NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

PRELIMINARY GEOHYDROLOGIC STUDY OF A PORTION OF THE OWENS VALLEY GROUND-WATER RESERVOIR

by

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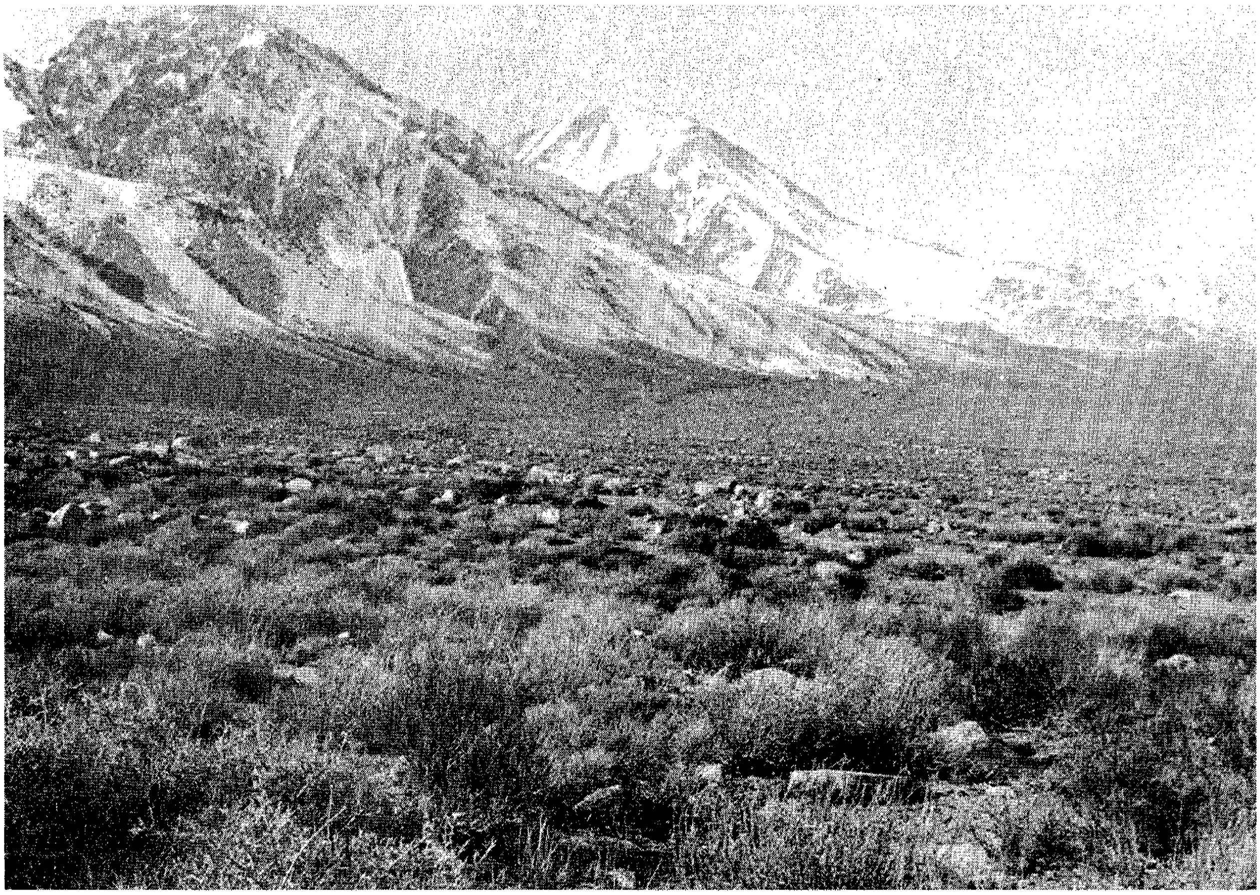

HYDROLOGIC PROCESSES AT WORK IN THE OWENS VALLEY

ACKNOWLEDGEMENTS

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ABSTRACT

The Owens Valley is located approximately 200 miles north of Los Angeles, along the eastern edge of the southern Sierra Nevada.

The geology and hydrology of the area are studied in order to obtain a quantitative description of the ground-water supply. The geologic boundaries are delineated using techniques of field geology. Photogeology, coupled with microscopic analysis of outcrops and well cuttings, aids in identifying the geohydrologic subdivisions.

The major aquifers are the alluvial fans and volcanic flows flanking the eastern edge of the Sierra Nevada. Over one million acre-feet of water is presently stored in these aquifers.

Pumping tests are conducted on selected aquifers in the study area and formation parameters obtained. The theory of multiple well-field analysis is applied to the pumping period 1960-62. Analysis of these results reveals average transmissivities of over 200,000 gpd/ft, and storativities of .01.

A hydrologic budget is applied to the study area using average records of precipitation, runoff, and evaporation. From the results of this budget, the ground-water safe yield is determined as 221 cfs.

A linear model of the Independence ground-water region is created, and the hydraulic properties simulated mathematically with a digital computer. Predictions of future water levels are obtained using several regimens of pumping and artificial recharge.

Salvage of ground water is accomplished by lowering the water table in areas supporting phreatophyte growth.

Semi-pervious faults exist transverse to ground-water movement in many areas on the alluvial fans. These faults retard the flow of ground water causing areas of heavy phreatophyte growth.

Storage of ground water is optimized by artificially recharging aquifers adjacent to alluvial fault zones. In this manner, leakage from the toe of the alluvial fans is minimized.

The theory of a well pumping in the vicinity of a semi-pervious fault is developed in order to predict water-level declines caused by backward leakage through the fault zones.

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PRELIMINARY GEOHYDROLOGIC STUDY OF A PORTION OF THE OWENS VALLEY GROUND-WATER RESERVOIR

INTRODUCTION

A 12-year drought around the turn of the century prompted city officials of Los Angeles to seek out a supplemental water supply. This they did by acquiring water rights to Owens River. A 233-mile aqueduct was constructed, which upon completion in November 1913, delivered approximately 420 cfs to the City of Los Angeles.

Recent water demands, culminating in the 1960's, have prompted Department engineers to seek still further development of the Owens River-Mono Basin sources by building a second aqueduct from the Owens Valley. This second aqueduct will in part be supplied from ground water pumped from underground reservoirs. The expected mean annual draft from the ground-water reserves is estimated to be about 120 cfs. The total combined aqueduct flow to the City of Los Angeles would be about 700 cfs, 450 cfs from the present aqueduct and 250 cfs from the second aqueduct.

Due to the commitment of underground water, it is of prime importance that knowledge of the total underground supply be obtained.

Purpose and Scope

It is the main purpose of this dissertation to make a quantitative estimate of the ground-water reserves available for supplemental use. More specifically, the investigation has the following objectives:

1. To determine the size and extent of the individual hydrologic units which comprise the area under investigation.

2. To determine the source of the ground water in this area and the hydrologic factors which govern its movement from the areas of recharge to the areas of discharge.

3. To determine the present amount of recharge to the ground-water reservoir and its manner of fluctuation.

4. To determine the amount of storage in the aquifers of the reservoir.

5. To evaluate ground-water withdrawal schemes and their effect on the available supply in the reservoir.

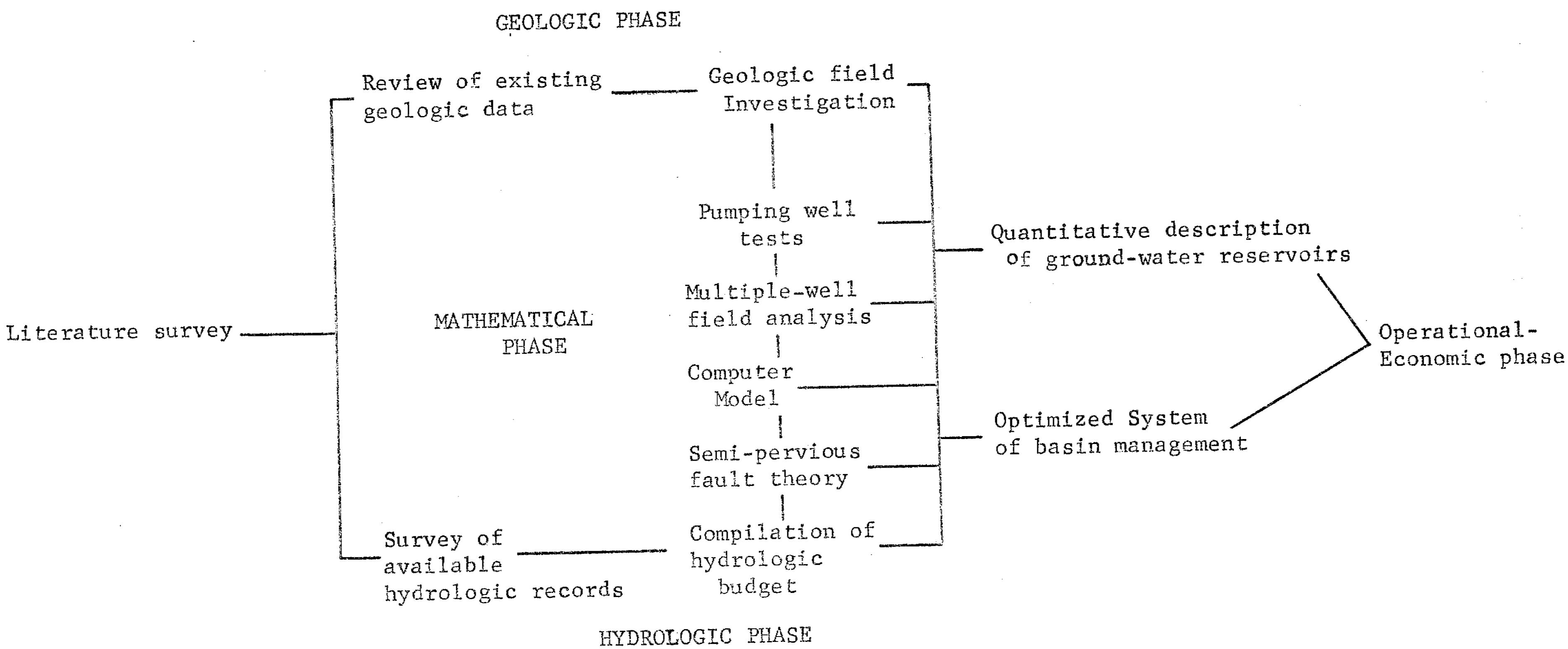
6. To determine the amount of natural discharge and the amount of salvage appropriate to insure proper development.

The scope of the investigation ranges from detailed geologic mapping in the field, to development of a highly sophisticated computer model which simulates mathematically the behavior of the reservoir.

The theory of multiple well fields, as developed by Cooper and Jacob (1946), is applied in the area, and the pumping period 1960-62 analyzed.

The non-steady state theory of a well pumping in the vicinity of a semi-pervious fault is developed analytically and applied in the study area to gain insight into salvage operations.

This study investigates the laws and principles which govern the occurrence, movement and storage of ground water in the Owens Valley. The results of this study will be coordinated with the operational-economic phase of the second aqueduct (see organizational model, Plate I).



ORGANIZATIONAL MODEL OF THE INVESTIGATION

Methods of Investigation

The methods of investigation can be systematically summarized in the following order:

1. LITERATURE RESEARCH - This consisted of a critical review and evaluation of all the previous reports written on the area. The major conclusions by each of the authors were noted. These results aided in the compilation of the basic knowledge required to undertake a study of this type.

2. FIELD INVESTIGATION - Investigation of the area was first undertaken in June 1965. Since then, numerous field trips have been taken involving both geologic and hydrologic studies. Areas in which knowledge is sparse have been investigated by a well-drilling program. Bore-hole cuttings were analyzed both in the field and by petrographic analysis. Major geologic formations were mapped using field-geology procedures (Lahee, 1952) in conjunction with actual aerial reconnaissance.

A six-week field investigation in the summer of 1968 provided important insight into the nature of the alluvial faults in the valley. Trenches were cut across many of these faults using a "drag line" and a "back hoe."

Pumping tests were conducted on wells representing different aquifer types in the region. These data were analyzed to obtain estimates of the formation parameters.

3. MATHEMATICAL ANALYSIS - Analysis of data from the pumping period 1960-62 were analyzed using hydrographs of selected recorder wells. The theory of multiple well-field analysis, as developed by Cooper and

Jacob (1946), was applied to determine regional values of the formation parameters. The tedious procedure of reducing these data were simplified by programming the routine into a digital computer.

A model of the Independence area was created by dividing the area up into polygons. Transmission and storage properties were assigned to each polygon and the area simulated mathematically using a digital computer.

The theory of a well pumping near a semi-pervious fault was developed to predict water-level declines near the fault. A family of curves was developed to facilitate application of this theory.

4. UTILIZATION OF HYDROLOGIC RECORDS - To obtain inflow, outflow and storage characteristics in the study area, hydrologic records were analyzed over a chosen base period. Records of stream flow, precipitation and ground-water levels were carefully analyzed. The data were then synthesized into a hydrologic budget for the study area.

Previous Work

Most of the lands in the Owens Valley are owned by, or withdrawn for, the City of Los Angeles. Most of the previous investigations are engineering studies centering around available surface-water supply. There are no comprehensive geohydrologic reports, prepared by state agencies, as is common in many other basins of California.

There are, however, several important geologic contributions to the literature concerning the area.

Knopf and Kirk (1918) laid the basic geologic groundwork of the area. Their investigation provided much of the information regarding geologic structure, history and rock types. Certain details are lacking in their work, such as detailed fault and outcrop mapping; but considering the limited data available, the report still represents the most comprehensive geologic investigation in the area.

Pakiser, Kane and Jackson (1964) made a geophysical study oriented towards explaining the structural geology of the Owens Valley region. Seismic, gravity and magnetic surveys were run throughout the valley. Their interpretation of the structure was based on results of the geophysical data and the geology as explained by Knopf and Kirk (1918). In general, their results are broad, on a regional scale, and therefore of little use for ground-water exploration programs.

Several reports on availability of supplemental surface water have been written on behalf of the City of Los Angeles in connection with the aqueduct system. These reports contain useful data from precipitation, stream flow, runoff and consumptive-use records (R. V. Phillips, 1963; Los Angeles Department of Water and Power, 1962).

C. H. Lee (1912) studied the water resources of the Independence area. Lee's work is important in that it represents the first comprehensive study in the area relating phreatophyte growth to ground-water discharge.

Sources of Data

Hydrologic data for the Owens Valley area were obtained from hydrographic records kept by the Los Angeles Department of Water and

Power. Los Angeles owns a large percentage of the land in the Owens Valley and controls most of the major water-supply and distribution systems within the valley. Some of the important records used in this study were those concerning precipitation and stream flow. From these were obtained estimates of the quantity of flow issuing from the base of the mountains and of the flow entering the aqueduct. The difference between the two is an indication of the loss of flow due to deep percolation. This is important because it provides an estimate of the amount of influent seepage which is recharging the ground-water reservoir. Along with stream-flow data, data regarding spring flows and well flows were also available.

Pumping records have been kept, and therefore, extractions from the ground-water basin are known for every period of pumping. Elevation of water levels in most of the wells are known throughout the valley, enabling one to obtain an idea of the direction of the movement of the ground water, as well as depth.

Unfortunately, a large percentage of the wells are located along the aqueduct, near the center of the valley, restricting most of the borehole knowledge to this area. There is at present an exploratory drilling program in progress which, it is hoped, will answer many questions in heretofore unexplored areas.

Drillers' logs on many wells were reviewed as an aid to understanding the subsurface geologic structure.

Hydrologic Base Period

In any watershed, the original source of local water is from precipitation. The amount of precipitation on a ground-water basin, and on its tributary areas, serves as an index to the total water supply available to that basin. From the analysis of long-term precipitation records, it is possible to select as a base period a relatively short and recent period which represents the long-time available water supply. Such a period is needed for study purposes because long-term hydrologic data are generally unavailable.

The base period should be reasonably representative of hydrologic conditions and should include normal and extreme wet and dry years. The base period should also be within a period of available records and should include recent cultural conditions as an aid to future basin operational studies. The long-term period in the Owens Valley was determined from studying precipitation of the Independence and Bishop areas. The hydrographic years (October 1 through September 30) of 1937/38 to 1959/60 inclusive were selected as the base period for this study as they meet all of the criteria.

Terms and Definitions

Definitions

Aquiclude - A body of earth material of low permeability, which can absorb water but cannot transmit it at a rate sufficient for economic extraction by wells.

Aquifer - A body of earth material capable of transmitting water through its pores at a rate sufficient for economic extraction by wells.

Aquifuge - A body of earth material which is impervious and nonabsorptive.

Darcy's law - Basically states that the velocity of moving ground water is directly proportional to the head difference between two points and inversely proportional to the path length. In its simplest form:

$$\text{velocity} = v = - K\ dh/dx$$

where K is the proportionality constant and is called the hydraulic conductivity. dh/dx is the hydraulic gradient. The negative sign is a matter of convention and indicates that the ground water is moving in the direction of decreasing head.

Drawdown in a pumping well is the difference between the pumping level and the extrapolated standing level. It is made up of two components, the formation loss (BQ) and well loss (CQ^n).

Formation-loss coefficient (B) is the ratio of the formation head loss to the discharge. For convenience it may be expressed in ft/100 gpm or ft/1000 gpm.

Hydraulic conductivity - In soil mechanics and foundation engineering the term "permeability" is often applied to another constant. This second constant or characteristic typifies not only the porous media but also the fluid flowing through it. In addition to the permeability as defined below, the fluid factors viscosity and specific weight are considered. In this report this product is termed "hydraulic conductivity." In terms of the hydraulic conductivity, Darcy's law of flow may be expressed as follows: The volume-flow per unit area is equal to the product of the hydraulic conductivity by the hydraulic gradient, or loss of head per unit distance in the direction of flow. The hydraulic conductivity is the permeability multiplied by the specific weight of fluid and divided by its viscosity.

Permeability - (Specific or intrinsic) That property of the porous medium which is independent of the fluid properties of viscosity and specific weight. It is related to the pore diameter, which is assumed proportionate to a representative grain diameter d.

It is usually written $K = Cd^2$ where C is a dimensionless constant, a property of the medium only.

Pumping level - The water level observed inside a well when it is discharging.

Recovery - The difference between the extrapolated time-drawdown curve that would have existed if the well had continued to pump and the observed water level in the well.

Safe yield - For this study, the average annual amount of ground water that could be extracted from a ground-water basin over a long period of time without causing long-continuing reduction of ground water.

Specific capacity - The ratio of the discharge to the drawdown it produces, measured inside the well and expressed in gpm/ft or in cfs/ft.

Specific drawdown - The ratio of drawdown to the discharge that produces it. It is the reciprocal of specific capacity and may be expressed in ft/gpm or ft/cfs.

Standing level - The level observed inside a well when its pump is idle.

Static level - The water level that would have been observed at any time in a well if it had never been pumped.

Storativity - The ability of an aquifer to store water is expressed by a number called its storativity. This is the same as "coefficient of storage" or "storage coefficient" of Theis. It is defined as the volume of water removed from storage under a unit surface area by a unit decline of head, or expressed otherwise, it is the volume of water stored under a unit surface area by a unit rise of head. In confined aquifers the storativity ranges from about 10^{-5} to 10^{-3}, in unconfined aquifers storativity is the same as specific yield and ranges from about .05 to .40. Intermediate values imply semi-confinement.

Thiessen Method - A method used to determine the amount of precipitation on an area by constructing polygons or areas of influence about each gaging station. The polygon is formed by the perpendicular bisectors of the straight lines joining adjacent gaging stations. When using this method, it is assumed the depth of precipitation within the polygon is equal to the depth of precipitation at the corresponding gaging station.

Transmissivity - A convenient term used to describe the ability of a uniformly thick bed or aquifer to transmit water. This is the same as the "transmissibility" of Theis; but, since the water in the aquifer is transmissible, while the aquifer itself is transmissive, the word "transmissivity" is currently being accepted in describing the aquifer. The transmissivity is the hydraulic conductivity multiplied by the saturated thickness of the transmissive formation.

Well-loss coefficient (C) - The ratio of the well loss to the n^{th} power of the discharge. (n = 2 is based on the assumption that the hydraulic friction accompanying the flow of water through the perforations in the casing and upward inside the casing to the pump intake is fully turbulent as in a "rough" channel.) That is, the hydraulic resistance is assumed proportional to the n^{th} power of the mean velocity at any point in the stream or to the n^{th} power of the discharge.

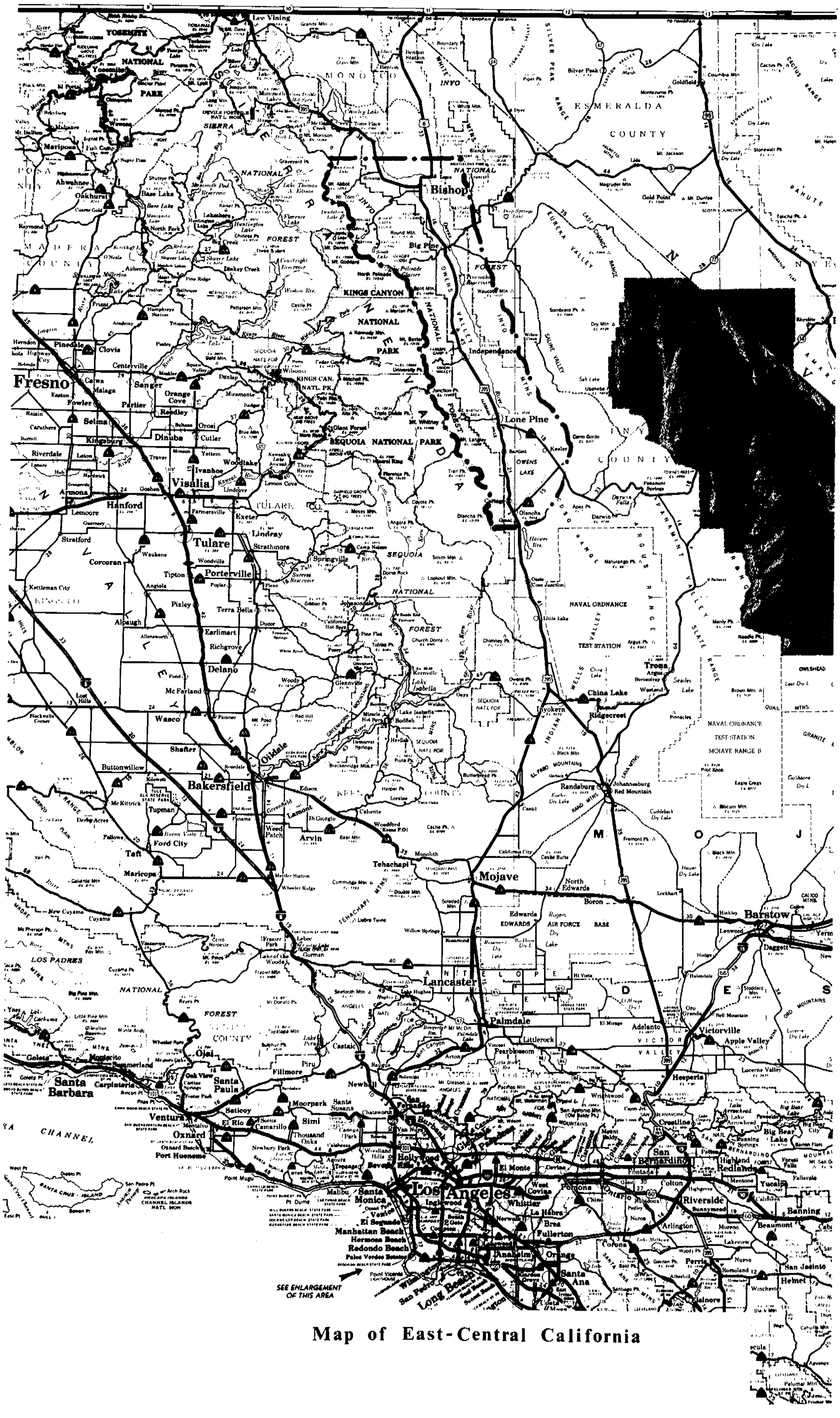
DESCRIPTION OF AREA

Physiography, Areas and Boundaries

Owens Valley is located in east-central California along the western edge of the great Basin (Plate II). It is generally characteristic of that region except to the west where typical high Sierra features exist. It is bordered on three sides by desert regions. Mono Basin lies to the north, White, Inyo and Coso Mountains to the east, and a series of open valleys to the south. The well-watered Sierra Nevada lies to the west (Plate III). The Owens Valley area includes not only Owens Valley proper, which is a narrow trough extending from the volcanic tableland to Owens Lake, but also Round Valley, which is a branch of Owens Valley northwest of Bishop, Long Valley which is the depressed area that contains Lake Crowley, and the extension of the Owens Valley trough north of Laws along the White Mountains front.

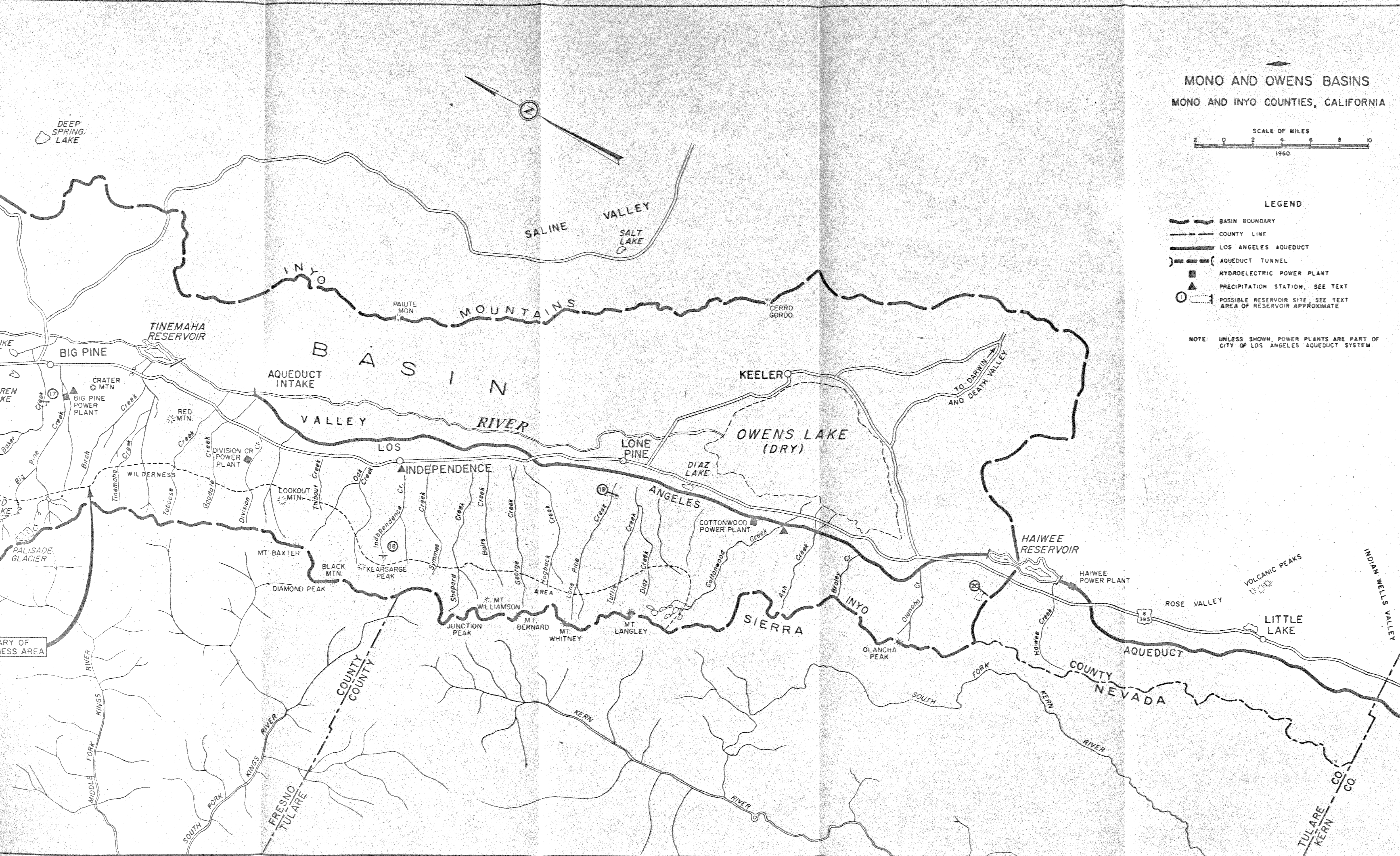
The shape of the valley is long and narrow, trending northwest-southeast. Its length from the Mono divide to the south end of Owens Lake is 120 miles. Its width from crest to crest of the confining mountain ranges varies from 40 miles at the north end, to 25 miles at Owens Lake, its minimum width being 15 miles between Bishop and Big Pine. The total area of the valley as far south as Olancha, with its tributary mountain drainage, is about 3,300 square miles, of which 1,200 square miles are occupied by desert mountains that yield practically no runoff, 536 square miles in the Sierra Nevada yield a large runoff and

