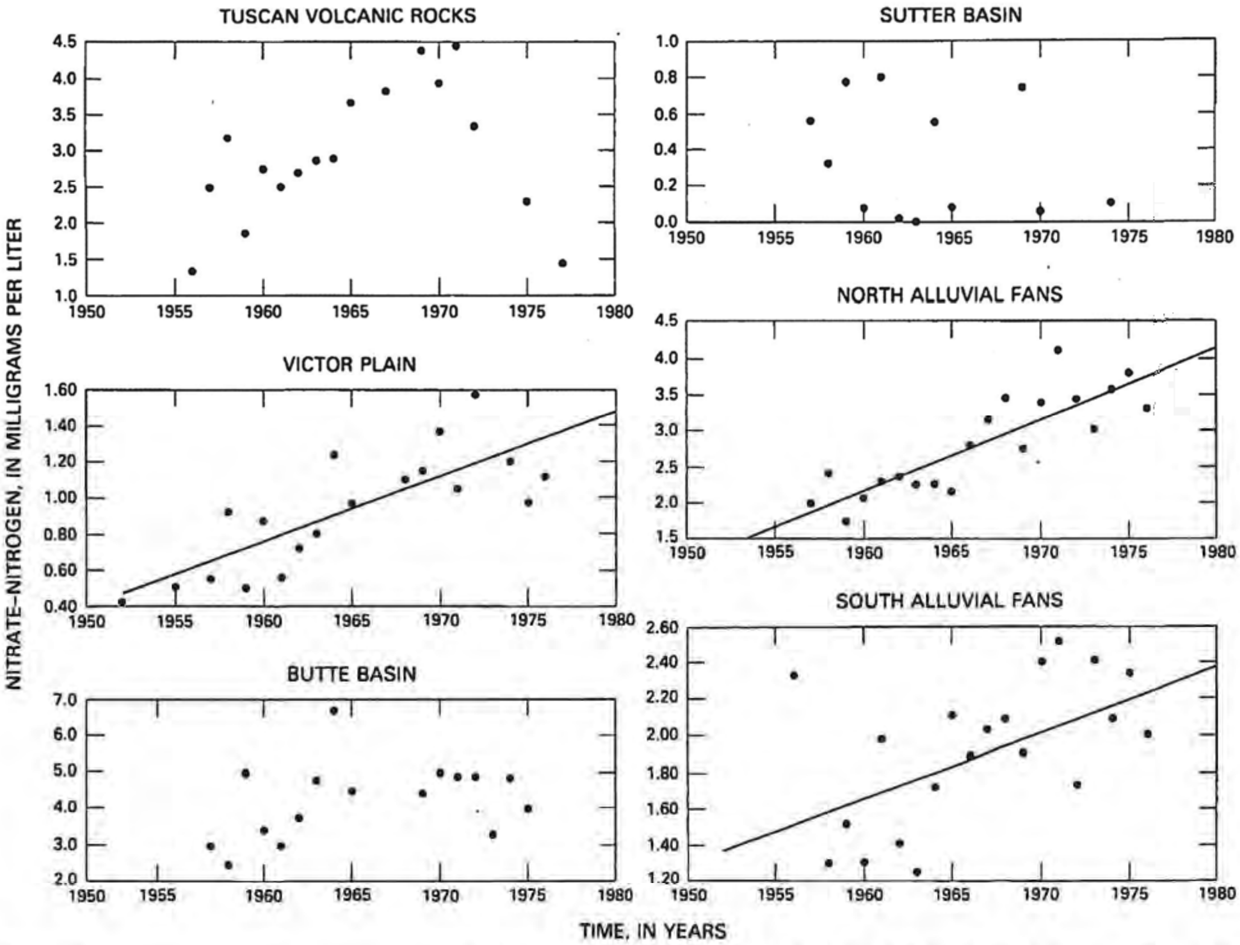

FIGURE 8.—Average yearly nitrate-nitrogen concentrations versus time for the six hydrochemical facies in the Sacramento Valley. The coefficients and significance tests for the trend lines are given in table 7. If no line is shown, then the slope of the trend line is not significantly different from zero at the 90 percent confidence level. The technique by which the average yearly nitrate-nitrogen values were derived is explained in the text.

trend with a slope of 0.099 (mg/L)/yr. Seven of the 26 wells in this facies showed significant upwards trends. The plot of the trend in figure 8 shows that the average concentration of nitrate-nitrogen in this facies has exceeded 3.0 mg/L, the maximum expected under natural conditions.

For the south alluvial fans hydrochemical facies, a linear trend having a slope of 0.036 (mg/L)/yr explains 30 percent of the temporal variation in the average annual nitrate-nitrogen concentrations. Thirteen wells had six or more observations over time, and 5 of them show significant temporal changes. Four have upwards trends, and 1 a downwards trend.

HYPOTHESIS TESTING

Because trends in the data for the individual wells were tested at the 90 percent confidence level, there is a 10 percent chance that no significant trend exists in the valley. The significant slopes that were observed could result from normally distributed random fluctuations about a true true slope of zero. If this were the case, 5 percent of the wells could show a significant increase, and 5 percent a significant decrease, although no real trend existed. If more than 5 percent of the dissolved-solids or nitrate wells show significant trends in the same direction, then it can be concluded that there has been a significant change for that species.

Of 140 wells in the Sacramento Valley tested for trends in dissolved solids, 28 (20 percent) showed an increase and 7 (5 percent) showed a decrease with time. Under the null hypothesis that no change in dissolved solids is occurring at the 90 percent confidence level, it would be expected that by random variation, 7 of the wells would show a significant decrease and 7 would show a significant increase. For dissolved solids, the number of wells showing increases exceeds the number expected by random variation, and the increase in dissolved solids is significant.

Of 62 wells tested for trends in nitrate, 18 (29 percent) showed increases, but only 1 (2 percent) showed a decrease with time. Under the null hypothesis of no change, 3 can be expected to increase and 3 to decrease by random variation at the 90 percent confidence level. Because 29 percent of the wells showed significant increases in nitrate, the null hypothesis can be rejected, which indicates significant increases in nitrate are occurring in the Sacramento Valley.

PROCESSES CONTROLLING GROUND-WATER CHEMISTRY

Differences in the chemical composition of ground water among the six hydrochemical facies in the Sacramento Valley indicate that either different processes control the water chemistry in different areas, or that there are spatial variations in the same process. In this section, the major controlling processes are delineated from the chemical data using principal components analysis. Factor scores are than calculated for each well that reflect the magnitude of each component in that well. By studying the spatial trends in the factor scores using trend surface analysis, the areal variations in processes can be determined. Contour maps of these surfaces show the spatial distributions of the more important processes controlling ground-water chemistry.

METHODS OF DATA ANALYSIS

PRINCIPAL COMPONENTS ANALYSIS

Principal components analysis (Rummel, 1970; Davis, 1973) is used to separate the variance of a data matrix into common and unique components. Variables, in this case dissolved chemical species, that are controlled by the same process will share a common variance structure. Principal components analysis will group the variables on the basis of this shared variation and will calculate a correlation between variables and components. These components represent independent sources of variation in a data matrix and can be interpreted in terms of controlling processes using knowledge of geochemical principles.

From the correlations, or loadings as they are termed, between variables and components, factor scores can be calculated for each well that measure the intensity of a component in that well. These factor scores are a composite of all the chemical species that load on a component and summarize similar behavior in a number of different species. Where several of the chemical species are controlled by the same process, this transformation to factor scores reduces the number of variables needed to account for the significant variation in the data. The factor scores can be further analyzed as any other numerical variable.

TREND SURFACE ANALYSIS

Trend surface analysis (Davis, 1973) is a technique for separating variation in geographically distributed data into regional and local parts. Either of these parts might be the goal of a particular study. For the distribution of processes in the Sacramento Valley, however, the regional variation is of interest. A trend surface is delineated by a polynomial equation that predicts the magnitude of some variable in terms of the geographic coordinates of a set of observations. The criteria for fitting the polynomial is to minimize the squared deviations about the surface. In this study, the trend surface represents the spatial variation in processes controlling ground-water chemistry. By contouring the surface, maps can be prepared that show the spatial variation in the magnitude of the process.

PROCESSES AND THEIR SPATIAL VARIATION

For the Sacramento Valley, 15 variables (table 9) were included in the principal components analysis. A major assumption of components analysis is that the data are normally distributed. This requirement was reasonably well met by using logarithmic transformations of the chemical concentrations. Four principal components explained 73 percent of the total variation in the data and accounted for all the significant common variation (that is, only these four components had eigenvalues greater than one). The four individual components explained 36, 17, 11, and 9 percent of the total variation. Because neither the third nor fourth component yielded clear interpretations that could be attributed to processes, only the first two components are presented. These two components, however, explain

TABLE 9.—*Chemical variables included in the principal components analysis of the Sacramento Valley*

Dissolved solids	Potassium	Silica	Nitrate
Calcium	Manganese	Bicarbonate	Phosphate
Magnesium	Arsenic	Sulfate	Fluoride
Sodium	Boron	Chloride	

TABLE 10.—*Results of principal components analysis on chemical data from the Sacramento Valley*

[All loadings with absolute values less than 0.30 have been omitted for clarity]

	Components		Communalities
	1	2	
Dissolved solids	0.94		0.93
Calcium	.76		.60
Magnesium	.81		.67
Sodium	.83		.76
Bicarbonate	.85		.72
Chloride	.76		.62
Sulfate	.63		.41
Boron	.65		.42
Fluoride	.30	−0.46	.30
Silica	−0.54	.42	.46
Potassium		.67	.48
Nitrate		−0.71	.52
Phosphate		.50	.30
Manganese		.63	.41
Arsenic		.62	.38
Percent variation explained	36	17	
Cumulative percent variation explained	36	53	

over 50 percent of the variation in the chemical data from the Sacramento Valley.

Table 10 shows the results of the principal components analysis. On component one, dissolved solids, calcium, magnesium, sodium, bicarbonate, chloride, sulfate, boron, and fluoride all have positive loadings. Silica is the only species to have a significant negative loading on this component. The inverse loadings of dissolved solids and silica indicate that low silica concentrations tend to be found in conjunction with high dissolved-solids concentrations, and vice versa. The positive loadings of all the major chemical species on this factor indicate a source high in calcium, magnesium, sodium, bicarbonate, chloride, and sulfate. This source is also high in fluoride and boron, and low in silica.

The trend surface map of this component (fig. 9) shows a distinct linear trend across the valley, which accounts for 36 percent of the spatial variation in component one. Low values of component one along the eastern margin and in the northern end of the valley indicate low dissolved-solids and high silica concentrations. In the southwestern corner, high concentrations of dissolved species and boron are indicated. This distribution in the ground water is very similar to the distribution of water chemistry in surface streams draining into the valley. Table 11 shows the average concentrations of dissolved species in streams entering the valley from certain areas. East side streams are low in dissolved solids, and contain twice as much silica as streams from the southwestern margin. The silica in east side streams is likely from the weathering of volcanic detritus in the Sierra Nevada and Cascade Range. High dissolved-solids concentrations in the southwest originate in thermal springs in the Coast Ranges.

The first principal component represents the effects of the chemistry of recharge to the valley on the chemistry of the ground water. This process is active along both margins of the valley and produces fairly uniform chemical compositions along the eastern side. Along the western margin, changes in surface-water chemistry from north to south induce changes in ground-water chemistry. The effects of recharge chemistry are the single most important control on ground-water chemistry, accounting for over one-third of the total variation in the chemical data.

The second principal component (table 10) explains 17 percent of the variation in the chemical data, and contains positive loadings of silica, potassium, phosphate, manganese, and arsenic. Nitrate and fluoride have negative loadings on this component. The trend surface for component two (fig. 10) explains 38 percent of the spatial variation in this component. The pattern indicates high factor scores in the center of the valley with low values along the margins. The occurrence of high factor scores in wells in the flood basins suggests that the fine-grained sediments and reducing conditions in the basins are an important control on water chemistry.

Measurements of dissolved oxygen in the ground water in the south alluvial fans facies (table 12) show an average of 3.8 mg/L of dissolved oxygen. Although no data are available for other parts of the valley, it is reasonable to assume that the coarse-grained sediments along the valley margins would contain some dissolved oxygen. In the flood basins, where sediments are water saturated and fine grained, reducing conditions probably exist. The increase in manganese and arsenic, and decrease in nitrate, support an oxidation-reduction effect. The solubility of manganese and arsenic increases in reducing conditions, and nitrate could be removed by denitrification.

Longer residence times in the fine-grained sediments of the flood basins and weathering of volcanic detritus from Sutter Buttes could supply the higher silica and potassium concentrations indicated by component two. The inverse relation between phosphate and fluoride probably reflects spatial differences in their sources rather than equilibrium with a mineral phase, such as apatite. Phosphate, introduced along with nitrate, would not be removed by reduction reactions and would persist in the ground water. Fluoride is probably derived from thermal springs in the hills surrounding the valley and lacks a source in the central basins.

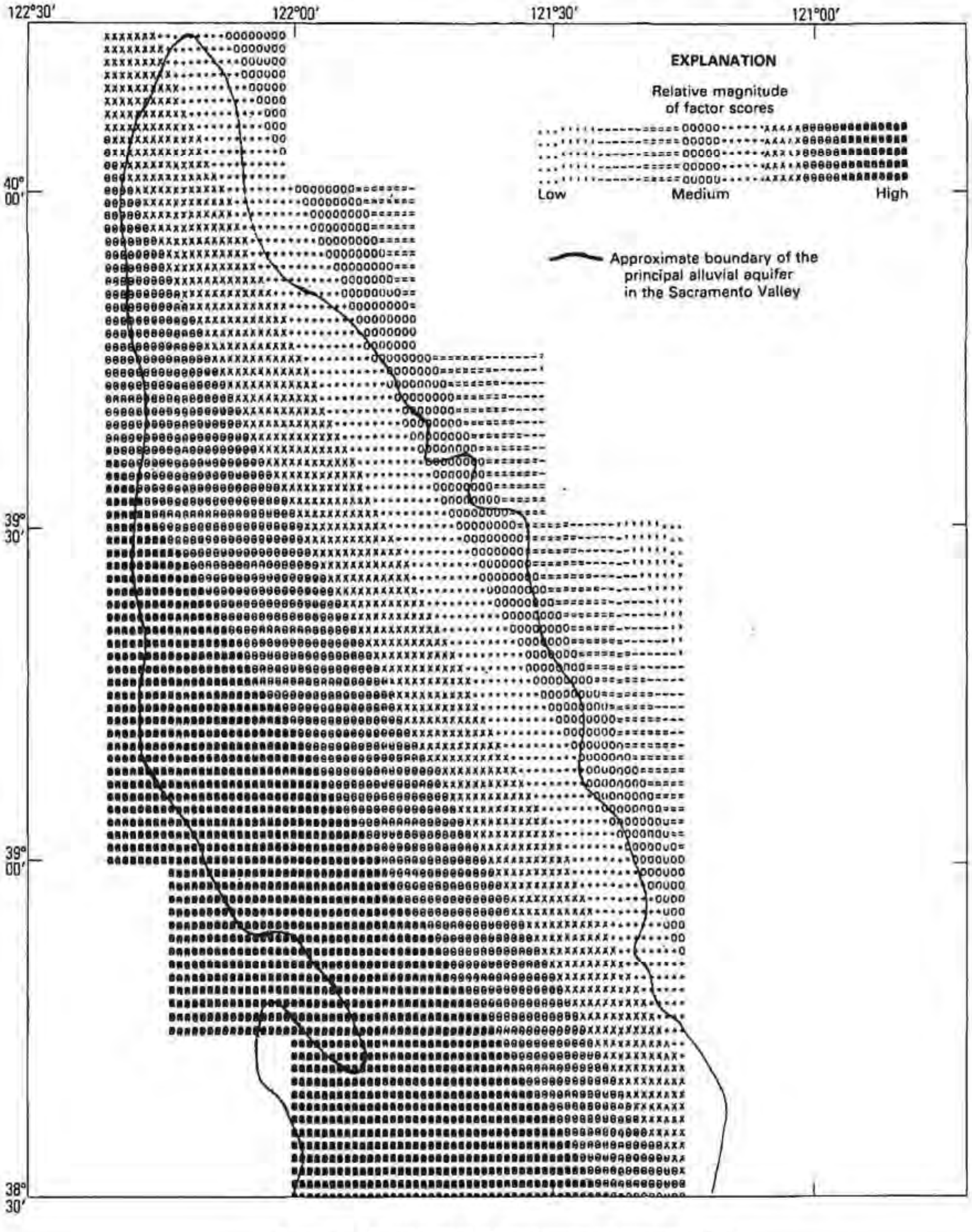

FIGURE 9.—Trend surface of factor scores for component one.

Principal components analysis shows that two components account for over 50 percent of the variation in the chemical data from the Sacramento Valley. While other processes will affect water chemistry, they seem to be either more localized or much less important than the two discussed. Recharge from the valley margins

TABLE 11.—*Average chemical compositions of surface water entering the Sacramento Valley*

Species (mg/L)	East side	Northern west side	Southern west side
Dissolved solids	85	215	592
Calcium	11	36	53
Magnesium	4.7	12	40
Sodium	6.3	13	101
Bicarbonate	55	164	314
Chloride	5.4	16	150
Sulfate	7.0	28	82
Boron	.10	.07	.51
Fluoride	.08	.08	.4
Silica	22	14	11

EXPLANATION OF LOCALITIES

East side: Antelope Creek, Mill Creek, Big Chico Creek, Butte Creek, Feather River, Yuba River, Bear River, and American River.

Northern west side: Red Bank Creek, Elder Creek, Thomes Creek, and Stony Creek.

Southern west side: Stone Corral Creek, Lurline Creek, Freshwater Creek, Salt Creek (west of Williams), Cortina Creek, Sand Creek, Oat Creek, Cache Creek, and Putah Creek.

is the most important control on ground-water chemistry, with reactions in the flood basin sediments also being important.

MINERAL STABILITY RELATIONS

Sediments deposited in the Sacramento Valley have been derived from erosion of the surrounding mountains. These mountains contain igneous and metamorphic rocks which were formed at higher temperatures and (or) pressures than are found at shallow depths in the valley sediments. Because the environment of deposition is radically different from that of formation, these minerals are generally not in equilibrium with their surroundings. As a result, the minerals react with the ground water, which dissolves the unstable primary minerals and forms secondary minerals that are more stable. Reaction rates may be very slow, so the process is gradual and can take tens of millions of years or longer. During this diagenesis, phases, such as pyroxenes, feldspars, micas, and volcanic glass, weather to more stable phases, such as clay minerals and iron hydroxides.

Water chemistry will be affected by water-rock interactions, and the three parts of the system (primary minerals, aqueous solution, and secondary minerals) are interdependent. Using thermodynamic calculations, the mineral phases that will be stable in equilibrium with solutions of various compositions can be predicted. It cannot be justifiably presumed, however, that the mineral assemblage and the ground-water chemistry are in thermodynamic equilibrium, particularly where aluminosilicate minerals are involved. Water chemistry may reflect incomplete reactions or partial equilibrium with metastable phases.

In this section, the relations between water chemistry and aquifer mineralogy are examined. Mineralogy is presented from two U.S. Geological Survey test wells. Mineral saturation indices are examined to determine any likely phases that may be controlling water chemistry. Finally, stability and metastability fields of mineral phases are compared to measured water chemistry to determine what secondary minerals will be most stable in contact with Sacramento Valley ground water.

MINERALOGY OF SEDIMENTS

Sidewall samples were collected from various depths in two test wells drilled by the U.S. Geological Survey during 1979. Data from two wells do not provide a comprehensive evaluation of sediment mineralogy, but they do provide a partial guide to what minerals may be present. Not all the samples have been analyzed as of the time of this writing and additional mineralogic data will be published in the future as basic data reports.

WELL 12N/01E-34Q

The mineralogy of sidewall samples from well 12N/01E-34Q was determined by optical microscope identification of the 0.5- to 0.125-mm size fraction. Table 13 shows the percent compositions of minerals, in this size range, for five samples collected from 323 feet to 897 feet. Data from an additional sample at 1,845 feet is also given. Feldspars compose an average of about two-thirds of the mineral grains, with about one-fifth being quartz and one-tenth being rock fragments. In all the shallower samples, the percent plagioclase having an anorthite content greater than 34 percent is smaller in the fine fraction than in the medium. The sample from 1,845 feet has an unusually small amount of anorthite-rich plagioclase in the medium fraction. The albitic plagioclase component increases between medium and fine fractions in all but one sample. The smaller size fractions, which are chemically more reactive, are dominated by albitic plagioclase.

Lithic fragments from a gravel at 1,856 feet, having a distinct greenish hue, were examined by X-ray diffraction. The sample near this depth was unusually rich in heavy lithic fragments (table 13). X-ray analysis of these fragments indicates that the composition is quartz, plagioclase, and chlorite (Ivan Barnes, U.S. Geological Survey, personal commun., 1979). The mineralogy of the sediments determined by optical methods may not reflect the complete mineralogy, especially where some minerals are contained in rock fragments which are not differentiated mineralogically. Mineral phases identified in samples from this well are shown in table 14.

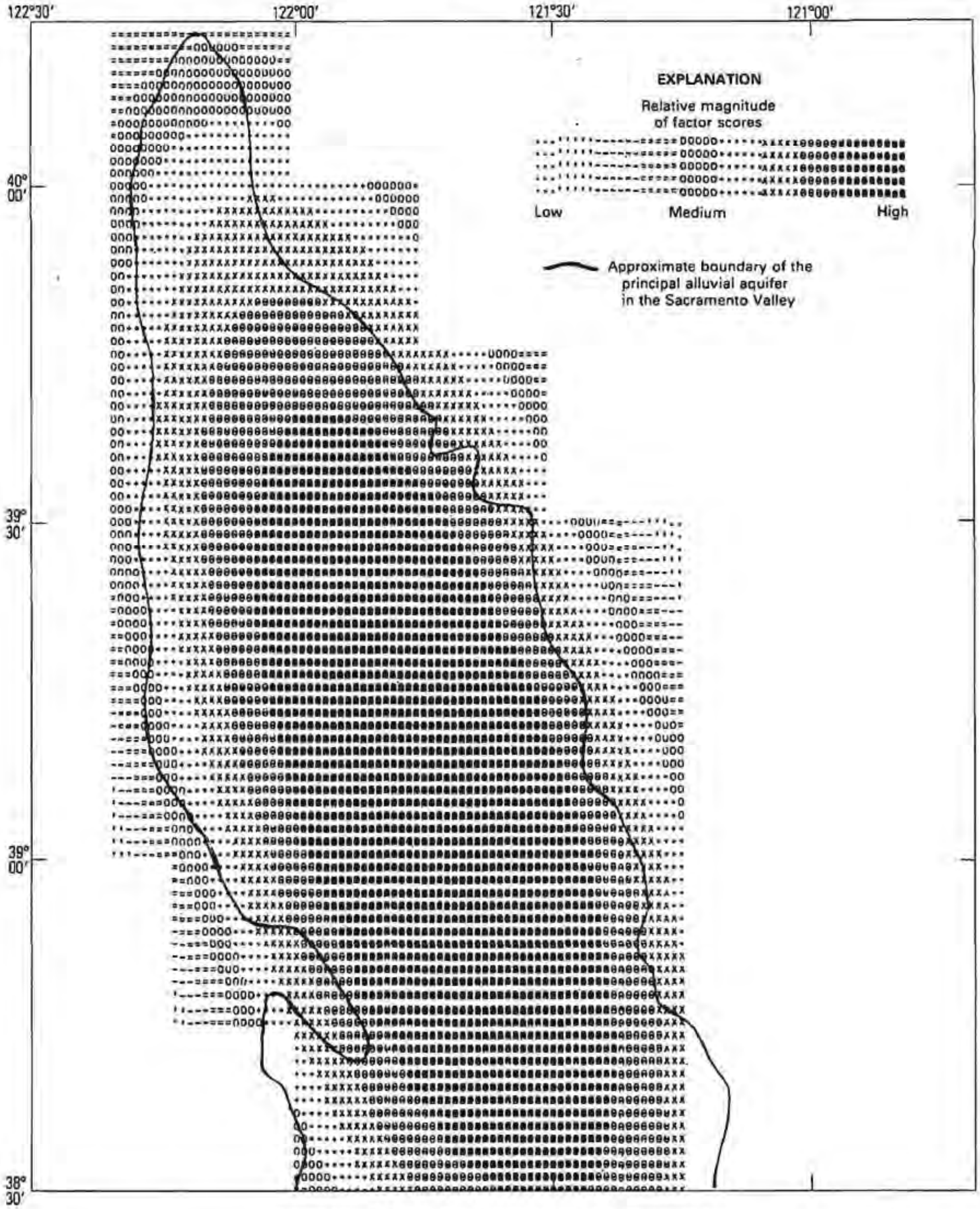

FIGURE 10.—Trend surface of factor scores for component two.

WELL 19N/01W–32G

The mineralogy of a number of fine-grained layers was determined by X-ray diffraction analysis of sidewall samples from well 19N/01W–32G. The results of the analyses are shown in table 15. Below a depth of about 562 feet, a large component of X-ray amorphous material is present in the sediments. Whether this is primary volcanic glass or an intermediate weathering

TABLE 12.—*Dissolved-oxygen concentrations in well water in the south alluvial fans facies*

Well	Date	Dissolved oxygen (mg/L)
08N/03E–05N04M	08–01–79	1.9
08N/03E–06M01M	08–01–79	2.0
08N/01E–06B01M	07–31–79	5.9
08N/01E–17C01M	07–26–79	5.0
09N/03E–31L01M	08–01–79	2.0
09N/02E–18N01M	07–31–79	4.4
09N/02E–33E01M	07–31–79	7.8
09N/01E–35H02M	07–31–79	3.8
09N/01W–25M01M	07–31–79	3.2
10N/02E–03E01M	07–25–79	2.8
11N/01W–01D01M	07–25–79	3.5
Mean		3.8

product, such as an amorphous aluminosilicate (Paces, 1978) was not investigated. The two clay minerals present in quantity are halloysite and illite. The presence of halloysite rather than kaolinite was determined using transmission electron microscopy. Figure 11 shows an electron micrograph of sediments from the 407-foot depth. The tubular structures at the center and top of the figure are halloysite, with poorly formed flakes of illite also visible. The dark, blocky particles are fine-grained quartz and plagioclase.

Optical examination of sand-size grains shows that the mineralogy is consistent with an andesitic sand. The major mineral is plagioclase, which is zoned and shows etching. Some pyroxenes are present and are clear to light green. Many of the grains are stained by ferric hydroxides.

SATURATION INDICES

According to the law of mass action, when an aqueous solution is in equilibrium with a mineral, the ion-activity product for that mineral will equal the thermodynamic equilibrium constant. The degree of saturation of a water can be represented by the saturation index (*SI*), which is the logarithm of the quotient of the ion-activity product (*IAP*) divided by the equilibrium constant (*K*):

$$SI = \mathrm{Log}\,\frac{IAP}{K}, \qquad (1)$$

where

SI=saturation index

IAP=ion-activity product, and

K=thermodynamic equilibrium constant.

The saturation index has a value of zero when the solution is in equilibrium with a solid phase. A positive saturation index indicates supersaturation and a negative index undersaturation with respect to some mineral. Minerals that are present in an aquifer and have negative saturation indices can dissolve. Minerals that have positive saturation indices may precipitate from solution, although whether this actually occurs depends on additional factors. By examining the saturation indices of water samples collected from the Sacramento Valley, some idea can be obtained about which minerals may be influencing ground-water chemistry.

TABLE 13.—*Mineralogic compositions of sidewall samples from U.S. Geological Survey test well 12N/01E–34Q*

c—coarse >0.5 mm.
m—medium 0.5–0.25 mm.
f—fine 0.25–0.125 mm.
vf—very fine 0.125–0.0625 mm.
p—pan <0.0625 mm.

VAB—very abundant, from 25–50 percent of the heavy minerals.
AB—abundant, from 10–25 percent of the heavy minerals.
SP—sparse, from 1–4 percent of the heavy minerals.

Sample depth, in feet	323		467		685		788		897		1845	
Texture, in percent c/m/f/vf/p	7/2/41/34/17		2/2/8/43/45		3/5/19/38/36		60/22/10/3/5		8/52/28/4/8		59/18/6/4/12	
Size interval	m	f	m	f	m	f	m	f	m	f	m	f
Composition, in percent:												
Potassium feldspar	12	13	6	16	27	13	15	14	15	12	10	12
Plagioclase (Anorthite<34)	25	44	40	33	22	32	21	36	28	39	19	24
Plagioclase (Anorthite>34)	28	10	24	14	25	16	23	12	23	14	3	13
Quartz	20	23	20	28	20	26	21	18	7	13	31	18
Lithic fragments	11	10	7	6	4	10	14	13	21	12	21	11
Heavy minerals[1]	3	1	3	3	2	2	5	6	6	13	15	23
Nonopaque heavy grains:												
Sausserite	VAB		VAB		VAB		VAB		AB		AB	
Uralite	VAB		VAB		VAB		VAB		AB		AB	
Goethite	VAB		VAB		VAB		VAB		AB		AB	
Lithic fragments	AB		SP		SP		AB		AB		VAB	

[1] Heavy minerals have specific gravities greater than 2.9.

TABLE 14.—*Minerals identified in sidewall samples from U.S. Geological Survey test well 12N/01E–34Q, in alphabetical order*

Actinolite-tremolite (series)[1]
Amphiboles
Analcite
Apatite
Augite-ferroaugite (series)[1]
Basic glass
Biotite
Bronzite-ferrohypersthene (series)[1]
Chlorite
Chromite
Chrysotile
Clinozoisite
Cordierite
Cummingtonite
Diopside-hedenbergite (series)[1]
Enstatite-bronzite (series)[1]
Epidote
Fluorite
Garnet (red)
Glauconite
Glaucophane
Graphite
Hematite (some specular)
Hercynite
Hornblende (green, brown, and oxy-varieties)
Hypersthene
Lawsonite
Marcasite
Pigeonite
Plagioclase (series)[1]
Potash feldspar (undifferentiated)
Pumpellyite
Richterite (part of series)[1]
Riebeckite
Serpentine (?)
Sideromelane
Sphene (titanite)
Spinel
Staurolite
Zircon
Zoisite

[1] "Series" means several varieties within the series were found.

Saturation indices were calculated for 271 water analyses selected from those published by Fogelman (1975, 1976) and Fogelman and Rockwell (1977). Of the 271, 153 had aluminum analyses and 183 had iron analyses. Temperature, pH, and alkalinity were determined in the field. Samples for cation determinations were passed through a 0.1-micrometer filter and acidified with concentrated nitric acid. Some controversy exists as to the validity of aluminum and iron data gathered in this manner; however, the possible error introduced is generally small (Kennedy and others, 1974; Barnes, 1975). Some of the supersaturation in the aluminosilicate and iron minerals may be due to particulate iron and aluminum passing through the filter. Saturation indices were calculated using WATEQF (Plummer, and others, 1978).

Table 16 shows the mean, minimum, and maximum saturation indices for selected mineral phases along with log equilibrium constants at 20°C, the average temperature of ground waters in the Sacramento Valley. Although many minerals, such as the feldspars and montmorillonite, show variations in chemical composition, saturation indices were calculated for ideal mineral phases. Therefore, stability calculations for these minerals only approximate actual conditions, but they do provide useful indicators of the types of reactions that may be occurring.

TABLE 15.—*Percent mineral composition of sidewall samples from U.S. Geological Survey test well 19N/01W–32G*

[Tr, trace; unid., unidentified; inter., intermediate; ND, not detected]

Depth (feet)	Quartz	Plagioclase	Amorphous	Halloysite	Illite	Other
260	35–45	25–35	ND	15–20	5–10	Tr unid.
353	40	15–20	ND	10–15	ND	Tr minor.
407	35–40	20–25	ND	10–15	2–5	Tr minor.
478	35–40	25–30	ND	10–15	5–10	5–10 Chlorite.
562	10–20	15–25	Major	5–15	2–5	ND.
630	20–25	15–20	Inter.	5–10	2–10	Tr unid.
930	15–20	10–15	Inter.	10–15	5–10	ND.
984	5–15	5–10	Major	10–15	1–5	Tr unid.
1,098	5–10	5–10	Major	5–10	1–5	ND.
1,193	5–15	5–10	Major	5–10	1–5	Tr minor.
1,390	5–10	2–5	Major	2–5	2–5	ND.

Most waters are close to saturation with respect to silicaglass, as might be expected from the volcanic detritus in the sediments. All samples were supersaturated with respect to amorphous ferric hydroxide, which may reflect the variability in solubility with particle size or particulate iron passing through the 0.1-micrometer filter during sampling. The waters tend to be at saturation with respect to gibbsite and slightly below saturation with respect to amorphous aluminum hydroxide.

Ground water is fairly close to saturation with respect to the carbonate minerals, calcite, dolomite, and magnesite. No carbonate minerals were recorded in sediments from either of the wells examined for mineralogy. Apparently, the formation of secondary carbonate minerals is of limited extent despite a number of samples indicating supersaturation with respect to calcite.

Potassium and sodium feldspars, which are abundant in the sediments, average close to saturation in Sacramento Valley ground water. Dissolution of these phases probably contributes to water chemistry where ground water is undersaturated with respect to these feldspars. All water samples are undersaturated with respect to anorthite, which is less abundant in the sediments. Halloysite is the only clay mineral with which the ground water is not supersaturated. Any of the other clay minerals could potentially form from most of the waters. When stability fields are considered, however, only one phase will be the most stable. These phase relations can be illustrated using activity diagrams.

ACTIVITY DIAGRAMS

Activity diagrams can be used to illustrate the phase relations among primary and secondary minerals and to predict the most stable secondary phases as a function of water chemistry. Such diagrams have been used by Feth, Roberson, and Polzer (1964), Tardy (1971) and White (1979) to depict weathering reactions in ground

FIGURE 11.—Electron micrograph of sediments from the 407-foot depth of well 19N/01W–32G. (Photograph by Technology of Materials, Santa Barbara, Calif.)

waters. The technique for calculating such diagrams is given in Garrels and Christ (1965), and Helgeson, Brown, and Leeper (1969) give numerous examples of such diagrams. A slightly different type of diagram, though basically similar, was presented by Kittrick (1969), and it depicts equilibrium between solid phases and an aqueous solution.

As an example of the calculation of the equilibrium boundary between two phases, the calculation of the phase boundary between illite and montmorillonite is given below. Formulas for these minerals are taken from WATEQF (Plummer, and others, 1978). For the reaction illite ⇆ montmorillonite, the chemical equation is written

TABLE 16.—*Mean, minimum, and maximum saturation indices in Sacramento Valley ground water for selected mineral phases*

Phase[1]	n	[2]Log *K* at 20 °C	Saturation index		
			Mean	Minimum	Maximum
Silica glass	271	–3.07	–0.14	–0.58	0.16
$Fe(OH)_3$ amorph.	183	4.885	1.31	.62	3.67
$Al(OH)_3$ amorph.	153	–31.77	–1.13	–2.32	.03
Gibbsite	153	–32.95	.05	–1.16	1.22
Fluorite	269	–11.02	–2.38	–3.50	–0.10
Hydroxyapatite	270	–59.57	–2.22	–7.57	1.64
Strengite	183	–26.37	–0.61	–2.06	1.05
Calcite	271	–8.45	–0.33	–1.80	.50
Dolomite	271	–16.92	–0.54	–3.37	1.24
Magnesite	271	–8.16	–0.53	–1.96	.43
Adularia	153	–20.96	.22	–1.81	1.66
Albite	153	–18.32	–0.82	–2.93	.47
Anorthite	153	–19.55	–3.27	–5.95	–1.77
Halloysite	153	–33.38	–0.89	–3.76	1.38
Kaolinite	153	–37.52	3.26	.32	5.58
Illite	153	–40.99	2.31	–1.33	4.53
Montmorillonites:					
1. Calcium	153	–45.73	3.40	–0.37	5.84
2. Belle Fouche.	95	[3]–34.97	7.49	4.04	9.01
3. Aberdeen	95	[3]–29.69	6.69	3.43	8.10
Muscovite	153	–49.94	1.35	–3.12	4.61
Chlorite	153	–91.29	–1.83	–12.11	3.52

[1] Chemical formulas for these phases are as written in WATEQF (Plummer and others, 1978.)

[2] Data from the latest version of WATEQF.

[3] The log equilibrium constant at 25°C is used because no enthalpy is given in WATEQF.

$$\begin{aligned}&(K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2)+2.48H_4SiO_4\\ &\qquad +0.52Fe^{+3}+0.45Mg^{+2}\leftrightarrows\\ &3.13H_2O+0.6K^{+1}+1.86H^{+1}\\ &\qquad +1.56(H_{0.42}Mg_{0.46}Fe_{0.34}Al_{1.47}Si_{3.82}O_{10}(OH)_2). \quad (2)\end{aligned}$$

At the phase boundary, the ion-activity product for this reaction will equal the equilibrium constant (*K*):

$$\frac{[K^{+1}]^{0.6}[H^{+1}]^{1.86}}{[H_4SiO_4]^{2.48}[Fe^{+3}]^{0.52}[Mg^{+2}]^{0.45}}=K. \quad (3)$$

Brackets denote free ion activities, which are concentrations corrected for the nonideality of aqueous solutions. Rewriting in terms of log activities gives the equation:

$$\begin{aligned}&0.61\log[K^{+1}]/[H^{+1}]-0.52\log[Fe^{+3}]/[H^{+1}]^3\\ &-0.45\log[Mg^{+2}]/[H^{+1}]^2-2.48\log[H_4SiO_4]=\log K. \quad (4)\end{aligned}$$

To plot this line on a two-dimensional graph, the equation must be reduced to two variables. The assumptions that may be considered when plotting phase diagrams include (1) controlling the concentration of a component by equilibrium with a solid phase, (2) conserving a component in solid phases during phase transformations, and (3) assigning a specified concentration for a species in solution, commonly the average for that species in the study area.

In all plots below, it is assumed that the logarithm of the activity quotient of free ferric iron to hydrogen cubed ($\log [Fe^{+3}]/[H^{+1}]^3$) is controlled by the solubility of amorphous ferric hydroxide at 4.885 (Plummer and others, 1978). The average for the log activity ratio of potassium to hydrogen ($\log [K^{+1}]/[H^{+1}]$) in the valley is 2.75, and ratio of magnesium to hydrogen squared ($\log [Mg^{+2}]/[H^{+1}]^2$) is 11.25. The average log activity of silica in ground waters is -3.21. The use of these averages where a concentration must be assumed in the calculation of a phase transformation does not significantly affect the depicted relations between data points and phase boundaries in the following activity diagrams.

For the equilibrium between illite and montmorillonite, $\log [Fe^{\ 3}]/[H^{+1}]^3$ is assumed to be controlled by the solubility of ferric hydroxide, and $\log [H_4SiO_4]$ is assigned a value of -3.21. Replacing these quantities in equation 4 gives the following equation for the phase boundary between illite and montmorillonite:

$$\log [K^{+1}]/[H^{+1}]=0.122+0.743\log [Mg^{+2}]/[H^{+1}]^2. \quad (5)$$

Two types of diagrams are presented here to illustrate phase relations in the system $MgO\text{-}K_2O\text{-}Fe_2O_3\text{-}Al_2O_3\text{-}SiO_2\text{-}H_2O$. The diagrams depart, to some extent, from the traditional presentation in that metastable phases are included. Recent work by Paces (1973, 1978) and Busenberg (1978) indicates that during the weathering of feldspars, the initial solids formed are amorphous to poorly crystalline aluminosilicates which may be reversible with respect to the aqueous solution. Subsequent crystallization results in the formation of a metastable aluminosilicate commonly called halloysite. Eventually, the thermodynamically most stable mineral will form. This pathway between primary and secondary minerals generally follows Ostwald's Rule (Darken and Gurry, 1953), which states that when a system is proceeding from a less to a more stable state, the final most stable state is not necessarily reached directly but may be attained through a series of intermediate states. Neither halloysite nor illite are stable with respect to montmorillonite or kaolinite, yet they are present in the sediments. Activity diagrams showing metastable states indicate the intermediate steps, as well as the final secondary minerals that are expected to form.

All minerals included in the following diagrams are from WATEQF and have formulas and log equilibrium constants from that program. Because no information is available on the chemistry of clay minerals from the Sacramento Valley, particularly illite and montmorillonite, no better substitute is available. This use of surrogate minerals will introduce some uncertainty in the exact locations of phase boundaries in the diagrams. Considering the uncertainty in the knowledge of thermodynamic data on montmorillonites and illites, it is doubtful if full knowledge of mineral chemistry would improve the situation. The montmorillonite used in all the diagrams is Aberdeen montmorillonite (Kittrick, 1971) with modifications by Truesdell and Jones (1974).

Figure 12 shows the stability fields of minerals as a function of $pH\text{-}\frac{1}{3}pAl^{+3}$ and $p[H_4SiO_4]$, where p stands for -log as in $pH=-\log [H^{+1}]$, and $pAl^{+3}=-\log [Al^{+3}]$. This diagram depicts the formation of secondary minerals from an aqueous solution. The solution, in this case, is assumed to have the average ion activity ratios and silica activity observed in the Sacramento Valley. No solid phase will form from solutions with low aluminum to hydrogen ratios and low silica concentrations (bottom right corner of figure 12). At higher aluminum to hydrogen ratios, the stable solid phase changes from gibbsite to kaolinite to montmorillonite with increasing silica. Halloysite and amorphous aluminum hydroxide phase boundaries are dashed to emphasize that they are both metastable phases. A solution in equilibrium with halloysite will be supersaturated with respect to montmorillonite or kaolinite. All samples from the valley plot in the montmorillonite stability field. Only 10 percent of the samples are supersaturated with respect to halloysite.

