BIG VALLEY
GROUND-WATER RECHARGE
INVESTIGATION

- For LAKE COUNTY FLOOD CONTROL
  And WATER CONSERVATION
  DISTRICT

March 1967
# BIG VALLEY GROUND-WATER RECHARGE INVESTIGATION

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I. INTRODUCTION

This report presents the results of an investigation of the ground-water geology and hydrology of Big Valley, in Lake County, California. The investigation was undertaken in order to achieve three basic aims: 1) to determine the technical feasibility of carrying out supplemental recharge of the ground water in Big Valley; 2) to define the ground-water geology and hydrology of Big Valley; and 3) to develop a preliminary plan for ground-water replenishment in the Valley. These determinations have provided bases for establishing the feasibility of carrying out operations for supplementary recharge of ground water in certain of the Valley's aquifers, and for developing a preliminary plan for conjunctive water resources development and management in the Valley.

The report was prepared for the Lake County Flood Control and Water Conservation District and the West Lake Soil Conservation District (SCD) by Soil Mechanics and Foundation Engineers, Inc. in accordance with formal agreements between the two local agencies, the State of California, and this consulting firm. The investigation was initiated and planned by staff members of the two local Districts, the State Division of Soil Conservation, the U. S. Soil Conservation Service, and members of two consulting firms. One-half of the funds for this project was provided by the Lake County Flood Control and Water Conservation District and one-half by the State of California Soil Conservation Commission through the West Lake Soil Conservation District. The project is part of the area flood control and water development program being conducted by the Lake County Flood Control and Water Conservation District.

The investigation was carried out in two stages. Stage I was completed with the acceptance by the Lake County Flood Control and Water Conservation District of an interim report in July 1966. That report contained brief discussions of geology, ground-water geology and hydrology, ground-water recharge, and water management in the Big Valley area, together with supplemental material and four illustrative plates.
The Stage II investigation involved extending and refining the work done in the first stage and preparing the final report presented here. This report includes more detailed discussions of the subjects covered in the interim report, appendices, illustrative figures, and five plates showing geology, geologic-hydrologic conditions, geologic cross sections, ground-water recharge conditions, and well location and data availability in Big Valley. The overall investigation involved three general categories of work. These were 1) collection, compilation, and review of existing data from all sources; 2) generation of new data from field, office, and laboratory work; and 3) analysis and synthesis of all data and presentation of the results of this work in a report.

Published and unpublished recorded data were obtained from the Lake County Flood Control and Water Conservation District, the California Department of Water Resources (California State D.W.R.), the California Department of Natural Resources, Division of Mines and Geology, the U. S. Geological Survey (U.S.G.S.), and the Lake County Farm Advisor's office of the Agricultural Extension Service, University of California. Helpful discussions were held with Mr. Willard Hansen, Mr. Tom Wales, Mr. D. W. Dresbach of the State Division of Soil Conservation, Mr. A. J. Andresen of the Soil Conservation Service, Mr. Tom Williams, President of the West Lake Soil Conservation District, members of the Lake County Flood Control and Water Conservation District Board of Directors, Mr. C. L. Hemstreet, Jr., Lake County Farm Advisor, Professor C. J. Hansen of the University of California at Davis, personnel of the California State Department of Water Resources, personnel of the U. S. Bureau of Reclamation, and various residents of Big Valley.

Field work by Soil Mechanics and Foundation Engineers, Inc. included geologic mapping, subsurface exploration of the channels of Kelsey and Adobe Creeks, sampling of the materials present in these channels, and sampling of outcrops of the "volcanic ash" aquifer material.
II. SUMMARY OF CONCLUSIONS

A. FEASIBILITY OF SUPPLEMENTARY RECHARGE OF THE GROUND-WATER SYSTEMS IN BIG VALLEY

Augmentation or replenishment of ground-water storage in the main basin-aquifer systems in Big Valley by supplementary recharge is feasible during periods when the water table is lowered below the level of the principal creek channels. Ground water stored in the "Volcanic ash" aquifer, present under portions of the Big Valley upland areas, may also be augmented or replenished to some extent if appropriate facilities are constructed. Supplementary recharge of other, less important ground-water systems in Big Valley does not appear to be technically feasible.

1. The principal aquifers in Big Valley underlie the lowlands of Kelsey Creek, north of Kelseyville, and the valleys of Adobe and Manning Creeks. Ground water in the aquifers of the basins underlying these areas is naturally recharged by percolation from portions of the channels of the major creeks, and by underflow from adjoining areas. In years of normal rainfall, the basins are filled to the levels of the creek channels by March, and no more recharge is possible until water tables are lowered by pumping from wells and by natural outflow from the basins. This lowering of the water tables takes place after most stream flow percolation has ceased. During such conditions of lowered water tables, supplementary recharge of the basins is feasible, providing that water for recharge can be made available. Recharge can be carried out by percolation of water introduced into suitable portions of the natural creek channels. The channels have the capacity to transmit more water to underlying aquifers than can be accommodated by the available volume of unsaturated aquifer storage space. The limit to the amount of water which can be introduced into the basin aquifers is therefore dependent on the maximum amount of unsaturated aquifer storage volume available. As of 1966, this amount is approximately 14,000 acre feet, at the time of greatest lowering of the water tables in September and October.

2. The upland areas within and marginal to Big Valley are underlain by
generally fine grained deposits having very limited water transmitting properties. However, a thin layer of permeable "volcanic ash" is incorporated within these deposits at one horizon. This layer underlies extensive portions of the Western and Central Uplands, at depths ranging from surface outcroppings to more than 200 feet. It constitutes the most important aquifer in these areas. Some supplementary recharge of the "Volcanic ash" aquifer can be accomplished in the Central Upland by construction of infiltration basins over outcrop areas, and diverting water to such basins, and/or by use of recharge wells.

3. Other smaller and less continuous ground-water systems in the upland and hill areas in and around Big Valley are not amenable to supplementary recharge.

B. PRELIMINARY PLAN FOR CONJUNCTIVE WATER RESOURCES DEVELOPMENT AND MANAGEMENT IN BIG VALLEY

Development and management of the water resources of Big Valley will require construction of a reservoir on upper Kelsey Creek, and facilities for diversion of stored water from Kelsey Creek to Adobe Creek, and to the upland area in the central portion of Big Valley. Accomplishment of this would permit management of water resources according to the following general program:

1. During the winter rainy season, enough water would be released to the lower reach of Kelsey Creek to recharge the basin below Kelseyville to capacity. The basin under Adobe Creek would be recharged to capacity at the same time by natural runoff in Adobe Creek.

2. When the aquifer in the basin below Kelseyville is filled to capacity, releases to the creek could be reduced to the minimum needed for fish and game and/or surface diversion requirements; and the excess, comprising the greater part of the flow now lost to Clear Lake, could be retained for use as recharge and surface supply water during the summer dry season.

3. When the late spring and summer irrigation season is under way, stored
water could be released to Kelsey Creek, and diverted to upper Adobe Creek, in amounts sufficient to maintain basin ground water at near maximum levels, with percolation from the creek channels to the basin approximately balancing withdrawals by pumping from the basin. Water could also be diverted to the Central Upland area for surface supply and for partial recharge of the "volcanic ash" aquifer underlying it.

4. During the following rainy season, water levels in the basin aquifers would recover fully, and the cycle of storage of runoff from Kelsey Creek for surface and recharge use during the following irrigation season would be repeated.

C. BENEFITS OF A PROGRAM OF CONJUNCTIVE SURFACE AND GROUND-WATER DEVELOPMENT IN BIG VALLEY

Benefits of the program of conjunctive surface and ground-water development and management just outlined would include the following:

1. The total amount of water actually available for beneficial use within Big Valley would be greatly increased.

2. Supplemental recharge of the basin aquifers would result in maintenance of higher water levels during the irrigation season, with consequent decrease in pump lifts, and would, in effect, distribute additional lower cost (through decreased pump lift) water to the majority of water users in the valley, without construction of special distribution facilities.

3. Water from the high level reservoir on upper Kelsey Creek would be available for direct surface diversion to present and potential future water users in the Central Upland area. Water diverted to this area could also be used for some supplementary recharge of the "volcanic ash" aquifer there.

4. Supplementary recharge of the basin aquifers should result in some improvement in the overall quality of ground water in the basin and should reduce the
concentration of boron in water produced by some wells which draw from both shallow and deep levels.

D. RECOMMENDATIONS FOR CONTINUED PROGRAMS OF DATA ACQUISITION AND FOR FUTURE STUDIES

Data acquisition programs and future studies relating to the ground-water hydrology of Big Valley should yield present and future benefits to the Lake County Flood Control and Water Conservation District in its planning for development and management of water resources in that area. Three general programs, the first two of which consist largely of continuing activities already being carried out by the District or by other agencies, are recommended. The three programs are:

1. Maintenance of records of ground-water and hydrologic conditions, both for purposes of having contemporary data, and for having long term records which would show changes in conditions. The spring and fall water-level survey, monthly water-level measurements in selected wells, and stream gaging measurements comprise the principal items of this program.

2. Compilation and periodic assimilation of new data. This has been carried out by the District in the past, and by their consultants during this investigation. This work includes reviewing the results of new investigations which have pertinence to hydrologic conditions in Big Valley, obtaining special data such as well logs and water analyses which become available periodically, and maintaining liaison with appropriate agencies concerned with conditions or developments in Big Valley.

3. Special studies for extending, refining, and quantifying knowledge about particular aspects of ground water or related subjects in Big Valley. Studies of this sort could be undertaken or commissioned by the Lake County Flood Control and Water Conservation District as required for future planning, or as otherwise needed. Specific, quantitative studies of aquifer characteristics or of water quality in certain areas, could be carried out as required.
Additionally, studies of economic factors, legal factors, projected water requirements, and engineering design of water retention and distribution facilities will be required when action is taken to implement a program of water resources management.
III. THE BIG VALLEY AREA

Area Location and Description
The area known as Big Valley is located in the west-central portion of Lake County in the northern Coast Ranges of California. The location, form, and principal topographic and cultural features of the Valley are shown in Figure 1. The Valley is triangular in outline, with southwest and southeast sides being bounded by the Mayacmas Mountains and by Mt. Konocti, respectively, and with the north side opening to Clear Lake. The Valley area comprises extensive lowland flood plains and terrace-like uplands. For convenience of reference, the names indicated on the Reference Map, Figure 1, have been assigned to the corresponding outlined areas. Names such as "Kelseyville Basin" and "Central Upland" are used throughout this report to indicate specific areas within the Valley.

Big Valley has a total area of 30.5 square miles, or 19,600 acres. Its maximum width and length are each about 7 miles. Elevations of the lowland portions of the Valley range from 1330 feet, adjacent to Clear Lake, to 1440 feet below Adobe Creek Dam. The upland areas are 1440 to about 1600 feet in elevation, with local hilly areas rising to 1800 feet elevation. The surrounding mountains rise to elevations of 2500 to about 4000 feet.

Land Use
Land use in Big Valley is predominantly agricultural. Most of the lowland area is cultivated, and the greater part of this land is irrigated. Some of the upland areas are dry farmed, and a few tracts are irrigated, but much of the land in these areas is still undeveloped. Pear orchards predominate in the lowland in northern Big Valley, where ground water for irrigation is readily obtainable. Walnuts are grown both in the lowlands and in the drier upland areas. Considerable land also is used for raising feed crops, and irrigated alfalfa fields are located at various places in the lowlands and also on the terrace benches adjacent to Kelsey Creek above Kelseyville.
Most of the undeveloped land in Big Valley is covered with dense California chaparral type brush, though areas of open grassland with scattered brush and trees exist near the head of the Valley.

Two small towns, Kelseyville and Finley, are located in Big Valley. Local industries include several fruit packing and processing establishments, walnut drying plants, and sand and gravel pits and processing plants. Most of the sand and gravel is obtained from the channel of Kelsey Creek and the adjacent flood-plain area west of the creek, where all of the processing plants are located. Some sand and gravel is also obtained from the channel of Adobe Creek, near the Bell Hill Road crossing.

The pattern of land and water use in Big Valley in 1960 was determined by the California State Department of Water Resources and is shown in DWR Bulletin No. 94-13, "Land and Water Use in Putah-Cache Creeks Hydrographic Unit", published in 1964. Another investigation of land and water use in this area is presently (1966-67) being carried out by the U. S. Bureau of Reclamation. The results of that investigation will become available in December 1967 in their report "English Ridge Unit - Reconnaissance Report on Water Supply and Land Use".

**Hydrology**

The hydrology of Big Valley encompasses the rainfall, the flow of five major creeks and of a number of minor drainage courses, irrigation and other water use and disposal activities, and the ground-water regime. Flow of the creeks and minor drainages is very responsive to rainfall and thus is mostly seasonal, with moderate to heavy flow during the rainy season, rapidly diminishing to light flow or cessation of flow when the winter rains stop. The principal elements of the ground-water regime, referred to in this report as the "Kelseyville" and the "Adobe Creek-Manning Creek" basins, are directly recharged by percolation from the channels of the overlying creeks. Since ground water normally flows from these basins toward Clear Lake, their water levels will fall if recharge is not occurring constantly. The seasonal distribution of creek flow and, consequently, of recharge, would result in a certain amount of ground-water
level fluctuation even under natural conditions. The ground water of the basins, however, is drawn upon heavily by pumping for irrigation during the summer and early fall dry season. This schedule greatly accentuates the seasonal ground-water fluctuation pattern. Most rainfall occurs during the period of November through March. The quantity of mean seasonal precipitation, as determined by the California State DWR and reported in their Bulletin 14, ranges from 23 inches near Kelseyville to 37 inches at the uppermost end of the Valley.

Five major creeks -- Cole, Kelsey, Adobe, Highland, and Manning -- enter Big Valley and cross portions of its surface before reaching Clear Lake. Flow in the creeks is highly seasonal. Heavy flow occurs in all of the creeks after periods of rainfall and appreciable flow is maintained throughout the wet season. Some flow continues in Kelsey Creek, above Kelseyville, throughout the year, but the other creeks do not maintain surface flow during the dry season for more than a fraction of a mile after entering Big Valley.

Daily records of the flow of Kelsey, Adobe, and Highland Creeks are obtained by the U. S. Geological Survey, using water stage recorders. Recorded seasonal flow of the principal creeks is presented in Table A.

The flow of Adobe and Highland Creeks is regulated by the operation of flood control reservoirs on each creek above their confluence in Upper Big Valley. These reservoirs also have a recreational purpose and are stocked with fish. The necessity for maintaining flood control storage in these reservoirs, together with their limited capacity, dictates that large releases be made from them during the wet season. Consequently, the existing reservoirs have very little opportunity to store water for use during the dry season.

Under natural conditions, the channels of both Kelsey and Adobe Creeks tended to migrate over their flood plains in response to lateral erosion and deposition; also, the creeks commonly overflowed their banks and flooded adjacent lowland areas after
# TABLE A

SEASONAL RUNOFF OF THE PRINCIPAL CREEKS IN THE BIG VALLEY AREA

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<td>53,400</td>
<td>71,500</td>
<td>61,300</td>
<td>50,800</td>
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<td>Adobe Creek (including Highland Creek)</td>
<td>11,200</td>
<td>11,900</td>
<td>18,000</td>
<td>*</td>
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<td>Manning Creek</td>
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<td>1,300</td>
<td>2,500</td>
<td>*</td>
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<td>Cole Creek</td>
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<td>41,600</td>
<td>112,600</td>
<td>32,600</td>
<td>32,900</td>
</tr>
<tr>
<td>Adobe Creek</td>
<td>11,100</td>
<td>45,200</td>
<td>15,100</td>
<td>48,400</td>
<td>13,900</td>
<td>12,100</td>
</tr>
<tr>
<td>Manning Creek</td>
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<tr>
<td>Cole Creek</td>
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</tr>
</thead>
<tbody>
<tr>
<td>Kelsey Creek</td>
<td>33,000</td>
<td>45,800</td>
<td>70,600</td>
<td>25,500</td>
<td>81,400</td>
<td>45,940</td>
</tr>
<tr>
<td>Adobe Creek</td>
<td>14,500</td>
<td>21,100</td>
<td>28,900</td>
<td>7,600</td>
<td>30,900</td>
<td>19,780</td>
</tr>
<tr>
<td>Manning Creek</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Cole Creek</td>
<td>*</td>
<td>*</td>
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<td>*</td>
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</tr>
</tbody>
</table>

(*) No record.