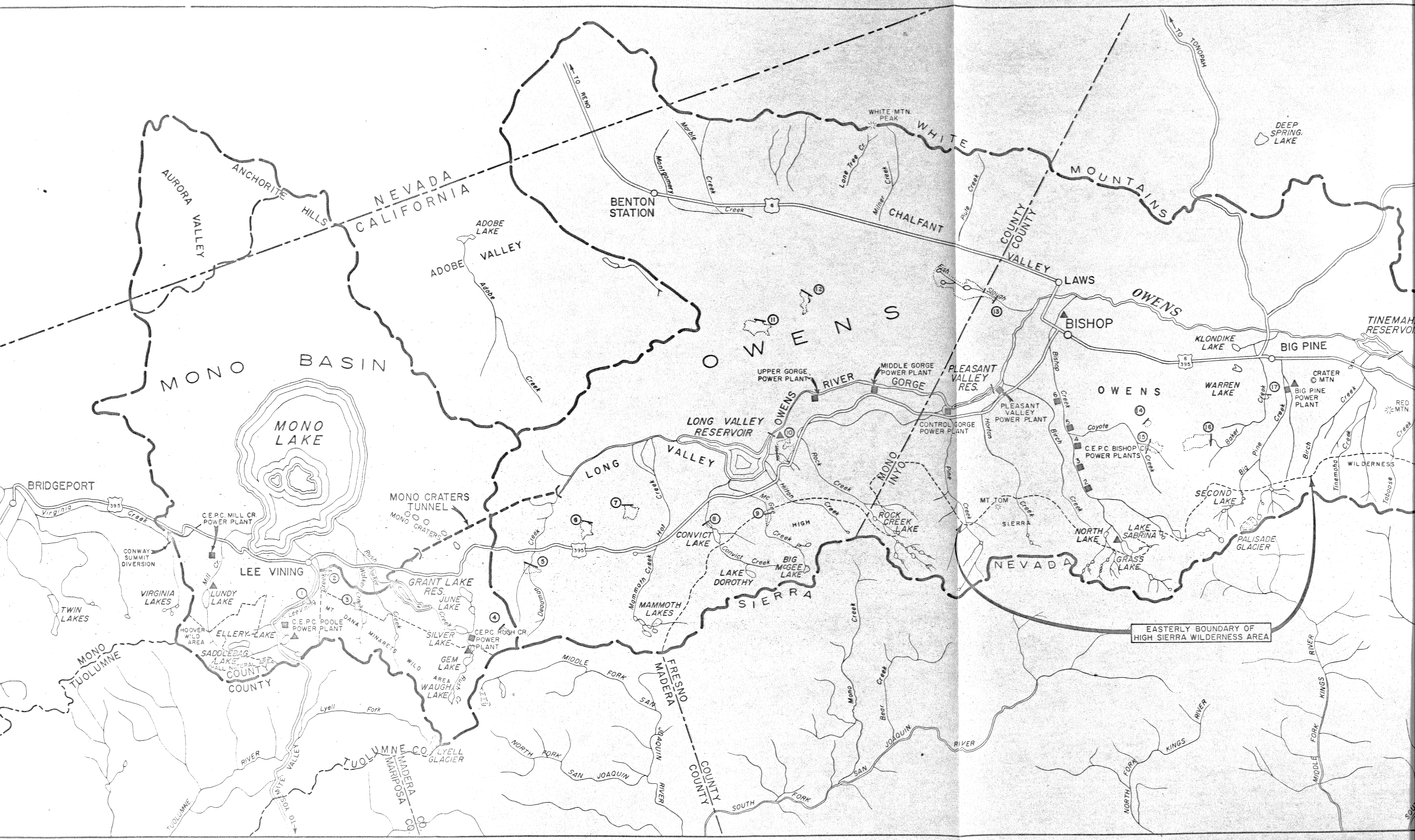
PLATE II



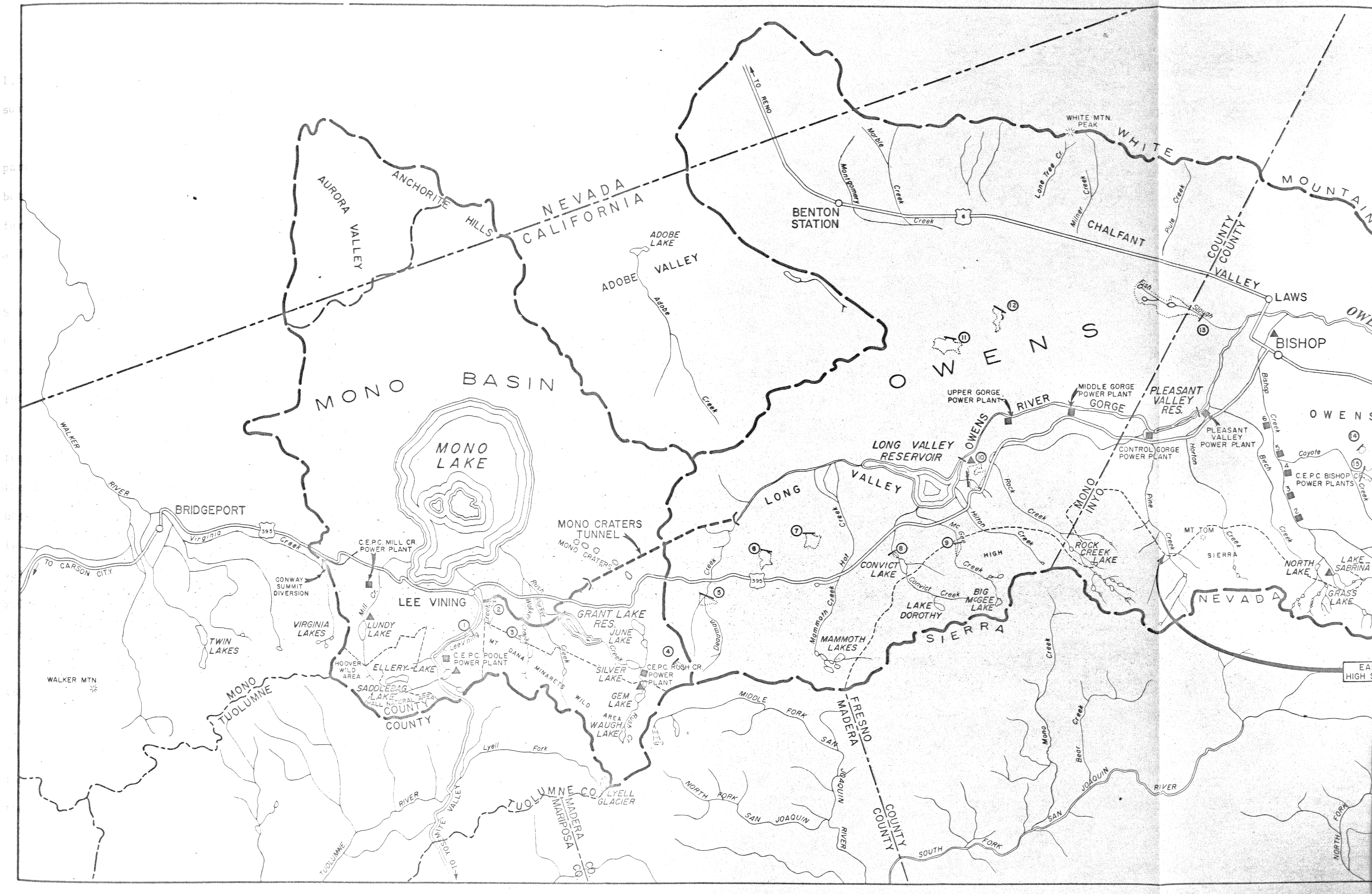
Map of East-Central California

PLATE III


MONO AND OWENS BASINS
MONO AND INYO COUNTIES, CALIFORNIA
SCALE OF MILES
2 0 2 4 6 8 10
1960
LEGEND
BASIN BOUNDARY
COUNTY LINE
LOS ANGELES AQUEDUCT
AQUEDUCT TUNNEL
HYDROELECTRIC POWER PLANT
PRECIPITATION STATION, SEE TEXT
POSSIBLE RESERVOIR SITE, SEE TEXT
AREA OF RESERVOIR APPROXIMATE
NOTE: UNLESS SHOWN, POWER PLANTS ARE PART OF CITY OF LOS ANGELES AQUEDUCT SYSTEM.
N
DEEP SPRING LAKE
SALINE VALLEY
SALT LAKE
INYO MOUNTAINS
PAIUTE MON
CERRO GORDO
TINEMAHA RESERVOIR
BIG PINE
OWENS VALLEY BASIN
AQUEDUCT INTAKE
CRATER MTN
BIG PINE POWER PLANT
RED MTN.
DIVISION CR POWER PLANT
RIVER
LOS ANGELES AQUEDUCT
INDEPENDENCE
LONE PINE
KEELER
TO DARWIN AND DEATH VALLEY
OWENS LAKE (DRY)
DIAZ LAKE
WILDERNESS AREA
LOOKOUT MTN
COTTONWOOD POWER PLANT
HAIWEE RESERVOIR
HAIWEE POWER PLANT
ROSE VALLEY
VOLCANIC PEAKS
INDIAN WELLS VALLEY
LITTLE LAKE
US 395
PALISADE GLACIER
MT BAXTER
BLACK MTN.
KEARSARGE PEAK
DIAMOND PEAK
MT. WILLIAMSON
JUNCTION PEAK
MT. BERNARD
MT. WHITNEY
MT LANGLEY
OLANCHA PEAK
SIERRA NEVADA
Baker Creek
Big Pine Creek
Birch Creek
Tinemaha Creek
Taboose Creek
Goodale Creek
Division Creek
Thibaut Creek
Oak Creek
Independence Cr.
Symmes Creek
Shepard Creek
Bairs Creek
George Creek
Hogback Creek
Lone Pine Creek
Tuttle Creek
Diaz Creek
Cottonwood Creek
Ash Creek
Braley Cr.
Olancha Cr.
Haiwee Creek
17
18
19
20
MIDDLE FORK KINGS RIVER
SOUTH FORK KINGS RIVER
KERN RIVER
SOUTH FORK KERN RIVER
FRESNO COUNTY
TULARE COUNTY
INYO COUNTY
TULARE CO.
KERN CO.
...ARY OF ...ESS AREA



NEVADA
CALIFORNIA
AURORA VALLEY
ANCHORITE HILLS
MONO BASIN
MONO LAKE
ADOBE LAKE
ADOBE VALLEY
Adobe Creek
TO RENO
BENTON STATION
Marble Creek
Montgomery Creek
WHITE MTN. PEAK
WHITE MOUNTAINS
Lone Tree Cr.
Milner Creek
CHALFANT VALLEY
Piute Creek
MONO COUNTY
INYO COUNTY
TO TONOPAH
DEEP SPRING LAKE
LAWS
BISHOP
Fish Slough
OWENS
OWENS RIVER
OWENS VALLEY
KLONDIKE LAKE
BIG PINE
TINEMAHA RESERVOIR
UPPER GORGE POWER PLANT
MIDDLE GORGE POWER PLANT
GORGE
PLEASANT VALLEY RES.
PLEASANT VALLEY POWER PLANT
CONTROL GORGE POWER PLANT
WARREN LAKE
CRATER MTN
BIG PINE POWER PLANT
RED MTN.
LONG VALLEY RESERVOIR
LONG VALLEY
Rock Creek
Horton Creek
Bishop Creek
Birch Creek
Coyote Creek
C.E.P.C. BISHOP POWER PLANTS
Baker Creek
Big Pine Creek
Tinemaha Creek
Taboose Creek
WILDERNESS
BRIDGEPORT
Virginia Creek
C.E.P.C. MILL CR. POWER PLANT
CONWAY SUMMIT DIVERSION
MONO CRATERS TUNNEL
MONO CRATERS
Mill Cr.
LEE VINING
LUNDY LAKE
VIRGINIA LAKES
TWIN LAKES
Lee Vining Creek
C.E.P.C. POOLE POWER PLANT
Rush Creek
Walker Creek
Parker Creek
GRANT LAKE RES.
JUNE LAKE
MT DANA MINARETS WILD AREA
SILVER LAKE
GEM LAKE
WAUGH LAKE
C.E.P.C. RUSH CR. POWER PLANT
Deadman Creek
Mammoth Creek
Hot Creek
MAMMOTH LAKES
CONVICT LAKE
Convict Creek
Mc Gee Creek
Hilton Creek
HIGH SIERRA
BIG McGEE LAKE
LAKE DOROTHY
ROCK CREEK LAKE
MT TOM
Pine Creek
NORTH LAKE
LAKE SABRINA
GRASS LAKE
SECOND LAKE
PALISADE GLACIER
NEVADA
EASTERLY BOUNDARY OF HIGH SIERRA WILDERNESS AREA
HOOVER WILD AREA
ELLERY LAKE
SADDLEBAG LAKE
NATURAL AREA
MONO COUNTY
TUOLUMNE COUNTY
Lyell Fork
TUOLUMNE RIVER
TO YOSEMITE VALLEY
TUOLUMNE CO.
MADERA CO.
MARIPOSA CO.
LYELL GLACIER
MIDDLE FORK SAN JOAQUIN
NORTH FORK SAN JOAQUIN RIVER
FRESNO COUNTY
MADERA COUNTY
Mono Creek
Bear Creek
SAN JOAQUIN RIVER
SOUTH FORK SAN
NORTH FORK KINGS RIVER
MIDDLE FORK KINGS RIVER



NEVADA
CALIFORNIA
AURORA VALLEY
ANCHORITE HILLS
TO RENO
BENTON STATION
WHITE MTN. PEAK
WHITE MOUNTAINS
CHALFANT VALLEY
LAWS
BISHOP
ADOBE LAKE
ADOBE VALLEY
Adobe Creek
MONO BASIN
MONO LAKE
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INYO COUNTY
BRIDGEPORT
WALKER RIVER
Virginia Creek
TO CARSON CITY
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VIRGINIA LAKES
LUNDY LAKE
TWIN LAKES
HOOVER WILD AREA
ELLERY LAKE
SADDLEBAG LAKE
HALL NATURAL AREA
MT DANA
MINARETS WILD AREA
WALKER MTN.
MONO COUNTY
TUOLUMNE COUNTY
TUOLUMNE CO.
MADERA CO.
MARIPOSA CO.
LYELL GLACIER
Lyell Fork
TUOLUMNE RIVER
TO YOSEMITE VALLEY
CONVICT LAKE
LAKE DOROTHY
BIG McGEE LAKE
MAMMOTH LAKES
Mammoth Creek
Hot Creek
Rock Creek
ROCK CREEK LAKE
McGee Creek
Convict Creek
HIGH SIERRA
SIERRA NEVADA
MT TOM
NORTH LAKE
LAKE SABRINA
GRASS LAKE
FRESNO COUNTY
MADERA COUNTY
MIDDLE FORK SAN JOAQUIN
NORTH FORK SAN JOAQUIN
SAN JOAQUIN RIVER
SOUTH FORK SAN JOAQUIN
Mono Creek
Bear Creek
Marble Creek
Montgomery Creek
Lone Tree Cr.
Milner Creek
Piute Creek
Fish Slough
Bishop Creek
Birch Creek
Horton Creek
Pine Creek
Coyote Creek
Hilton Creek
Deadman Creek
Rush Creek
Walker Creek
Parker Creek
Mill Cr.
Lee Vining Creek
395
6
EAST HIGH S

1,580 square miles consist of transition slopes, valley floor, and the surface of Owens Lake.

The upper valley is separated into two parts, the western part being known as Long Valley. A depression called Round Valley lies between Owens Valley proper and Long Valley. Owens Valley extends as far south as the southern end of Owens Lake, a distance of 80 miles; and its floor ranges in width from 2 to 8 miles.

U. S. Highway 395 parallels the entire eastern front of the Sierra Nevada throughout the length of the Owens Valley area. U. S. Highway 6 follows the western front of the northern White Mountains southward and joins Highway 395 at Bishop. California State Highway 190 enters Owens Valley from the east at Lone Pine.

The elevation of the valley floor ranges from about 8,000 feet above sea level at the Mono divide to 3,570 feet at Owens Lake, the lowest point in the valley. The average slope in Long Valley is between 25 and 35 feet to the mile, and the elevation at its lower end is about 6,670 feet. From the end of Long Valley to the head of Owens Valley proper, there is a drop of 2,200 feet in a distance of about 20 miles. Owens River here has cut a deep gorge through volcanic deposits which extend across the valley. From the big bend in the river northeast of Bishop, at an elevation of about 4,100 feet, the slope to Owens Lake is fairly uniform and averages 7.5 feet to the mile. The average elevation of the outer borders of the valley along the base of the Sierra Nevada is about 6,000 feet, and the elevation along the eastern rim ranges from 4,000 feet near Owens Lake, to 6,000 feet at the base of the White Mountains. The slopes that flank the valley are steep. The eastern face of the Sierra Nevada drops off at an average rate of 1,500 to 2,000 feet to the mile, and the slopes of the alluvial deposits flanking the range vary from 350 to 600 feet to the mile. The slopes of the western faces of the White and Inyo Mountains range from 700 to 2,000 feet to the mile. The valley floor has very light transverse slopes.

The elevation of the crest of the Sierra Nevada averages 12,500 feet, though many peaks exceed this altitude, some of them by more than 1,500 feet. The lowest portion of the range is that extending from Mammoth Pass northward to the head of Glass Creek. The most northerly tributary of Owens River, and the highest, is in the vicinity of Mount Whitney. The White and Inyo Mountains have an average elevation of 10,000 feet, and northeast of Bishop they attain a height of over 13,000 feet.

The specific area of the Owens Valley covered in this study ranges from about 10 miles south of Bishop on the north, to Owens Lake on the south. Emphasis will be placed on areas of maximum future ground-water withdrawal which, in the near future, will be in the Independence to Big Pine area.

Surface Stream Systems

The Owens River is the main or trunk stream, and is fed by about 40 small tributaries entering at fairly regular intervals from the west (see Plate III). Water reaching the river from the east is derived from sparse cloud bursts and is negligible in amount. The waters of Owens River used to empty into Owens Lake, from which they escaped only by evaporation. There is heavy precipitation on the western side of the Owens Valley, resulting from the great elevation of the Sierra Nevada. The moisture-laden winds from the west lose much of their moisture in passing over this high range, and as a consequence, rainfall is very light in the main part of Owens Valley and the districts farther east. Numerous streams enter the valley from the Sierra Nevada. The larger of these are Rock, Pine, Bishop, Coyote, Big Pine, Tinemaha, Taboose, Oak, Sheperd, and Lone Pine creeks. South of Mount Whitney the tributaries are smaller and intermittent because of the small amount of snow on the summit of the range. The streams are torrential in character, flowing through deep, narrow gorges on the higher slopes and emerging onto the lower detrital cones which they have deposited.

Climatological Characteristics

Annual temperatures in Owens Valley range from well over 100°F in the summer, to less than 0°F in the winter. However, cool temperatures prevail throughout the summer on the higher slopes of the Sierra Nevada. The climate of Owens Valley and the Great Basin area to the east is arid. The climate of the Sierra Nevada is subhumid, and extensive snowfields form during the cold winter months and melt off during the spring and summer. Glaciers exist in some of the higher elevations.

History of Land and Water Use

Owens Valley is rich in natural resources. Owens Lake contains 160 million tons of various salts, including carbonates, bicarbonates, sulfates, chlorides, and borates of sodium and potassium. Five plants have been constructed for the manufacture of soda ash, and one for caustic soda. All alkali operations have since been discontinued. Altogether, about 1,000,000 tons of alkali and 30,000 tons of borax have been produced from the brine of Owens Lake.

Deposits of tungsten are extensive in the Bishop area. The tungsten minerals that are mined are found in tactite and include scheelite and members of the wolframite group. The Pine Creek mine, operated by the Union Carbide Company, provides a large percentage of the current tungsten production in California. Silver, lead, and zinc deposits have been mined for many years at the Cerro Gordo mine east of Lone Pine in the Inyo Mountains and at other small mines. Small vein deposits of gold have been mined intermittently in the Owens Valley region. Talc, perlite, absorbent clay, and pumice have been produced from several deposits in the Owens Valley area.

The water of Owens River and its tributaries in the Sierra Nevada is an important resource which is supplied to the City of Los Angeles through the Los Angeles Aqueduct.

Agriculture includes cattle grazing on the desert shrubland of Owens Valley, fruit orchards near Bishop, and some grain production.

Owens Valley is an important major resort area, and the towns serve as headquarters for a variety of summer and winter sports.

GEOLOGY

Geologic History

About 150 million years ago, in the Mesozoic Era of geologic time, (Fig. 1), volcanic and sedimentary deposits had collected in the Owens Valley Geosyncline to a depth of at least 50,000 feet (Knopf, 1918). The lower portion of the trough was tightly folded and broken along faults. Granitization of these sediments occurred at depth due to extreme metamorphism (Anderson, 1937). The Sierra Nevada batholith intruded the area at this time.

Relatively stable crustal conditions were ended about 20-25 million years ago by three distinct uplifts which occurred over possibly a 10-million year period. These uplifts were not rapid enough to cause mountain ranges of great consequence, but accompanying them was extensive volcanic activity. Volcanic rocks extruded during this period are found from the Tehachapi Mountains through northern California, and from the San Joaquin Valley to areas east of the Inyo Mountains (Bateman, 1954). It may be that ancestral Owens Valley existed at this time, since sediments were deposited in lakes which occupy the present flanks of the Coso Mountains (Smith, 1957). However, there is no direct evidence to show when the valleys were formed, and it may be that they were not delineated until after the first glaciation.

The periods of extensive volcanism and minor uplift were separated from those of glaciation by about 10 million years of relative quiet in which some volcanism occurred. The products of this volcanism

AGE	GEOLOGIC TIME		GEOLOGIC EVENTS
(Yrs.) 10,000		Quaternary	Late Sierran Glaciation
22,000	Tioga		
			Late Volcanism (Visible Basalt Flows, Cones, etc.)
40,000			
	Tenaya		Earlier Sierran Glaciation (Lower Elev. Moraines)
	Tahoe		
700,000			
	Sherwin		
			Earlier Quaternary Basalt (Lower Aquifer Taboose Area)
1,500,000			
	McGee		
2,700,000			
		Tertiary	Major Uplift In Southern Sierras With Volcanism
50,000,000			
			Intrusion Of Sierra Nevada Batholith Followed By Uplift
100,000,000	Mesozoic Era		Batholithic Intrusion (Nevadan Orogeny)
			Formation Of Owens Valley Geosyncline (Deposition Of Sediments And Volcanics)
200,000,000	Paleozoic Era		
400,000,000			

Fig. 1 Chart of Geologic History and Events in the Owens Valley

can be seen in the lava flows interbedded with the sediments of older volcanic flows of the Coso Mountains (Pakiser, 1960). During this time, the sea retreated from the San Joaquin Valley and minor uplifts of the Sierra occurred. The greatest elevation in the region during this time was probably no greater than 1,500 feet or possibly 2,000 feet. Because of its low elevation, the Sierra was not glaciated during the first period of continental glaciation.

The first Sierran glaciation, the Sherwin glacial stage, occurred possibly 700,000 years ago and was contemporaneous with the second advance of ice over the continent (Blackwelder, 1931). At this time the Sierra, and probably the Inyo Range as well, had undergone the first of two major series of uplifts, and the Sierra probably stood at 5,000 to 6,000 feet in elevation with peaks up to 8,000 feet high. Owens Valley had now certainly taken on its present form, and the deep canyons in the mountains on either side of the valley were being entrenched.

During the following interglacial period and the second Sierran glaciation, (Tenaya-Tahoe stage) the range probably attained its present elevation. This was the most extensive of the three glacial periods that sculptured the high Sierra, and tongues of glacial debris extended far down the mountain valleys. The southernmost point at which glaciers formed was Olancha Peak, and with the third glacial stages (Tahoe stage), the finishing touches were put on the landscape of the Sierran upland (Blackwelder, 1931).

During these last two glacial periods, which were also periods of extreme crustal unrest, volcanic rocks, such as the extensive Bishop tuff which covers a large area north of Bishop, were extruded (Gilbert, 1938). Volcanism occurred in the whole region, from the El Pasos to the northern end of Owens Valley, and in the Sierra and Inyo Mountains. The youngest volcanic flows show few signs of erosion. The lithology at three sections in the study area can be seen graphically in Fig. 2.

Seismically the Owens Valley is still very active, as evidenced by the 1872 Lone Pine earthquake and numerous smaller earthquakes. An average rate of displacement across the Sierran fault zone since the first glaciation, is estimated at approximately 1 foot per century (Hudson, 1955). As of this writing, there are no accurate records of recent changes in elevation across the fault zone to make a valid comparison between the present rate of displacement, and that of the geologically recent past. This is being corrected however, by the installation of strain gages at several places across active faults near the town of Lone Pine. This investigation is being conducted by the U. S. Coast and Geodetic Survey in conjunction with Earthquake Mechanism Laboratories of San Francisco.

Geologic Structure

The Owens Valley region is part of the Basin and Range province, which is characterized by a sub-parallel series of northward-trending ranges separated by elongate basins. This pattern is caused by structural geologic features which resulted from the last geologic events to occur in the province (Pakiser, 1964).

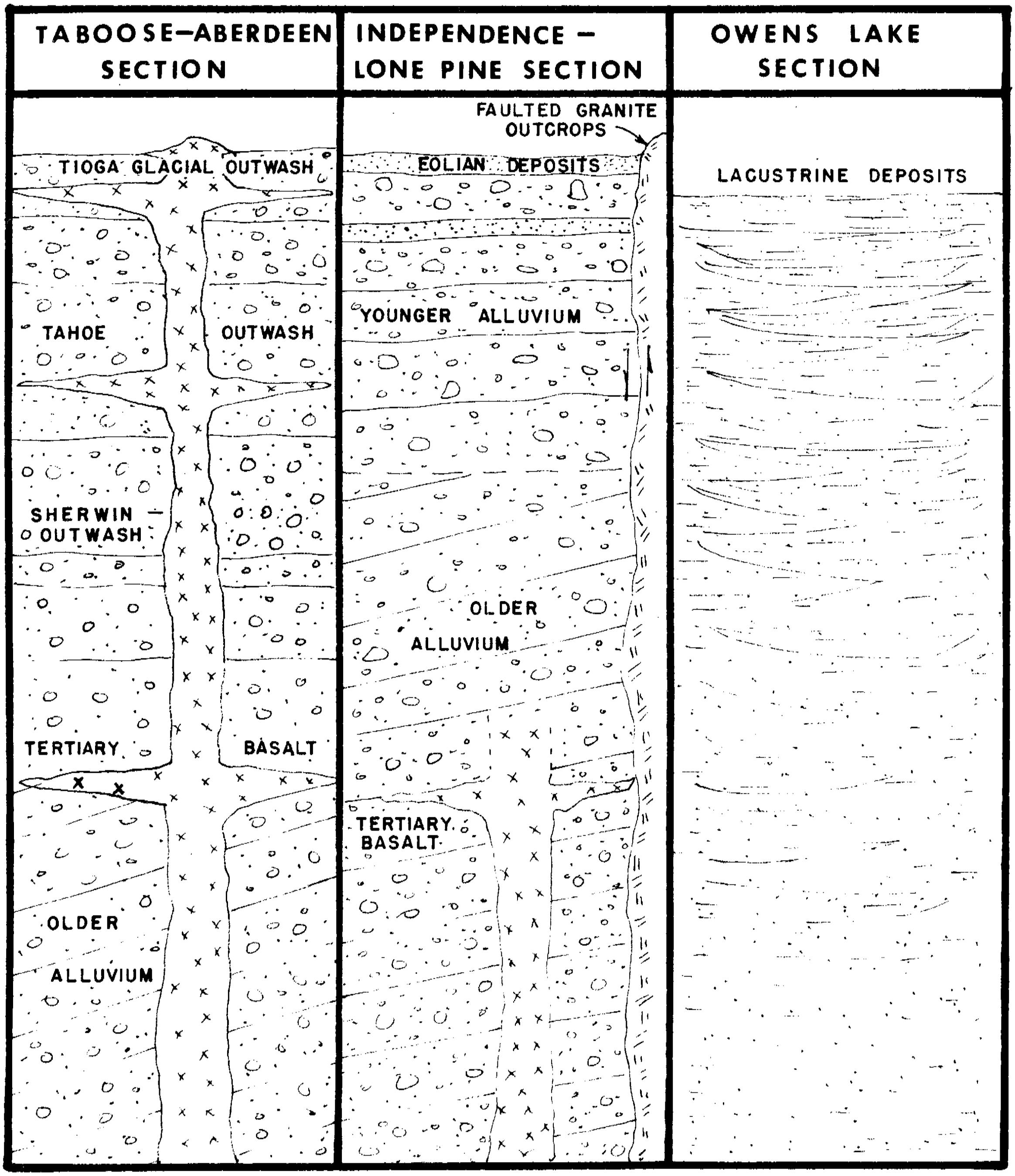


Fig. 2 LITHOLOGIC SECTIONS

Owens Valley is a large block of the earth's crust which is depressed along fault zones between mountain blocks. The erosional agents of water, wind and ice have destroyed original surface features along the great faults of the region. In the formation of the valley, the granitic mountain blocks were separated by faults from the valley block which was sinking and receiving a thick deposit of sediments. The faults, which separate the valley from the mountain blocks, slope toward the valley and occur in a fault zone three or more miles wide (Fig. 3). This fault zone is a series of steps descending from the mountain areas into the valley, and vertical separations of more than 900 feet occur on some steps. The lowest point in this cross section is 6,000 feet below the surface or about 4,000 feet below sea level. About 12,000 to 14,000 feet of relative vertical separation has occurred across the fault zone (Pakiser, 1964).

Many complicated geologic events have structured Owens Valley (Fig. 4). The simple structural concept voiced by geologists in the 1870's - that the valley is an elongate depressed block bounded by fault zones, lying between two elevated and in part tilted blocks - is essentially valid.

A detailed geologic map of the Owens Valley can be seen in Plate IV.

Aquifers

In discussing the geohydrologic properties of the study area, the fact that the westward originating storms deposit most of their