Regression analysis was used to determine if any significant linear relation exists between aluminum and silica. Each hydrochemical facies was treated separately to preserve as much detail as possible. Only two of the regression equations were significant, those for the Tuscan volcanic rocks and the Sutter Basin facies.

The equation for the Tuscan volcanic rocks facies is

$$pH\text{-}\tfrac{1}{3}pAl^{+3}=2.10+0.39p\,[H_4SiO_4] \qquad (6)$$

with r^2 equal to 0.26 and coefficients and their 90 percent confidence limits of

$$2.10\pm0.83$$

and

$$0.39\pm0.27.$$

Rewriting the equation in terms of log activities gives

$$0.33\log [Al^{+3}]/[H^{+1}]^3=2.10\text{-}0.39\log [H_4SiO_4]. \qquad (7)$$

The inverse relation between the aluminum to hydrogen ratio and silica is indicative of control by a mineral phase. As silica increases in solution, $\log [Al^{+3}]/[H^{+1}]^3$ decreases to compensate.

The slope is close to and not significantly different from 0.33. Assuming that it is 0.33 and rearranging gives

$$\frac{[Al^{+3}][H_4SiO_4]}{[H^{+1}]^3}=10^{6.31}. \qquad (8)$$

The solution of halloysite or kaolinite is given by the equation:

$$\tfrac{1}{2}Al_2Si_2O_5(OH)_4+3H^{+1}\leftrightharpoons\tfrac{1}{2}H_2O+Al^{+3}+H_4SiO_4. \qquad (9)$$

The ion activity product is

$$\frac{[Al^{+3}][H_4SiO_4]}{[H^{+1}]^3}=K. \qquad (10)$$

For halloysite log K equals 6.83 and for kaolinite, 4.76. The close agreement between the ion activity product of halloysite in ground water from the Tuscan volcanic rocks facies with the equilibrium constant is strong evidence that halloysite is controlling the aluminum and silica concentrations in ground water.

The Sutter Basin hydrochemical facies also showed a significant relation between $pH\text{-}\frac{1}{3}pAl^{+3}$ and $p[H_4SiO_4]$.

$$pH-\tfrac{1}{3}pAl^{+3}=6.13-0.92p[H_4SiO_4] \qquad (11)$$

with r^2 equal to 0.27 and coefficients and their 90 percent confidence limits of

$$6.13\pm2.91$$

and

$$0.92\pm0.91.$$

Rewriting the equation in terms of log activities gives

$$0.33\log [Al^{+3}]/[H^{+1}]^3=6.13+0.92\log [H_4SiO_4]. \qquad (12)$$

The positive slope is indicative of solution control of water chemistry, with both aluminum and silica increasing as some mineral phase is attacked by hydrogen ion. The slope is close to and not significantly different from one. This gives an aluminum to silica ratio in the dissolving phase of 1 to 3. The most likely minerals are, therefore, potassium and sodium feldspars, which have an aluminum to silica ratio of 1 to 3. This aluminum to silica ratio, along with the etched surfaces of feldspar grains observed under the microscope, may reflect stoichiometric dissolution of feldspars as found by Holdren and Berner (1979) and Berner and Holdren (1979).

Figure 13 shows the phase stability fields for minerals in terms of the log activity ratios of magnesium to

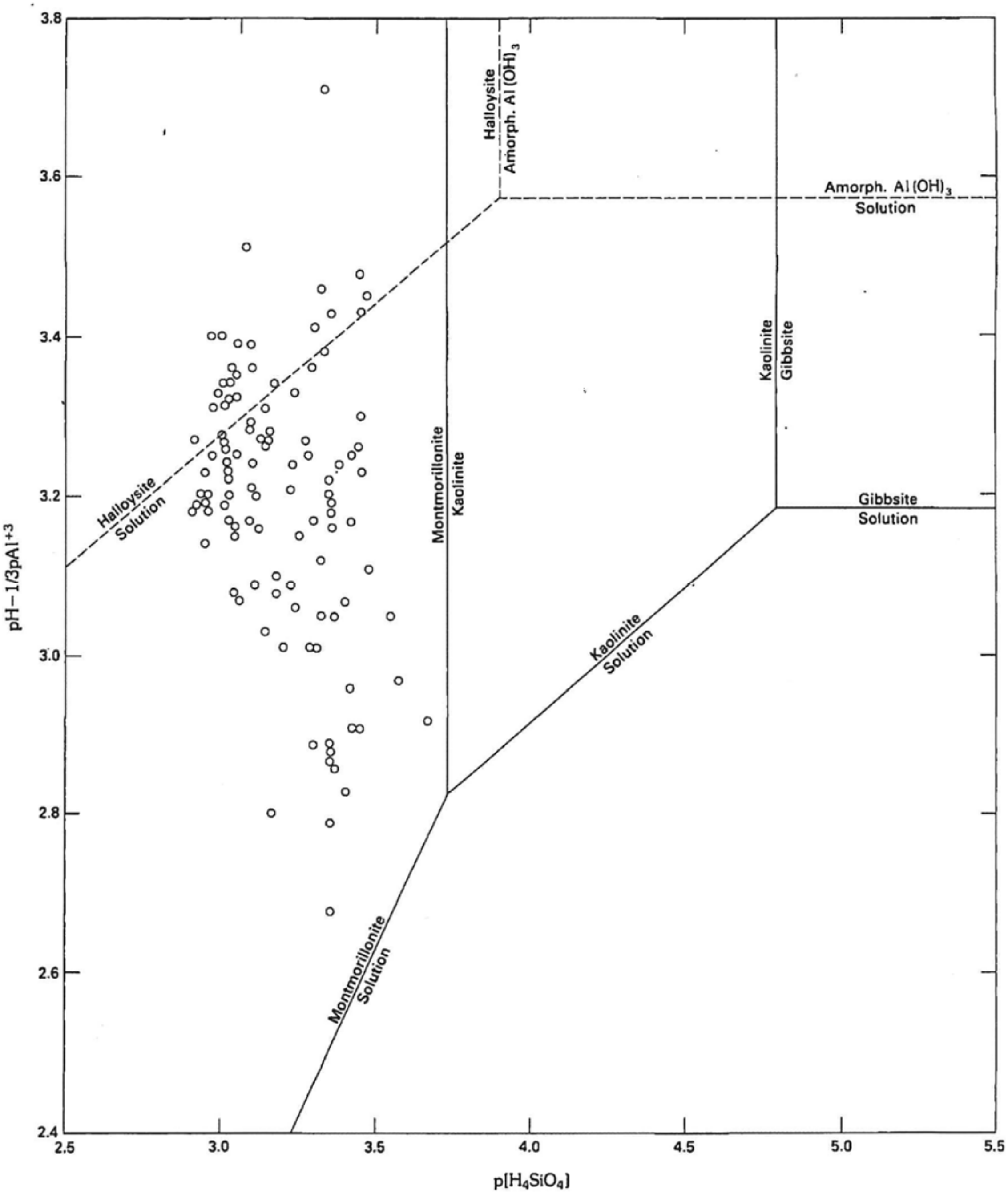

FIGURE 12.—Phase relations among minerals and aqueous solution in terms of pH-⅓pAl^{+3} and p[H_4SiO_4] at 20°C. (NOTE.—The aqueous solution is assumed to have the following ion activity ratios: log $[Fe^{+3}]/[H^{+1}]^3$ =4.885, log $[K^{+1}]/[H^{+1}]$=2.75, and log $[Mg^{+2}]/[H^{+1}]^2$=11.25.)

hydrogen squared and potassium to hydrogen. Aluminum is assumed to be strictly conserved in solid phases during phase transformations. Assumptions about iron and silica activities are as described at the beginning of this section on activity diagrams.

Figure 13 is actually two diagrams superimposed, so that illite, a metastable phase, can be shown. Illite is unstable with respect to montmorillonite or adularia if the three phases are considered simultaneously. The solid lines represent phase relations among the minerals

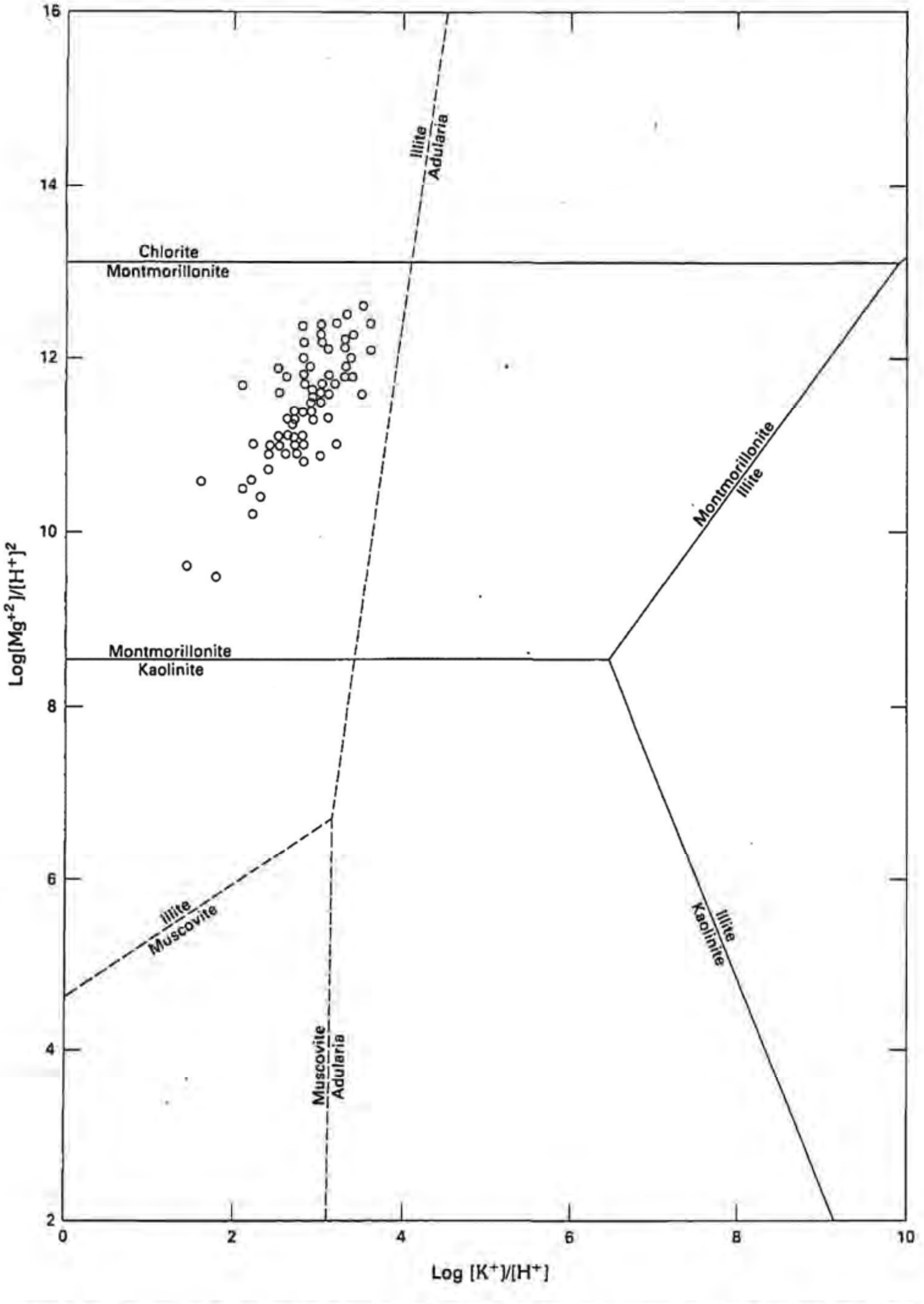

FIGURE 13.—Phase relations among minerals and coexisting aqueous solution in terms of log $[Mg^{+2}]/[H^{+1}]^2$ and log $[K^{+1}]/[H^{+1}]$ at 20°C. (NOTE.—Phase relations among chlorite, montmorillonite, illite, and kaolinite are shown by solid lines, and among illite, adularia, and muscovite by dashed lines. The aqueous solution is assumed to have the following activities of dissolved species: log $[Fe^{+3}]/[H^{+1}]^3=4.885$, log $[H_4SiO_4]=-3.21$.)

chlorite, montmorillonite, illite, and kaolinite. Among these minerals, montmorillonite is the most stable phase in equilibrium with ground water in the valley. The dashed lines represent phase relations among adularia, muscovite, and illite. Of these three minerals, illite is the most stable in contact with Sacramento Valley ground waters.

Illite is highly resistant to weathering (Berner, 1971), and most of the illite found in samples from well 19N/01W-32G is probably detrital. Some of the illite may have formed from the weathering of primary minerals. Illite has been reported to form from orthoclase (Stumm and Morgan, 1970) and from muscovite (Berner, 1971).

Log activities from ground water in the Sacramento Valley plot in the stability field of a montmorillonite having the formula and stability of Aberdeen montmorillonite. Differences in activity ratios of ions in solution will probably produce montmorillonites of somewhat different composition in the Sacramento Valley, but some form of montmorillonite will be the most stable phase. Metastable phases either form as intermediate steps during the diagenesis of primary minerals (halloysite) or persist due to resistance to weathering (illite).

SUMMARY AND CONCLUSIONS

Shallow sediments in the Sacramento Valley were laid down as alluvial deposits in a freshwater environment. These sediments, from which ground-water samples were collected, have always been in contact with freshwater. Sediments along the valley margins are coarse grained, poorly sorted, and oxidized. In the central part of the valley, flood-basin deposits are finer grained and reduced. Most of the streams entering the valley are losing streams, at least over part of their courses, and much of the ground-water recharge is from this source.

The chemistry of ground water in the valley is greatly influenced by the chemistry of this recharge from the valley margins. Approximately one-third of the variation in ground-water chemistry can be attributed to this effect. The reducing conditions and finer grained sediments in the midvalley flood basins also influence ground-water chemistry. These processes have distinct spatial patterns that produce spatial variations in the chemical character of ground water in different areas.

Six areas, or hydrochemical facies, were delineated on the basis of geology, hydrology, and distinctions in chemical composition of ground water. Two of the facies lie along the eastern margin and receive recharge from the Cascade Range and Sierra Nevada. These waters are low in dissolved solids and high in silica. Two facies are located in the midvalley flood basins, and reducing conditions there produce higher concentrations of iron, manganese, and arsenic in the ground water. While the relative concentrations of these species are higher in the flood basins than in the rest of the valley, the absolute concentrations remain fairly low. Upwelling of saline water from underlying marine sediments contributes to high dissolved-solids concentrations in ground water in the southern parts of the flood basins.

Water along the west side of the valley is low in silica, and the water grades from moderate dissolved-solids levels in the north to high dissolved-solids levels in the south. Ground water in the southwest of the valley is also high in boron. The source of the high boron and dissolved-solids concentrations is thermal springs in the Coast Ranges. Two facies were delineated along the western margin to separate the waters having moderate and high dissolved solids. Because of the heterogeneity of ground-water chemistry in the valley, division into areas having more uniform chemical compositions provides additional detail in any investigation of water chemistry.

Dissolved-solids and nitrate concentrations were examined for linear trends with time for each of the hydrochemical facies. Significant increases in both were observed in parts of the valley. On the east side of the valley, the Tuscan volcanic rocks facies showed a significant increase in dissolved solids of 0.95 (mg/L)/yr but no significant change in nitrate concentrations. The Victor Plain facies showed significant increases in both dissolved solids [1.6 (mg/L)/yr] and nitrate-nitrogen [0.036 (mg/L)/yr]. Neither Butte Basin nor Sutter Basin hydrochemical facies, in the midvalley flood basins, showed a significant trend in nitrate with time. There were very few wells with multiple nitrate measurements, however, and the lack of significant changes may be due to the small sample size. Dissolved-solids concentrations in Butte Basin have been increasing at an average rate of 1.37 (mg/L)/yr, but are unchanged in Sutter Basin.

Both the north and south alluvial fans facies, adjacent to the Coast Ranges, show significant upward trends in dissolved solids and nitrate. The south alluvial fans facies has the greatest rate of increase for dissolved solids [4.75 (mg/L)/yr] of all the facies, and the north alluvial fans facies has the greatest rate of increase for nitrate-nitrogen [0.099 (mg/L)/yr]. The midvalley basins have fine-grained poorly permeable soils that protect the ground water from contamination. Infiltration rates are slow, and reducing conditions permit the removal of nitrate by denitrification reactions. Along the valley margins, however, significant increases in dissolved solids and nitrates have occurred since the mid-1950's.

Alkali feldspars and halloysite appear to be the most significant aluminosilicate minerals affecting water chemistry. Where waters are undersaturated, dissolution of feldspars takes place, bringing the water to near saturation with respect to adularia and albite. There is a general parallel increase in aluminum and silica reflecting the solution of aluminosilicates by ground water. In Sutter Basin, the relation between log $[Al^{+3}]/[H^{+1}]^3$ and log $[H_4SiO_4]$ indicates an increase in both aluminum and silica at a ratio 1 to 3. In the Tuscan volcanic rocks facies, the relation between log $[Al^{+3}]/[H^{+1}]^3$ and log $[H_4SiO_4]$ is inverse. Rearranging the regression equation yields the same equation as for equilibrium between halloysite and an aqueous solution. The regression constant is very close to the equilibrium constant for halloysite, which supports the theory of solubility control by halloysite. Illite and halloysite were identified in sediments from the Sacramento Valley. Neither of these clay minerals is stable in the ground-water environment. The most stable clay minerals in equilibrium ground water of the valley is montmorillonite. Halloysite occurs as a mestastable intermediate step in the weathering of primary minerals to stable secondary minerals.

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U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Orchard Irrigation in Sutter-Yuba Area

STATE OF CALIFORNIA
EARL WARREN
GOVERNOR

PUBLICATION OF
STATE WATER RESOURCES BOARD

Bulletin No. 6

SUTTER-YUBA COUNTIES INVESTIGATION

September, 1952

Additional copies of this publication may be obtained from Documents Section, Division of Printing, 11th and O Streets, Sacramento

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EARL WARREN
GOVERNOR

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A. D. EDMONSTON, STATE ENGINEER
SECRETARY

August 27, 1952

ADDRESS ALL COMMUNICATIONS TO THE SECRETARY

HONORABLE EARL WARREN, *Governor, and*
Members of the Legislature of
the State of California

GENTLEMEN: I have the honor to transmit herewith Bulletin No. 6 of the State Water Resources Board, entitled "Sutter-Yuba Counties Investigation," as authorized by Chapter 1514, Statutes of 1945, as amended.

Under provisions of the cited statute, an agreement dated October 7, 1947, was entered into between the State Water Resources Board, the Counties of Sutter and Yuba, and the Department of Public Works acting through the agency of the State Engineer. The agreement provided for

> ". . . investigation and report on the underground water supply of the valley floor in the Counties of Sutter and Yuba, including quality, replenishment and utilization thereof, and, if possible, a method or methods of solving the problems involved . . .",

and authorized funds to meet the costs of the investigation for one year. A supplemental agreement executed by the same parties on December 3, 1948, authorized funds to complete the investigation and report.

The Sutter-Yuba Counties Investigation was conducted and Bulletin No. 6 was prepared by the Division of Water Resources of the Department of Public Works, under the direction of the State Water Resources Board. Funds to meet the cost of investigation and report were provided as follows: State of California (State Water Resources Board), $20,000; County of Sutter, $10,000; and County of Yuba, $10,000. Additional funds provided by the Legislature have been expended by the State Water Resources Board in connection with the current State-Wide Water Resources Investigation, certain results of which were used in connection with the Sutter-Yuba Counties Investigation.

Bulletin No. 6 contains an inventory of the underground and surface water resources of the valley floor in the Counties of Sutter and Yuba, estimates of present and probable ultimate water utilization, estimates of present and probable ultimate supplemental water requirements, and preliminary plans and cost estimates for water development works.

Very truly yours,

C. A. Griffith
Chairman

ACKNOWLEDGMENT

Valuable assistance and data used in the investigation were contributed by agencies of the Federal Government, cities, counties, public districts, and by private companies and individuals. This cooperation is gratefully acknowledged.

Special mention is also made of the helpful cooperation of the Boards of Supervisors of the Counties of Sutter and Yuba, the Sutter County Water Council, the Yuba County Water Development Association, the Yuba County Farm Advisor, the California Water Service Company, and the Pacific Gas and Electric Company.

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CHAPTER I

INTRODUCTION

In common with many other parts of California, the area under this investigation has recently experienced an increase in water utilization, and as a result is confronted with a need for more complete conservation of its water resources. An accelerated increase in ground water use in recent years, combined with progressive lowering of pumping levels and deterioration in quality of water at a number of wells, has brought about local concern regarding the adequacy of the ground water resources of Sutter and Yuba Counties.

AUTHORIZATION FOR INVESTIGATION

In consideration of the adverse ground water situation in Sutter and Yuba Counties, members of the Sutter County Water Council and the Yuba County Water Development Committee appeared before the State Water Resources Board at Sacramento on August 1, 1947, and proposed a state-county cooperative survey of ground water supplies of valley floor lands of the two counties. The Board referred the request to the State Engineer for preliminary examination and report on the need for such an investigation, and an estimate of its scope, duration, and cost.

The State Water Resources Board on September 5, 1947, approved a recommendation by the State Engineer, based on findings of the preliminary examination, for a two-year cooperative investigation, and authorized negotiation of an agreement with local agencies. The agreement, between the State Water Resources Board, the Counties of Sutter and Yuba, and the State Department of Public Works acting through the agency of the State Engineer, was executed on October 7, 1947. It provided that the work under the agreement "shall consist of investigation and report on the underground water supply of the valley floor lands in the Counties of Sutter and Yuba, including quality, replenishment and utilization thereof, and, if possible, a method or methods of solving the problems involved." This agreement authorized the provision of funds to meet the costs of investigation for one year. A supplemental agreement executed by the same parties on December 3, 1948, authorized funds to complete the investigation and report.

Funds to meet the costs of the investigation and report to the extent of $40,000 were provided as follows: State of California (State Water Resources Board), $20,000; County of Sutter, $10,000; and County of Yuba, $10,000. Additional funds have been expended in investigation of the Sutter-Yuba Area by the State Water Resources Board in connection with the current State-wide Water Resources Investigation, certain results of which have been used in connection with the Sutter-Yuba Counties Investigation.

Copies of the two agreements between the State Water Resources Board, the Counties of Sutter and Yuba, and the Department of Public Works, are included in Appendix A.

RELATED INVESTIGATIONS AND REPORTS

The following reports of prior investigations, containing information pertinent to evaluation of ground water problems in Sutter and Yuba Counties, were reviewed in connection with the current investigation:

"Soil Survey of the Marysville Area, California, 1909," by A. T. Strahorn, W. W. Mackie, L. C. Holmes, H. L. Westover, and Cornelius Van Duyne. Bureau of Soils, United States Department of Agriculture. October 25, 1911.

"Geology and Ground Water Resources of the Sacramento Valley, California," by Kirk Bryan. United States Geological Survey, Water-Supply Paper 495. 1923.

"Preliminary Report on the Proposed Sutter Irrigation District," by Milo B. Williams, Consulting Engineer. Typewritten. March 12, 1931.

"Report on Ground Water Conditions in the Proposed Sutter Irrigation District," by S. T. Harding, Consulting Engineer. Unpublished. November, 1931.

"Sacramento River Basin," Bulletin No. 26, Division of Water Resources, California State Department of Public Works. 1931.

"Memorandum on Ground Water Conditions in Area of Proposed Sutter Irrigation District During 1932," by S. T. Harding, Consulting Engineer. Unpublished. February, 1933.

"Sacramento Valley Water Investigations — Agricultural Aspects," Bureau of Agricultural Economics, United States Department of Agriculture. Mimeographed. March, 1944.

"Salt-Balance Conditions of Reclamation District No. 1500 in Sutter Basin for the Year Ending December 31, 1946," by L. V. Wilcox. Mimeographed. June, 1947.

"Salt-Balance Conditions of Reclamation District No. 1500 in Sutter Basin for the Year Ending December 31, 1947," by L. V. Wilcox. Mimeographed. April, 1948.

"Water Resources of California," Bulletin No. 1, California State Water Resources Board. 1951.

The Division of Water Resources is presently conducting surveys and studies for the State-wide Water Resources Investigation, authorized by Chapter 1541, Statutes of 1947. This investigation, under direction of the State Water Resources Board, has as its objective the formulation of The California Water Plan for full conservation, control, and utilization of the State's water resources to meet present and future water needs for all beneficial purposes and uses in all parts of the State insofar as practicable. Surveys and studies are also being conducted by the Division of Water Resources for the Survey of Mountainous Areas, authorized by Chapter 30, Statutes of 1947. This investigation, which is coordinated with the state-wide investigation, has as its primary objective the determination of probable ultimate water requirements of certain counties of the Sierra Nevada, and the formulation of plans for projects which will meet those requirements. Results of both of the foregoing investigations will have direct bearing on solutions to the water problems of the Sutter-Yuba Area, particularly with regard to plans to meet supplemental water requirements of the area under ultimate conditions of cultural development.

SCOPE OF INVESTIGATION AND REPORT

It has been stated that under provisions of the authorizing agreements the general objectives of the Sutter-Yuba Counties Investigation included investigation and study of the underground water supply of valley floor lands in the investigational area, including quality, replenishment and utilization thereof, and, if possible, a method or methods of solving the water problems involved. In attaining these objectives it was necessary that the scope of the investigation include full consideration of surface as well as ground water supplies, and that it involve determination of present and ultimate water utilization and supplemental water requirements.

Field work in the investigational area, and office studies, as authorized by the initial and supplemental cooperative agreements, commenced in October, 1947, and continued into 1952.

In the course of the investigation, available precipitation and stream flow records were collected and compiled in order to evaluate water supplies available to the investigational area. Five new stream gaging stations were installed and maintained to supplement the available hydrographic data. These stations were on Pleasant Grove Creek at Lincoln Road, Auburn Ravine at Highway 99E, Coon Creek at Highway 99E, Dry Creek near Waldo, and South Honcut Creek at La Porte Road.

In order to determine ground water storage capacity and yield, geologic features of the ground water basin underlying the investigational area were investigated and reported on by the Ground Water Branch of the United States Geological Survey, under terms of a cooperative agreement with the Department of Public Works. This survey included the collection and study of about 700 well logs throughout the area. The report of the Geological Survey is included as Appendix B.

The effects of draft on and replenishment of the ground water basin were determined by measurements of static ground water levels made at about 850 wells during each spring and fall of the period of investigation. These wells were chosen to form a comprehensive measuring grid over the entire area. In addition, measurements to determine monthly fluctuations of water levels were made at approximately 90 control wells.

Present land use in the investigational area was determined by a complete survey of all culture on valley floor lands. This survey was conducted in 1948, and checked in 1949 to determine changes. The total area surveyed was about 327,000 acres. The cultural survey data were used in conjunction with available data on unit water use to determine total present water utilization in the investigational area.

In order to determine future water utilization, all valley floor lands were classified with regard to their suitability for irrigated agriculture. This involved collection, field checking, and re-evaluation of land classification data from the United States Bureau of Reclamation, supplemented by data from field surveys conducted by the Division of Water Resources.

Current irrigation practices in the investigational area were surveyed in order to determine unit application of water to important crops on lands of various soil types. During the 1948 irrigation season records of application of water were collected at 35 plots, and during the following season at 21 plots. The data collected included records of pump discharge, acreage served, crops irrigated, number and period of irrigations, and amount of water applied.

Studies were made of the mineral quality of surface and ground waters, in order to evaluate their suitability for irrigation use, and to determine the cause of degradation in their mineral quality during recent years. Data used in these studies included some 200 partial and 38 complete mineral analyses of ground water from wells. In addition, a large number of analyses of surface water supplies, covering the period since 1943, were collected and studied.

Field reconnaissance surveys, including geologic examinations, were made to locate and evaluate possible dam and reservoir sites for conservation of surface runoff. Reconnaissance surveys were also made of possible routes for conveyance of water to areas of use.

Results of the Sutter-Yuba Counties Investigation are presented in this report in the four ensuing chapters. Chapter II, "Water Supply," contains evaluations of precipitation, surface and subsurface inflow and outflow, and imports of water. It also includes results of investigation and study of the ground water basin, and contains data regarding mineral quality of surface and ground waters. Chapter III, "Water Utilization and Supplemental Requirements," includes data and estimates of present and probable ultimate land use and water utilization, and contains estimates of present and probable ultimate supplemental water requirements. It also includes available data on demands for water with respect to rates, times, and places of delivery. Chapter IV, "Plans for Water Development," describes preliminary plans for conservation and utilization of available water supplies to meet supplemental water requirements, including operation and yield studies, design considerations and criteria, and cost estimates. Chapter V, "Conclusions and Recommendations," includes conclusions and recommendations resulting from the investigation and studies.

AREA UNDER INVESTIGATION

The area under investigation comprises those portions of the valley floor of Sutter and Yuba Counties which are in whole or in part served by ground water, and has been designated the "Sutter-Yuba Area." It includes the portions of Sutter County situated east of Feather River, Sutter By-pass, and a north-south line through the center of Sutter Buttes. It includes the portion of Yuba County lying on the Sacramento Valley floor from Feather River on the west to a line marking the approximate limit of the ground water service area near the base of the foothills on the east.

The Sutter-Yuba Area is situated on the east side of the central portion of the Sacramento Valley, and its southern boundary is about 10 miles north of the City of Sacramento. The area extends north and south for a distance of about 39 miles, varying in width from about 6 to about 19 miles. Its location is indicated on Plate 1, "Location of Sutter-Yuba Area," and the area is shown in greater detail on Plate 2, entitled "Hydrologic Zones and Organized Water Agencies, 1952."

In order to facilitate reference to its several parts, the Sutter-Yuba Area was divided into four principal zones, based on geographical considerations and on respective types of water service and sources of water supply. These were designated "West Side Zone," "Northeast Zone," "East Central Zone," and "South Side Zone," and are shown on Plate 2. The West Side Zone embraces the area between the Butte-Sutter county line and Nicolaus, and west of Feather River. The Northeast Zone consists of lands between Honcut Creek and Yuba River, and east of Feather River. Similarly, the East Central Zone consists of lands between the Yuba and Bear Rivers, and east of Feather River. The South Side Zone comprises those lands lying between Bear River and the Sutter-Sacramento county line, and east of the Feather and Sacramento Rivers. As shown on Plate 2, the West Side Zone was further subdivided into the area generally devoted to orchards and served by ground water, herein designated the "Peach Bowl," and the remainder of the zone which is largely served by surface water.

Drainage Basin

The eastern portion of the Sutter-Yuba Area comprises a gently rolling plain, which merges into nearly flat land over a large part of the central and western portions. The general ground surface slopes gently from east to west. Included valley floor lands lie below an elevation of about 100 feet. The Sutter Buttes, located in the northwest corner of the area, rise to 2,132 feet above sea level.

All watersheds on the west slope of the Sierra Nevada that head between Donner and Fredonyer Passes are tributary to the Sutter-Yuba Area. Their combined drainage areas total about 5,600 square miles. In order of importance, the principal tributary stream systems are those of the Feather, Yuba, and Bear Rivers. Minor tributary streams include Honcut, Dry, Coon, and Pleasant Grove Creeks, and Markham and Auburn Ravines. The extent of the various drainage basins is shown in the following tabulation:

Drainage basin	*Area, in square miles*
Feather River, above Oroville gaging station	3,611
Yuba River, above Smartville gaging station	1,194
Bear River, above gaging station near Wheatland	294
Minor streams, above valley floor, from Wyman Ravine to Pleasant Grove Creek	500
TOTAL	5,600

The tributary watersheds are in a zone of relatively heavy precipitation, and their aggregate mean seasonal natural runoff during the 53-year period from 1894-95 to 1946-47 is estimated to have approximated 1,360 acre-feet per square mile.

The Feather River traverses and roughly bisects the Sutter-Yuba Area from north to south, and joins the Sacramento River near Verona. The Yuba and Bear Rivers are tributary to the Feather within this reach, as are Honcut Creek and Nigger Jack Slough. Reeds, Hutchinson, and Dry Creeks, drain the East Central Zone and are tributary to Bear River within the area. Coon and Pleasant Grove Creeks and Markham and Auburn Ravines drain into Sacramento River near Verona by way of the Cross Canal. Gilsizer Slough, which flows more or less parallel to the Feather River through the West Side Zone and into Sutter By-pass, and Nigger Jack Slough are important as natural surface drains. Wadsworth Canal and its tributaries, together with other minor channels, drain the portion of the West Side Zone outside the Peach Bowl, discharging into Sutter By-pass.

Climate

The climate of the Sutter-Yuba Area is characterized by dry summers with high daytime temperatures and warm nights, and wet winters with moderate temperatures. More than 80 percent of the precipitation occurs during the five-month period from November to March, inclusive. The growing season is long, the 40-year recorded average for Marysville, centrally located in the area, being 273 days between killing frosts. Temperatures at Marysville have ranged from 16° F. to 118° F., and the monthly average for the period from 1871 to 1948 ranges from 46.9° F. in January to 79.3° F. in July.

Geology

The geologic formations of the Sutter-Yuba Area include pre-Cretaceous metamorphic and igneous rocks of the Sierra Nevada block, which extends beneath the valley fill, overlain principally by Tertiary sedimentary formations derived from these and other rocks which are exposed in the Sierra Nevada to the east. The sedimentary rocks are of both marine and continental origin and are frequently interbedded with tuff-breccias. Volcanic rocks are also represented in the area in and about the Sutter Buttes, which are erosional remnants of an extinct Pliocene volcano. Only the sedimentary rocks can be considered as being water-bearing to any appreciable degree. The principal aquifers are composed of continental sediments of Pleistocene and Recent age. These consist of as much as 100 feet of Pleistocene sands and gravels overlain by up to 125 feet of Recent alluvial fan, flood plain, and stream channel deposits.

Soils

Soils of the Sutter-Yuba Area vary in their chemical and physical properties in accordance with differences in parent material, drainage, and age or degree of development since their deposition. The soils may be divided into two broad groups: (1) those derived from recent alluvial depositions, and (2) those derived from old alluvial fans or terraces. The first group may be further divided into stream bottom soils and basin soils.

Stream bottom soils occupy the flood plains immediately adjacent to stream channels generally throughout the area. They consist of unmodified to slightly modified alluvial deposits. These soils are highly productive and suited to a wide variety of crops, and have the highest agricultural value.

Basin soils of the Sutter-Yuba Area occupy large flat basin-like areas in the southwest portion of the West Side Zone and western portion of the South Side Zone. These basin soils are derived largely from fine-grained depositions by flood flows, and have developed under poor drainage conditions. Those areas of basin soils that have been drained and protected by levees from flooding are suitable for production of rice and other shallow-rooted crops.

Soils that have developed from old alluvial fans or terraces occupy most of the remainder of the Sutter-Yuba Area. These soils have undergone considerable physical and chemical change since their deposition and are entirely underlain by hardpan. They are restricted in their agricultural use by the depth of soil over the hardpan, and are only suited to the production of shallow-rooted crops.

Present Development

Development of the eastern portion of the Sacramento Valley has centered in the Sutter-Yuba Area since the first settlements early in the Nineteenth Century. Marysville became an important transportation center during the Gold Rush period, being the head of river traffic to the mining areas. The Counties of Sutter and Yuba embrace a rich agricultural region, and both irrigation and dry farming are of major importance.

The 1950 federal census showed that the population of Sutter County was 26,140, and that of Yuba County 24,240. The principal urban centers, Marysville and Yuba City, are situated only about two miles apart, near the confluence of the Yuba and Feather Rivers, and account for some 31 percent of the total population of the two counties. The 1950 census enumerated 7,856 persons in Yuba City, while 7,777 were counted in Marysville. Wheatland and Live Oak are the largest of a number of small communities, and the rural population is distributed generally throughout the area.

Agricultural development in the Sutter-Yuba Area is said to have begun with the growing of grain about 1845 near the site of Captain John A. Sutter's Hock Farm, south of Yuba City. Early agriculture on the valley floor was stimulated by the influx of settlers during and after the gold rush, but for many years was largely restricted to the growing of dry-farmed grain crops and stock raising. By 1865, a large portion of the area was given over to the production of wheat. Irrigation developed slowly, but it is probable that the first lands on the east side of the Sacramento Valley to receive irrigation water were near the confluence of Honcut Creek and Feather River. Diminishing profits from grain farming, together with the development of more satisfactory pumping plants, gave impetus to the increase in irrigated acreage after 1910. The transition from dry farming to irrigated cropping has continued to this time.

A survey conducted in 1949 as a part of the current investigation showed that irrigated lands in the Sutter-Yuba Area totaled about 149,000 acres, while approximately 140,000 acres were dry-farmed or fallow. Principal irrigated crops, in order of acreage devoted to each crop, were deciduous orchard consisting largely of peaches, and rice, permanent pasture, beans, and alfalfa. Principal dry-farmed crops were barley and wheat.

Industry in the Sutter-Yuba Area is supported largely by agricultural production. About 100 plants are operated during the harvest seasons to can and dehydrate fruits and vegetables, and to dry fruits, nuts, rice, and seed crops. Packing houses for packing fresh fruits and melons, and cold storage and refrigeration plants, have also been established. Several lumber reprocessing and molding plants near Marysville produce finished lumber and by-products. Sand and gravel works supply local demand for aggregates, while concrete pipe, generally used in irrigation distribution systems, is manufactured locally. A large gold dredging field is situated near the edge of the valley floor at Hammonton, south of Yuba River. Electric energy is available from nearby hydroelectric installations.

Water service agencies in the Sutter-Yuba Area are described in Chapter III. However, many public agencies have been organized in the area to deal with the problems of land reclamation and drainage. The provisions of California reclamation district laws have been used extensively to effect the unwatering of low lands and their protection from overflow. Active reclamation districts in the area and data concerning them are listed in the following tabulation:

Reclamation district	*Year organized*	*County*	*Gross area of district, in acres*
No. 10	1913	Yuba	11,300
No. 777	1907	Sutter	12,500
No. 784 (Plumas Lake)	1908	Yuba	19,600
No. 803 (Rideout)	1909	Sutter	2,000
No. 817	1910	Yuba	3,120
No. 823 (Marcuse)	1911	Sutter	2,800
No. 1000 (Natomas)	1911	Sutter, Sacramento	55,100
No. 1001 (Natomas)	1911	Sutter, Placer	31,200
No. 2054	1921	Sutter, Butte	12,900
No. 2056	1921	Sutter, Butte	9,100
No. 2066 (Abbott Lake)	1924	Sutter	609

Portions of Sutter and Yuba Counties are within the boundaries of the Sacramento and San Joaquin Drainage District, which comprises practically all swamp and overflow lands of both the Sacramento and San Joaquin Valleys. This large district was formed in 1911. Two levee districts in Sutter County, organized during the period of early agricultural development, built levees to protect eastern Sutter Basin lands from floods and overflow of Feather River. These districts, Sutter County Levee District No. 1, organized in 1873, and Sutter County Levee District No. 2, organized in 1879, contain 44,000 and 17,500 acres, respectively. The Sutter By-pass, and levees of the Feather and Yuba Rivers, are parts of the Sacramento River Flood Control Project. The function of Sutter By-pass is to receive and convey excess flood waters of Sacramento River and Butte Basin through Sutter Basin.

Areas included within the boundaries of the foregoing agencies, together with water service agencies in the Sutter-Yuba Area, are shown on Plate 2.

CHAPTER II

WATER SUPPLY

The sources of water supply of the Sutter-Yuba Area are direct precipitation on overlying lands, tributary surface and subsurface inflow, and imports by surface canals of water for irrigation. The water supply of the area is considered and evaluated in this chapter under the general headings "Precipitation," "Runoff," "Imported and Exported Water," "Underground Hydrology," and "Quality of Water."

The following terms are used as defined in connection with the discussion of water supply in this report:

Annual—This refers to the 12-month period from January 1st of a given year through December 31st of the same year, sometimes termed the "calendar year."

Seasonal—This refers to any 12-month period other than the calendar year.

Precipitation Season—This refers to the 12-month period from July 1st of a given year through June 30th of the following year.

Runoff Season—This refers to the 12-month period from October 1st of a given year through September 30th of the following year.

Investigational Seasons—This is used in reference to the two runoff seasons of 1947-48 and 1948-49, during which most of the field work on the Sutter-Yuba Counties Investigation was performed.

Mean Period—This is used in reference to periods chosen to represent conditions of water supply and climate over a long period of years.

Base Period—This is used in reference to periods chosen for detailed hydrologic analysis because prevailing conditions of water supply and climate were approximately equivalent to mean conditions, and because adequate data for such hydrologic analysis were available.

In studies for the current State-wide Water Resources Investigation it was determined that the 50 years from 1897-98 to 1946-47, inclusive, constituted the most satisfactory period for estimating mean seasonal precipitation generally throughout California. Similarly, the 53-year period from 1894-95 to 1946-47, inclusive, was selected for determining mean seasonal runoff. In studies for the Sutter-Yuba Area, conditions during these periods were considered representative of mean conditions of water supply and climate.

Studies were made to select a base period for hydrologic analysis of the Sutter-Yuba Area during which conditions of water supply and climate would approximate mean conditions, and for which adequate data on inflow, outflow, and ground water levels would be available. It was determined that the nine-year period from 1939-40 to 1947-48, inclusive, was the most satisfactory in this respect. Conditions during this chosen base period so closely approached conditions prevailing during the mean period that they were considered to be equivalent. For this reason, determined relationships between base period water supply and present and probable ultimate water utilization were assumed to be equivalent to corresponding relationships which might be expected under mean conditions of water supply and climate.