Note: Data from California State D. W. R. Bulletin No. 14, and U. S. G. S. records.
heavy storms. Channel clearing, straightening, local deepening, and bank stabilization measures, together with operation of the Adobe and Highland Creek Reservoirs, apparently have largely eliminated the flooding.

Very little water is diverted from the creeks, largely because they do not maintain flow in the main agricultural areas through the irrigation season. Most runoff entering Big Valley presently becomes available for use only if it percolates to and joins the groundwater system. The larger portion of the runoff passes directly through the Valley and is discharged to Clear Lake.

The overall ground-water regimen in Big Valley is divided by conditions of geology, topography, and water supply into a series of "compartments" having greater or less intercommunication with one another. The effect of geologic conditions on the distribution, movement, recharge, and quality of ground water is so important that the "compartments" are referred to in this report as "geologic-hydrologic subunits". A total of eight geologic-hydrologic subunits were recognized as comprising the whole of the Big Valley hydrologic unit.

Ground water in Big Valley is intensively developed for irrigation, municipal, domestic, and industrial use. Wells are located throughout the Valley, though the greatest concentration of wells is in the lowland areas, over the principal aquifers. Use of ground water has increased, especially in recent years, which has resulted in progressively greater lowering of the water table and pressure surface in the basin aquifers through the course of the dry seasons. In years of normal rainfall, however, the basins always refill to their original water table and pressure surface levels during the winter. The significant consequence of the greater lowering of water levels during the dry season, therefore, seems to be mainly that pumping lifts are increased and some shallow wells go dry toward the end of the irrigation season.
IV. GEOLOGY OF THE BIG VALLEY AREA

INTRODUCTION

The geology of the Big Valley area is shown on Plate I, "Geologic Map", and Plate III, "Geologic Cross Sections". Detailed descriptions and discussion of geologic units, geologic structure, and geomorphic and structural evolution of the valley are presented as Appendix D, accompanying this report.

The area known as "Big Valley" is a broad structural depression which is continuous with the northwestern portion of Clear Lake. This basin-like depression originated through repeated episodes of down faulting and warping, each followed by basin-filling sedimentation. The depression is bounded by dissected fault-line escarpments forming the margins of the Mayacamas Mountains to the south and west, and by the volcanic Camelback Ridge and Mount Konocti on the east. The north boundary is the Clear Lake Basin.

Within Big Valley itself there are two general landform areas: 1) the lowland flood plain and lake margin lands; and 2) the uplands. The lowlands are areas which were down-dropped or tilted during successive, relatively recent episodes of faulting and which were subsequently filled to their present surface levels with lake, flood-plain, and channel deposits. The uplands are areas made up of partially dissected remnants of moderately consolidated older, higher level lake, flood-plain and terrace deposits.

Geologic Units Four general categories of geologic units are present in the Big Valley area. These are:

1. Younger alluvial and lake deposits, ranging in age from Recent to late Pleistocene, which occur as terrace, basin-fill, and channel deposits. Well log data indicate that these deposits attain a maximum thickness of about 220 feet in the area north of Kelseyville.

2. Older sedimentary deposits of Pleistocene age which overlap onto the dissected fault-line escarpments fronting the Mayacamas Mountains and the flanks of
the mountains of volcanic origin along the eastern side of the valley. These deposits also comprise the upland areas within Big Valley. Their thickness in the Big Valley area is about 500 feet.

3. The Clear Lake Volcanic Series of Plio-Pleistocene age, including the extrusive rocks of Mt. Konocti, and the extrusive and shallow intrusive rocks of the "volcanic ridge" (the northwest end of Camelback Ridge).

4. The Franciscan Formation of Jurassic-Cretaceous age, consisting of metamorphosed sedimentary and volcanic rocks and tectonically intruded ultrabasic crystalline rocks and serpentinites. These rocks constitute the "basement rock" in this area.

Fourteen individual geologic units which were recognized and mapped during this investigation are shown on the "Geologic Map" and "Geologic Cross Sections", Plates I and III.

Structure. The existence of Big Valley and the distribution of its principal landform subdivisions are the results of fault movement. The steep linear slope rising above the upland along the Valley's west side is an old dissected fault escarpment (the west margin fault), against which the "older sedimentary" materials were deposited. Other, more recent fault movements have created the Adobe Creek basin and the Kelseyville basin, in each case by dropping the basement rocks in the basin areas relative to the central upland area. The fault which apparently formed the Kelseyville basin (the Big Valley fault) extends across the Valley, passing south of Finley and immediately north of Kelseyville and then swinging south, cutting a spur of Mt. Konocti and extending up Cole Creek. Strata of the "older sedimentary" category have been deformed both by tilting of large areas within the Valley and by local drag folding adjacent to fault breaks.
V. GROUND-WATER GEOLOGY AND HYDROLOGY

A. GENERAL

Ground water occurs in Big Valley in several distinct systems. The elements which define these systems include the surface water and/or ground-water supply for each system, geologic conditions including distribution of materials of varying permeability, presence of boundaries to ground-water flow or storage, and the topographic setting. In order to facilitate description and discussion of ground-water conditions, a number of "geologic-hydrologic subunits" have been designated within the Valley. The subunits were defined on the basis of their geologic character, as related to ground-water storage, transmission, and recharge, and by behavior of ground water within them as indicated by well water level readings and by initial water interception data recorded by well drillers. The subunits form the constituent parts which make up the Big Valley hydrologic unit.

Elements of the geologic-hydrologic regimen in Big Valley are illustrated on Plate II, "Geologic-Hydrologic Map"; Plate III, "Geologic Sections"; and Plate IV, "Ground-Water Recharge Map". Seasonal change in ground-water storage in the Valley's principal aquifers is illustrated in Figure 2. Patterns of ground-water movement within the two main geologic-hydrologic subunits, the "Kelseyville" and "Adobe Creek-Manning Creek" basins, and in the confined "Volcanic ash" aquifer, are illustrated diagrammatically in Figures 3, 4, and 5, respectively.

The four general modes of ground-water occurrence in the geologic-hydrologic subunits of the Big Valley area are as follows:

1. The principal occurrence of ground water is in the alluvium and lake sediment-filled basins underlying Adobe and Manning Creeks and lower Big Valley (lower Kelsey Creek). Much of the ground water in these basins is unconfined, but confined areas or zones exist locally where extensive horizons of relatively impermeable clay are present near the surface. Recharge is mainly by infiltration from the
channels of Adobe Creek and the reach of Kelsey Creek below Kelseyville. Additional recharge takes place by underflow of ground water from adjacent, higher level subunits and, to a limited extent, from irrigation.

2. Ground water occurs in relatively permeable zones in the older, high level alluvial deposits of the Central, Western, and Cole Creek uplands. The ground water in occurrences of this type is in aquifers of limited areal extent which are perched on relatively impermeable older lake sediments. Limited recharge occurs by infiltration from the surface and from the channels of ephemeral upland streams.

3. Confined ground water occurs in a thin bed of "volcanic ash" (lithic tuff) present within the older lake deposits underlying the upland areas (and the upper portion of the Adobe Creek-Manning Creek basin). The "ash" consists of angular fragments of volcanic rock, of coarse sand to pea gravel size, and it is quite permeable. Recharge to this aquifer is believed to occur by infiltration in areas where the "ash" crops out in stream courses and by leakage into the aquifer from saturated confining strata.

4. Varying, though generally limited, amounts of ground water occur in permeable fracture zones in the volcanic rocks and Franciscan Formation bedrock surrounding Big Valley.

Most of the ground water pumped in Big Valley is extracted from the Kelseyville and Adobe Creek-Manning Creek basins. Wells in the Western and Central Upland subunits draw from the "volcanic ash" aquifer and also, to a limited extent, from the upper aquifers in these areas. No data are available relating to wells in the Cole Creek Upland. The volcanic ridge subunit yields water to at least one developed spring (in the NE ¼ of section 2, R9W, T12N) and to two wells. No ground water is known to be extracted directly from the Big Valley side of Mt. Konocti or from the Mayacmas Mountains immediately above Big Valley.

Ground-water and pertinent geologic conditions in the geologic-hydrologic subunits of
Big Valley are discussed in the sections of this chapter following.

B. GEOLOGIC-HYDROLOGIC SUBUNITS

1. KELSEYVILLE BASIN

a. General The Kelseyville Basin is a lake and alluvial sediment-filled structural basin about 10 square miles in area. It is the principal ground-water storage and production subunit in Big Valley.

The basin is bounded by the buried lower west slope of Mt. Konocti on the east, and by the escarpment of the Big Valley fault on the south and west. This escarpment is exposed at the surface along the north end of the Central Upland, but is buried beneath 90 to 120 feet of valley fill of the Adobe-Manning Creek basin, at the interface between the subunits. The sedimentary fill in the basins is continuous, so ground water contained within two basins is in complete hydraulic continuity. To the north, the basin merges with the sediments underlying northwestern Clear Lake.

b. Geology Sediments contained within the Kelseyville Basin range in character from lake silt and clay to stream sand and gravel. The fine grained materials tend to occur in relatively continuous layers, extending over sizable areas. A near surface layer of clayey material is present over most of the basin except for the flood plain of Kelsey Creek for a distance of about two miles north of Kelseyville. A persistent layer or series of layers of "blue clay" is present at a depth of about 70 feet through much of the basin. The layer is missing at this depth in the area east of Kelsey Creek, but a similar layer exists at about 130 feet depth there. It is possible that this is the same layer offset by displacement along a (postulated) branch of the Big Valley fault. Generally coarse grained material laid down as channel, flood-plain, and delta deposits by the ancestral Kelsey and Adobe Creeks predominates in the south-central portion of Kelseyville Basin at depths of 20 to 70 feet. (See Sections B-B, C-C, and D-D, Plate III.)

The sands and gravels of this area interlens with and gradually give way to finer grained sediments to the north, toward the lake. Other, less continuous zones of coarse
material are present elsewhere in the basin, notably between depths of 50 and 200 feet in the area east of Kelsey Creek. A summary of data on perforated intervals of well casings indicating the depth intervals from which water is withdrawn for thirty-five recently drilled wells in the Kelseyville Basin is given below.

<table>
<thead>
<tr>
<th>Perforation Interval (depth in feet)</th>
<th>Number of Wells</th>
<th>Percentage of Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-80</td>
<td>19</td>
<td>54</td>
</tr>
<tr>
<td>40-120</td>
<td>6</td>
<td>17</td>
</tr>
<tr>
<td>40-200</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td>over 250</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

The near surface clayey layer acts as a confining membrane or "capping" for ground water in the basin north of where the water table intersects the bottom of this layer. Buried layers of fine grained material may also confine water in deeper aquifers so that several levels of pressure water may exist within the basin. Apparently, however, the pressure in deeper zones is not high enough to raise water above the elevation of the overlying water table.

c. Recharge Water is recharged to the Kelseyville Basin aquifers by infiltration from the channel of Kelsey Creek between the vicinity of Kelseyville and the middle of Section 3, two miles to the north, and by underflow from the Adobe Creek-Manning Creek Basin. A limited amount of underflow probably enters the basin from the Central Upland and also from Mt. Konocti. Some water may be recharged by infiltration of rain, irrigation, and creek water in areas other than the Kelsey Creek flood plain, but such recharge is greatly inhibited by the clayey subsoil and near surface clay layer.

(1) Kelsey Creek The reach of the Kelsey Creek channel where most infiltration occurs extends from a point 4000 feet south of the old Highway 29 bridge to just north of the last gravel pit toward the lake, a total distance of 13,000 feet. Downstream (north) of this reach, the channel is underlain by a sandy "clay pan" which serves both to inhibit downward percolation of surface water and to confine underlying ground water. In the percolation area, the channel varies from about 200 to 500
feet width. The creek's east bank is stabilized to a greater or lesser extent by slope and bank protection features. Gravel borrow operations are carried out in the channel and in the flood-plain terrace along the creek's west bank in the 9000 feet distance between the old Highway 29 bridge and the center of Section 3. The borrowing has deepened the channel by about 10 feet in the last twenty years, according to reports of pit operators and others familiar with the area. This channel deepening, together with the bank stabilization and channel straightening, has greatly changed the character of stream discharge near Kelseyville. Formerly, the channel was only a few feet below the general level of the plain, and the stream flowed in any, or all, of several courses, which shifted back and forth over an area of up to 1500 feet width. This condition frequently led to flooding of the area around and within Kelseyville, but it also provided a much larger area for the first stages of infiltration from the creek to the aquifers of Kelseyville Basin.

The subsurface character of the channel, as it existed in October 1966, was investigated by excavation, logging, and limited sampling of seventeen backhoe test pits. This investigation showed that the channel contained 6 to more than 14 feet of gravel overlying a layer of sandy to clayey alluvium. The gravel grades to silty sand along the channel margins and in local areas within the main channel. Most of the gravel sections exposed in pit walls contain subhorizontal "open work" zones, although the gravel is fairly sandy in bulk composition. These zones, and the presence of layers of finer grained material, give the channel fill a significantly higher permeability in the horizontal than the vertical direction. Consequently, infiltrated creek water tends to percolate laterally into the flood-plain gravels adjacent to the channel. Percolation to the deeper aquifers within the basin then takes place from the flood-plain gravels. Because of the lateral percolation aspect of the process of ground-water recharge from channel infiltration, removal of gravel from greater depths beneath the present channel surface level could seriously impair the effectiveness of basin recharge by Kelsey Creek by restricting or partially sealing off the hydraulic connection between the channel and the adjacent near surface aquifer gravels.

Measurements made by the California State Department of Water Resources in 1948, 1949, and 1950 indicated losses in the flow of Kelsey Creek between Kelseyville and
Soda Bay Road of 2400 to 3600 acre-feet per month (during months of continuous, mostly heavy flow). This loss represents the amount of water infiltrated into the creek channel and banks. Assuming an average rate of infiltration of 3000 acre-feet per month, and assuming that the channel area in the zone of infiltration was about the same as at present, seventy acres, this figure indicates a percolation rate of roughly 1.5 acre-feet per day per wetted acre of channel. A rough check measurement of flow loss in Kelsey Creek above and below the reach of maximum infiltration, made in November 1966, indicated a percolation rate of 1.7 acre-feet per acre per day. Such amounts are comparable to the lower range of spreading basin recharge rates in other basins in California. The relatively low rate observed for Kelsey Creek probably results from the presence of finer grained material under the channel gravel and the consequent necessity for lateral diffusion of infiltrated water as part of the recharge process.

(2) Relation to Adobe Creek-Manning Creek Basin The "interface" between Adobe Creek-Manning Creek Basin and Kelseyville Basin is roughly 1200 feet wide, if the area northwest of Manning Creek is neglected. The interface extends 70 to 100 feet below the water table to the bottom of the younger fill in the Adobe Creek-Manning Creek Basin. Underflow from this basin occurs mainly from relatively more permeable zones at depths of 25 to 45 feet and 70 to 90 feet. No data are available which would permit determination of the actual quantity of underflow.

d. Ground-Water Movement The general direction of movement of ground water in Kelseyville Basin is northward toward Clear Lake, as shown by the slope and form of the water table and piezometric surface. Under natural, high water-level conditions, flow of ground water in the unconfined zone is radial away from the upper (south) end of the channel infiltration area, down a hydraulic gradient ranging between 20:1 and 40:1. In the confined zone, movement is in response to a pressure gradient caused by the difference in elevation between the water table at the upper, south edge of the confining layer, and the surface of Clear Lake. In the spring, the head difference is 20 to 30 feet. Movement of the confined water is to submerged springs under Clear Lake, where the water enters the lake by effluent flow.
At present, the configuration and elevation of the water table and pressure surface are considerably altered by midsummer, mainly by extensive pumping withdrawal. Ground-water movement in the unconfined zone is still to the north. In the confined zone, however, an east-west aligned shallow trough of reduced pressure is created, with the maximum lowering of piezometric head being in the area north and northwest of Finley. When this condition develops, movement of ground water becomes radial toward the axis or centers of reduced pressure. Normal flow northward to the lake is re-established only after pumping ceases and the trough is eradicated by the gradual restoration of pressure in the area.

The movement of ground water just described occurs principally in the upper 70 feet of the basin, above the persistent "blue clay" horizon. It is probable that natural circulation of ground water in deeper aquifers is limited and that movement may be largely in response to pressure gradients caused by withdrawals through deeper wells. There is, however, no positive evidence to support this view.

e. Changes in Ground-Water Storage  Changes in the volume of ground water stored in the Kelseyville Basin are indicated by fluctuations in the level of the (unconfined) water table. Variations in the piezometric surface in the (confined) pressure area only indicate changes in pressure and are not a direct measure of changes in the volume of stored water.