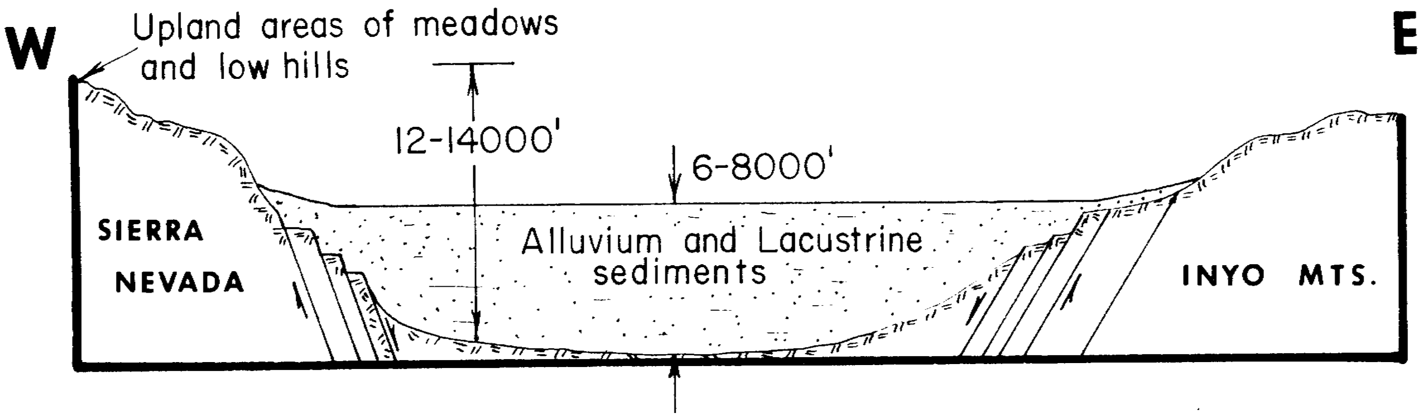


Fig. 3 GENERALIZED GEOLOGIC CROSS-SECTION IN SOUTHERN OWENS VALLEY

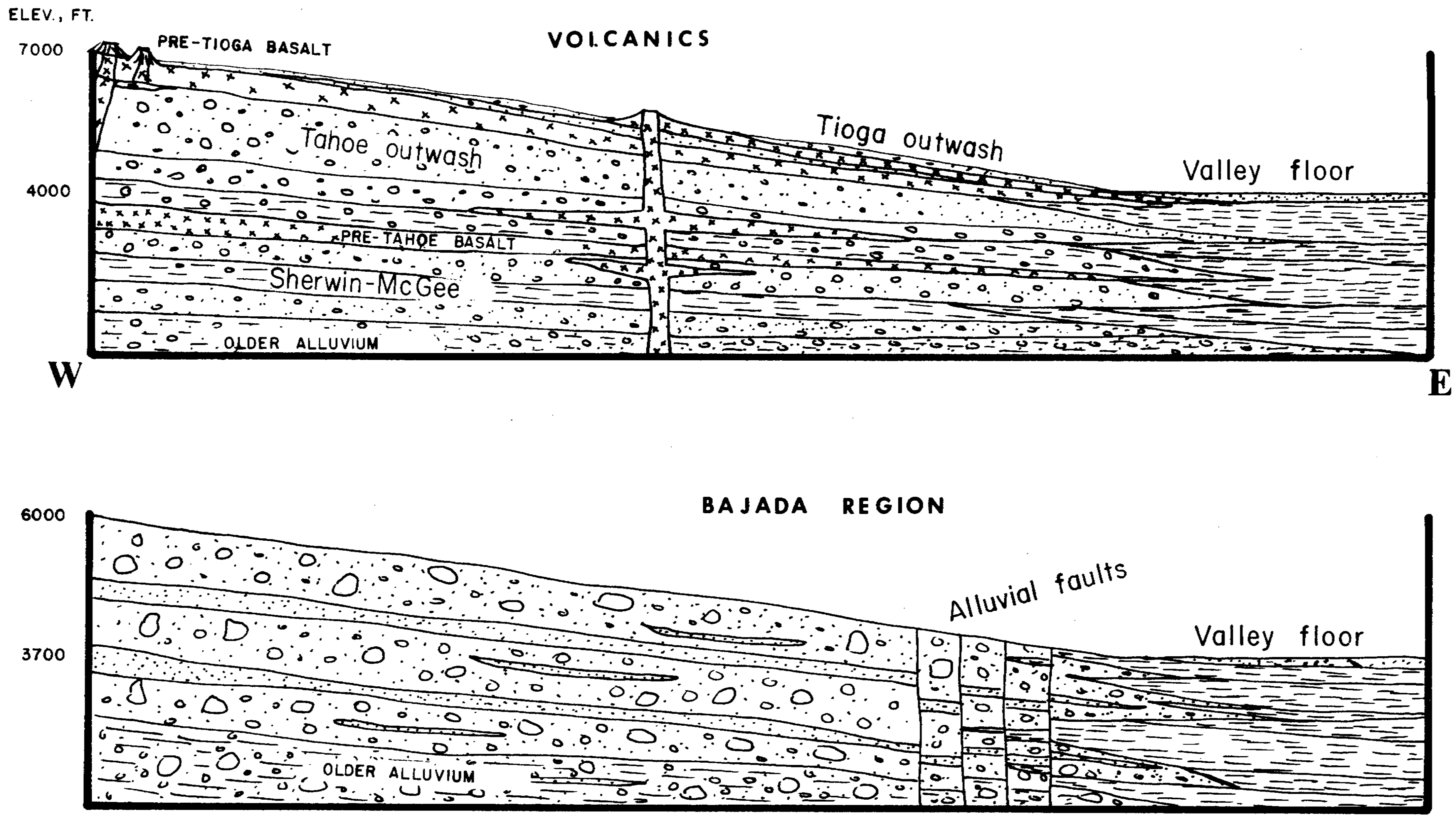
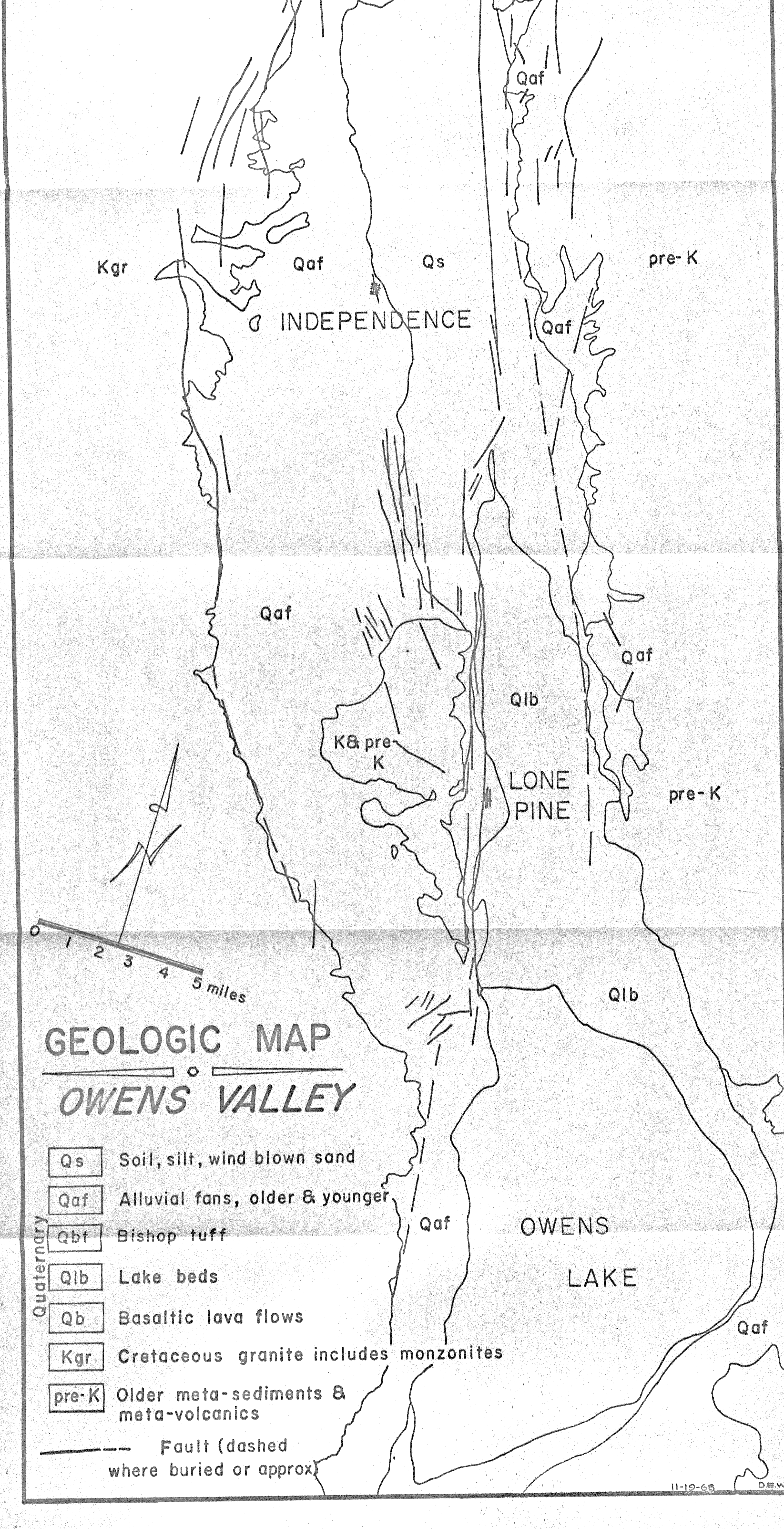
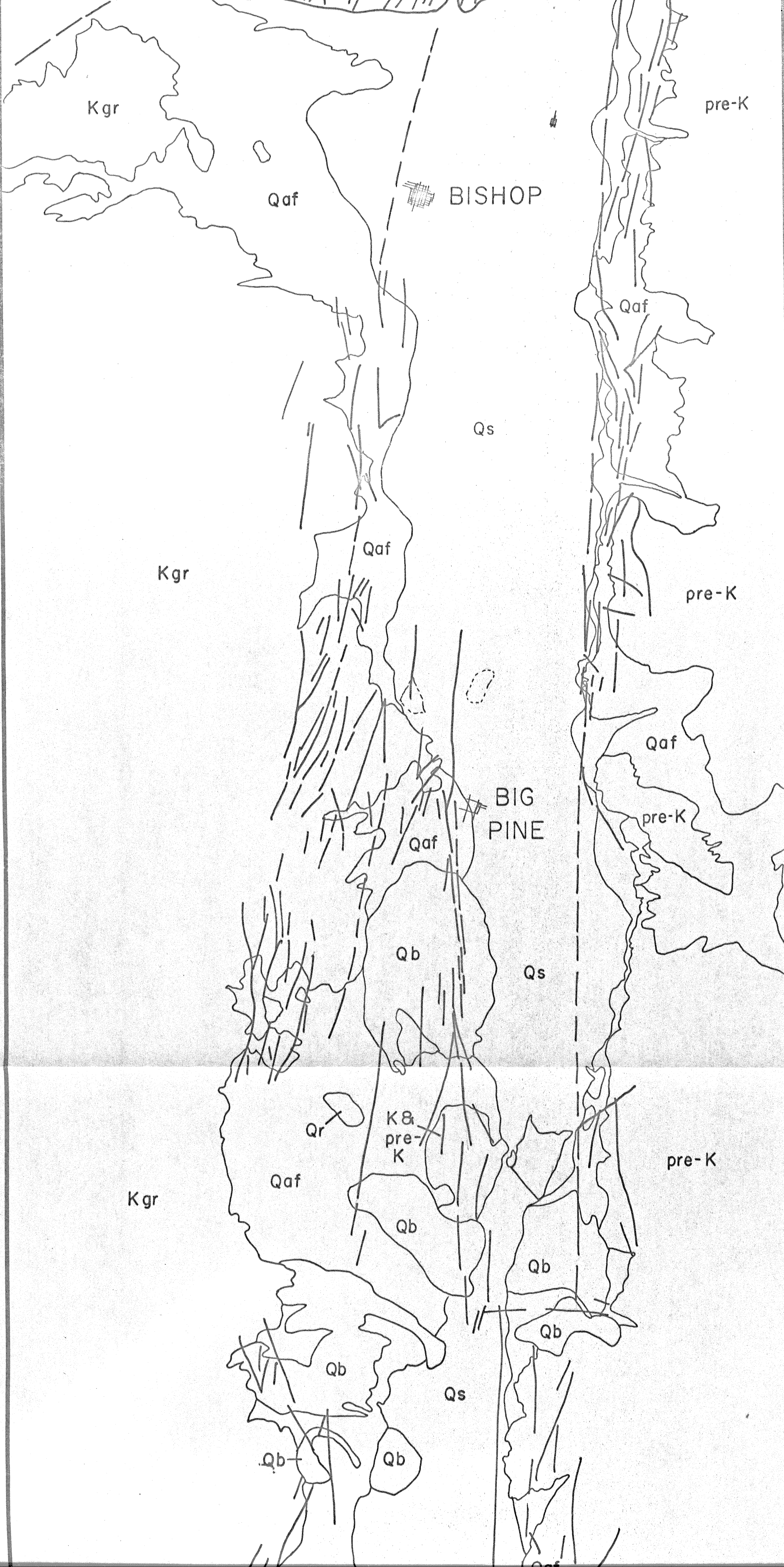


Fig. 4 GENERALIZED GEOLOGIC SECTIONS IN THE STUDY AREA

PLATE IV


GEOLOGIC MAP
OWENS VALLEY
Kgr
Qaf
Qs
pre-K
INDEPENDENCE
Qaf
Qaf
Qaf
Qlb
K& pre-K
LONE PINE
pre-K
0 1 2 3 4 5 miles
Qlb
Qaf
OWENS LAKE
Qaf
Qs Soil, silt, wind blown sand
Qaf Alluvial fans, older & younger
Qbt Bishop tuff
Qlb Lake beds
Qb Basaltic lava flows
Quaternary
Kgr Cretaceous granite includes monzonites
pre-K Older meta-sediments & meta-volcanics
Fault (dashed where buried or approx)
11-19-68
D.E.W.



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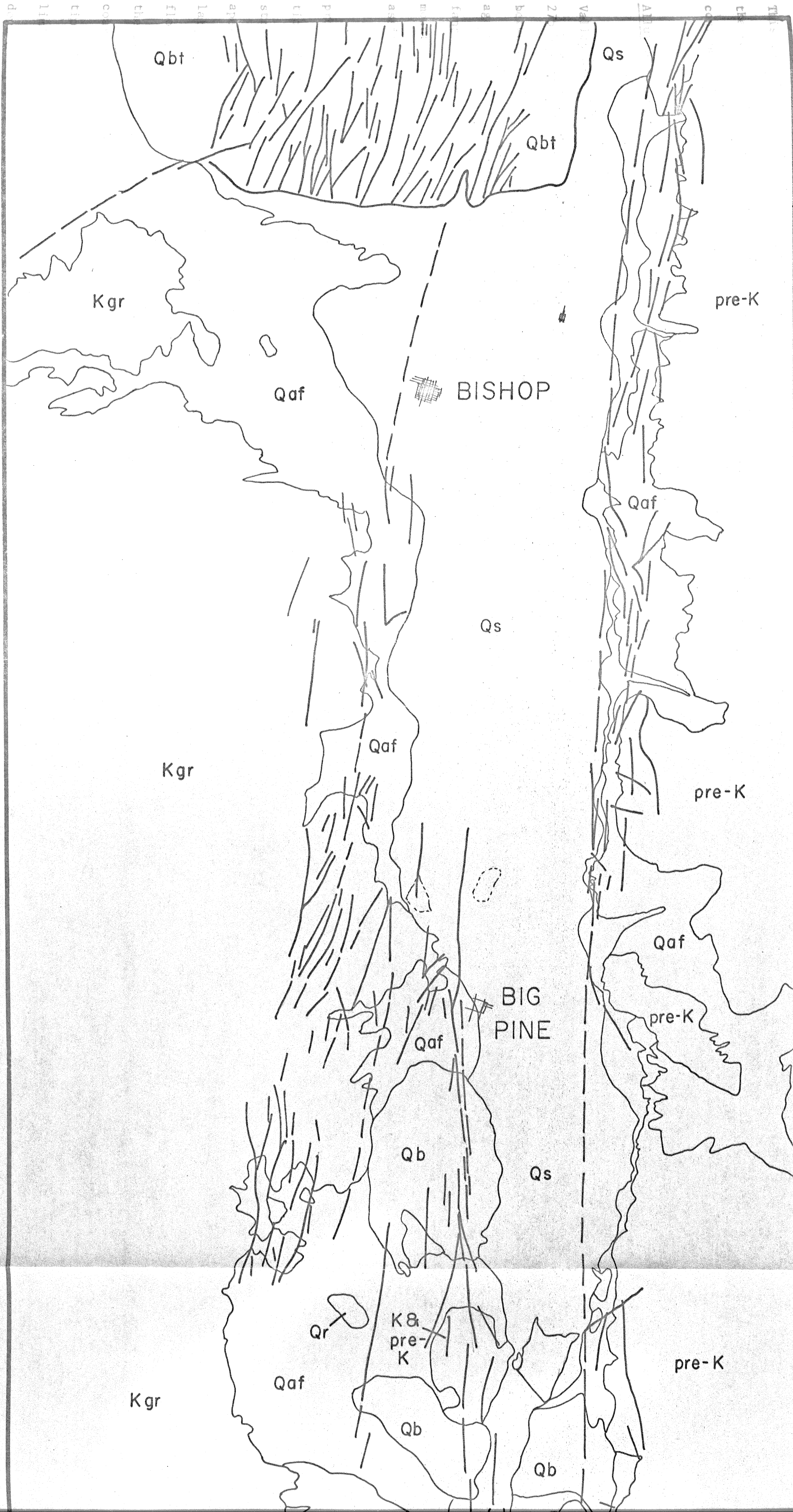
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precipitation on the Sierra Nevada simplifies matters considerably. This lack of precipitation results in very little water supply from the east side of the valley. The discussion therefore, will be confined strictly to the area west of the Owens River.

Alluvial Fans

The most extensive water-bearing formations in the Owens Valley are the massive alluvial detritus fans. Comprising more than 275 square miles of surface area on the eastern flank of the Sierras between Bishop and Owens Lake, these alluvial fans provide vast storage reservoirs for underground water. The general appearance of these fans is that of a broad apron (bajada) gently merging the base of the mountains with the valley floor and the name "Bajada Reservoir" is assigned to these ground-water reservoirs (Plate V).

The general depositional pattern of the alluvial fans has probably changed very little since the original uplifting and degradation of the Sierra front. The pattern is simple in context. Perennial stream flows form pervious sand deposits in channels extending from the apex to the foot of the cone. Torrential downpour then might furnish large amounts of material of intermixed sizes, which is deposited by floods beyond the stream channels, the coarse material at the apex and the fine material toward the foot of the cone. A heavy flood may spread coarse material, including great boulders (Plate VI), over the upper portion of the cone, but lower down the deposition of coarse material is limited to the stream channel, and the subsiding flood waters may lay down a layer of silt and clay over the lower portion of the cone.

Independence-Oak Bajada reservoir (S.W. view).

Sawmill Canyon - Bajada region.

Heterogeneous alluvial fan deposits northwest of the Alabama Hills (Boulder in lower photo is approximately 15 ft. across).

This heterogeneity in the alluvial cones of the Owens Valley is evident by observing their cross sections in dissected stream channels.

The general hydrologic structure is the same for most alluvial fans but the quantity of water absorbed and delivered to the aquifers, the velocity of subsurface motion of water, and the degree of confinement of the deeper waters are of great variety.

If the material of the fans is derived from mechanically disintegrated granitic formations, as are the ones in the Owens Valley, the deposit may be more permeable downslope of the fan, where large bodies of sorted sand occur (Plate VII), than at the apex, where heterogeneous deposits of boulders cemented with finer material occur.

The recharge area is a belt covering the upper and pervious portion of the fan and extending down the present stream channel. The belt outside the stream channel absorbs rainfall and surface and subsurface runoff from the mountain watershed tributary to the cone. The quantity absorbed by this area is difficult to determine. In some cases it may be large and in others small.

Influent stream seepage in the intake area is usually the chief source of supply of ground water.

Volcanic Formations

The most prolific water-bearing formations found in the Owens Valley are the basaltic lava flows. These lava flows issued from volcanoes located along fault lines, at the base of the mountains or in the alluvial outwash slopes. Extensive sheets of black and red basaltic

Well sorted alluvial fan deposits in the lower zones of the Bajada region.

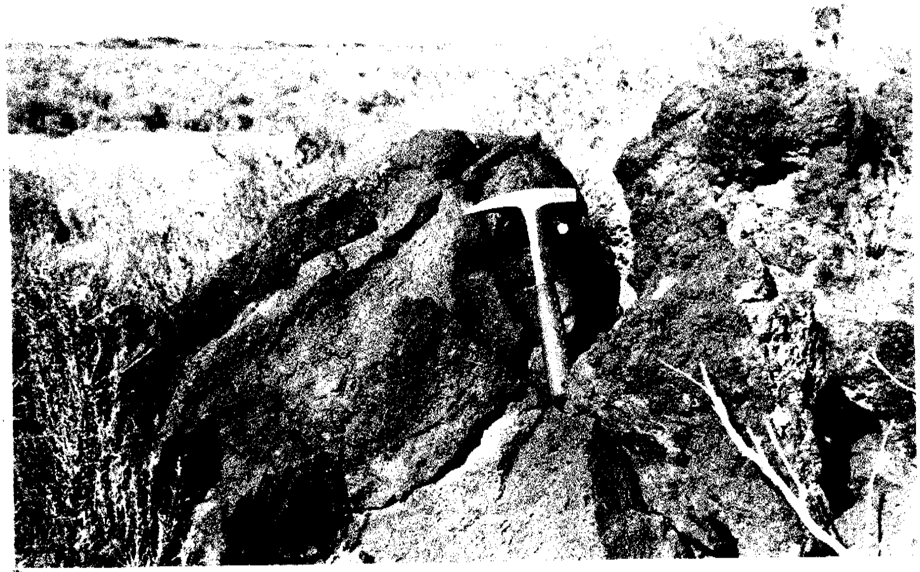
lava spread far and wide down the ancient outwash slopes at least two separate times in the geologic past. After the alluvial cones flanking the Sierra Nevada had attained their present heights, small flows of olivine basalt were emitted. Lavas of this period were later covered by moraines and aqueo-glacial deposits from the Tenaya-Tahoe glacial period. Existence of this early basalt flow was confirmed during the drilling of Well 342 near Taboose Creek. This earlier flow, and the accompanying pyroclastic deposits, constitute the main aquifer in the Taboose area; and properly developed wells in this aquifer have yields up to 10 cfs.

In pre-Tioga and post-Tahoe glacial time, another period of volcanism occurred (Pakiser, 1964). Remnants of this latest activity can be readily seen in numerous places throughout Owens Valley. This later flow appears as fresh as if it had cooled only yesterday (Plate VIII), but close examination reveals that it is partially buried in places by glacial outwash from the Tioga age. This partial covering is especially pronounced in the lower elevations near the floor of the valley. Where the water table occurs in this upper basaltic flow, as in the Big Pine and Aberdeen area, well yields are extremely high.

The upper lava flow is a potential site for artificial recharge of ground water. In this area there is virtually no runoff during storms, and the capacity for spreading ground water is a function of supply only.

The structure of the lava flows appears to be fairly predictable at depth, with porosity being a function mainly of thickness. In a very thick flow, the rock type is more massive and favoring a gray

Westward view near Taboose Creek showing recent basalt flows. (Post-Tahoe glacial age)



Close up of recent basalt showing excellent secondary porosity features.

dolerite rather than a true basalt. This is credited to the fact that the lava cooled more slowly and produced a rock of larger grain size.

The excellent secondary porosity, which sustains high yields to wells, originates from the fact that the top and bottom of the lava flow cooled quicker than the inner part. Contact with the relatively cool alluvium on the bottom, and the atmosphere on top, induced extensive formation of caverns, vesicles, and shrinkage cracks. On the top of a moving lava flow, crust forms, and due to viscous drag produced by the moving fluid inner portion, the upper crust is broken into twisted heaps and jumbles of blocks grotesquely piled together forming quite an irregular surface. If the flow is thin, this structure extends clear through. It is this characteristic "broken-up" structure along with the accompanying pyroclastic debris that makes these lava flows the prolific aquifers that they are. Aquifer tests have shown high yields, low drawdowns and very small recovery times (virtually non-measurable).

Semi-Pervious Formations (Aquicludes)

Pre-Tertiary Rocks

The pre-Tertiary rocks in the Owens Valley include basically the Cretaceous granites and monzonites of the Sierras, and the metamorphosed sediments and volcanics of the White and Inyo Mountains. Numerous isolated outcrops occur throughout the valley, the larger ones are Crater Mountain and Alabama and Poverty Hills. The fact that rocks of this type have essentially no primary porosity results in low permeabilities; and any that does exist is due solely to secondary porosity existing in the form of faulting, jointing, and weathering cracks. This secondary porosity is many times limited to a superficial zone, as seen from examination of several mines dug in both the granite and in the meta-sediments. Excellent secondary porosity and seepage was, however in one case, evident in a mine tunnel several hundreds of feet in. Evidence of ground-water movement can be seen in pre-Tertiary rocks from observation of springs on the eastern flank of the Alabama Hills and at numerous locations on the lower east flank of the Sierra Nevada. Usually the pre-Tertiary rocks in the Owens Valley are not thought of as being water bearing. The fact that secondary porosity exists in the form of the near surface weathered layer must place these rocks in the class of aquicludes.

The actual quantity of water moving through the pre-Tertiary structure is difficult to determine due to the randomness of the secondary porosity cracks. This quantity is undoubtedly small compared to the quantity of water transmitted through the alluvium and volcanics.

Older Alluvium

Lying beneath the present piedmont alluvial slope is a layer of older alluvium deposited as the result of the degradation of the Sierra after the original mid-Tertiary uplift (Pakiser, 1964). This period was one of relatively arid conditions as compared to subsequent glacial times. The alluvial cones formed during that time were probably individual and well defined, similar to the present-day cones lying on the west side of the White and Inyo Mountains (Knopf, 1918). This older alluvium is generally believed to be more consolidated and consequently less permeable than the overlying younger alluvium. This fact is known from studies of other alluvial fans (Toleman, 1937). The decrease of permeability with depth is due to increased consolidation as the result of disintegration and alteration of the constituent minerals, intensified by aridity.

Depth to bedrock in the Owens Valley varies from section to section due to the nonuniform nature of faulting. Gravity and seismic surveys reveal from 5,000 to 8,000 feet of "undifferentiated Cenozoic deposits" (Pakiser, 1964). In these are included the older and younger fans. Wells drilled to depths of 500 feet near the toe of these fans end in permeable strata, and for estimation of the ground-water reserves stored in the fans, it is assumed that generally there is at least 500 feet of saturated unconsolidated alluvium above the older fans. This may be a conservative estimate, but until more wells are drilled high on the fans, the exact depth to the older alluvium still remains unknown.

Lacustrine Deposits and Fine-Grained Sediments in the Valley Floor

Lake beds in the center of basins usually form aquifers of secondary importance only. Even the extensive beds deposited in the Pleistocene lakes Bonneville and Lahontan in Utah and Nevada are not productive aquifers. Ancient lake beds may be important locally as in upper Owens Valley near Bishop, where stratified beds of pumice or "glass sand" apparently constitute the important aquifer. The conditions are entirely dissimilar in lower Owens Valley where the small specific yield of the fine lake beds of the Quaternary Owens Lake results in only very small flows to deep wells. These differences were discovered by drilling and show the heterogeneity in the same region where surface examination indicates similarity in occurrence of ground water.

Occasionally the gravels deposited by streams flowing down the axis of the valley are of importance, as in upper Owens Valley near Bishop; or they may be of little importance where deposits of limited extent only have been laid down in channels cut in clay and silt, as in lower Owens Valley. In general, the deposits of the valley floor consist of at least 800 feet of fine silt and clay as measured in borings. It is for this reason that the fines of the valley floor, from the toe of the alluvial fans eastward, are considered as only semi-pervious at best and do not constitute aquifers.

Non-Water-Bearing Formations (Aquifuges)

Pre-Tertiary Rocks

The only truly non-water-bearing formations in the Owens Valley aquifer system are the interior portions of the Cretaceous granites and the metamorphosed sediments and volcanics. The lake beds and clay deposits, even with extremely low hydraulic conductivities, must be considered as semi-pervious formations (aquicludes) and not impervious to the flow of ground water. The major importance of the non-water-bearing formations is their effect upon the movement and direction of the ground water and is discussed appropriately in the next section entitled "Geologic structures affecting ground-water movement."

With the exception of near-surface features previously discussed, the major bodies of the Sierra Nevada, White and Inyo Mountains, and isolated "bedrock" outcrops are considered to be aquifuges and therefore non-water-bearing.

Geologic Structures Affecting Ground-Water Movement

Prominent Bedrock Outcrop Features

Bedrock outcrops of varying size occur scattered throughout the valley obstructing, or at least partially altering the path of the moving ground water (Plate IX). Major outcrop features such as the Alabama Hills, the Poverty Hills, and Crater Mountain serve as large scale obstacles which determine local flow patterns in their respective areas.

The Alabama Hills and the Poverty Hills are similar in geologic structure, both consist partially of Cretaceous granite and partially of older metamorphosed sediments and volcanics. At best, the fractured surface layers of these structures constitute aquicludes and extensive faulting undoubtedly exists in their interior. On the macroscopic flow scale, they act as definite hydrologic barriers to the moving ground water. At first glance, Crater Mountain located south of Big Pine appears to be a volcano of great height. Closer examination, however, reveals granitic outcrops poking out of the flanking lava flows.

Faults

The major geologic structures affecting movement of ground water are the numerous faults cutting the valley aquifers (Plate IV). These faults, for the most part, act as semi-pervious "dikes," partially damming the flow on the upstream side thus creating a high ground-water

Cretaceous granite outcropping through the alluvium north of Big Pine.

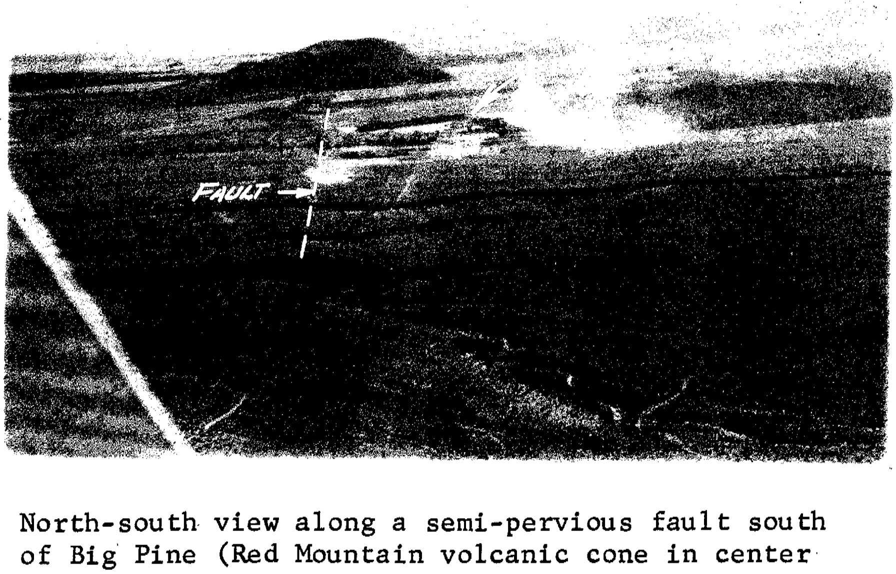
Western edge of Poverty Hills (left center) showing damming effect of ground water (high ground-water area shown by arrow in center of photo).

condition (see Plate X). The reduced permeability probably occurs as a result of the formation of clay minerals from alteration of the potassium feldspars in the gouge zone. The degree of impermeability varies from fault to fault, and in general, the older alluvial faults appear to be less pervious than the younger ones.

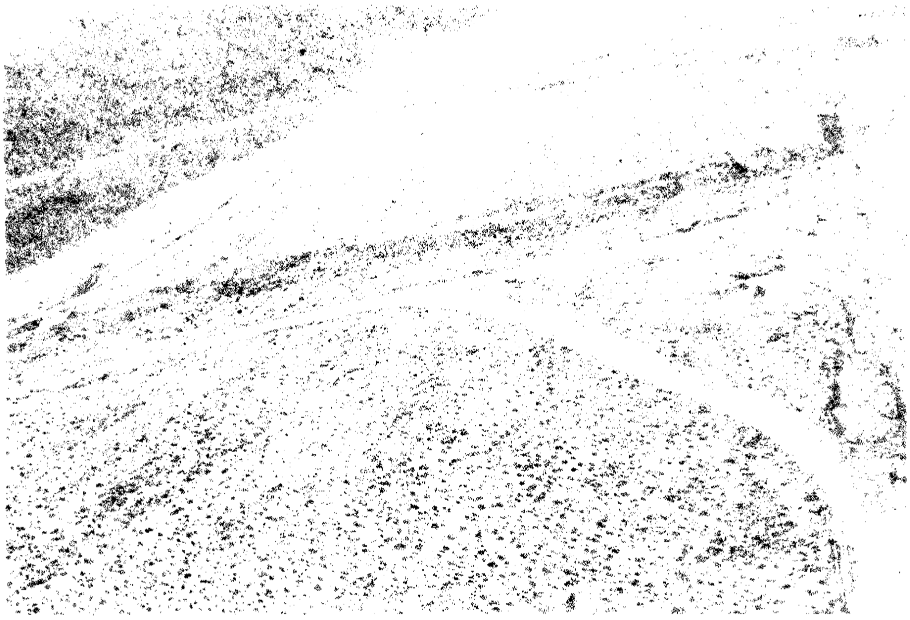
Extensive research as to the nature of these alluvial faults in the Owens Valley was conducted in the summer of 1968 in conjunction with the Mackay School of Mines of the University of Nevada. Trenching across several major faults was undertaken in order to obtain information regarding their attitude and nature of the gouge zone (see Plates XI and XII). Close examination of the trenches cut in the 1872 fault scarps north of Lone Pine reveal literally no alteration of the constituent minerals, and in fact the gouge zone is only a few inches wide (Plate XIII). The most impressive feature of these younger fault scarps is their lack of alteration. Except for minor weathering of the steeper scarps, they appear as fresh and unaltered as if they were heaped up by a bulldozer only yesterday (Plate XIII). Older faults such as east of Independence and near Shepards Creek reveal "clayey" minerals dominating the gouge zone which, in the case of the Independence fault, measures 20 feet or more in width.

The main areas of moving ground water affected by faults in the Owens Valley can be seen in Plate IV by studying the mapped north-south faults in the alluvial-fan material. The alluvial faults appear as an "en echelon" or "shatter" type pattern and are rarely seen as a single break. This "shatter" zone acts as a barrier to ground water

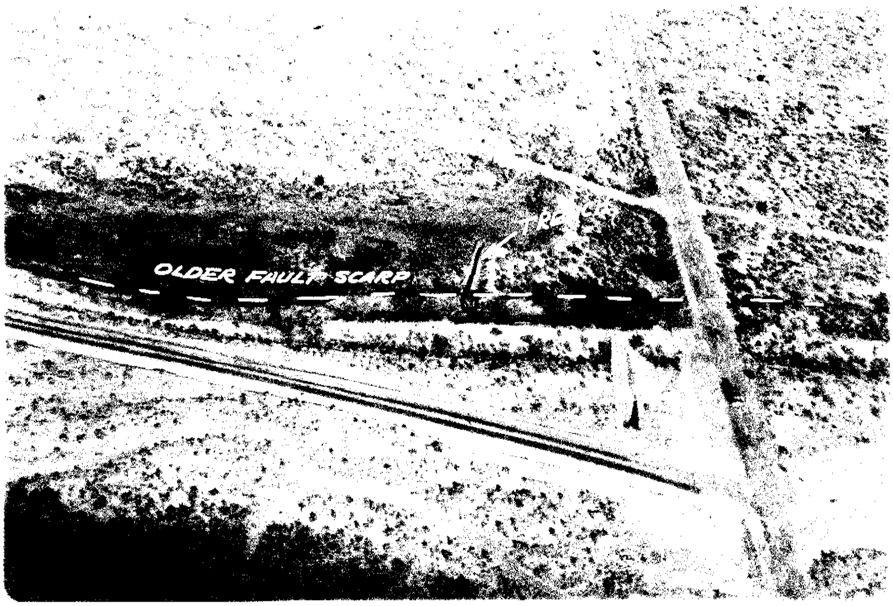
High ground-water condition caused by semi-pervious alluvial fault near Red Mountain. (Note heavy phreatophyte growth on lower half of photo.)



North-south view along a semi-pervious fault south of Big Pine (Red Mountain volcanic cone in center of photo). Note high ground-water area in center of photo (arrow) caused by damming action of the fault.