PRECIPITATION

The Sutter-Yuba Area lies within the southern fringe of storms which periodically sweep inland from the North Pacific during winter months. Although the rainfall resulting from these storms is moderate on the average, direct precipitation provides a substantial portion of the water supply of the area.

Precipitation Stations and Records

Fifteen precipitation stations in or adjacent to the Sutter-Yuba Area have unbroken records of 10 years duration or longer. These stations are fairly well distributed areally and their records were sufficient to provide an adequate pattern of precipitation. All of the records of precipitation have been published in bulletins of the United States Weather Bureau, with exception of the record obtained by the Sutter Basin Corporation for the station at Robbins. The Robbins record is included as Appendix C to this report. Locations of the precipitation stations are shown on Plate 3, "Lines of Equal Mean Seasonal Precipitation," with map reference numbers corresponding to those utilized in State Water Resources Board Bulletin No. 1, "Water Resources of California." The stations and map reference numbers are listed in Table 1, together with elevations of the stations, periods and sources of record, and mean, maximum, and minimum seasonal precipitation. In those instances where it was necessary, precipitation records were extended to cover the 50-year mean period by comparison with records of nearby stations having records covering this period.

Precipitation Characteristics

Because of the uniformity of the general precipitation pattern in the Sutter-Yuba Area, as indicated on Plate 3, and the central location of Marysville, precipitation at Marysville was considered to be fairly representative of rainfall over the area. A record of precipitation at Marysville was available from a United States Weather Bureau station maintained since

TABLE 1

MEAN, MAXIMUM, AND MINIMUM SEASONAL PRECIPITATION AT SELECTED STATIONS IN OR NEAR SUTTER-YUBA AREA

Map reference number	Station	Elevation, in feet	Period of record	Source of record	Mean seasonal precipitation, in inches	Maximum and minimum seasonal precipitation	
						Season	Inches
5-69	Biggs	98	1899-1916	USWB	*21.04	1913-1914 1911-1912	21.20 12.29
5-76	Camptonville	2,850	1907-1951	USWB	*64.17	1908-1909 1923-1924	108.30 30.13
5-75	Chute Camp	1,250	1907-1940	USWB	*54.74	1937-1938 1923-1924	78.17 23.87
5-73	Colgate	700	1907-1951	USWB	*39.92	1940-1941 1923-1924	56.61 18.51
5-82	Colusa	60	1871-1951	USWB	15.89	1940-1941 1938-1939	31.65 6.78
5-74	Dobbins	1,650	1904-1946	USWB	*41.03	1906-1907 1923-1924	64.28 20.13
5-70	Gridley	97	1884-1951	USWB	24.00	1889-1890 1897-1898	47.00 12.34
5-97	Marysville	61	1871-1951	USWB	20.68	1889-1890 1884-1885	38.91 8.15
5-107	Nicolaus	46	1912-1951	USWB	*18.32	1940-1941 1912-1913	32.46 7.07
5-62	Oroville	250	1884-1951	USWB	27.27	1889-1890 1930-1931	49.64 14.71
5-71	Palermo	213	1891-1914	USWB	*23.29	1904-1905 1897-1898	32.77 10.94
5-106	Robbins	20	1926-1951	SBCo	*16.81	1940-1941 1930-1931	31.93 9.51
5-120	Rocklin	239	1870-1951	USWB	23.14	1906-1907 1923-1924	38.63 10.42
5-131	Sacramento	69	1849-1951	USWB	16.37	1852-1853 1850-1851	36.35 4.71
5-98	Wheatland	84	1887-1945	USWB	*20.84	1889-1890 1887-1888	33.69 11.07

* Estimated.
SBCo—Sutter Basin Corporation.
USWB—United States Weather Bureau.

1871-72. Recorded seasonal precipitation at this station is presented in Table 2 and shown on Plate 4, "Recorded Seasonal Precipitation at Marysville, 1871-72 Through 1950-51."

Precipitation in the Sutter-Yuba Area consists almost entirely of rainfall and snowfall is rare. It increases generally from west to east, as is shown on Plate 3, except on the Sutter Buttes where a sharp rise in elevation probably results in relatively heavy precipitation. Mean seasonal depth of precipitation ranges from about 18 inches along the western boundary of the area to about 23 inches at its extreme easterly limit. At Nicolaus in the southern portion of the area mean seasonal precipitation is about 18 inches, whereas at Biggs, about eight miles north of the area, it is approximately 21 inches.

Precipitation varies over wide limits from season to season, ranging from less than 40 percent of the seasonal mean to nearly 200 percent. Maximum seasonal precipitation at Marysville occurred in 1889-90 when 38.91 inches of rain were recorded. In 1884-85, the minimum season at this station, precipitation was only 8.15 inches. Long-term trends in precipitation in the Sutter-Yuba Area are indicated on Plate 5, "Accumulated Departure From Mean Seasonal Precipitation at Marysville."

More than 80 percent of the seasonal precipitation in the Sutter-Yuba Area occurs during the five months from November through March on the average, and the summers are dry. Mean monthly distribution of precipitation as recorded at Marysville is presented in Table 3.

TABLE 2

RECORDED SEASONAL PRECIPITATION AT MARYSVILLE 1871-72 THROUGH 1950-51

(In inches)

Season	Precipitation	Season	Precipitation	Season	Precipitation
1871-1872	21.57	1899-1900	28.07	1929-1930	20.81
73	13.10	01	24.02	31	12.40
74	27.74	02	20.54	32	17.35
		03	21.26	33	12.64
1874-1875	13.68	04	22.50	34	14.10
76	17.36				
77	12.16	1904-1905	26.50	1934-1935	23.33
78	23.74	06	27.76	36	22.79
79	15.76	07	32.25	37	21.88
		08	16.91	38	28.26
1879-1880	18.93	09	20.72	39	9.76
81	17.43				
82	14.38	1909-1910	19.48	1939-1940	27.32
83	15.25	11	26.42	41	33.28
84	15.28	12	11.76	42	29.13
		13	13.76	43	21.43
1884-1885	8.15	14	28.54	44	20.02
86	22.27				
87	12.80	1914-1915	27.57	1944-1945	19.72
88	14.28	16	21.69	46	17.33
89	23.28	17	16.17	47	15.21
		18	12.56	48	17.60
1889-1890	38.91	19	21.52	49	15.51
19	15.72				
92	18.99	1919-1920	12.90	1949-1950	16.96
93	22.93	21	25.08	51	23.21
94	10.27	22	21.02	Average for 9-year base period, 1939-40 through 1947-48: 22.31	
		23	22.20		
1894-1895	26.83	24	11.53		
96	19.61				
97	17.77	1924-1925	25.82		
98	12.74	26	21.26	Mean for 50-year period, 1897-98 through 1946-47: 20.68	
99	16.53	27	26.59		
		28	17.28		
		29	14.04		
				Average for 80-year period of record, 1871-72 through 1950-51: 19.82	

TABLE 3

MEAN MONTHLY DISTRIBUTION OF PRECIPITATION AT MARYSVILLE

Month	Precipitation		Month	Precipitation	
	In inches	In percent of seasonal total		In inches	In percent of seasonal total
July	0.00	0.0	January	4.16	20.1
August	0.00	0.0	February	3.97	19.2
September	0.27	1.3	March	2.67	12.9
October	0.93	4.5	April	1.34	6.5
November	2.23	10.8	May	0.74	3.6
December	4.14	20.0	June	0.23	1.1
			TOTALS	20.68	100.0

Quantity of Precipitation

The mean seasonal quantity of precipitation in the Sutter-Yuba Area was estimated by plotting recorded or estimated mean seasonal depth of precipitation at stations in or near the area on a map. Lines of equal mean seasonal precipitation, or isohyets, were then drawn, as are shown on Plate 3. By planimetering the areas between these isohyets, the weighted mean seasonal depth and total quantity of precipitation were estimated.

In order to determine seasonal depth and quantity of precipitation during the base period and investigational seasons, the foregoing estimates for the mean period were adjusted on the basis of recorded precipitation at Marysville. The results of the estimates are presented in Table 4, which also shows the precipitation index for the base period and each of the investigational seasons. The term "precipitation index" refers to the ratio of the amount of precipitation during a given season to the mean seasonal amount, and is expressed as a percentage.

TABLE 4

ESTIMATED WEIGHTED SEASONAL DEPTH AND TOTAL QUANTITY OF PRECIPITATION ON SUTTER-YUBA AREA

Season	Precipitation index	Precipitation	
		Depth, in inches	Quantity, in acre-feet
1947-48	89	18.2	529,000
1948-49	76	15.4	448,000
Average for 9-year base period, 1939-40 through 1947-48	107	21.8	635,000
Mean for 50-year period, 1897-98 through 1946-47	100	20.3	592,000

RUNOFF

Runoff from the highly productive watersheds of the Sierra Nevada constitutes the most important source of water supply available to the Sutter-Yuba Area. The Feather River, which traverses the area from north to south, is the principal tributary of the Sacramento River. The Feather River system, including the Yuba and Bear Rivers which join the Feather within the area, is largely unregulated and undeveloped and is a potential source of water to meet future requirements not only in the Sutter-Yuba Area but in water-deficient areas in other parts of California.

Stream Gaging Stations and Records

Available records of runoff of the principal streams of the Sutter-Yuba Area were sufficient in number, length, and reliability for purposes of required hydrographic studies. With respect to certain of the smaller streams, however, records of runoff were nonexistent or confined principally to measurements made during the investigational seasons. By comparison with records of nearby stations on major streams, adequate estimates were made of runoff of these smaller streams.

Table 5 lists those stream gaging stations pertinent to the hydrography of the Sutter-Yuba Area, together with their map reference numbers, drainage areas above stations where significant, and periods and sources of records. These stations are also shown on Plate 3. The map reference numbers for the first 11 stations listed correspond to those used in State Water Resources Board Bulletin No. 1, "Water Resources of California." New map reference numbers were assigned to the remaining stations listed. The last five stations listed in Table 5 were installed, operated, and maintained as a part of the Sutter-Yuba Counties Investigation. Most of the runoff records listed in Table 5 have been published by the United States Geological Survey in its Water-Supply Papers or by the Division of Water Resources in its Reports of Sacramento-San Joaquin Water Supervision. The following records have not been published elsewhere and are included in Appendix D to this report:

Coon Creek at Highway 99E—November, 1947–December, 1948
Auburn Ravine at Highway 99E—November, 1947–December, 1948
Dry Creek near Waldo—November, 1947–May, 1949
South Honcut Creek at La Porte Road—November, 1947–December, 1948

Runoff Characteristics

An excellent continuous record of flow of the Feather River at or near Oroville is available for the period since January, 1902, when a stream gaging station was established at Oroville by the United States Geological Survey. The station was moved five miles upstream in October, 1934, but without appreciable effect on characteristics of the record. Although this record does not provide an exact measure of flow of the Feather River into the Sutter-Yuba Area, it is the most important record of the Feather River system, and does reflect characteristics of tributary mountain runoff to the Sutter-Yuba Area.

Flow of the Feather River to the valley floor is impaired by operation of Lake Almanor and several smaller upstream reservoirs, and by operation of hydroelectric power plants. An estimate of the natural runoff of the Feather River at Oroville, as it would be if unaltered by upstream diversion, storage, importation, and exportation, is included in State Water Resources Board Bulletin No. 1, "Water Resources of California." This estimate, together with recorded seasonal runoff of the Feather River at or near Oroville, is presented in Table 6. The

TABLE 5

STREAM GAGING STATIONS IN OR NEAR SUTTER-YUBA AREA

Map reference number	Stream	Station	Drainage area, in square miles	Period of record	Source of record
5-192	Feather River	at Oroville	3,640	1902-1934	USGS
5-191	Feather River	near Oroville	3,611	1934-1951	USGS and DWR
5-193	Feather River	near Gridley		1944-1951	DWR
5-244	Feather River	at Nicolaus		1921-1942 1943-1951	USGS and DWR
5-234	Feather River	below Shanghai Bend		1944-1951	DWR
5-194	Feather River	at Yuba City		1944-1951	DWR
5-222	Yuba River	at Narrows Dam	1,110	1941-1951	USGS and DWR
5-233	Yuba River	at Marysville		1939-1951	USGS and DWR
5-228	Yuba River	at Smartville	1,201	1903-1941	USGS
5-227	Deer Creek	near Smartville	83.5	1935-1951	USGS and DWR
5-238	Bear River	near Wheatland	295	1928-1951	USGS and DWR
SY-1	Sutter Butte Canal	at Diversion		1923-1951	DWR
SY-2	Wadsworth Canal	near Sutter		1929-1951	DWR
SY-3	Pleasant Grove Creek	at Lincoln Road	12.5	1950-1951	DWR
SY-4	Auburn Ravine	at Highway 99E	34.6	1947-1951	DWR
SY-5	Coon Creek	at Highway 99E	82.5	1947-1951	DWR
SY-6	Dry Creek	near Waldo	69.4	1947-1949	DWR
SY-7	South Honcut Creek	at La Porte Road	68.6	1947-1949	DWR

USGS—United States Geological Survey.
DWR—Division of Water Resources.

estimate of natural flow is also shown graphically on Plate 6, "Estimated Seasonal Natural Runoff of Feather River at Oroville."

Estimates of natural flow of streams of the Feather River system indicate that average seasonal runoff during the nine-year base period approximated the seasonal mean during the 53-year period. For the Feather, Yuba, and Bear Rivers these estimates were obtained from State Water Resources Board Bulletin No. 1. Natural flow of minor streams, including those tributary to the Sutter-Yuba Area but not in the Feather River system, were estimated during the current investigation. The estimates of natural flow are presented in Table 7, together with runoff indices for the combined natural flow of the Feather River system. The term "runoff index" refers to the ratio of the amount of runoff during a given season to the mean seasonal amount, and is expressed as a percentage.

Discharge of streams of the Sierra Nevada which are tributary to the Sutter-Yuba Area varies between wide limits from season to season, and within the season. This is indicated by flow of the Feather River at

TABLE 6

RECORDED SEASONAL AND ESTIMATED NATURAL SEASONAL RUNOFF OF FEATHER RIVER AT OROVILLE

(In acre-feet)

Season	Recorded runoff at or near Oroville	Estimated natural runoff at Oroville
1894-1895		7,093,000
1895-1896		7,786,000
1896-1897		5,440,000
1897-1898		2,304,000
1898-1899		2,872,000
1899-1900		6,788,000
1900-1901		6,281,000
1901-1902		4,048,000
1902-1903	4,430,000	4,555,000
1903-1904	9,330,000	9,451,000
1904-1905	4,490,000	4,606,000
1905-1906	6,710,000	6,833,000
1906-1907	9,340,000	9,504,000
1907-1908	3,490,000	3,651,000
1908-1909	7,380,000	7,527,000
1909-1910	4,500,000	4,651,000
1910-1911	6,980,000	7,136,000
1911-1912	2,090,000	2,276,000
1912-1913	2,600,000	2,785,000
1913-1914	6,540,000	6,928,000
1914-1915	5,200,000	5,422,000
1915-1916	5,910,000	6,156,000
1916-1917	4,380,000	4,637,000
1917-1918	2,450,000	2,684,000
1918-1919	3,390,000	3,621,000
1919-1920	2,050,000	2,231,000
1920-1921	5,600,000	5,940,000
1921-1922	4,730,000	5,040,000
1922-1923	2,890,000	3,112,000
1923-1924	1,180,000	1,317,000
1924-1925	2,780,000	3,114,000
1925-1926	2,870,000	3,126,000
1926-1927	5,000,000	5,679,000
1927-1928	3,650,000	4,142,000
1928-1929	2,010,000	1,910,000
1929-1930	3,590,000	3,984,000
1930-1931	1,490,000	1,485,000
1931-1932	2,810,000	3,351,000
1932-1933	1,640,000	1,986,000
1933-1934	1,840,000	2,071,000
1934-1935	3,864,000	4,253,000
1935-1936	4,079,000	4,328,000
1936-1937	2,821,000	3,175,000
1937-1938	8,175,000	8,547,000
1938-1939	1,773,000	1,912,000
1939-1940	5,275,000	5,672,000
1940-1941	6,116,000	6,516,000
1941-1942	6,258,000	6,662,000
1942-1943	5,296,000	5,638,000
1943-1944	2,622,000	2,830,000
1944-1945	3,412,000	3,767,000
1945-1946	3,996,000	4,185,000
1946-1947	2,273,000	2,579,000
1947-1948	3,368,000	3,401,000
1948-1949	2,495,000	2,590,000
1949-1950	3,465,000	3,837,000
1950-1951	5,403,000	5,676,000

Mean seasonal natural runoff for 53-year mean period, 1894-95 through 1946-47: 4,596,000

TABLE 7

ESTIMATED SEASONAL NATURAL FLOW OF STREAMS OF THE FEATHER RIVER SYSTEM, 1939-40 THROUGH 1947-48

(In acre-feet)

Season	Runoff index	Feather River at Oroville	Yuba River at Smartville	Bear River at Wheatland	Minor streams	Combined flow
1939-1940	124	5,672,000	2,860,000	406,000	293,000	9,231,000
1940-1941	142	6,516,000	3,209,000	483,000	339,000	10,547,000
1941-1942	145	6,662,000	3,407,000	502,000	355,000	10,926,000
1942-1943	123	5,638,000	3,133,000	464,000	328,000	9,563,000
1943-1944	62	2,830,000	1,395,000	191,000	141,000	4,557,000
1944-1945	82	3,767,000	2,112,000	289,000	211,000	6,379,000
1945-1946	91	4,185,000	2,401,000	323,000	239,000	7,148,000
1946-1947	56	2,579,000	1,365,000	170,000	131,000	4,245,000
1947-1948	74	3,401,000	1,510,000	216,000	156,000	5,283,000
Average for 9-year base period, 1939-40 through 1947-48	100	4,583,000	2,377,000	339,000	244,000	7,542,000
Mean for 53-year period, 1894-95 through 1946-47	100	4,596,000	2,415,000	356,000	248,000	7,615,000

or near Oroville, where the maximum recorded seasonal runoff occurred in 1906-07 and amounted to more than 9,300,000 acre-feet. The minimum seasonal runoff recorded at this station occurred in 1923-24 and was less than 1,200,000 acre-feet. Maximum recorded instantaneous discharge was 230,000 second-feet on March 19, 1907, and the estimated minimum discharge was about 300 second-feet on November 9, 1931. Estimated mean monthly distribution of natural flow of the Feather River at Oroville is presented in Table 8.

TABLE 8

ESTIMATED MEAN MONTHLY DISTRIBUTION OF NATURAL FLOW OF FEATHER RIVER AT OROVILLE

Month	Runoff, in acre-feet	Percent of seasonal total
October	101,000	2.2
November	188,000	4.1
December	290,000	6.3
January	423,000	9.2
February	556,000	12.1
March	722,000	15.7
April	873,000	19.0
May	744,000	16.2
June	368,000	8.0
July	152,000	3.3
August	101,000	2.2
September	78,000	1.7
TOTALS	4,596,000	100.0

Quantity of Runoff

Available records of stream flow, including those obtained from measurements made in connection with the investigation, were sufficient to permit fairly reliable determination of surface inflow to and surface outflow from the Sutter-Yuba Area during the nine-year base period and during the two seasons of the investigation.

Surface inflow to the Sutter-Yuba Area from the Feather and Bear Rivers was directly measured at the stations near Gridley and near Wheatland, respectively. Inflow from Yuba River was determined by recorded flow at Smartville until the season of 1940-41, after which season that station was discontinued and inflow was determined as the combined flow of Yuba River at Narrows Dam and Deer Creek near Smartville. For seasons when records of inflow from South Honcut Creek at La Porte Road and French Dry Creek near Browns Valley were not available, inflow was estimated by correlation with the combined flow of Yuba River at Narrows Dam and Deer Creek near Smartville. Inflow to the area from Dry Creek near Waldo, Coon Creek at Highway 99E, Auburn Ravine at Highway 99E, and Pleasant Grove Creek at Lincoln Road, was estimated for seasons when records were not available by correlation with the flow of Bear River near Wheatland. Inflow to the area through the Sutter

TABLE 9

MEASURED AND ESTIMATED SEASONAL SURFACE INFLOW TO AND OUTFLOW FROM SUTTER-YUBA AREA, 1939-40 THROUGH 1948-49

(In acre-feet)

Source	Season										Average for 9-year base period, 1939-40 through 1947-48
	1939-40	1940-41	1941-42	1942-43	1943-44	1944-45	1945-46	1946-47	1947-48	1948-49	
Inflow											
Feather River	4,634,000	5,103,000	5,581,000	4,326,000	1,536,000	2,208,000	3,106,000	1,724,000	2,751,000	1,742,000	3,441,000
Yuba River	2,364,000	2,550,000	2,778,000	2,562,000	948,000	1,583,000	1,877,000	924,000	1,503,000	1,063,000	1,899,000
Bear River	411,000	505,000	516,000	494,000	149,000	314,000	368,000	151,000	208,000	197,000	346,000
Deer Creek	125,000	137,000	162,000	155,000	72,000	111,000	105,000	54,000	52,000	50,000	108,000
South Honcut Creek*	48,000	53,000	57,000	52,000	23,000	35,000	40,000	23,000	25,000	29,000	40,000
French Dry Creek†	91,000	102,000	108,000	100,000	45,000	67,000	76,000	44,000	48,000	35,000	76,000
Dry Creek*	39,000	46,000	48,000	44,000	18,000	28,000	31,000	16,000	21,000	18,000	32,000
Coon Creek*	35,000	42,000	43,000	40,000	17,000	25,000	28,000	15,000	19,000	36,000	29,000
Auburn Ravine*	71,000	85,000	88,000	81,000	34,000	51,000	57,000	30,000	38,000	47,000	59,000
Pleasant Grove Creek†	9,000	11,000	12,000	11,000	4,000	7,000	8,000	4,000	5,000	4,000	8,000
Snake Slough†	49,000	49,000	55,000	40,000	44,000	49,000	47,000	39,000	38,000	39,000	46,000
Sutter Butte Canal†	111,000	112,000	130,000	153,000	161,000	167,000	186,000	163,000	136,000	160,000	147,000
Minor Drainage†	10,000	11,000	12,000	11,000	4,000	7,000	8,000	4,000	5,000	5,000	8,000
TOTALS	7,997,000	8,806,000	9,590,000	8,069,000	3,055,000	4,652,000	5,937,000	3,191,000	4,849,000	3,425,000	6,239,000
Outflow											
Feather River	7,104,000	9,827,000	9,703,000	7,268,000	3,326,000	5,026,000	5,999,000	2,784,000	4,737,000	3,234,000	6,197,000
Wadsworth Canal	95,000	119,000	105,000	72,000	93,000	106,000	102,000	67,000	53,000	62,000	90,000
Drainage into Sutter By-Pass†	13,000	18,000	19,000	17,000	0	7,000	10,000	0	0	0	9,000
Cross Canal†	32,000	35,000	37,000	34,000	0	18,000	25,000	0	0	0	20,000
TOTALS	7,244,000	9,999,000	9,864,000	7,391,000	3,419,000	5,157,000	6,136,000	2,851,000	4,790,000	3,296,000	6,316,000

* Partially estimated.
† Estimated.

Butte Canal was estimated by adjusting measured diversions from Feather River on the basis of acreages of crops served each season within and outside the area. Inflow to the area from Snake Slough at Sanders Road during seasons of no record was estimated by correlation with flow in the Sutter Butte Canal. Inflow from minor unmeasured drainage areas was estimated by correlation with the flow of Bear River near Wheatland.

Surface outflow from the Sutter-Yuba Area in Feather River and the Wadsworth Canal was directly measured during the nine-year base period and during the investigational seasons at the stations at Nicolaus and near Sutter, respectively. Estimates of the net amount of outflow as drainage to the Sutter By-pass were based on partial records of pumping to and from the by-pass at pumping plants operated by the Division of Water Resources. Outflow from the Cross Canal was estimated by correlation with measured runoff of streams tributary to the canal, corrected for measured pumping diversions from the canal.

Measured and estimated seasonal surface inflow to and outflow from the Sutter-Yuba Area during the base period and during 1948-49 are presented in Table 9.

IMPORTED AND EXPORTED WATER

Water is imported to the Sutter-Yuba Area through the Sutter Butte Canal system for irrigation of lands in that portion of the West Side Zone outside of the Peach Bowl. This water is diverted from the Feather River at a point about 14 miles upstream from the north boundary of the area, and is conveyed in unlined canals through a service area situated along the right bank of the Feather River both inside and outside the Sutter-Yuba Area. The estimated amount of the import was 160,000 acre-feet during the 1948-49 season, and the estimated seasonal average during the base period was 147,000 acre-feet. These estimates are shown in Table 9. For purposes of current studies the Sutter Butte Canal import was considered to be a part of surface inflow to the Sutter-Yuba Area.

So far as was determined during the investigation, there is no record of export of water from the Sutter-Yuba Area.

UNDERGROUND HYDROLOGY

The Sutter-Yuba Area overlies a portion of the ground water basin of the Sacramento Valley, and water pumped from storage in the basin presently serves nearly two-thirds of the lands irrigated in the area. Percolation of rainfall, stream flow, and drainage from adjacent hills, and of the unconsumed portion of applied irrigation water, is the most important source of ground water replenishment.

The term "free ground water," as used in this report, generally refers to a body of ground water not overlain by impervious materials and moving under control of the water table slope. "Confined ground water" refers to a body of ground water overlain by material sufficiently impervious to sever free hydraulic connection with overlying water, and moving under pressure caused by the difference in head between intake and discharge areas of the confined water body. In areas of free ground water, the ground water basin provides regulatory storage to smooth out fluctuations in available water supplies, and changes in ground water storage are indicated by changes in ground water levels.

Data and information collected during the Sutter-Yuba Counties Investigation indicated that free ground water exists in present zones of pumping, although there may be some temporary or partial confinement in certain depth zones. Study of historic fluctuation of the water table in the Sutter-Yuba Area, under varying conditions of draft and replenishment, permitted a determination of changes in ground water storage in the basin, and its safe yield of water under stated conditions. Underground hydrology is discussed in this section under the following headings: "Ground Water Geology," "Specific Yield and Ground Water Storage Capacity," "Ground Water Levels," "Change in Ground Water Storage," "Subsurface Inflow and Outflow," "Yield of Wells," "High Water Table Areas," and "Safe Ground Water Yield."

Ground Water Geology

Geologic features of the ground water basin underlying the Sutter-Yuba Area were investigated by the Ground Water Branch of the United States Geological Survey, under terms of an agreement between that agency and the State Department of Public Works. Appendix B comprises a detailed report by the Geological Survey on ground water storage capacity, within given pumping lifts, and on geologic features of the Sutter-Yuba Area, with a general geologic map, four geologic cross-sections, and a map showing ground water storage units, prepared under the direction of Joseph F. Poland, District Geologist, by G. H. Davis and F. H. Olmsted. Portions of an abstract of the geologic report follow:

> "The Sutter-Yuba area occupies the east-central Sacramento Valley and part of the western foothills of the Sierra Nevada. The Sacramento Valley is a trough that has been receiving sediments from both sides since the middle part of Cretaceous time. Most of the sediments in the Sutter-Yuba area have been derived from the Sierra Nevada on the east, which is a block mountain range tilted about 1½° westward. Evidence indicates that the block continues westward beneath the sediments of the valley trough.
>
> "The Sutter Buttes, erosional remnants of a Pliocene volcano, occupy a circular area about 10 miles in diameter near the center of the Sacramento Valley.
>
> "Rocks exposed in the Sutter-Yuba area range in age from pre-Cretaceous metamorphic and igneous rocks of the Sierra Nevada block to Recent alluvium still undergoing deposition. The rocks may be divided into two general categories: (1) the basement complex of the Sierra Nevada, which extends beneath the Sacramento Valley at depth, and (2) the superjacent rocks; a sedimentary blanket of marine and continental deposits transported from the Sierra Nevada and deposited in the Great Valley trough.

Deep Well and Turbine Pump Installation in Sutter-Yuba Area

"The water-bearing deposits considered in this report are included in the superjacent rocks, although weathered and fractured zones in the basement complex contain small quantities of ground water. The marine sediments of Cretaceous and Tertiary age are penetrated by water wells in only a few places in the Sutter-Yuba area. Where marine sediments are encountered they are generally impervious and contain water of poor chemical quality.

"Volcanic activity in the Sierra Nevada during the Tertiary period produced tuff-breccia of mud-flow origin which are impermeable and yield little water, but interbedded volcanic sands and gravels are moderately permeable and yield water to deep wells in the Marysville, Wheatland, Roseville, and Camp Beale districts.

"Local volcanic activity at Sutter Buttes during the Pliocene epoch produced two principal groups of rocks: (1) intrusive rhyolite and andesite and vent tuffs of the central core; and (2) andesitic tuff-breccias that encircle the core. The core is hard and impervious, but sands and gravels interbedded with the tuff-breccias yield some water to wells in the Pennington and Sutter City district.

"Following the close of volcanic activity in the Sierra Nevada the streams deposited predominantly fine-grained sediments during the remainder of the Pliocene epoch. These old alluvial deposits underlie the dissected uplands or 'red lands' along the valley margin and extend westward beneath younger alluvial deposits. Poorly sorted alluvium composed of silt, clay, and cemented sand and gravel as much as 350 feet thick represent this time interval. Many wells penetrate thick sections of these materials, but well yields are low to moderate.

"Uplift of the Sierra block at the beginning of the Pleistocene epoch caused the deposition of coarser materials. Alluvium of Pleistocene age as much as 100 feet thick underlies the low plains of the Sutter-Yuba area. These deposits are moderately permeable throughout and tongues of sand and gravel provide large supplies of water to irrigation wells.

"Recent alluvium, defined as those materials undergoing deposition, falls into three general categories: (1) alluvial fans of the Sutter Buttes, (2) basin deposits, and (3) stream-channel deposits. Most of the alluvial-fan deposits of Sutter Buttes are poorly sorted and groundwater yields from them are low. Basin deposits consist of an accumulation of relatively impermeable clays and silts which have been laid down by overflow waters of the Sacramento and Feather Rivers. Generally these deposits produce little water. Stream-channel deposits of the major streams contain well sorted sands and gravels to depths of 125 feet. Well defined channels are found beneath the flood plains of the Feather, Yuba, and Bear Rivers. Wells penetrating these coarse deposits are highly productive."

Specific Yield and Ground Water Storage Capacity

The term "specific yield," when used in connection with ground water, refers to the ratio of the volume of water a saturated soil will yield by gravity to its own volume, and is commonly expressed as a percentage. Ground water storage capacity is estimated as the product of the specific yield and the volume of material in the depth intervals considered.

In its investigation of the Sutter-Yuba ground water basin, the United States Geological Survey estimated specific yield of different depth zones after study of some 700 well logs. The estimates were based on previously determined characteristics of the various types of material classified in the well logs. Ground water storage capacity of the Sutter-Yuba Area was determined by the Geological Survey for depth intervals from 20 to 50 feet, 50 to 100 feet, 100 to 200 feet, and for the entire interval from 20 to 200 feet below ground surface. However, in an area of saline ground water centered near the southern end of the West Side Zone, where storage capacity in the 100- to 200-foot depth interval was considered not usable under present conditions, the determination was limited to the 20- to 50-foot, and 50- to 100-foot depth intervals.

Storage capacity of the ground water basin underlying the Sutter-Yuba Area and the weighted average specific yield, as estimated by the United States Geological Survey, are shown in Table 10.

TABLE 10

ESTIMATED SPECIFIC YIELD AND GROUND WATER STORAGE CAPACITY, SUTTER-YUBA AREA

Depth interval, in feet from ground surface	Weighted average specific yield, in percent	Ground water storage capacity, in acre-feet
20 to 50	7.4	840,000
50 to 100	6.9	1,290,000
100 to 200	6.0	1,760,000
20 to 200	6.6	3,890,000

Ground Water Levels

The first indication of a cone of depression in the water table in the Sutter-Yuba Area was found by Kirk Bryan and reported in 1913 in United States Geological Survey Water-Supply Paper 495. At that time a small cone had developed along Gilsizer Slough southwest of Shanghai Bend.

In 1931, in a "Report on Proposed Sutter Irrigation District," S. T. Harding described a study of ground water conditions in the eastern portion of Sutter County. A fully developed depression cone was found in the water table existing at that time. In discussing the growth of pumping draft in the Peach Bowl up to 1931, the author wrote:

> "Draft in 1920 was probably double that in 1913, much of the orchards being young in 1920 less water would be used. From 1920 there has been a continual increase in area and draft. Since 1924 the annual draft has probably varied more largely with variations in rainfall than of area. For the past five years there has been little new orchard planting and the existing orchards have been sufficiently mature to represent full draft.
>
> "These conclusions correspond generally with the ground water record. Some lowering occurred prior to 1920 but this was not sufficient to cause concern. Lowering appears to have attracted attention in 1924 and to have increased in below normal years since 1924 being particularly marked in the last 3 years."

The Division of Water Resources has measured fall water levels at a series of control wells throughout the Sacramento Valley during most years from 1929 through 1940, and each year from 1947 to date. Forty of these control wells are in or adjacent to the Sutter-Yuba Area. The Sutter County Farm Adviser furnished data on water levels at 25 additional wells in the area which were measured several times annually from 1931 through 1941. The Pacific Gas and Electric Company has made frequent measurements since 1946 at approximately 25 wells in or adjacent to the Sutter-Yuba Area. This company also furnished records of

TABLE 11

MEASURED FALL DEPTHS TO GROUND WATER AT REPRESENTATIVE WELLS IN ZONES OF SUTTER-YUBA AREA

(In feet)

Year	West Side Zone			Northeast Zone		East Central Zone		South Side Zone	
	Well number								
	17N/3E-30F1	14N/3E-3P1	13N/3E-14C2	16N/4E-8A1	16N/4E-27N1	14N/4E-15C3	14N/4E-28N1	13N/4E-33R1	12N/4E-33L3
1929	4.7	28.3	15.4	18.4	10.4	15.4	10.5	20.7	15.4
1930	3.3	32.4	15.6	17.6	7.8	14.9	10.4	20.1	16.0
1931	6.2	33.8	15.4	19.5	10.8	15.4	11.0	20.8	16.4
1932	5.4	32.4	15.2	19.2	------	14.7	11.1	20.1	12.7
1933	5.6	33.4	16.3	19.6	------	10.0	11.2	20.5	15.6
1934	5.4	34.1	16.7	19.8	------	------	11.5	20.5	16.3
1936	------	28.4	13.4	18.1	------	9.7	11.9	22.7	12.5
1937	3.7	26.2	11.8	17.8	------	14.8	12.0	24.8	9.4
1938	6.4	20.4	10.8	15.7	------	11.1	9.2	19.0	8.9
1940	3.1	24.0	8.2	16.8	4.8	14.3	10.9	------	3.4
1947	7.8	33.8	14.8	18.1	7.5	23.2	13.1	23.4	11.5
1948	9.3	34.2	14.2	21.0	12.0	24.3	13.4	25.3	11.0
1949	7.6	36.0	15.5	22.1	11.7	28.2	15.5	19.6	13.4
1950	8.6	39.1	15.5	23.6	8.8	29.7	14.6	28.1	13.0
1951	------	32.0	------	23.0	10.5	33.1	------	23.3	------

standing and operating water levels measured during pump tests, together with results of the tests.

A complete series of measurements of static ground water levels at approximately 850 wells in the Sutter-Yuba Area was made in the spring and fall of each year during the period of investigation, beginning with the fall of 1947 and continuing through 1951. The wells were chosen to form a comprehensive grid covering the entire area. In addition, monthly measurements were made at approximately 90 control wells during the first half of 1948 and through 1949, in order to observe behavior of the ground water table under conditions of draft and recharge. Available records of depth to ground water at wells in or adjacent to the Sutter-Yuba Area are included as Appendix E to this report.

Depths to ground water throughout the Sutter-Yuba Area, as measured each fall from 1947 through 1951, were plotted on maps and lines of equal depth drawn. These are shown on Plates 7 to 11, inclusive, "Lines of Equal Depth to Ground Water." Plate 12, "Lines of Equal Elevation of Ground Water, Fall 1949," was prepared from the data used for Plate 9, depths to ground water being subtracted from elevations of the measuring points above sea level to obtain elevations of the water table.

Table 11 shows depths from the surface of the ground to the water table at selected representative wells in the several zones of the Sutter-Yuba Area during the fall of most years from 1929 through 1951. The measurements were made following the summer period of irrigation pumping draft and prior to recovery in ground water storage resulting from winter rains. The wells are numbered in accordance with the system utilized by the United States Geological Survey, and described in Appendix B. Fluctuations in depth to ground water at a representative well in each zone of the Sutter-Yuba Area are depicted graphically on Plate 13, "Measured Fall Depths to Ground Water at Representative Wells."

From study of all available well measurements, estimates were made of the approximate average depth to ground water in the Sutter-Yuba Area in the fall of each year from 1929 through 1951. These estimates, which constitute arithmetical averages of available measurements, are presented in Table 12 and are illustrated graphically in Plate 14, entitled "Average Fall Depth to Ground Water."

TABLE 12

ESTIMATED AVERAGE FALL DEPTH TO GROUND WATER IN SUTTER-YUBA AREA

(In feet)

Year	Depth to ground water	Year	Depth to ground water
1929	15.9	1940	12.3
		1941	12.0
1930	16.1	1942	11.9
1931	17.7	1943	11.6
1932	16.6	1944	13.1
1933	17.6		
1934	17.2	1945	14.2
		1946	16.2
1935	16.8	1947	17.6
1936	16.4	1948	18.3
1937	15.2	1949	19.8
1938	15.2		
1939	14.5	1950	21.7
		1951	21.8

It is indicated that a moderate lowering of the water table over the Sutter-Yuba Area occurred from 1929 until 1931, followed by a slight rise in 1932, and a lowering again in 1933. Although 1935 marked the end of a series of dry years, ground water levels rose in 1934 because of reduced pumping. The water table continued to rise during a generally wet series of years until 1943, and in that year the estimated average depth to ground water was the least during the entire period from 1929 through 1951. Since 1943, coincidental with dry years and expansion of irrigation, a continuous lowering of the water table has occurred, reaching its greatest average depth during the entire period in the fall of 1951.

In order to estimate weighted average changes in ground water elevations in the Sutter-Yuba Area during the nine-year base period and each investigational season, maps were drawn showing lines of equal change in elevation during these periods. An example of these maps is presented as Plate 15, "Lines of Equal Change in Ground Water Elevation from Fall of 1947 to Fall of 1951." By planimetering the areas between lines of equal change, the weighted average change in elevation of water levels was estimated for each zone of the Sutter-Yuba Area. The results of these estimates are presented in Table 13.

TABLE 13

ESTIMATED WEIGHTED AVERAGE SEASONAL CHANGES IN FALL GROUND WATER ELEVATION IN ZONES OF SUTTER-YUBA AREA

(In feet)

Zone	1939-40 to 1947-48	1947-48	1948-49
West Side			
Peach Bowl	−0.7	−0.7	−1.5
Outside Peach Bowl	+0.1	+0.1	−0.2
Northeast	+0.1	+0.3	−1.0
East Central	−0.7	−1.2	−2.3
South Side	−0.6	−1.3	−2.1

Change in Ground Water Storage

In an area of free ground water, the volume of soil unwatered or resaturated over a period of time, when multiplied by the specific yield, measures the change in ground water storage during that time. Available data on fluctuations of water levels at wells in the Sutter-Yuba Area were sufficient to estimate the volume of soil unwatered or resaturated during the base period, and during the two investigational seasons. Changes in ground water storage were estimated for each zone of the area by multiplying changes in elevation of ground water, presented in Table 13, by the area of each zone and by the average value of specific yield of 7.4 percent, found by the Geological Survey for the depth interval from 20 to 50 feet below ground surface. The results of these estimates are presented in Table 14.

TABLE 14

ESTIMATED WEIGHTED AVERAGE SEASONAL CHANGES IN GROUND WATER STORAGE IN ZONES OF SUTTER-YUBA AREA

(In acre-feet)

Zone	Area, in acres	1939-40 to 1947-48	1947-48	1948-49
West Side				
Peach Bowl	61,400	−3,000	−3,000	−7,000
Outside Peach Bowl	62,370	+500	0	−1,000
Northeast	42,860	+300	+1,000	−3,000
East Central	77,870	−4,000	−7,000	−13,000
South Side	82,460	−4,000	−8,000	−13,000
TOTALS	326,960	−10,200	−17,000	−37,000

It is indicated that an average seasonal net decrease in ground water storage in the Sutter-Yuba Area of about 10,000 acre-feet occurred during the nine-year base period, in which conditions of water supply and climate were approximately equivalent to conditions during the mean periods. The estimated net decrease in ground water storage during the two investigational seasons was approximately 17,000 acre-feet in 1947-48, and 37,000 acre-feet in 1948-49. It may be noted that the decrease in storage was substantial in the Peach Bowl portion of the West Side Zone, and in the East Central and South Side Zones. In the high water table lands of the Sutter Butte Canal service area in the West Side Zone, and in the Northeast Zone, changes in ground water storage were of minor importance.

Subsurface Inflow and Outflow

Lines of equal elevation of ground water in the Sutter-Yuba Area in the fall of 1949 are shown on Plate 12. Slopes of the water table as defined by these ground water contours, together with information on the permeabilities of the various subsurface geologic formations, indicate that the greater portion of subsurface inflow to the area probably came from the east, and a smaller amount from the north between Sutter Buttes and the eastern foothills. It is probable that about half of the subsurface inflow from the east entered from Placer County south of the historic Bear River flood plain, and that the other half moved across the investigational boundary from the east in Yuba

County, including the whole of the historic Bear River flood plain.