The volume of the ground within the zone of unconfined water-level fluctuation within the Basin, multiplied by the specific yield of material comprising that ground, represents the minimum change in the amount of stored ground water. In the Kelseyville Basin, the volume of ground within the zone of water level fluctuation is approximately 34,000 acre-feet. The specific yield of this ground is estimated, from well logs, to average 22 percent. The change in volume of stored ground water between times of high and low water levels is therefore a minimum of 7500 acre-feet. This amount, however, represents only the difference in quantity of water stored at one time and is not a measure of the amount of water which passes through the basin during a season. This could be calculated only by determination of the quantity of surface and subsurface
inflow to the basin compared with the volume of outflow and of total extraction, plus the
volume change in storage. Data which would permit determination of this amount are
not available. Elements of information which are lacking are 1) amounts of water re-
charged to Kelsey and Adobe Creek-Manning Creek Basins, and 2) amounts of water
extracted from these basins under current conditions.

f. Operation of the Kelseyville Basin Ground-Water System The
hydraulic system within the basin operates in response to the following variable condi-
tions:

1. Level of unconfined ground water and piezometric surface
(pressure head) of confined ground water.

2. Head difference between water at the interfaces between
Kelseyville Basin and upstream sources of underflow, notably the Adobe Creek-Manning
Creek Basin.

3. Availability of water in the recharge area of the channel of
Kelsey Creek.

4. Head difference between confined water at the lower (north)
margin of the basin and the level of Clear Lake.

No. 1, above, is dependent on the extent to which the basin has been recharged by per-
colation and underflow or drawn down by well pumping and outflow.

The two extremes of these conditions are represented by the time of maximum basin
ground-water filling in the spring, and basin drawdown in mid-autumn.

Spring High Ground Water The water table is at its maximum possible
elevation, being essentially up to the elevation of the bottom of the channel of Kelsey
Creek. The piezometric surface in the pressure zone has recovered to the maximum
elevation permitted by the pressure differential between the water table level at the
upper edge of the capping layer, and the level of Clear Lake. Dynamic equilibrium
exists between inflow and outflow with underflow and percolation into the basin equaling
subsurface outflow to the Lake. Since the water table is at creek channel level, only
as much percolation can occur as is required to maintain a balance as outflow to the lake tends to lower the water table. The remainder of the creek flow is discharged to the lake as surface flow. The amount of underflow from the Adobe Creek-Manning Creek Basin which can enter Kelseyville Basin is similarly restricted. Consequently, the upstream basin stays filled to capacity and the flow of Adobe Creek continues on to Clear Lake also.

Mid-autumn Low Ground Water The water table and piezometric surface in the basin are lowered by amounts ranging from 5 feet around the basin margins to about 25 feet in the area around and northwest of Finley. Water is extracted through wells throughout the basin, and enough wells are pumped at any given time to maintain a broad trough of depression, with deeper local cones of depression, in this area. The small summer flow of Kelsey Creek percolates into the channel, generally in the 4000 foot reach south of the old Highway 29 bridge. Underflow from the Adobe Creek-Manning Creek Basin is at the maximum permitted by the hydraulic gradient between it and the Kelseyville Basin. Outflow from subsurface springs to Clear Lake is probably greatly reduced though it does not cease entirely.

This condition is maintained until the general reduction in pumping occurs at the end of the harvest. Thereafter, there is some recovery of the pressure head in the pressure zone. Recovery probably continues gradually in response to the pressure differential caused by underflow from Adobe Creek-Manning Creek Basin until runoff from the winter rains begins to percolate into the basin.

2. ADOBE CREEK-MANNING CREEK BASIN
   a. Geology Adobe Creek-Manning Creek Basin, in common with its downstream continuation, the Kelseyville Basin, is a lake and alluvial sediment filled structural trough. The basin comprises three areas; 1) the main trough underly-
   ing the channel and flood plain of Adobe Creek, 2) a subsidiary trough underlying the channel and flood plain of Manning Creek, oriented normal to the main trough, and 3) a "shelf" between the Western Upland the Big Valley fault, north of Manning Creek.
The main trough is 80 to 120 feet deep and contains three distinctive horizons; a gravel layer 10 to 20 feet thick at the bottom, a 20 to 40 foot thick clay layer in the middle, at depths of 60 to 100 feet, and an uppermost horizon of mixed alluvial silt and sand with streaks and channels of gravel. These sediments extend into and merge with the fill in Kelseyville Basin.

Some wells in the basin draw water from the "Volcanic ash" aquifer confined in the underlying "Older lake and flood-plain deposits". This aquifer appears to be hydraulically independent of the aquifers in the overlying basin fill.

b. **Recharge** Water is recharged to the Adobe Creek-Manning Creek Basin by percolation from the channels of three major and a number of minor creeks and by underflow from the Western and Central Upland areas. The most favorable areas for percolation are the channels of Highland and Adobe Creeks from below the dam on each creek to the confluence of the two channels, and the channel of Adobe Creek for a distance of 2.3 miles (12,000 feet) below this confluence, and also a half mile reach in the channel of Manning Creek where the creek flows from the mountains into Big Valley.

The subsurface character of the channel of Adobe Creek was investigated by excavation, logging, and partial sampling of nine backhoe test pits. The investigation showed that the channel is quite similar in character to the channel of Kelsey Creek around Kelseyville, with an upper horizon of 10 or more feet of sandy gravel having zones of "open work" gravel, underlain by silt and fine grained sand. The fine grained bottom layer was not encountered in some pits, and so may be discontinuous. Alternatively, it may exist at greater depth than could be reached with the backhoe. At the north end of the wide channel reach, the creek bed changes from a gravel and sand to a sandy clay or clayey sand "clay pan". Test pits in this area showed that the gravel extends under the clayey capping but that the capping increases in thickness downstream.

c. **Ground-Water Movement** Flow of ground water in the Adobe Creek-Manning Creek Basin is to the north in the Adobe Creek trough and to the east
in the Manning Creek trough. The water table in each area is nearly parallel to the
ground surface and slopes down a hydraulic gradient of 15:1 to 20:1. The ground water
flows into and continues flowing within the Kelseyville Basin. This flow pattern continues
throughout the year, with the water table merely being lowered, but not changed in slope
direction, during the summer and autumn.

d. Changes in Ground-Water Storage Nearly all of the Adobe Creek-
Manning Creek Basin is in the free (unconfined) ground-water zone. Only the "shelf"
area, north of the Manning Creek trough, is in the confined, pressure area. Changes
in water level within the basin, therefore, indicate changes in quantity of "stored" water
(or, in the case of this basin, water in transitory storage). The variation in elevation
of the water table between spring and fall ranges from 5 to 30 feet, with 10 feet being
the average for the larger portion of the basin. The difference in volume of water
present in the basin between spring high and mid-autumn low water levels is calculated,
using an estimated specific yield of 15 percent for material in the zone of fluctuation,
to be approximately 6700 acre-feet.

e. Operation of the Adobe Creek-Manning Creek Ground-Water System
The hydraulic ground-water system within this basin operates in response to the following
variable conditions: 1. Level of the water table.

2. Level of unconfined ground water and of the piezometric sur-
face in Kelseyville Basin, at the interface between the two basins.

3. Availability of water in the creek channel recharge areas.

4. Amount of underflow from adjacent areas.

Item No. 1 is dependent, as in the case of Kelseyville Basin, on the extent to which the
basin has been recharged by percolation and underflow, or drawn down by well pumping
and outflow.

The hydraulic operation of the basin can most easily be described starting from a condi-
tion of a lowered water table. Normally, flow in Highland and upper Adobe Creeks, as
released from the reservoirs on these creeks, is quite small when ground-water levels are low. The entire flow of each creek percolates into the channel gravels in the reach around and above the confluence of the two creeks. This water joins with the basin ground-water body and flows northward, down the hydraulic gradient.

When extraction by pumping drops off and losses to evapotranspiration are reduced after mid-autumn, the water table rises somewhat, but the recharge-flow system just described continues. However, when Adobe Creek begins to flow more or less continuously, the water table rises to the level of the bottom of the channel, whereupon the basin is essentially filled to capacity. Thereafter, the level of the ground water in the basin is maintained by underflow from adjacent areas and by very limited percolation in the uppermost reach of the main creek channel. About midway down the length of the basin, the water table intersects and then rises slightly above the level of the channel bottom. Below this zone of intersection, ground water seeps into the channel and escapes as surface flow, rather than being recharged from surface flow. This was demonstrated by the comparative creek flow measurements made by the California State Department of Water Resources in 1948, 1949, and 1950. After the first few weeks of flow, the quantity of flow measured near the downstream end of the basin exceeded the quantity measured at Bell Hill Road, near the upstream end, although no significant tributaries discharge into the creek along this reach. The observed excess must have been derived from effluent ground-water discharge into the creek.

3. WESTERN UPLAND

The "Western Upland" is a sloping, partially dissected, one-half to one mile wide topographic bench along the western margin of Big Valley. The upland is underlain by older terrace deposits, resting on older flood-plain and lake deposits. The "Volcanic ash" layer is confined within the fine grained flood-plain and lake deposits but is not known to crop out at the surface. Projection of intercepts of the "ash" layer indicates that it and its enclosing strata dip toward the east and north with an inclination of about 1 to 2 degrees. Wells in the Western Upland extract ground water from the "volcanic ash" and, near Manning Creek, from a gravel lens in the terrace deposits.
Logs of wells situated in the area adjacent to Manning Creek report encountering roughly 20 to 40 feet of water-bearing gravel at depths of 5 to 40 feet. This gravel is probably a buried alluvial fan or flood-plain deposit laid down at an earlier time by the ancestral Manning Creek. Wells further south, away from this creek, encounter only fine grained materials. The gravels constitute the only known aquifer, other than the "Volcanic ash", in the deposits underlying the Western Upland. The gravel may be in hydraulic communication with the saturated alluvial fill under the channel of Manning Creek, since fluctuations of the water level in Section 7 correspond to fluctuations of the water table in the Manning Creek basin. Recharge of the gravel, therefore, probably occurs by lateral flow from the basin ground-water body. The only available data indicates a specific capacity of only 1.25 gpm per foot of drawdown for a well drawing from this aquifer.

The characteristics and ground-water system of the "Volcanic ash" aquifer are discussed in Section 5 of this chapter.

4. CENTRAL UPLAND AND UPPER BIG VALLEY

The Central Upland-Upper Big Valley area is geologically similar to the Western Upland but is separated from it topographically by the Adobe Creek flood plain, and structurally by the Adobe Creek Fault system. The Big Valley Fault forms the northern boundary of the area, separating it from the Kelseyville Basin. The east and southeast margin of the Central Upland abuts against Mt. Konocti and the Volcanic Ridge, or grades to the higher Cole Creek Upland. The area is characterized at its northern end by broad, gently sloping surfaces which give way to hills and ravines to the south. The Central Upland is underlain by "Older terrace deposits" and by the semi-consolidated siltstone-claystone, and fine grained sandstone of the "Older flood-plain and lake deposits". The continuity of geologic structure (and ground-water regimen) is interrupted by the Wight Way Fault and by another fault which extend across the central portion of the area and bound a block of relatively younger sediment which is faulted down into the "Older flood-plain and lake deposits" unit.

The northern portion of the Central Upland is underlain by materials of the upper member
of the "Older flood-plain and lake deposits" unit. Well logs indicate 10 to 40 feet of "soil" and "brown clay" directly beneath the surface, and then sand or sand and gravel on down to depths of 63 to 104 feet. The sand and gravel zone is partially saturated and yields some water to wells. The "Volcanic ash" layer is enclosed in the fine grained material of the lower member of the "Older flood-plain and lake deposits" at depths of 100 to 130 feet beneath the base of the sand and gravel horizon at about 80 to more than 240 feet below the ground surface.

The down-faulted block across Sections 27, 28, and 29 is underlain by "Upland terrace deposits" at least to depths of 110 to 144 feet. The lower portion of this unit consists of as much as 90 feet of sand or sand and gravel, which is partially water saturated. Wells penetrating this section bottom in "blue clay" or "blue hard pan" which is probably the "Older flood-plain and lake deposits" unit.

South of the Wight Way Fault, in the area here referred to as Upper Big Valley, materials of the "Older flood-plain and lake deposits" unit are exposed at the surface. Logs of wells in this area report clayey materials down to shale or volcanic rock. Wells for which pumping test data are available have very low yields unless they draw from the underlying volcanic rock.

The upper sand and gravel horizon under the northern portion of the Central Upland is recharged by slow downward percolation of infiltrated rain, irrigation, and runoff water. Seasonal fluctuations in the level of the ground-water body in this aquifer probably result from drawdown by pumping during the irrigation season, followed by recovery and some recharge during the wet season.

The sand and gravel at the base of the Upland terrace deposits in the fault block in Sections 27, 28, and 29 must also be recharged to some extent by downward percolation of rain water. However, the channels of several drainage courses are incised into this unit so it probably receives much of its recharged water by percolation from these channels during times of runoff. The aquifer may be in partial hydraulic communication
with the ground-water body of the upper Adobe Creek basin, but, having a higher water
table, would tend to discharge to rather than be recharged by this ground water. The
"Volcanic ash" aquifer is discussed in Section 5 of this chapter.

5. "VOLCANIC ASH" AQUIFER
   a. General. The "Volcanic ash" aquifer is a thin bed of lithic tuff,
      confined within the older semiconsolidated sediments, which underlies the northern por-
      tion of the Central Upland and most of the Western Upland and the Adobe Creek-Manning
      Creek Basin. The "ash" layer contains ground water under artesian pressure and yields
      water to wells located at various places throughout much of the upland areas. Available
      evidence indicates that the aquifer is offset by the Adobe Creek fault system, and so
      occurs as two hydraulically independent units.

      The distribution and characteristics of the "ash" are described in Appendix D, pages
      D-5 and D-6 of this report. In discussing its character as an aquifer, the "Volcanic
      ash" is considered to have an average thickness of 2 feet. The underlying "mixed" clay
      or silt and ash layer is 3 feet in thickness in the Central Upland area and 2 feet in thick-
      ness in the area west of the Adobe Creek fault system.

   b. Geology. In the Central Upland area, the ash layer lies at depths
      of 130 to more than 230 feet beneath the ground surface, except along the area's east
      margin, under Kelsey Creek. There, the layer is warped (or possibly faulted) up to
      crop out at two places in the bed of Kelsey Creek, and is encountered by wells at depths
      of 78 and 107 feet in Section 23.

      The ash layer is tilted down to the northeast in the area west of the Adobe Creek fault.
      Its depth increases from a projected outcrop under the Adobe Creek basin fill in the
      vicinity of the Bell Hill Road crossing, to maximum of 230 feet, where it is intercepted
      by a well in Section 15. The layer probably continues to the north to greater depths in
      this area, but no positive evidence of this is presently available.
Ground water contained within the "Volcanic ash" aquifer is under pressure, with pressure heads of 100 to 150 feet being reported from initial water intercept data by well drillers, and from measured water levels in wells which are perforated only where they intersect the "ash". The piezometric head reported from a well located near the north end of the Central Upland is only slightly above the level of the water table in the adjacent basin, however, which suggests that the aquifer is in hydraulic communication with, and discharges into the free ground water in the basin fill.

c. **Ground-water Recharge**  Under natural conditions, the aquifer is recharged by infiltration of surface water or of overlying ground water into the volcanic ash layer where it crops out from its enclosing strata. Some water also enters the aquifer by flow from the adjacent saturated, but only slightly permeable, fine grained sediments. Probably much of the water derived from such "leakage" into the confined aquifer is transmitted through fractures rather than by intergranular flow.

d. **Ground-water Movement**  Flow within the aquifer is from areas of higher pressure, such as up-dip outcrop infiltration areas, to areas of lower pressure such as zones of outflow into lower level free ground-water bodies. Diversions to or interruptions of intra-aquifer flow could result from constrictions, or offsets, caused by thinning, warping, or faulting of the volcanic ash layer. The only known offset is along the northwest side of the Central Upland, where the Adobe Creek fault drops the aquifer down some 180 feet on the Adobe Creek side. Since the "ash" layer is only a few feet thick, even relatively minor fault displacement would completely offset the aquifer and break hydraulic continuity across the fault. The apparent continuity of piezometric head within the aquifer suggests, however, that it is not displaced within the areas on either side of the Adobe Creek fault.