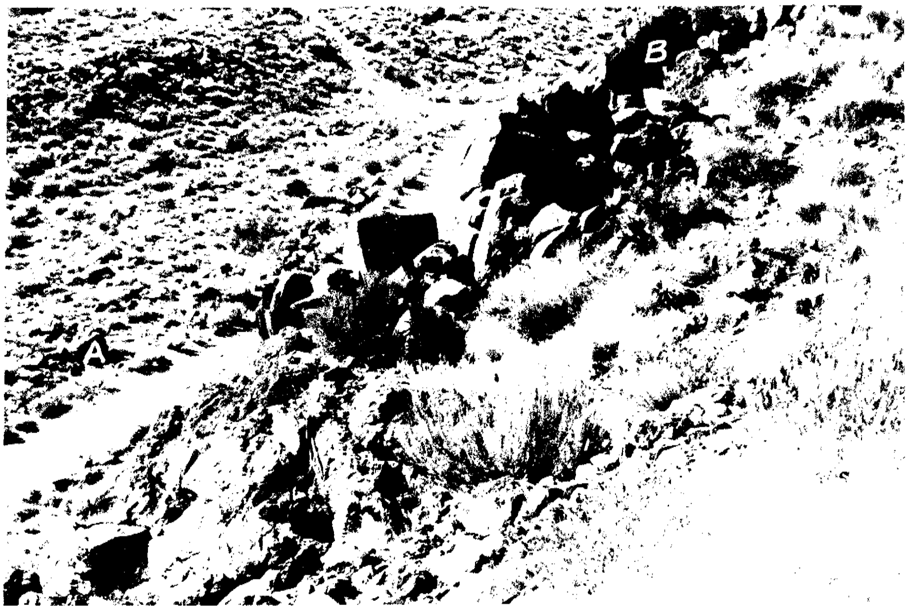
Aerial view of trench across 1872 fault scarp north of Lone Pine near Joe White gravel pit.



Aerial view of older mid valley fault after trenching east of Independence near Citrus Road.

Dragline digging trench across the 1872 fault scarp at the north end of the Alabama Hills.

Close up of above trench. (Note seepage of water encountered about halfway up scarp.)



View from the top of an alluvial fault scarp produced by the earthquake of 1872. Relative relief from point A to B is 23 ft. (Photo taken NW of Lone Pine.)

Cross section through recent alluvial fault scarp (1872). Note hairline cracks showing no alteration in the plane of faulting. Attitude of fault breaks dip 65° E.

moving across it, as typically illustrated in the phreatophyte growths seen in the photographs of Plate X.

This paper proposes to utilize beneficially the retarding properties of these alluvial faults. An artificial recharge system involving the spreading the creek flow on the alluvial fans well up gradient from these faults, and then extracting the stored water through wells just above the faults where pumping lifts would be low, is proposed. By selectively spreading and extracting water in this manner, maximum use and salvage of high ground-water areas could be obtained. The theory of a well pumping in the vicinity of a semi-pervious fault was developed by the writer in conjunction with this phase of the study and is discussed separately in a later section.

The Owens Valley is still very active seismically and many young alluvial fans, such as west of Lone Pine and Owens Lake, show the effects of recent faulting. Classic examples of these fresh fault scarps can be seen throughout the valley.

HYDROLOGY

General Water Supply, Use, and Disposal

The Owens Valley, hydrologically speaking, is a closed basin. All of the water entering the basin as precipitation within the watershed area is lost due to evaporation and transpiration within the boundaries of the basin. At least, such was the case in the relatively recent geologic past.

The main arterial trunk stream which drains the valley no longer discharges its cargo of mineral-laden water to Owens Lake, the natural sink at the southern end. The lake no longer serves as an evaporating basin sending water vapor back into the atmosphere and hosting the accumulation of vast deposits of mineral salts leached out of the material of the outwash slope many years before.

Since the early 1900's, man has altered the hydrologic cycle in the Owens Valley by exporting water from the basin.

Precipitation

The average annual precipitation in the Owens Basin varies from a minimum of about 3 inches on the valley floor in the southerly end, to over 40 inches near the top of the Sierra Nevada on the west. Precipitation in the area occurs predominantly as snow, and over two-thirds of the average annual precipitation occurs during the months of November through March. Summer thundershower activity results in high intensity rainfall but adds only a small amount to the water supply of the area. Average annual precipitation for the area is presented graphically in Fig. 5. Precipitation stations represented are located in Independence, Bishop, and at Haiwee Reservoir. Records of precipitation of significant length are not available in the easterly portions of the basin, and for purposes of the water budget were estimated.

Surface Inflow

Surface inflow is confined to the tributary streams draining the Sierra Nevada and to the main arterial trunk stream the Owens River.

Surface runoff in Owens Basin occurs chiefly as the result of the melting snowpack. (Phillips, 1963.)

The primary stream flow in the basin originates from the west on the easterly slopes of the snow-laden Sierra Nevada. Only minor amounts of runoff are contributed from the White and Inyo Mountains along the eastern side of the Owens Basin. With the exception of the Owens River, all streams within Owens Basin originating in the Sierra Nevada are generally short, and the magnitude of runoff in these streams decreases in a north to south direction. The total annual quantity of runoff in major streams also decreases in the same general direction.

The values for the creeks involved in the water budget as well as estimates of the ungaged areas between them are presented in Table 1, Appendix I. These values of runoff are measured at the base of the mountains where the creeks enter the valley fill. Where gaging stations were not appropriately located, estimates had to be made to account for stream bed loss for the reach of stream crossing the alluvium.

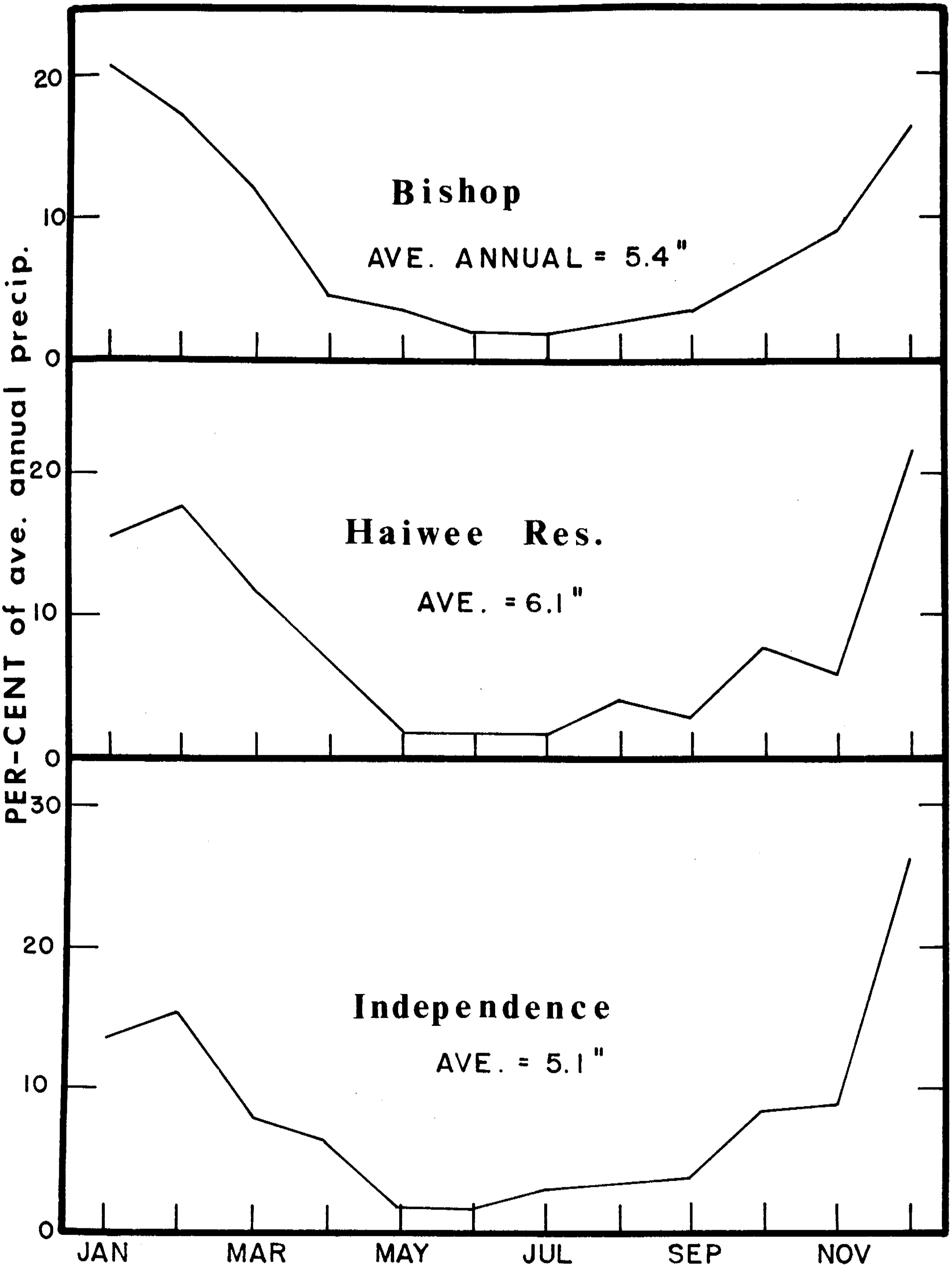


Fig. 5 GRAPH SHOWING AVERAGE ANNUAL PRECIPITATION

Water Quality

Water quality in Owens Valley is generally good to excellent. The water is predominantly calcium bicarbonate in nature. Total dissolved solids average about 50 to 200 parts per million in the surface waters and about 60 to 300 parts per million in most of the aquifers.

Some poor quality waters do exist. For example, some springs yield water with dissolved solids of as much as 600 parts per million and water from wells at Keeler contain over 1,000 parts per million.

Fresh Water Import and Export

Water has been imported into Owens Basin from Mono Basin since 1940 at an average rate of 70.3 cfs. The import into the study area is 348 cfs for the base period.

Export of water from Owens Basin has been occurring since completion of the first Los Angeles Aqueduct in 1913. The average rate of export for the base period is 436 cfs.

Subsurface Inflow and Outflow

The subsurface inflow to the study area across the imaginary line delineating the southern end of the Bishop injunction area (see page 58) is estimated to be 15 cfs. This is based on existing gradients in the area and average transmissivities.

There is no evidence to support existence of subsurface outflow from the area south of Owens Lake. A bedrock barrier consisting of pre-Tertiary structures prevents ground-water outflow (Knopf, 1918).

Consumptive Use

For purposes of this study it was necessary to determine the consumptive use of water for various types of land use on the lands overlying the ground-water basin. This consumptive use was broken down into that on irrigated lands and that in areas of high ground water sustaining phreatophyte growth. In addition, excessive spreading or wasting by evaporation was also delineated for the base period. These values are summarized in Table 2 (Appendix I).

In the Owens Basin large areas are subject to high ground-water conditions, consequently a large portion of the water supply is consumed by evaporation and phreatophyte growth. This is the area of considerable interest regarding salvage operations. By a review of aerial photographs of the area in conjunction with an exhaustive field study, the large areas of high ground-water table can be distinguished by a salt crust on the ground surface or by heavy vegetative growth (Ray, 1960). In the entire Owens Valley ground-water basin, including Owens Lake, it is estimated that as much as 200,000 acres have been subject at one time or another to high ground-water levels (Lee, 1912).

The amount of water used by evaporation and transpiration from areas of high ground water varies with the type of soil, plant growth, and the depth to ground water. Under the conditions obtained in the Owens Valley area, this use may vary from 1 foot to 4 or more feet per year where the ground-water table is 6 feet to 1 foot, respectively, below the ground surface (Lee, 1912). Where the average depth to ground water is less than 8 feet, a water use of 2.6 feet was calculated using the empirical method outlined by Thornwaite (Table 3, Appendix I).

The areas of high ground water in the region were planimetered from aerial photographs. The area presently sustaining phreatophyte growth in the study area occupies approximately 56,000 acres. This evapotranspiration loss amounts to a continuous flow of 200 cfs.

Water Budget and Safe Yield Determination

Using the data obtained from records over the base period 1937/38 to 1959/60 a water budget was computed for the area. Basically the hydrologic budget is:

$$I = O + \Delta S$$

where: I = total inflow, both surface and subsurface.

O = total outflow, both surface and subsurface.

ΔS = net storage gain, both surface and subsurface.

Since the net storage gain for both the surface and subsurface reservoirs over the base period was considered to be zero, the hydrologic budget reduces to Inflow = Outflow. The different components of the budget are presented in Table 2. The budget was forced to a balance by lumping the residual into unknown seeps and springs in the ground-water discharge term. This term was the most intangible of the terms. The result of 221 cfs is not unreasonable, and in fact, represents closely that which was determined from the aerial photographs.

The safe yield of the basin, or more correctly, "optimized safe yield" of the area, was obtained from the outflow side of the equation, mainly from the ground-water discharge term.

Although the optimized safe yield appears to be 221 cfs, the actual practicable safe yield or, the actual amount of water that could be extracted from wells in this basin more than likely would fall into the range of 60 to 80 percent of this optimized value, or somewhere between 130 to 180 cfs.

An illustrative example of the hydrologic cycle in the study area is presented in Plate XIV.

Ground-Water Movement and Storage

Direction and Rate of Ground-Water Movement

1968 "static" elevations of the ground-water surface were obtained throughout Owens Valley, and equipotential and flow lines were drawn on an overlay of the Geologic map (Plate XV).

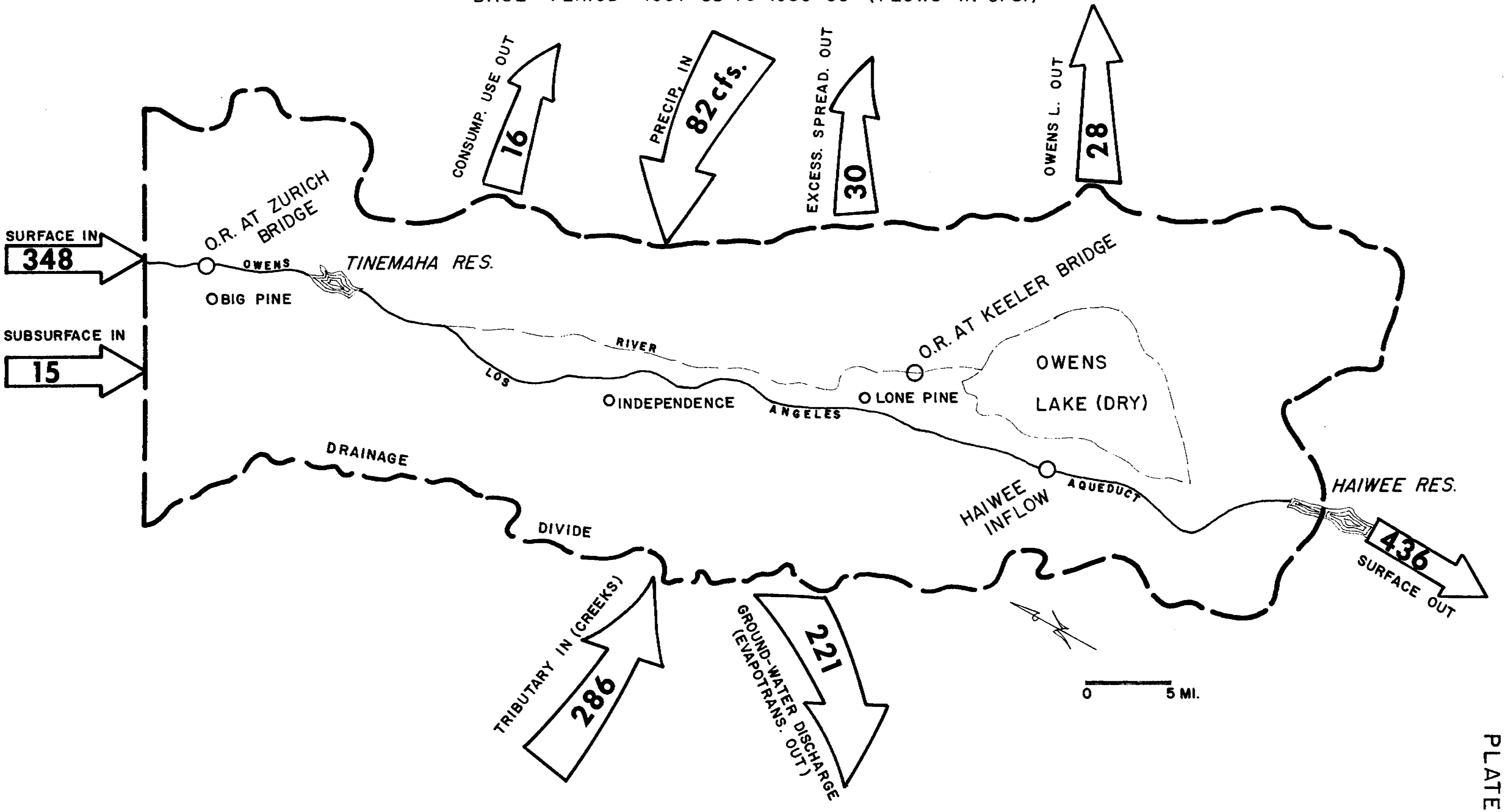
From this plate the general direction of ground-water movement was discerned as mainly eastward in the southern Owens Valley area, and the gradient seems to vary from 20 feet per mile near the toe of the alluvial fans, to 150 feet per mile farther up the slopes. The gradient also varies from place to place throughout the valley due to the heterogeneous nature of the formations. Control is noticeably lacking on the western edge of the map, and the levels plotted here are estimated from expected gradients in the area.

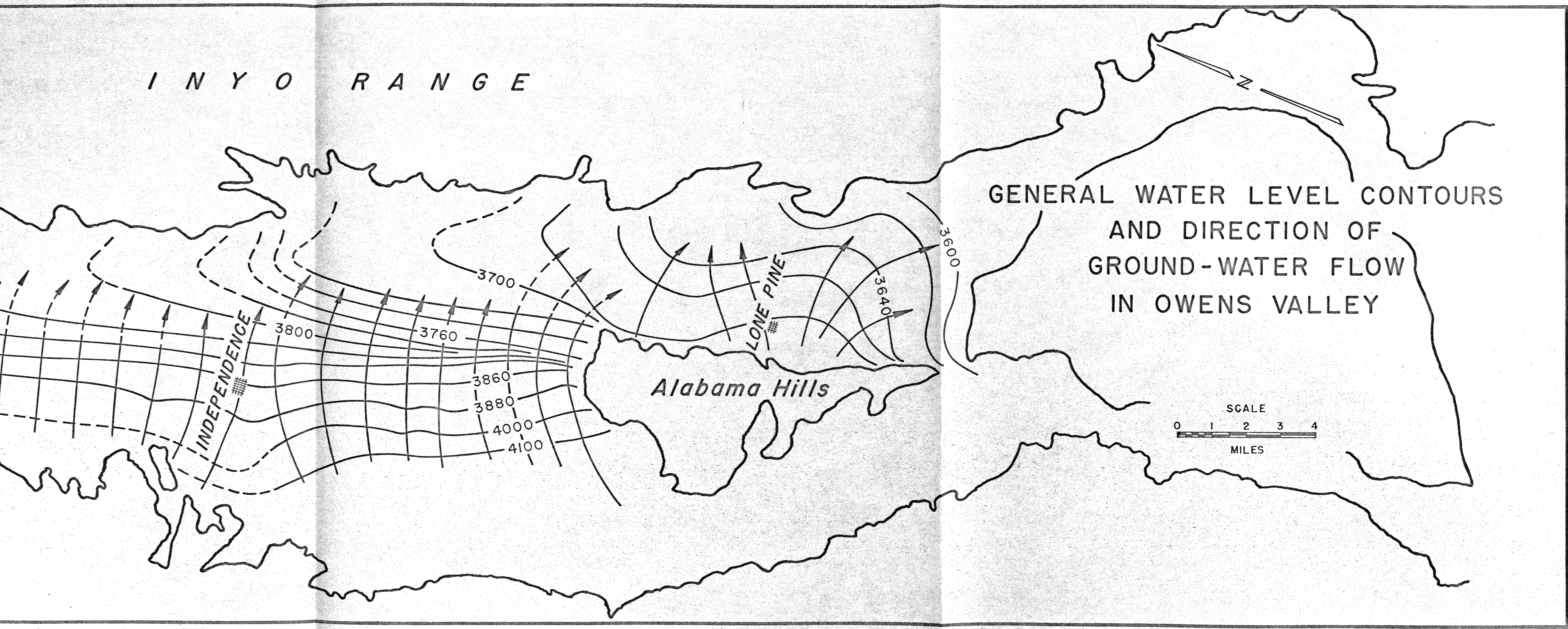
For purposes of estimating the approximate transit time, it is assumed that the "free fall" deep percolation in the recharge areas of the fans is completed and unidirectional flow occurs in a 2-mile stretch west of the discharge area.

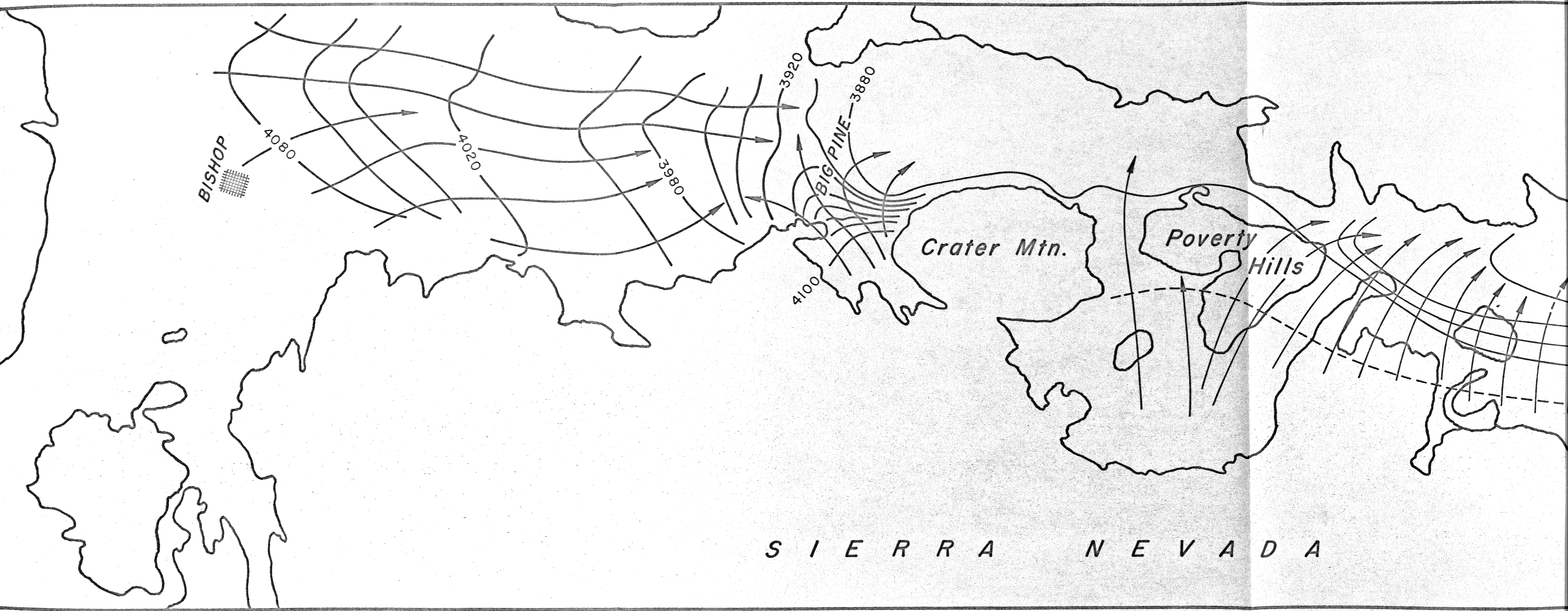
PLATE XIV

HYDROLOGIC BUDGET - BISHOP CONE TO OWENS LAKE

BASE PERIOD 1937-38 TO 1959-60 (FLOWS IN CFS.)




INYO RANGE
GENERAL WATER LEVEL CONTOURS AND DIRECTION OF GROUND-WATER FLOW IN OWENS VALLEY
N
3700
3800
3760
3860
3880
4000
4100
3600
3640
INDEPENDENCE
LONE PINE
Alabama Hills
SCALE
0 1 2 3 4
MILES



BISHOP
4080
4020
3980
3920
3880
BIG PINE
4100
Crater Mtn.
Poverty
Hills
SIERRA NEVADA

From aquifer tests in the Independence-Oak bajada, an apparent hydraulic conductivity is obtained by dividing the regional transmissivity with the saturated thickness penetrated in the observation well. More specifically,

$$K = 318000/352 \cong 1000 \text{ gpd/ft}^2.$$

From Plate XV (General water level contours), the hydraulic gradient in the Independence area is measured as 20 ft/mi.

The actual seepage velocity is obtained by dividing the hypothetical, or Darcian velocity, with the effective porosity. The effective porosity for the region is taken as the average of the storativities obtained from the multiple-well field analysis (i.e. $\overline{S} = 0.01$).

The travel time for a particle of water to reach the area of discharge from the area of recharge, some 2 miles westward up the alluvial slope, is computed from the seepage or effective velocity as follows:

$$t = \frac{\ell \theta}{K \, dh/dx}$$

$$t = \frac{(2)(.01)(7.48)(5280^2)}{(1000)(20)} = 209 \text{ days}$$

where: ℓ = path length (2 miles)

θ = effective porosity (0.01)

K = hydraulic conductivity (1000 gpd/ft^2)

dh/dx = hydraulic gradient (20 ft/mi)

The rate of movement in the volcanic areas can be similarly obtained. A transmissivity estimate of 838000 gpd/ft is taken as representative of the volcanics. (See aquifer test well 342.)

The apparent hydraulic conductivity is:

$$K = 838000/85 \cong 10000 \text{ gpd/ft}^2.$$

The hydraulic gradient in the volcanic areas is measured from Plate XV as 40 ft/mi.

From grain size estimates, an effective porosity of 0.10 is taken as representative of the region.

The travel time for a particle of water to traverse a 2-mile distance in the volcanic areas is:

$$t = \frac{(2)(.10)(7.48)(5280^2)}{(10000)(40)} = 104 \text{ days}$$

Description of Ground-Water Reservoirs

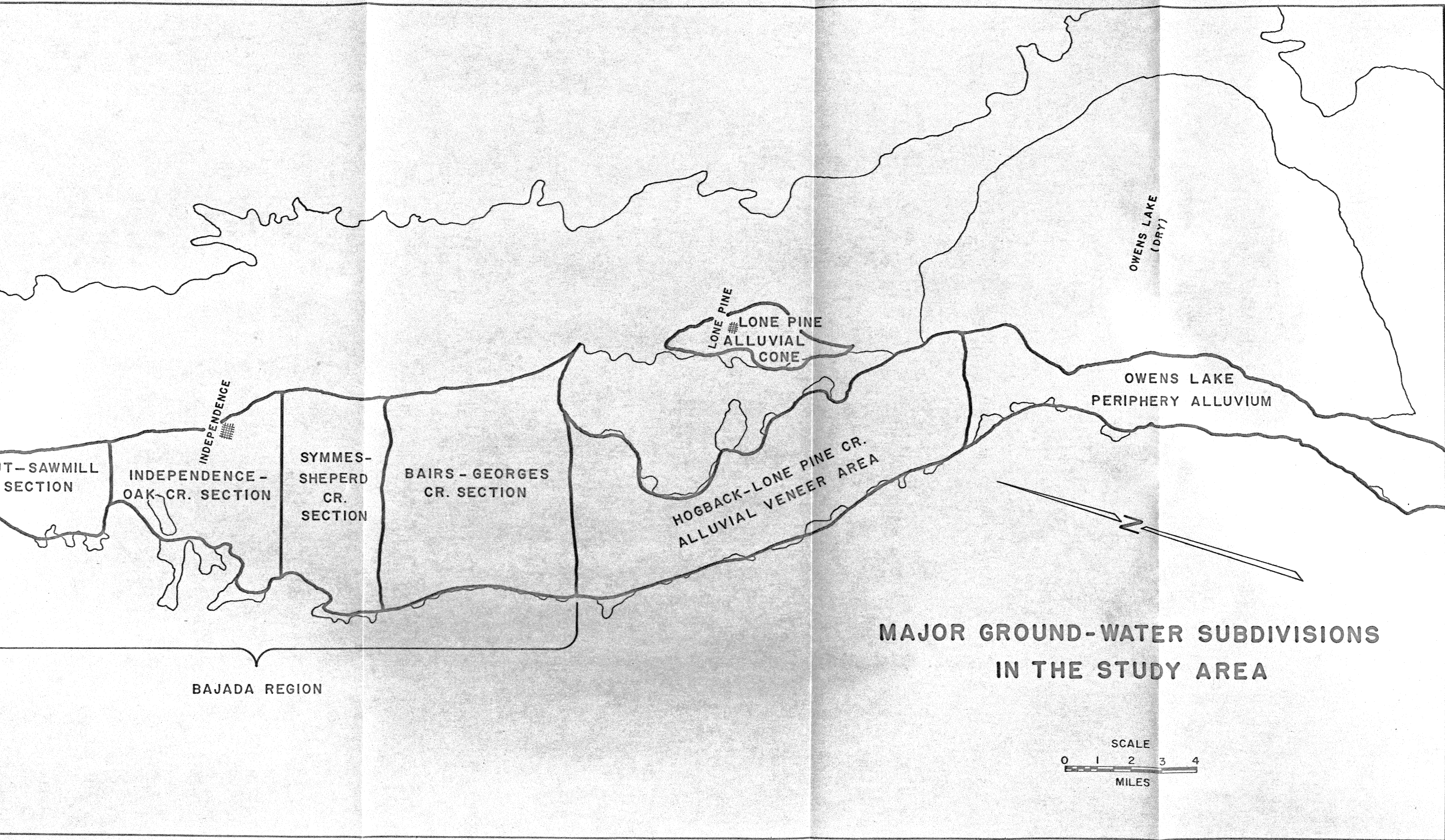
The individual ground-water reservoirs comprising the study area are shown graphically in Plate XVI. The distinctions are based on the best known hydrology and geology of the regions and represent separate geohydrologic entities.

Bishop Cone Injunction Area

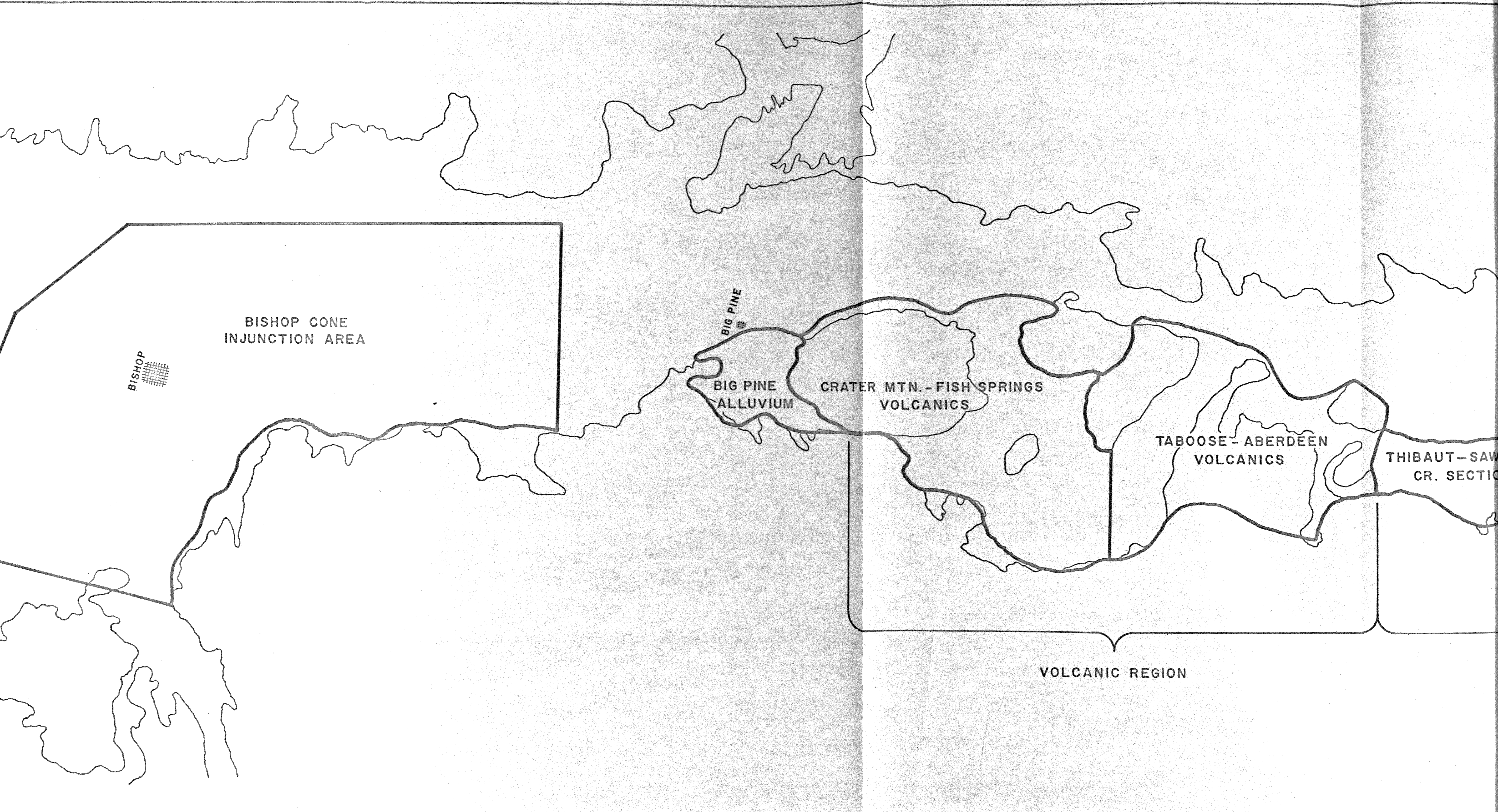
The area shown on the map as the Bishop Cone Injunction area is not included in the study area and is discussed only as a boundary area. The injunction resulted from a 1931 suit filed against the City of Los Angeles by the Hillside Water Company of Bishop. As a final outcome of this suit, there is no ground-water export from within the boundaries of the injunction area shown on Plate XVI.