The ground water gradients shown on Plate 12 indicate that there was little subsurface outflow from the Sutter-Yuba Area during or immediately following the 1949 season of heavy pumping draft. Sufficient data were not available to depict ground water contours in the area during the wet years from 1939 to 1943, when there was substantial ground water replenishment and when subsurface outflow may have been significant. Study of available data, however, does show that average seasonal subsurface outflow from the Sutter-Yuba Area during the nine-year base period was probably small.

The ground water contours shown on Plate 12 indicate the presence of a depression cone in the water table extending approximately north and south through the Peach Bowl during 1949. There was a general convergence of ground water around the perimeter of the depression and into the trough, showing that such ground water movement as may have occurred was inflow to the cone, rather than outflow.

The northern and western portions of the West Side Zone, and adjacent areas outside of the Sutter-Yuba Area, are served with surface water supplies, and ground water levels have been fairly stable and close to the ground surface even in dry years. However, during dry years, ground water levels in the Peach Bowl have lowered as a result of increased pumping. These conditions have probably resulted in relatively greater subsurface inflow to the Peach Bowl during such dry years, owing to the steeper gradients existing in the water table.

An indirect method was used to estimate the net effect of subsurface inflow to and outflow from the Sutter-Yuba Area. This involved evaluation of the difference between subsurface inflow and outflow as the item necessary to effect a balance between water supply and disposal. The sum of the items comprising the water supply of a given hydrologic unit or area must be equal to the sum of the items of water disposal. This is a statement of what is referred to as the "equation of hydrologic equilibrium." In the case of the Sutter-Yuba Area, values for pertinent items other than the difference between subsurface inflow and outflow, including surface inflow and outflow, precipitation, change in ground water storage, and consumptive use of water, were quantitatively measured or estimated. Determination of values for consumptive use of water is explained in Chapter III. Retention of subsurface inflow, or the difference between subsurface inflow and outflow, was the remaining unknown quantity in the equation of hydrologic equilibrium. Table 15 sets forth this equation for the Sutter-Yuba Area.

Certain of the values in the equation of hydrologic equilibrium presented in Table 15 are of large magnitude as compared to the derived excess of subsurface inflow over subsurface outflow. Small percentage errors in these larger quantities might introduce relatively large errors in the derived remainders. In this connection, independent geologic analysis of the cross section of the perimeter of the Sutter-Yuba ground water basin, including consideration of the porosity of the aquifers, indicated that with existing slopes of the water table the derived values for net subsurface inflow might be excessive. However, study of disposal of water supplies in areas adjacent to the Sutter-Yuba Area tended to corroborate the derived values.

TABLE 15

ESTIMATED EXCESS OF SEASONAL SUBSURFACE INFLOW OVER SUBSURFACE OUTFLOW IN SUTTER-YUBA AREA

(In acre-feet)

Item	Average for 9-year base period 1939-40 through 1947-48	1947-48	1948-49
WATER SUPPLY			
Precipitation	635,000	529,000	448,000
Surface inflow	6,239,000	4,849,000	3,425,000
Decrease in ground water storage	10,000	17,000	37,000
TOTALS	6,884,000	5,395,000	3,910,000
WATER DISPOSAL			
Surface outflow	6,316,000	4,790,000	3,296,000
Consumptive use of water	710,000	764,000	794,000
TOTALS	7,026,000	5,554,000	4,090,000
REMAINDER—EXCESS OF SUBSURFACE INFLOW OVER SUBSURFACE OUTFLOW	142,000	159,000	180,000

Yield of Wells

Yield of wells is an important factor in the use of ground water in the Sutter-Yuba Area. In certain small portions of the area ground water is not utilized for irrigation because of inability to obtain wells of adequate capacity to meet the agricultural requirements. On the other hand, throughout most of the area adequate agricultural wells can generally be obtained.

Yield of wells in the Sutter-Yuba Area was analyzed by the United States Geological Survey, as reported in Appendix B, utilizing data obtained from well pumping tests made by the Pacific Gas and Electric Company during the period from 1933 through 1948. Results of the Geological Survey's analysis are summarized in Table 16, which shows for each zone of the Sutter-Yuba Area the number of wells tested, and their average discharge, specific capacity, depth, and yield factor. The term "specific capacity" refers to the number of gallons of water per minute produced by a pumping well per foot of drawdown. "Drawdown" refers to the lowering of the water level in a well caused by pumping, and is measured in feet. The "yield factor" reflects the production of water per foot of depth of well, and is determined by multiplying the specific capacity by 100 and dividing by the depth of the well, in feet.

TABLE 16

ESTIMATED AVERAGE YIELD OF WELLS IN ZONES OF SUTTER-YUBA AREA

Zone	Number of wells tested	Average discharge, in gallons per minute	Average specific capacity, in gallons per minute per foot of drawdown	Average depth of wells, in feet	Average yield factor
West Side					
Peach Bowl	249	728	47	182	25.7
Outside Peach Bowl	48	878	54	320	16.8
Northeast	28	838	60	201	29.8
East Central	109	846	48	292	16.7
South Side	104	960	47	324	14.7

Insofar as may be determined from consideration of Table 16, it is indicated that the better wells of the Sutter-Yuba Area are located in the Peach Bowl and in the Northeast Zone. While wells of adequate capacity may generally be obtained throughout the remainder of the area, it is usually necessary to drill to greater depths for equivalent yields. However, although not apparent from the foregoing data, it was determined during the investigation that in the southeastern portion of the East Central Zone there is an area of approximately 3,400 acres of irrigable land upon which efforts to obtain wells of sufficient capacity to support irrigation demands have been unsuccessful.

High Water Table Areas

Under about 8,000 acres in the Northeast Zone, ground water was less than 10 feet from the ground surface continuously from November, 1947, through 1951, as was also the case under about 23,000 acres in the West Side Zone north of the East and West Intercepting Canals. Under about 1,000 acres of such lands in the Northeast Zone, and 4,500 acres in the West Side Zone, depth to the water table ranged from 0 to 5 feet from the ground surface.

The foregoing high water table lands were entirely irrigated by surface waters. It was indicated that the perennially high water table was largely caused by heavy applications of the abundant surface water supply to crops of rice and permanent pasture. The geologic investigations showed that the lands overlie good water-bearing formations which are capable of being developed by wells of relatively high yield, and that increase in use of ground water would probably result in lowering of ground water levels.

Studies indicated that the high water table lands would be suitable for a much wider range of crops than at present, if ground water levels were held at greater depths, and that an existing drainage problem would be eliminated. Furthermore, it is probable that consumptive use of water on these lands, as evidenced by heavy growth of native vegetation, is substantially in excess of such use on similar nearby lands where ground water levels are lower. The term "consumptive use of water," as used in this report, refers to water consumed by vegetative growth in transpiration and building of plant tissue, and to water evaporated from adjacent soil, from water surfaces, and from foliage. It also refers to water similarly consumed and evaporated by urban and nonvegetative types of culture.

Safe Ground Water Yield

The term "safe ground water yield" refers to the maximum rate of extraction of water from a ground water body which, if continued over an indefinitely long period of years, will result in the maintenance of certain desirable fixed conditions. Commonly, safe ground water yield is determined by one or more of the following criteria:

1. Mean seasonal extraction of water from the ground water body does not exceed mean seasonal replenishment to the body.

2. Water levels are not so lowered as to cause harmful impairment of the quality of the ground water by intrusion of other water of undesirable quality, or by accumulation and concentration of degradants or pollutants.

3. Water levels are not so lowered as to imperil the economy of ground water users by excessive costs of pumping from the ground water body.

Safe ground water yield, as derived in this report, was measured by net extraction of water from the Sutter-Yuba ground water basin, as differentiated from total pumpage from the basin. Since the Sutter-Yuba Area overlies a free ground water body, the unconsumed portion of total pumpage may return to the ground water body and become available for re-use. The net rate of extraction, therefore, was considered to be only that portion of total pumpage from the ground water basin which was consumptively used.

Under natural conditions, ground water is expended by consumptive use from seep lands and from lands where the water table is close to the ground surface, by effluent stream flow, and by subsurface outflow. Artificial development and utilization of ground water salvages all or a portion of such natural disposal, by lowering ground water levels. This, in turn, affords opportunity for additional replenishment of ground water.

With the present general patterns of water utilization in the Sutter-Yuba Area, the extraction of water from the ground water basin might be increased. Such increase in draft would undoubtedly be accompanied by recession of ground water levels in areas of pumping. However, this lowering of the water table would induce increased subsurface inflow to the areas of pumping and reduce natural disposal of the ground water, the probable effects of which would be to increase replenishment in an amount approximately equal to the increase in draft. This would probably hold true even in a series of dry years because of the continuous availability of large amounts of ground water in adjacent areas, maintained by percolation from relatively large surface water supplies. For this reason, the first of the foregoing criteria for determination of safe yield was not considered to be applicable in the Sutter-Yuba Area.

Because of expressed local concern over recent progressive lowering of pumping levels and deterioration in mineral quality of the ground water, the second and third of the foregoing criteria for determination of safe ground water yield were adopted as applicable to the Sutter-Yuba Area. It was therefore arbitrarily assumed that seasonal net extraction of ground water in 1948-49, with ground water levels prevailing at that time, defined the desirable limit beyond which net extraction should not be increased at the expense of further lowering of ground water levels.

As previously stated, consumptive use of ground water was considered to be equal to net extraction of water from the Sutter-Yuba ground water basin. An estimate of average seasonal consumptive use of ground water in the area during the nine-year base period is presented and explained in Chapter III. After correction for average seasonal change in ground water storage, this value was considered to represent average seasonal replenishment of the ground water basin during the base period. When further corrected for the increase in replenishment during 1948-49, over and above the base period average, as measured by increase in subsurface inflow, the value was considered to be equal to safe seasonal ground water yield.

The estimate of safe seasonal ground water yield is presented in Table 17.

Certain of the items included in the estimate of safe ground water yield are based on the assumption that present practice of irrigation by surface water supplies in and adjacent to the Sutter-Yuba Area will continue indefinitely. Under such circumstances adjacent ground water basins will remain the sources of sufficient subsurface inflow to areas of ground water pumping in the Sutter-Yuba Area to meet increases in pumping draft. While there is no assurance that surface irrigation practices will continue indefinitely as at present, there is reason to believe that any changes will not be of material significance to the estimated yield for many years in the future.

TABLE 17

ESTIMATED SAFE SEASONAL GROUND WATER YIELD IN SUTTER-YUBA AREA

Item	Acre-feet
Average seasonal consumptive use of ground water for 9-year base period, 1939-40 through 1947-48	158,100
Average seasonal decrement in ground water storage for base period	10,000
Average seasonal replenishment of ground water basin for base period	148,100
Increase in replenishment in 1948-49 over base period seasonal average	38,000
SAFE SEASONAL GROUND WATER YIELD	186,100

The foregoing estimate of safe seasonal ground water yield may be considered to represent the net seasonal extraction from the ground water basin that might be maintained without permanent lowering of the water table and degradation of mineral quality of the ground water beyond conditions prevailing in 1948-49. Having so chosen the determining criteria, estimated safe seasonal ground water yield may be considered to be a property of the ground water basin, not affected by changes in irrigation efficiency, patterns, or practices.

QUALITY OF WATER

The surface water supplies of the Sutter-Yuba Area are of excellent mineral quality and well suited from that standpoint for irrigation and other beneficial uses. With respect to ground water supplies, however, salinity sufficient to impair use of the ground water for irrigation, domestic, and many industrial uses has been observed at scattered wells throughout the area for many years. In the Peach Bowl, in the adjacent southern portion of the West Side Zone, and in the western portion of the South Side Zone this salinity of ground water has been general. The principal objectives of the water quality investigation, therefore, were to evaluate these conditions and to determine the extent of the area presently affected and the source of the saline ground waters.

It is desirable to define certain terms commonly used in connection with discussion of quality of water:

Contamination—This refers to impairment of the quality of water by sewage or industrial waste to a degree which creates a hazard to public health through poisoning or spread of disease.

Degradation—This refers to any impairment in the quality of water due to causes other than disposal of sewage and industrial wastes.

Pollution—This refers to impairment of the quality of water by sewage or industrial waste to a degree which does not create a hazard to public health, but which adversely and unreasonably affects such water for beneficial uses.

Quality of Water—This refers to those inherent characteristics of water affecting its suitability for beneficial uses.

The term "mineral analysis" refers to the quantitative determination of inorganic impurities or dissolved mineral constituents in the water. The complete mineral analysis included a determination of three cations, consisting of calcium, magnesium, and sodium; four anions, consisting of bicarbonate, chloride, sulphate, and nitrate; total soluble salts; boron; and computation of percent sodium. The partial analysis included determination of chlorides and total mineral solubles only.

With the exception of boron, the concentrations of cations and anions in a water sample are expressed in this report in terms of "equivalents per million." This was done because ions combine with each other on an equivalent basis, rather than on basis of weight, and a chemical equivalent unit of measurement provides a better and more convenient expression of concentration. This is especially true when it is desired to compare the composition of waters having variable concentration of mineral solubles. In the case of boron, concentrations are expressed on a weight basis of "parts per million" of water. In order to convert equivalents per million to parts per million, the concentration, expressed in equivalents per million, should be multiplied by the equivalent weight of the cation or the anion in question. Equivalent weights of the common cations and anions are presented in the following tabulation:

Cation	*Equivalent weight*	*Anion*	*Equivalent weight*
Calcium	20.0	Bicarbonate	61.0
Magnesium	12.2	Chloride	35.5
Sodium	23.0	Sulphate	48.0
		Nitrate	62.0

Data used to determine the quality of water in the Sutter-Yuba Area included complete mineral analyses of eight surface water samples and complete mineral analyses of water samples collected from 38 wells. The data also included partial analyses of water samples collected from 226 wells during the 1948 irrigation season and partial analyses of samples collected from 296 wells during the 1949 irrigation season. Other data used during the course of the investigation included well water analyses that were obtained from the Federal Land Bank in Berkeley and the Rubidoux Laboratory of the United States Department of Agriculture at Riverside, California.

Standards of Quality for Water

Investigation and study of the quality of surface and ground waters of the Sutter-Yuba Area, as reported herein, were largely limited to consideration of mineral constituents of the waters, with particular reference to their suitability for irrigation use. However, it may be noted that, within the limits of the mineral analyses herein reported, a water which is determined to be suitable for irrigation may also be considered as being either generally suitable for municipal and domestic use, or susceptible to such treatment as will render it suitable for that purpose.

The major criteria which were used as a guide to judgment in determining suitability of water for irrigation use comprised the following: (1) chloride concentration, (2) total soluble salts, (3) boron concentration, and (4) percent sodium.

1. The chloride anion is usually the most troublesome element in most irrigation waters. It is not considered essential to plant growth, and excessive concentrations will inhibit growth.

2. Total soluble salts furnishes an approximate indication of the over-all mineral quality of water. It may be approximated by multiplying specific electrical conductance (Ec $\times 10^6$ at 25° C.) by 0.7. The presence of excessive amounts of dissolved salts in irrigation water will result in reduced crop yields.

3. Crops are sensitive to boron concentration, but require a small amount (less than 0.1 per million) for growth. They will usually not tolerate more than 0.5 to 2 parts per million, depending on the crop in question.

4. Percent sodium reported in the analyses is the proportion of the sodium cation to the sum of all cations, and is obtained by dividing sodium by the sum of calcium, magnesium, and sodium, all expressed in equivalents per million, and multiplying by 100. Water containing a high percent sodium has an adverse effect upon the physical structure of the soil by dispersing the soil colloids and making the soil "tight," thus retarding movement of water through the soil, retarding the leaching of salts, and making the soil difficult to work.

The following excerpts from a paper by Dr. L. D. Doneen, of the Division of Irrigation of the University of California at Davis, may assist in interpreting water analyses from the standpoint of their suitability for irrigation:

> "Because of diverse climatological conditions, crops, and soils in California, it has not been possible to establish rigid limits for all conditions involved. Instead, irrigation waters are divided into three broad classes based upon work done at the University of California, and at the Rubidoux, and Regional Salinity laboratories of the U. S. Department of Agriculture.
>
> "Class 1. *Excellent to Good*—Regarded as safe and suitable for most plants under any condition of soil or climate.
>
> "Class 2. *Good to Injurious*—Regarded as possibly harmful for certain crops under certain conditions of soil or climate, particularly in the higher ranges of this class.

"Class 3. *Injurious to Unsatisfactory*—Regarded as probably harmful to most crops and unsatisfactory for all but the most tolerant.

"Tentative standards for irrigation waters have taken into account four factors or constituents, as listed below.

Factor	*Class 1 excellent to good*	*Class 2 good to injurious*	*Class 3 injurious to unsatisfactory*
Conductance (Ec × 10^6 at 25° C.)	Less than 1000	1000–3000	More than 3000
Boron, ppm	Less than 0.5	0.5–2.0	More than 2.0
Percent sodium	Less than 60	60–75	More than 75
Chloride, epm	Less than 5	5–10	More than 10

(End of quotation)

Quality of Surface Water

Analyses of surface water samples, collected in March, 1949, from the Feather River and four of its tributaries, showed that at that time the waters in these streams were of excellent mineral quality and well suited for irrigation and other beneficial uses. The waters were characterized by a very low content of total mineral solubles, chloride, and boron, and by low percent sodium. The occurrence of excellent quality water in the Feather River is also indicated by analyses of water from that stream which are presented in the Sacramento-San Joaquin Water Supervision Reports of the Division of Water Resources dating from 1946. Analyses of drainage water samples collected from Sutter By-pass and Snake Slough indicated that both drainage waters contain higher concentrations of mineral solubles than waters of Feather River and its tributaries, but that they are well within the limits of Class 1 irrigation waters. Analyses of representative surface waters of the Sutter-Yuba Area, sampled in 1949, are presented in Table 18.

Quality of Ground Water

Although in the course of the present investigation surveys were made of the mineral quality of ground water throughout the Sutter-Yuba Area, particular emphasis was placed on those areas where saline degradation has been general, and of a degree sufficient to limit beneficial use of the ground water. Results of the surveys are presented and discussed in this section under the headings "Area of Degraded Ground Water" and "Source of Ground Water Salinity."

Area of Degraded Ground Water. Two comprehensive surveys of the average mineral quality of ground water in the Sutter-Yuba Area were made during the irrigation seasons of 1948 and 1949. Both surveys involved the partial analysis of water samples collected from numerous wells to determine total mineral solubles and chlorides. Results of the two surveys are summarized in Table 19, and show that in 1948 and 1949 the mineral quality of native ground water supplies was excellent or good in all zones of the Sutter-Yuba Area, except in that portion of the West Side Zone south of Oswald Road where abnormally high concentrations of chloride were found in many of the well water samples. The 1949 survey embraced a larger area than the 1948, and included lands south and west of Sutter By-pass. Results of this extended survey showed that high chloride salinity of ground water also occurred locally near the town of Robbins, some seven miles westerly from Nicolaus.

The foregoing present areas of comparatively high chloride salinity are shown on Plate 16, "Lines of Equal Concentration of Chlorides in Ground Water, July 1949." It may be noted that the concentration of chlorides in the ground water decreased progressively with distance from both of the affected areas, in the

TABLE 18

COMPLETE MINERAL ANALYSES OF REPRESENTATIVE SURFACE WATERS OF SUTTER-YUBA AREA

	Date of sample	Conductance, Ec × 10^6 at 25° C.	Boron, in ppm	Mineral constituents in equivalents per million							Percent sodium
				Ca	Mg	Na	$HCO_3 + CO_3$	Cl	SO_4	NO_3	
Tributary Streams											
Feather River at Rednal Road	3/15/49	99	0.0	0.39	0.47	0.27	0.91	0.06	0.09	Trace	24
Feather River at Nicolaus	3/14/49	92	0.0	0.43	0.46	0.40	0.77	0.03	0.20	0.09	31
South Honcut Creek at La Porte Road	3/15/49	124	0.0	0.43	0.62	0.36	1.08	0.12	0.15	Trace	26
Dry Creek near Waldo	3/21/49	164	0.0	0.71	0.85	0.40	1.37	0.13	0.31	Trace	20
Coon Creek at Highway 99E	3/11/49	175	0.0	0.70	0.93	0.36	1.51	0.16	0.32	0.06	18
Auburn Ravine at Highway 99E	3/11/49	143	0.0	0.54	0.69	0.39	1.04	0.16	0.28	0.10	24
Drainage Waters											
Sutter By-pass at Colusa Highway	7/19/49	400	0.09	1.49	1.79	1.35	3.94	0.52	0.21	Trace	28
Snake Slough at Sanders	7/19/49	380	0.09	1.29	1.80	1.80	3.88	0.38	0.08	Trace	26

TABLE 19

SUMMARY OF PARTIAL MINERAL ANALYSES OF GROUND WATERS IN ZONES OF SUTTER-YUBA AREA, SUMMERS OF 1948 AND 1949

Zone	Number of samples		Chlorides, in equivalents per million				Conductance, $Ec \times 10^6$ at 25° C.	
			Average		Range			
	1948	1949	1948	1949	1948	1949	1948	1949
West Side								
North of Oswald Road	41	25	1.5	0.84	0.3- 4.8	0.3- 2.1	600	730
South of Oswald Road	129	159	5.13	6.10	0.3-28.7	0.3-62.5	1,010	1,300
Northeast	4	2	0.8	0.73	0.3- 1.1	0.3- 1.1	340	280
East Central	31	14	0.7	0.7	0.3- 1.7	0.3- 1.7	300	210
South Side	21	6	1.1	1.0	0.6- 4.8	0.5- 2.0	500	380

West Side Zone south of Oswald Road and near the town of Robbins. It may be inferred from this condition that, when hydraulic conditions are favorable, saline ground water from these two areas may move laterally, thus causing degradation in the mineral quality of remaining fresh ground water resources of surrounding areas.

The areas delimited by the lines of equal chloride concentration on Plate 16 indicate that at the present time wells on approximately 4,500 acres of land in the West Side Zone south of Oswald Road yield water containing chlorides in amounts exceeding 10 equivalents per million, which amount is considered to be the upper limit for safe irrigation use. When such saline waters are used for irrigation, quantities of water exceeding normal crop demands are commonly applied in order to dilute the soil solution and leach accumulations of excess salts away from the root zone.

Source of Ground Water Salinity. The presence of saline ground waters in and adjacent to the Sutter-Yuba Area has been observed to exist for many years, and was remarked upon in reports of salt balance studies conducted by the Division of Soil Management and Irrigation of the United States Department of Agriculture. These studies, which were made in cooperation with the Sutter Mutual Water Company during 1931, 1932, 1933, 1946, and 1947, showed that the amount of dissolved solids in water drained from lands adjacent to and west of the southern portion of the Sutter-Yuba Area greatly exceeded the amount brought onto the lands in irrigation water. The salt output during each of the five years, expressed as a proportion of the input, is reported to have ranged between 248 and 655 percent, and the average was about 407 percent.

The opinion was expressed in a report on the foregoing 1947 salt balance study that the salt in the drainage waters was probably derived from saline waters underlying the area. Preliminary studies made by the Division of Water Resources similarly indicated that the chloride salinity in many of the wells was due to admixture of deep-seated brines with native fresh ground waters. There is evidence that such brines may underlie aquifers of good quality water throughout large areas of the Sacramento and San Joaquin Valleys, and that they may have originated during past geologic time when the floor of the valley was inundated by the ocean. Such brines sometimes appear in water pumped from the deeper wells in the two valleys, or from areas wherein the fresh ground water levels are markedly lowered through overdraft. In many instances these relatively deep-seated brines are under considerable pressure and readily rise to the surface through defective, abandoned, or improperly constructed wells. A case in point is a natural gas well located near the town of Robbins which yields water under artesian and/or gas pressure, at a rate of about 200 gallons a minute. The water from this well, No. 12N/2E-18, has a conductivity of about 8,600, a chloride content of about 100 equivalents per million, and about 10.8 parts per million of boron.

A geochemical study was made to determine whether salinity of ground water in the Sutter-Yuba Area was caused principally by a common degradant, and whether the foregoing deep-seated brines constituted that degradant. The study to identify the degradant was made on the basis of complete mineral analyses of water samples collected from 38 scattered wells located in the West Side Zone south of Oswald Road and in adjacent lands to the west. These water samples were first classified into eight groups according to the range in concentration of total anions. For purposes of the study it was considered that native fresh ground waters contained total anions in amounts less than about 7 equivalents per million, chlorides in amounts less than about 2.5 equivalents per million, and that degradation had occurred if these amounts were exceeded. A discussion of the characteristics of each group follows:

Group 1. This comprised unaltered normal ground water. Four analyses were available for Group 1 water. The wells which yielded this water were located within the present zone of high chloride concentration, and the samples were taken and analyses made in 1934 and 1935 prior to recent degradation of ground water in the zone. The water had total anions ranging from 4.72 to 6.31 equivalents per million, and chlorides from 0.85 to 2.06 equivalents per million. Its mineral quality was excellent.

Group 2. This group comprised waters containing a trace of salinity. Total anions ranged from 8.95 to 10.68 equivalents per million, and chlorides from 5.45 to 6.39 equivalents per million. Four analyses repre-

TABLE 20

COMPLETE MINERAL ANALYSES OF GROUND WATERS IN AREA OF SALINE DEGRADATION IN AND ADJACENT TO SUTTER-YUBA AREA, GROUPED IN ACCORDANCE WITH TOTAL ANIONS

Ground water group	Well location or number	Date of sample	Conductance, $Ec \times 10^6$ at 25° C.	Boron, in ppm	Mineral constituents, in equivalents per million							Percent sodium
					Ca	Mg	Na	$HCO_3 + CO_3$	Cl	SO_4	NO_3	
1	N½ Sec. 9, T13N, R3E	5/31/34	483	....	1.40	1.81	1.51	3.30	1.33	0.09	....	32
	S½ Sec. 10, T14N, R3E	1/ 2/35	543	....	1.70	1.97	1.43	4.25	0.85	Trace	....	28
	NE¼ Sec. 15, T14N, R3E	1/15/35	515	....	1.50	2.13	1.54	3.70	1.47	Trace	....	30
	NW¼ Sec. 28, T14N, R3E	4/30/34	635	....	2.10	2.30	1.91	4.20	2.06	0.05	....	30
	Average	----	544	....	1.67	2.05	1.59	3.86	1.43	0.03	....	30
2	11N/3E-2B1	7/ /49	944	0.16	2.80	2.24	4.31	3.02	5.90	0.03	0.0	46
	13N/3E-3D1	7/ /49	980	0.09	3.59	5.02	2.05	4.20	6.39	0.09	0.0	19
	14N/3E-28R1	7/ /49	1,000	0.12	2.71	5.62	2.58	3.94	6.38	0.13	Trace	24
	14N/3E-33A2	7/ /49	1,037	0.0	2.98	4.29	3.32	5.09	5.45	0.03	0.0	31
	Average	------	990	0.09	3.02	4.29	3.06	4.06	6.03	0.07	Trace	30
3	13N/3E-2P3	7/ /49	1,317	0.17	3.13	3.39	6.46	3.78	9.21	0.04	0.0	50
	13N/3E-5K1	7/ /49	1,353	0.07	3.70	5.53	4.07	4.15	9.14	0.09	0.0	31
	13N/3E-10A1	7/ /49	1,190	0.05	4.40	5.83	2.13	3.91	8.06	0.22	0.0	17
	14N/3E-27E1	7/ /49	1,361	0.0	4.51	5.94	3.38	5.53	7.86	0.45	Trace	24
	14N/3E-29Q1	7/ /49	1,390	0.14	4.14	5.33	4.47	3.23	10.15	0.02	Trace	32
	14N/3E-34J1	7/ /49	1,087	0.0	4.05	5.76	2.57	6.84	3.40	2.01	0.10	21
	Average	--------	1,283	0.07	3.99	5.31	3.85	4.54	7.97	0.14	0.02	29
4	13N/3E-2E1	7/ /49	1,503	0.49	2.96	3.05	8.75	3.78	11.11	0.03	0.0	59
	13N/3E-11D1	7/ /49	1,408	0.06	5.21	7.34	1.96	4.17	9.34	0.81	0.0	13
	13N/3E-14G1	7/ /49	1,307	0.06	4.43	6.85	3.44	6.20	7.49	0.71	0.06	23
	13N/3E-23H1	7/ /49	1,408	0.03	5.45	6.73	2.92	4.98	10.23	0.17	0.0	19
	13N/3E-24D1	7/ /49	1,460	1.64	3.23	2.15	9.05	3.90	11.68	0.03	0.0	63
	14N/3E-33A1	7/ /49	1,460	0.0	4.88	6.99	2.82	5.11	9.44	0.09	0.0	19
	Average	------	1,425	0.36	4.36	5.52	4.86	4.52	9.88	0.31	0.01	33
5	13N/3E-5C1	7/ /49	1,835	0.21	4.83	6.00	6.70	3.52	14.08	0.03	0.0	38
	13N/3E-11F1	7/ /49	1,710	0.85	3.29	4.51	9.40	3.26	13.04	0.28	0.0	55
	13N/3E-14J1	7/ /49	1,710	0.31	4.68	8.18	4.87	4.12	12.78	0.43	0.0	27
	14N/3E-28G2	7/ /49	1,653	0.0	5.18	6.92	4.51	5.21	10.95	0.37	0.0	27
	14N/3E-32F1	7/ /49	1,640	0.24	4.90	7.36	4.77	4.35	12.37	0.03	0.0	28
	Average	------	1,709	0.32	4.58	6.59	6.05	4.09	12.64	0.23	0.0	35
6	11N/3E-3B1	7/ /49	2,162	0.93	4.63	2.98	13.94	3.42	18.08	0.03	0.0	65
	13N/3E-2N1	7/ /49	1,802	0.07	5.71	6.31	6.02	4.63	13.61	0.15	Trace	33
	13N/3E-14R1	7/ /49	1,870	0.72	5.35	6.68	6.89	4.88	14.06	0.26	0.0	36
	13N/3E-16R1	7/ /49	2,222	0.03	5.96	8.25	7.27	4.24	17.42	0.03	0.0	34
	13N/3E-32L1	7/ /49	2,062	0.21	5.27	10.09	5.75	2.64	17.26	0.30	0.0	27
	Average		2,059	0.39	5.38	6.86	7.97	3.95	16.09	0.15	Trace	39
7	13N/3E-6K1	7/ /49	2,550	0.28	6.62	11.33	8.81	5.08	20.42	0.05	0.0	33
	13N/3E-23B1	7/ /49	3,390	0.0	11.83	16.80	6.71	5.50	29.01	0.34	Trace	19
	14N/3E-31J1	7/ /49	2,425	0.0	7.28	11.08	6.20	5.06	19.26	0.26	Trace	25
	14N/3E-31R1	7/ /49	2,552	0.07	7.36	11.09	6.97	4.98	20.44	0.12	0.0	27
	14N/3E-32L2	7/ /49	2,776	0.27	7.10	9.30	9.81	2.82	23.52	0.04	0.0	37
	14N/5E-21A1	8/ 3/49	2,702	1.71	10.78	4.17	12.60	1.72	22.94	2.01	Trace	46
	Average		2,732	0.39	8.55	10.63	8.52	4.19	22.60	0.47	Trace	31
8	SE¼ Sec. 2, T12N, R2E	7/ 9/49	10,000	0.60	30.37	35.30	39.90	4.10	99.45	0.05	0.0	38
	SW¼ Sec. 18, T12N, R2E	3/14/47	8,600	10.8	19.83	7.22	76.12	2.71	99.92	0.08		74
	Average		9,300	5.7	25.10	21.26	58.01	3.40	99.67	0.05		56

senting wells yielding Group 2 waters were available. These waters were classed as of good mineral quality and suitable for general irrigation use.

Group 3. This group comprised slightly saline ground waters. Total anions ranged from 12.19 to 13.40 equivalents per million, and chlorides ranged from 3.40 to 10.15 equivalents per million. Six analyses were available for wells yielding Group 3 waters. These waters were considered to be generally satisfactory for irrigation use.

Group 4. This group comprised moderately saline ground waters, with total anions ranging from 14.32 to 15.38 equivalents per million, and chlorides ranging from 7.49 to 11.68 equivalents per million. Six analyses were available for wells yielding Group 4 waters. These waters were classed as usable with caution for general irrigation under most conditions.

Group 5. This group comprised saline ground waters with total anions ranging from 16.53 to 17.63 equivalents per million, and chlorides ranging from 10.95 to 14.08 equivalents per million. Five analyses were available for wells yielding Group 5 waters. These waters would normally be considered usable for irrigation only after dilution with water of better mineral quality.

Group 6. This group comprised saline ground waters having total anions ranging from 18.35 to 21.69 equivalents per million, and chlorides ranging from 13.61 to 18.08 equivalents per million. Five analyses were available for wells yielding Group 6 water. This water was classed as unsuitable for irrigation use.

Group 7. This group comprised highly saline ground waters, having total anions ranging from 25.54 to 34.88 equivalents per million, and chlorides ranging from 19.26 to 29.04 equivalents per million. Analyses were available for six wells yielding Group 7 waters. These waters were not considered usable for irrigation or domestic purposes.

Group 8. This group comprised briny ground waters. Group 8 waters were yielded in June 1949 by a reputedly shallow well, and in April 1930 and March 1947 by a nearly 1500-foot abandoned gas well, both located near Robbins to the west of the Sutter-Yuba Area. These waters had total anions in excess of 100 equivalents per million. Chlorides accounted for about 95 per cent or more of the anions.

Results of complete mineral analyses of ground waters in the zone of degradation, segregated into the foregoing groups, are presented in Table 20.

The character formula of a water expresses the percent of each cation and anion of mineral constituents of the water with respect to their total, and is useful in comparing mineral quality characteristics of several waters. In order to compare the groups of saline ground waters in and adjacent to the Sutter-Yuba Area, the average equivalents per million of each cation and anion in unaltered normal ground water, represented by Group 1, were first subtracted from corresponding average mineral constituents in ground water of each of the other groups, with exception of those of Group 8. The character formulae of waters of Groups 2 to 7 were then derived as determined by use of these remainders. Both the character formulae of these differences and the mineral constituents are shown in Table 21. They may be considered to represent the mineral characteristics of the ground water degradant as they were prior to alteration through mingling of the degradant with fresh ground water, but after being subjected to base exchange during movement of the degradant from its source. It may be noted that both the concentration and composition of waters in Group 8 were taken directly from the average analysis presented in Table 20. This was done on the assumption that the brines of that group were not significantly diluted with fresh water.

TABLE 21

AVERAGE MINERAL CHARACTER AND CONSTITUENTS OF SALINE GROUND WATERS IN AND ADJACENT TO SUTTER-YUBA AREA

(Corrected for effects of dilution with unaltered normal ground water)

Ground water group	Mineral constituents in equivalents per million and character formulae in percent					
	Ca	Mg	Na	HCO_3	Cl	SO_4
2	1.35 13.3%	2.24 22.2%	1.47 14.5%	0.20 2.0%	4.60 47.6%	0.04 0.4%
3	2.32 14.0%	3.26 20.8%	2.26 14.4%	0.68 4.6%	6.54 44.6%	0.11 0.8%
4	2.69 14.3%	3.47 18.4%	3.27 17.3%	0.66 3.5%	8.45 45.0%	0.28 1.5%
5	2.91 12.2%	4.54 19.1%	4.46 18.7%	0.23 1.0%	11.21 48.1%	0.20 0.9%
6	3.71 13.7%	4.81 15.6%	6.38 20.7%	0.09 0.3%	14.66 49.3%	0.12 0.4%
7	6.88 15.4%	8.58 19.1%	6.93 15.5%	0.33 0.8%	21.17 48.2%	0.44 1.0%
8	25.10 21.0%	21.26 10.0%	58.01 28.0%	3.40 1.7%	99.67 48.0%	0.06 0.3%

Table 21 shows that, irrespective of variations in concentration, the character formula of the degradant in each of the ground water Groups 2 through 7 is strikingly similar to that of the brines comprising Group 8. This is especially true of the anions which are not subject to base exchange reactions. This similarity in composition, together with apparent absence of any other like degradant, indicates that degradation of the native ground waters is due to admixture of deep-seated brines of the type exemplified by Group 8.

Although the chloride content of water from wells in the area of saline ground water is generally high, it is quite variable with respect to the depth of wells. Examination of analyses of water from 33 wells of known depth in the West Side Zone south of Oswald Road did not indicate any correlation between chloride content of the water and depth. The wells studied for this purpose ranged in depth from about 50 to 300 feet, and the average depth was of the order of 145 feet. The lack of any significant correlation in this matter cannot be fully explained on the basis of data compiled during the course of the present investigation. However, it is probable that the explanation may lie in precise identification of the aquifers which contribute water to the respective wells. For example, wells pumping from both fresh and saline aquifers would probably yield water containing lower concentrations of chlorides than wells pumping only from saline aquifers. In this connection it is noted that additional more detailed investigation of the quality of the water resources of the Sutter-Yuba Area is in progress under the provisions of Section 229 of the Water Code. This work is being conducted by the Division of Water Resources in connection with its assigned responsibilities for a state-wide survey of quality of surface and ground waters, the results of which will be published at a later date.

Studies to date of saline ground water conditions in the Sutter-Yuba Area indicate that the brines of Group 8 may migrate upward into fresh water aquifers both through permeable zones in the alluvium and through unplugged test wells and abandoned, defective, or improperly constructed water wells. Furthermore, when the water table is lowered by heavy irrigation pumping, it is probable that upward movement of the brines is accelerated. Possible subsequent lateral movement of the brines may be inferred from the observed progressive decrease in ground water chloride concentrations with distance from the two areas of high chloride salinity, in the West Side Zone south of Oswald Road and near Robbins.

CHAPTER III

WATER UTILIZATION AND SUPPLEMENTAL REQUIREMENTS

The nature and extent of water utilization and requirements for supplemental water in the Sutter-Yuba Area, both at the present time and under probable conditions of ultimate development, are considered in this chapter. In connection with the discussion, the following terms are used as defined:

Water Utilization—This term refers to the sum of consumptive use of water and those irrecoverable losses of water incidental to its beneficial use.

Consumptive Use of Water—This term refers to water consumed by vegetative growth in transpiration and building of plant tissue, and to water evaporated from adjacent soil, from water surfaces, and from foliage. It also refers to water similarly consumed and evaporated by urban and nonvegetative types of culture.

Supplemental Requirement—This term refers to the amount of water, over and above the sum of safe ground water yield and safe surface water yield, which must be developed to satisfy water utilization.

Ultimate—This term refers to an unspecified but long period of years into the future when cultural development will be essentially stabilized. (It is realized that any present forecasts of the nature and extent of such ultimate cultural development, and resultant water utilization, are inherently subject to possible large errors in detail and appreciable error in the aggregate. However, such forecasts, when based upon best available data and present judgment, are of value in establishing long-range objectives for development of water resources. They are so used herein, with full knowledge that their re-evaluation after the experience of a period of years may result in considerable revision.)

Present water utilization in the Sutter-Yuba Area was estimated by the application of appropriate unit consumptive use of water factors to the present cultural pattern. Probable ultimate water utilization was similarly estimated, by the use of an ultimate cultural pattern projected from the present pattern on the basis of land classification data, the assumption being made that under ultimate conditions of cultural development all irrigable lands would be irrigated. As indicated by the foregoing definition, supplemental requirements for water were estimated as the differences between derived values of safe yield and utilization, under both present and ultimate conditions of cultural development.

Water utilization is considered and evaluated in this chapter under the general headings "Present Water Supply Development," "Land Use," "Unit Use of Water," "Past and Present Water Utilization," "Probable Ultimate Water Utilization," and "Demands for Water." Supplemental water requirements are similarly treated under the two general headings "Present Supplemental Requirements" and "Probable Ultimate Supplemental Requirements."

WATER UTILIZATION

Of the total amount of water presently utilized in the Sutter-Yuba Area, approximately 65 percent is consumed in the production of irrigated crops, while the remainder is consumed by dry-farmed crops and fallow lands, native vegetation, and miscellaneous culture including domestic and municipal. It is considered probable that the predominant importance of irrigated agriculture, as related to utilization of water in the area, will continue to prevail in the future.

Present Water Supply Development

Approximately two-thirds of the acreage under water service in the Sutter-Yuba Area is presently supplied by water pumped from the underlying ground water basin. Irrigated lands utilizing ground water are generally served by individually owned wells and pumps. Because of this fact and the extensive ground water utilization, the amount of water developed for irrigation use by individuals is larger than by organized agencies. As of April 1, 1949, there were 2,198 wells and pumping plants of heavy draft, powered with motors of more than five horsepower, and of this number 2,159 were used for irrigation. The 39 remaining wells supplied water for urban and industrial uses. A number of additional wells of light draft supplied limited amounts of water for noncommercial gardens and orchards, and for domestic purposes. Lands served principally with ground water comprise the Peach Bowl, the East Central Zone, and the portion of the South Side Zone adjacent to and south of Bear River.

Surface diversions for irrigation in the Sutter-Yuba Area are made from the Sacramento and Feather Rivers and tributary streams, and from the Wadsworth and Natomas Canals, various surface drains, and the Sutter By-pass. The major diversions are made by irrigation companies and districts, with service to the lands being largely by means of open ditch transmission and distribution systems. Minor surface diversions are made for the most part by individuals whose lands are adjacent to the surface supplies. The Sutter Butte Canal Company is the principal diverter of water from Feather River, serving lands in the West Side Zone outside of the Peach Bowl. The joint diversion of the Hallwood Irrigation Company and the

Cordua Irrigation District is the largest of a number of irrigation diversions from Yuba River, and serves water to lands in the Northeast Zone. The Nevada Irrigation District supplies some surface water to lands in the South Side Zone through ditches diverting from Auburn Ravine. Lands served principally by surface waters comprise the Northeast Zone, the West Side Zone outside the Peach Bowl, and the west portion of the South Side Zone.