When water is withdrawn from a confined aquifer through a well, the naturally existing pressure and flow conditions in the aquifer are disturbed. Before pumping, water in an aquifer within which a regional pressure gradient exists has a tendency to flow in the direction of decreasing pressure. Also, in any small area, there is approximate
static (pressure) equilibrium, or steady state seepage conditions, resulting from a pressure differential between the water in the aquifer and the pore or fracture water in the confining sediments. As soon as water is pumped from the well, however, a local pressure gradient is created with a low pressure zone being formed around the well. Water in the aquifer then moves radially toward the zone of reduced pressure. Additionally, the local pressure gradient causes some water to be forced from the pore space in the saturated confining, fine grained sediments and to move into the aquifer. This is illustrated diagrammatically in Figure 5, A and B. In some aquifers, the aquifer material is compressed because of the reduction in supporting pore-water pressure, and additional water is forced out; but tests indicate that the "volcanic ash" is only slightly compressed when subjected to confining pressures approximating those in Big Valley, so compression of the aquifer consequent on reduction of water pressure is probably of very small magnitude. On the other hand, the relatively good yield (considering the thinness of the aquifer) of many of the wells drawing from the volcanic ash, contrasted with the probably limited direct recharge of the aquifer, suggests that quite appreciable amounts of water may enter it by flow from the saturated confining sediments in response to local pressure differentials. It is theoretically possible to determine what fraction of the water produced by a well is derived from "leakage" into the aquifer, by obtaining data from a careful pumping-drawdown test with measurement of decline of piezometric head in a nearby observation well, and application of mathematical analysis to the data. Such an operation, however, is beyond the scope of this investigation.

e. **Yield to Wells** Pumping tests of wells drawing from the "volcanic ash" aquifer report yields of 35 to 1000 gallons per minute, with drawdowns of 1 to 30 feet. Indicated specific capacities of wells range from 11 to 140 gallons per foot of drawdown.

f. **Ground-water Storage and Availability** Calculations of the volume of water actually contained within the "ash" and "mixed ash" layer, using the porosity of the ash determined in the laboratory, and an assumed lesser porosity for the mixed material, indicate that approximately 21,000 acre-feet of water is stored in the aquifer.
under the Central Upland, and a minimum of 10,500 acre feet is stored under the Western Upland and Adobe Creek-Manning Creek Basins. This is the approximate amount of water contained within the intergranular pore space in the aquifers, rather than the amount available for pumping by wells. That amount could be determined only by working out the "formation constants" ("S", the "storage coefficient", indicating the amount of water in storage released from a column of aquifer with unit cross section with unit decline of head; and "T", the "transmissivity, defined by the hydraulic conductivity multiplied by the aquifer thickness and the "leakage factor", the quantity of water that flows across a unit area of the boundary between the main aquifer and its semiconfining bed, if the difference between the head in the aquifer and that of the "leakage" water is unity), from mathematical analysis of drawdown and observation well test data.

6. COLE CREEK UPLAND

No direct information relating either to subsurface conditions or to groundwater conditions in the Cole Creek Upland is presently available. The following discussion, consequently, is based on inference and geologic projection.

The lower, main portion of the Cole Creek Upland is underlain by the "Older flood-plain and lake deposits" unit. Excellent exposures of the upper member of this unit may be seen in the road cuts for Highway 29 southeast of Kelseyville. It is possible that the "Volcanic ash" layer may extend under the area within the lower member of the "Older flood-plain and lake deposits", but no evidence for this is available.

Ground-water occurrence in this subunit is probably similar to that in the northern Central Upland, with a saturated zone in the more permeable horizons of the "Older flood-plain and lake deposits". Water would be recharged to this zone by downward percolation of infiltrated rain water, by percolation from the channel of Cole Creek and, probably, by underflow from the bordering volcanic hills. Some shallow ground water also is contained in the alluvial fill under Cole Creek in Sections 25 and 36. Water could leave the subunit by limited underflow to the Central Upland or by effluent flow through the rock of the lower slope of Mt. Konocci back into Cole Creek in Section 23.
7. VOLCANIC RIDGE

The Volcanic Ridge (Camelback Ridge) is an elongate composite volcano, composed of fine to coarse grained pyroclastic deposits with intercalated thin lava flows and masses of intrusive lava. The surface of the higher part of the ridge is covered by a well preserved flow of obsidian breccia. Most of these materials are highly permeable, either through intergranular permeability or through jointing and fracturing in the flow and intrusive lava rock.

Ground water is contained in some zones in the ridge where barriers of reduced permeability impede outflow. Recharge is entirely through infiltration of rainfall. This is quite effective because a very high percentage of the water which falls on the ridge surface infiltrates immediately, or after a short time and brief surface flow. Percolation occurs so rapidly that surface drainage courses are poorly developed or nonexistent over much of the ridge's area. Where no internal barriers to ground-water flow are present, much of the percolating water is rapidly discharged from temporary springs along the lower margin of the ridge. An internally eroded cavernous opening along Kelsey Creek probably was formed by episodes of rapid outflow following periods of heavy percolation. A spring consisting of a zone of seepage several hundred feet long along the base of the ridge in the northeast $\frac{1}{4}$ of Section 2 (T12N, R9W), reportedly flows year round. This spring contributes a small, but appreciable fraction of the flow of Kelsey Creek during the summer months. The ridge may also contribute water to the Cole Creek Upland subunit by underflow.

Two wells are known to tap ground water from the volcanic rocks. One of these wells, at least, reportedly yields water very high in iron.

8. MOUNT KONOCTI

Mount Konocti, like the Volcanic Ridge, is a composite volcano, made up of alternating layers, or series of layers, of pyroclastic and flow rock. Rain water infiltrates into the surface of the mountain and percolates downward through zones of higher permeability. Much of this water escapes through springs in the vicinity of
Soda Bay, outside the Big Valley area. Water from these springs contains considerable boron which is probably derived from mixing of infiltrated rain water and mineral-bearing thermal water within the volcanic pile. It is probable that underflow of similarly contaminated high-boron water from Mt. Konocti to the aquifers of the Kelseyville Basin causes the local high-boron content of ground water from some wells near the mountain.

9. MAYACMAS MOUNTAINS

The Mayacmas Mountains are underlain by metasedimentary rocks and, locally, by intrusive masses of serpentine and ultrabasic rock. None of these rocks possesses significant primary permeability, but they are all fractured to a greater or lesser extent, and so have some degree of secondary permeability.

Water enters the rocks through infiltration of rain water and percolation from the upper reaches of creeks. The water is stored in or passes through fracture zones, and finally seeps out as effluent flow to the lower reaches of creeks within the mountains, or as underflow to the adjacent basins. Mineralized water, some of which may have risen from a source at depth, emerges from springs where the Wight Way Fault extends into the mountains.

C. GROUND-WATER QUALITY

1. GENERAL

The chemical character or "quality" of ground water is dependent, generally, on the quality of water which recharges the ground-water system, on the character of materials within which the ground water travels or is stored and on particular natural conditions or human activities which give rise to a contribution of chemical or bacterial constituents to the water.

Water in the ground-water systems of Big Valley is principally supplied by runoff from the watersheds of Kelsey, Adobe, Highland, and Manning Creeks. This water originates in largely uninhabited mountainous terrain comprised of metamorphic and igneous rocks. The water is of good quality for irrigation, food processing, and domestic uses.
Some additional water is supplied to the ground water by direct infiltration of rain and of irrigation water in Big Valley. This water is also of good quality except in cases where the water is pumped from Clear Lake or from wells producing water of inferior quality. Irrigation water, however, may be modified in quality by contact with chemical or natural fertilizer materials.

Finally, water enters the Big Valley ground-water system by subsurface flow from the surrounding highlands and also, apparently, from buried springs rising beneath the basin-filling sediments. Much of this water is also of good quality, but some, notably that originating as underflow from Mt. Konocti and as rising spring water, has a relatively high mineral content.

Much data on the chemical composition of both ground and surface water in the Big Valley area has been obtained during investigations by the California State Department of Water Resources and by the California Agriculture Extension Service. DWR Bulletin No. 14, "Lake County Investigation" presents complete mineral analyses of numerous samples of ground water from Big Valley and also of samples of water from other areas around Clear Lake. This body of data is particularly useful in that it permits comparison of the general compositions of ground and surface waters in differing areas and geologic regimens.

The typical ground water of Big Valley, from the Kelseyville and Adobe Creek-Manning Creek basins, possesses a distinctive composition which differs somewhat from the composition of ground water and surface water from other areas around Clear Lake, and from the water of Clear Lake itself. The principal mineral constituents of Big Valley ground water are magnesium, calcium, and bicarbonate. Sodium is always present, but in amounts subordinate to calcium. Chloride and sulfate are also present but are greatly subordinate to bicarbonate. The distinctive characteristic of Big Valley water is the magnesium to calcium ratio. In most ground water, calcium is present in appreciably greater concentration than magnesium; but in Big Valley, the absolute concentration of magnesium is equal to or greater than that of calcium. In terms of
chemical equivalents, the magnesium to calcium ratio ranges from 1.5:1 to 3:1.

The amount of total dissolved solids (TDS) in most Big Valley ground water ranges from 350 ppm to 1200 ppm, averaging 400 to 500 ppm.

The presence of boron in water from some wells in Big Valley in concentrations high enough to be potentially injurious to crops has long been a matter of concern. The water analysis data in DWR Bulletin 14 show that there is generally a moderate (0.10-.67 ppm) amount of boron present in ground water throughout Big Valley. Additionally, water from a number of individual wells contained concentrations of 0.67-2.50 ppm boron, and one well yielded water containing 7.28 ppm boron.

Standards relating boron concentration to suitability of water for irrigation purposes, as set forth in the United States Department of Agriculture Technical Bulletin No. 962, are presented in the following table.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Grade</th>
<th>Sensitive crops</th>
<th>Semitolerant crops</th>
<th>Tolerant crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Excellent</td>
<td>less than 0.33</td>
<td>less than 0.67</td>
<td>less than 1.60</td>
</tr>
<tr>
<td>2</td>
<td>Good</td>
<td>0.33 to 0.67</td>
<td>0.67 to 1.33</td>
<td>1.00 to 2.00</td>
</tr>
<tr>
<td>3</td>
<td>Permissible</td>
<td>0.67 to 1.00</td>
<td>1.33 to 2.00</td>
<td>2.00 to 3.00</td>
</tr>
<tr>
<td>4</td>
<td>Doubtful</td>
<td>1.00 to 1.25</td>
<td>2.00 to 2.50</td>
<td>3.00 to 3.75</td>
</tr>
<tr>
<td>5</td>
<td>Unsuitable</td>
<td>greater than 1.25</td>
<td>greater than 2.50</td>
<td>greater than 3.75</td>
</tr>
</tbody>
</table>

However, it should be noted that the effect on a crop of irrigation water containing boron is dependent on a number of factors besides the boron concentration in the water. The more important factors include the sensitivity of the plant to boron, the character of the soil, the amount of irrigation, and the weather or conditions of evapotranspiration. The effect of a given concentration of boron will be less, ordinarily, if the soil is free draining, and if evapotranspiration is not high. Heavy application of irrigation will tend to
leach boron and prevent a buildup of its concentration in free draining soil, but will tend to cause it to accumulate in a poorly draining soil.

Most wells in Big Valley yield water containing less than 0.30 ppm boron. Areas may be identified, however, where several wells produce water with 0.60 ppm or more boron content. Comparative analyses made in the spring and fall indicate that the wells usually but not invariably produce water containing a higher boron concentration in the fall, when water levels are lower and the wells draw from deeper in the aquifer. Also, analyses were made by the Agricultural Extension Service of water drawn from two depths in a well (13/9-12D(2) near Mt. Konocti. The boron content of water from 210 feet depth was 0.32 ppm while it was 1.03 ppm in water from 247 feet depth.

Damage to plants resulting from irrigation with high-boron water has been reported from only a few local areas in Big Valley. This seems to bear out the indication from water analyses that high boron concentrations occur only in a few specific areas and that there is no general stratum or horizon of high-boron water.

2. RELATION OF WATER QUALITY TO GEOLOGY IN BIG VALLEY

Geologic conditions in Big Valley and in the watershed areas of the streams which flow into it largely determine the chemical quality of ground water in the Valley's aquifers. Four principal determining conditions may be recognized: 1) The nature of rock, soil, and springs in the watershed of the streams which flow into Big Valley. This determines the character of surface and underflow water entering Big Valley. 2) Distribution of aquifer materials, capping layers, and other elements comprising the framework of the ground-water system in Big Valley. This determines the paths followed by surface water in gaining, or being denied, access to the ground-water system, and to some extent, the course of migration of water within the system. 3) The nature of materials comprising and adjacent to aquifers. This is important in determining what constituents may be added to (or removed from) ground water; and 4) Special geologic or other conditions which give rise to contributions of mineral or other constituents to the ground water. The occurrence of subsurface high-boron springs in the Valley can be considered to be in this category.
The conditions enumerated above are discussed in turn:

a. Geologic Conditions in Watershed Areas  The watersheds of Kelsey, Adobe, Highland, and Manning Creeks are mountainous areas underlain by metamorphic and igneous rocks. Some volcanic and sedimentary rocks are also present in the lower watershed area of Kelsey Creek. The predominant bedrock material in these areas is the Franciscan Formation consisting mainly of greywacke sandstone, chert, and shale. All these rock types are composed of quartz, clay, carbonates, and silicate minerals. Decomposition and solution of these rocks probably yields most of the calcium, sodium, and bicarbonate observed in the water of Kelsey and Adobe Creeks. However, large quantities of serpentine and serpentinized peridotite also occur in these mountains, particularly in the watershed of Kelsey Creek. Minerals of the serpentine group are hydrous magnesium silicates, often also containing iron and aluminum, and solution of the serpentine and its weathering products gives rise to a magnesium-rich water. The serpentine, then, is the source of the relatively high magnesium concentrations and the unusual magnesium to calcium ratio present both in the water of Kelsey and Adobe Creeks and also in the ground water of Big Valley.

The sedimentary rocks in the watershed of Kelsey Creek are not known to contribute significant constituents to water other than the common mineral constituents which are also derived from the Franciscan Formation rocks. Locally, the volcanic rocks yield water containing unusually high concentrations of iron.

b. Geologic Factors Governing Recharge and Movement of Ground Water

A feature of the Big Valley ground-water system is that it is mainly recharged by percolation from creek channels and by underflow from higher ground water. The presence of near surface clay layers over most of the agriculturally developed portions of the Valley greatly inhibits direct downward infiltration of irrigation or waste water, or of rainfall. Contamination of the ground water by fertilizer or sewage is therefore greatly restricted, and probably occurs on only a small scale in local areas.

The continuous flow of ground water in the aquifers of Big Valley tends to dilute and
disperse any unusual constituents which are introduced into the ground water, either from downward percolation, from underflow, or from subsurface spring discharge.

c. Materials in the Ground-Water Systems of Big Valley  The aquifers of the Big Valley ground-water system are generally made up of relatively non-reactive, chemically stable materials, so water passing through or stored within them is not greatly affected chemically. However, comparison of analyses of water from Kelsey and Adobe Creeks with analyses of ground water from wells shows increases in the content of mineral constituents in the ground water, which indicates that some material is taken into solution by the circulating ground water. The composition of water is more strongly affected where iron-rich materials in or adjacent to aquifers is oxidized and partially dissolved, giving a locally high iron content to the ground water and where buried organic matter is incorporated in the aquifer system. Among the products of the decomposition of organic material are the gases carbon dioxide, methane, and ammonia, and appreciable quantities of these gases may be dissolved in ground water which circulates through areas of gas formation or accumulation. No specific data on the presence of these gases are available, since carbon dioxide (CO₂) is reported with bicarbonate (HCO₃⁻) in water analyses, and methane is not reported. Ammonia is not reported, but one of its oxidation products is nitrate. Some of the nitrate shown in analyses may therefore be derived from decomposition of organic material in the aquifers. Dissolved carbon dioxide probably causes the slightly acidic character of some ground water. Methane is discharged from springs emerging from near shore areas in Clear Lake.

The volcanic ash aquifer is composed of relatively nonreactive fragments and particles of volcanic rock. The high iron content of water from Well 13N/9W-27B(1), which draws from this aquifer near its outcrop, is probably derived from iron-cemented zones in sandstone adjacent to the ash layer.

High iron content is reported from Well 13N/9W-27K(1) which draws from the rocks of the volcanic ridge, near Kelsey Creek. The source of this iron is not known, but is doubtless within the volcanic material.
d. Special Geologic Conditions  The presence of a moderate concentration of boron throughout the ground water of Big Valley and of local higher concentrations of this element is due, ultimately, to the existence of the Clear Lake volcanic field. Boron is one of the notable constituents of thermal water associated with remnant volcanic activity in this area. The question is, then, how the boron is introduced into and distributed within the ground water in Big Valley.