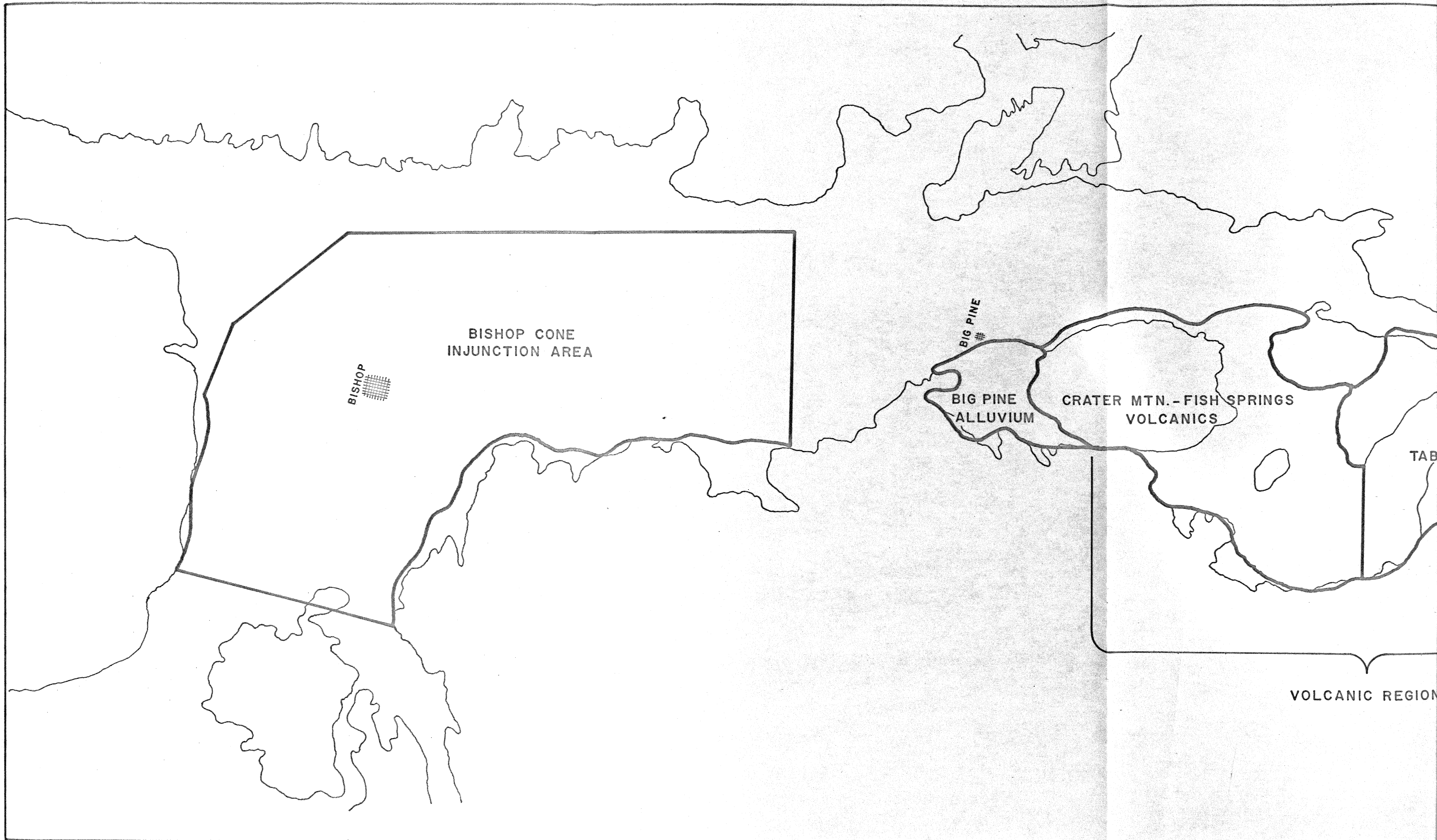
Big Pine Alluvium

The alluvial outwash west of the town of Big Pine is complicated geologically by the presence of numerous north-south alluvial



MAJOR GROUND-WATER SUBDIVISIONS IN THE STUDY AREA


BISHOP CONE
INJUNCTION AREA
BISHOP
BIG PINE
BIG PINE
ALLUVIUM
CRATER MTN.-FISH SPRINGS
VOLCANICS
TABOOSE-ABERDEEN
VOLCANICS
THIBAUT-SAW
CR. SECTIO
VOLCANIC REGION


BISHOP CONE
INJUNCTION AREA
BISHOP
BIG PINE
BIG PINE
ALLUVIUM
CRATER MTN.-FISH SPRINGS
VOLCANICS
TAB
VOLCANIC REGION

faults. These faults are excellent barriers to the movement of ground water and produce high ground-water areas on their upthrown blocks (see Plate X). The main bulk of the fan was formed from aqueo-glacial outwash during Pleistocene time. Consequently, borings in the area reveal many intercalated mud flows; in fact, even in recent times spectacular mud flows have been observed in the area just north of Crater Mountain.

The area is considerably less permeable than the Bajada areas farther to the south due to the amount of admixed clay and silt, at least in the area of the aquifer test performed on Well 341.

Crater Mountain - Fish Springs Volcanics

This area comprises the bulk of Crater Mountain on the north and extends to the drainage divide near Red Mountain on the south. The area is one of lava flows intercalated with alluvial deposits of fluviatile and/or aqueo-glacial origin. The main aquifer in this area is the recent lava flow (post-Tahoe) and associated pyroclastics. Water also occurs in the alluvium overlying this flow, but by far the extremely high yields experienced by wells in this area are due to the porous nature of the fractured basalt and cinders. Wells in the Big Pine "string" and near Fish Springs pump 5 to 7 cfs with relatively low drawdowns and no interference. Water percolating into the volcanics via the alluvium discharges at the toe of the basaltic lava flows in large springs. In this peripheral area, along the eastern edge of Crater Mountain, high yields to wells can be expected.

Taboose-Aberdeen Volcanics

The area shown on Plate XVI lying between Red Mountain Creek on the north and Sawmill Creek on the south is known collectively as the Taboose-Aberdeen volcanics. This area is similar to the Crater Mountain-Fish Springs area in that there are lava flows intercalated with alluvium. The main difference in the two volcanic fields is that the Crater Mountain-Fish Springs Reservoir is centered mainly around one main lava flow, Crater Mountain, while the Taboose-Aberdeen Reservoir is centered in a multitude of flows, originating along fracture lines both at the base of the mountains and in the middle of the outwash slope. Another difference between the two areas is that in the Taboose-Aberdeen area, evidence of the last two periods of volcanism (pre- and post-Tahoe) has been uncovered by drilling. The main aquifer is the fractured basaltic lava and associated cinders and lapilli. In this area very high yields are to be expected by drilling through the upper lava flow, and the interbedded alluvial detritus, to the lower lava flow (see aquifer tests - Well 342 and fig. 4). Underlying the lower lava flow of pre-Tahoe-glacial age is encountered a thick sequence of lacustrine silts and clays deposited by the freshwater predecessor of Owens Lake when it inundated the upper reaches of the valley during glacial times. It is not known how far west the shores of this ancestral lake extended, but it is generally believed that the pre-glacial alluvial cones were better defined than the present-day ones and had their peripheral margins closer to the base of the mountains. This tends to indicate that the shores of the ancestral lake were also closer to the base of the mountains (Knopf and Kirk, 1918).

The volcanic cones of the area are very well defined and appear fresh and unweathered. Closer examination, however, reveals that the processes of degradation are still taking place and have, in the case of Red Mountain, exposed the crude layered breccias making up the internal framework of the volcano. Outwash from late Sierran glaciation, along with the general alluviation processes, has partially covered the flows in this area giving a very disjointed and incoherent picture on the ground. Photogeology coupled with aerial reconnaissance in the field have revealed a clear picture of the processes which formed the Taboose-Aberdeen area, those of magma working its way up through conduits in the earth caused by faulting.

Bajada Reservoirs

The area occupying the alluvial fans between Sawmill Creek on the north and the Alabama Hills on the south is called "Bajada Reservoirs" in this report.

The significance of these areas is that the ground-water reservoirs occupy true Bajadas, coalesced alluvial fans (Frontispiece). As the geologic name implies, the reservoirs take the general appearance of broad aprons similar to each other in surface appearance, but aquifer tests have shown them to differ hydraulically. Buried localized bedrock features, faults, and character of the ancestral parent stream all contribute to the heterogeneity of the Bajada Reservoirs. For instance, the difference between the Bairs-Georges Creek Bajada and the others is the presence of a "shatter pattern" of semi-pervious alluvial faults near the lower edge of the fan producing areas of high ground water and evapotranspiration loss (fig. 4). This area favors salvage of high ground water more than others due to the existence of these faults. (See section on ground-water recovery and salvage schemes.)

The actual depth of the Bajada Reservoirs is difficult to determine accurately, but seismic and gravity profiles indicate that there is at least 1,000 feet of unconsolidated alluvium in this area (Pakiser, 1964).

Deep wells near the edge of these Bajadas encounter permeable sands and gravels throughout their depth, and for purposes of estimating reserves a saturated thickness of at least 500 feet is assumed.

Hogback-Lone Pine Veneer Area

In this area, the overlying alluvium forms a relatively thin veneer over the underlying bedrock granite beneath. Evidence of shallow bedrock was first confirmed from seismic and gravity surveys and can be observed in the numerous granitic outcrops poking up through the alluvium west of the Alabama Hills. The depth to water is probably relatively shallow, and several springs appear as the result of localized faulting. The area has less value as a ground-water reservoir than the deeper Bajadas to the north.

Lone Pine Alluvial Fan

This area is the result of outwash from Lone Pine Creek and receives a considerable amount of recharge. The area is too small and saturated for any large-scale spreading operations and would primarily favor pumping-salvage type operations of the high ground-water areas only.

Owens Lake Peripheral Alluvium

The area located around the periphery of Owens Lake consists mainly of small alluvial-fan deposits. On the west side, where water supply permits, reasonable yields to wells could be expected if location and source of supply were carefully considered. This is based upon the assumption that the hydraulic properties are similar to the Bajada region. Fresh-water springs occur in and around Owens Lake, indicating that a possible water supply exists on the lake's western flanks.

Volume of Water Presently Stored in Underground Reservoirs

Only areas classed as aquifers are considered as having potential for underground storage. There is undoubtedly a vast amount of water contained in the lacustrine sediments of the valley floor, but due to the low hydraulic conductivities, this water is not considered economically available. From analysis of the well logs in the areas, it is assumed for calculations that there is at least 500 feet of available saturated thickness in the Bajada areas, and 100 to 200 feet in the volcanic, alluvial veneer, and other areas.

The surface areas were planimetered and the storage computed and summarized in Table 4 of Appendix I.

The volume of water in storage was computed from the following equation:

$V = A \times b \times S$

V = Volume in acre-feet

A = Area in acres

b = Assumed saturated thickness in feet

S = Storativity

An average storativity of 0.01 was estimated by averaging the values obtained from the multiple-well field analysis.

Hydraulic Characteristics of the Individual Reservoirs

Aquifer Tests

The aquifer tests used in this study consisted of pumping well tests and multiple-well field analyses. A summary of the formation parameters obtained is presented in Table 5, Appendix I. The test data is presented in Table 6.

The pumping tests used in this study consisted of data collected from the pumping well itself. Due to the lack of proper observation wells, interference data could not be obtained.

Due to this lack of interference data, the method of analysis was restricted to step-drawdown theory. (Hantush, 1964.) Analysis of the first step of the step-drawdown data was used to obtain values of transmissivity (Jacob, 1946).

The artesian well theory was safely applied to the pumping well test data, as the correction factor ($s^2/2D_o$) was insignificant. (Hantush, 1964.) The denominator is defined as twice the saturated thickness.

In the cases of the pumping-well tests, the formation loss and well-loss component of the total drawdown were differentiated. These values were graphically plotted against well discharge as an aid to future operations.

Comment on Step-Drawdown Theory

In a pumping well, the observed drawdown is composed of two parts. One component represents laminar resistance of the formation to flow, while the other component reflects the head loss associated with turbulence.

Jacob (1947) suggested that differentiation of these components could be accomplished by assuming that formation-head loss vary as the first power of the discharge (BQ) and turbulent-head loss vary with the square of the discharge (CQ^2). "B" and "C" are constants representing well geometry and aquifer characteristics.

Rorabaugh (1953) in a general treatment of the theory suggested that turbulent-flow head loss vary as the "n^{th}" power of the discharge (CQ^n).

The exponent "n" in Rorabaugh's expression theoretically should never surpass 2 (Jacob, 1969), and that in actuality, fully developed turbulence in a "rough pipe" varies as $Q^{1.85}$ (Binder, 1962).

Values of n usually obtained from step-drawdown analysis typically are much higher than 2. The difference can be explained by the assumptions necessary for graphical analysis.

The constants "B" and "C" in Rorabaugh's equation are in most cases not constant at all but vary as a function of aquifer transmissivity and borehole geometry. For instance, the formation-loss "constant" B varies as $W(t)/4\pi T$. The "constant" C is a function of well geometry and closely reflects packing arrangement in the vicinity of the well.

Step-drawdown, or step-recovery tests conducted on undeveloped wells, or on wells where dewatering appreciably changes the saturated thickness, may lead to erroneous results.

In the graphical curve-fitting procedure, the equation thus derived is based on theory alone. This equation assumes ideal conditions.

If conditions during the test were ideal (as in a fully developed artesian well) where B and C actually remained constant, then the physical meaning of the head loss could be explained in terms of the theory. Too often the opposite situation is true. Dewatering of part of the formation produces macro-geometric changes in the well. Micro-geometric changes occur as the result of rearrangement of the media immediately surrounding the casing.

For the theoretical equation to fit the field data, these well-geometry changes must be incorporated into a variable. Since the theory allows no variable other than the exponent n in the well loss term, a hypothetical drawdown equation is often created. In other words, the theoretical well-loss term may not represent the actual well loss, but an unrealistic value derived as a result of inadequate theory.

To cope with this problem, Jacob (1969) suggested a more practical approach by assuming the pumping-well drawdown to vary as:

$$s_w = BQ^m + CQ^n \qquad 1 \leq m,\ n \leq 2$$

From the above discussion, it is obvious that equations relating pumping-well discharge to drawdown must be interpreted with caution.

In the wells tested in this study, values higher than 2 were obtained. These equations are still useful for predicting drawdown as a function of discharge, but the efficiencies obtained are undoubtedly higher than actual.

In one case (Well 341) the exponent n was found to be lower than 1. This low value was interpreted as being due to large macro- and micro-geometric changes, common in the developing stages of a well.

Pumping Well Test, Well 342

Two separate pumping tests were conducted on Well 342. One on March 9, 1966, and another on May 5, 1966.

The first test was conducted during the course of the drilling when the total depth was only 245 feet. Casing existed, unperforated, from the surface down to 165 feet, so that a true evaluation of the lower aquifer was obtained. A step-drawdown test was run consisting of 3 steps; and an effort was made to calculate the well loss.

The second pumping test was more elaborate and an effort was also made to determine the transmissivity as well as the well loss constant. The well was perforated in the upper water-bearing sands and gravels. The lower aquifer was left uncased in an effort to minimize as much of the entrance losses as possible. The summary of all the tests is given in Table 5, Appendix I.

The well was fitted with a high-lift pump consisting of 3 stages on a 12-inch column. The bottom of the bowls was set at 157 feet. Power was supplied to the pump by an industrial gasoline engine. The speed of the pump shaft was monitored by using a tachometer placed directly upon the exposed end of the rotating pump shaft. The discharge was measured with a Sparling "Measure Rite" flow meter installed in the discharge pipe. A 1/4-inch pipe was run down adjacent to the pump column and the upper end fitted with a pressure gage. This was used to measure the drawdown in the well while the pump was on. In addition to the step-drawdown test run, a test to determine formation constants was run by pumping the well at a high rate of discharge (7.9 cfs) for a period of 12 hours. During regular intervals of this extended pumping, the surrounding wells were observed to record any change in their water levels.

First, it should be explained that during the extended pumping of Well 342, the surrounding deep wells showed no measurable change in water level. It was hoped that a nearby domestic well, located approximately 600 feet away, would reflect the pumping. This well is 85 feet deep and penetrates only a few feet of the upper aquifer. It may be, since 90 percent of Well 342's yield was coming from the lower aquifer, that this well did not represent an accurate reflection of the piezometric head in the lower aquifer.

Without any observation-well data, the formation constants (transmissivity and storativity) could not be determined by standard methods of analysis. Due to the extremely fast recovery and stabilization of the water level during pumping, the non-steady-state methods could not be applied. If one could obtain several reliable drawdown measurements before the water surface reached a steady level, an estimate of the transmissivity could be made using methods such as discussed by Jacob (1947). But, due to the extremely fast stabilization of this well, it would probably take a pump capable of 20 cfs to obtain these measurements. With the present pump (rated at about 11 cfs), dynamic equilibrium was attained within less than 30 seconds. Any intermediate drawdowns could not be accurately made using the air-line method.

If a nearby observation well were available, close enough to reflect the pumping, one could apply any of the equilibrium methods to determine the transmissivity. (Johnson, 1966.)

Considering the limited data available, the only way to obtain a transmissivity value was to estimate it from the specific capacity (California, State Department of Water Resources, 1962). This is actually not a very consistent method as the specific capacity (Q/s) decreases with increasing discharge while the transmissivity is constant for any given aquifer.

Taking the average discharge value of 7 cfs, we see from fig. 6 the specific capacity (Q/s) is 419 gpm/ft. Applying the above procedure, which is based on an empirical constant, the transmissivity is computed to be:

$$(419)(2000) = 838000 \text{ gpd/ft.}$$

Although the transmissivity value had to be estimated from the specific capacity, an accurate measurement of the well loss was made by analyzing the data collected during the test.

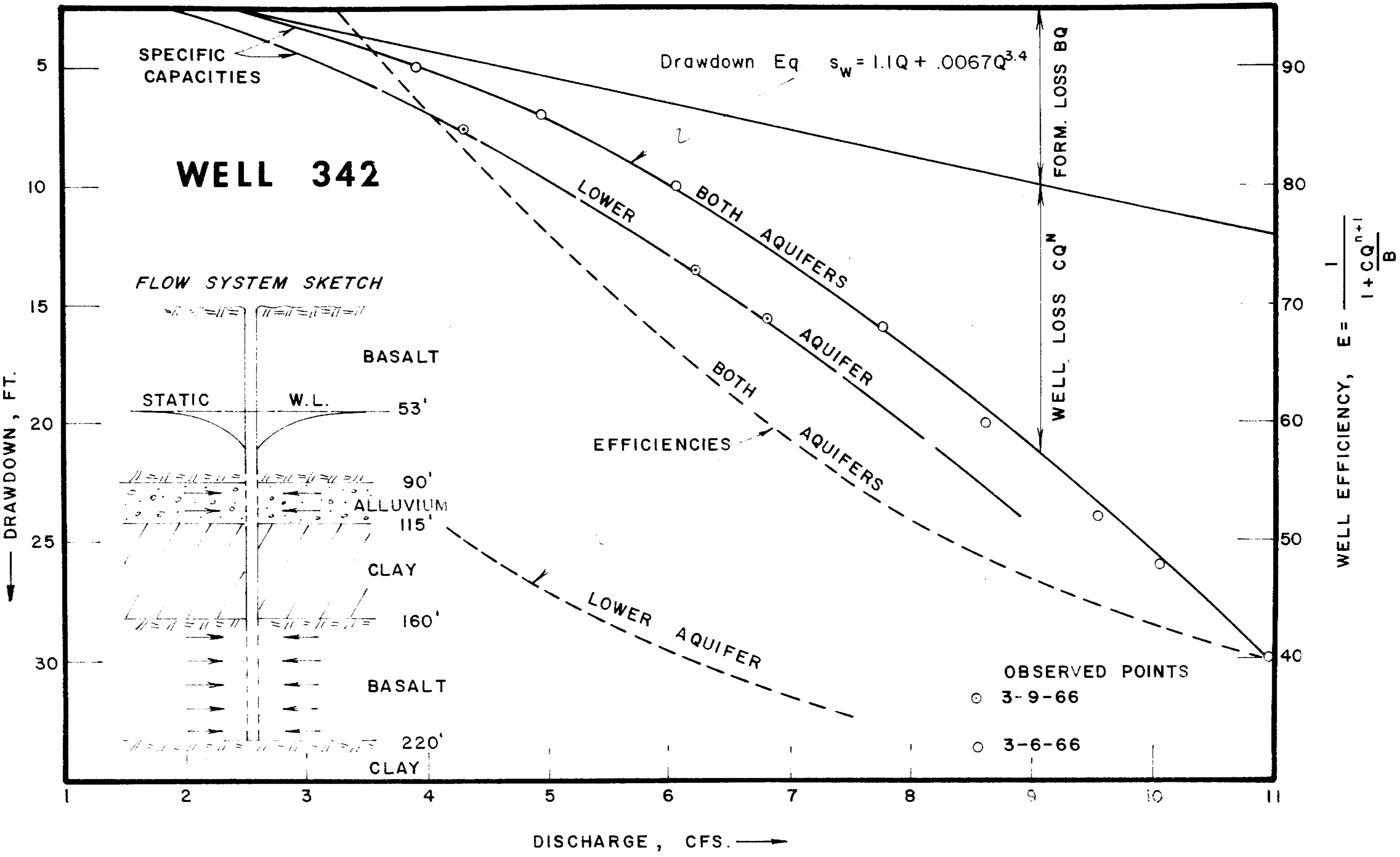


Fig. 6 SPECIFIC-CAPACITY DIAGRAM FOR WELL 342

Briefly, this procedure consists of a log-log plot of "$(s_w/Q-B)$" against values of the discharge, for assumed values of "B." The slope of the best fit straight line through these points determines "n-1," and the "$(s_w/Q) - B$" intercept at "Q = 1" determines the value of "C" (see fig. 7). The resulting drawdown equation for Well 342 is:

$$sw = 1.1(Q) + 0.0067(Q)^{3.4}$$

where 1.1(Q) represents the head-loss component due to the formation resistance, and $0.0067(Q)^{3.4}$ represents the head-loss component due to turbulence.

In fig. 6 drawdown was plotted versus discharge for both aquifers from data obtained in the May 5 test and again for the March 9 test. One can easily calculate the contribution of the upper aquifer at any discharge by subtracting the difference in discharge between the two specific capacity curves for any constant drawdown. At the maximum discharge tested (11 cfs), this contribution from the upper aquifer was only about 0.8 cfs.

From these two curves, the specific capacity (Q/sw) can be determined. It ranges from 396 gpm/ft at the 3 cfs discharge to 165 gpm/ft at the 11 cfs discharge.

Also in fig. 6, values of the formation loss, 1.1(Q), divided by the total drawdown in the well, sw, were plotted against values of the discharge. This is a direct measure of the efficiency of the well, in other words, a well that was 100 percent efficient would have no head loss due to turbulent flow, and the total drawdown observed in the well would be that head loss which was caused by the laminar formation resistance only.

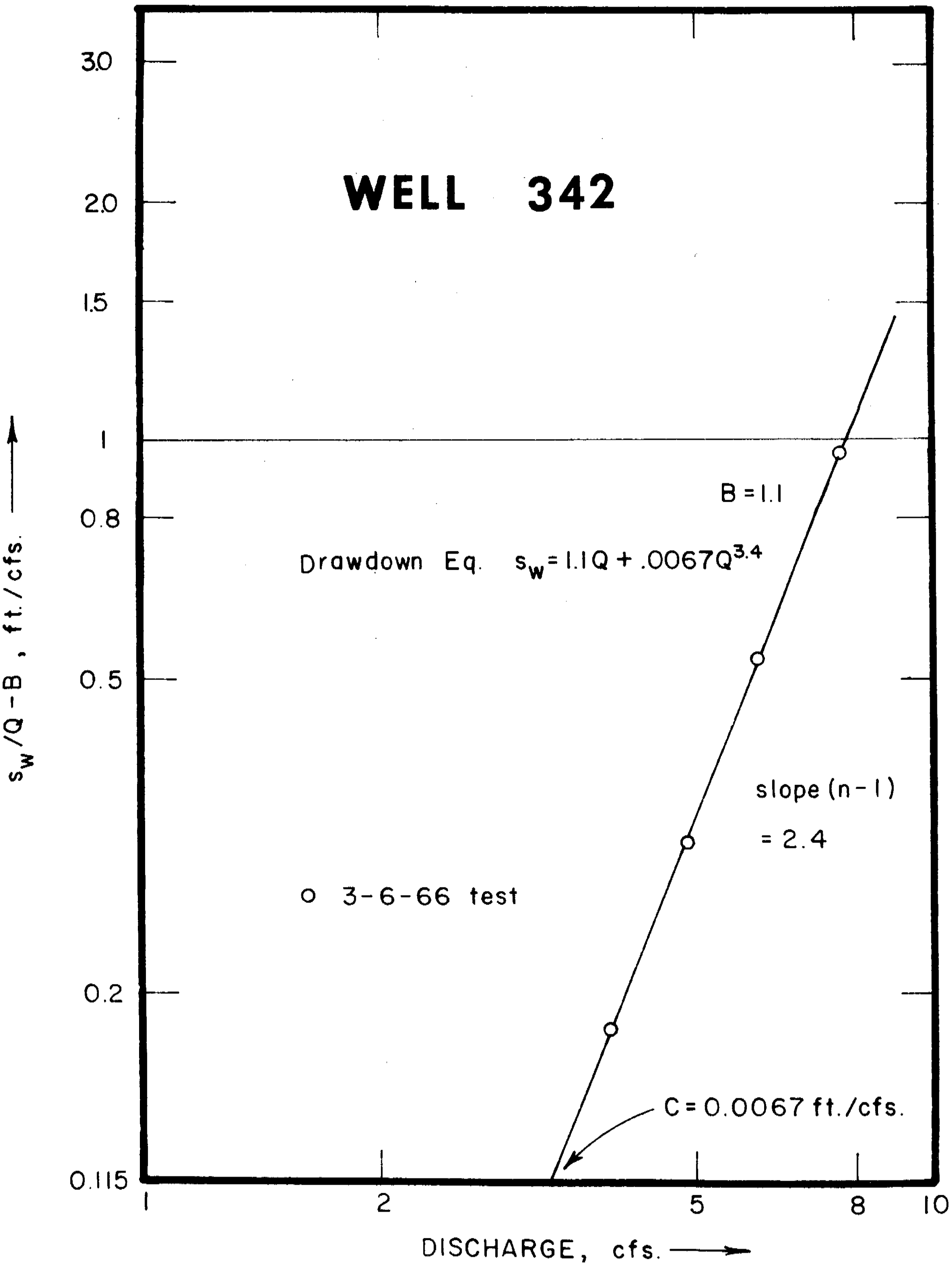


Fig. 7 STEP-DRAWDOWN ANALYSIS OF WELL 342

It is interesting to note that although the upper aquifer contributes very little towards the total discharge, its part in reducing the well loss, or raising the efficiency, is very significant. By perforating the upper aquifer, the discharge was increased only 7 percent, but the well efficiency was increased over 20 percent of the original value. This increase in efficiency is directly related to the increase in entrance area due to the perforation of the upper aquifer. Increasing the entrance area decreases the entrance velocity for the same discharge, thereby reducing turbulent flow losses.

Another aspect of fig. 6, that seems worthy of attention, is the shape of the upper efficiency curve. The efficiency (E) of a well can be written as:

$$E = \frac{1}{1 + CQ/B}$$

If E vs. Q is plotted on arithmetic paper, the locus is hyperbolic. The shape of the upper efficiency curve in fig. 6 verifies this equation.

Well 341

On January 3, 1968, a pumping test was conducted on Well 341, west of the town of Big Pine. The well was drilled for domestic supply to the town of Big Pine. Analysis of the test revealed that the well was still in the developing stages and the values obtained should be viewed accordingly. This test is illustrated to point out the necessity of testing only fully developed wells. A semi-log plot of recovery in feet versus time, after pumping stopped, is shown in fig. 8.

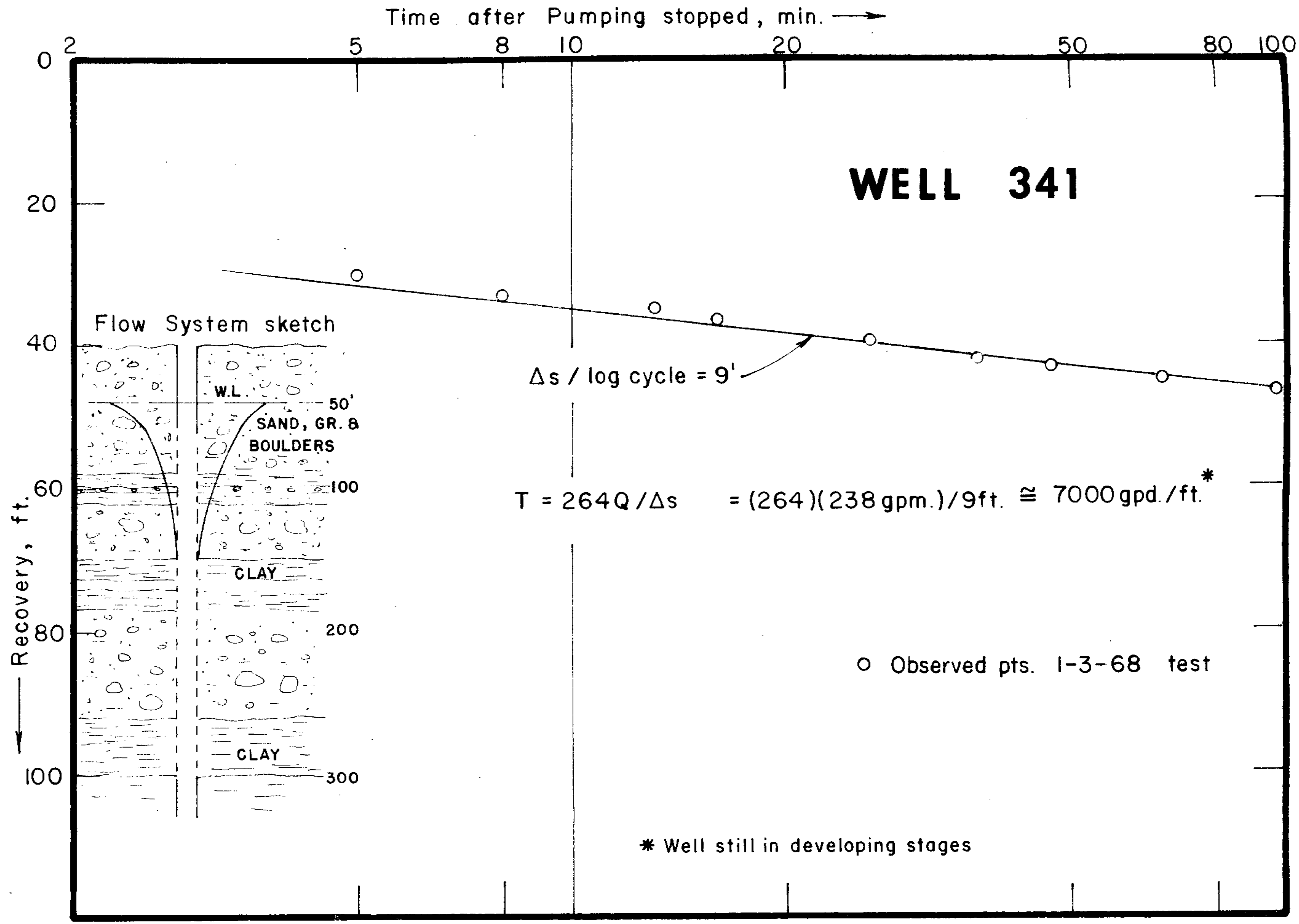


Fig. 8 RECOVERY GRAPH OF WELL 341

The data were analyzed using standard semi-log techniques (Johnson, 1966).