Water used for municipal, industrial, and domestic purposes in the Sutter-Yuba Area is obtained almost entirely from wells. The greater part of such use is in the Cities of Marysville and Yuba City, and is scattered and of relatively minor significance throughout the remainder of the area.

The City of Marysville is served by the California Water Service Company, a public utility which pumps water from wells into storage tanks, from which it is delivered to consumers by gravity. Water services are metered. The quantity of water pumped for use in Marysville in the calendar year 1948 was 506,000,000 gallons, or 1,550 acre-feet. With an approximate population of 7,500 in July, 1948, the daily production averaged about 185 gallons per capita.

Yuba City is served by the Yuba City Municipal Water Works, which charges for water on a flat-rate basis. It was estimated that the quantity of water pumped for use in Yuba City in the calendar year 1948 was about 750,000,000 gallons, or 2,300 acre-feet. With an approximate population of 6,300 in March, 1948, the daily per capita production was about 330 gallons.

In addition to the foregoing figures regarding ground water pumped in 1948 under the municipal systems of Marysville and Yuba City, it was estimated that approximately 1,000 acre-feet was pumped and used by industries operating their own wells within the cities. Wheatland has a community water system that distributes water from a storage tank supplied by two wells. The estimated amount of water pumped in Wheatland during the calendar year 1948 was approximately 200 acre-feet. Assuming that the per capita water production in remaining small towns and communities in the Sutter-Yuba Area was about 200 gallons per day, it was estimated, on the basis of 1948 population estimates, that total annual pumpage from ground water for these communities was about 700 acre-feet.

The respective areas within the several zones of the Sutter-Yuba Area served by ground water and surface water are shown in Table 22. The data presented for the two investigational seasons resulted from field surveys during the current investigation, while the averages for the base period were largely based on records of crop surveys made by the Division of Water Resources in connection with the Sacramento-San Joaquin Water Supervision, and on pumping power consumption records furnished by the Pacific Gas and Electric Company.

TABLE 22
GROUND AND SURFACE WATER SERVICE AREAS IN ZONES OF SUTTER-YUBA AREA
(In acres)

Zone	Ground water		Surface water	
	1948	1949	1948	1949
West Side	48,990	44,050	18,750	21,590
Northeast	6,050	8,240	11,540	11,850
East Central	24,230	33,140	2,500	990
South Side	11,280	10,770	15,420	18,070
TOTALS	90,550	96,800	48,210	52,500
Averages for 9-year base period, 1939-40 through 1947-48	68,490		42,810	

Table 23 lists the principal water service agencies, together with notations on their sources of water supply, locations of service areas within the Sutter-Yuba Area, and acreages within the area irrigated by water served by each agency in 1948. Areas included within the boundaries of these agencies are shown on Plate 2.

TABLE 23
PRINCIPAL WATER SERVICE AGENCIES SUTTER-YUBA AREA

Agency	Source of water supply	Service area by zones	Acreage irrigated in 1948
California Water Service Company	Ground water	Northeast	Municipal use in Marysville
Camp Far West Irrigation District	Bear River	East Central	1,580
Cordua Irrigation District	Yuba River	Northeast	4,736
Farm Lands Investment Company	Feather River	East Central	1,833
Feather River Water Company	Feather River	West Side	0
Garden Highway Mutual Water Company	Feather River	West Side	2,075
Hallwood Irrigation Company	Yuba River	Northeast	6,365
Natomas Central Mutual Water Company	Sacramento River	South Side	11,298
Natomas Northern Mutual Water Company	Sacramento River	South Side	*
Nevada Irrigation District	Yuba and Bear Rivers	South Side	1,240
Oswald Water District	Feather River	West Side	608
Sutter Butte Canal Company	Feather River	West Side	12,840
Sutter Extension Water District	Feather River	West Side	Formed in 1949
Yuba City Municipal Water Works	Ground water	West Side	Municipal use

* Included in acreage of Natomas Central Mutual Water Company.

Rice Field in Sutter-Yuba Area

Land Use

As a first step in estimating the amount of water utilization in the Sutter-Yuba Area during the base period and investigational seasons, determinations were made of the nature and extent of land use prevailing during these periods. Similarly, the probable nature and extent of ultimate land use, as related to water utilization, was forecast on the basis of land classification survey data which segregated lands of the area in accordance with their suitability for irrigated agriculture.

Past and Present Cultural Patterns. In connection with the Sacramento-San Joaquin Water Supervision, the Division of Water Resources for some 25 years has made annual crop surveys of those lands in the Sutter-Yuba Area utilizing surface water. In 1946 the United States Bureau of Reclamation made a complete crop survey of the area. A comprehensive cultural survey was made during the season of 1947-48 as a part of the current investigation. Additional data on culture were obtained in 1948-49 from a supplementary survey made in order to determine any changes in land use since the preceding season.

Data available from the foregoing surveys were sufficient to estimate the average cultural pattern in the Sutter-Yuba Area during the nine-year base period. For purposes of this report, the cultural pattern existing during the 1948-49 season was considered to represent "present" conditions of culture and development in the area, and is so referred to in subsequent discussion.

Summaries of the results of the cultural surveys of 1947-48 and 1948-49 and the estimated average cultural pattern for the base period are presented in Table 24. The Sutter Buttes, comprising some 22,300 acres of waste land in the West Side Zone, are not included in the tabulation. Lands irrigated in the Sutter-Yuba Area during the 1947-48 season are shown on Plate 17, "Irrigated and Irrigable Lands, 1948."

The most significant indicated recent trend in irrigated agriculture in the Sutter-Yuba Area is toward increased plantings of rice and permanent pasture. The data presented in Table 24 show that the area of rice increased from an estimated average of some 25,500 acres during the base period to over 44,000 acres in 1948-49. At the same time, permanent pasture increased from some 17,500 to 25,500 acres. Deciduous orchard, which had long been the largest irrigated crop in the area on an acreage basis, showed an increase of less than 3,000 acres in 1948-49 over the base period average, and was surpassed by the acreage of rice during the latter season. The foregoing increases in irrigated agriculture were largely reflected by corresponding decreases in acreage of dry-farmed and fallow lands. Table 24 shows that there was moderate increase in farmstead and urban development in 1948-49 over the base period averages, but no very significant changes in remaining types of culture in the Sutter-Yuba Area.

Probable Ultimate Cultural Pattern. Classification of lands of the Sutter-Yuba Area with respect to their suitability for irrigated agriculture was largely accomplished by other agencies prior to the Sutter-Yuba Counties Investigation. Many valuable data on land classification were available from and furnished by the United States Bureau of Reclamation. The available data were supplemented and checked as required in the course of field surveys conducted as a part of the investigation.

On the basis of their suitability for irrigation, agricultural lands of the Sutter-Yuba Area were segregated into the following five classes:

Class 1. This class comprises lands that are highly desirable in every respect for continuous irrigated agricultural use, and capable of producing all climatically adapted crops. The soils are deep, with good surface and subsoil drainage, of medium to fairly fine texture, and of good water-holding capacity. The soil structure is such as to permit easy penetration of roots, air, and water, and the land surface is smooth and gently sloping.

Class 2. This class comprises lands that are generally limited in their use to climatically adapted crops of medium root depths. Restrictive features with regard to use of the lands are soil depth and, to some extent, topography or drainage.

Class 3. This class comprises lands that are generally limited in their use to climatically adapted shallow-rooted crops, owing to deficiencies in soil depth, topography, or drainage characteristics. This class of lands is suitable for development under irrigation, but because of shallow soil depths, greater care and skill are required in the application of water than are necessary in the case of lands of Classes 1 and 2.

Class 4. This class comprises lands that fail to meet the standards of Classes 1, 2, and 3, as to topography, drainage, and depth of soil. These lands are generally suitable only for permanent pasture or similar crops.

Class 6. This class comprises all lands that do not meet the minimum requirements of suitability for irrigation use.

In addition to agricultural lands, 5,550 acres in the Sutter-Yuba Area were classified as urban, and 22,270 acres comprising the waste lands of the Sutter Buttes were not otherwise classified. Results of the land classification of the Sutter-Yuba Area, summarized by zones, are presented in Table 25.

By use of the land classification data a probable ultimate cultural pattern for the Sutter-Yuba Area was forecast. The general assumption was made that under

TABLE 24

PAST AND PRESENT CULTURAL PATTERNS IN ZONES OF SUTTER-YUBA AREA

(In acres)

Class and type of culture	West Side Zone			Northeast Zone			East Central Zone			South Side Zone			Totals		
	Estimated base period average, 1939-40 through 1947-48	1947-48	Present, 1948-49	Estimated base period average, 1939-40 through 1947-48	1947-48	Present, 1948-49	Estimated base period average, 1939-40 through 1947-48	1947-48	Present, 1948-49	Estimated base period average, 1939-40 through 1947-48	1947-48	Present, 1948-49	Estimated base period average, 1939-40 through 1947-48	1947-48	Present, 1948-49
Irrigated lands															
Deciduous orchard	30,610	32,660	31,820	3,830	4,380	4,410	3,190	3,970	4,080	3,050	3,220	3,190	40,680	44,230	43,500
Rice	9,200	13,480	13,120	1,170	3,440	4,320	3,350	7,800	12,080	11,800	13,630	14,920	25,520	38,350	44,440
Permanent pasture	5,750	8,760	8,530	5,030	6,710	7,580	3,860	5,130	5,860	2,800	3,330	3,560	17,440	23,940	25,530
Beans	3,470	3,610	3,700	1,270	1,460	1,140	3,640	4,190	5,680	1,330	1,390	1,870	9,700	10,650	12,390
Alfalfa	3,100	3,780	3,770	780	1,030	1,630	1,430	1,940	2,210	2,760	3,310	3,530	8,070	10,060	11,140
Truck	2,950	3,060	3,010	210	230	250	510	600	650	680	1,000	930	4,350	4,890	4,840
Tomatoes	980	1,020	1,000	70	80	140	180	210	600	320	70	140	1,550	1,370	1,880
Corn	350	370	300	190	220	270	310	350	550	370	390	410	1,230	1,330	1,530
Hops	520	540	540				560	650	650				1,090	1,190	1,190
Sugar beets	240	250	190	10	10	180	560	640	640	210		40	1,020	900	1,050
Olives	50	40	40	20	20	20	240	290	280				310	350	340
Vines	140	150	150				70	80	80		10	10	200	240	240
Miscellaneous	20	20	70			150	810	890	770	310	350	240	1,140	1,260	1,230
Subtotals	57,380	67,740	66,240	12,580	17,580	20,090	18,710	26,740	34,130	23,630	26,700	28,840	112,300	138,760	149,300
Dry-farmed and fallow lands	53,980	42,610	44,110	24,700	19,150	16,640	47,440	38,440	31,050	53,810	50,120	47,980	179,920	150,310	139,770
Native vegetation	3,580	3,580	3,580	2,750	2,750	2,750	5,280	5,280	5,280	1,400	1,400	1,400	13,010	13,010	13,010
Miscellaneous															
Farmsteads	2,320	2,690	2,690	460	590	590	1,080	1,460	1,460	1,070	1,380	1,380	4,930	6,120	6,120
Roads	2,320	2,690	2,690	460	590	590	1,080	1,460	1,460	1,070	1,380	1,380	4,930	6,120	6,120
Urban	1,840	2,110	2,110	900	1,190	1,190	1,850	2,060	2,060	190	190	190	4,780	5,550	5,550
Water surface	1,350	1,350	1,350	470	470	470	1,040	1,040	1,040	130	130	130	2,990	2,990	2,990
Railroads and highways	720	720	720	380	380	380	660	660	660	690	690	690	2,450	2,450	2,450
Airfields				160	160	160	590	590	590				750	750	750
By-pass overflow lands										470	470	470	470	470	470
Tules	160	160	160				20	20	20				180	180	180
By-pass levees	120	120	120										130	130	130
Waste lands							120	120	120				120	120	120
Subtotals	8,830	9,840	9,840	2,380	3,380	3,380	6,440	7,410	7,410	3,620	4,240	4,240	21,730	24,880	24,880
TOTALS	*123,770	*123,770	*123,770	42,860	42,860	42,860	77,870	77,870	77,870	82,460	82,460	82,460	*326,960	*326,960	*326,960

* Excluding 22,270 acres of waste lands in Sutter Buttes.

TABLE 25

CLASSIFICATION OF LANDS IN ZONES OF SUTTER-YUBA AREA

(In acres)

Zone	Land classes						
	1	2	3	4	6	Urban	Totals
West Side	45,520	41,040	27,440	220	7,440	2,110	*123,770
Northeast	4,240	18,420	13,190	190	5,630	1,190	42,860
East Central	8,330	14,070	44,450	1,270	7,690	2,060	77,870
South Side	10,200	30,880	36,770	------	4,420	190	82,460
TOTALS	68,290	104,410	121,850	1,680	25,180	5,550	*326,960

* Excluding 22,270 acres of waste lands in Sutter Buttes.

an increasing pressure of demand for agricultural products all irrigable but presently dry lands would eventually be provided with irrigation service. Provision was also made for probable increase in lands devoted to farmsteads, roads, urban, and other miscellaneous purposes under conditions of probable ultimate development.

The estimated ultimate cultural pattern of the Sutter-Yuba Area, summarized by general classes of culture and by zones of the area, is presented in Table 26. Irrigable lands, as determined by the land classification survey data and as indicated by the probable ultimate cultural pattern, are shown on Plate 17.

TABLE 26

PROBABLE ULTIMATE CULTURAL PATTERN IN ZONES OF SUTTER-YUBA AREA

(In acres)

Class of culture	West Side Zone	North-east Zone	East Central Zone	South Side Zone	Totals
Irrigated lands	100,000	31,200	54,000	64,700	249,900
Dry-farmed lands	9,600	5,100	9,300	11,100	35,100
Native vegetation	3,600	2,700	5,300	1,400	13,000
Miscellaneous	10,600	3,900	9,300	5,200	29,000
TOTALS	*123,800	42,900	77,900	82,500	*327,000

* Excluding waste lands in Sutter Buttes.

Unit Use of Water

The second step in evaluation of water utilization involved the determination of unit values of consumptive use of water for each type of water consuming culture. Estimates of these unit values were largely based on the results of prior investigations and studies in other areas.

A procedure suggested by Harry F. Blaney and Wayne D. Criddle of the Soil Conservation Service, United States Department of Agriculture, in their reports entitled "A Method of Estimating Water Requirements in Irrigated Areas from Climatological Data," dated December, 1947, and "Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data," dated August, 1950, was generally utilized for adjustment of available data on unit consumptive use by irrigated crops in other localities to correspond with conditions existing in the Sutter-Yuba Area. This method involved correlation of the data on the basis of variations in average monthly temperatures, monthly percentages of annual daytime hours, precipitation, and lengths of growing season. It disregarded certain generally unmeasured factors such as wind movement, humidity, etc. Average monthly temperatures at Marysville were considered representative of the Sutter-Yuba Area. Monthly percentages of annual daytime hours were determined for latitude 39° N., which passes approximately through the center of the area.

The following is an outline of the procedure utilized for estimating unit values of consumptive use:

1. The unit value for each irrigated cultural type during its growing season was taken as the product of available heat and an appropriate coefficient of consumption, where: (a) the available heat was the product of average monthly temperature and monthly percent of daytime hours, and (b) the coefficient of consumption was one which had been selected as appropriate for California by Harry F. Blaney as a result of his studies for the Soil Conservation Service. Certain exceptions involved the use of coefficients estimated from consumptive use data available from other sources.

2. The unit value for each irrigated cultural type during its nongrowing season was taken as the amount of precipitation available, but not exceeding one to two inches of depth per month, depending upon the type of culture and cover crop.

3. The seasonal unit value for each irrigated cultural type was taken as the summation of values determined under items 1 and 2 for that type.

4. Unit seasonal values for native annual grasses were taken as equal to the available precipitation up to but not exceeding 1.3 feet in depth.

5. Unit seasonal values for native vegetation other than annual grasses were estimated on the basis of available data on corresponding consumptive use in similar localities, due consideration being given to density and type of vegetation and depth to ground water.

6. Unit seasonal values for free water surfaces were estimated from available records of evaporation at Gridley.

7. Unit seasonal values for remaining miscellaneous types of culture were estimated on the basis of available data on corresponding consumptive use in similar localities.

Estimated unit seasonal values of consumptive use of water in the Sutter-Yuba Area, including consumption of precipitation, are presented in Table 27. In view of the indicated water supply and climatological similarities of the mean and base periods, the estimated average unit seasonal values of consumptive use for the base period were considered to approximate corresponding values for the mean period.

TABLE 27

ESTIMATED UNIT VALUES OF SEASONAL CONSUMPTIVE USE OF WATER IN SUTTER-YUBA AREA

(In feet of depth)

Class and type of culture	Average for 9-year base period, 1939-40 through 1947-48	1947-48	1948-49
Irrigated lands			
Deciduous orchard	2.7	2.5	2.7
Rice	5.0	5.0	5.0
Permanent pasture	3.7	3.3	3.6
Beans	2.0	2.0	1.8
Alfalfa	4.0	3.6	3.9
Truck	2.3	2.3	2.2
Tomatoes	2.3	2.3	2.2
Corn	2.8	2.7	2.6
Hops	3.0	2.9	3.0
Sugar beets	3.1	3.0	3.0
Olives	2.7	2.5	2.7
Vines	2.0	2.0	1.9
Miscellaneous	2.4	2.3	2.2
Dry-farmed and fallow lands	1.3	1.3	1.2
Native vegetation			
Heavy brush, trees, grass	4.5	4.5	4.5
Medium brush, trees, grass	3.8	3.8	3.8
Light brush, grass	2.8	2.8	2.8
Sparse brush, grass	1.3	1.3	1.3
Miscellaneous			
Farmsteads	2.0	2.0	2.0
Roads	1.0	1.0	1.0
Urban	2.0	2.0	2.0
Water surfaces	5.0	5.0	5.0
Railroads, highways	1.0	1.0	1.0
Airfields	1.3	1.3	1.3
By-pass overflow lands	4.0	4.0	4.0
Tules	5.0	5.0	5.0
By-pass levees	1.0	1.0	1.0
Waste lands	0.5	0.5	0.5

Past and Present Water Utilization

The total amount of utilization of water in the Sutter-Yuba Area was estimated by multiplying the acreage of each type of culture by its respective unit value of consumptive use of water. The results of the estimates of seasonal water utilization during the base period and investigational seasons are presented in Table 28, summarized by general classes of culture. These estimates include consumptive use of precipitation.

TABLE 28

ESTIMATED SEASONAL UTILIZATION OF WATER IN SUTTER-YUBA AREA DURING BASE PERIOD AND INVESTIGATIONAL SEASONS

(In acre-feet)

Class of culture	Average for 9-year base period, 1939-40 through 1947-48	1947-48	1948-49
Irrigated lands	382,000	469,000	524,000
Dry-farmed and fallow lands	234,000	195,000	171,000
Native vegetation	49,000	49,000	49,000
Miscellaneous	45,000	51,000	50,000
TOTALS	710,000	764,000	794,000

Mean seasonal water utilization in the Sutter-Yuba Area was also estimated as it would be with present cultural development but under mean conditions of water supply and climate. The estimate was based on the cultural pattern determined by the 1949 survey, and on estimated average unit seasonal values of consumptive use of water for the nine-year base period which were considered to approximate those for the mean period. The estimate, which includes consumptive use of precipitation, is presented in Table 29, summarized for the four zones of the area and segregated by general cultural classes.

In order to facilitate certain phases of the analysis of ground water hydrology, presented in Chapter II, it was desirable to estimate seasonal utilization of ground water in the Sutter-Yuba Area. Unit seasonal values of consumptive use of ground water were derived by subtracting the amount of available precipitation, up to but not exceeding 1.3 feet of depth, from the appropriate unit seasonal values presented in Table 27. The corrected values were then multiplied by the acreages of each cultural type served by ground water during the respective periods. These included native vegetation in high water table areas. The 1949 cultural pattern was considered representative of present conditions, and average unit seasonal values of consumptive use for the base period were considered to be equal to corresponding mean period values. The estimates of utilization of ground water are summarized by general classes of culture in Table 30.

TABLE 29

ESTIMATED MEAN SEASONAL UTILIZATION OF WATER IN ZONES OF SUTTER-YUBA AREA UNDER PRESENT CULTURAL DEVELOPMENT

(In acre-feet)

Class of culture	West Side Zone	North-east Zone	East Central Zone	South Side Zone	Totals
Irrigated lands	219,100	73,400	125,500	120,100	538,100
Dry-farmed and fallow lands	57,300	21,600	40,400	62,400	181,700
Native vegetation	13,600	10,400	20,000	5,300	49,300
Miscellaneous	20,700	7,100	15,300	5,900	49,000
TOTALS	310,700	112,500	201,200	193,700	818,100

TABLE 30

ESTIMATED SEASONAL UTILIZATION OF GROUND WATER IN SUTTER-YUBA AREA

(In acre-feet)

Class of culture	Average for 9-year base period, 1939-40 through 1947-48	1947-48	1948-49	With present culture under mean conditions of water supply and climate
Irrigated lands	119,400	165,600	222,400	224,600
Native vegetation	31,900	31,900	31,900	31,900
Miscellaneous	6,800	8,200	8,200	8,200
TOTALS	158,100	205,700	262,500	264,700

Probable Ultimate Water Utilization

The total seasonal amount of water utilization in the Sutter-Yuba Area was estimated as it would be under probable ultimate conditions of cultural development and under mean conditions of water supply and climate. This was accomplished by multiplying acreages of cultural types derived in the forecast of the ultimate cultural pattern by corresponding average unit seasonal values of consumptive use of water for the base period. It was considered that unit consumptive use during the base period was equal to that under mean conditions of water supply and climate. The estimate of probable ultimate water utilization is summarized in Table 31 by general cultural classes and by zones of the Sutter-Yuba Area. The estimate includes consumptive use of precipitation.

TABLE 31

PROBABLE ULTIMATE MEAN SEASONAL UTILIZATION OF WATER IN ZONES OF SUTTER-YUBA AREA

(In acre-feet)

Class of culture	West Side Zone	North-east Zone	East Central Zone	South Side Zone	Totals
Irrigated lands	336,300	111,500	205,000	249,300	902,100
Dry-farmed lands	12,400	6,700	12,100	14,400	45,600
Native vegetation	13,600	10,400	20,000	5,300	49,300
Miscellaneous	22,000	7,600	18,400	9,300	57,300
TOTALS	384,300	136,200	255,500	278,300	1,054,300

Demands for Water

The term "demands for water," as used in this report, refers to those factors pertaining to rates, times, and places of delivery of water, imposed by the control, development, and use of the water for any and all beneficial purposes. Certain possible present or future nonconsumptive demands for water in the Sutter-Yuba Area, such as those for hydroelectric power generation, flood control, conservation of fish and wildlife, recreation, etc., were considered to be outside the scope of the current investigation. Since they would have little significance in preliminary design of works to meet supplemental requirements for water in the Sutter-Yuba Area, they are not further discussed herein.

Irrigation practice in the Sutter-Yuba Area, as determined by rates of application, gross diversions, monthly demands, and permissible deficiencies in application of water, must be given consideration in preliminary design of works to meet supplemental water requirements. These demand factors, which were not measured or considered in the foregoing estimates of water utilization, are discussed in the following sections.

Application of Water. The term "applied water," as used in this report, refers to that water other than precipitation which is delivered to a farmer's headgate in the case of irrigation use, or to an individual's meter in the case of urban use, or its equivalent. During each of the two seasons of the investigation measurements were made of the amount of water applied for irrigation of selected plots of principal crops grown on various soil types in the Sutter-Yuba Area. Records of such application of water pumped from wells were obtained for 35 plots during 1948, and 21 plots during 1949. For each well the pump discharge, acreage of each type of crop irrigated, number of irrigations, periods of irrigation, and amounts of water applied in each irrigation were recorded. From these data, monthly and total seasonal applications of water to each crop were determined. Results of these studies, which may be considered representative of prevailing irrigation practice in the Sutter-Yuba Area, are summarized in Table 32. Detailed results of the plot studies are presented in Appendix F, and location of the plots is indicated on Plate 17.

TABLE 32

MEASURED AVERAGE SEASONAL APPLICATION OF IRRIGATION WATER ON REPRESENTATIVE PLOTS OF PRINCIPAL CROPS IN SUTTER-YUBA AREA

Crop	Number of plots			Applied water, in feet of depth		
	1948	1949	Total	1948	1949	Weighted average for the two seasons
Alfalfa	2	3	5	5.69	6.14	5.98
Almonds	3	2	5	1.07	1.71	1.29
Beans	2	1	3	1.21	0.95	1.15
Cherries	2	0	2	2.29	--	2.29
Clover	1	0	1	4.29		4.29
Corn	1	1	2	2.62	1.76	1.91
Flax	1	0	1	0.87	---	0.87
Hops	1	1	2	0.92	0.87	0.89
Irrigated pasture	1	3	4	2.18	6.50	5.19
Peaches	9	5	14	2.46	2.68	2.53
Prunes	4	1	5	1.04	3.02	1.21
Rice	3	3	6	5.14	5.56	5.36
Sugar beets	1	0	1	1.45	-----	1.45
Walnuts	4	1	5	2.04	1.90	2.00

Studies were made to determine the approximate average irrigation efficiency realized from application of ground water in the Sutter-Yuba Area during the 1947-48 season. "Irrigation efficiency" is defined as the ratio of consumptive use of applied water to the total amount of applied water, and is commonly expressed as a percentage.

In order to estimate the total amount of ground water applied for irrigation in the Sutter-Yuba Area in 1947-48, appropriate crop acreages, as mapped in the cultural survey, were multiplied by average seasonal values of depth of applied water for the several crops, as measured at the representative plots listed in Table 32. This computation resulted in an estimate of 347,000 acre-feet. As a check on this figure, the Pacific Gas and Electric Company furnished a corresponding estimate of 317,000 acre-feet based on records of electric power consumption for pumping. The company's estimate gave consideration to the relationship between pumping plant horsepower, drawdown, and power consumption per unit of water pumped at various lifts, as determined by pump performance tests conducted in the area by the company. In view of the nature of the basic data, the check furnished was believed to have been reasonably close.

By dividing the estimated value of 165,600 acre-feet for consumptive use of ground water on irrigated lands in the Sutter-Yuba Area in 1947-48, presented in Table 30, by the foregoing estimated value of 347,000 acre-feet, it was estimated that the irrigation efficiency realized from application of ground water in the Sutter-Yuba Area during 1947-48 was approximately 48 percent. This efficiency may be considered to be indicative of average irrigation practice in the Sacramento Valley. It was impracticable to make a corresponding estimate of irrigation efficiency realized from use of surface water in the Sutter-Yuba Area because of lack of sufficient data regarding application of surface water for irrigation purposes.

Gross Diversion of Water. The amount of the gross diversion for irrigation by ground water in the Sutter-Yuba Area was considered to be equivalent to the amount of applied ground water. As discussed in the preceding section, this was estimated to have totaled 347,000 acre-feet during 1947-48.

The gross diversion for irrigation by surface water in the Sutter-Yuba Area was estimated to have totaled about 362,000 acre-feet during 1947-48. This estimate was based on records of measurement of all surface diversions in the area, plus the estimate of importation by the Sutter Butte Canal system presented in Chapter II.

By subtracting from total consumptive use of water on irrigated lands the corresponding consumptive use of ground water and precipitation, the approximate amount of consumptive use of applied surface water was estimated. An estimate of total consumptive use of water on irrigated lands of the Sutter-Yuba Area in 1947-48, in the amount of 469,000 acre-feet, was presented in Table 28. Consumptive use of ground water on irrigated lands was estimated to have been 165,600 acre-feet in 1947-48, as shown in Table 30. It was further estimated that consumptive use of precipitation on the 138,700 acres of irrigated lands in the Sutter-Yuba Area in 1947-48 was equal to 1.3 feet of depth, or a total amount of 180,400 acre-feet. It follows that the estimated amount of consumptive use of surface water applied for irrigation in the area was approximately 123,000 acre-feet in 1947-48.

It is indicated from the foregoing that only about 123,000 acre-feet, or about 34 percent of the estimated 362,000 acre-feet of gross surface diversion for irrigation in the Sutter-Yuba Area in 1947-48, was actually consumed in production of crops. It should be noted that this figure is not comparable with estimated irrigation efficiency attained in connection with use of ground water in the area, evaluated in the preceding section, since it is based on the amount of gross diversion rather than the amount of applied water. Insufficient data were available to permit evaluation of transmission and other losses encountered in connection with use of surface water between points of diversion and places of use.

Monthly Demands for Irrigation Water. Because of the wide variety of crops produced in the Sutter-Yuba Area there is considerable variation in both rate and period of demand for irrigation water. On the average, the irrigation demand occurs during the months of April through October. Studies of irrigation practice in the Sutter-Yuba Area indicated that for certain crops the maximum monthly demand might be as much as 45 percent of the seasonal total. Based on these studies, and on similar studies made in other areas, the estimated average monthly distribution of demand for irrigation water in the West Side Zone and in the remainder of the Sutter-Yuba Area is set forth in Table 33. Because of the predominance of orchard and truck crops in the West Side Zone, monthly distribution in that zone varies somewhat from that in the remainder of the area. Early applications to rice and irrigated pasture account for the greater part of the demand for water in April and May.

TABLE 33
ESTIMATED AVERAGE MONTHLY DISTRIBUTION OF DEMAND FOR IRRIGATION WATER IN SUTTER-YUBA AREA

(In percent of seasonal total)

	West Side Zone	Remainder of Sutter-Yuba Area
April	2	10
May	13	16
June	21	17
July	27	22
August	21	17
September	12	11
October	4	5
November		2
	100	100

Permissible Deficiencies in Application of Irrigation Water. Studies to determine deficiencies in the supply of irrigation water that might be endured without permanent injury to perennial crops were not made in connection with the Sutter-Yuba Counties Investigation. However, the results of past investigation and study of endurable deficiencies in the Sacramento River Basin are believed to be applicable to the Sutter-Yuba Area. In this respect, the following is quoted from Division of Water Resources Bulletin No. 26, "Sacramento River Basin," 1931.

> "* * * A full irrigation supply furnishes water not only for the consumptive use of the plant but also for evaporation from the surface during application and from the moist ground surface, and for water which is lost through percolation to depths beyond the reach of the plant roots. Less water can be used in years of deficiency in supply by careful application and by more thorough cultivation to conserve the ground moisture. In these ways the plant can be furnished its full consumptive use with much smaller amounts of water than those ordinarily applied and the yield will not be decreased. If the supply is too deficient to provide the full consumptive use, the plant can sustain life on smaller amounts but the crop yield will probably be less than normal.
>
> "It is believed from a study of such data as are available that a maximum deficiency of 35 per cent of the full seasonal requirement can be endured, if the deficiency occurs only at relatively long intervals. It is also believed that small deficiencies occurring at relatively frequent intervals can be endured. * * *"

SUPPLEMENTAL WATER REQUIREMENTS

The previously presented data, estimates, and discussion regarding water supply and utilization in the Sutter-Yuba Area indicate that present and probable future water problems of the area are largely limited to those connected with ground water and that their effects are largely related to irrigated agriculture. It is further indicated that ground water problems, including those created in various portions of the area by progressive lowering of water levels, degradation of mineral quality of ground water, and low yield of wells, may be eliminated or prevented if adequate supplemental water supplies are developed and utilized in the area. The estimated present and probable ultimate requirements for supplemental water in the Sutter-Yuba Area are discussed and evaluated in the following sections. As previously defined, requirement for supplemental water refers to the amount of water, over and above the sum of safe ground water yield and safe surface water yield, which must be developed to satisfy water utilization. Water utilization in turn refers to the sum of consumptive use of water and those irrecoverable losses of water incidental to its beneficial use.

Present Supplemental Requirement

The present requirement for supplemental water in the Sutter-Yuba Area was evaluated as the difference between safe yield of ground water and present consumptive use of ground water. It might be argued that this evaluation fails to give consideration to possible inadequacies in service of surface water to portions of the area. However, in the solution of the equation of hydrologic equilibrium, presented in Table 15, upon which the estimate of safe ground water yield was based, the unit consumptive use factors chosen assumed a full and sufficient application of water on all irrigated lands whether from surface sources or ground water. It follows that any possible present inadequacy in surface water service was taken into account and provided for in the estimate of safe ground water yield.

It was estimated in Chapter II that safe seasonal ground water yield in the Sutter-Yuba Area amounted to 186,100 acre-feet. This was determined as the seasonal net extraction of water from the ground water basin that might be maintained, under mean conditions of water supply and climate, without further progressive lowering of the water table below levels prevailing in 1948-49. Seasonal consumptive use of ground water in the area, with present culture and under mean conditions of water supply and climate, was estimated to be 264,700 acre-feet, as shown in Table 30. The estimated present requirement for supplemental water in the Sutter-Yuba Area, therefore, is 78,600 acre-feet per season. This estimate is presented in Table 34, which shows distribution of the supplemental water requirement among the several zones of the area. The distribution was based on the assumption that lowering of water levels which occurred during the season of 1948-49 would have been proportionately the same had mean water supply and climatic conditions prevailed.

TABLE 34

ESTIMATED PRESENT MEAN SEASONAL SUPPLEMENTAL WATER REQUIREMENT IN ZONES OF SUTTER-YUBA AREA

Zone	Acre-feet
West Side	
Peach Bowl	14,900
Outside Peach Bowl	2,100
Northeast	6,400
East Central	27,600
South Side	27,600
TOTAL	78,600

It was shown in Chapter II that an area of about 4,500 acres in the West Side Zone south of Oswald Road was irrigated in the summer of 1950 with ground water containing chlorides at or above the upper limit of safe use for irrigation. A substitute water supply is presently required for these lands, the amount of which may be determined by the required amount of applied water. This is true because any unconsumed portion of applied water would be so degraded after percolating to the underlying saline ground water as to preclude its re-use. Seasonal application of water to the orchard and truck crops grown in the Peach Bowl averages about 3.0 feet of depth, as determined by plot studies conducted during the investigation. However, if water of good mineral quality were substituted for the inferior ground water now used, leaching irrigations would not be required. It was estimated that under such conditions the seasonal application of water would be about 2.5 feet of depth, corresponding to average good practice in the Sutter-Yuba Area for irrigation of orchard and truck crops. On this basis the estimated amount of the substitute water supply presently required in the West Side Zone in lieu of ground water of excessive salinity is about 11,300 acre-feet per season. This is less than the estimated present supplemental requirement of 17,000 acre-feet per season required to prevent progressive and permanent lowering of water levels in the West Side Zone. Therefore, by furnishing a supplemental surface water supply to the West Side Zone sufficient to prevent progressive and permanent lowering of the water table, the present problem with respect to inferior mineral quality of the ground water would be eliminated.

Probable Ultimate Supplemental Requirement

The probable ultimate requirement for supplemental water in the Sutter-Yuba Area was evaluated as the difference between present and probable ultimate utilization of water, plus the present requirement for supplemental water. Development and utilization of a supplemental water supply in the amount of this forecast would assure an adequate supply of water for lands presently irrigated in the area, as well as for those irrigable lands not presently served with water. Furthermore, present problems resulting from progressive and permanent lowering of water levels, degradation of mineral quality of ground water, and low yield of wells would be eliminated.

Estimates of present and probable ultimate utilization of water in the Sutter-Yuba Area, under mean conditions of water supply and climate, were presented in Tables 29 and 31, respectively, and a corresponding estimate of the present requirement for supplemental water was developed in the preceding section. Utilizing these estimates, the forecast of probable ultimate seasonal requirement for supplemental water by zones of the Sutter-Yuba Area, under mean conditions of water supply and climate, is presented in Table 35.

TABLE 35

PROBABLE ULTIMATE MEAN SEASONAL SUPPLEMENTAL WATER REQUIREMENT IN ZONES OF SUTTER-YUBA AREA

(In acre-feet)

Zone	1	2	3	4	5
	Present water utilization	Probable ultimate water utilization	Probable increase in water utilization (2 — 1)	Present supplemental water requirement	Probable ultimate supplemental water requirement (3 + 4)
West Side	310,700	384,300	73,600	17,000	90,600
Northeast	112,500	136,200	23,700	6,400	30,100
East Central	201,200	255,500	54,300	27,600	81,900
South Side	193,700	278,300	84,600	27,600	112,200
TOTALS	818,100	1,054,300	236,200	78,600	314,800

CHAPTER IV

PLANS FOR WATER DEVELOPMENT

It has been shown heretofore that the present basic water problems in the Sutter-Yuba Area are progressive and permanent lowering of ground water levels and attendant degradation of mineral quality of the ground water. Elimination of these problems, prevention of their recurrence in the future, and irrigation of irrigable lands not presently served with water will require further conservation development of available water supplies. In the preceding chapter, estimates were presented as to the amount of supplemental water required for these purposes both at the present time and under probable ultimate conditions of cultural development.

It has been shown that large surplus flows of water are presently available to the Sutter-Yuba Area from the highly productive watershed of the Feather River system, including the Yuba and Bear Rivers and minor tributary streams. This surface water is available during the snowmelt period of every season, and, in all but very dry seasons, flows sufficient to meet present supplemental requirements of the area are available into the summer months. Studies which are described in this chapter indicate that the surplus flows, if properly controlled and regulated, would more than supply the probable ultimate water requirements of the Sutter-Yuba Area.

As was stated in Chapter I, the Division of Water Resources is presently conducting surveys and studies for the State-wide Water Resources Investigation, under direction of the State Water Resources Board. This investigation has as its objective the formulation of The California Water Plan, for full conservation, control, and utilization of the State's water resources, to meet present and future water needs for all beneficial purposes and uses in all parts of the State, insofar as practicable. Surveys and studies are also being conducted by the Division of Water Resources for the Survey of Mountainous Areas. This investigation, which is coordinated with the state-wide investigation, has as its primary objective the determination of probable ultimate water requirements of certain counties of the Sierra Nevada, and the formulation of plans for projects which will meet those requirements. Although these investigations are still in progress, they are sufficiently advanced to permit tentative description of certain major features of The California Water Plan which would provide supplemental water to meet the probable ultimate requirements of the Sutter-Yuba Area. The projects would also provide supplemental water supplies for other water-deficient areas of California. In addition, benefits from the projects would include hydroelectric power, flood and salinity control, mining debris storage, and incidental benefits in the interests of recreation and the preservation of fish and wildlife.

In general, the major features of The California Water Plan, which were mentioned in the preceding paragraph, would be large multipurpose projects requiring relatively large capital expenditures. Their scope, with regard to both location of the works and benefits derived from their operation, would not be limited to the Sutter-Yuba Area, but would embrace other portions of California. Much additional study will be required to estimate costs and to determine possible means of financing these large projects. Under the Sutter-Yuba Counties Investigation, therefore, numerous surveys and studies were made in order to estimate costs of supplemental water supplies for the Sutter-Yuba Area under more localized plans that might be suitable for current financing, construction, and operation by appropriate local public agencies. These plans for initial development generally are such that the works could be integrated into future major projects. Their purposes are largely limited to conservation of new water supplies sufficient to meet the present requirements of the Sutter-Yuba Area and to provide for limited future growth in water demands of the area.

Major features of The California Water Plan which would be pertinent to solution of the ultimate water problems of the Sutter-Yuba Area are described in general terms in this chapter under the heading "The California Water Plan." These projects will be more specifically described in future reports of the State Water Resources Board. The several plans for possible initial local development of supplemental water supplies which were given consideration in connection with the Sutter-Yuba Counties Investigation are described in this chapter under the heading "Plans for Initial Local Development." All such plans considered would be subject to vested rights. Specific plans are presented for the more favorable of these local projects, together with estimates of capital and annual costs and unit costs of the developed supplemental water supplies. Location of the principal features of the several possible plans, for both initial and future construction, are shown on Plate 18, "Potential Water Storage Developments."

THE CALIFORNIA WATER PLAN

The Feather River Project, an adopted feature of The California Water Plan, is described in the following section, where it is shown that it will provide supplemental water to meet the probable ultimate requirement of the West Side Zone. Several other major projects, which would involve multipurpose water resources developments on the Yuba and Bear Rivers and other tributaries of the Feather River, are briefly described in an ensuing section. These latter projects would provide supplemental water to meet the probable ultimate requirements of the Northeast, East Central, and South Side Zones, and are tentatively being considered as possible features of The California Water Plan.

Feather River Project

The probable ultimate supplemental water requirement in the West Side Zone could be met under a plan which would provide upstream regulatory storage on the Feather River to enhance and firm the summer flow of the stream. Such storage will be made available by construction of Oroville Dam and Reservoir, units of the Feather River Project, which are described in detail in a publication of the State Water Resources Board entitled "Report on Feasibility of Feather River Project and Sacramento-San Joaquin Delta Diversion Projects Proposed as Features of The California Water Plan," dated May, 1951. These projects were authorized and adopted by the 1951 Legislature in an act which authorized their construction, operation, and maintenance by the Water Project Authority of the State of California. Provision was made in the authorizing act for financing construction of the proposed works through issuance and sale of revenue bonds and through receipt of contributions from other sources. In May, 1952, the Legislature provided $800,000, by budgetary appropriation to the Division of Water Resources, for necessary investigations, surveys, and studies, and preparation of plans and specifications for the Feather River and Sacramento-San Joaquin Delta Diversion Projects.