Locations of wells which are known to have produced water containing 0.60 ppm or greater concentration of boron are indicated on Plates II and V of this report. The plot shows a group of high-boron wells in the area adjacent to Mt. Konocti and other groups of wells and individual wells at various places in the Valley. Some of these appear to be randomly located, but several are situated along or near the buried trace of the Big Valley fault. Data on boron content of waters from these wells are presented in Table B.

The location of isolated high-boron wells in relation to alignments of suspected buried fault breaks suggests the possibility that some of the boron comes from subsurface springs which rise at various places along the faults. If this is the case, the high-boron spring water apparently becomes diluted by mixing with ground water, so relatively high boron concentrations are found only in wells drawing water from the vicinity of the subsurface springs.

The general occurrence of high-boron water in wells located adjacent to Mt. Konocti (together with the known occurrence of boron-rich springs issuing from the other side of the mountain) suggests that ground water in that area is mixed with boron-contaminated underflow from aquifers within the mountain. Strata from which water contaminated either by rising spring water or by underflow from Mt. Konocti is withdrawn are of varying extent and continuity but are interconnected with other water-bearing strata in the basins. Mixing of water within this system of interconnected strata serves both to dilute the higher-boron water away from its immediate area of inflow and to maintain the general moderate (0.05-0.67 ppm) boron content of ground water in the basin.
<table>
<thead>
<tr>
<th>Well No.</th>
<th>Date of Analysis</th>
<th>Boron Content (in ppm)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>T14N/R9W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31N1</td>
<td>8/8/52</td>
<td>0.92</td>
<td>Well 70 ft. deep; perforated 0-68 ft.</td>
</tr>
<tr>
<td>21P1</td>
<td>8/13/49</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>31Q1</td>
<td>6/5/45</td>
<td>0.72</td>
<td>Well 107 ft. deep.</td>
</tr>
<tr>
<td>T13N/R9W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1N1</td>
<td>9/18/47</td>
<td>2.48</td>
<td></td>
</tr>
<tr>
<td>2F1</td>
<td>(D3605*)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>4D1</td>
<td>8/8/52</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>(D3121*)</td>
<td>1960</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4M(1)</td>
<td>(W-636*)</td>
<td>12.9</td>
<td>Well completed 1961, 57 ft. deep; perforated 37-57 ft.</td>
</tr>
<tr>
<td></td>
<td>1962</td>
<td>6.9</td>
<td>Well cased to 91 ft; perforated bottom 15 ft., and alternating 4 ft. intervals above.</td>
</tr>
<tr>
<td>6C1</td>
<td>9/3/58</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6/12/62</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>6H1, 2</td>
<td></td>
<td></td>
<td>Reported &quot;high&quot;</td>
</tr>
<tr>
<td>8N1</td>
<td>6/27/49</td>
<td>1.80</td>
<td></td>
</tr>
<tr>
<td>8N2</td>
<td>8/8/52</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td>10H(4)</td>
<td>6/13/62</td>
<td>2.7</td>
<td>Well 548 ft. deep. Reported hard water, about 1.0 ppm boron in Fall, temp. above 70°, no boron in Spring, temp. cold.</td>
</tr>
<tr>
<td>11Q(2)</td>
<td>(W464*)</td>
<td>1962</td>
<td>0.76</td>
</tr>
<tr>
<td>12D(2)</td>
<td>(D3272*)</td>
<td>1960</td>
<td>0.32 at 210 ft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.03 at 247 ft.</td>
</tr>
<tr>
<td>12M1</td>
<td>3/24/48</td>
<td>0.92</td>
<td>Other analyses 1958-1962, .55 to .71 ppm boron.</td>
</tr>
<tr>
<td></td>
<td>8/8/52</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>14F1</td>
<td>11/17/48</td>
<td>7.28</td>
<td></td>
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<tr>
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<td>8/8/52</td>
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<td></td>
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<tr>
<td>14N(1)</td>
<td>(W96*)</td>
<td>1962</td>
<td>2.3</td>
</tr>
<tr>
<td>16D1</td>
<td>1957-1962</td>
<td>.53-.69</td>
<td></td>
</tr>
</tbody>
</table>

(*) Number used for analysis by Lake County Farm Advisor’s Office.

Note: Data from California State D.W.R. and U. C. Agriculture Extension Service Farm Advisor's office.
It has been suggested that the construction and operation of wells drawing partially or wholly from aquifers yielding boron-rich water might give rise to contamination of other ground water, which presently has low or moderate boron content. Two possible mechanisms for this are: 1) Where a well serves to interconnect aquifers at different levels (by providing a conduit through intervening strata of low permeability), boron-rich water from a particular level might enter the well, or be conducted in the space between the well casing and the walls of the well hole, and thus gain access to and flow into another level, with resultant contamination of the ground water at that level; and 2) Where boron-rich well water from a deep aquifer is used for irrigation and then percolates to and contaminates a shallow aquifer.

For the first mechanism to be of significance, three conditions are necessary: 1) The well and/or the space around it should permit flow of a relatively large volume of water from one level to another; 2) Water in the boron-rich level should be under appreciably greater head than the water at other levels; and 3) There should be a considerable difference in boron concentration between the boron-rich water and the other water.

In the case of the second mechanism, significant contamination of shallow ground water could occur if a large volume of boron-rich irrigation water percolated freely to the water table.

In Big Valley, it is unlikely that large scale mixing of boron-rich ground water with the ground water of average composition occurs other than by natural diffusion and mixing. For the mechanism of mixing by intercommunication of strata through wells, two considerations mitigate against contamination: 1) Boron-rich water seems usually to come from deeper aquifers, and the head in these aquifers is not known to be significantly higher than the head in overlying aquifers, relative to the depth of each; and 2) The boron content of most of the "high-boron" well waters is still low enough (commonly less than 2 ppm) that dilution factors of as little as two to four times would reduce this content to the general level of ground water in Big Valley.

Contamination of shallow ground water by percolation of high-boron irrigation water is
not likely to occur in Big Valley because there is relatively little percolation of surface water to the ground water except from the creek channels, especially in the areas where most high-boron water producing wells are located and, again, because typical "high-boron" ground water in Big Valley still contains relatively little boron.

3. **EFFECT OF RECHARGE OPERATIONS ON GROUND-WATER QUALITY**

The effect of recharge operations on the quality of ground water in Big Valley will, naturally, be largely dependent on the quality of the water used for recharge. For the purposes of this discussion, it will be assumed that the recharge water will be equivalent in quality to the water of Kelsey and Adobe Creeks. This water is chemically similar to, but of lower mineral content than, the average ground water of Big Valley. It contains 0.10 ppm or less boron.

Under the system of recharge envisioned in this report, water would be percolated from the appropriate reaches of the channels of Kelsey and Adobe Creeks, during times of heavy pumping, into the upper aquifers of Kelseyville and Adobe Creek-Manning Creek basins. This would result in maintenance of higher water levels in the basins throughout the dry season. In effect, water would be constantly circulated from the percolation areas to the wells drawing from the basin. More water of better mineral quality (lower mineral concentration) would therefore be introduced into the basins, and the ground water would be maintained at higher levels. Wells would therefore pump a higher percentage of the upper, better quality water throughout the season. Additionally, the increased circulation of better quality water in the Valley's aquifers should tend to dilute the ground water having a higher mineral content.

Maintenance of higher water levels should tend to decrease the amount of underflow to the Kelseyville basin from Mt. Konocti. This could serve both to reduce inflow of high-boron water from this source and to dilute the ground water, thereby further reducing boron concentration in the area.

Where wells draw ground water in proximity to subsurface boron-rich springs,
concentration of boron in water from these wells would be reduced by maintenance of higher water levels, if the well casings are perforated in the present zone of groundwater level fluctuation.
VI. GROUND-WATER RECHARGE

A. GENERAL

The feasibility of introducing water into any portion of the ground-water system in Big Valley for purposes of replenishing or supplementing the existing supply is dependent on three general conditions: 1) the geology of the portion of the system to be recharged; 2) technical, economic, and legal factors related to the recharge scheme; and 3) availability of water for recharging. These are discussed briefly in turn.

1. GEOLOGY

This is the fundamental condition which determines the feasibility of recharge operations. Of primary importance are the extent and hydraulic conductivity or transmissivity of and the availability of storage space within the underground reservoir or aquifer system. Thus, the system to be recharged should be extensive enough and possess high enough hydraulic conductivity or transmissivity to continuously conduct significant amounts of water away from its area of introduction and into an appreciable portion of the volume of the reservoir. Extent may be limited by a condition of an initially small body of reservoir material or by discontinuities or impermeable barriers in the system. Hydraulic conductivity or transmissivity depends on the primary and/or secondary permeability of the reservoir material and on the dimensions of the system. Zones or planes of reduced permeability in the system will reduce its transmissivity.

The availability of storage space is of particular importance in the unconfined basin aquifers of Big Valley, for these aquifers directly underlie the surface soil zone and are in more or less direct hydraulic communication with the channel alluvium in portions of the principal creeks of the area. This facilitates recharge of the ground water in the aquifer but also imposes a positive limit on their capacity to store water, for any rise in the water table above the level of the creek channels results in effluent discharge into the channels and escape of the water as surface creek flow.

In the case of confined aquifers, the question of availability of storage space applies
only if the aquifer, or a portion of it, is actually unsaturated. However, all significant confined aquifers in Big Valley are saturated, under existing conditions. Water introduced into these aquifers will displace water already contained in them, if the newly introduced water is under higher pressure than that in the aquifer, by increasing outflow from the aquifer elsewhere, by forcing water from the aquifer into the porous but only slightly permeable adjacent confining strata, or by lifting these strata away from the aquifer. Only in the latter ways is "storage" increased in a saturated confined aquifer.

2. TECHNICAL AND ECONOMIC FACTORS

Factors of this class which affect the feasibility of carrying out any given recharge operation include the cost of obtaining right of way for, and of constructing, operating, and maintaining facilities to effect recharge, balanced against the value of benefits derived from this recharge. Most of the recharge program in Big Valley can be accomplished using only the existing channels of Kelsey and Adobe Creek, but construction and use of infiltration ditches and basins, and also of recharge injection wells, is technically feasible. The value of benefits includes the value of water made available for beneficial use and/or of reduced pumping lifts, and also, in some instances, the savings which could be realized by developing ground-water supplies instead of constructing expensive surface diversion facilities.

3. AVAILABILITY OF WATER FOR RECHARGE

Under existing conditions, water is available for supplementary recharge in Big Valley only during the late winter and spring when natural recharge of the basin aquifers is occurring and these aquifers are filled to capacity. Also, most of this water is available only in the channels of the principal creeks. However, technically, water in sufficient amounts to fulfill all possible recharge requirements can be made available anywhere in the basin, at any time of the year, if appropriate retention and diversion facilities are constructed. The water could be obtained either by management of runoff of Kelsey Creek or, possibly, from water being diverted through Clear Lake as part of some future large scale water development project.
Since a supply of water which can be used for recharge operations does exist, the question of water availability reduces to one of economics; i.e., the cost of carrying out the operations necessary to make this water available when and where it is required.

B. KELSEYVILLE BASIN

Under existing conditions, Kelseyville basin is recharged naturally through lateral and downward percolation of water infiltrated into a portion of the channel of Kelsey Creek and by underflow from upstream aquifers and basins. The natural recharge process is sufficiently effective to refill the estimated 7500 acre-feet of storage space which is available in the unconfined aquifer zone in the basin in two to three months' time, when Kelsey Creek begins to flow the length of the percolation zone in its channel, and the water levels in the Adobe Creek-Manning Creek basin are rising.

The effectiveness of this process dictates, from geologic, technical, and economic considerations, that supplementary recharge operations be conducted simply as an extension of the natural recharge process. The recharge facility, consisting of the channel of Kelsey Creek, is already in existence, though it might be improved by limited grading, and probably should be protected from excessive replacement of highly pervious gravel by finer grained material as a consequence of gravel borrowing and processing operations. The process of carrying out supplementary recharge operations then reduces to one of making a supply of water available during the time when the water table is drawn down and aquifer storage space is available. This is discussed in Chapter VII "Preliminary Plan for Conjunctive Water Resources Development and Management in Big Valley".

1. NATURAL RECHARGE

Hydrologic and geologic conditions in the area of principal recharge to the Kelseyville Basin are described in Part B-1-c of Chapter IV of this report. In brief, it is stated that most recharge occurs in a 13,000 foot reach of Kelsey Creek, within which there are approximately 70 acres of channel area. Water from the creek infiltrates into the 6 to more than 14 feet of gravel which directly underlies the channel, and
from there passes by lateral percolation into the adjacent near-surface flood-plain gravels where aquifer storage space, resulting from lowering of the water table, is available. Measurements carried out by the California State D.W. R. in 1948, 1949, and 1950 and checked by the Lake County Flood Control and Water Conservation District in 1966, indicated that the infiltration rate in the channel is roughly 1.5 acre-feet per wetted acre per day, and that the entire channel would accept an average of 3000 acre-feet of infiltrated water per month.

2. SUPPLEMENTARY RECHARGE

Supplementary recharge operations can be carried out only when unused storage space is available within the aquifers of the Kelseyville basin. As has been noted, such storage space becomes available only after the water table is drawn down by pumping during the summer irrigation season. When aquifer storage space is available, water may be introduced into the Kelseyville basin by a) percolation, either from the favorable reach of the channel of Kelsey Creek, or from specially constructed basins located elsewhere over the near-surface flood-plain gravels, b) by injection through wells, and c) by underflow from adjacent, higher level ground-water bodies. Processes (a) and (c) go on continuously throughout the dry season under existing conditions but at a much slower rate than the rate of ground-water withdrawal by pumping.

3. PERCOLATION BASINS AND RECHARGE WELLS

Supplemental recharge operations could be augmented to some extent by construction and operation of percolation basins and/or injection wells located away from the channel of Kelsey Creek. The basins would have to be situated in the area of "near surface permeable deposits" (shown on Plate IV), but wells could be placed either in this area or in the area of confined ground water. Utilization of a system of basins and wells would permit more direct recharge of ground water in areas of heavy extraction, although it would not greatly increase the overall amount of water recharged. However, such a system would still have to be supplied with water pumped from surface sources which are not presently available during the dry season. Additionally, the system would be costly to construct and maintain and, while subject to the same limitations as the natural recharge system, would not greatly enhance the capabilities of the natural system.
4. RECHARGE FROM THE CHANNEL OF KELSEY CREEK

The present condition of the high-percolation reach of the channel of Kelsey Creek appears to be adequate to permit infiltration at the rate of approximately 3000 acre-feet per month when the water table in Kelseyville basin is lowered. The infiltration capacity of the channel may be reduced if the highly permeable underlying gravel is replaced by less permeable, fine grained material during the course of gravel borrowing operations. However, there is no evidence that the operations to date have caused any diminution of infiltration capacity.

The infiltration capacity of the channel probably could be improved somewhat by periodically grading and disk ing its surface. Construction of check dams would probably result in undesirable siltation which would introduce problems of maintenance and would probably not greatly increase percolation rates in any case. Additionally, such construction would probably create difficulties for (and with) gravel pit operators.

C. ADOBE CREEK-MANNING CREEK BASIN

Conditions of natural recharge in the Adobe Creek-Manning Creek basin are similar to those in the Kelseyville basin, with the upper portion of the basin being filled to capacity during the wet season by percolation of water from the channels of Adobe and Manning Creeks and by some underflow from adjacent higher level ground-water bodies. Similarly, the problem of achieving supplementary recharge of the basin is principally one of extending the time of flow in the creeks into the season when the basin water table is lowered by pumping for irrigation.

1. NATURAL RECHARGE

Hydrologic and geologic conditions in the areas of recharge to the Adobe Creek-Manning Creek basin are described in Part B-2-b of Chapter IV of this report. Recharge occurs from a 16,000 foot reach of Adobe Creek, having approximately 110 acres of channel area, and from a 3000 foot reach of Manning Creek, having 29 acres of channel area. Infiltration rates in these channels are probably similar to the rate of 1.5 acre-feet per day per wetted acre determined for Kelsey Creek. The capacity of
the basin to accept recharge water is limited, however, by the condition wherein the water table quickly rises to the level of the Adobe Creek channel bottom in the area north of Section 20, thus preventing further infiltration. This occurs fairly early in the wet season, with the result that most of the flow of Adobe Creek is lost to Clear Lake.