A step-drawdown test was also performed prior to the recovery test. The results are summarized in figures 9 and 10.

Well 344

On January 11 and 12, 1968, a pumping test was performed on Well 344. Well 344 is located near Lone Pine and was drilled to provide a source of supply for domestic use by the town of Lone Pine.

Five measurable observation wells are located in the Lone Pine area. However, the nearest of these wells was more than 1,000 feet from Well 344. Installation of an observation well 50 feet south of Well 344 was attempted by jetting. However, the observation well could not be completed as boulders were encountered at a depth of 20 to 30 feet.

The pump test was performed over a two-day period.

On the first day, as the proposed observation well had not been installed, a step-drawdown test was performed. The well was pumped in four steps at discharges of 0.25, 1.05, 1.54 and 2.30 cfs. Pumping continued from 9:30 a.m. to 3:38 p.m.

At 9:00 a.m. on the second day, pumping was resumed at a rate of 3.07 cfs, which was the maximum steady rate at which the generator could operate. Pumping was continued at this rate until 3:30 p.m.

Water level measurements during the test were made by using an electric sounding device.

Analysis of the step-drawdown data from the first day and from the steady pumping on the second day can be seen in figures 11, 12 and 13.

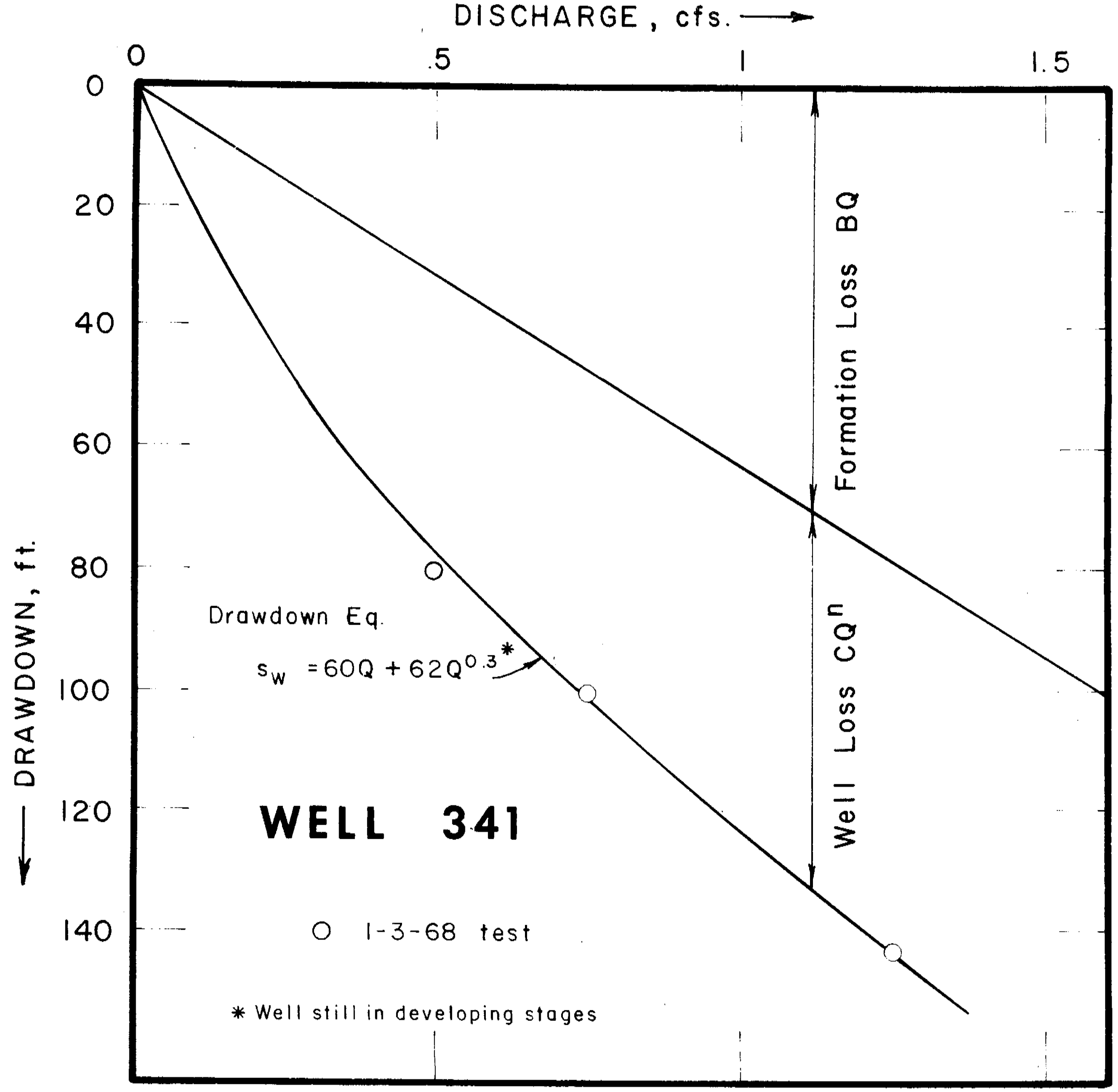


Fig. 9 SPECIFIC-CAPACITY DIAGRAM FOR WELL 341

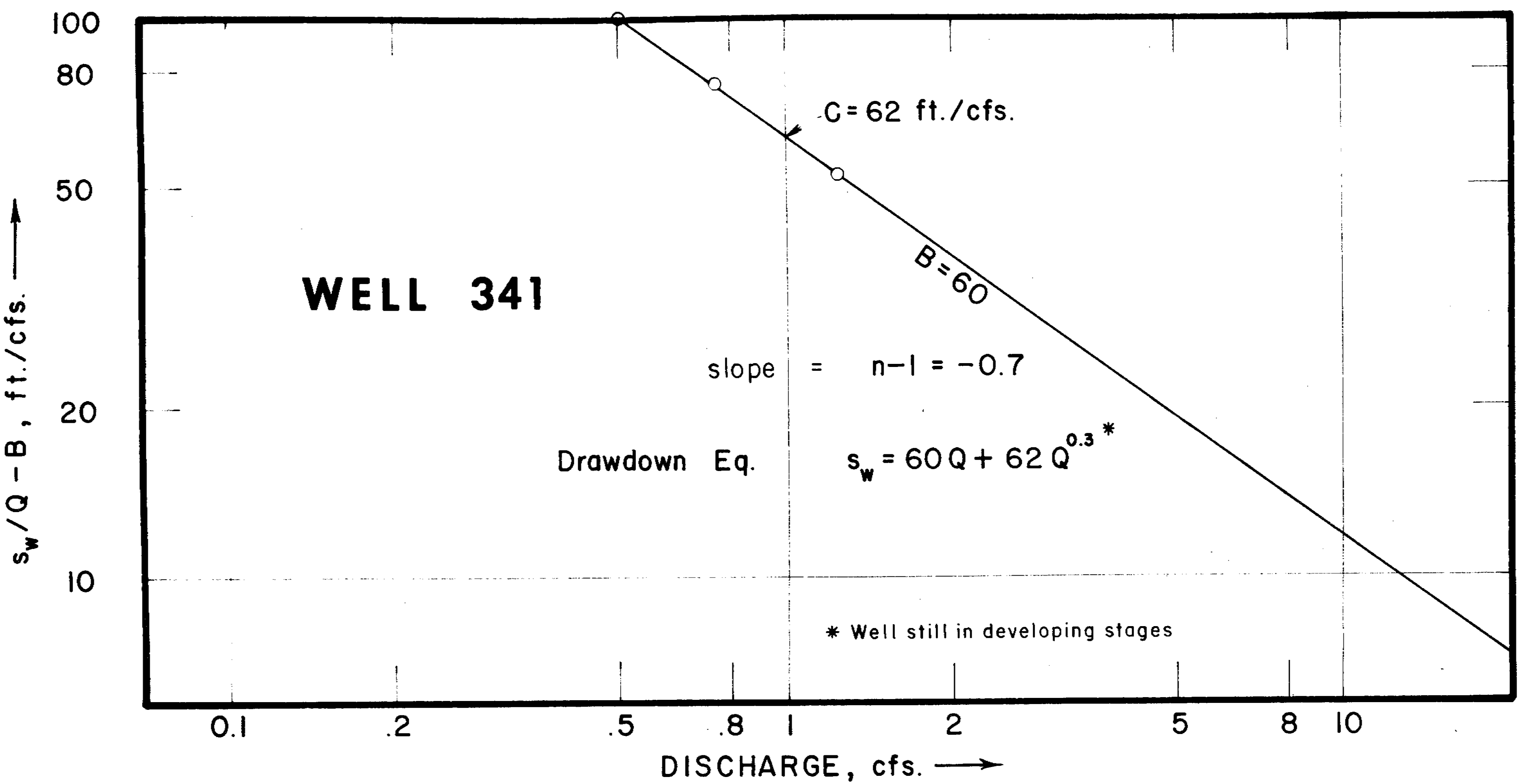


Fig. 10 STEP-DRAWDOWN ANALYSIS OF WELL 341

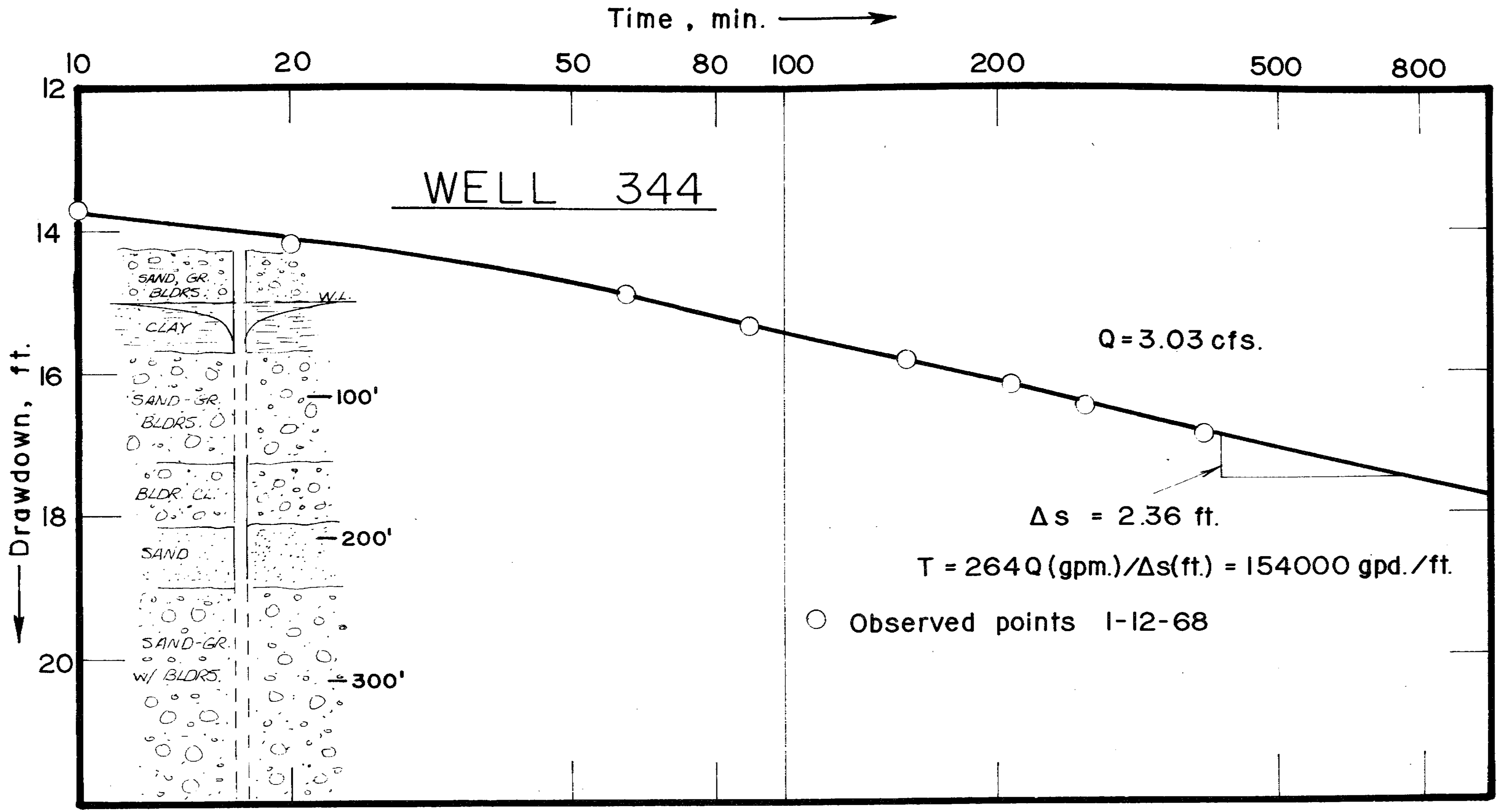


Fig. 11 TIME VS. DRAWDOWN GRAPH FOR WELL 344

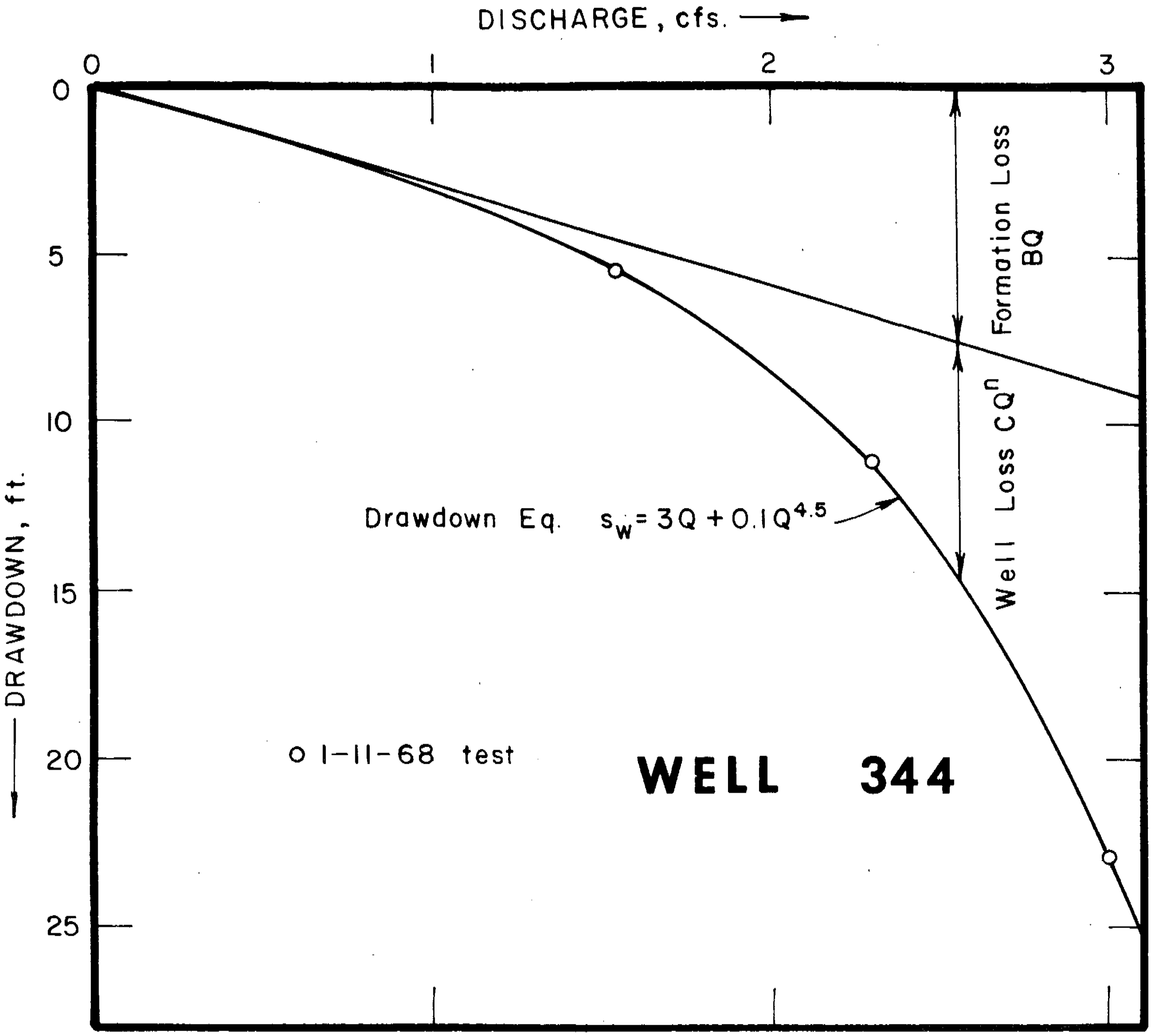


Fig. 12 SPECIFIC-CAPACITY DIAGRAM FOR WELL 344

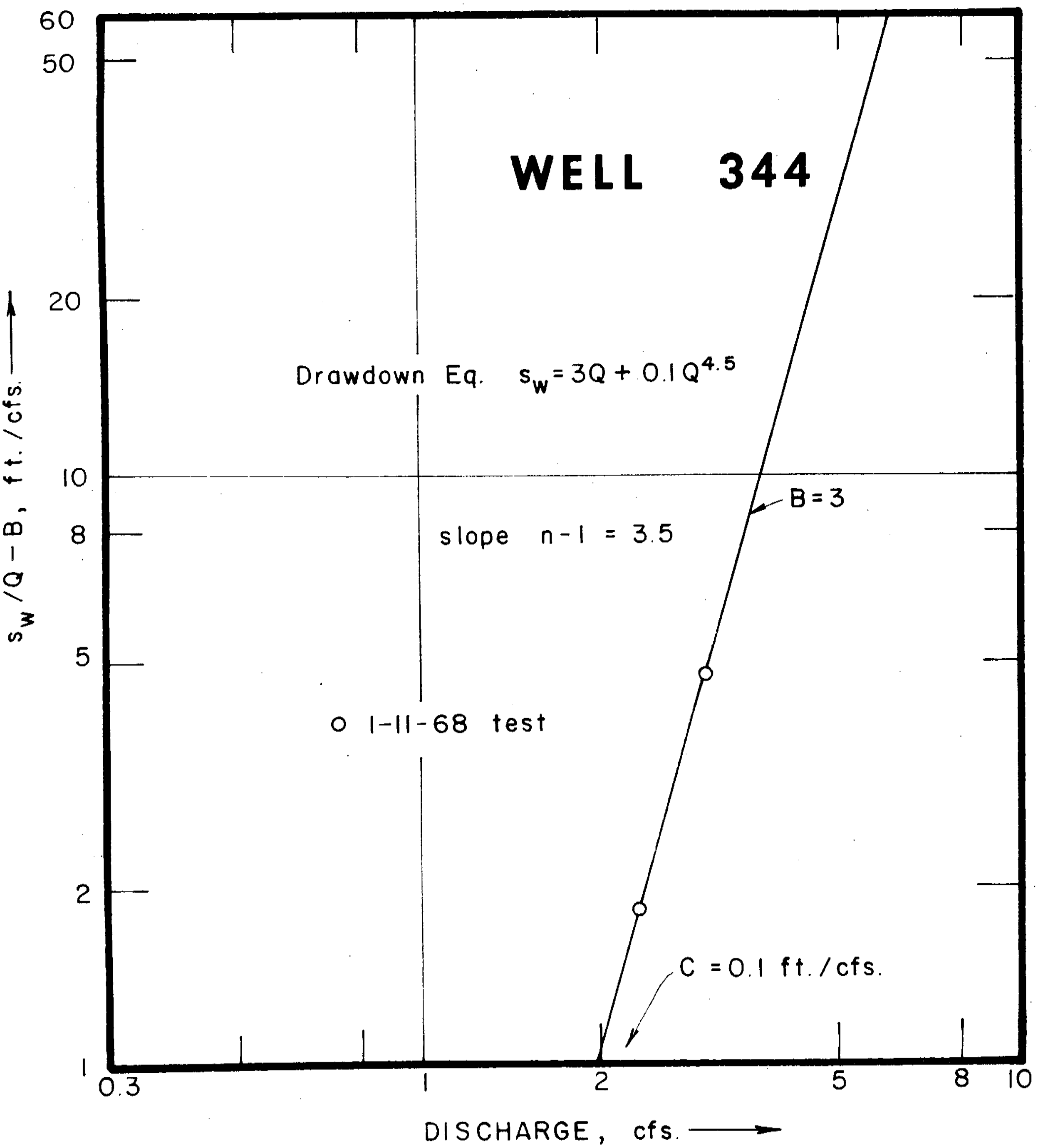


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Fig. 13 STEP-DRAWDOWN ANALYSIS OF WELL 344

The step-drawdown data were analyzed according to the method developed by Jacob (1947), and the continuous pumping on the second day was analyzed using the Jacob semi-log method.

Multiple Well-Field Analysis

Bajada Areas

In the treatment of problems involving multiple discharging wells, use is made of the principle of superposition. In this principle it is assumed that the total drawdown produced at any point at a given time, is the algebraic sum of the drawdowns that would be produced independently by each well pumping alone. Results of discharging well tests have verified this assumption. (Cooper and Jacob, 1946)

According to the principle of superposition, the drawdown, at any time, at the point X_i, Y_i in a field of n wells is:

$$s_i^n = \Delta s_i^1 + \Delta s_i^2 + \Delta s_i^3 + \cdots + \Delta s_i^n = \sum_{k=1}^{n} \Delta s_i^k \quad \cdots \quad (1)$$

where the subscripts refer to spatial location, and the superscripts denote index of wells in the field.

The equation for the partial drawdown produced at some location X_i, Y_i in a multiple discharging well field is developed by Cooper and Jacob (1946) to be:

$$\Delta s_i^k = \frac{2.30 \Delta Q_k}{4\pi T} \log \left(\frac{2.25 T t^k}{r_{ik}^2 S} \right) \quad \cdots \quad (2)$$

where

Δs_i^k = The increment of drawdown at the i^{th} well produced by the k^{th} well in a field of "n" wells.

ΔQ_k = The increment of discharge produced by the k^{th} well.

If the initial discharge of the well was zero, then

$\Delta Q_k = Q_k$.

t^k = The length of the pumping period of the k^{th} well pumping at a constant rate Q_k.

r_{ik} = The distance from the k^{th} well to the point (X_i, Y_i) at which the increment of drawdown is desired.

The total drawdown at the i^{th} well, $s_i^n(X_i, Y_i)$, produced by a well field consisting of n wells is:

$$s_i^n = \sum_{k=1}^{n} \Delta s_i^k = \sum_{k=1}^{n} \frac{2.30 \Delta Q_k}{4\pi T} \log \left(\frac{2.25 T t^k}{r_{ik}^2 S} \right) \quad \cdots (3)$$

Dividing both sides of equation (3) by the total discharge of the well field Q_n, where $Q_n = \sum_{k=1}^{n} \Delta Q_k$

results in:

$$s_i^n / Q_n = \sum_{k=1}^{n} \frac{2.30 \Delta Q_k}{4\pi T Q_n} \log \left(\frac{2.25 T t^k}{r_{ik}^2 S} \right) \quad \cdots\cdots (4)$$

Equation (4) may be rewritten as:

$$(s/Q)_i^n = -(2.30/4\pi T) \sum_{k=1}^{n} \left\{ (\Delta Q_k / Q_n) \log (r^2/t)_i^k - \log (2.25 T/S) \right\} \cdot\cdot (5)$$

The first term in brackets is the weighted logarithmic mean of (r^2/t) and can be thought of as an index of the contribution from each well in the field. This weighted logarithmic mean is rewritten symbolically for simplicity as $\overline{\log (r^2/t)_i^n}$.

Rewriting equation (5) using the weighted logarithmic mean,

$$(s/Q)_i^n = -(2.30/4\pi T) \left\{ \overline{\log (r^2/t)_i^n} - \log (2.25 T/S) \right\} \cdot\cdot (6)$$

The left hand side of equation (6) is the "specific drawdown" (drawdown per unit discharge). Thus, equation (6) is the straight-line plot of the specific drawdown $(s/Q)_i^n$ vs. the weighted logarithmic mean $\overline{(r^2/t)}_i^n$ on semi-log paper.

The slope of the plot is $\frac{2.303}{4\pi T}$, and the intercept of the plot at $(s/Q)_i^n = 0$, is 2.25T/S.

It is now readily apparent that the formation constants of any multiple discharging well field can be analyzed analagous to the semi-log method for one well.

By obtaining time-drawdown data, or time recovery data, from observation well hydrographs, regional values of transmissivity and storativity can be obtained.

Due to the lack of individual well tests in the Bajada region, this method was chosen to analyze the alluvial fan aquifers.

The method of analysis is systematically defined as follows:

1. The pumping period from 1960 to 1962 was chosen for analysis due to the uniformity of discharge and quality of available records.

2. Hydrographs of key wells in four different well fields were selected which represented the best reflection of the pumping.

3. The recovery portion of these hydrographs was selected for measurement as this implies a constant discharge. (Johnson, 1966.)

4. The physical data were obtained from measurements of hydrographs, well field maps, and discharge records. These data were then arranged into a computer routine which produced the desired parameters of specific drawdown and weighted logarithmic mean $\overline{(r^2/t)}$. (See Table 6, Appendix I.)

5. The specific drawdown vs. weighted logarithmic mean $\overline{(r^2/t)}$ was then plotted for each of the four well fields on semi-log paper.

6. The regional transmissivities and storativities were computed by the following relations:

$$T = \{2.30/4\pi T\}/\Delta(s/Q)_i^n/\text{log cycle} \quad \text{cfs/ft}$$

$$S = 2.25T/\overline{(r^2/t)}_o \quad \text{where } \overline{(r^2/t)}_o \text{ is the}$$

$$\text{intercept of the line at } (s/Q)_i^n = 0$$

The above analysis, as applied to the Bajada region, is graphically represented in figures 14 through 21. A map showing the well-field locations can be seen in Plate XVII.

Formation Parameters in the Bajada Region

The values of transmissivity and storativity resolved from the multiple-well field analyses reveal important facts regarding the hydraulic character of the region.

Transmissivities range from lows of 115000 and 146000 gpd/ft on the northern and southern sections respectively (Plate XVII), to highs of 255000 and 318000 gpd/ft in the central regions. The difference is attributed to local variance in saturated thickness rather than hydraulic conductivity. Seismic and gravity data support this.

Storativities range from 0.004 in the Bairs-Georges Creek section and increase to the north with the high value being 0.024 in the Thibaut-Sawmill section. The magnitude of the storativities imply unconfined to semi-confined aquifers with the average value being 0.01. Well cuttings and drillers' logs verify these values.