The multipurpose Feather River Project contemplates construction of a gravity concrete dam, 710 feet in height above stream bed, at a point on the Feather River 1.7 miles below the junction of the North and Middle Forks and 5.5 miles above the City of Oroville. The dam will have an overpour spillway. It will create a reservoir of 3,500,000 acre-foot storage capacity, and will provide a large measure of control of the runoff of the Feather River for purposes of conservation, flood control, hydroelectric power generation, and other beneficial uses. Provision will be made for a power plant located at the dam, of 440,000 kilowatt capacity, and for an afterbay dam, and power plant of 25,000 kilowatt capacity, located four miles downstream from the main dam. The foregoing features of the Feather River Project are shown on Plate 18. The project also includes construction of a power transmission line from the Oroville power plants to Bethany, near Tracy in San Joaquin County, and a switch yard at the terminal. A channel crossing of the Sacramento-San Joaquin Delta will be required to carry Oroville Reservoir releases from the Sacramento River to the San Joaquin River Delta for subsequent transmission to water-deficient areas in other parts of California.

In studies for the cited feasibility report of the State Water Resources Board, Oroville Reservoir was operated to first meet the water requirements of the Feather River Service Area, shown on Plate 18. The West Side Zone of the Sutter-Yuba Area is contained within the described Feather River Service Area.

Under the plan of operation of Oroville Reservoir described in the foregoing feasibility report, releases of water would be made sufficient to meet gross demands of the Feather River Service Area under ultimate conditions of irrigation development. The estimate of seasonal gross demand for water under such conditions was 970,000 acre-feet, which, with an assumed irrigation efficiency of 65 percent, would provide for consumptive use of water, over and above effective rainfall, in the amount of 631,000 acre-feet per season. Of this estimated ultimate consumptive use of applied water in the Feather River Service Area, 311,000 acre-feet per season would be new water over and above present utilization. Studies indicate that the probable ultimate supplemental water requirement of the West Side Zone, estimated to be some 90,000 acre-feet per season, could readily be supplied from the foregoing 311,000 acre-feet of new water from Oroville Reservoir.

Detailed estimates of cost of the Feather River Project are presented in the feasibility report. A summary of estimated capital costs of the project is given in Table 36. The estimates of capital cost were based on prices prevailing in 1951, and included allowances of 10 percent for administration and engineering, 15 percent for contingencies, and 3 percent for interest during one-half of the estimated construction period.

TABLE 36

SUMMARY OF ESTIMATED CAPITAL COSTS OF FEATHER RIVER PROJECT

Oroville Dam and Reservoir	$342,626,000
Oroville Power Plant	64,509,000
Oroville Afterbay and Power Plant	14,146,000
Oroville Transmission Line	17,124,000
Terminal Switchyard	2,610,000
Delta Cross Channel	3,798,000
TOTAL	$444,813,000

It was assumed in the cost analyses presented in the feasibility report that the Federal Government would contribute to the Feather River Project the sum of $50,000,000, without reimbursement, in the interest of flood control. Substantial flood control benefits to land

and communities along the Feather River would result from operation of the project. There is well-established federal policy for such financial participation in projects of this character. It was also assumed that the State of California would contribute to the Feather River Project the sum of $86,926,000 in the interests of flood control and water development. This contribution would likewise be without reimbursement, and would be accomplished by assuming the costs of lands and improvements flooded and of necessary relocation of utilities. Such financial participation by the State would be justified under the policy set forth in the State Water Resources Act of 1945, as amended. If these federal and state contributions to the Feather River Project were forthcoming, capital costs shown in Table 36 would be reduced to $307,887,000. Based on this estimated capital cost, it was further estimated that annual costs of the project would be about $14,791,000 based upon 2 percent interest, and about $16,272,000 based on 3 percent interest. The annual costs included interest, repayment, replacement, operation and maintenance, insurance, and general expenses. In the cost analysis it was shown that annual costs based upon the 2 percent interest rate could be met under the schedule of revenues shown in the following tabulation, but that an annual deficit of some $1,426,000 would occur with the 3 percent rate.

Item	*Unit charge*	*Annual revenue*
311,000 acre-feet of new water delivered to Feather River Service Area (includes West Side Zone)	$1.00	$311,000
2,845,000 acre-feet of new water delivered to Delta	1.00	2,845,000
1,670,000,000 kilowatt-hours of electrical energy at terminal substation	0.007	11,690,000
TOTAL		$14,846,000

Based on the foregoing assumptions, the estimated cost of water from the Feather River Project to water users in the West Side Zone would be about $1 per acre-foot at the streamside. This estimate does not include costs for diverting the water from the Feather River and conveying it to and distributing it in areas of use in the West Side Zone. Studies indicate that a practicable means for diverting the water from the river would be by pumping plants strategically located along the river, discharging into appropriate conveyance and distribution systems. Diversion also could be made by gravity with construction of a diversion weir and headgates at a suitable upstream site.

Other Major Projects Under Consideration

Surveys and studies in connection with the Statewide Water Resources Investigation and the Survey of Mountainous Areas indicate that it would be feasible from the engineering standpoint to so regulate and conserve the relatively large flood flows of the Yuba and Bear Rivers and other tributaries of the Feather River as to yield firm water supplies considerably in excess of the probable ultimate supplemental water requirements of the Northeast, East Central, and South Side Zones. Existing water resources developments on these streams, together with tentative locations of possible future dams and reservoirs, are shown on Plate 18.

In addition to the studies by the Division of Water Resources, the Oroville-Wyandotte Irrigation District is currently investigating a plan for multipurpose development of the water resources of the South Fork of the Feather River. Principal features of this project, which is in an advanced planning phase, are delineated on Plate 19, "Plans for Development of South Fork of Feather River." The district is considering the diversion of waters of both the South Fork of the Feather River and Slate Creek through tunnels to the proposed Lost-Sly Creek Reservoir, to be created by construction of a dam immediately above the flow line of the existing Lost Creek Reservoir on the stream of that name. Conservation and regulatory storage would be created on the South Fork by construction of Little Grass Valley Reservoir, and on Slate Creek by construction of the small Slate Creek Reservoir. Water released from Lost-Sly Creek Reservoir would flow into Lost Creek Reservoir, and then through a proposed pressure tunnel to the penstock of the proposed Woodleaf Power House, to be located on the South Fork about one mile below its junction with Lost Creek. From the afterbay of this plant the water would flow through another tunnel to the penstock of the proposed Forbestown Power House, also to be located on the South Fork. Construction of a canal is proposed from the Forbestown Power House afterbay along the left or south bank of the South Fork of the Feather River to a point about two miles west of Lake Wyandotte, to serve lands of the Oroville-Wyandotte Irrigation District to the west of the canal. It is feasible from an engineering standpoint to extend the canal in a southerly direction a distance of some 25 miles to South Honcut Creek.

As a possible alternative to the Oroville-Wyandotte Irrigation District's project, the Division of Water Resources is studying another plan for multipurpose development of the South Fork of the Feather River. This plan contemplates construction of the proposed Little Grass Valley Reservoir on the South Fork, and diversion of the conserved water at a point about 1½ miles below the dam through a tunnel to Fall River. Water would also be diverted from South Branch of Middle Fork of Feather River to Fall River through a tunnel. A dam on Fall River would divert its own flows and water from the two foregoing diversions through a tunnel to the penstock of the proposed Lumpkin Power House on the South Fork of Feather River. A tunnel would convey the water from the afterbay of this plant to an enlarged Lost Creek Reservoir, which would be created by construction of a higher dam approximately at the site of the existing structure. The plan also contemplates construction of a small reservoir on Canyon Creek, and a diversion tunnel to the proposed Slate Creek Diversion Dam. From this dam the Slate Creek water and water from Canyon Creek would be diverted through a tunnel to a point on Lost Creek above the proposed enlarged reservoir. Releases from Lost Creek Reservoir would be made through a tunnel to a diversion dam on Grizzly Creek and from this dam through a canal and siphons to the penstock of the proposed Golden Gate Power House, to be located on Golden Gate Canyon at the headwaters of French Dry Creek. From the afterbay of this plant, a conduit, including canal and siphon sections, would lead to the penstock of the proposed Brownsville Power House, to be located on French Dry Creek at Brownsville. A canal would lead from the afterbay of the Brownsville plant to a saddle between the drainage areas of French Dry and South Honcut Creeks. At this point the canal would divide, with one branch bearing generally westerly and discharging into the existing Forbestown Ditch and thence into Lake Wyandotte. The other branch would bear southwesterly and terminate at the penstock of the proposed Honcut Power House, to be located on South Honcut Creek below its confluence with Natchez Creek. From the afterbay of the Honcut Power House a canal would extend along the right bank of South Honcut Creek and then bear northerly, terminating east of Oroville. This canal would serve lands of the Oroville-Wyandotte Irrigation District and adjacent irrigable lands lying to the west of the canal. Construction of a dam on South Honcut Creek is contemplated under the plan to create a reservoir the flow line of which would extend to the Honcut Power House afterbay. Water released from South Honcut Creek Reservoir would be diverted at appropriate downstream points on South Honcut Creek to serve lands in Browns Valley and on the Sacramento Valley floor east of the Feather River. Other diversions for irrigation and other beneficial uses in remaining water service areas between the Feather and Yuba Rivers could be made from the system.

Tentative plans for ultimate development of the Yuba River contemplate increasing the storage capacity of the existing Bullards Bar Reservoir on the North Yuba River, or providing equivalent increased capacity upstream at Kellys Bar, together with hydroelectric power development of the upper North Yuba River. Construction of a dam and reservoir on the Middle Yuba River at Granite Point is also under consideration, together with a diversion tunnel to the existing afterbay of the Bullards Bar Power House. Waters of the South Yuba River would be diverted at Edwards Crossing and conveyed by a proposed tunnel to the Granite Point Reservoir. Both the Middle and South Yuba Rivers offer possibilities for construction of dams and reservoirs, principally in the interests of mining debris storage and flood control.

The State Water Plan, as adopted by the Legislature in 1941, contemplates a storage capacity in the Englebright Reservoir on the Yuba River of about 850,000 acre-feet, as compared to the 70,000 acre-foot capacity of the existing Englebright Reservoir. This additional capacity would provide substantial conservation, flood control, and hydroelectric power, but would inundate the existing Colgate Power House, recently enlarged by the Pacific Gas and Electric Company. As a possible alternative, construction of offstream storage for waters of the Yuba River at the Waldo site, on Dry Creek, about nine miles northeast of Wheatland, is under consideration. This plan would involve construction of a conduit, diverting from Englebright Reservoir at the spillway elevation, to convey flood waters of the Yuba River to the proposed Waldo Reservoir. Under the plan, Waldo Reservoir in turn would spill into the proposed enlarged Camp Far West Reservoir on Bear River, which is hereinafter described. Consideration is also being given to possible construction of one or more additional reservoirs at the Garden Bar, Parker, or Rollins sites, upstream from the Camp Far West site on the Bear River, to effect more complete conservation of flood waters of that stream.

Studies indicate that the Northeast Zone could be served with an ultimate supplemental water supply either from the South Fork of the Feather River under the plan of development hereinbefore described, or from the Yuba River. Service from the Yuba River could be made by enlargement of the existing Hallwood-Cordua system or by diversion from the Yuba River at a suitable site in the vicinity of Parks Bar, and distribution by gravity from a main conduit bearing in a northerly direction roughly along the eastern boundary of the zone. It has been estimated that the amount of the probable ultimate mean seasonal supplemental water requirement of the Northeast Zone will be about 30,000 acre-feet. A water supply in this amount, under an appropriate schedule of demands, could be made available to the Northeast Zone by construction of one or more of the previously described major upstream projects.

It is indicated that under ultimate conditions of development the East Central Zone could also be served with supplemental water from the Yuba River. It has been estimated that the amount of the probable ultimate mean seasonal water requirement of the zone will be about 82,000 acre-feet. A portion of the required supplemental supply could be diverted, under an appropriate schedule of demands, directly from the Yuba River above Hammonton, and conveyed in a southerly direction to Hutchinson Creek, by rehabilitation and extension of the abandoned Yuba River Ditch of the Yuba Consolidated Gold Fields. Conserved water of the Yuba River to meet the remainder of the ultimate supplemental water requirement of the East Central Zone could be released from the proposed Waldo Reservoir for downstream diversion and conveyance to areas of use.

Studies also indicate that under ultimate conditions of development the South Side Zone could be served with a supplemental water supply released, under an appropriate schedule of demands, from the proposed Camp Far West Reservoir. It has been estimated that the amount of the probable ultimate mean seasonal supplemental water requirement of the zone will be about 112,000 acre-feet. A supply in this amount would be available in Camp Far West Reservoir, and would consist of waters of the Yuba and Bear Rivers and Dry Creek conserved jointly by the proposed Waldo Reservoir, Camp Far West Reservoir, and upstream reservoirs on the Bear River. It could be conveyed to points of use in the South Side Zone by an enlarged system similar to that described hereinafter in connection with the Camp Far West Project.

PLANS FOR INITIAL LOCAL DEVELOPMENT

Possible plans for initial local development of supplemental water supplies for the Sutter-Yuba Area, together with cost estimates, are described in this section. Design of features of the plans was necessarily of a preliminary nature and primarily for cost estimating purposes. More detailed investigation, which would be required in order to prepare plans and specifications, might result in designs differing in detail from those presented in this report. However, it is believed that such changes would not be significant.

Capital costs of dams, reservoirs, diversion works, conduits, pumping plants, and appurtenances, included in the considered conservation, conveyance, and distribution systems, were estimated from preliminary designs based largely on data from surveys made during the current investigation. Approximate construction quantities were estimated from these preliminary designs. Unit prices of construction items were determined from recent bid data on projects similar to those in question, or from manufacturers' cost lists, and are considered representative of prices prevailing in April, 1952. The estimates of capital cost included costs of rights of way and construction, and interest during one-half of the estimated construction period at 3 percent per annum, plus 10 percent for engineering, and 15 percent of construction costs for contingencies. Estimates of annual costs included interest on the capital investment at 3 percent, amortization over a 50-year period on a 3 percent sinking fund basis, replacement, operation, and maintenance costs, and costs of electrical energy for pumping.

Because of geographical considerations, and respective types of water service and water supplies in the several zones of the Sutter-Yuba Area, possible plans for initial water development are presented in this section separately for the West Side, Northeast, East Central, and South Side Zones.

West Side Zone

In Chapter III it was shown that the present requirement for supplemental water in the West Side Zone is about 17,000 acre-feet per season. However, in the design of projects for initial local development to meet this requirement, it was considered desirable to provide some capacity for future growth in water demand which would occur through development of irrigable lands not presently irrigated. This additional capacity was estimated at about 7,000 acre-feet per season, giving consideration to the extent of undeveloped irrigable lands that might readily be served, and to the available sources of water supply. For reasons hereinafter discussed it was considered that the new water supply would be applied to about 7,000 acres of land in the Peach Bowl, of which about 4,500 acres are presently irrigated by ground water containing chlorides at or above the safe limit for irrigation use, and 2,500 acres are irrigable lands not presently served with water. These lands are contained within a service area lying generally to the south of Oswald Road, and delineated on Plate 20, "Peach Bowl Project."

Three possible alternative plans of works for initial construction to provide supplemental water to the West Side Zone were considered. For reasons hereinafter mentioned, after preliminary investigation and study the first two plans were given no further consideration for present cost estimating purposes, but may warrant future study. The third plan is described in some detail later in this section.

Alternative Plans Considered. The first of the alternative plans considered for initial construction included salvage of water in high water table lands of the Sutter Butte Canal service area, and its conveyance to and use in the Peach Bowl. This would involve the installation of batteries of wells in the high water table area, conveyance of the pumped ground water to the Peach Bowl either in conduits or in the channel of the Feather River, and distribution of the water in a strategically situated service area of heavy ground water pumping draft in the Peach Bowl. The new water supply would largely replace ground water presently used in the Peach Bowl service area, thereby preventing progressive and permanent lowering of ground water levels and attendant degradation of mineral quality of the ground water throughout the Peach Bowl and adjacent ground water service areas. However, preliminary investigation and study indicated that changes in the crop pattern and in irrigation practice in the Sutter Butte Canal service area, which would be necessary for consummation of this plan, would be difficult to effect, and that cost of the salvaged water would be greater than for water yielded under the third plan

Feather River in the Vicinity of Starr Bend, Looking Upstream herein described. For these reasons, this plan was given no further present consideration.

Consideration was also given to the provision of a supplemental water supply to the Peach Bowl service area from the Feather River, by extension of the conveyance and distribution system of the Sutter Butte Canal. As in the case of the first plan described, use of the new surface water supply would prevent progressive and permanent lowering of water levels, and attendant degradation of mineral quality of ground water, in the area served and in adjacent areas. Preliminary investigation and study of this second plan for initial construction indicated that existing diversion facilities might be adequate for such purpose, but that conveyance facilities would require enlargement. Furthermore, a canal to serve lands requiring supplemental water in the Peach Bowl would have to be constructed on a relatively flat slope over a long distance through highly developed orchard lands. The canal would also pass through urban areas lying immediately south and west of Yuba City. It was indicated from investigation and study that cost of the new water supply would be greater than under the third plan hereinafter described. For these reasons, this plan was given no further present consideration.

The third of the alternative plans considered for initial construction would provide for the present supplemental water requirement in the West Side Zone, and for growth in water utilization for a number of years in the future. It would include the construction of facilities for pumping water directly from the Feather River and for its conveyance to and distribution in the service area in the Peach Bowl. As in the case of the two previous plans, use of the new surface water supply would prevent progressive and permanent lowering of ground water levels and degradation of mineral quality of the ground water, in the area served and in adjacent areas. This plan is hereinafter referred to as the "Peach Bowl Project," and its principal features are delineated on Plate 20.

Peach Bowl Project. Satisfactory sites for a pumping plant to divert flow of the Feather River exist on the right or west bank of the river along the reach one-half mile north and south of the prolongation of Hutchinson Road. The site selected for cost estimating purposes is at a point about four miles south of Shanghai Bend, near the center of Section 26, Township 13 North, Range 3 East, M.D.B. & M. Conveyance and distribution of water pumped from the Feather River to the area of use would be accomplished by means of a combination system including lined and unlined canals, and ditches, and the utilization of existing individual distribution systems insofar as possible. The lands which would be irrigated with the new water supply comprise the aforementioned 7,000 acres within the service area shown on Plate 20, ranging in elevation from approximately 45 feet at the north boundary to approximately 30 feet in the southerly portion.

Since the Peach Bowl constitutes a free ground water area, water losses in conveyance and distribution of the new water supply would largely percolate to the ground water. For this reason it was assumed that these losses, plus the unconsumed portion of the new water supply applied to irrigation would be effective in preventing progressive and permanent lowering of ground water levels and degradation of mineral quality of the ground water. The acreage to be irrigated by the supplemental supply would depend on the amount of the gross diversion, water losses encountered in conveyance and distribution, and the requirement for application of water to the lands irrigated.

For cost estimating purposes the Peach Bowl Project was designed to provide a gross seasonal supplemental surface water supply of approximately 24,000 acre-feet, of which about 17,000 acre-feet is necessary to meet the present supplemental requirement, and the remainder would be available for additional development of irrigable lands. An estimate of the monthly distribution of demand for irrigation water in the West Side Zone was presented in Table 33. Based on these data, the monthly gross demand for water for the Peach Bowl Project would be as shown in Table 37.

TABLE 37

ESTIMATED MONTHLY DISTRIBUTION OF GROSS DEMAND FOR WATER FOR THE PEACH BOWL PROJECT

Month	Percent of seasonal total	Demand for water, in acre-feet
April	2	480
May	13	3,120
June	21	5,040
July	27	6,480
August	21	5,040
September	12	2,880
October	4	960
TOTALS	100	24,000

Based upon known soil characteristics in the Peach Bowl and upon irrigation experience elsewhere, it was assumed that water losses in conveyance and distribution of a new surface water supply would amount to about 25 percent of the gross diversion, leaving about 18,000 acre-feet per season for application to irrigated lands. Lands in the Peach Bowl to be served with the new water supply and presently irrigated by ground water comprise about 4,500 acres of highly developed orchard. From results of the plot studies of water application described in Chapter III, it was estimated that these orchard lands would require a seasonal application of irrigation water in an amount of about 2.5 acre-feet per acre, or a total of about 11,000 acre-feet. The remaining 7,000 acre-feet of water per season available under the Peach Bowl Project, as designed, would serve about 2,500 acres of irrigable lands, presently not served with water, lying to the west of the foregoing orchard lands. If developed, it was considered that these irrigable lands would probably largely be devoted to truck and general row crops, with limited amounts of rice and irrigated pasture. Based on results of the cited plot studies, it was estimated that these lands would require a seasonal application of irrigation water in an amount of about 2.8 acre-feet per acre.

No record was available of flow in the Feather River at the proposed point of pumping diversion. However, records were available of monthly flow at Shanghai Bend some four miles upstream from the proposed diversion point, and at Nicolaus some 11 miles downstream therefrom. The Shanghai Bend record dated from 1940, while that for Nicolaus was continuous since 1921, although prior to 1939 records of stream flow at the latter station were obtained only during summer months of low flow. Studies were made of these records and of measurements of diversions from the Feather River in the reach between the two stations. These studies indicated that during the irrigation season probable flow at the proposed diversion for the Peach Bowl Project was greater than recorded flow in the Feather River at Nicolaus. Therefore, the assumption that flows available for the pumping diversion were equal to those measured at Nicolaus was considered to be conservative.

It was determined that during the critical months of July, August, and September, tributary inflow to the Feather River from the Bear River was negligible. For this reason, any future conservation development on this tributary would not adversely affect the assumption as to flow in the Feather River at the proposed point of diversion during the critical summer months. Furthermore, records of the Sacramento-San Joaquin Water Supervision indicated that the amount of existing diversions from the Feather River between Nicolaus and the confluence with the Sacramento River, during the critical summer months of low flow, is insufficient to materially affect the estimates of water supply available in the Feather River for diversion to the Peach Bowl.

Available records of monthly stream flow of the Feather River at Nicolaus during the irrigation season are presented in Table 38. Comparison of these recorded flows with the estimated monthly gross demands of the Peach Bowl Project, presented in Table 37, indicates that during the period from 1921 through 1950 ample water was available from the Feather River to meet demands of the project, as designed, except during the two seasons of 1924 and 1931. During these seasons irrigation deficiencies of approximately 40 and 25 percent, respectively, would have occurred. From past experience in the Sacramento Valley, it is considered probable that such deficiencies could be endured without permanent damage.

TABLE 38
MEASURED MONTHLY FLOW OF FEATHER RIVER AT NICOLAUS DURING THE IRRIGATION SEASON, 1921 THROUGH 1950

(In acre-feet)

Year	Runoff index	April	May	June	July	August	September	October
1921	129				61,870	23,195	25,035	49,140
1922	109				181,000	48,300	49,200	19,200
1923	67				111,000	52,100	72,000	126,000
1924	28			6,780	1,780	609	20,900	93,500
1925	67				55,600	33,400	49,000	106,000
1926	67			57,500	24,900	24,300	60,100	109,000
1927	122				99,000	43,600	61,300	131,000
1928	90			89,300	54,800	30,700	60,700	104,000
1929	40		371,000	160,000	49,700	70,100	104,000	132,000
1930	85		536,000	183,000	52,000	57,300	112,000	163,000
1931	32		68,900	17,700	935	5,070	32,800	68,200
1932	72		904,000	453,000	75,600	29,900	26,700	40,100
1933	42		118,000	331,000	34,900	18,300	25,100	61,100
1934	44		114,000	40,500	21,800	19,600	39,200	67,710
1935	93				84,430	69,850	70,070	123,400
1936	94			385,200	81,780	63,020	82,050	110,000
1937	69				66,950	18,130	38,780	129,000
1938	186				217,000	83,360	90,100	149,800
1939	41	359,700	107,800	27,070	9,870	19,660	57,700	77,200
1940	123	1,593,900	711,200	200,100	43,700	36,760	92,230	128,700
1941	111	1,416,200	1,467,000	548,000	191,300	52,800	54,500	99,400
1942	145	1,480,000	1,254,000	793,600	166,500	44,140	67,200	137,600
1943	122	1,220,600	663,300	314,800	57,350	22,040	32,360	119,000
1944	61	597,600	633,000	179,800	33,300	13,280	32,190	83,300
1945	82	726,800	736,100	262,900	40,890	27,620	53,160	106,800
1946	90	836,000	679,900	171,900	38,500	30,040	53,690	87,650
1947	55	573,300	124,000	74,330	16,780	24,640	40,820	135,600
1948	74	1,326,000	1,091,000	590,200	73,600	16,170	48,190	132,900
1949	57	809,700	533,500	98,060	13,920	9,230	27,480	39,430
1950	84	1,099,000	834,900	327,200	40,030	18,230	71,500	163,500

Studies indicated that the maximum monthly diversion for the Peach Bowl Project would occur in July, and that it would amount to about 27 percent of the total seasonal diversion of 24,000 acre-feet, equivalent to a continuous flow of about 105 second-feet throughout the month. For cost estimating purposes the pumping plant for the project was designed with a total pumping capacity of 135 second-feet. This installation would meet the estimated maximum rate of demand, provide additional capacity for shorter-term peaking in excess of the average monthly rate, and provide stand-by capacity to assure continuous service in case of breakdown.

Features of the pumping plant considered for the Peach Bowl Project are shown on Plate 29. In order to permit flexibility in operation of the project, design of the pumping plant was based on the installation of three electrically driven vertical axial-flow propellor type pumping units. Each of the units would comprise a 36-inch diameter pump with capacity of 45 second-feet, driven by a 100-horsepower motor. The pumps would operate at a maximum pumping head of about 15 feet, pumping from an estimated minimum water surface elevation in the river of about 31 feet to a discharge elevation of about 46 feet. The pumping units would be of the all-weather type, mounted on steel beams, and supported on concrete piles driven into the stream bed at the toe of the river face of the right bank levee of the Feather River. The battery of pumps would be operated from a corrugated metal control house, also mounted on the concrete piles, and would be served by a steel trestle from the levee crest. The units would pump from a reinforced-concrete sump into three 30-inch diameter steel pipes supported by ring girders and reinforced-concrete piers on the slopes of the levee. The pipes would pass through the levee five feet beneath the crest, and discharge into a reinforced-concrete sand trap at the landward base of the levee.

From the sand trap the water would be conveyed by gravity to areas of use by the system of lined and unlined canals shown on Plate 20. The main canal extending in a southerly direction along the levee would be concrete-lined, in order to prevent seepage which might otherwise damage orchards or the toe of the Feather River levee. This canal would be approximately 6.1 miles in length, and would be of trapezoidal section, with 1.5:1 side slopes, bottom width of 8.0 feet, depth of 3.4 feet, and 1.0 foot freeboard. The slope would be approximately 1.0 foot per mile, the velocity about 2.5 feet per second, and the capacity would be 100 second-feet. A second main canal would extend from the sand trap in a westerly direction a distance of approximately 0.7 mile to a concrete division box near the Southern Pacific Railroad right of way. This canal would have characteristics similar to the one already described. From the division box a lateral would extend south along the railroad right of way a distance of approximately 4.8 miles. This lateral would also be concrete-lined, to prevent possible damage by seepage to adjacent orchards and to the railroad. It would be of trapezoidal section, with 1.5:1 side slopes, bottom width of 6.0 feet, depth of 2.4 feet, and freeboard of 1.0 foot. The slope would be approximately 1.5 feet per mile, the velocity about 2.3 feet per second, and the capacity 50 second-feet. A second lateral from the division box would extend in a westerly and then southerly direction a distance of approximately 5.2 miles. This canal would be unlined, since seepage from it would probably result in no damage. The canal would be of trapezoidal section, with 2:1 side slopes, bottom width of 6.0 feet, depth of 3.2 feet, and freeboard of 1.0 foot. Its slope would be approximately 1.5 feet per mile, its velocity about 1.3 feet per second, and its capacity 50 second-feet. Cost estimates for the conveyance canals were based on preliminary designs utilizing data from field location surveys.

Detailed design of works for distribution of water from the conveyance canals was considered to be outside the scope of the current investigation. Existing pressure irrigation systems of individuals and agencies could be adapted to use of the new surface water supply by means of gravity diversions or individual low-head pumps, as required. Cost estimates for the distribution systems were based on known costs of similar irrigation works elsewhere in California, adjusted to correspond with conditions prevailing in the Sutter-Yuba Area.

Pertinent data with respect to general features of the Peach Bowl Project, as designed for cost estimating purposes, are presented in Table 39.

TABLE 39

GENERAL FEATURES OF PEACH BOWL PROJECT

Pumping Plant
- Pumps—3 each, vertical, propeller type, axial-flow, 45 second-foot capacity
- Estimated minimum water surface elevation in Feather River—31 feet
- Discharge elevation—46 feet
- Estimated maximum pumping head—15 feet
- Installed pumping capacity—135 second-feet
- Estimated maximum monthly demand—105 second-feet
- Estimated gross seasonal diversion—24,000 acre-feet
- Motors—3 each, all-weather type, 100 horsepower
- Pump support—steel beams on concrete pile structure
- Pumping sump—reinforced-concrete, 13 feet by 65 feet, 5 feet deep, equipped with trash racks
- Discharge lines—3 each, 30-inch diameter, welded-steel, supported on concrete piers by ring girders
- Sand trap—reinforced-concrete, 10 feet by 40 feet, 6 feet deep, equipped with baffles and sluice gates

Conveyance System

	Main canals	Central lateral	West lateral
Type	Trapezoidal, concrete-lined	Trapezoidal, concrete-lined	Trapezoidal, unlined
Length, in miles	6.8	4.8	5.2
Side slopes	1.5:1	1.5:1	2:1
Bottom width, in feet	8.0	6.0	6.0
Depth, in feet	3.4	2.4	3.2
Freeboard, in feet	1.0	1.0	1.0
Slope, in feet per mile	1.0	1.5	1.5
Velocity, in feet per second	2.5	2.3	1.3
Capacity, in second-feet	100	50	50

Daguerre Point Weir on Yuba River

Capital cost of the Peach Bowl Project, based on prices prevailing in April, 1952, was estimated to be about $1,384,900. Corresponding annual costs of the Peach Bowl Project were estimated to be about $100,900. Resultant estimated average unit cost of the 24,000 acre-feet of water per season diverted at the river was about $4.20 per acre-foot. The estimated average unit cost of the 18,000 acre-feet of water per season actually applied for irrigation was about $5.60 per acre-foot.

Estimated capital and annual costs of the Peach Bowl Project are summarized in the following tabulation. Detailed cost estimates are presented in Appendix II.

	Estimated costs	
	Capital	*Annual*
Pumping plant	$107,900	$16,000
Conveyance system	813,900	43,800
Distribution system	463,100	41,100
TOTALS	$1,384,900	$100,900

Northeast Zone

In Chapter III it was shown that the present requirement for supplemental water in the Northeast Zone is about 6,000 acre-feet per season. However, in the design of projects for initial local development to meet this requirement, it was considered desirable to provide some capacity for future growth in water demand which would occur through development of irrigable lands not presently irrigated. This additional capacity was estimated at about 6,000 acre-feet per season, giving consideration to the extent of undeveloped irrigable lands that might readily be served, and to the available sources of water supply as determined by engineering and economic limitations on size of the proposed conservation works. For reasons hereinafter discussed, it was considered that the new water supply would be applied to about 2,300 acres in the Northeast Zone, of which about 1,700 acres are presently irrigated by ground water and 600 acres are irrigable lands not presently served with water. These lands are contained within a service area adjoining and lying to the east and north of the Cordua Irrigation District, and delineated on Plate 21, "South Honcut Creek Project."

Three possible alternative plans of works for initial construction to provide supplemental water to the Northeast Zone were considered. For reasons hereinafter mentioned, after preliminary investigation and study, the first two plans were given no further consideration for present cost estimating purposes, but may warrant future study. The third plan is described in some detail in this section.

Alternative Plans Considered. The first of the alternative plans considered for initial construction involved the substitution of surface water from the Yuba River to replace ground water presently utilized in the foregoing service area. The substitute supply would be furnished by extension and enlargement of portions of the Cordua Irrigation District canal system. Its use would prevent progressive and permanent lowering of ground water levels in the described service area and in adjacent areas. The Cordua Irrigation District and the Hallwood Canal Company jointly divert from the Yuba River through a 1,200-foot tunnel with capacity of 325 second-feet, heading at the northwest end of the Daguerre Point Weir. Surface flow in the Yuba River at Daguerre Point during the peak of the irrigation season is generally not greater than present demands of the Cordua and Hallwood systems, and at times these demands cannot be met. Much of the surface flow in the Yuba River during such periods as measured at Marysville does not occur on the surface at the Daguerre Point Weir. Measurements indicate that this water is lost to surface flow by percolation in an extensive area of dredger tailings above the weir, and reappears at the Marysville gaging station. For this reason, a preliminary survey was made to determine the feasibility of diverting the Cordua-Hallwood water supply from the Yuba River at a site upstream from the area of dredger tailings. This would be excessively expensive because of the necessity for increasing capacity of the Cordua-Hallwood system, providing a diversion structure, and providing a closed conduit for the diverted water for a considerable distance until stable bank could be reached. For these reasons, and because of uncertainty regarding the available water supply, this plan was given no further present consideration.

The second of the alternative plans considered for initial construction involved the purchase of Feather River water from the Oroville-Wyandotte Irrigation District at a point of delivery on South Honcut Creek, diversion of the water from South Honcut Creek, and its conveyance to and distribution in the Northeast Zone. As in the case of the first plan described, use of the new surface water supply would prevent progressive and permanent lowering of ground water levels in the area served and in adjacent areas. The water purchased and utilized would be a portion of that which the district proposes to develop on the South Fork of the Feather River under the multipurpose project described earlier in this chapter, principal features of which are shown on Plate 19. The water would be delivered to South Honcut Creek at an elevation of about 600 feet, by the district. The amount of water that might be made available to the Northeast Zone would depend upon design of features of the proposed Oroville-Wyandotte Irrigation District project, and in turn upon the outcome of possible negotiations between the district and an agency representing interests of the Northeast Zone. For these reasons, features of the plan were not surveyed and studied in detail, nor estimates of cost prepared.

The third plan considered for initial construction would include the construction of a dam and reservoir on South Honcut Creek, facilities for diversion of flood

South Honcut Creek Dam Site Viewed From Point Within Reservoir Area waters of French Dry Creek to the reservoir, and facilities for diversion of the conserved waters from South Honcut Creek below the dam, and for their conveyance to and distribution in both the Northeast Zone and the Browns Valley service area. This latter area, lying to the east of the Northeast Zone, is also in need of a supplemental water supply and could be advantageously served as indicated. As in the case of the two previous plans, use of the new surface water supply would prevent progressive and permanent lowering of ground water levels in the area served in the Northeast Zone and in adjacent areas. This plan is hereinafter referred to as the "South Honcut Creek Project," and its principal features are delineated on Plate 21.

South Honcut Creek Project. The proposed dam would be an earthfill structure with side channel spillway, located on South Honcut Creek near Sugar Loaf, in Section 25, Township 18 North, Range 5 East, M. D. B. & M., some 20 miles upstream from the confluence of Honcut Creek with the Feather River. The stream bed elevation at this point is about 730 feet. Flood waters of French Dry Creek would be diverted at a point on that stream at an elevation of approximately 2,125 feet, about one-half mile below Brownsville, and conveyed a distance of about two miles in a canal, discharging into a tributary of South Honcut Creek above the reservoir. The conserved waters of both South Honcut and French Dry Creeks, after release from the reservoir, would be diverted from South Honcut Creek at a point about two miles downstream from the dam and 300 feet downstream from the county bridge southeast of Bangor, at an elevation of about 600 feet. From this diversion point the waters would be conveyed by a conduit a distance of about 4.7 miles to a point about one mile northeast of Loma Rica, where the elevation is about 500 feet. Diversions could be made for the Browns Valley service area along the conduit and at its terminus. Water for the Northeast Zone would be conveyed from this terminus in a natural drainage channel, a short canal section, and the natural channel of Prairie Creek to a diversion point for the Northeast Zone on Prairie Creek about one mile upstream from its confluence with South Honcut Creek, at an elevation of approximately 135 feet. From this point the waters would be conveyed to and distributed in the Northeast Zone by means of an unlined canal and ditch system. The lands which would be served by the new water supply comprise the aforementioned 2,300 acres contained within the service area shown on Plate 21, ranging in elevation from about 150 feet along its eastern boundary to about 75 feet on the west.

As a first step in determination of size of the project, estimates were made of yield of the proposed works for various reservoir storage capacities. It was estimated that mean seasonal runoff of South Honcut Creek, from the approximately 24 square miles of watershed above the dam site, was about 23,400 acre-feet. Estimated mean seasonal runoff of French Dry Creek at the proposed point of diversion to South Honcut Creek was about 27,100 acre-feet, from some 22 square miles of watershed. Of these French Dry Creek waters, studies indicated that flood flows in an estimated mean seasonal amount of about 22,000 acre-feet could be diverted to the proposed South Honcut Creek Reservoir through a 200 second-foot capacity conduit, during the months from November to April, inclusive.

Based upon records and estimates of runoff during the critical dry period which occurred in the Sacramento Valley from 1920-21 through 1934-35, yield studies were made for five sizes of reservoir at the South Honcut Creek site. It was assumed that a seasonal irrigation deficiency up to 35 percent could be endured in one season of the period. Monthly demands on the reservoir were assumed to be proportional to the estimated distribution of irrigation demands in the Sutter-Yuba Area, as presented in Table 33. A summary of results of the yield studies is presented in Table 40.

TABLE 40

ESTIMATED SAFE SEASONAL YIELD OF SOUTH HONCUT CREEK RESERVOIR WITH FRENCH DRY CREEK DIVERSION, BASED ON CRITICAL DRY PERIOD FROM 1920-21 THROUGH 1934-35

(In acre-feet)

Reservoir storage capacity	Safe seasonal yield
12,000	12,800
20,000	16,400
30,000	20,900
38,000	24,300
70,000	27,100

After consideration of the results of the yield studies, together with topography of the dam site and cost analyses hereinafter discussed, a reservoir of 38,000 acre-foot storage capacity, with estimated safe seasonal yield of 24,300 acre-feet, was chosen for purposes of cost estimates to be presented in this report. The yield study for this size of reservoir is included in Appendix G.

Although the estimate of the present requirement for supplemental water in the Northeast Zone was only about 6,000 acre-feet per season, essentially all irrigable but presently nonirrigated lands in the zone would be physically susceptible of irrigation under the South Honcut Creek Project. However, a substantial acreage of irrigable lands lying in the Browns Valley service area could be developed with water from the South Honcut Creek Project. For this reason, studies of present utilization of water from the South

Honcut Creek Project were based on an assumed release of water for the Northeast Zone equal to approximately one-half of the estimated safe yield of the project. It was assumed that remaining safe yield of the project would be made available to the Browns Valley service area.

For design purposes it was assumed that minor losses of water released from South Honcut Creek Reservoir would occur in the stream channel between the dam and the downstream point of diversion and in the lined canal leading to the point of release north of Loma Rica, and would amount to about 300 acre-feet per season. Thus a gross supplemental water supply of approximately 12,000 acre-feet per season would be made available to the Browns Valley service area. It was estimated that losses in conveyance and distribution of this supply would be about 25 percent, leaving some 9,000 acre-feet per season for application to irrigation. On the assumption that the imported water would be largely used on irrigated pasture, with an estimated average unit seasonal application of about 3.5 acre-feet per acre, about 2,600 acres of irrigable but presently nonirrigated lands in the Browns Valley service area could be served by the new water supply.

It was assumed that seasonal losses by transpiration, evaporation, and percolation in conveying the new water supply to the point of diversion on Prairie Creek would be about 10 percent of the gross reservoir release, or about 1,200 acre-feet, leaving approximately 10,800 acre-feet for distribution in the zone. Since the Northeast Zone constitutes a free ground water area, water losses in the unlined canal and ditch system would largely percolate to the ground water. For this reason it was assumed that these losses, plus the unconsumed portion of the new water supply applied to irrigation, would be effective in preventing progressive and permanent lowering of ground water levels.

The acreage to be irrigated by the supplemental supply in the Northeast Zone would depend on the gross amount of the import, water losses encountered in conveyance and distribution, and the requirement for application of water to the lands irrigated. It was assumed that losses to be encountered in conveyance and distribution within the zone would be 25 percent of the gross import, or about 2,700 acre-feet per season, leaving some 8,100 acre-feet for application to irrigated lands. It was also assumed that water imported to the Northeast Zone would largely be used on irrigated pasture, and that the average seasonal application of the new water would be 3.5 acre-feet per acre. On this basis it was estimated that the imported supply would be applied to some 2,300 acres in a service area adjoining and lying to the east and north of the Cordua Irrigation District. Of the lands which would be served with the new water supply, about 1,700 acres are presently irrigated by ground water and 600 acres are irrigable lands not presently irrigated.

An estimate of the monthly distribution of demand for irrigation water in the Sutter-Yuba Area was presented in Table 33. Based on these data, the monthly demand on the South Honcut Creek Project would be as shown in Table 41.

TABLE 41

ESTIMATED MONTHLY DISTRIBUTION OF DEMAND FOR WATER FROM SOUTH HONCUT CREEK PROJECT

(In acre-feet)

Month	Percent of seasonal total	Reservoir release	Gross import to Northeast Zone	Gross import to Browns Valley
April	10	2,430	1,080	1,200
May	16	3,890	1,730	1,920
June	17	4,130	1,830	2,040
July	22	5,350	2,380	2,640
August	17	4,130	1,830	2,040
September	11	2,670	1,190	1,320
October	5	1,210	540	600
November	2	490	220	240
TOTALS	100	24,300	10,800	12,000

Plane table topographic surveys were made of the South Honcut Creek dam and reservoir sites by the Division of Water Resources in 1949. The reservoir site was mapped at a scale of 1 inch to 400 feet, and the dam site at a scale of 1 inch to 100 feet, both with 10-foot contour intervals. Storage capacities of South Honcut Creek Reservoir at various stages of water surface elevation are given in Table 42.