2. SUPPLEMENTARY RECHARGE

As with the Kelseyville basin, supplementary recharge operations can be carried on in the Adobe Creek-Manning Creek basin only when unused storage space is available within the aquifers of the basin, which occurs only after the water table has been lowered by pumping for irrigation. When aquifer storage space is available, water may be introduced into the basin by percolation from the creek channels or from pits, or by injection through wells. However, operations involving wells or specially constructed pits are subject to the same limitations and disadvantages as were outlined in the discussion of recharge for the Kelseyville basin.

3. RECHARGE FROM THE CHANNEL OF ADOBE CREEK

The channel of Adobe Creek between Adobe Creek Reservoir and the Merritt Road crossing may be used for infiltration of water in connection with supplementary recharge operations, without alteration. Additional infiltration or injection facilities should not be required.

D. VOLCANIC ASH AQUIFER

1. GENERAL

Conditions governing the operation of a program of supplementary recharge of the "volcanic ash" aquifer are defined by the geology, geometry, and hydraulic properties of the aquifer. Obviously, the requirements for introducing significant amounts of water into a thin, confined layer, which either has no known communication with the surface, or crops out in normally dry water-courses well above the elevation of the nearest major streams, are very different from those of merely extending the period during which an effective, natural recharge system operates in a large alluvial sediment-filled basin.
Possible means of recharging the "ash" aquifer are: 1) Construct infiltration basins along the line of up-dip outcrops of the ash layer and divert water to these basins; and 2) Construct recharge injection wells or, utilizing existing wells which penetrate the aquifer, divert water to these wells and pump water into the aquifer.

Unfortunately, the potential of the aquifer for accepting appreciable amounts of water from the infiltration basin type of recharge system is limited by its thinness and, probably, also by the high pore pressure conditions within it at depth.

Calculations made using simplifying assumptions indicate that approximately 30 acre-feet of water per year might be recharged from each of two possible infiltration basins which could be located in the Central Upland area. This amount would be helpful for replenishing the aquifer to sustain its yield to wells under existing conditions but would not greatly increase its capacity for additional development.

The economic feasibility of establishing and carrying out an infiltration basin recharge operation is principally dependent on the cost of diverting water to supply it. If a diversion were constructed across the Central Upland for the primary purpose, for example, of carrying water from Kelsey Creek to Adobe Creek, then some water could easily be made available to the two potential recharge infiltration basins. Construction of diversion facilities solely for the purpose of supplying the basins, on the other hand, probably could not be economically justified.

There is no technical limit to the number of injection wells which might be operated for recharge of the aquifer. Also, it appears, on the basis of present knowledge, that injection wells would be much more effective in introducing recharge water into the aquifer system. For example, one well, recharging at a rate of 45 gallons per minute (0.1 cubic foot per second), 24 hours per day, 300 days per year, would inject 60 acre-feet of water into the aquifer per year. Other advantages to the use of wells for recharge operations are that the wells could be sited near areas of heavy drawdown and would not be restricted by the absence of surface outcrops of the aquifer.
Development of a water supply capable of yielding relatively large amounts of water by drawing from the volcanic ash aquifer, and replenishing water in the aquifer by recharge through injection wells, should be technically feasible, but would be quite expensive. Major items of expense would include the following:

a. Diversion of water to the injection wells.
b. Construction of the injection wells.
c. Operation and maintenance of the system.
d. Construction and operation of wells to draw from the aquifer.

Advantages of such a system would include:

a. A less extensive surface water distribution system would be required than for a system using only surface conduits.
b. The aquifer would serve as storage, as well as distribution system.

Disadvantages result from the very high cost of constructing 150 to 200 foot deep wells, and from the fact that the surface diversion system required to supply injection wells, at least in the Upland areas, would involve many of the same items of expense as a system to supply surface water directly without the additional cost of constructing and operating two sets of wells.

2. INFILTRATION BASINS

The first recharge system, construction and operation of infiltration basins, can be accomplished only for the portion of the aquifer underlying the Central Upland, since it is only in this area that the "Volcanic ash" crops out. Four outcrops are known; two in the bed of Kelsey Creek, one in the north central portion of Section 27, and one in the southeast quarter of Section 21, with both of the latter outcrops being in the bottoms of small canyons. The Section 21 and 27 outcrops appear to have the greatest potential as recharge sites, since they are both in the central portion of the up-dip margin of the aquifer.

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Construction of infiltration basins at either site should be relatively simple. The outcrop area could be enlarged somewhat by excavation work along the canyon bottoms. Retention structures might be gated concrete weirs, constructed in such fashion as to allow relatively unrestricted passage of heavy runoff so as to preclude siltation.

The drainage courses within which the basins would be constructed each head in the south-central portion of Section 28. This area is near one of the logical routes for diversion of water from upper Kelsey Creek across the Central Upland to Adobe Creek. If a diversion facility were constructed, some water could be conveyed by ditch or pipeline to the heads of these drainage courses, and discharged into them to flow the one to one and one-half miles' distance to the infiltration sites.

Estimates of the amount of water which could be recharged through infiltration basins at the sites just described are based on calculations made using the measured permeability of the "Volcanic ash" material and the average hydraulic gradient down the length of the Central Upland. Continuous flow through the aquifer is assumed. This gives conditions wherein water could move from the basins into the aquifer (which has a permeability of 4000 feet/year) and flow steadily down a hydraulic gradient of 10 to 1. Given these conditions, and assuming 500 feet of wetted exposure along the edge of the ash layer, approximately 30 acre-feet of water per year could be introduced at each site.

3. INJECTION WELLS

It is probably physically feasible to locate injection wells virtually anywhere in the areas underlain by the "Volcanic ash" aquifer and achieve some recharge of ground water to the aquifer. Technical limitations to well location exist, so far as is known, only near areas of potential surface or subsurface outflow (of recharged water) such as outcrops at the surface or under permeable valley fill. Certain advantages are associated with particular areas of possible locations, however. An obvious advantage is an existing nearby source of water. This condition obtains along Kelsey Creek, where flow continues through most or all of the year, and in the Adobe Creek-
Manning Creek basin, where ground water is available at shallow depth. It would be advantageous from the standpoint of well efficiency to inject into thicker portions of the "ash" layer, but data are not available which permit the prediction of areas of greater or less thickness.

The amount of water which could be recharged to the aquifer through any particular well, or through an "average" well of given characteristics, cannot be closely predicted. Published reports on injection well recharge operations indicate, generally, that the amount of water which can be injected into an aquifer from a well is significantly smaller than the amount which can be withdrawn. This results from a number of factors, including growth of algae in wells, reaction of recharged water with minerals in the aquifer, and the fact that migrating fines (suspended solid particles) are flushed out of the aquifer when water is pumped out, but are forced in, tending to clog pore space, when water is injected.

The character of the "Volcanic ash" material appears to be favorable for its acceptance of injected water with minimal problems. The ash possesses a strong stable intergranular structure, and it seems to contain relatively few "fines". This should inhibit clogging and reduction of permeability, if the injected water is free of suspended particles. Also, the ash contains very little clay, and so should not be reactive with introduced water.

Reported yields of wells drawing from the "ash" range from 35 to 1000 gallons per minute, with most indicating yields of more than 100 gallons per minute. Because of the apparently favorable character of the aquifer material, it is believed that properly constructed injection wells could sustain recharge rates of at least 45 gpm (0.1 c.f.s.) with reasonable applied pressures, and might possibly achieve rates of twice this amount.

E. OTHER GEOLOGIC-HYDROLOGIC SUBUNITS

Geologic, topographic, and hydrologic conditions in geologic-hydrologic subunits other than the ones just discussed are such as to preclude carrying out operations for
effective, economically feasible supplementary recharge of ground water. The principal restrictive factors are the absence of extensive aquifers in these subunits (other than the "Volcanic ash" aquifer), and their elevated topographic settings, above the levels of the main drainage courses.

Recharge of the higher areas would not be affected by supplemental recharge operations in the basins. However, agricultural development of the Central Upland giving rise to increased irrigation or to additional flow in drainage courses should result in some recharge of the upper aquifers there.

Future studies may show that some form of supplemental recharge operations are possible in the Cole Creek Upland area.
VII. PRELIMINARY PLAN FOR CONJUNCTIVE WATER RESOURCES DEVELOPMENT IN BIG VALLEY

Development of a plan for management of water resources in Big Valley requires consideration of a number of factors. Chief among these are the following:

1. Total seasonal surface water availability in the Valley under natural conditions, and amount of surface water lost through stream discharge to Clear Lake under existing conditions. (Not considering possible legal restrictions resulting from prior rights of downstream users to this water.)

2. Total amount and seasonal distribution of present and future water requirements in Big Valley.

3. The capabilities and limitations of development and management of the ground-water system in Big Valley. Natural limitations include the geologic framework of the system which governs aquifer distribution and character, and also largely governs recharge processes, and the structural and topographic setting which, together with geology, determines the relation of surface water supply to the ground-water bodies and fixes the pattern of ground-water movement.

Under existing conditions, the seasonal pattern of surface water (other than from Clear Lake) availability is one of the most critical limitations to the management of Big Valley's water resources. However, this is susceptible to alteration, either by provision of facilities for retention and distribution of water from Kelsey Creek, or by obtaining water from some regional development scheme such as the proposed Eel River Project.

This study was not specifically concerned with the items in Factors 1 and 2. Up-to-date figures and projections are not presently available for either item. However, the following assumptions relating to Factors 1 and 2 are believed to be valid:

For Factor 1, data on "Measured and estimated seasonal surface inflow to and outflow
from Units of Clear Lake Area", presented as Table 8 in the California D.W.R. Bulletin 14, are valid for use in planning for water resources development and management, since no significant climatic changes, alterations to watersheds, or water diversions have occurred since these data were compiled. The data indicate that an average of more than 55,000 acre-feet of water annually flow into Big Valley in Kelsey and Adobe Creeks and that an average of more than 40,000 acre-feet of this water continues as surface flow to Clear Lake, where it is lost (from the Valley).

For Factor 2, it is known that water requirements are greater at present than they were when the data for California D.W.R. Bulletin No. 14 were compiled. However, the general nature of water use and the seasonal distribution of water requirements have not changed significantly. By far the greatest water requirement is still for irrigation, and irrigation still takes place during the months of April through October, with the greatest demands being during the months of May through September. In formulating a general plan for managing the water resources of Big Valley, given the particular conditions of hydrology and ground-water geology obtaining there, it is believed that the pattern of seasonal requirement for water is the critical consideration, rather than the total amount required.

Conditions of ground-water geology and hydrology which fix the limits of subsurface water resources development and management include the following:

a. The principal ground-water bodies in Big Valley are in the aquifers of the Kelseyville and Adobe Creek-Manning Creek basins. Ground water in these basins is principally recharged during the wet season by percolation from the channels of Kelsey, Adobe, and Manning Creeks. By March of a year of normal rainfall and runoff, the basins are filled to capacity, and surface flow in the creeks continues to Clear Lake. Thereafter, unsaturated storage space in the basin aquifers becomes available only after the water table has been lowered during the dry season, after stream flow has stopped or become greatly diminished.
b. The aquifers of Kelseyville and Adobe Creek-Manning Creek basins can be recharged from the existing channels of Kelsey and Adobe Creek, when unsaturated aquifer storage space is available. Under existing conditions of seasonal water level lowering, approximately 14,000 acre-feet of unsaturated aquifer storage volume becomes available by late summer. Construction of special infiltration basins or use of injection wells should not be necessary to carry out supplemental recharge operations effectively.

c. Water which is introduced into Adobe Creek-Manning Creek basin will flow toward Kelseyville basin and water introduced into Kelseyville basin will flow toward Clear Lake if, in each case, the water is not withdrawn by pumping from wells.

d. The "Volcanic ash" aquifer, present under much of the Central and Western Upland areas, could be supplementally recharged to a limited extent in the Central Upland by operation of surface water-supplied infiltration basins. Supplemental recharge of this aquifer in the Western Upland, and possibly even in the Northern Central Upland area, would require use of injection wells.

e. Other aquifers in Big Valley are of limited extent and are not susceptible to economically feasible recharge operations.

A plan to develop and manage the Valley's water resources must provide for 1) retaining a portion of the large volume of surface flow now lost to Clear Lake, and 2) making this water available for beneficial use in the Valley.

In view of the geologic conditions governing recharge of ground water, it is apparent that no single operation can benefit all of Big Valley. However, provision of high-level (elevation) storage for the water of Kelsey Creek, and construction of a surface diversion facility for a portion of this water across the upper end of the Central Upland,
would make possible the following:

1. Retention of winter runoff which would otherwise be lost to Clear Lake.

2. Controlled releases to Kelsey Creek to supply users of surface water, and provide water for recharge to the Kelseyville basin whenever aquifer storage space was available there.

3. Diversion of water to Adobe Creek for recharge of the Adobe Creek-Manning Creek basin after flow in those creeks ceases, when aquifer storage space was available.

4. Diversion of water to the Central Upland area both in order to effect some recharge of the "Volcanic ash" aquifer, and to supply water users directly.

The benefits of such operations would include:

1. Retention of water now being lost, for beneficial use within Big Valley.

2. Maintenance of higher water levels in Kelseyville and Adobe Creek-Manning Creek basins, with consequent decrease in pumping lifts and expense.

3. Water for use in developing the Central Upland, other than that presently obtained by drawing from its small upper aquifer or from the deep "Volcanic ash" aquifer, would become available. Also, some supplementary recharge of the "Volcanic ash" could be carried out.

Some secondary benefits from the reservoir on Kelsey Creek, including flood control and recreation, and probably improvement in water quality in the basin aquifers, could also be realized.
In practice, the indicated plan would call for controlling the flow of Kelsey Creek so as to maintain near maximum water levels in the aquifers of Kelseyville and Adobe Creek-Manning Creek basins throughout the year. The basins would be recharged to capacity during the winter, and then releases other than those required for surface diversions or fish and game requirements could be stopped and stream water could be stored for next season's period of controlled releases. During the summer irrigation season, water could be released to Kelsey Creek and diverted to Adobe Creek in such amounts as would be required to maintain a balance between percolation into the basins and withdrawals from them by pumping. The general ground-water level would then be held at near maximum levels at all times, although local drawdown cones and troughs would be formed in it during the months of heavy withdrawal.

In addition to conveying water from Kelsey Creek to Adobe Creek, a surface diversion, probably consisting of a combination of inverted syphon pipe line, and open ditch, could deliver water by gravity feed to ditches or pipe lines extending northward the length of the Central Upland. Such a diversion would also supply gravity feed water to recharge basins for the "Volcanic ash" aquifer in the Central Upland area.

At present, recharge operations involving use of water pumped up into Big Valley from Clear Lake are not technically feasible because of the relatively high boron content of the lake water. If future developments should result in an improvement of the quality of the lake water, however, such an operation could be carried out. Delivering water from the lake to appropriate areas in the Valley for recharge operations would require conveying and lifting the water 3 miles and 40 feet for the Kelseyville basin and 5 miles and 80 feet for the Adobe Creek-Manning Creek basin. Delivery of water to the upper end of the Central Upland would require conveying it 6 miles, with a lift of 280 feet.
VIII. RECOMMENDATIONS FOR FUTURE STUDIES AND FOR CONTINUING PROGRAMS OF DATA ACQUISITION

This investigation has been concerned with determining the geologic and geo-hydrologic conditions in Big Valley, and with establishing the character, and behavior, and degree of inter-relation of the several ground-water regimens in the Valley. These determinations have provided bases for establishing the feasibility of carrying out operations for supplementary recharge of ground water in certain of the Valley's aquifers, and for developing a preliminary plan for conjunctive water resources development and management in the Valley.

Although sufficient data were available, or were obtained during the investigation, to permit working out the significant conditions of geology, and of ground-water distribution and behavior, knowledge of the operation of the complex ground-water system is necessarily still largely qualitative. Also, the ground-water system, and some of the geologic conditions which affect it, are subject to changes as wells are drilled or abandoned, land use changes, or stream regimens are altered.

Final planning and actual design of a program of conjunctive water resources management can best be accomplished if long term data on ground-water conditions, extending through the time when planning is carried out, are available, and also if quantitative data relating to certain aspects of ground-water behavior, about which present knowledge is largely or wholly qualitative, have been obtained. Because of this, it is suggested that continuing programs of data acquisition and future studies for Big Valley be concerned with the following general objectives:

1. Maintenance of records of ground-water and hydrologic conditions, both for purposes of having current data, and for having long term records which would show changes in conditions.
2. Compilation and periodic assimilation of new data, including data from established programs such as stream flow and water-level measurements, and data from special programs such as the studies of land and water use now being carried out by the U. S. Bureau of Reclamation. This would also include maintaining liaison with agencies such as the California State D. W. R. to obtain results of pertinent studies, and get special data such as new well logs, which become available from time to time, and with other agencies operating in Big Valley such as the Farm Advisor, the Soil Conservation Service, etc. to learn of developments or problems known to them. The data would be maintained on file, and new or significant developments could be summarized by the Lake County Flood Control and Water Conservation District.