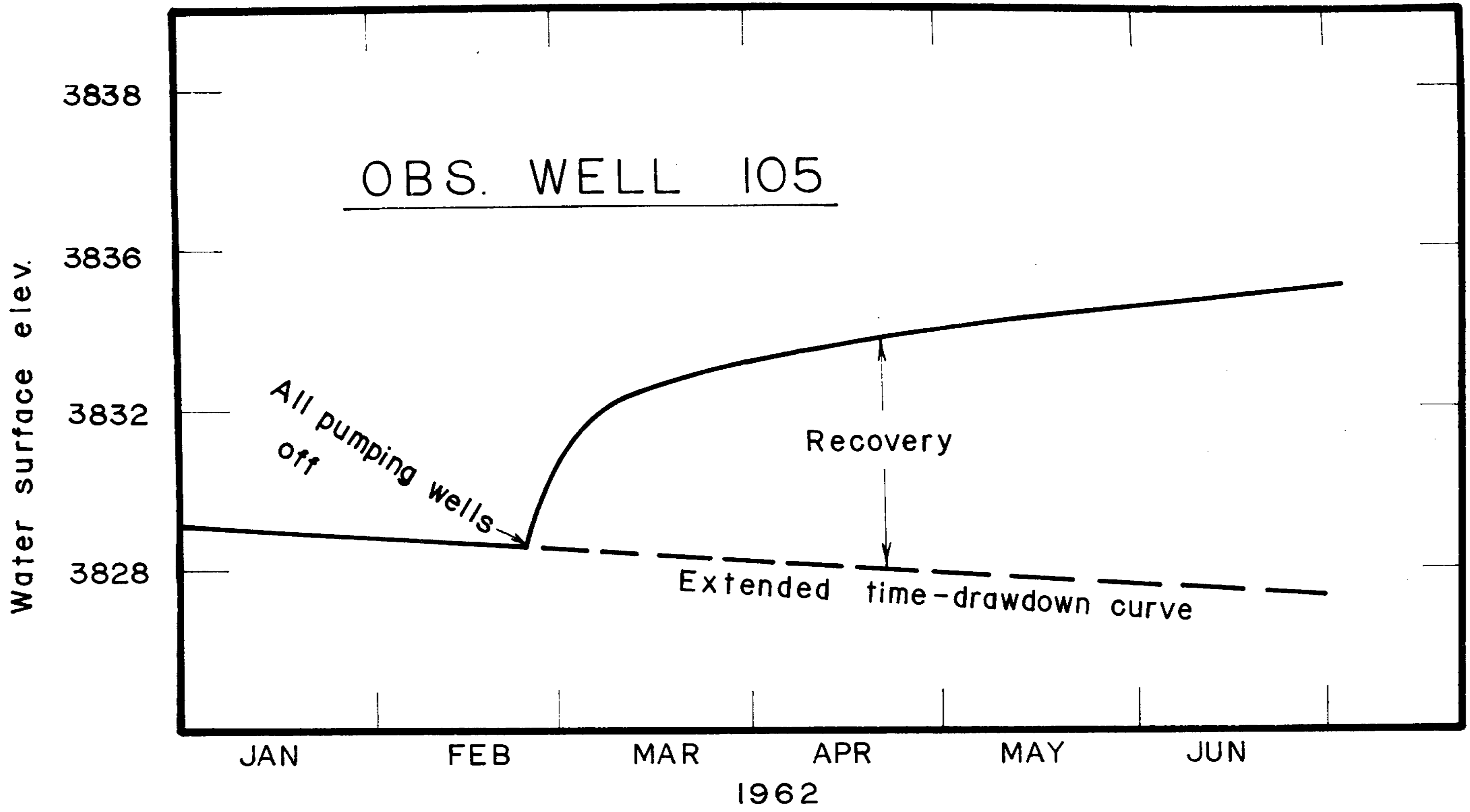


Fig. 14 RECOVERY HYDROGRAPH FOR WELL 105

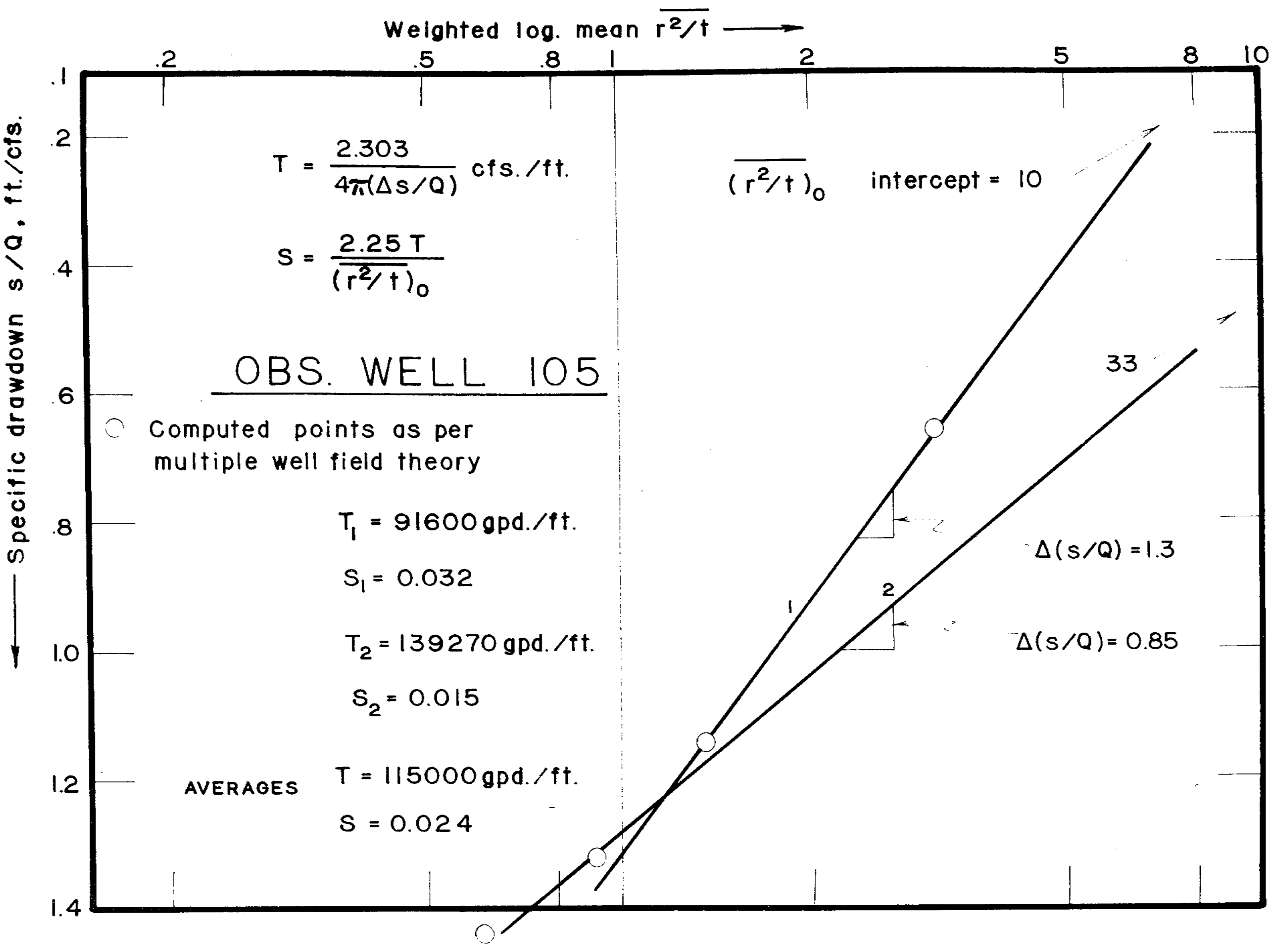


Fig. 15 SPECIFIC DRAWDOWN VS. WEIGHTED LOGARTHMIC MEAN FOR WELL 105

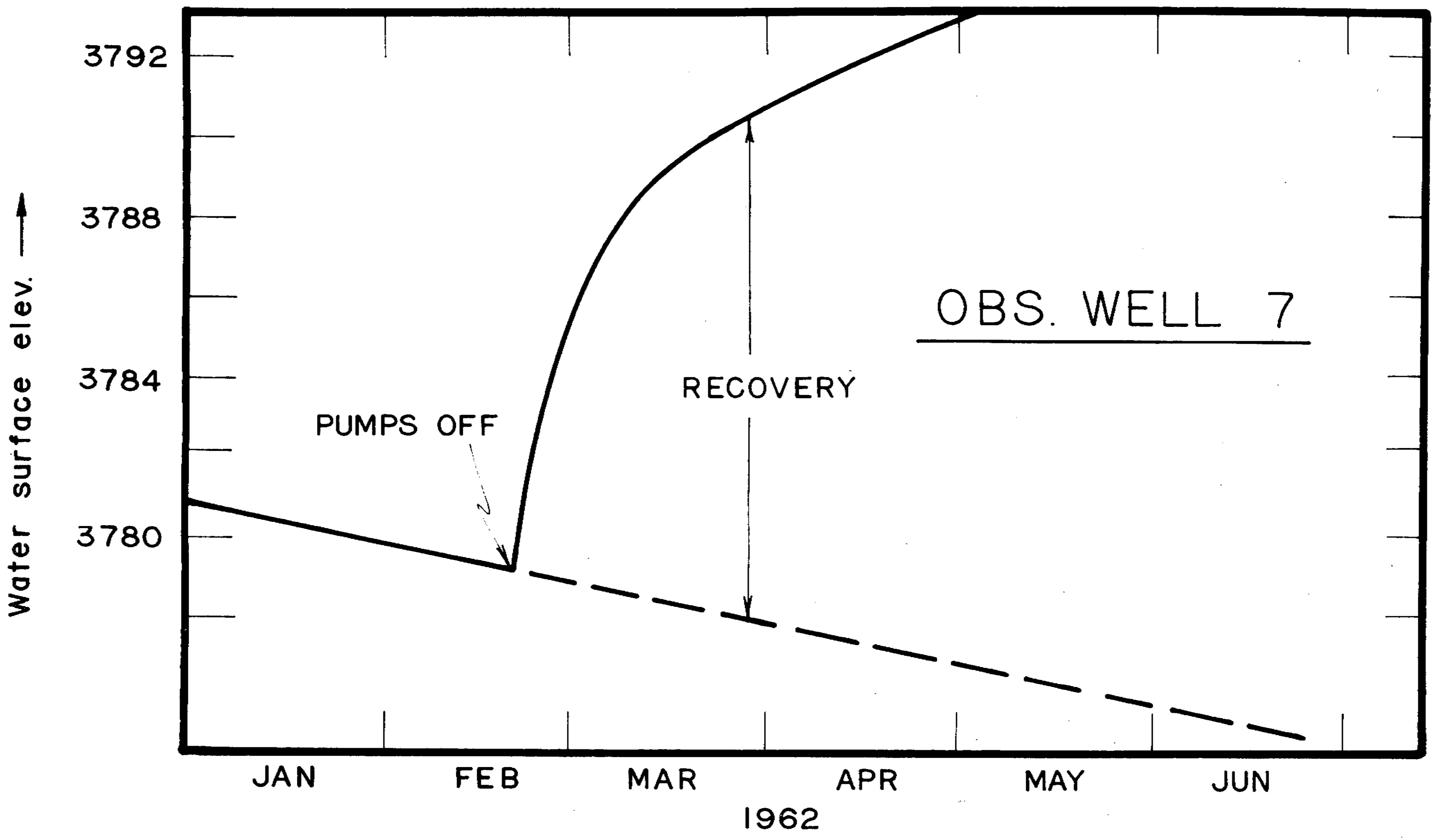


Fig. 16 RECOVERY HYDROGRAPH FOR WELL 7

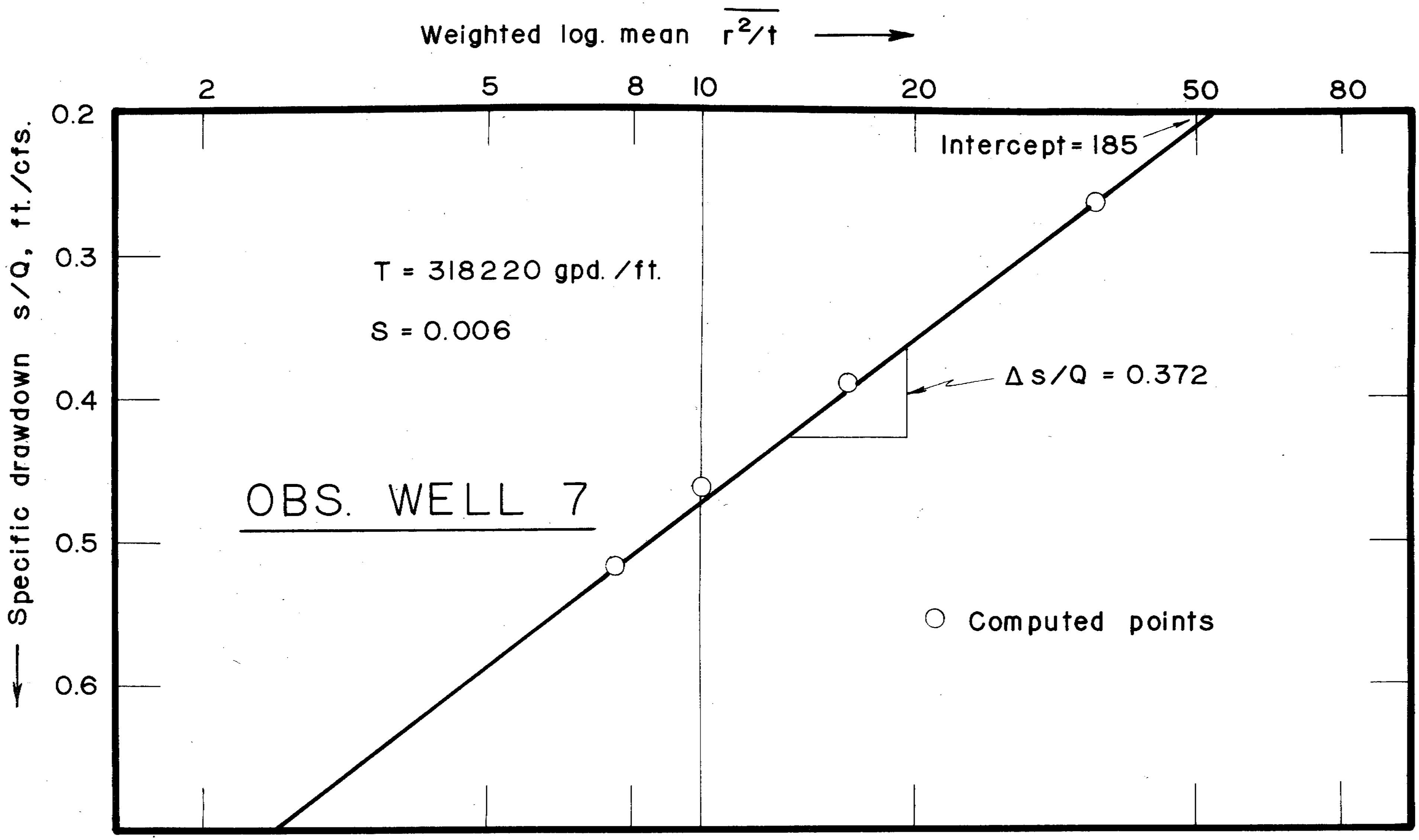


Fig. 17 SPECIFIC DRAWDOWN VS. WEIGHTED LOGARITHMIC MEAN FOR WELL 7

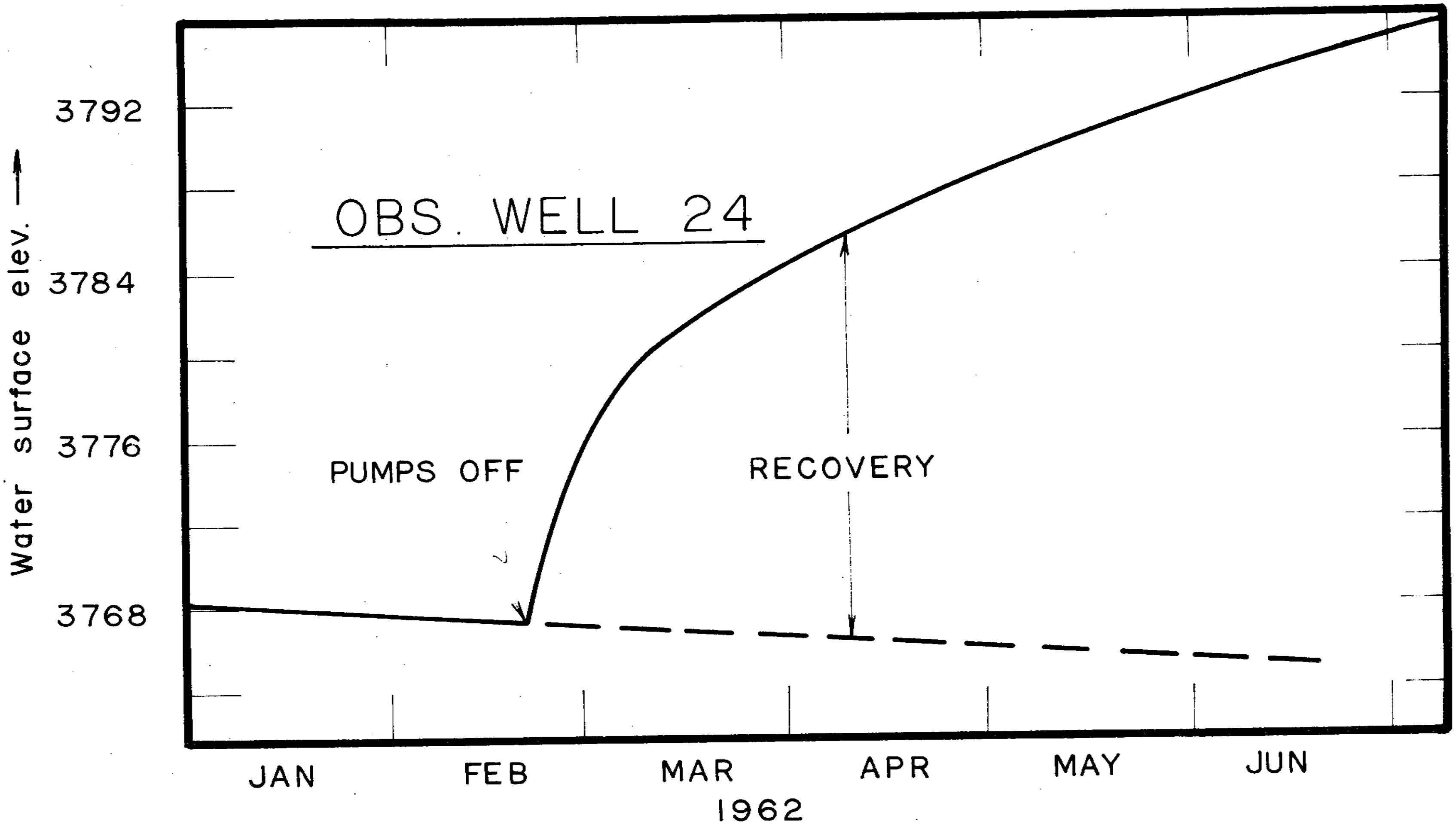


Fig. 18 RECOVERY HYDROGRAPH FOR WELL 24

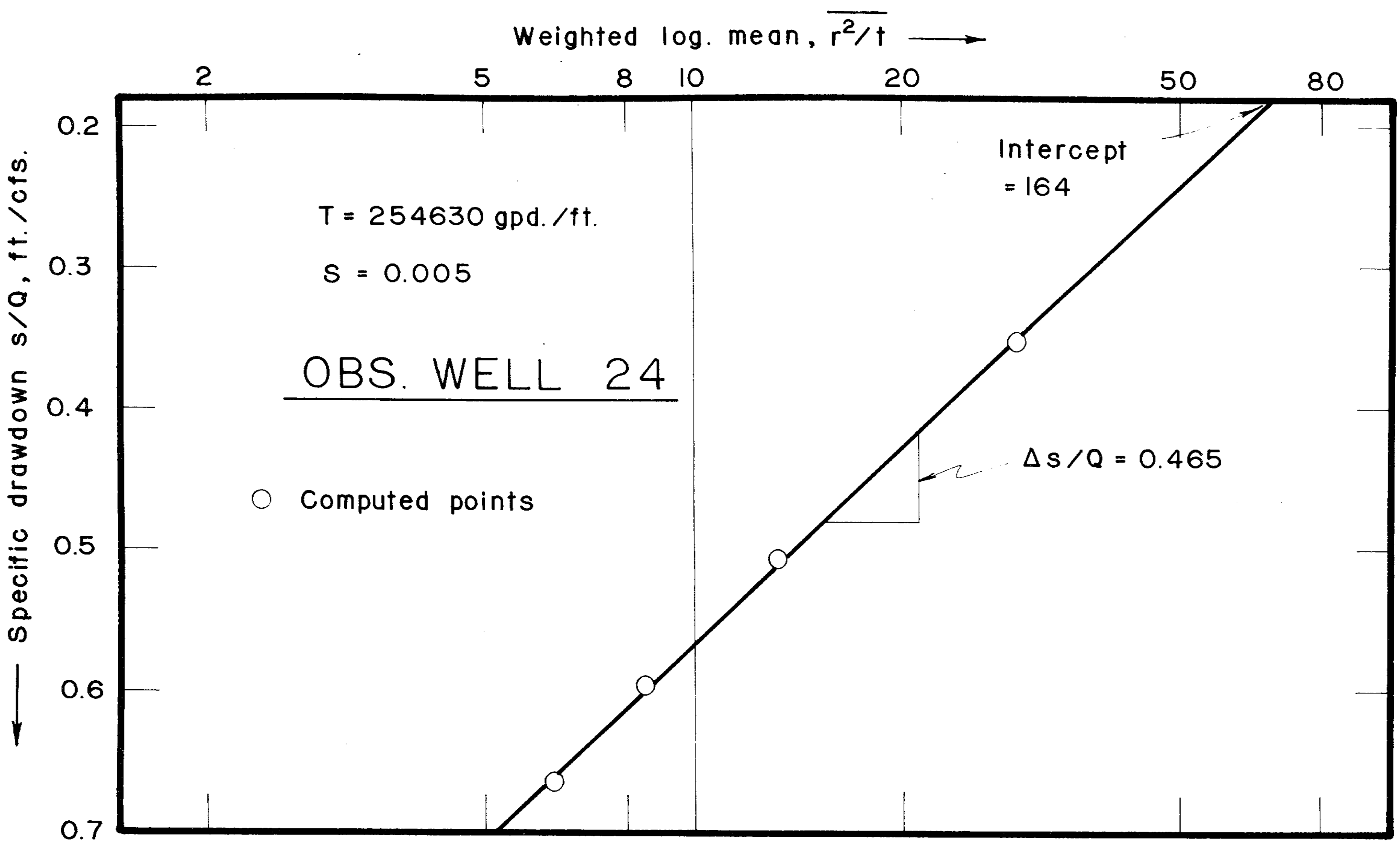


Fig. 19 SPECIFIC DRAWDOWN VS. WEIGHTED LOGARITMIC MEAN FOR WELL 24.

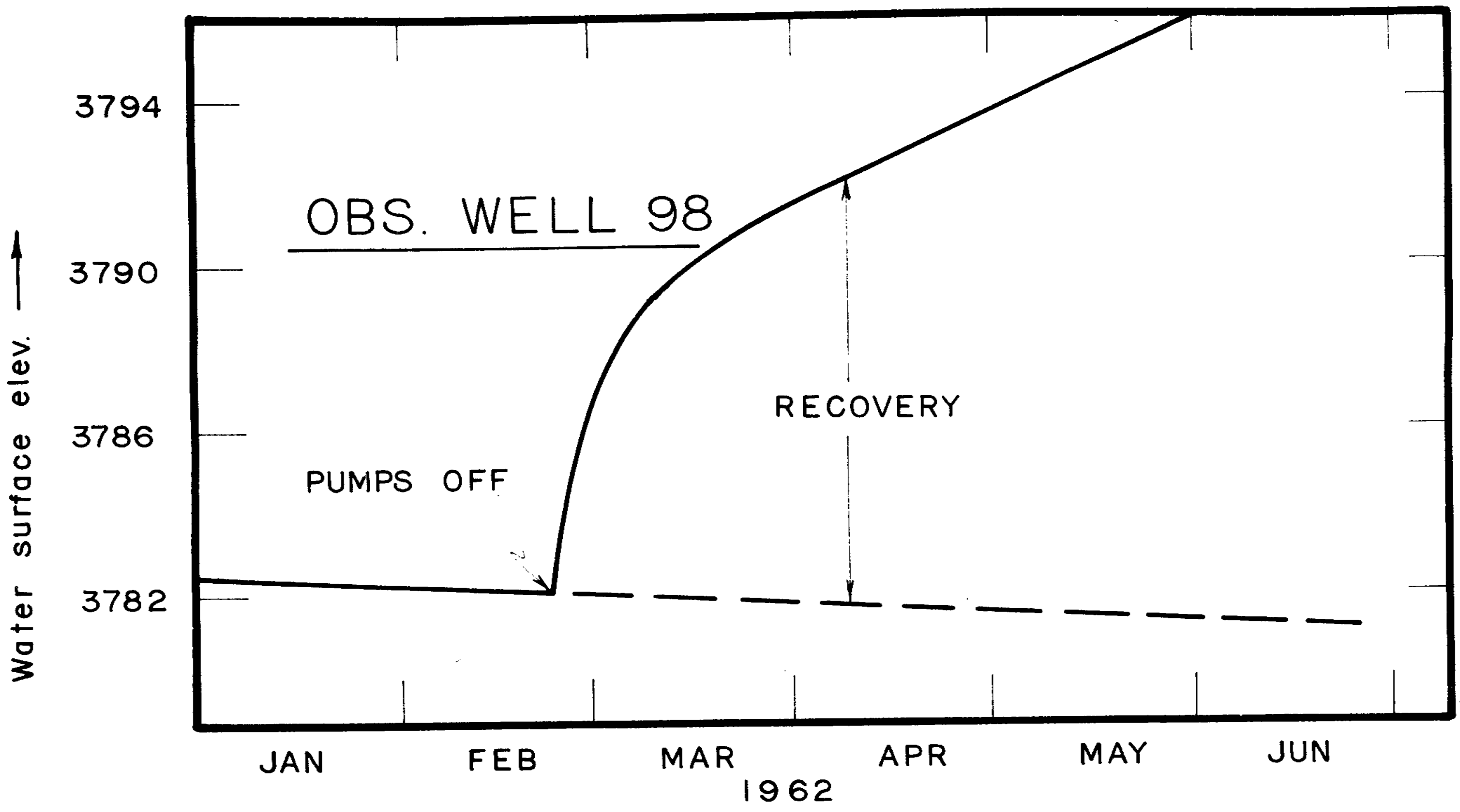


Fig. 20 RECOVERY HYDROGRAPH FOR WELL 98

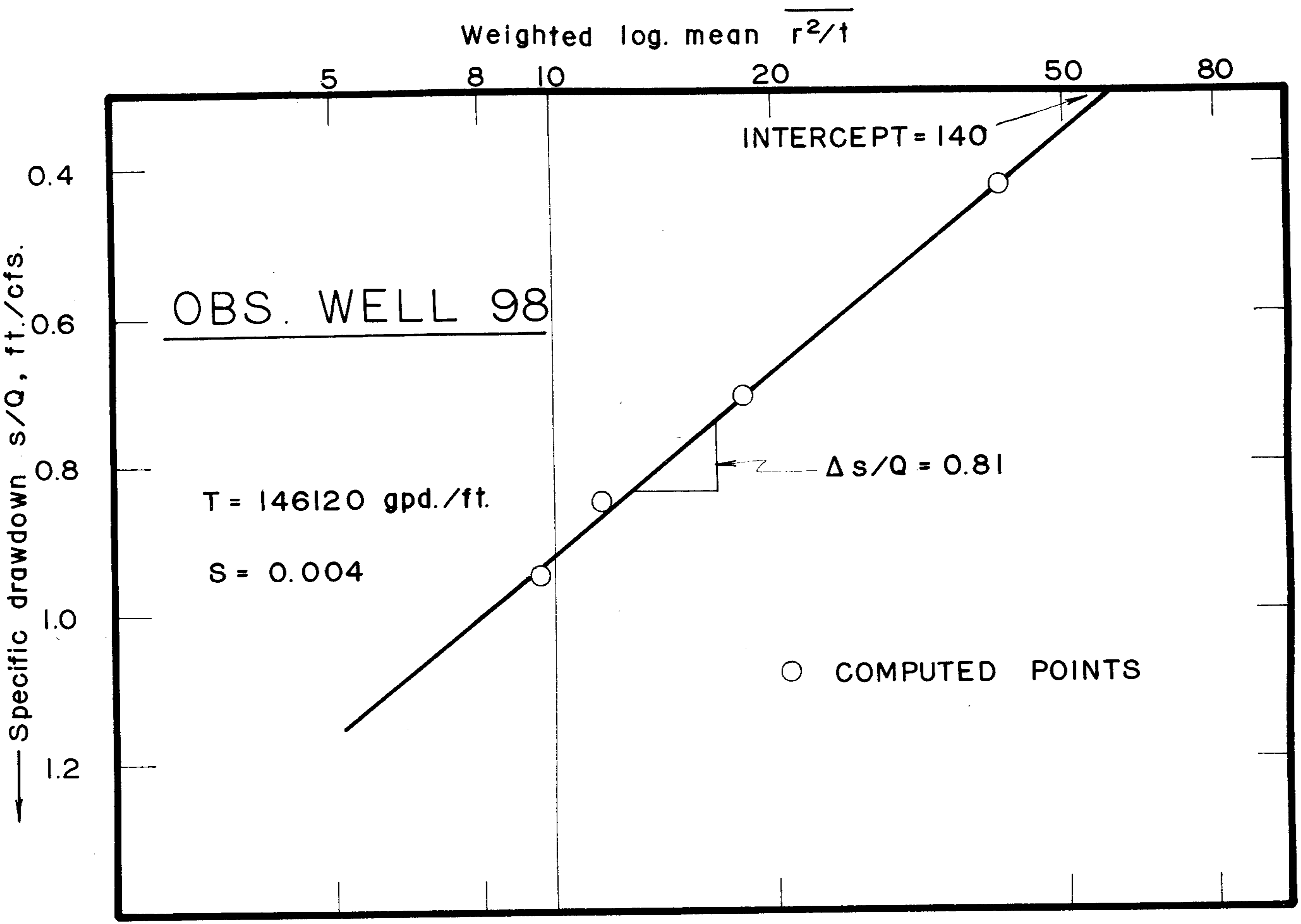
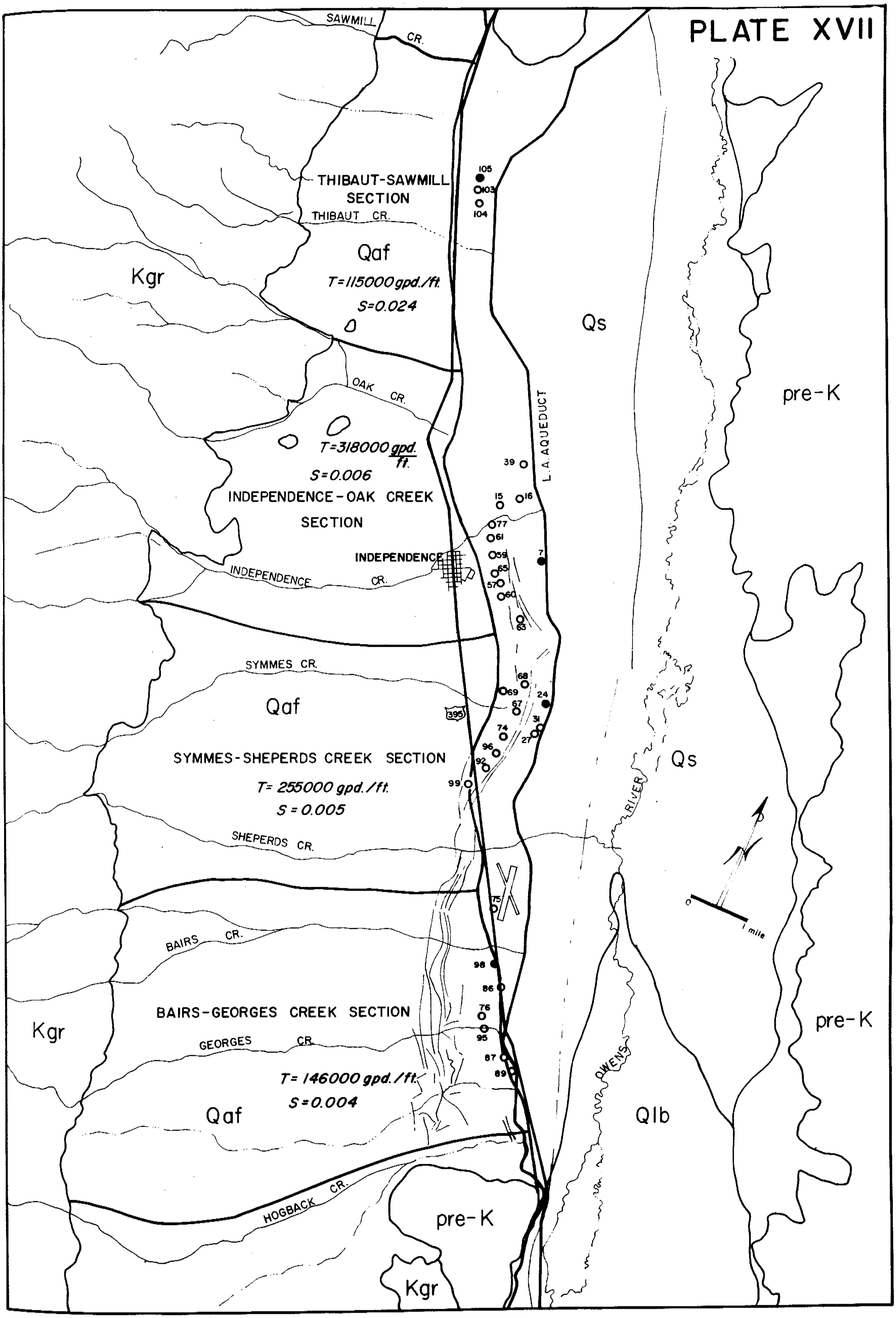


Fig. 21 SPECIFIC DRAWDOWN VS. WEIGHTED LOGARITHMIC MEAN FOR WELL 98.

PLATE XVII



SAWMILL CR.
THIBAUT-SAWMILL SECTION
THIBAUT CR.
Qaf
T=115000 gpd./ft.
S=0.024
Kgr
Qs
OAK CR.
T=318000 gpd./ft.
S=0.006
INDEPENDENCE-OAK CREEK SECTION
L.A. AQUEDUCT
INDEPENDENCE
INDEPENDENCE CR.
pre-K
SYMMES CR.
Qaf
395
SYMMES-SHEPERDS CREEK SECTION
T= 255000 gpd./ft.
S = 0.005
SHEPERDS CR.
RIVER
Qs
BAIRS CR.
0
1 mile
BAIRS-GEORGES CREEK SECTION
GEORGES CR.
Kgr
pre-K
T= 146000 gpd./ft.
S=0.004
Qaf
OWENS
Qlb
HOGBACK CR.
pre-K
Kgr
105
103
104
39
15
16
77
61
59
7
65
57
60
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DIGITAL MODEL SIMULATION OF THE INDEPENDENCE REGION

The technique of modeling ground-water basins by use of a digital computer is becoming increasingly popular in geohydrologic studies. This technique enables prediction of the fluctuations of the ground-water levels with any set of socio-economic restrictions imposed on the area.

The ability to estimate the time-dependent fluctuation of ground-water levels at various locations in the basin under a wide range of operating conditions is also a necessary requirement for reliable operational and economic basin management.

To meet this requirement in the Independence region, a mathematical model was developed that could simulate the hydraulic properties of the basin and thus enable predictions of future ground-water levels in this area. The Independence area was selected out of the study area for its immediate importance in future ground-water operations. It is in this area that a large number of pumping wells already exist, and it is also in this area that the extensive Bajadas exist. It is in these Bajadas that maximum effort will be made to utilize underground storage of ground water.

Mathematical Model

As a future aid to the operational phase of the aqueduct system, a model of the Independence ground-water region was created. A linear model was developed, that is to say, one in which the transmissivity was assumed constant as the result of changes in head. This assumption proved valid, as the decline in water level was small compared to the total saturated thickness.

Generalized Ground-Water Equation

A generalized ground-water equation defining the storage, transmissive, and water inflow-outflow characteristics has been developed and used extensively in California (California State Department of Water Resources, 1962). The equation shown in Fig. 22 defines the storative and transmissive characteristics of any unit area of the ground-water basin. Fig. 22 also shows the relation of the items in the equation. The symbol definitions are as follows:

h_i = water-level elevation associated with node i, in feet.