Based upon preliminary geological reconnaissance, the South Honcut Creek dam site is considered suitable for an earthfill dam of any height up to a maximum of 200 feet. Foundation rock at the site consists of a slightly metamorphosed series of igneous rocks, chiefly of volcanic origin. The original nature of the rocks ranged from basalt to gabbro. The bulk of the material is a blue-gray, hard, very slightly metamorphosed basalt. The entire mass has been intruded by a number of small dikes, of later origin, consisting of unmetamorphosed andesite and/or basalt. The foundation bedrock as a whole is relatively hard and unweathered where exposed in outcrops. Joints are prominently developed in several sets. The predominant set has a strike approximately parallel to the stream course and apparently controls the primary drainage pattern in the vicinity. Small shears are common throughout the rock mass but these have generally been recemented. Some of the joints also have been recemented by deposition of minerals from percolating waters. Seepage may be observed from remaining open seams in the bedrock in several places.

TABLE 42

AREAS AND CAPACITIES OF SOUTH HONCUT CREEK RESERVOIR

Depth of water at dam, in feet	Water surface elevation, USGS datum, in feet	Water surafce area, in acres	Storage capacity, in acre-feet
0	730	0	0
20	750	3	25
40	770	26	226
60	790	62	1,090
80	810	132	2,980
100	830	256	6,530
119	849	344	12,000
120	850	355	12,300
138	868	484	20,000
140	870	512	20,900
156	886	634	30,000
160	890	691	32,800
168	898	720	38,000
180	910	801	47,600
200	930	933	65,000
205	935	976	70,000
220	950	1,070	85,100

Three hundred feet downstream from the axis a fault zone is encountered which follows the base of the right abutment longitudinally for an additional 200 feet before lensing out. The plane of this fault apparently has a dip of 55 degrees into the left abutment. The zone appears to die out rapidly in both upstream and downstream directions but at the point of maximum development it is eight feet in width. There is some gouge and much crushed rock along this fault. The inconsistency of the zone on the surface would seem to indicate that it may also lens out vertically at a relatively shallow depth. Indications are that there has been no recent movement on the fault. Special treatment of the dam foundation in the area of this fault would undoubtedly be necessary.

Stripping for the foundation of an earthfill type of dam at this site should not exceed, for the right abutment, five feet of overburden, consisting chiefly of soil, plus three feet of weathered bedrock, and for the left abutment, three feet of overburden plus three feet of weathered bedrock. These estimates apply only under the impervious section of an earthfill type of dam and are for any height of dam up to a maximum of 200 feet. Only the overburden would have to be stripped from under the pervious sections of such a dam. The stated depths are estimated normal to the surface. Stripping in the channel section should consist of about two feet of gravel and one foot of weathered bedrock.

A satisfactory location for a spillway for an earthfill dam at this site would be around the end of the structure, with the excavation being largely in hard bedrock. The material from such excavation, as well as the weathered rock stripped from the abutments, should prove about 80 percent recoverable for construction use as pervious fill, rockfill, or riprap. Tailings from former hydraulic mining operations which choke the channel one mile upstream from the dam site could also be used as pervious fill material. A small quantity of concrete aggregate could be recovered locally for use in appurtenant structures for an earthen dam, but large amounts would either have to be crushed at the site or imported. Soil suitable for use in the construction of an impervious embankment is available in limited quantities from sloping flats of the reservoir area. Although the depth of this material is probably not great, it is believed that enough could be obtained from this source to provide for a minimum impervious earth section.

As a result of yield studies, geologic reconnaissance, and preliminary economic analysis, an earthfill dam, 168 feet in height from stream bed to spillway lip, and with a crest elevation of 910 feet, was selected to illustrate estimates of cost of the South Honcut Creek Project. The dam would have a crest length of about 670 feet and a crest width of 30 feet, and 2.5:1 upstream and down-stream slopes. The central impervious core would have a top width of 10 feet and 0.8:1 slopes, and would be blanketed with sand and gravel filters. The outer pervious zones of the dam would consist of dredger tailings and materials excavated in construction of the spillway. The volume of the fill would be an estimated 919,000 cubic yards. The maximum depth of water above the spillway lip would be 8 feet, and an additional 4 feet of freeboard would be provided. The spillway would be of the side channel type, excavated from rock of the right abutment and concrete-lined. It would have a capacity of 10,000 second-feet, required for an assumed discharge of 400 second-feet per square mile of drainage area, and would discharge into South Honcut Creek below the dam. Outlet works would consist of a 42-inch diameter steel pipe placed in a trench excavated in rock beneath the dam, and encased in concrete. Releases from the dam would be controlled at the upstream end by two 30-inch hydraulically controlled high pressure slide gates located at a submerged inlet upstream from the dam, and operated by hydraulic controls from the crest of the dam. The outlet would be controlled at the downstream end by a Howell-Bunger valve.

The diversion works on French Dry Creek would be located approximately at the site of a former diversion weir, portions of which are still in existence. The site was examined and cross sections taken during the course of the investigation. The proposed diversion weir would consist of a concrete gravity overpour section and apron, 7 feet in height above stream bed and some 55 feet in length. An opening at the right end of the weir would provide entrance to a side channel leading downstream about 100 feet to the headworks of the diversion canal. The side channel would have a concrete gravity parapet wall of the overpour type, and a 5- by 4-foot sluice gate would be provided for sand clearance. The headworks would consist of a concrete headwall across the end of the side channel, in which there would be two 5- by 4-foot slide gates. The diversion canal, which for a portion of its route would be aligned roughly along an abandoned canal, would be about 2.0 miles in length, discharging into an unnamed tributary of South Honcut Creek. Location of the canal was based on a map study, and was checked in the field. The canal chosen for cost estimating purposes would have a capacity of 200 second-feet, a shotcrete-lined trapezoidal section with 1:1 side slopes, bottom width and depth of 4.0 feet, and freeboard of 1.0 foot, and a slope of approximately 7.0 feet per mile. The velocity would be about 6.3 feet per second.

The diversion works on South Honcut Creek to serve Browns Valley and the Northeast Zone would be similar to those described for the French Dry Creek diversion, except that the weir would be 9 feet high and 84 feet in length, and the headworks would be located at the left end of the weir. The site was examined and cross-sectioned during the course of the investigation. The diversion conduit chosen for cost estimating purposes would have a capacity of 150 second-feet and would bear in a general southerly direction a distance of approximately 4.7 miles. Location of the conduit was based on a map study, and was checked in the field. For the most part the conduit would consist of a shotcrete-lined canal, but would include a steel pipe siphon, 5.5 feet in diameter and about 1,500 feet in length, across Tennessee Creek. The canal portion would have a trapezoidal section with 1:1 side slopes, bottom width of 5.0 feet, depth of 4.0 feet, and freeboard of 1.0 foot. Its slope would be approximately 4.0 feet per mile, and the velocity would be about 4.2 feet per second. Releases of water for use in Browns Valley could be made along the conduit and at its terminus.

From the terminus, about one mile northeast of Loma Rica, water for the Northeast Zone would be released to flow southerly in a tributary of Little Dry Creek for about 6,000 feet, and then would be diverted by temporary earthen works into a short unlined canal leading westerly and discharging into an unnamed tributary of Prairie Creek. The water would flow in Prairie Creek and its tributary a distance of about six miles to the point of diversion for the Northeast Zone. This diversion site and the route of the conduit to serve the Northeast Zone were surveyed during the course of the investigation. The diversion works would consist merely of a temporary earthen structure, replaced each season. The conduit from the diversion to the Northeast Zone would bear in a general southerly direction a distance of approximately 6.3 miles, terminating in a tributary of Nigger Jack Slough. It would be an unlined canal, having capacities of 75 second-feet at the diversion point and 25 second-feet at the terminus. At the diversion point the canal would have a trapezoidal section with 2:1 side slopes, bottom width of 4.0 feet,

TABLE 43

GENERAL FEATURES OF SOUTH HONCUT CREEK PROJECT

Earthfill Dam
Crest elevation—910 feet
Crest length—670 feet
Crest width—30 feet
Height, spillway lip above stream bed—168 feet
Side slopes—2.5:1
Freeboard, above spillway lip—12 feet
Elevation of stream bed—730 feet
Volume of fill—919,000 cubic yards

Reservoir
Surface area at spillway lip—720 acres
Capacity at spillway lip—38,000 acre-feet
Drainage area
Honcut Creek—24 square miles
French Dry Creek—22 square miles
Estimated mean seasonal runoff
Honcut Creek—23,400 acre-feet
French Dry Creek—27,100 acre-feet
Estimated mean seasonal diversion from French Dry Creek—22,000 acre-feet
Estimated safe seasonal yield—24,300 acre-feet
Type of spillway—Side channel, concrete-lined
Spillway capacity—10,000 second-feet
Type of outlet—42-inch diameter steel pipe beneath dam

Diversion Works

French Dry Creek	Concrete gravity weir, with ogee overpour section, 55 feet in length, and 7 feet high above stream bed elevation of about 2,125 feet; side channel diversion box, with overpour parapet wall, and 5- by 4-foot slide sluice gate; two 5- by 4-foot slide headgates in concrete headwall.
South Honcut Creek	Concrete gravity weir, with ogee overpour section, 84 feet in length, and 9 feet high above stream bed elevation of 600 feet; side channel diversion box, with overpour parapet wall, and 5- by 4-foot slide sluice gate; two 5- by 4-foot slide headgates in concrete headwall.
Prairie Creek	Temporary earthen structure, at stream bed elevation of 135 feet.

Conduits

	French Dry Creek Diversion	South Honcut Creek Diversion	Prairie Creek Diversion
Type	Trapezoidal, shotcrete-lined canal	Trapezoidal, shotcrete-lined canal, and 1,500 feet of 5.5-foot diameter steel pipe siphon	Trapezoidal, unlined canal
Length, in miles	2.0	4.7	6.3
Side slopes	1:1	1:1	2:1
Bottom width, in feet	4.0	4.0	4.0 (maximum)
Depth, in feet	4.0	5.0	3.7 (maximum)
Freeboard, in feet	1.0	1.0	1.0
Slope, in feet per mile	7.0	4.0	2.5
Velocity, in feet per second	6.3	4.2	1.7
Capacity, in second-feet	200	150	75 to 25

depth of 3.7 feet, and freeboard of 1.0 foot. Its slope would be approximately 2.5 feet per mile, and the velocity would be about 1.7 feet per second.

Cost estimates for the canals to convey water to the service areas in Browns Valley and the Northeast Zone were based on designs utilizing data obtained by reconnaissance field location surveys. Detailed design of the distribution systems in Browns Valley and the Northeast Zone, however, was considered to be outside the scope of the current investigation. Cost estimates for the systems were based on known costs of similar irrigation works elsewhere in California, adjusted to correspond with conditions prevailing in the Sutter-Yuba Area.

Pertinent data with respect to the general features of the South Honcut Creek Project, as designed for cost estimating purposes, are presented in Table 43.

The capital cost of the South Honcut Creek Project, based on prices prevailing in April, 1952, was estimated to be about $3,009,600. Corresponding annual costs of the South Honcut Creek Project were estimated to be about $154,200. The resultant estimated average unit cost of the 24,300 acre-feet of water per season conserved by South Honcut Creek Reservoir was about $6.40 per acre-foot. The estimated unit costs of water applied for irrigation in the Northeast Zone and in the Browns Valley service area were about $9.70 and $8.40 per acre-foot, respectively.

Estimated capital and annual costs of the South Honcut Creek Project are summarized in the following tabulation. Detailed cost estimates are presented in Appendix H.

	Estimated costs	
	Capital	*Annual*
Dam and reservoir	$2,225,600	$94,400
French Dry Creek diversion and conduit	151,100	8,100
South Honcut Creek diversion and conduit	379,100	20,500
Prairie Creek diversion and conduit	131,300	7,100
Browns Valley distribution system	65,000	14,400
Northeast Zone distribution system	57,500	9,700
TOTALS	$3,009,600	$154,200

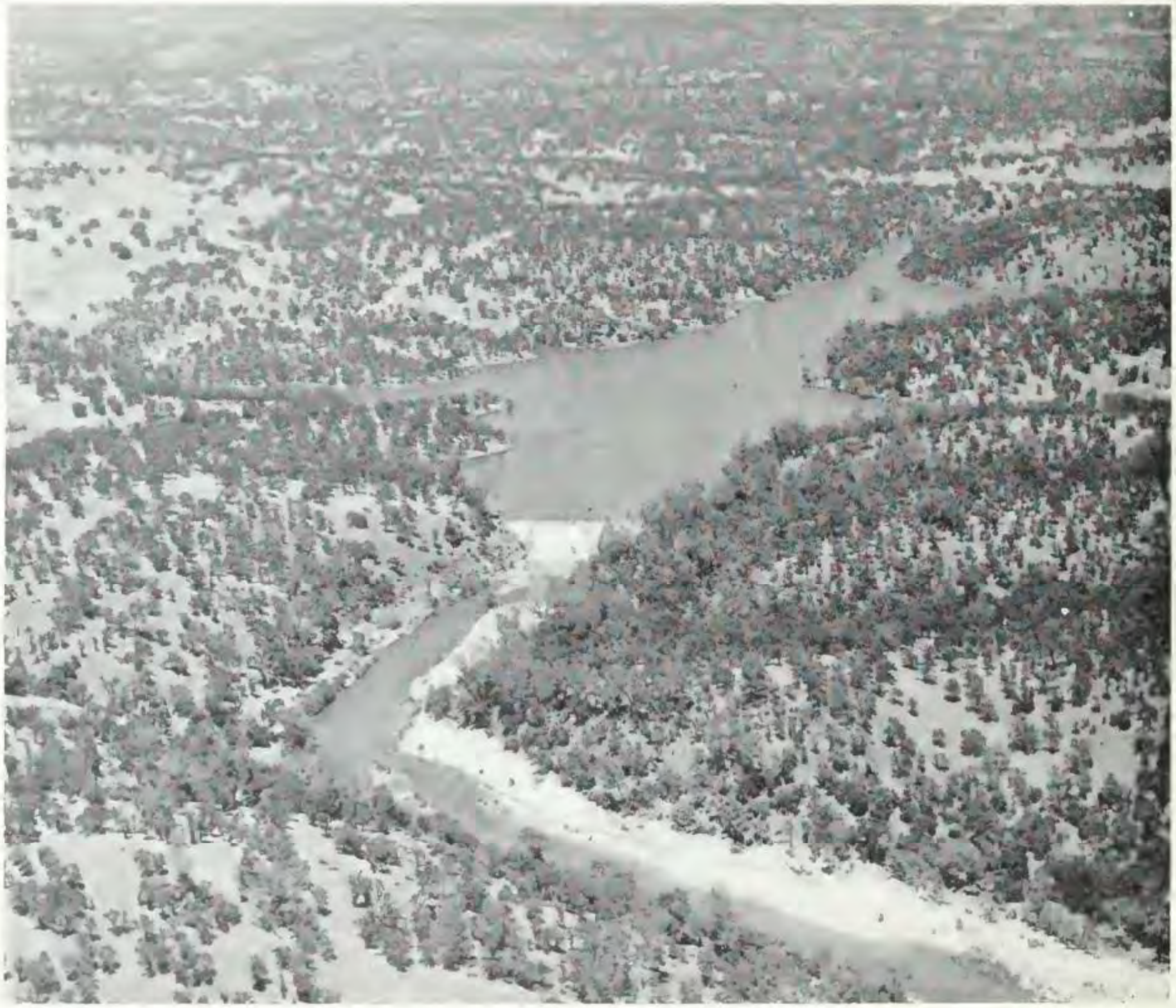
East Central Zone

In Chapter III it was shown that the present requirement for supplemental water in the East Central Zone is about 28,000 acre-feet per season. However, in the design of projects for initial local development to meet this requirement, it was considered desirable to provide some capacity for future growth in water demand which would occur through development of irrigable lands not presently irrigated. This additional capacity was estimated at about 12,000 acre-feet per season, giving consideration to the extent of undeveloped irrigable lands that might readily be served, and to the available sources of water supply. For reasons hereinafter discussed it was considered that the new water supply would be applied to about 8,500 acres in the East Central Zone, of which about 3,300 acres are presently irrigated by ground water and 5,200 acres are irrigable lands not presently served with water. These lands are contained within a service area lying generally south of Hutchinson Creek and east of the Western Pacific Railroad, and delineated on Plate 22, "Camp Far West Project."

Four possible alternative plans of works for initial construction to provide supplemental water to the East Central Zone were considered. For reasons hereinafter mentioned, after preliminary investigation and study the first three plans were given no further consideration for present cost estimating purposes, but may warrant future study. The fourth plan is described in some detail in this section.

Alternative Plans Considered. The first of the alternative plans considered for initial construction involved the substitution of surface water from the Yuba River to replace ground water presently utilized in an area in the East Central Zone. The substitute supply would be diverted at a point on the Yuba River about four miles upstream from Daguerre Point by means of existing headworks of the Yuba River Ditch, owned by the Yuba Consolidated Gold Fields. The Yuba River Ditch, an abandoned canal some four miles in length, with a designed capacity of approximately 115 second-feet, would be rehabilitated and extended in a southerly direction to Hutchinson Creek. Use of the new surface water supply would prevent progressive and permanent lowering of ground water levels in the area served and in adjacent areas. During study of the plan it was determined that surplus flows are available in the Yuba River at the proposed point of diversion during the snowmelt period and into summer months in all but the driest years. However, during the peak of the irrigation season in many years, flows at the diversion point are no more than adequate to maintain the required downstream diversion at Daguerre Point for the Cordua and Hallwood systems. Until such time as additional upstream conservation storage and regulation of flood flows of the Yuba River are accomplished, excessive irrigation deficiencies would be experienced under this plan. For this reason the plan was given no further present consideration for initial construction.

The second of the alternative plans considered for initial construction would include the construction of a dam and reservoir at the Waldo site on Dry Creek, facilities for release of the conserved waters from the reservoir, and facilities for their downstream diversion, conveyance, and distribution in the East Central Zone. Preliminary studies indicated that this plan would not provide sufficient yield to meet the present requirement for supplemental water in the East Central Zone, and that the unit cost of the conserved water would be greater than the corresponding unit cost with the fourth plan described in this section. For these reasons the plan was given no further present consideration. Studies were also made of a plan which included a



Existing Camp Far West Dam and Reservoir larger dam and reservoir at the Waldo site, together with facilities for diversion of flood waters of Yuba River to the larger reservoir. Yield studies and preliminary cost estimates indicated that this plan should probably be deferred for future development. It was indicated that only a portion of the yield of the enlarged project could be readily utilized in the Sutter-Yuba Area at the present time. The capital cost of the larger project would be more than twice that of the fourth plan for initial construction described in this section. Costs of developed water would be excessive until such time as the major portion of the yield could be put to beneficial use. For these reasons this plan was given no further present consideration for initial construction.

The third of the alternative plans considered for initial construction involved the possible purchase of water from the Nevada Irrigation District and conveyance to places of use in the natural channel of Dry Creek. Preliminary studies indicated that additional water could be supplied to the East Central Zone by development and extension of existing facilities of the district, including the China and Tarr Ditches. As in the case of the first plan described, use of the new surface supply would prevent progressive and permanent lowering of ground water levels in the area served and in adjacent areas. The amount of water that might be made available to the East Central Zone would depend upon construction and enlargement of works of the Nevada Irrigation District, and, in turn, upon the outcome of possible negotiations between the district and an agency representing interests of the Northeast Zone. For these reasons, features of the plan were not surveyed and studied in detail, nor estimates of cost prepared.

The fourth plan considered for initial construction would provide for the present supplemental water requirement in the East Central Zone and for growth in water utilization for a number of years in the future. In addition, it would provide corresponding benefits to the South Side Zone. The plan would include the construction of a larger dam and reservoir on the Bear River at the site of the existing Camp Far West Dam and Reservoir, and facilities for conveyance of the conserved water to and its distribution in both the East Central and South Side Zones. Use of the new surface water supply would prevent progressive and permanent lowering of ground water levels in the areas served and in adjacent areas. This plan is hereinafter referred to as the "Camp Far West Project," and its principal features are delineated on Plate 22.

Camp Far West Project. The proposed dam would be an earthfill structure with chute spillway, located on the Bear River, in Section 21, Township 14 North, Range 6 East, M. D. B. & M., some 16 miles upstream from the confluence with the Feather River, and 6.6 miles upstream from Highway 99E. Stream bed elevation at the site is 145 feet. The proposed dam would be superimposed upon an existing curved concrete gravity dam, 62 feet in height from stream bed to dam crest, which creates a reservoir of about 5,000 acre-foot capacity, and is owned by the Camp Far West Irrigation District. Flood waters of the Bear River conserved by the proposed reservoir would be released at an elevation of approximately 180 feet to canals serving the East Central and South Side Zones, respectively. The lands which would be served by the new water supply comprise the aforementioned 8,500 acres in the East Central Zone, and an additional 8,500 acres in the South Side Zone, in the respective service areas shown on Plate 22. Both service areas range in elevation from about 150 feet along their eastern boundaries to about 50 feet on the west.

In Chapter III it was estimated that the present requirement for supplemental water in the East Central Zone is about 28,000 acre-feet per season and in the South Side Zone an additional 28,000 acre-feet, a total of about 56,000 acre-feet per season. In the design of the Camp Far West Project for cost estimating purposes, it was considered necessary to provide about 10,000 acre-feet of water per season for the Camp Far West Irrigation District to replace yield of the existing reservoir. Based upon the area of lands irrigated by the district, this estimate is believed to be adequate. As has been stated, it was also considered desirable to provide some capacity for future growth in demand on the project, which would occur through development of irrigable lands not presently irrigated.

As a first step in determination of size of the project, estimates were made of yield of the proposed works for various storage capacities. It was estimated that mean seasonal runoff of the Bear River, from the approximately 280 square miles above the dam site, was 347,000 acre-feet. Based upon records and estimates of runoff during the critical dry period which occurred in the Sacramento Valley from 1920-21 through 1934-35, yield studies were made for three sizes of reservoirs at the Camp Far West site. It was assumed that a seasonal irrigation deficiency up to 35 percent could be endured in one season of the period. A summary of results of the yield studies is presented in Table 44.

TABLE 44

ESTIMATED SAFE SEASONAL YIELD OF CAMP FAR WEST RESERVOIR, BASED ON CRITICAL DRY PERIOD FROM 1920-21 THROUGH 1934-35

(In acre-feet)

Reservoir storage capacity	Safe seasonal yield
55,000	55,000
104,000	90,000
151,000	122,000

After consideration of the results of the yield studies, together with topography of the dam site and cost analyses hereinafter discussed, a reservoir of 104,000 acre-foot storage capacity, with estimated safe seasonal yield of 90,000 acre-feet was chosen for purposes of cost estimates to be presented in this report. The yield study for this size of reservoir is included in Appendix G.

For cost estimating purposes a tentative distribution of yield of the proposed Camp Far West Reservoir was made. Of the estimated 90,000 acre-feet of safe seasonal yield, 10,000 acre-feet per season was assigned to the Camp Far West Irrigation District. The remaining yield was divided equally between the East Central and South Side Zones, in the amount of 40,000 acre-feet per season to each zone.

Since the East Central Zone constitutes a free ground water area, water losses in the proposed canal and ditch system would largely percolate to the ground water. For this reason it was assumed that these losses, plus the unconsumed portion of the new water supply applied to irrigation would be effective in preventing progressive and permanent lowering of ground water levels. It was estimated that losses in conveyance and distribution of the 40,000 acre-feet of safe seasonal yield assigned to the East Central Zone would be about 25 percent, leaving some 30,000 acre-feet per season for application to irrigation. It was also assumed that water imported to the East Central Zone would be used largely on irrigated pasture, and that the average seasonal application of the new water would be 3.5 acre-feet per acre. On this basis it was estimated that the imported supply would be applied to some 8,500 acres in a service area lying generally south of Hutchinson Creek and east of the Western Pacific Railroad. Of the lands which would be served with the new water supply, about 3,300 acres are presently irrigated by ground water and about 5,200 acres are irrigable lands not presently irrigated.

An estimate of the monthly distribution of demand for irrigation water in the Sutter-Yuba Area was presented in Table 33. Based on these data, monthly demands on the Camp Far West Project would be as shown in Table 45.

A topographic survey of the Camp Far West reservoir site up to an elevation of 225 feet was made by the Camp Far West Irrigation District in 1922. This survey was extended to an elevation of 320 feet by the Division of Water Resources in 1930, and a map was drawn from both surveys at a scale of 1 inch equals 500 feet, with a contour interval of 10 feet. Storage capacities of the Camp Far West Reservoir at various stages of water surface elevation are given in Table 46.

TABLE 45

ESTIMATED MONTHLY DISTRIBUTION OF DEMAND FOR WATER FROM CAMP FAR WEST PROJECT

Month	Percent of seasonal total	Gross release to Camp Far West Irrigation District, in acre-feet	Gross import to East Central Zone, in acre-feet	Gross import to South Side Zone, in acre-feet
April	10	1,000	4,000	4,000
May	16	1,600	6,400	6,400
June	17	1,700	6,800	6,800
July	22	2,200	8,800	8,800
August	17	1,700	6,800	6,800
September	11	1,100	4,400	4,400
October	5	500	2,000	2,000
November	2	200	800	800
TOTALS	100	10,000	40,060	40,000

TABLE 46

AREAS AND CAPACITIES OF CAMP FAR WEST RESERVOIR

Depth of water at dam, in feet	Water surface elevation, USGS datum, in feet	Water surface area, in acres	Storage capacity, in acre-feet
0	145	0	0
25	170	100	1,400
45	190	180	4,200
65	210	380	9,800
85	230	600	19,400
105	250	890	34,200
125	270	1,260	55,500
145	290	1,750	85,600
155	300	2,020	104,400
165	310	2,330	126,100
175	320	2,620	151,000

Based upon preliminary geological reconnaissance, the Camp Far West dam site is considered suitable for an earthfill dam of any height up to a maximum of 180 feet. Bedrock at the site consists of a slightly porphyritic, compact, and massive dark greenstone with gradations into coarse-grained plutonic rock. A complex joint system exists in this vicinity with joint cracks opened a few inches on the surface by weathering. The joints probably do not persist to appreciable depths other than as hairline cracks in the rock. However, some moderate grouting would be necessary. Shears are not abundant in the bedrock, and no serpentine was found locally. While slopes up to an elevation of about 160 feet above stream bed on both abutments consist essentially of barren bedrock with scattered patches of overlying soil, the abutment slopes above 100 feet show only occasional bedrock outcrops with a much heavier mantle of overburden. Stripping under the impervious section of an earthfill type of dam at this site should not exceed four feet of depth of loose material up to 100 feet above stream bed on both abutments, and eight feet of depth above 100 feet on the abutments. Topographic considerations indicate that the spillway should be located across the ridge forming the right abutment of the dam, utilizing a natural saddle and drainage channel.

The material stripped from the foundation and abutments and excavated from the spillway should prove largely recoverable for construction use as pervious fill, rockfill, or riprap. Deposits of dredger tailings about two miles downstream from the dam, as well as sands and gravels accumulated in the existing reservoir, could be used as pervious fill material for the proposed dam. Soil suitable for use in the construction of an impervious embankment is available in limited quantities within a radius of about two miles from the dam. Although the depth of this material is probably not great, it is believed that enough could be obtained from several sources to provide for a minimum impervious earth section.

As a result of yield studies, geologic reconnaissance, and preliminary economic analysis, an earthfill dam, 155 feet in height from stream bed to spillway lip, and with a crest elevation of 311 feet, was selected to illustrate estimates of costs of the Camp Far West Project. The dam would have a crest length of about 2,980 feet and a crest width of 30 feet, and 3:1 upstream and 2.5:1 downstream slopes. The central impervious core would have a top width of 10 feet and 0.8:1 slopes. The outer pervious zones of the dam would consist of stream bed gravels, dredger tailings, and salvaged material from stripping and excavation. A 3-foot blanket of gravel riprap would protect the upstream face of the dam. The volume of the fill would be an estimated 2,070,000 cubic yards. The spillway would be of the chute type, located across the ridge forming the right abutment, and concrete-lined. The maximum depth of water above the spillway lip would be 7 feet, and an additional 4 feet of freeboard would be provided. The spillway would have a capacity of 60,000 second-feet, required for an assumed discharge of 215 second-feet per square mile of drainage area. The spillway would discharge into a draw that joins the Bear River about 900 feet downstream from the toe of the dam. The outlet works would include a horseshoe type tunnel, 10 feet in diameter and 880 feet in length, excavated through the left abutment and concrete-lined. The tunnel would be used to divert flow of the Bear River during the construction period. After completion of the dam a concrete plug would be placed in the tunnel at the axis of the dam, and a 5- by 5-foot high pressure slide gate would be installed to control releases from the reservoir. A 66-inch diameter steel pipe, with capacity of 440 second-feet, would convey the water through the tunnel and terminate in a 60-inch diameter needle valve at a location about 250 feet downstream from the tunnel portal. This needle valve would discharge into a concrete-lined stilling basin, from which water would enter a concrete-lined canal at an elevation of 187 feet. Another needle valve, of 36-inch diameter, would be installed in the steel outlet pipe just outside of the tunnel portal, and would discharge directly into the Bear River.

The canal from the stilling basin would be of trapezoidal section, with 1:1 side slopes, bottom width of 7.0 feet, depth of 6.0 feet, and freeboard of 1.0 foot. Its slope would be about 2.5 feet per mile, its velocity about 5.1 feet per second, and its capacity 400 second-feet. The canal would extend along the left bank of the Bear River a distance of about 8,000 feet, terminating in a concrete division box at an elevation of 183 feet. From this structure a steel pipe siphon, 66 inches in diameter and about 800 feet in length, with capacity of 200 second-feet, would convey water across the Bear River, discharging into a canal to serve the East Central Zone. The division box would also contain an outlet to a canal to serve the South Side Zone, and another outlet to a wasteway emptying into the Bear River.

The canals to serve both the East Central and South Side Zones would have capacities at their intakes of 200 second-feet. The canal to serve the East Central Zone would extend from the siphon outlet in a northwesterly direction a distance of approximately 3.6 miles, where about one-half of the water would be discharged into the channel of South Dry Creek to be diverted by downstream users. The remaining water would be carried a distance of about 0.8 mile and discharged into the channel of North Dry Creek for similar downstream rediversion. For an initial distance of about 3,500 feet from the Bear River siphon the canal would be shotcrete-lined and of trapezoidal section, with 1:1 side slopes, bottom width of 6.0 feet, depth of 4.5 feet, and freeboard of 1.0 foot. The slope would be about 2.5 feet per mile, and the velocity about 4.3 feet per second. For the remainder of the distance to South Dry Creek the canal would be unlined and of trapezoidal section, with 2:1 side slopes, bottom width of 8.0 feet, depth of 5.0 feet, and freeboard of 1.0 foot. The slope would be about 2.5 feet per mile, and the velocity about 2.2 feet per second. From South Dry Creek to North Dry Creek the canal would be unlined and of trapezoidal section, with 2:1 side slopes, bottom width of 7.0 feet, depth of 3.7 feet, and freeboard of 1.0 foot. The slope would be about 2.5 feet per mile, and the velocity about 1.9 feet per second. Capacity of this portion of the canal would be 100 second-feet.

The canal to serve the South Side Zone would extend from the division box in a southerly direction a distance of approximately 10.0 miles to Coon Creek, where about one-half of the flow would be discharged for rediversion by downstream users. The remaining water would be carried in a canal with capacity reduced to 100 second-feet, a distance of about 5.5 miles in a general southerly direction, where it would be similarly discharged into and conveyed in the natural channel of Markham Ravine for a distance of about 1.1 miles. The conserved water would be diverted from Markham Ravine by a flashboard dam and conveyed in a canal for a distance of about 1.2 miles where it would be discharged into Auburn Ravine for rediversion by downstream users. For an initial distance of about 1.0 mile from the division box the canal would be shotcrete-lined and of trapezoidal section, with 1:1 side slopes, bottom width of 6.0 feet, depth of 4.5 feet, and freeboard of 1.0 foot. The slope would be about 2.5 feet per mile, and the velocity about 4.3 feet per second. For the remainder of the distance to Coon Creek the canal would be unlined. It would be of trapezoidal section, with 2:1 side slopes, bottom width of 8.0 feet, depth of 5.0 feet, and freeboard of 1.0 foot. Its slope would be about 2.5 feet per mile, and its velocity about 2.2 feet per second. From Coon Creek to Auburn Ravine the constructed canal would be unlined and of trapezoidal section, with 2:1 side slopes, bottom width of 7.0 feet, depth of 3.7 feet, and freeboard of 1.0 foot. Its slopes would be about 2.5 feet per mile, and its velocity about 1.9 feet per second.

TABLE 47

GENERAL FEATURES OF CAMP FAR WEST PROJECT

Earthfill Dam
- Crest elevation—311 feet
- Crest length—2,980 feet
- Crest width—30 feet
- Height, spillway lip above stream bed—155 feet
- Side slopes—3:1 upstream
2.5:1 downstream
- Freeboard, above spillway lip—11 feet
- Elevation of stream bed—145 feet
- Volume of fill—2,070,000 cubic yards

Reservoir
- Surface area at spillway lip—2,020 acres
- Capacity at spillway lip—101,000 acre-feet
- Drainage area—280 square miles
- Estimated mean seasonal runoff—347,000 acre-feet
- Estimated safe seasonal yield—90,000 acre-feet
- Type of spillway—Chute, concrete-lined
- Spillway capacity—60,000 second-feet
- Type of outlet—10-foot diameter pressure tunnel and 66-inch diameter steel pipe through left abutment

Conduits

	Outlet	Bear River Canal	Bear River Siphon	East Central Zone Conduit			South Side Zone Conduit		
Type	66-inch diameter steel pipe	Trapezoidal, concrete-lined	66-inch diameter	Trapezoidal			Trapezoidal		
				Lined section	Unlined section		Lined section	Unlined section	
Length, in miles	0.21	1.5	0.15	0.7	2.9	0.8	1.0	10.0	6.7
Side slopes		1:1		1:1	2:1	2:1	1:1	1:1	2:1
Bottom width, in feet		7.0		6.0	8.0	7.0	6.0	8.0	7.0
Depth, in feet		6.0		4.5	5.0	3.7	4.5	5.0	3.7
Freeboard, in feet		1.0		1.0	1.0	1.0	1.0	1.0	1.0
Slope, in feet per mile		2.5		2.5	2.5	2.5	2.5	2.5	2.5
Velocity, in feet per second	18.5	5.1	8.1	4.3	2.2	1.9	4.3	2.2	1.9
Capacity, in second-feet	440	100	200	200	200	100	200	200	100

Cost estimates for the canals to convey water to the service areas in the East Central and South Side Zones were based on designs utilizing data obtained by field location surveys. Detailed design of the distribution systems in the East Central and South Side Zones, however, was considered to be outside the scope of the current investigation. Cost estimates for the distribution systems were based on known costs of similar irrigation works elsewhere in California, adjusted to correspond with conditions prevailing in the Sutter-Yuba Area.

Pertinent data with respect to general features of the Camp Far West Project, as designed for cost estimating purposes, are presented in Table 47.

The capital cost of the Camp Far West Project, based on prices prevailing in April, 1952, was estimated to be about $5,592,900. The corresponding annual costs of the Camp Far West Project were estimated to be about $299,600. The resultant estimated unit cost of the 80,000 acre-feet per season of new water conserved by the Camp Far West Reservoir was about $3.70 per acre-foot. The estimated unit cost of water applied for irrigation in the East Central Zone was about $4.70 per acre-foot, and the estimate for water applied for irrigation in the South Side Zone was about $5.30 per acre-foot.

Estimated capital and annual costs of the Camp Far West Project are summarized in the following tabulation. Detailed cost estimates are presented in Appendix H.

	Estimated costs	
	Capital	*Annual*
Dam and reservoir	$3,979,900	$170,000
Bear River canal	233,000	12,600
East Central Zone canal and siphon	286,600	15,400
South Side Zone canal	668,400	36,000
East Central Zone distribution system	212,500	32,800
South Side Zone distribution system	212,500	32,800
TOTALS	$5,592,900	$299,600

South Side Zone

Three possible alternative plans of works for initial construction to provide supplemental water to the South Side Zone were considered. The first of these plans was the Camp Far West Project, which, as described in the preceding section, would provide supplemental water for both the East Central and South Side Zones. The second of the alternative plans considered for initial construction involved the possible purchase of water from the Nevada Irrigation District and conveyance to places of use in the natural channels of Coon Creek and Auburn Ravine. The amount of water that might be made available to the South Side Zone would depend upon design and construction of additional works of the Nevada Irrigation District, and in turn upon the outcome of possible negotiations between the district and an agency representing interests of the South Side Zone. For these reasons, features of the plan were not surveyed and studied in detail, nor estimates of cost prepared.

The third of the plans involved the construction of a dam and reservoir on Coon Creek, at a site approximately seven miles northeast of Lincoln, the utilization of an existing diversion works and ditch to convey flood flows of the Bear River to the reservoir, the reconstruction of existing abandoned facilities for diversion of the conserved waters from Coon Creek below the dam, and the construction of facilities for conveyance of the waters to and their distribution in the South Side Zone. This plan is hereinafter referred to as the "Coon Creek Project," and its principal features are delineated on Plate 23, "Coon Creek Project."

Under each of the alternative plans use of the new surface water supplies would prevent progressive and permanent lowering of ground water levels in the areas served and in adjacent areas. Each plan would provide for the present supplemental water requirement of the South Side Zone and for growth in water utilization for a number of years in the future.

Camp Far West Project. In the earlier description of the Camp Far West Project a reservoir of 104,000 acre-foot capacity, with estimated safe seasonal yield of 90,000 acre-feet, was chosen at the Camp Far West site on the Bear River for cost estimating purposes. A tentative distribution of this yield was made that would provide 40,000 acre-feet per season to the South Side Zone, some 12,000 acre-feet per season greater than the present requirement for supplemental water in the zone, which was estimated in Chapter III to be about 28,000 acre-feet per season. The 12,000 acre-feet per season of indicated present surplus yield was assigned to irrigation of irrigable lands not now served with water.

Since the South Side Zone constitutes a free ground water area, water losses in the proposed conveyance and distribution system for the new water supply would largely percolate to the ground water. For this reason it was assumed that these losses, plus the unconsumed portion of the new water supply applied to irrigation, would be effective in preventing progressive and permanent lowering of ground water levels. It was assumed that losses in conveyance and distribution of the 40,000 acre-feet per season of safe seasonal yield assigned to the South Side Zone would be about 25 percent, leaving some 30,000 acre-feet per season for application to irrigation. It was also assumed that water imported to the South Side Zone would largely be used on irrigated pasture and that the average seasonal application of the new water would be 3.5 acre-feet per acre. On this basis it was estimated that the imported supply would be applied to some 8,500 acres in a service area lying generally adjacent to Coon Creek and Auburn Ravine and easterly of the boundaries of Reclamation Districts 1000 and 1001. Elevation of this service area ranges from about 150 feet along the eastern boundary to about 50 feet on the west. Of the lands which would be served with the new water supply, about 3,300 acres are presently irrigated by ground water, and 5,200 acres are irrigable lands not presently irrigated. An estimate of monthly distribution of demand for the 40,000 acre-feet of gross seasonal import to the South Side Zone from the Camp Far West Project was presented in Table 45.

As described in the preceding section, direct releases would be made from Camp Far West Reservoir to the intake of a canal to serve the South Side Zone. The intake would be at a concrete division box, located on the left bank of the Bear River, about 1.5 miles downstream from Camp Far West Dam, at an elevation of 183 feet. From the intake the canal, with capacity of 200 second-feet, would extend in a southerly direction approximately 10.0 miles to Coon Creek. At this point about one-half of the flow would be discharged into Coon Creek for rediversion by downstream users. The remaining water would be carried in a general southerly direction an additional 5.5 miles, in a canal with capacity reduced to 100 second-feet, where it would be similarly discharged into and conveyed in the natural channel of Markham Ravine for a distance of about 1.1 miles. The conserved water would be diverted from Markham Ravine by a flashboard dam and conveyed in a canal for a distance of about 1.2 miles where it would be discharged into Auburn Ravine for rediversion by downstream users. Additional pertinent data with respect to general features of the Camp Far West Project, as designed for cost estimating purposes, were presented in Table 47.

The cost estimate for the canal to convey water to the South Side Zone was based on designs utilizing data obtained by field location surveys. Detailed design of the distribution system for the South Side Zone was considered to be outside the scope of the current investigation. The cost estimate for the distribution system was based on known costs of similar irrigation works elsewhere in California, adjusted to correspond with conditions prevailing in the Sutter-Yuba Area.

As stated in the preceding section, the capital cost of the Camp Far West Project, based on prices prevailing in April, 1952, was estimated to be about $5,592,900. Corresponding annual costs of the Camp Far West Project were estimated to be about $299,600. The resultant estimated unit cost of new water conserved by Camp Far West Reservoir was about $3.70 per acre-foot of safe seasonal yield. The estimated unit cost of water applied for irrigation in the South Side Zone was about $5.30 per acre-foot, and the estimate for water applied for irrigation in the East Central Zone was about $4.70 per acre-foot. Detailed cost estimates for the Camp Far West Project are presented in Appendix H.