3. Carrying out of special studies for extending, refining, and quantifying knowledge about particular aspects of ground water or related conditions in Big Valley.

Additionally, studies of economic factors, legal factors, projected water requirements, and engineering design of water retention and distribution facilities will be required when action is taken to implement a program of water resources management.

A. RECOMMENDED CONTINUING PROGRAMS OF DATA ACQUISITION

1. Spring and fall water-level survey (presently under way by the Lake County Flood Control and Water Conservation District).


3. Daily measurement of stream flow on upper Kelsey, Adobe, and Highland Creeks (presently under way by the Lake County Flood Control and Water Conservation District).

4. Daily measurement of stream flow on the lower reaches of Kelsey and Adobe Creeks, downstream from their reaches of heavy percolation. This would require
establishment of an additional gaging station on each creek.

B. **RECOMMENDED LIAISON, AND COMPILATION AND ASSIMILATION OF NEW DATA**

1. Review the report "Reconnaissance Report on Land and Water Use in the English Ridge Hydrographic Unit", by the U. S. Bureau of Reclamation, when this report becomes available around December 1967, noting especially the data on land use and ground-water use in Big Valley, and maintain liaison with the Bureau of Reclamation relative to other aspects of their investigations pertinent to Big Valley.

2. Review reports and compilations of data published by the California State D. W. R.; maintain liaison with the Department relative to pertinent aspects of their investigations; and obtain special data, such as well logs, as they become available.

3. Maintain liaison with the California Agricultural Extension Service Farm Advisor for current information on problems of water quality, well failures, etc.

4. Maintain liaison, or periodically check, with other agencies such as the U. S. Geological Survey, the Soil Conservation Service, etc. for information or data pertinent to conditions in Big Valley.

5. Maintain data and information from the above operations in a systematic fashion; summarize this information periodically; and evaluate the conclusions of the present investigation periodically in the light of the new data. Make recommendations and/or initiate action if information indicating particular problems (e.g., increasing boron concentrations in water or boron damage to crops) is noted.

C. **SUGGESTED SPECIAL STUDIES**

1. Determination of aquifer hydraulic conductivity and, where applicable, of "formation constants" at selected areas in the Kelseyville and Adobe Creek-Manning...
Creek basins, and in the "Volcanic ash" aquifer, by specific pumping-drawdown tests with monitoring of observation wells.

2. Detailed studies of channel percolation on Kelsey and Adobe Creeks, using upstream and downstream gaging stations (if available) or special weirs.

3. Injection testing of wells in the "Volcanic ash" aquifer, possibly combined with tracer studies of water movement in this aquifer.

4. Detailed studies of boron distribution in one or more known high-boron wells, for which logs and perforation data are available, involving water sampling of specific depth intervals within the well(s).
APPENDIX A

INDEX OF SOURCE MATERIAL AND DATA

I. PUBLISHED INFORMATION

A. Publications of the State of California, Department of Water Resources (DWR)

1. Investigations

   Bulletin No. 14, "Lake County Investigation" (1937)
   Bulletin No. 90, "Clear Lake-Cache Creek Basin Investigation" (1961)
   Bulletin No. 143-2, "Clear Lake Water Quality Investigation" (1966)

2. Reports of Basic Hydrologic Data, Issued in Series by the Department of Water Resources

   Bulletin Series No.
   66 - Quality of Ground Water in California
   77 - Ground-Water Conditions in Central and Northern California
   130 - Hydrologic Data

B. Publications of the State of California, Department of Conservation, Division of Mines and Geology

Geologic Map of California, Santa Rosa and Ukiah sheets (scale 1:250,000)

C. Publications of the U. S. Department of Agriculture, Bureau of Chemistry and Soils

Soil Survey of the Clear Lake Area, California, by R. Earl Storie and Stanley W. Cosby

D. Maps published by the U. S. Geological Survey

15 minute series, 1:62,500 scale topographic maps of the Kelseyville and Lakeport Quadrangles, California

7.5 minute series, 1:24,000 scale topographic maps of the Lakeport, Lucerne, Highland Springs, and Kelseyville Quadrangles, California
E. Reference Books
"Ground-Water Hydrology" - David K. Todd, 1959, John Wiley and Sons, Inc.
"Ground Water and Wells" - published by Edward E. Johnson, Inc., 1966

II. UNPUBLISHED INFORMATION AND DATA

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<td>Logs of wells drilled in Big Valley subsequent to 1952.</td>
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<td>B. California Division of Mines and Geology</td>
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<td>Logs of exploratory trenches in the channels of Kelsey Creek and Adobe Creek, 1966</td>
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<td>Geological Field notes, 1965-66</td>
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<td>F. U. S. Department of Agriculture, Commodity Credit Stabilization Service</td>
<td>Aerial photos of the Big Valley Area, at scale 1:20,000 (1958)</td>
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G. U. S. Geological Survey

H. University of California Agricultural Extension Service
Farm Advisor's Office

Records of Runoff of Kelsey, Adobe and Highland Creeks, 1953–1965

Analyses of well waters
APPENDIX B

ANSWERS TO THE BASIC QUESTIONS STATED IN THE AGREEMENT DATED OCTOBER 4, 1965 BETWEEN LAKE COUNTY FLOOD CONTROL AND WATER CONSERVATION DISTRICT AND SOIL MECHANICS AND FOUNDATION ENGINEERS, INC.

1. Q. Is the underground basin underlying Big Valley one basin or is it more than one basin, part being served by Kelsey Creek and the remainder being served from other sources?
   A. The Big Valley area is underlain by a number of "geologic-hydrologic sub-units". Aquifer and hydrologic conditions differ significantly in these subunits so that, although they are hydraulically interconnected to varying extents, the overall Big Valley hydrologic unit cannot be considered to be a single groundwater basin. The various subunits are served by water from a number of sources. The geologic-hydrologic subunits are named and delineated on the "Geologic-Hydrologic Map", Plate II, accompanying this report.

2. Q. Are these basins, if there is more than one, interconnected so that water being introduced into Kelsey Creek basin will find its way into the other basins?
   A. The flow of Kelsey Creek recharges much of the principal geologic-hydrologic subunit, the Kelseyville basin, which underlies the lowland north and northwest of Kelseyville. The geologic distribution and hydraulic conditions for other aquifers in the Big Valley area are such that subsurface flow occurs only from them into the Kelseyville basin. Consequently, ground water introduced into the Kelseyville basin will not find its way into the other basins (or subunits).

3. Q. Is the natural percolation rate in the channel of Kelsey Creek adequate to satisfy the demand placed upon the underground storage?
   A. Percolation from the channel of Kelsey Creek has been adequate to completely fill the eastern portion of the Kelseyville basin during years of normal rainfall. The basin as a whole is filled by percolation from both Kelsey Creek and the lower reach of Adobe Creek (which reaches the Kelseyville basin as
underflow from the Adobe Creek-Manning Creek basin), though the amount of percolation is usually considerably less than the total runoff from the two creeks. Percolation from the channel of Kelsey Creek has little or no direct influence on ground water used to supply demands placed on storage in subunits other than the Kelseyville basin.

4 and 5.

Q. If there is more than one basin, what can be done to improve the transmissibility of water from the Kelsey Creek area to the Adobe Creek basin? Will surface diversion facilities be required?
A. Geologic and hydrologic conditions in the Big Valley area are such that ground water infiltrated from Kelsey Creek is not transmitted to the Adobe Creek-Manning Creek basin in significant quantities. Transmission of water from Kelsey Creek to the Adobe Creek area will require surface diversion facilities.

6. Q. Will artificial recharge areas be required?
A. Recharge of the Adobe Creek-Manning Creek basins and the Kelseyville basin can be carried out in the existing channels of Adobe Creek and Kelsey Creek. Operations to recharge the "volcanic ash" aquifer beneath the upland areas would call for construction of recharge basins in selected areas and, probably, for use of injection wells and for extensive surface diversions to supply these basins and wells.

7. Q. Where is the downstream limit of the recharge area which would minimize the loss of water from the ground-water basin?
A. The area where recharge of the Kelseyville basin subunit can be effectively carried out is limited downstream by the zone of near surface capping deposits of low permeability, shown on Plate IV accompanying this report. Water infiltrated into the ground upstream of this line will go into storage provided the ground-water level is low enough for unsaturated aquifer storage space to be available.
8. Q. What is the approximate amount of water which can be introduced into the ground-water basin within the reach of Kelsey Creek below the dam but upstream of the limit referred to in subparagraph above?
A. Under existing conditions, the amount of free ground water present in the Kelseyville basin varies by about 7500 acre-feet between spring, when the basin is filled to capacity, and fall, when ground-water levels are at their lowest. About two thirds of this amount of ground-water storage space lies within the area which is principally recharged by Kelsey Creek. The remaining third underlies the western side of the valley where recharge is by underflow from the Adobe Creek-Manning Creek basin. The amount of water which can be introduced into the ground-water basin from the channel of Kelsey Creek is therefore limited by the amount of aquifer storage space available, and this amounts to approximately 4000 acre-feet. This is much less than the amount which could be percolated from this channel for supplementary recharge if aquifer space capable of accepting more water were available. The 2½ mile reach of the channel of Kelsey Creek extending downstream from a point ½ mile above the old Highway 29 bridge, at Kelseyville, has been shown to have a percolation capacity of about 1.5 acre-feet per wetted acre per day, or, for the present area of channel bottom, 3000 acre-feet per month.

9. Q. Are there any areas within Big Valley which would not be benefited directly by recharging the basin?
A. In general, conditions in the Big Valley area are such that recharge of a particular geologic-hydrologic subunit will be of direct benefit only to the area overlying, or drawing from, that subunit. Limited underflow will take place from upstream subunits into adjacent lower areas. Recharge of the lower subunits will tend to diminish such underflow, thereby conserving the ground-water supply in the upstream subunits. Aside from this theoretical "conservation of water through diminished underflow" benefit, upland areas in Big Valley will not benefit directly from recharge of the Kelseyville and Adobe Creek-Manning Creek basins.
10. Q. What is the continuity of known strata of water-bearing material within the underground basin and the interconnection of various strata as related to those particular water-bearing strata known to have a high boron content?

A. Water containing concentrations (greater than 0.67 ppm) of boron which are potentially injurious to some types of plants has been reported from at least twenty wells in the Big Valley area. Relatively high (greater than 0.60 ppm) concentrations of boron are known to occur in ground water from a number of wells located adjacent to Mt. Konocti, and from other wells at isolated locations in the Kelseyville and Adobe Creek-Manning Creek subunits. The boron is not known to occur in particular water-bearing strata, but seems usually to come from the deeper strata penetrated by the well. Boron concentrations in water from a given well vary considerably at different times.

The location of isolated high-boron wells in relation to alignments of suspected buried fault-breaks suggests the possibility that some of the boron comes from subsurface springs which rise at various places along the faults. If this is the case, the high-boron spring water apparently becomes diluted by mixing with ground water, so relatively high-boron concentrations are found only in wells drawing water from the vicinity of the subsurface springs.

The general occurrence of high-boron water in wells located adjacent to Mt. Konocti (together with the known occurrence of boron-rich springs issuing from the other side of the mountain) suggests that ground water in that area is mixed with boron-contaminated underflow from aquifers within the mountain. Strata from which water contaminated either by rising spring water or by underflow from Mt. Konocti is withdrawn are of varying extent and continuity but are interconnected with other water-bearing strata in the basins. Mixing of water within this system of interconnected strata serves both to dilute the higher-boron water away from its immediate area of inflow, and to maintain the general moderate (0.05 - 0.67 ppm) boron content of ground water in the basin.
APPENDIX C

KEY TO PROVISIONAL WELL NUMBERS SHOWN ON THE PRELIMINARY
"WELL LOCATION AND DATA AVAILABILITY MAP"

Explanatory note:
Well numbers are assigned to wells by the California Department of Water Resources (DWR) only after the well has been described by completion of a DWR Form 429 "Well Data" sheet and all applicable State documents and publications have been checked by the DWR office having jurisdiction over the area where the well is located.

In the Big Valley area, no systematic assignment of Well Numbers is known to have been carried out since the completion of the DWR "Lake County Investigation" published as DWR Bulletin No. 14 in 1957. Logs of many wells drilled since that time have been filed with the appropriate State Regional Water Pollution Control Board, (RWPCB) but the wells have no specific official designation other than a serial number given each log upon its receipt by the Board.

To facilitate description of wells for which data are available, provisional numbers have been assigned during this study, and are shown on the Preliminary "Well Location and Data Availability Map". These numbers anticipate assignment of State Well Numbers by the DWR at some future time, but at present have no official significance. The list appended refers each provisional well number assigned during this study to the corresponding Regional Water Pollution Control Board log serial number or other identifying designation.
## WELL DATA KEY AND CROSS INDEX

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SOIL MECHANICS and FOUNDATION ENGINEERS Inc.

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| 32J-R(?)   | 32433                    | J. L. Morrison                              |                          | 7-9-53              |
| 32Q-R(?)   | 32416                    | Allen Spurr                                 |                          | 6- -52              |
| 32R(2)     | 2962*                    | O. C. Thurman                               |                          | 11-7-50             |
| 32R(3)     | 2961*                    | James L. Morrison                           |                          | 11-12-50            |
| 33K(2)     | 102535                   | John Medina                                 |                          | 2-23-65             |
| 33L(3)     | 120655                   | Robert C. Stone                             |                          | 10-8-65             |
| 33R(2)     | 74329                    | C. C. Blower                                |                          | 2-18-63             |
| 34D(1)     | 120651                   | Lake Dredging Company                       |                          | 9-3-65              |
| 34K(3)     | 32403                    | A. M. Stage                                 |                          | 8-18-51             |
| 34K(4)     | 32406                    | Herbert Porter                              |                          | 1-2-54(?)           |
| 36F(1)     | 33282                    | California Division Parks and Beaches       |                          | 5-17-56             |

(*) Number assigned by the (old) California Division of Water Resources to logs on DWR Form 246.

(a) Number used by U. C. Agricultural Extension Service Farm Advisor's Office for water analysis.

(#) Well located and measured by LCFC&WCD, November 1965.
APPENDIX D

GEOLOGY OF THE BIG VALLEY AREA

A. GEOLOGIC UNITS

Twelve principal geologic units, grouped into four main categories and ranging in age from Recent to Jurassic, were recognized and mapped during this investigation. Two distinctive subunits, the "Volcanic ash" layer in the "Older lake and flood-plain deposits" unit, and serpentine in the Franciscan Formation, also were identified and mapped. Additionally, two subdivisions of the "Older lake and flood-plain deposits" were used when drawing cross sections of that unit, and extensive or persistent zones of sand and gravel, and also of clayey lake sediments, were differentiated in cross sections of the "Big Valley flood-plain and lake deposits". Thick, continuous surface soil was shown as a distinct unit on the cross sections, but is not represented on the map. The four main categories of units and the individual units of which they are comprised are described below, starting with the youngest.

CLASS I - YOUNGER ALLUVIAL AND LAKE DEPOSITS

Materials of this class range in age from Recent to late Pleistocene and occur as terrace, basin-fill, and channel deposits. This is the most important class of groundwater bearing units. The deposits vary in thickness from a few feet for some of the channel alluvium to about 220 feet for the Big Valley flood-plain and lake deposits unit.

a. Channel Alluvium Material of this unit is present in all drainage channels other than the sloughs adjacent to the lake. The alluvium consists predominantly of sand and gravel sized material mixed with lesser amounts of silt and clay. Concentrations of fine grained material are also present as bars, lenses, and layers within the sand and gravel. The channel alluvium occurs both as deposits of appreciable depth and extent, as in portions of the Kelsey and Adobe Creek channels, and also as discontinuous patches and bars resting on or being carried over an older consolidated clay, or bedrock channel bottom.
The character and distribution of channel alluvium in Kelsey and Adobe Creeks was investigated by excavation, logging, and partial sampling of twenty-six backhoe test pits. Exposures of channel gravel in pit walls were seen to have distinct foreset layered structure. Many zones of "open-work" gravel, characterized by open voids rather than sand and silt filling in space between pebbles, occur along the bedding in much of the gravel. The presence of such zones gives the gravelly alluvium a very high lateral permeability.

The deeper channel alluvium deposits are coextensive with older but similar flood-plain deposits.

b. Residual, Slopewash, and Flood-plain Soil  This is a generalized unit used to identify all thicker surficial soil deposits, both on slopes and upland surfaces, and on the flood plain. Soils included within the unit are, therefore, of residual, colluvial, alluvial and, along the lower margin of the Big Valley lowland, lacustrine origin. Generally, surface layers of soil shown on geologic cross sections have been identified on the basis of water well drillers' logs indicating "topsoil", "clay", etc.

Surface soil in the Big Valley area is of variable permeability, but deeper layers of "clay pan" within the soil horizon are generally of low permeability. This condition inhibits deep percolation of rain or irrigation water, and thus inhibits recharge of such water to the ground-water zone. Tests conducted by the California Division of Water Resources indicated an average "irrigation efficiency" (the ratio of consumptive use of applied water to the total amount of applied water, expressed as a percentage) of 55 percent for irrigated land in Big Valley. This means that 45 percent of the applied water was not used in evapotranspiration and was at least available for percolation. Probably only a small fraction of the 45 percent of nonconsumptively used water actually reaches the underlying ground-water body, however, the rest being taken up as soil moisture, vadose water, etc.

c. Big Valley Flood-plain and Lake Deposits  (Listed as "Basin-filling channel, flood-plain, and lake deposits" for the geologic cross sections). Materials of
this unit fill the Kelseyville and Adobe-Manning Creek basins of Big Valley. The character of the materials, however, is known only from descriptions on water well drillers' logs and by analogy with materials exposed at the surface. This basin-filling unit includes the aquifers which contain most of the ground water stored in Big Valley. The sedimentary deposits of which the unit is comprised range in character from lake clay to cobble and boulder gravel, with all gradations between. The distribution of material types within the basin fill is regular in some areas but may also be extremely variable. However, some horizons or zones appear to be fairly continuous over wide areas. Relatively continuous horizons of either coarser grained material (sand and gravel) or of clay, are differentiated in the geologic cross sections (Plate III). Where lateral continuity of distinctive horizons is not recognizable or where data is lacking, the sections show only undifferentiated basin fill. Gravel and sand flood-plain alluvium deposited at various times by Kelsey and Adobe Creeks constitutes the most important material for water storage and transmission within the basin fill. Extensive horizons of this material are present under the surface soil north of Kelseyville and along Adobe Creek, and at deeper levels in the same areas. The upper horizon of sand and gravel receives water by lateral percolation from saturated channel alluvium and also directly from surface flow in the creeks. The water thus received eventually percolates down to recharge the underlying ground water.

d. Shaul Valley Fill; Alluvial Fan Deposits These two units were differentiated on the basis of their location and surface expression. The Shaul Valley Fill unit reportedly consists of fine grained sediments. The composition of the Alluvial Fan Deposits is probably similar to that of slopewash soil. Neither of these units have particular significance relative to the ground-water geology of Big Valley.

e. Kelsey Creek Terrace Deposits These deposits are present on a terrace bench marking an earlier, higher level channel of Kelsey Creek. The bench is 5 to 10 feet above the present channel level. The deposits occur in a band on both sides of the creek, and consist of a few feet of soil underlain by sand and sandy cobble and boulder gravel. The total thickness of the Terrace Deposits is about 10 feet along the channel, and they probably thin away toward the inner margins of the terrace surface.
CLASS II - OLDER ALLUVAL AND LAKE DEPOSITS

a. Upland Terrace Deposits  This unit includes flood-plain and delta deposits which occur as a dissected capping over the older sediments along the Western Upland, and which are preserved in a down-faulted block extending across the Central Upland. Materials of the unit are exposed in cuts along Big Valley Road and in cut banks of gullies in the Western and Central Uplands.

In the exposures along Big Valley Road, the deposits consist of silt, fine grained silty sand, and silty sandy small gravel. The sediments show well developed, large scale fore-set bedding so that at first glance they appear to be tilted. The orientation of this apparent tilting, however, is not consistent with the Valley's structure but is consistent with an origin of deposition by an ancestral Adobe-Highland Creek.

Other exposures consist of an apparently unstratified deposit of gravelly or rocky sandy silty clay or clayey sand. The upper reaches of Hill Creek, in Section 28, traverse a section of gray or blue gray, medium to coarse grained sand, with zones or channels of gravel from $\frac{1}{8}$ inch to 2 inch size. This same horizon is penetrated by water wells drilled in Section 27. A driller's log of one of these wells reads as follows: 0-3, soil; 3-30, brown clay; 30-130, brown sandy clay; 130-144, blue sand and gravel; 144-158, blue hard pan. The "blue hard pan" below 144 feet depth is probably the "Older lake and flood-plain deposits" unit. A limited quantity of water is obtained from the "blue sand and gravel" horizon.

b. Older Lake and Flood-plain Deposits  Materials included within this unit underlie most of the Central and Cole Creek Upland areas and are exposed where gullies have cut through the "Upland Terrace deposits" capping on the Western Upland.

The "Older lake and flood-plain deposits" unit is divisible into two members, both in outcrops and in well drillers' logs. The lower member consists of well consolidated but un cemented massive gray silty clay, sometimes grading in composition to clayey silt or clayey silty sand. The clay or claystone is very stiff to hard (in terms of soil consistency). It tends, however, to crack and gradually disintegrate when exposed to
drying. The upper member consists predominantly of silty fine grained sand or soft sandstone with some horizons grading to sandy silt or clay. Thin beds of pebble conglomerate and occasional thicker channels of pebble and cobble conglomerate occur within the upper member.

c. **Volcanic Ash subunit** A layer of "volcanic ash" (lithic tuff) is present in the lower member of the Older lake and flood-plain deposits unit. This "ash" layer is significant because it is an important aquifer and, in fact, is the only good source of ground water in the upland areas. Additionally, the layer provides a reliable, easily recognized stratigraphic horizon which is useful in working out the geologic structure of the area.

The "ash" consists entirely of angular, completely unaltered fragments and grains of porous volcanic rock, probably of rhyolitic-dacitic composition. Particle size ranges from medium sand to small gravel (about \( \frac{1}{2} \) inch). The material is fairly coherent and can be broken into chunks. The coherence seems to result from the presence of a clayey coating, possibly containing a trace of calcium carbonate, on individual particles. Laboratory testing of a sample of the "ash" showed it to have the following properties:  
Dry density, 87.6 pcf; Void ratio, 0.889; Porosity, 47 percent; and Permeability, 4.1 \( \times 10^{-8} \) cm/sec.

The permeability was not affected by subjecting the sample to confining pressures of up to 90 psi, indicating that the material has a strong structural framework and is not subject to collapse.

The known horizontal extent of the "volcanic ash", as determined from well logs and from field mapping, is indicated on Plate IV. The "ash" layer probably continues to the north to greater depths, in the Western Upland area, and also is probably present at depth in areas of down-faulted Older lake and flood-plain deposits, but no positive evidence of its existence in such areas is presently available. Future deep drilling, however, will probably disclose its presence beyond the northern limit shown, at least in the Adobe-Manning Creek area.
The "volcanic ash" is best exposed in a small canyon cut into the Central Upland in the north-central portion of Section 27. In that exposure, the ash occurs in a 6 to 7 foot thick section, having a 2 foot thick interbed or parting of silty sandstone, enclosed between sandstone and massive siltstone. "Volcanic ash" or "volcanic gravel" is reported in the logs of fifteen wells. Thicknesses of $\frac{1}{2}$ to 4 feet are indicated, sometimes with associated material described as "blue clay and volcanic ash (or gravel) mixed", in thicknesses of 4 to 5 feet. The minimum thickness noted is $\frac{1}{2}$ foot; the maximum thickness of the combined units is 7 feet.

**CLASS III - MATERIALS OF VOLCANIC ORIGIN**

a. **Volcanic Ash and Obsidian Breccia** Material of this unit occurs at the upper end of the Cole Creek Upland and is best exposed in cuts along Bottle Rock Road. The unit consists of white unconsolidated tuff containing brecciated and intricately deformed masses of obsidian.

b. **Camelback Ridge Obsidian Flow** The obsidian flow is present on the broad crest of Camelback Ridge. The surface of the flow consists almost entirely of angular blocks of obsidian.

c. **Mt. Konocbi Volcanic Rocks** Mt. Konocbi is a composite volcano built up of alternating layers of lava flows and pyroclastic rocks. The rocks generally fall between rhyolite and dacite in composition. The flow rock may be fairly hard and massive but usually is considerably fractured. Some of the interlayered pyroclastic material is indurated to form massive or bedded rock, while some is relatively non-coherent granular sediment.

d. **Kelsey Creek Volcanic Rocks** The volcanic ridge, through which Kelsey Creek has cut a deep, steep walled gorge, is also a composite volcanic accumulation. The ridge has a central core of mixed pyroclastic and flow material which contains tabular or contorted masses of dacitic rock, intruded into the core zone from underlying fissures. Flanking deposits of flows and indurated pyroclastic rocks are present along the sides of the ridge. The harder rocks are extensively fractured,
probably largely in consequence of deformation during successive episodes of intrusion, extrusion, and cooling.

CLASS IV - FRANCISCAN FORMATION AND RELATED ULTRABASIC ROCKS

a. Franciscan Formation  Rocks of the Franciscan Formation make up the bedrock of the Mayacamas Mountains and underlie the Big Valley basin at depth. The formation comprises a variety of rock types, but dark colored sandstone (greywacke), shale, and chert predominate in the vicinity of Big Valley. Where fresh, these rocks are quite dense and hard, though pervasively fractured. In exposures, the rocks are generally quite broken up, though harder masses of greywacke remain intact even when weathered. Zones of crushing and shearing are present throughout the Franciscan Formation in this area.

b. Serpentine  Masses of ultrabasic rock altered to serpentine have been emplaced along shear zones at many places in the Franciscan Formation. This material was originally formed as the crystalline igneous rock peridotite or pyroxinite, but was altered in varying degrees to serpentine prior to emplacement in the Franciscan rock. The serpentine occurs in bodies of a few cubic feet volume, intruded along shear zones, to larger masses forming entire hills. The less thoroughly sheared serpentine is relatively more resistant to erosion than the enclosing weathered Franciscan rocks, so isolated hills along the edges of the valley are largely composed of serpentine rock.

B. GEOLOGIC STRUCTURE

Geologic structure in the Big Valley area is illustrated on the Geologic Map, Plate I, and the Geologic Cross Sections, Plate III.

The form of Big Valley as a whole, and the distribution of its principal land-form subdivisions, is largely controlled by the position of and relative movements along a number of faults. The steep linear slope rising above the upland along the valley's west side is an old dissected fault escarpment, against which the Older flood-plain and lake deposits materials were deposited. Other, more recent fault movements have created the Adobe Creek-Manning Creek basin and the Kelseyville basin, in each case by dropping the
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of the main elements of the recent geologic history of the basin's evolution. This is outlined as follows:

1. Basin Formation  The ancestral Big Valley–Clear Lake basin was formed by downdropping or tilting of a block along bounding faults including the Big Valley west-margin fault and the Clear Lake axial fault. Deposition of some Cache Formation or equivalent sediments took place in the structural basin thus formed.

2. Clear Lake Volcanics Activity  The "Volcanic Ridge" was formed by eruptions through a northwest oriented fissure system along the margin of an ultrabasic rock-serpentine intrusion in the Franciscan Formation bedrock. Masses of "Cache Formation" sedimentary rock and Franciscan bedrock were incorporated in the intrusive and extrusive volcanic pile. Mount Konocti was formed during the later stages of volcanic activity.

3. Deposition of the "Older Flood-plain and Lake Deposits" in the Big Valley Area  The ancestral Clear Lake extended to the head, or southern margin of Big Valley during the early stages of deposition of the "Older flood-plain and lake deposits" unit, with the "Volcanic Ridge" forming a peninsula. At this time, the west side of the basin was the eroded escarpment of the Big Valley west-margin fault, and the east side was the flank of Mt. Konocti. An arm of the lake extended between Mt. Konocti and the Volcanic Ridge into the present area of the "Cole Creek Upland". Coarse clastic sediments were laid down as deltas and alluvial fans by the ancestral Kelsey, Adobe, and Highland Creeks. Finer grained material was deposited throughout the lake basin. A single episode of explosive volcanic activity occurred during this phase of basin-filling sedimentation. Pyroclastic ejecta from this volcanic explosion, consisting of small angular fragments of vesicular rhyolite or dacite, fell throughout the basin forming a layer ranging up to 7 feet thickness. This layer, which is now the important "Volcanic ash aquifer", was subsequently buried and incorporated within the lake clays as normal basin-filling sedimentation continued. During the latter portion of this time of deposition, the area of Big Valley was a low flood plain rather than a lake, and sediments consisting of silts and fine sands with occasional gravel layers predominated. An
interval of erosion, perhaps brought on by a lowering of the local base level due to changes in the basin drainage system, apparently occurred before the capping delta deposits were laid down. This is suggested by the nature of the "Older flood-plain and lake deposits" which seem to be consolidated to a greater degree than can be accounted for by the amount of loading imposed by the existing overlying sediments. The overconsolidation, then, must have resulted from loading by a greater thickness of material, which was eroded away prior to deposition of the present capping delta sediments. Following this inferred period of erosion, large deltas of poorly sorted gravel, sand, and silty clay were formed. Portions of the deposits remain as a capping of the "Older flood-plain and lake deposits" unit and also in a section preserved in a down-faulted block in the Central Upland. The faulting which created this block probably occurred while the delta-forming alluviation was still going on.

At the close of this period, the Big Valley-Northern Clear Lake basin was filled with sediments consisting of lake and flood-plain deposits, and these deposits lapped onto the lower flanks of Mt. Konocti, the Volcanic Ridge, and the Mayacamas Mountains.

4. Post Older-Basin-Filling Period - Tectonic Activity and Sedimentation

Events in the latest period of the structural and geomorphic evolution of the Big Valley-Clear Lake basin have included extensive alterations and readjustments to the landscape by faulting within the basin, and additional sedimentation within the structural depressions thus formed.

The first episode of faulting formed the basin within which was deposited the 220 feet thickness of flood-plain and lake sediments that underlie the Big Valley lowland and northwestern Clear Lake. The lake itself, or at least its northwestern portion, presently occupies the largely filled remnant of this fault-formed basin. The fault in question trends north-northwest from a gap in the Volcanic Ridge, under the valley fill surface in the Cole Creek upland, then cuts a spur of Mt. Konocti before turning to a west-northwesterly course across Big Valley. Near the valley's western margin, the fault again turns north, and continues parallel to the mountain front. Total dip-slip offset along the fault is about 250 feet where it cuts the spur of Mt. Konocti, and 300 feet where it
crosses Big Valley. However, this total offset accumulated during more than one episode of movement. The effect of this fault movement was to drop an extensive area of land, including Mt. Konocti and most of the lake basin, relative to the surrounding country. Subsequent to the basin's formation, the lake level must have risen before streams such as Kelsey Creek could trench their channels into adjustment with the lowered local basin level. Filling of the enlarged and greatly deepened basin with lake deposits and, near regions of stream inflow, with deltaic deposits, began immediately.

Either at about the same time as, or at some time subsequent to the Big Valley faulting, a zone of north-northeast trending faults developed, extending toward the lake from the southwestern corner of the valley. The dip-slip component of offset on this fault zone was about 180 feet, with the area where the channel within which the combined flows of Adobe and Highland Creeks had traversed the upper valley dropped or tilted down against the fault. The depression created by this faulting became an arm of Clear Lake and also began filling with fine grained lake and deltaic sediments. Channel and flood-plain-terrace gravels of the drowned stream course were buried at the base of this accumulation.

Following these episodes of faulting, the main elements of the Big Valley landscape existed approximately in their present form, except that the lake covered the areas of the Big Valley and Adobe Creek lowlands. These last landscape features emerged only when the basins underlying them were filled with lake, delta, and finally flood-plain deposits. A lowering of the lake level by a few feet or tens of feet contributed to the relative emergence of the surfaces of the filled basins.

The present valley, therefore, includes uplands of older semiconsolidated lake and flood-plain sediments, which lap onto the flanks of the surrounding hills, and lowlands underlain by younger lake, delta, and flood-plain deposits which lap onto the buried escarpments of faults cutting the older sediments and also onto the downdropped lower slopes of Mt. Konocti.