Coon Creek Project. The proposed Coon Creek Dam would be an earthfill structure, with two earthen auxiliary saddle dikes and a chute spillway. It would be located in Sections 8 and 17, Township 13 North, Range 6 East, M.B.D. & M., at a site on Coon Creek some 7.5 miles northeast of Lincoln and 8.3 miles upstream from Highway 99E. Stream bed elevation at this site is 345 feet. For cost estimating purposes, it was assumed that flood waters of the Bear River would be diverted by existing works, conveyed in the existing Upper Gold Hill and Combie-Ophir Canals for a distance of about 2.4 miles, and discharged into a tributary of Coon Creek above the proposed reservoir. These diversion works and the canals belong to the Nevada Irrigation District. The conserved waters of both Coon Creek and Bear River, after release from the proposed reservoir, would flow down Coon Creek for a distance of approximately six miles to an existing abandoned diversion structure. At this point about one-half of the released water would be diverted into a canal, and conveyed in a general southerly direction for a distance of some 5.5 miles where it would be discharged into and conveyed in the natural channel of Markham Ravine for a distance of about 1.1 miles. The conserved water would be diverted from Markham Ravine by a flashboard dam and conveyed in a canal for a distance of about 1.2 miles where it would be discharged into Auburn Ravine. The new water supply would be available in the natural channels of Coon Creek and Markham and Auburn Ravines for downstream diversion and use.

The lands which would be served by the new water supply comprise some 12,000 acres in a service area lying generally adjacent to Coon Creek and Auburn Ravine and easterly of the boundaries of Reclamation Districts 1000 and 1001. A portion of this service area, shown on Plate 23, is in Placer County and outside of the Sutter-Yuba Area. For reasons hereinafter discussed, it was assumed that water yielded by the Coon Creek Project would be entirely applied to irrigable lands not presently served with water. Use of the new surface water supply would prevent progressive and permanent lowering of ground water levels in the area served and in adjacent areas in the South Side Zone.

In Chapter III it was estimated that the present requirement for supplemental water in the South Side Zone is about 28,000 acre-feet per season. However, in design of projects for initial local development to meet this requirement, it was considered desirable to provide some capacity for future growth in water demand which would occur through development of irrigable lands not presently irrigated. In the case of the Camp Far West Project, described in the preceding section, this additional capacity was estimated to be 12,000 acre-feet per season. However, in connection with the Coon Creek Project, giving consideration to the extent of undeveloped irrigable lands that might readily be served, and to the available source of water supply, the corresponding additional capacity was estimated to be 28,000 acre-feet per season.

As a first step in determination of the size of the Coon Creek Project, estimates were made of yield of the proposed works for various reservoir storage capacities. It was estimated that mean seasonal runoff of Coon Creek, from the approximately 40 square miles of watershed above the dam site, was about 32,800 acre-feet. Of the Bear River waters, studies indicated that flood flows in an estimated mean seasonal amount of about 35,700 acre-feet could be diverted to the proposed Coon Creek Reservoir, through the existing Combie-Ophir Canal of about 106 second-foot capacity, during the months of November through April.

Based on records and estimates of runoff during the critical dry period which occurred in the Sacramento Valley from 1920-21 through 1934-35, yield studies were made of two sizes of reservoir at the Coon Creek site. The limited number of yield studies was largely determined by topographic considerations. It was assumed that a seasonal irrigation deficiency up to 35 percent could be endured in one season of the period. Monthly demands on the reservoir were assumed to be proportional to the estimated distribution of irrigation demands in the Sutter-Yuba Area, as presented in Table 33. A summary of the results of the yield studies is presented in Table 48.

TABLE 48

ESTIMATED SAFE SEASONAL YIELD OF COON CREEK RESERVOIR WITH BEAR RIVER DIVERSION, BASED ON CRITICAL DRY PERIOD FROM 1920-21 THROUGH 1934-35

(In acre-feet)

Reservoir storage capacity	Safe seasonal yield
25,500	34,000
59,000	56,000

After consideration of the results of the yield studies, together with topography of the dam site and cost analyses hereinafter discussed, a reservoir of 59,000 acre-foot capacity with estimated safe seasonal yield of 56,000 acre-feet was chosen for purposes of cost estimates to be presented in this report. The yield study for this size of reservoir is included in Appendix G.

Since the considered service area constitutes a free ground water area, water losses in the proposed canal and ditch system would largely percolate to the ground water. For this reason it was assumed that these losses, plus the unconsumed portion of the new water supply applied to irrigation, would be effective in preventing progressive and permanent lowering of ground water levels in the area served and in adjacent areas in the South Side Zone.

It was assumed that seasonal losses in conveyance and distribution of the 56,000 acre-feet of safe seasonal yield would be about 25 percent, or 14,000 acre-feet, leaving some 42,000 acre-feet for application to irrigation. It was also assumed that the new water supply from the Coon Creek Project would largely be used on irrigated pasture, and that the average seasonal application of water would be 3.5 acre-feet per acre. On this basis it was estimated that the imported supply would be applied to some 12,000 acres in a service area lying generally adjacent to Coon Creek and Auburn Ravine and easterly of the boundaries of Reclamation Districts 1000 and 1001. Of the assumed average seasonal application of 3.5 acre-feet per acre, it was estimated that seasonal consumptive use would be about 2.3 acre-feet per acre, and that about 1.2 acre-feet per acre would be unconsumed. This unconsumed portion would aggregate about 14,400 acre-feet per season for the 12,000 acres which would be irrigated.

From the foregoing it was estimated that losses in conveyance and distribution of the new water supply, plus the unconsumed portion of the water actually applied to irrigation, both of which would largely percolate to ground water, would total about 28,400 acre-feet per season. Since the estimated present seasonal water requirement to prevent progressive and permanent lowering of ground water levels in the South Side Zone is about 28,000 acre-feet per season, no substitute water supply would have to be furnished lands presently irrigated by ground water in order to prevent such lowering. It was assumed, therefore, that lands to which the water supply from the Coon Creek Project would be applied would consist entirely of irrigable lands not presently served with water. In this connection, certain irrigable but unirrigated lands in Placer County lying immediately adjacent to the South Side Zone could readily and logically be served with water from the Coon Creek Project. For this reason the water service area shown on Plate 23 was extended outside the South Side Zone to include these lands.

An estimate of the monthly distribution of demand for irrigation water in the Sutter-Yuba Area was presented in Table 33. Based on these data, monthly demands on the Coon Creek Project would be as shown in Table 49.

TABLE 49

ESTIMATED MONTHLY DISTRIBUTION OF DEMAND FOR WATER FROM COON CREEK PROJECT

Month	Percent of seasonal total	Gross release to South Side Zone, in acre-feet
April	10	5,600
May	16	9,000
June	17	9,500
July	22	12,300
August	17	9,500
September	11	6,200
October	5	2,800
November	2	1,100
TOTALS	100	56,000

A topographic map of the Coon Creek dam and reservoir sites, at a scale of 1 inch equals 425 feet, with contour interval of 20 feet, was made by the Division of Water Resources in 1951, using photogrammetric methods. Topography of the dam site was shown on the map up to an elevation of 580 feet, while topography of the reservoir site was shown up to an elevation of 500 feet. Reservoir topography above that elevation was estimated. Storage capacities of Coon Creek Reservoir at various stages of water surface elevation are given in Table 50.

TABLE 50

AREAS AND CAPACITIES OF COON CREEK RESERVOIR

Depth of water at dam, in feet	Water surface elevation, USGS datum, in feet	Water surface area, in acres	Storage capacity, in acre-feet
0	345	0	0
15	360	5	50
35	380	25	300
55	400	65	1,200
75	420	110	3,000
95	440	180	5,800
115	460	260	10,300
135	480	360	16,600
155	500	500	25,500
175	520	610	37,600
195	540	740	51,000
205	550	810	58,000
207	552	820	59,000
215	560	880	65,000

Based upon preliminary geological reconnaissance, the Coon Creek dam site is considered suitable for an earthfill dam of any height up to a maximum of 220 feet. Foundation rock at the site consists essentially of amphibolite schist. In the vicinity of the site the rock varies between schistose and massive material, striking across the channel and dipping vertically. The foundation bedrock as a whole is relatively hard and unweathered where exposed in outcrops. Joints are prominently developed in several sets, with a horizontal joint set predominating. Minor faulting may be involved at this site, as evidenced by the sharp change in attitude of the joint sets of the rock slightly downstream from the tentative axis position. The trend of such a possible fault may strike obliquely upstream into the right abutment where considerable talus material exists. There are no indications of recent movement in this area.

The stream at this site has cut through the resistant rib of rock, forming a narrow gorge with steep side slopes to an elevation of about 150 feet above stream bed. A dam of the height considered for cost estimating purposes would require a dike across the saddle south of the left abutment, and two dikes across smaller saddles north and east of the right abutment. However, it is indicated that the spillway could be located across the ridge forming the right abutment of the dam, utilizing one of the saddles and eliminating the need for construction of a dike therein.

It is probable that stripping under the impervious section of an earthfill dam at the Coon Creek site would be relatively heavy, due to the jointed blocky nature of the rock. On the left abutment no removal of overburden would be required for a height of about 50 feet above stream bed, while above that height stripping of overburden, consisting of earth and loose rock, should not exceed two feet of depth. On the right abutment for a height of about 60 feet above stream bed stripping of overburden, consisting of loose talus rocks but including occasional blocks in place, should not exceed 15 feet of depth. Above that height on the right abutment stripping of overburden, consisting of loose rock and earth, should not exceed three feet of depth. Beneath the described overburden on both abutments it is anticipated that required stripping would involve the removal of blocky hard rock to a maximum of 20 feet of depth.

For an earthfill dam at this site, a large proportion of the material obtained from stripping operations could be salvaged for use in the pervious sections of the dam or as riprap. Aggregates, particularly fines, are lacking in the area and might require hauling from the vicinity of the Bear River. Soil suitable for use in the construction of an impervious core is available in only limited quantities. Deposits of residual clay overburden are scattered and thin in the vicinity. However, based on a preliminay sampling program, sufficient material is believed to be available within two to three miles of the dam site to provide for a minimum impervious earth section. Materials for the pervious sections of the dam could be obtained from salvage from stripping, and from stream bed gravels of Coon Creek and the Bear River.

As a result of yield studies, geologic reconnaissance, and preliminary economic analysis, an earthfill dam 207 feet in height from stream bed to spillway lip, and with a crest elevation of 560 feet, was selected to illustrate estimates of cost of the Coon Creek Project. The dam would consist of three earthfill structures, a main dam across Coon Creek and two auxiliary saddle dams. The main dam would have a crest length of about 1,420 feet, a crest width of 30 feet, and 3:1 upstream and 2.5:1 downstream slopes. The south saddle dam would have a crest length of about 1,450 feet and a maximum height of about 64 feet. The north saddle dam would have a crest length of about 550 feet and a maximum height of about 39 feet. Both saddle dams would have crest widths of 20 feet, and 2.5:1 upstream and downstream slopes. The central impervious cores of all dams would have top widths of 10 feet and 0.8:1 slopes, and would be blanketed with sand and gravel filters. The outer pervious zones of the dams would consist of stream bed gravels and materials salvaged from stripping and excavation. The upstream face of the main dam would be protected by a 3-foot blanket of riprap, and similar blankets 2 feet in depth would protect the upstream faces of the saddle dams. The main dam would have an estimated volume of fill of 2,201,000 cubic yards, and the estimated volume of fill of the two saddle dams would be 449,000 cubic yards.

The concrete spillway would be of the ogee weir type, located in a saddle between the main dam and the north saddle dam. It would have a capacity of 14,000 second-feet, required for an assumed discharge of 350 second-feet per square mile of drainage area, and would discharge into a tributary of Coon Creek. The maximum depth of water above the spillway lip would be 4 feet, and an additional 4 feet of freeboard would be provided. Outlet works would consist of a 48-inch diameter steel pipe placed in a trench excavated in rock beneath the dam, and encased in concrete. Releases from the reservoir would be controlled at the upstream end by two 30-inch hydraulically controlled high-pressure slide gates, located at a submerged inlet upstream from the dam, and operated by hydraulic controls from a house on the left abutment. The outlet would be controlled at the downstream end by a Howell-Bunger valve.

The proposed diversion works on Coon Creek would incorporate remaining features of an abandoned diversion structure at a site approximately 3.3 miles upstream from Highway 99E. The site was examined and surveyed during the course of the investigation. The existing works consist of a concrete gate structure with concrete abutments. An earthen dike which formerly completed stream closure of the left abutment has been destroyed. Stream bed elevation at the site is 140 feet, and the gate structure is 17 feet in height above stream bed. The gate opening is 35 feet in width, and contains seven bays to hold flashboards, each with an opening four feet in width.

For cost estimating purposes, it was planned to utilize the old concrete gate structure by installing removable flashboards to a height of 7 feet above stream bed elevation. The earthen dike would be replaced from the left abutment of the gate structure to the natural bank of Coon Creek, a distance of about 100 feet, to complete the stream closure. This embankment would be approximately 10 feet in height, with 2:1 side slopes and a crest elevation of 150 feet. A similar dike with crest elevation of 155 feet, portions of which are already in place, would extend upstream along the low left bank of Coon Creek for a distance of approximately 1,000 feet. At a point about 50 feet upstream from the main axis of the diversion structure a concrete headwall would be placed in the left side embankment, containing a 4- by 4-foot slide gate to control releases into a proposed canal. It was estimated that spillway capacity of the existing gate structure, after removal of the flashboards, would be in excess of 2,000 second-feet. It was considered that infrequent flood flows in Coon Creek in excess of this amount would wash out the closing earth embankment, and that the embankment would have to be replaced after such floods.

The proposed canal, with a capacity of 100 second-feet, would extend from the headgate in a general southerly direction a distance of approximately 5.5 miles to Markham Ravine. The conserved water would be conveyed in the natural channel of Markham Ravine for a distance of about 1.1 miles where it would be diverted by a flashboard dam and conveyed in a canal for a distance of about 1.2 miles and discharged into Auburn Ravine. For an initial distance of about 0.5 mile from the headgate the canal would be shotcrete-lined and of trapezoidal section, with 1:1 side slopes, bottom width of 4.0 feet, depth of 4.0 feet, and freeboard of 1.0 foot. Its slope would be approximately 2.5 feet per mile, and the velocity would be about 3.5 feet per second. The remaining portion of the constructed canal would be of an unlined trapezoidal section, with 2:1 side slopes, bottom width of 7.0 feet, depth of 3.7 feet, and freeboard of 1.0 foot. Its slope would be approximately 2.5 feet per mile, and the velocity would be about 1.9 feet per second. At a distance of about 1.3 miles before reaching Markham Ravine the conduit would cross Highway 99E and the Southern Pacific Railroad. The structure to carry the water underneath the highway and railroad tracks would be a steel pipe 48 inches in diameter.

Cost estimates for the canal were based on designs utilizing data obtained by a reconnaissance field location survey. Detailed design of the distribution system, however, was considered to be outside the scope of the current investigation. Cost estimates for the system were based on known costs of similar irrigation works elsewhere in California, adjusted to correspond with conditions prevailing in the Sutter-Yuba Area.

Pertinent data with respect to general features of the Coon Creek Project, as designed for cost estimating purposes, are presented in Table 51.

TABLE 51

GENERAL FEATURES OF COON CREEK PROJECT

Main Earthfill Dam
Crest elevation—560 feet
Crest length—1,420 feet
Crest width—30 feet
Height, spillway lip above stream bed—207 feet
Side slopes—3:1 upstream
2.5:1 downstream
Freeboard, above spillway lip—8 feet
Elevation of stream bed—345 feet
Volume of fill—2,201,000 cubic yards

Auxiliary Earthfill Dams
South saddle dam
Crest length—1,450 feet
Crest width—20 feet
Side slopes—2.5:1
Maximum height—64 feet
North saddle dam
Crest length—550 feet
Crest width—20 feet
Side slopes—2.5:1
Maximum height—39 feet
Volume of fill, both dams—449,000 cubic yards

Reservoir
Surface area at spillway lip—820 acres
Capacity at spillway lip—59,000 acre-feet
Drainage area, Coon Creek—40 square miles
Estimated mean seasonal runoff, Coon Creek—32,800 acre-feet
Estimated seasonal diversion of Bear River water through Combie-Ophir Canal—35,700 acre-feet
Estimated safe seasonal yield—56,000 acre-feet
Type of spillway—Ogee weir, concrete-lined
Spillway capacity—14,000 second-feet
Type of outlet—48-inch diameter steel pipe beneath dam

Diversion Works	
Bear River	Existing concrete gravity weir, with overpour section, approximately 300 feet in length, and approximately 15 feet high above stream bed elevation of about 1,500 feet; side channel diversion box, with overpour parapet wall and sluice gate; headgates in concrete headwall.
Coon Creek	Existing concrete diversion structure for flashboard control, with opening 35 feet in width and 17 feet in height above stream bed elevation of 140 feet; to be rehabilitated by installation of flashboards to height of 7 feet, construction of auxiliary earthen dikes, and installation of concrete headwall and 4- by 4-foot slide headgate.
Conduits	
Bear River Diversion	Existing conduit with estimated capacity of 106 second-feet, 2.4 miles in length, comprised of concrete-lined and unlined canal sections, wooden flume, and steel pipe siphons.

Coon Creek Diversion

Type	Trapezoidal, shotcrete-lined canal	Trapezoidal, unlined canal
Length, in miles	0.5	5.0
Side slopes	1:1	2:1
Bottom width, in feet	4.0	7.0
Depth, in feet	4.0	3.7
Freeboard, in feet	1.0	1.0
Slope, in feet per mile	2.5	2.5
Velocity, in feet per second	3.5	1.9
Capacity, in second-feet	100	100

The capital cost of the Coon Creek Project, based on prices prevailing in April, 1952, was estimated to be $5,303,500. The corresponding annual cost of the Coon

Creek Project was estimated to be about $254,100. The resultant estimated average unit cost of the 56,000 acre-feet per season of new water conserved by the Coon Creek Reservoir was about $4.50 per acre-foot. The estimated unit cost of water applied for irrigation in the service area considered for cost estimating purposes was about $6.10 per acre-foot. These estimates of cost do not include possible charges for use of the existing diversion works on the Bear River and the canals of the Nevada Irrigation District. They do, however, include estimated costs for acquiring the existing abandoned diversion structure on Coon Creek below the dam.

Estimated capital and annual costs of the Coon Creek Project are summarized in the following tabulation. Detailed cost estimates are presented in Appendix H.

	Estimated costs	
	Capital	*Annual*
Dam and reservoir	$4,773,700	$196,200
Coon Creek diversion and conduit	229,800	12,300
Distribution system	300,000	45,600
TOTALS	$5,303,500	$254,100

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

As a result of field investigation, and study and analyses of available data on the water resources and water problems of the Sutter-Yuba Area, the following conclusions and recommendations are made.

CONCLUSIONS

It is concluded that:

1. The present basic water problems in the Sutter-Yuba Area are progressive and permanent lowering of ground water levels and attendant degradation of mineral quality of ground water. Elimination of these problems, prevention of their recurrence in the future, and irrigation of irrigable lands not presently served with water will require further development of available water supplies.

2. Mean seasonal depth of precipitation over the Sutter-Yuba Area is about 20.7 inches, and precipitation contributes water to the area in a mean seasonal amount of about 590,000 acre-feet.

3. The highly productive tributary watersheds of the Sierra Nevada constitute the most important source of water supply available to the Sutter-Yuba Area, and mean seasonal surface inflow of water to the area from these sources is about 6,240,000 acre-feet.

4. The ground water basin underlying the Sutter-Yuba Area functions as a natural regulatory reservoir, and at the present time about two-thirds of the lands irrigated in the area are irrigated with water pumped from this reservoir. The gross extraction of ground water in the Sutter-Yuba Area during 1948 was about 350,000 acre-feet.

5. The storage capacity of the ground water basin underlying the Sutter-Yuba Area is about 3,890,000 acre-feet between the levels of 20 and 200 feet below the ground surface.

6. Because of the continuing development and extensive use of ground water in the Sutter-Yuba Area, a substantial cone of depression exists in the ground water plane, and the average level of ground water has fallen about 10 feet since 1943. This lowering of the ground water level has resulted in increased agricultural production costs, and in saline degradation of the ground water in portions of the area.

7. Hydraulic gradients existing in the plane of ground water at the present time result in a seasonal excess of subsurface inflow over subsurface outflow from the Sutter-Yuba Area of about 180,000 acre-feet. This water is an important source of replenishment to the ground water basin.

8. Satisfactory wells with yields sufficient for irrigation purposes may be obtained in all but certain small portions of the Sutter-Yuba Area.

9. High water table lands in certain portions of the Sutter-Yuba Area served with surface water would be suitable for a wider range of crops than at present if ground water levels were held at greater depths. Furthermore, existing drainage problems in these areas would be eliminated and some salvage of water now excessively consumed would result.

10. Safe seasonal yield of the ground water basin underlying the Sutter-Yuba Area, with average maintenance of ground water levels prevailing in 1949, is about 190,000 acre-feet.

11. The surface water supplies of the Sutter-Yuba Area are of excellent mineral quality.

12. The ground water supplies of the Sutter-Yuba Area are generally of excellent to good mineral quality. However, salinity sufficient to impair use of ground water for irrigation, domestic, and many industrial uses, has been observed at scattered wells throughout the area for many years. This condition is particularly prevalent in the Peach Bowl. Saline degradation of ground water in the Sutter-Yuba Area probably results from the upward migration and diffusion of deep saline brines through permeable zones in the alluvium, and through unplugged test wells and abandoned, defective, or improperly constructed wells. This upward and lateral movement of degraded water is probably accelerated when the ground water plane is lowered by heavy irrigation pumping.

13. Due to geographic and water service considerations, the Sutter-Yuba Area is naturally divided into four principal zones. These have been designated "West Side Zone," "Northeast Zone," "East Central Zone," and "South Side Zone," and are shown on Plate 2.

14. At the present time there are approximately 150,000 acres of irrigated land in the Sutter-Yuba Area. The present distribution of the irrigated land among the several zones is as follows: West Side Zone, 66,200 acres; Northeast Zone, 20,100 acres; East Central Zone, 34,100 acres; and South Side Zone, 28,800 acres.

15. The probable ultimate cultural pattern of the Sutter-Yuba Area will include about 250,000 acres of irrigated land. The probable ultimate distribution of irrigated land among the several zones is as follows: West Side Zone, 100,000 acres; Northeast Zone, 31,000 acres; East Central Zone, 54,000 acres; and South Side

Zone, 65,000 acres. This and subsequent conclusions set forth with reference to future conditions are based upon the general assumptions that: (a) All irrigable lands in the Sutter-Yuba Area will ultimately be brought under irrigation; (b) The type of irrigated crops and irrigation practice will not alter materially; (c) There will be no significant changes in irrigation practice in adjacent areas served with surface supplies; (d) Rainfall, water supply, and climatic conditions will have annual and secular variations as in the past.

16. Of the total amount of water, including rainfall, presently utilized in the Sutter-Yuba Area, approximately 65 percent is consumed in the production of irrigated crops. Dry-farmed and fallow lands, native vegetation, and miscellaneous culture including urban areas, consume the remaining 35 percent. At the present time mean seasonal utilization of water in the area is about 820,000 acre-feet. The estimated distribution of seasonal water utilization among the several zones is as follows: West Side Zone, 311,000 acre-feet; Northeast Zone, 113,000 acre-feet; East Central Zone, 201,000 acre-feet; and South Side Zone, 194,000 acre-feet.

17. Under conditions of ultimate development the mean seasonal utilization of water will probably increase to about 1,050,000 acre-feet. The probable distribution of this use among the several zones is as follows: West Side Zone, 384,000 acre-feet; Northeast Zone, 136,000 acre-feet; East Central Zone, 256,000 acre-feet; and South Side Zone, 278,000 acre-feet.

18. The present requirement for supplemental water in the Sutter-Yuba Area, in order to prevent progressive and permanent lowering of ground water levels and attendant degradation of mineral quality of the ground water, is about 79,000 acre-feet per season. The estimated distribution of the supplemental seasonal water requirement among the several zones is as follows: West Side Zone, 17,000 acre-feet; Northeast Zone, 6,400 acre-feet; East Central Zone, 27,600 acre-feet; and South Side Zone, 27,600 acre-feet. The distribution among the zones was based on the assumption that lowering of water levels which occurred during the season of 1948-49 would have been proportionately the same had mean water supply and climatic conditions prevailed.

19. Under ultimate conditions of development the corresponding requirement for supplemental water probably will be about 315,000 acre-feet per season. The estimated distribution of ultimate mean seasonal supplemental water requirement among the several zones is as follows: West Side Zone, 90,600 acre-feet; Northeast Zone, 30,100 acre-feet; East Central Zone, 81,900 acre-feet; and South Side Zone, 112,200 acre-feet. The estimate for each zone was determined as the sum of the probable increase in water utilization and the present supplemental water requirement.

20. Major features of The California Water Plan, which is presently being formulated under direction of the State Water Resources Board, will provide supplemental water to meet the probable ultimate requirements of the Sutter-Yuba Area. The Feather River Project, an adopted feature of The California Water Plan, will provide supplemental water to meet the probable ultimate supplemental water requirements of the West Side Zone. It is feasible from an engineering standpoint to so regulate and conserve the relatively large flood flows of the Yuba and Bear Rivers and other tributaries of the Feather River as to yield firm water supplies considerably in excess of the probable ultimate supplemental water requirements of the Northeast, East Central, and South Side Zones.

21. New water sufficient to meet the present supplemental requirement of the West Side Zone, together with additional water for growth in water demand for a number of years in the future, could be furnished by construction of facilities for pumping water directly from the Feather River and for its conveyance to and distribution in the Peach Bowl. Cost estimates indicate that the average unit cost of water diverted at the river would be about $4.20 per acre-foot, and that applied to irrigation would be about $5.60 per acre-foot.

22. Preliminary studies indicate that supplemental water could be furnished the Northeast Zone from a multipurpose development of the South Fork of the Feather River and tributaries of the North Fork of the Yuba River.

23. New water sufficient to meet the present supplemental requirement of the Northeast Zone, together with additional water for growth in water demands for a number of years in the future in both the Northeast Zone and the Browns Valley service area, could be furnished by construction of a dam and reservoir on South Honcut Creek, facilities for diversion of flood waters of French Dry Creek to the reservoir, and facilities for conveyance to and distribution of the conserved waters in the Northeast Zone and the Browns Valley service area. The estimated average unit cost of the water so developed and applied to irrigation would be about $9.70 per acre-foot in the Northeast Zone, and about $8.40 per acre-foot in the Browns Valley service area.

24. Preliminary studies indicate that supplemental water could be furnished both the East Central and South Side Zones from a development involving enlargement and extension of facilities of the Nevada Irrigation District.

25. New water sufficient to meet the present supplemental requirements of the East Central and South Side Zones, together with additional water for growth in water demands for a number of years in the future, could be furnished by construction of a larger dam and reservoir on the Bear River at the site of the existing Camp Far West Dam and Reservoir, and

facilities for conveyance of the conserved water to and its distribution in both the East Central and South Side Zones. The estimated average unit cost of the water so developed and applied to irrigation would be about $4.70 per acre-foot in the East Central Zone, and about $5.30 per acre-foot in the South Side Zone.

26. New water sufficient to meet the present supplemental requirement of the South Side Zone, together with additional water for growth in water demand for a number of years in the future, could be furnished by construction of a dam and reservoir on Coon Creek, utilization of existing facilities of the Nevada Irrigation District for diversion of flood waters of the Bear River to the proposed reservoir, and facilities for conveyance to and distribution of the new water in the South Side Zone. The estimated average unit cost of the water so developed and applied to irrigation would be about $6.10 per acre-foot.

27. The unit costs of water as given in the foregoing paragraphs are based on current prices of construction, and are illustrative of the cost of new water for the various zones of the Sutter-Yuba Area developed by works exclusively for water conservation purposes. The costs exceed that of surface water presently served within the area, and it is probable that under present conditions ground water pumping costs are somewhat less than the estimated costs of water developed by the considered conservation projects. It is indicated that in order to obtain new water at lower unit costs in the Sutter-Yuba Area, multipurpose developments providing other benefits and revenues in addition to water conservation will be required.

RECOMMENDATIONS

It is recommended that:

1. Public districts endowed with appropriate powers be created for the purposes of proceeding with further study of the local water problems and with financing, construction, and operation of projects found financially feasible.

2. Local development of water resources be accomplished by an orderly progression of phases of development, and in accordance with The California Water Plan. Successive steps in proposed plans should first develop those projects with indicated lowest capital and unit cost of water, and thence proceed in order of expense to phases of greater unit cost.

3. Additional engineering investigation and study be made for design, financing, and construction of the Peach Bowl Project.

4. Additional engineering investigation and study be made as required for design, financing, and construction of other local projects for initial development outlined in this report, when the financial feasibility of these projects has been determined.

5. A program be initiated for the acquisition of lands, easements, and rights of way necessary for construction of required local water conservation works.

6. Consideration be given to the implementation of plans for securing a firm ultimate supplemental water supply for the West Side Zone from the Feather River Project.

7. Continuing support be given to the investigation and study of major multipurpose developments under The California Water Plan, including those on the Feather, Yuba, and Bear river systems.

APPENDIX A

AGREEMENT, AND ITS SUPPLEMENT, BETWEEN THE STATE WATER RESOURCES BOARD, THE COUNTIES OF SUTTER AND YUBA, AND THE DEPARTMENT OF PUBLIC WORKS

AGREEMENT BETWEEN THE STATE WATER RESOURCES BOARD, THE COUNTIES OF SUTTER AND YUBA, AND THE DEPARTMENT OF PUBLIC WORKS

THIS AGREEMENT, executed in quintuplicate, entered into by the State Water Resources Board, hereinafter referred to as the "Board"; the Counties of Sutter and Yuba, hereinafter referred to as the "Counties"; and the Department of Public Works, acting through the agency of the State Engineer, hereinafter referred to as the "State Engineer."

WITNESSETH:

WHEREAS, in the State Water Resources Act of 1945, as amended, the Board is authorized to make investigations, studies, surveys, hold hearings, prepare plans and estimates, and make recommendations to the Legislature in regard to water development projects, including flood control plans and projects; and

WHEREAS, by said act, the State Engineer is authorized to cooperate with any county, city, State agency or public district on flood control and other water problems and when requested by any thereof may enter into a cooperative agreement to expend money in behalf of any thereof to accomplish the purposes of said act; and

WHEREAS, each of the Counties desires and hereby requests the Board to enter into a cooperative agreement for the making of an investigation and report on the underground water supply of the valley floor lands in the Counties of Sutter and Yuba, including quality, replenishment and utilization thereof, and if possible, to incorporate findings in said report as to a method or methods of solving the problems involved; and

WHEREAS, the Board hereby requests the State Engineer to cooperate in making an investigation and report on the underground water supply of said valley floor lands in said Counties, including quality, replenishment and utilization thereof, and, if possible, to incorporate in said report a method or methods of solving the problems involved;

NOW THEREFORE, in consideration of the premises and of the several promises to be faithfully performed by each as hereinafter set forth, the Board, the Counties, and the State Engineer do hereby mutally agree as follows:

ARTICLE I—WORK TO BE PERFORMED:

The work to be performed under this agreement shall consist of investigation and report on the underground water supply of the valley floor lands in the Counties of Sutter and Yuba, including quality, replenishment and utilization thereof, and, if possible, a method or methods of solving the problems involved.

The Board by this agreement authorizes and directs the State Engineer to cooperate by making said investigation and report and by otherwise advising and assisting in making an evaluation of present and ultimate underground water problems in the valley floor lands of said Counties, and in formulating a solution or solutions of said problems.

During the progress of said investigation and report all maps, plans, information, data and records pertaining thereto which are in the possession of any party hereto shall be made fully available to any other party for the due and proper accomplishment of the purposes and objects hereof.

The work under this agreement shall be diligently prosecuted with the objective of completion of the investigation and report on or before December 31, 1949, or as nearly thereafter as possible.

ARTICLE II—FUNDS:

Each of the Counties, upon execution by it of this agreement, shall transmit to the State Engineer the sum of Five Thousand Dollars ($5,000) for deposit, subject to the approval of the Director of Finance, into the Water Resources Revolving Fund (also known as the Water Resources Fund) in the State Treasury, for expenditure by the State Engineer in performance of the work provided for in this agreement. Also, upon execution of this agreement by the Board, the Director of Finance is requested to approve the transfer of the sum of Ten Thousand Dollars ($10,000) from funds appropriated either by the Budget Act of 1947, or by Chapter 1541, Statutes of 1947, or in part from each of said appropriations, to said Water Resources Board for expenditure by the State Engineer in performance of the work provided for in this agreement and the State Controller is requested to make such transfer.

If the Director of Finance, within thirty (30) days after receipt by the State Engineer of said sums from the Counties, shall not have approved the deposit thereof into said Water Resources Revolving Fund, together with the transfer of said sum of Ten Thousand Dollars ($10,000) from funds appropriated to said Board either by the Budget Act of 1947, or by Chapter 1541, Statutes of 1947, or in part from each of said appropriations, said Water Resources Revolving Fund for expenditure by the State Engineer in performance of the work provided for in this agreement, said sums contributed by said Counties shall be returned thereto by the State Engineer.

It is understood by and between the parties hereto that the sum of Twenty Thousand Dollars ($20,000) to be made available as hereinbefore provided is adequate to perform approximately half of the above specified work and it is the present intention of each of said Counties to make a further sum of Five Thousand Dollars ($5,000) available at the commencement of the second year of said investigation which will be subject to a matching or contribution in equal sums by said Board for the completion of said investigation and report.

The Board and the State Engineer shall under no circumstances be obligated to expend for or on account of the work provided for under this agreement any amount in excess of the sum of Twenty Thousand Dollars ($20,000) as made available hereunder and when said funds are exhausted, the Board and the State Engineer may discontinue the work provided for in this agreement and shall not be liable or responsible for the resumption and completion thereof until the further sums as specified in the preceding paragraph are made available.

Approved:

/s/ C. H. PURCELL
Director of Public Works

Approval Recommended:

/s/ SPENCER BURROUGHS
Principal Attorney
Division of Water Resources

Approved as to Form:

/s/ LOYD E. HEWITT
District Attorney
County of Sutter

/s/ JOSEPH L. HENNAN
District Attorney
County of Yuba

Approved:

/s/ JAMES S. DEAN
Director of Finance

Approved as to Legality:

/s/ C. C. CARLETON
Chief Attorney
Department of Public Works

Upon completion of and final payment for the work provided for in this agreement, the State Engineer shall furnish the Board and each of the Counties a statement of all expenditures made under this agreement. One-half of the total amount of all said expenditures shall be deducted from the sum advanced from funds appropriated to said Board, and one-fourth of the total amount of all said expenditures shall be deducted respectively, from the sum advanced by each of the Counties and any balances which may remain shall be returned to the Board, and to the counties, respectively.

ARTICLE III—EFFECTIVE DATE

This agreement shall become effective immediately upon its execution by all the parties hereto.

IN WITNESS WHEREOF, the parties hereunto have affixed their signatures, the County of Sutter on the 22nd day of September, 1947, the County of Yuba on the 22nd day of September, 1947, the Board on the 6th day of October, 1947, and the State Engineer on the 7th day of October, 1947.

COUNTY OF SUTTER

By /s/ ED. F. DACOSSE
Chairman, Board of Supervisors
/s/ ALBERT B. BROWN
Clerk, Board of Supervisors

COUNTY OF YUBA

By /s/ JAMES R. BROWN
Chairman, Board of Supervisors
/s/ ADRIENNE CONLEY
Clerk, Board of Supervisors

STATE WATER RESOURCES BOARD

By /s/ ROYAL MILLER
Chairman

DEPARTMENT OF PUBLIC WORKS
STATE OF CALIFORNIA

By /s/ EDWARD HYATT
State Engineer

(Initialled)

LJK	HA		
Form	Budget	Value	Descript.

DEPARTMENT OF FINANCE
APPROVED
Oct. 23, 1947

SUPPLEMENTAL AGREEMENT BETWEEN THE STATE WATER RESOURCES BOARD, THE COUNTIES OF SUTTER AND YUBA, AND THE DEPARTMENT OF PUBLIC WORKS

THIS AGREEMENT, executed in sextuplicate, entered into by the State Water Resources Board, hereinafter referred to as the "Board"; the Counties of Sutter and Yuba, hereinafter referred to as the "Counties"; and the Department of Public Works of the State of California, acting through the agency of the State Engineer, hereinafter referred to as the "State Engineer";

WITNESSETH:

WHEREAS, by agreement heretofore entered into by and between the parties hereto, executed by the Counties on the 22nd day of September, 1947, by the Board on the 6th day of October, 1947, and by the State Engineer on the 7th day of October, 1947, the making by the State Engineer of an investigation and report on the underground water supply of the valley floor lands in the Counties of Sutter and Yuba, including quality, replenishment and utilization thereof and, if possible, a method or methods of solving the problems involved, was provided for; and

WHEREAS, it was the expressed intention in said agreement that at the commencement of the second year of said investigation said Counties would make available in equal proportion a further sum of Ten Thousand Dollars ($10,000) subject to a matching or contribution in equal amount by the Board for the completion of said investigation and report; and

WHEREAS, said additional funds are required to complete said investigation and report, and it is the desire of the parties hereto that an additional sum of Twenty Thousand Dollars ($20,000) shall be provided, Five Thousand Dollars ($5,000) by each of the Counties, and Ten Thousand Dollars ($10,000) by the Board;

NOW THEREFORE, in consideration of the premises and of the several promises to be faithfully performed by each as hereinafter set forth, the Board, the Counties, and the State Engineer do hereby mutually agree as follows:

1. Each of the Counties, upon execution by it of this agreement, shall transmit to the State Engineer the sum of Five Thousand Dollars ($5,000) for deposit, subject to the approval of the Director of Finance, into the Water Resources Revolving Fund in the State Treasury for expenditure by the State Engineer in continuing performance of the work provided for in said prior agreement to which this agreement is supplemental.

2. Upon execution of this agreement by the Board, the Director of Finance will be requested to approve the transfer of the sum of Ten Thousand Dollars ($10,000) from funds appropriated to the Board by Item 335 of the Budget Act of 1948 for expenditure by the State Engineer in continuing performance of the work provided for in said prior agreement to which this agreement is supplemental, and the State Controller will be requested to make such transfer.

3. The Board and the State Engineer shall under no circumstances be obligated to expend for or on account of the work provided for in said prior agreement to which this agreement is supplemental any amount in excess of the sum of Forty Thousand Dollars ($40,000) as made available under said prior agreement and this supplemental agreement and if funds are exhausted before completion of said work the Board and the State Engineer may discontinue said work and shall not be liable or responsible for the completion thereof.

4. In so far as consistent herewith and to the extent adaptable hereto, all of the terms and provisions of said prior agreement to which this agreement is supplemental are hereby made applicable to this agreement and are hereby confirmed, ratified, and continued in effect.

5. This agreement shall become effective immediately upon its execution by all of the parties hereto.

IN WITNESS WHEREOF, the parties hereunto have affixed their signatures, the County of Sutter on the 4th day of October, 1948, the County of Yuba on the 22nd day of November, 1948, the Board on the 3rd day of December, 1948, and the State Engineer on the 30th day of November, 1948.

Approved as to form:

/s/ LOYD E. HEWITT
District Attorney
County of Sutter

/s/ JOSEPH L. HENNAN
District Attorney
County of Yuba

Approval Recommended:

/s/ SPENCER BURROUGHS
Principal Attorney
Division of Water Resources

Approved as to Legality:

/s/ C. C. CARLETON
Chief Attorney
Department of Public Works

Approved:

/s/ JAMES S. DEAN
Director of Finance

COUNTY OF SUTTER

By /s/ ED. F. DACOSSE
Chairman, Board of Supervisors
/s/ ALBERT B. BROWN
Clerk, Board of Supervisors

COUNTY OF YUBA

By /s/ JAMES P. BROWN
Chairman, Board of Supervisors
/s/ ADRIENNE CONLEY
Clerk, Board of Supervisors

STATE WATER RESOURCES BOARD

By /s/ C. A. GRIFFITH
Vice-Chairman

DEPARTMENT OF PUBLIC WORKS
STATE OF CALIFORNIA

By /s/ C. H. PURCELL
Director of Public Works
/s/ EDWARD HYATT
State Engineer

APPENDIX B

GEOLOGIC FEATURES AND GROUND-WATER STORAGE CAPACITY OF THE SUTTER-YUBA AREA, CALIFORNIA

By G. H. Davis and F. H. Olmsted, under the
direction of J. F. Poland, District Geologist

Ground Water Branch, Water Resources Division
UNITED STATES GEOLOGICAL SURVEY

Prepared in cooperation with the California Department of
Public Works, Division of Water Resources

Dated May, 1950

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UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GROUND WATER BRANCH
2520 Marconi Avenue
SACRAMENTO 21, CALIFORNIA

May 22, 1950

Mr. A. D. EDMONSTON, *State Engineer*
Division of Water Resources
P. O. Box 1079, Sacramento 5, California

DEAR SIR: I take pleasure in transmitting herewith a report on "Geologic features and ground-water storage capacity of the Sutter-Yuba area, California" by G. H. Davis and F. H. Olmsted. This report has been prepared by the Geological Survey as a part of the program of cooperative ground-water investigations with the California Division of Water Resources.

The report has been approved by the Director of the Geological Survey for publication by the State Water Resources Board as an appendix to its Bulletin No. 6 entitled "Sutter-Yuba Counties Investigation."

Very truly yours,

(Signed) JOSEPH F. POLAND
District Geologist