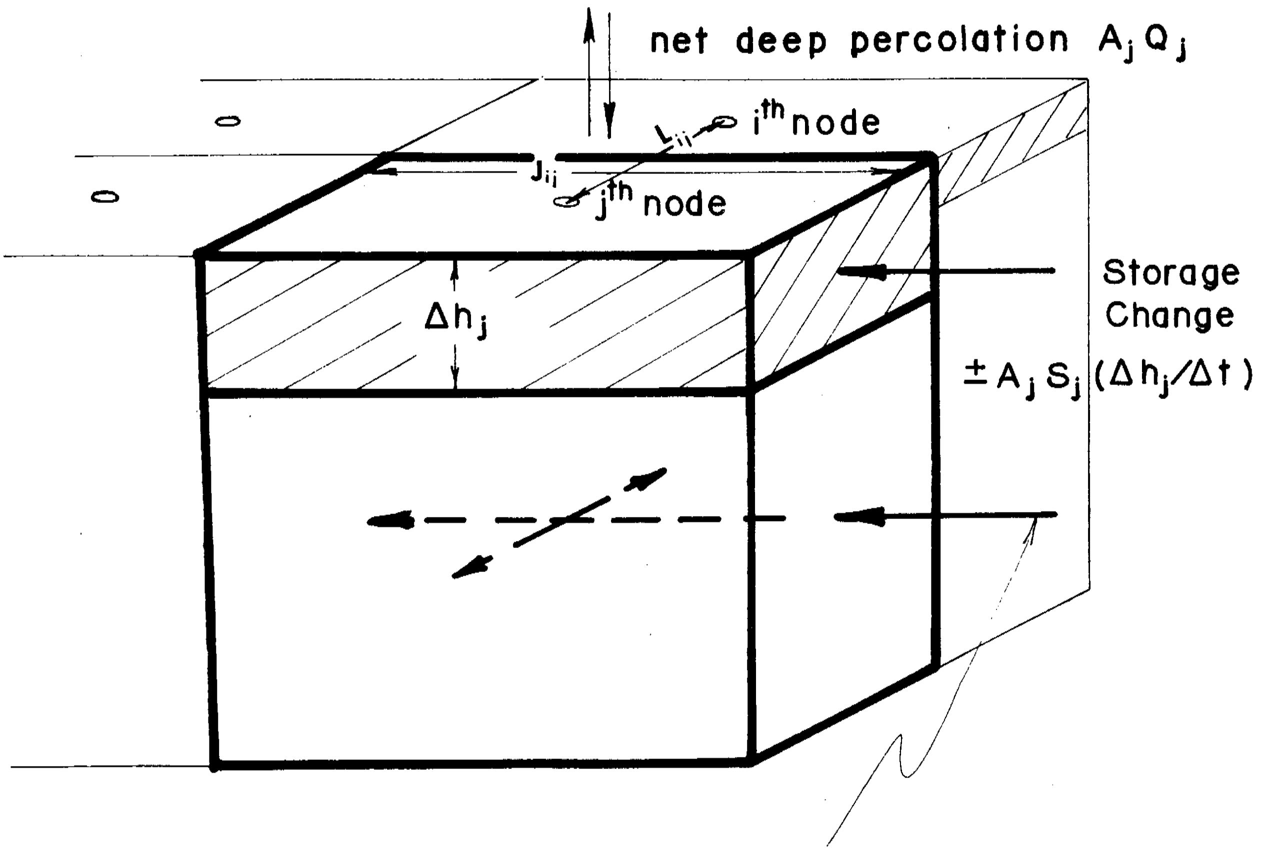
h_j = water-level elevation associated with node j, in feet. The first term on the left-hand side of the equation is the summation of the subsurface flows between a given unit area and its surrounding areas. The second term describes the surface flow rate from the ground surface into or out of the zone of saturation of the given unit area. The rate of change in storage is given by the right-hand expression. A set of these differential equations, one for each unit within the basin, with proper coefficients, forms the mathematical model of the ground-water basin.

$T_{i,j}$ = transmissivity at the midpoint between nodes i and j, in acre-ft/yr-ft.

FLOW EQ: INFLOW − OUTFLOW = ± CHANGE IN STORAGE

Differential Difference Equation

$$\sum_{i=3}^{n_j} \left[\left(\frac{h_i - h_j}{L_{ij}} \right) T_{ij} J_{ij} \right] + A_j Q_j = A_j S_j \Delta h_j / \Delta t$$



Net subsurface INFLOW − OUTFLOW from adjacent nodes

$$\sum_{i=3}^{n_j} \left[\frac{h_i - h_j}{L_{ij}} \right] T_{ij} J_{ij}$$

Fig. 22 SCHEMATIC DIAGRAM OF GENERALIZED GROUND-WATER FLOW EQUATION

$J_{i,j}$ = length of perpendicular bisector of the distance between nodes i and j, in feet.

$L_{i,j}$ = distance between nodes i and j, in feet.

A_j = areas associated with node j, in acres.

Q_j = volume rate of flow (net deep percolation) per unit area at node j, in $\frac{\text{acre-feet}}{\text{year-acre}}$.

S_j = storage coefficient of ploygonal zone associated with node j (dimensionless).

t = time, in years.

n_j = number of sides on polygon of node j.

Development and Verification of Mathematical Model

The general steps taken in developing the mathematical model and verifying its reliability were as follows:

1. The Independence Ground-Water Basin was subdivided into subareas, called polygons, by using the Thiessen Method of polygon construction. (See terms and definitions.)

2. Geologic data were analyzed and the transmissivity and storativity within each polygon determined.

3. Surface hydrologic data were analyzed and the seasonal net deep percolation at each polygon was determined for the period 1958/59 through 1962/63. Also, hydrographs of representative ground-water-level fluctuations, during the same period, were prepared for each polygon based on measurements of recorded ground-water-level elevations.

4. Once the parameters were properly programmed, the model was tested. The testing process consisted of matching water-level elevations generated by the computer, with recorded water-level elevations.

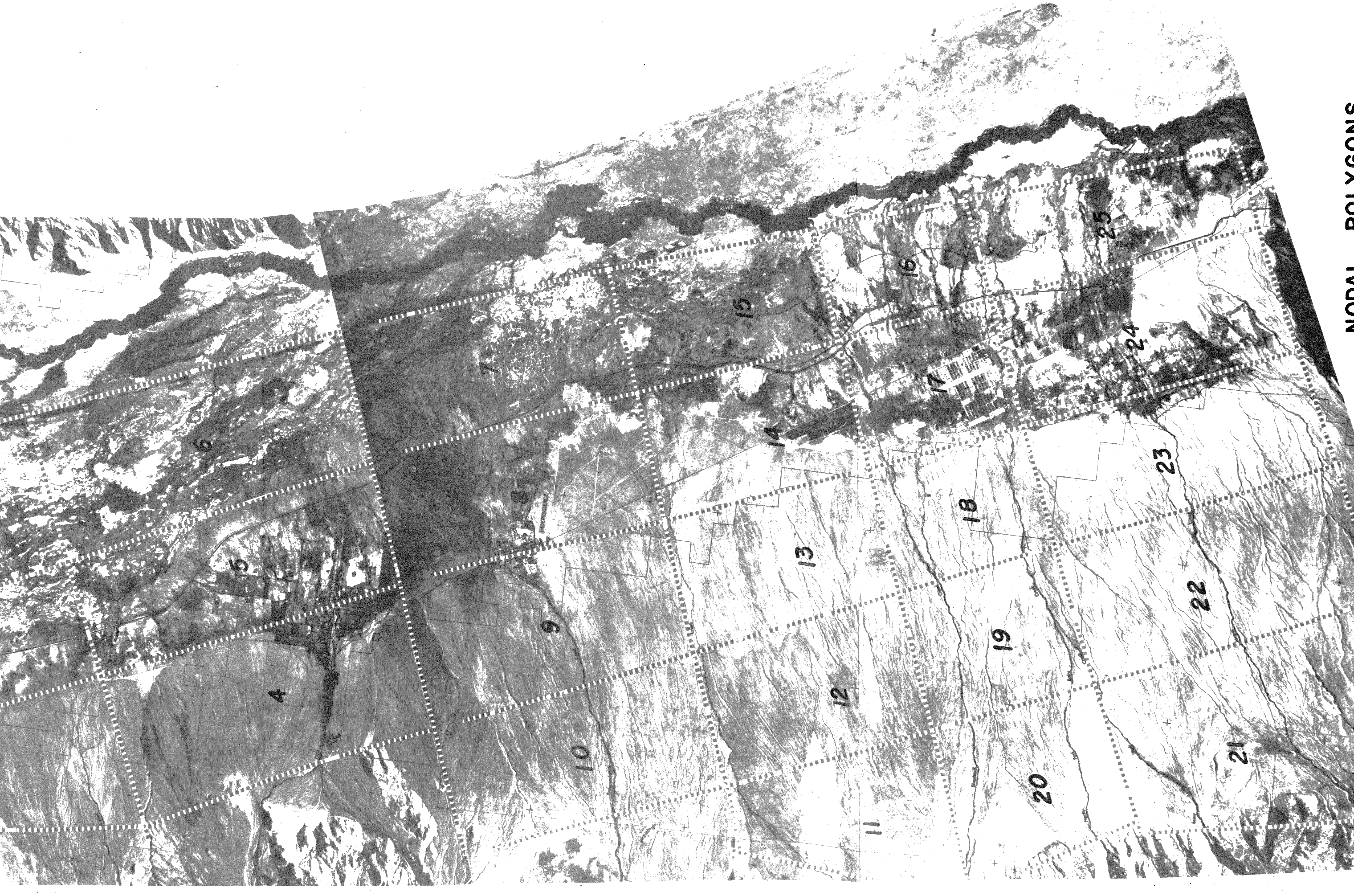
5. Based on the information developed during the testing period, final verification was achieved when machine-computed water-level elevations and recorded water-level elevations matched.

Determination of Number and Location of Control Nodes and Their Polygons

As stated above, the entire Independence Ground-Water Bajada Region was divided into polygons. In the computer analysis, each polygon was represented by a node. A 25-control-node network was used to simulate the basin.

The determination of the sizes and locations of the 25 nodes was based upon variations in replenishment, extraction, transmission, storage, and water-level factors. Geologic conditions and structures governed emplacement of the polygonal boundaries. On the western periphery the Sierra Nevada forms a bedrock barrier. A drainage divide in the vicinity of Hogback Creek marks the southern boundary. The northern end is bounded by basaltic lava flows of the Aberdeen area. The eastern boundary is delineated by a major north-south alluvial fault. Internal boundary conditions were dictated by geomorphology of the alluvial fans as well as localized faulting. The final nodal network used for the Independence Region is shown on Plate XVIII, entitled "Nodal Polygons of the Independence Ground-Water Reservoirs."

PLATE XVIII



NODAL POLYGONS
OF THE
INDEPENDENCE
GROUND-WATER RESERVOIRS


OWENS
RIVER
1
2
3
4
5
6
7
8
9
10
11
12
13
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18
19

Determination of Model Parameters

Results from the geologic investigation of the Owens Valley were used to estimate transmissivity and storativity values. Drillers' logs of wells located in the area were analyzed to delineate the aquifer types and to obtain estimates of the hydraulic properties of these aquifers.

Storativity and transmissivity values were assigned to all sides of the nodes. These values were estimates based on geohydrologic knowledge of the area.

To obtain the transmissive factor (TJ/L) which affects the subsurface flow between nodes, the transmissivity value (T) was multiplied by the width (J) of the nodal boundary and divided by the length (L) of the flow path between nodes (see Fig. 22).

The storage factor (AS) is considered a measure of the storage characteristics at each nodal polygon. This factor is the product of the area (A) of the nodal polygon times the average Storativity(S) of the water-bearing sediments within that area.

Historical Water Levels

Levels of ground-water elevations were obtained where possible throughout the area reflecting the ground-water elevations for the historic period 1958/59 to 1962/63. This period was chosen for calibrating because of the extensive pumping in the area. It was felt that if this recorded period could be matched analytically, by the use of a digital computer, then predictions based on the calibrated parameters could be accepted with a certain amount of confidence.

Water levels were obtained where possible and others estimated from gradients in the area.

Testing the Reliability of the Mathematical Model (Calibration Phase)

Testing of the model consisted of matching for each node, the water-level elevations generated by the computer with recorded water levels obtained from hydrographs. Although the initial water-level responses from the computer matched recorded water-level elevations reasonably well in most areas, there were deviations in some areas. To obtain a closer match of the water levels in all areas, some of the storage factors, transmissive factors, and net deep-percolation values were adjusted, based on reasonable limits of the prototype. These changes were made within limits of the reliability of the data used in the development of the parameters.

A number of adjustments in the various factors were incorporated in the program and the effects of these changes were graphically plotted. When the best overall match commensurate with the available data and equipment was achieved, the mathematical model was accepted as being représentative of the Independence region.

Predicting Future Operations (Operational Runs)

After the calibration phase of the model was completed and response was considered satisfactory, typical operations were superimposed on the area in an effort to obtain a practical feeling for the ground-water reservoir. Future operations were imposed on the model by changing the deep-percolation factor (A_jQ_j) in the equation which, in reality, would represent additional extractions by wells or replenishment by artificial recharge.

Three separate operational runs were imposed on the area. Their results are discussed separately in a subsequent section.

Hydraulic Characteristics of the Model

The information generated by the computer, during the testing period, provided valuable information regarding the hydraulic characteristics of the ground-water basin.

The changes in storage factors within the limits of specific yield data did not cause significant changes in water-level elevations. This was mainly due to the small differences in the water-level elevations between beginning and end of the study period. Thus, the initial values of storage factors were not changed.

A balance of the area was first obtained node by node using a desk calculator to obtain a rough balance of the area. Due to the geologic condition of a rising mountain front contributing sediments to the east for an extended period of time, directional transmissivity was assumed. The west-to-east transmissivities were assumed to be twice that of the north-to-south transmissivity due to this anisotropy effect.

Transmissivities and Storativities differed slightly from those obtained from pumping test, and this difference is attributed to the averaging process involved in the digital model mechanics. In all cases the nodal areas involved areas of several square miles which due to the heterogeneity and anisotropy of the sediments could possibly contribute to the difference in values. The analysis of the pumping tests necessitated the assumptions of homogeneity and isotropy.

It must be kept in mind that the values used in the digital model were altered within reasonable limits considering the geology of the area in order to force a match with the recorded water-level elevations. This is not to say that this particular set of parameters are those that actually exist, but rather the parameters of transmissivity, storativity and deep percolation used are within reasonable limits expected in the area.

It is not to be said that by mathematical manipulation, other combinations of transmissivity, storativity and deep percolation could not have been used which would also produce a fairly accurate match to the data.

Average values of transmissivity, storativity and deep percolation used in the calibration phase are shown in Table 7 (Appendix I).

Multiple Well-Field Operation Based On Computerized Base Model

Pumping Program Based on Existing Wells With no Artificial Recharge Program (Calibration Run)

In the verification of the ground-water model of the Independence area, a 5-year period was chosen that incorporated an extensive pumping program. It was felt that if this could be matched adequately, then future spreading-withdrawal operations could be imposed upon the area with a certain degree of assurance. This was done after several trials which required adjusting the model parameters within practicable limits.

Tables 8 through 11 of Appendix I are computer generated plots of water-level elevation vs. time. The first page of each table summarizes the important operational data used in the run.

Twelve selected nodes were chosen out of the 25 node system for each run on the basis of importance as pumping or artificial recharge areas.

Selected nodes where historical control of water levels was good are presented in Table 8. In general, the computed water levels matched closely the recorded levels.

Pumping Program Based on Existing Wells Plus Spreading the Mean Annual Creek Flow According to 1967 Diversion Practices (Operation Run 1)

This was the first of the operational runs imposed on the model.

The goal of the operational runs was to obtain estimates of water-level elevations as the result of different operational conditions.

If a pumping node had a steep initial drawdown, but reached equilibrium within a few years, with reasonable pumping lifts, this was considered acceptable. Likewise, if in a spreading node the rise stabilized or reached a dynamic equilibrium state within several years, this also was considered acceptable.

Monotonically dropping or rising water levels over the seven-year period were considered unacceptable. In these cases, adjustments of the pumping or spreading should be made for optimum use of the basin. In the first operation run there was no leeway in adjusting the pumping or spreading. But, in the last two runs adjustment was made in order to optimize the pumping-salvage-spreading operations.

The graphs shown in Table 9 are self explanatory illustrating the need for additional wells principally in nodes 2, 5, and 23 (see Plate XVIII for nodal configuration) with increased spreading in nodes 11, 12, and 13. In general, spreading facilities should be constructed closer to the base of the mountains to decrease the buildup of water near the toe of the fans.

<u>No Pumping With Maximum Spreading</u> (Operation Run 2)

In this run, the conditions of operation run 1 were imposed for the first 5 years; and then in an effort to see the effect of 2 extremely wet years, the pumping was discontinued and the maximum creek flow was spread continuously for 2 years using a selectively controlled spreading program (Table 10). In all of the nodes the capacity for storage was not exceeded, implying that this water could be stored underground if proper facilities did exist, and in the right locations.

Optimized Pumping, Artificial Recharge and Salvage Program Based on Selective Operation of Present Wells Plus Additional New Wells (Operation Run 3)

An optimized safe yield of 113 cfs for the Bajada area was computed using Darcy's law, the equation of continuity, and the formation parameters obtained in the multiple well-field analysis. This figure checks very closely with the discharge obtained from the high groundwater areas planimetered from the aerial photographs.

For this area a recharge-pumping-salvage program was simulated.

After several trial runs it was concluded that it was not practicable to pump the safe yield and artificially recharge the mean-annual creek flow. This is due primarily to the limitations imposed upon the locations of the pumping nodes. In other words, pumps could not be economically justified in nodes near the base of the mountains where lifts might exceed 1000 to 1500 feet. Likewise, increased extractions in the lower regions of the fans would result in too high of a well population for economical operation. The highest optimized system thus mathematically created could theoretically extract 169 cfs from the area over an extended period of time. This is 90 percent of the amount of water available under this pumping-spreading-salvage operation.

The graphs of selected nodes as well as the data imposed are displayed in Table 11.

GROUND-WATER RECOVERY AND SALVAGE SCHEMES

Artificial Recharge of the Ground-Water Reservoirs

Spreading Water on the Alluvial Fans

The use of underground storage facilities in the conservation of water resources is becoming increasingly popular with different agencies working in the field. By storing excessive runoff during wet periods, through water spreading, a reserve is created that is not subject to many of the problems of surface storage such as high evaporation loss and contamination.

In the Owens Valley region, the underground reservoirs are in the form of extensive alluvial-fan deposits which have merged together creating Bajada Reservoirs. This alluvium has potential for storing large amounts of surface runoff if proper facilities could be made available. Limited spreading is practiced at present into dry stream channels.

A large-scale program incorporating the techniques of off-channel spreading, in which impounding or velocity-checking facilities exist, should be constructed. In conjunction, the construction of levees to form shallow basins, and deep pits to enhance infiltration, should be undertaken. These two structures should be carefully studied as to their locations in the alluvial fans, and should be located in well-sorted portions of the fans where infiltration rates are high and danger of washout by high runoff rates is at a minimum. Many times, if the stream velocity is low enough, sheet flow can be induced across the stream channel itself by means of small dikes or levees. This "on-channel" spreading technique should be practiced whenever possible in conjunction with the off-channel spreading.

Use of Alluvial Faults in the Storage and Retention of Ground Water

Numerous alluvial faults cut the valley's aquifers. This is especially pronounced north of the Alabama Hills and south of Big Pine (see Geologic map, Plate IV). An interesting feature of these faults is their ability to retard the flow of ground water. This retarding effect is clearly illustrated in the areas of heavy phreatophyte growth on the upstream side of faults (see Plate X).

Ideally, the storage facilities in these alluvial fans could be greatly enhanced by constructing a subsurface barrier, extending from the surface down to the semi-pervious older alluvium. This would prevent subsurface runoff to discharge as evapo-transpiration from the toe of the fans.

The alluvial faults in the Owens Valley could, and do to a certain extent, serve as such barriers. By spreading the water from creeks such as Hogback, Georges, Bairs, Shepards and Symmes in such a manner as to induce maximum percolation, the water would be impounded by the fault pattern extending north of the Alabama Hills. A large underground storage reservoir could be allowed to accumulate over the years which, during drier seasons, could be drained through a proper system of withdrawal wells.

Another area which lends itself to this type of storage is the fault area between Red Mountain and Crater Mountain, just south of Big Pine.

With a controlled-spreading program of this type, withdrawal or drainage wells could be placed near the fault barrier, on the upstream side where lifts would be low.

During long periods of pumping, "backward" leakage would in time be induced across the faults due to the gradient created by the pumping wells. This would tend to lower the water level in these downstream sections thereby salvaging water otherwise lost due to evapotranspiration.

This type of spreading and salvage operation, utilizing semi-pervious faults as barriers, necessitated the development of the theory of flow of water across semi-pervious faults which is discussed in the following section.

In the past, faults, have generally been treated as impermeable boundaries. Investigation of faults in the Owens Valley, however, reveal that they are semi-pervious, or leaky in nature. The physical implication of this theory takes account of this leakage. Predictions can be made of the non-steady state water-level distributions, caused by induced leakage across a fault.

Theory of a Well Pumping in the Vicinity of a Semi-Pervious Fault

Assumptions:

After the initial transient has passed and the drawdown in Section 1 (Fig. 23) has attained an essentially steady or quasi-steady state distribution, then leakage will be induced across the fault towards the well at a rate dependent upon the hydraulic conductivity of the fault "gouge" layer (K'), the thickness of the layer (b') and the potential difference δ between the initial water level surface and the quasi-steady level. This quasi-steady distribution can be attained by the convential method of image well theory with the assumption that during the transient lowering of the head in Section 1 before attaining a steady-state distribution, the fault contributes no effective leakage and that during this time the fault acts as a true barrier ($K' \to 0$).

Due to the very low hydraulic conductivity of the fault zone, the lowering of the head in Section 1 can be considered as instantaneous for all practical purposes and the system will act hydraulically the same as one in which there is a sudden head change (lowering).

- Aquifer is effectively homogeneous and isotropic (except for semi-pervious "gouge" layer)
- Assume no storage in semi-pervious layer ($S' \to 0$)
- $\partial h/\partial t$ (in Section 1) $\to 0$
- Fault acts as a unidirectional line source

DIFFERENTIAL EQUATION GOVERNING SYSTEM

$$\nabla^2 s = \frac{1}{\nu}\frac{\partial s}{\partial t} \qquad \text{(s = drawdown in Section 2)}$$

with unidirectional flow:

$$\frac{\partial^2 s}{\partial \chi^2} = \frac{1}{\nu}\frac{\partial s}{\partial t} \qquad . . . (1)$$

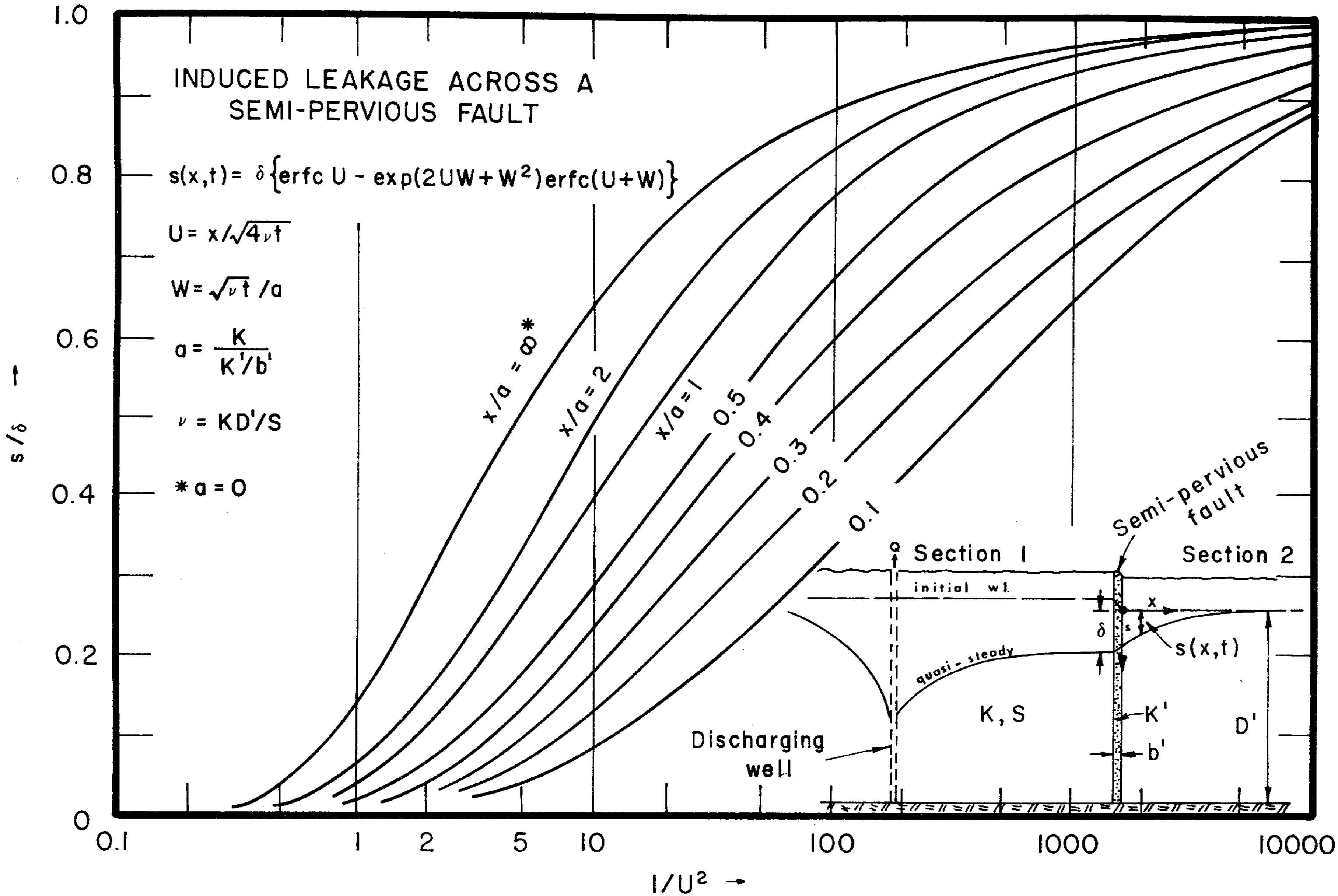


Fig. 23 FLOW TO A WELL PUMPING IN THE VICINITY OF A SEMI-PERVIOUS FAULT

INITIAL CONDITION:

$$s(x,0) = 0 \qquad \ldots (2)$$

BOUNDARY CONDITIONS:

$$s(\infty,t) = 0 \qquad \ldots (3) \;; \quad \bar{s}(\infty,p) = 0$$

$$-\,Kb \quad \frac{\partial s(0,t)}{\partial x} = b\,\frac{K'}{b'}\left(\delta - s(0,t)\right)$$

$$\frac{\partial s(0,t)}{\partial x} = -\frac{K'/b'}{K}\left(\delta - s(0,t)\right) \qquad \ldots (4)$$

$$\frac{\partial \bar{s}(0,p)}{\partial x} = -\frac{K'/b'}{K}\left(\delta/p - \bar{s}(0,p)\right)$$

APPLYING THE THEORY OF LAPLACE TRANSFORMS TO (1) and denoting $L\{s(x,t)\} = \bar{s}(x,p)$ we obtain:

$$\frac{\partial^2 \bar{s}}{\partial x^2} = \frac{p}{\nu}\,\bar{s} - s(x,0) \qquad \ldots (5)$$

applying initial condition (2) to (5):

$$\frac{\partial^2 \bar{s}}{\partial x^2} = \frac{p}{\nu}\,\bar{s} \qquad \ldots (6)$$

solving (6) by conventional operator methods

$$(D^2 - p/\nu)\bar{s} = 0$$

$$(D + \sqrt{p/\nu})(D - \sqrt{p/\nu})\bar{s} = 0$$

$$\bar{s} = C_1 \exp(-\sqrt{(p/\nu)}x) + C_2 \exp(+\sqrt{(p/\nu)}x)$$

Applying boundary condition (3) transformed

$$\bar{s}(\infty,p) = 0 = C_1 e^{-\infty} + C_2 e^{\infty}$$

$$C_2 = 0$$

$$\bar{s} = C_1 \exp(-\sqrt{(p/\nu)}x) \qquad \ldots (7)$$

applying (4) to (7) we have

$$\frac{\partial \bar{s}}{\partial x}(0,p) = -\frac{K'/b'}{K}\left(\frac{\delta}{p} - \bar{s}(0,p)\right) = C_1 e^{-\sqrt{p/\nu}(0)}\left(-\sqrt{p/\nu}\right)$$

$$-\frac{K'b'}{K}\left(\frac{\delta}{p} - \bar{s}\right) = -C_1\sqrt{p/\nu} \quad = \text{constant with respect to x so} \ldots$$

$$-1/a\ (\delta/p - C_1) = -C_1\sqrt{p/\nu}$$

and

$$C_1 = \delta/p\left(\frac{1}{a\sqrt{p/\nu}+1}\right) = \delta/ap\left(\frac{1}{\sqrt{p/\nu}+1/a}\right)$$

putting in (7) we have

$$\bar{s}(x,p) = \delta/ap\left(\frac{1}{\sqrt{p/\nu}+1/a}\right)\exp(-\sqrt{(p/\nu)}x)$$

Rearranging

$$\bar{s}(x,p) = \frac{\delta\frac{\sqrt{\nu}}{a}\exp(-x\sqrt{p/\nu})}{p\left(\frac{\sqrt{\nu}}{a}+\sqrt{p}\right)}$$

inverting refer to (Churchill, 1958, page 328, No. 86) where

$a = \sqrt{\nu}/a \qquad k = + \frac{x}{\sqrt{\nu}}$

$$s(x,t) = (\ \delta\ ) - \exp\left(+ \frac{\sqrt{\nu}}{a} \cdot \frac{x}{\sqrt{\nu}} \right) \ \exp\left(\frac{\nu}{a^2} \quad t \right) \cdot \left[\operatorname{erfc}\left(\frac{\sqrt{\nu t}}{a} + \frac{x}{2\sqrt{\nu t}} \right) \right] + \operatorname{erfc}\left(\frac{x}{2\sqrt{\nu t}} \right)$$

rearranging:

$$s(x,t) = \delta \left\{ - \exp \left(- U^2 + (U + W)^2 \right) \operatorname{erfc}\ (U + W) + \operatorname{erfc} U \right\}$$

SYMBOLS used:

$s(x,t)$ = drawdown in Section 2 (Area down gradient from the fault)

δ = difference between initial level in Section 2 and drawdown at face of fault in Section 1.

a = $K/K'/b'$ [L]

K = hydraulic conductivity of aquifer

K' = hydraulic conductivity of gouge layer

b' = thickness of gouge layer

ν = T/S = transmissivity (Kb)/Storativity

t = time since initial lowering of head in Section 1

U = $x / \sqrt{4\nu t}$

W = $\sqrt{\nu t}/a$

Fig. 23 is a graphical plot of the solution. Values of s/δ vs. $1/U^2$ are plotted on semi-log paper for different values of the parameter x/a. a is an indirect indication of the relative impermeability of the fault zone as compared to the surrounding aquifer. In other words, the value of a = 0 implies that $K \rightarrow K'$ and the gouge layer is as permeable as the aquifer. A value of x/a = 0.1 represents a very impermeable gouge layer as compared to the aquifer.

Application of this theory was made to the Georges Creek Well (343). This was the first of the series of wells to be drilled adjacent to fault lines, as proposed by the writer in 1966.

It may be of interest in the case of this well to know how long it would take to dewater an area on the other side of the fault. Because phreatophyte growth is not sustained when the depth to water drops below 8 or 10 feet (Meinzer, 1927), the desired dewatering depth is chosen as 10 feet. It must be remembered that the purpose of placing these wells close to these faults is not only to intercept the ground water where it is temporarily impounded, but also to salvage the areas of high ground water by inducing backward leakage across these semi-pervious fault zones.

From the results of "trenching" carried out across these alluvial faults in the summer of 1968, it can be assumed that the ratio of the hydraulic conductivity of the alluvial gravels to that of the "clayey" gouge zones is at least on the order of 10000 to 1.

Well 343 is located approximately 200 feet west of the first of a series of semi-pervious faults which retard the flow of ground water in the area, creating an extensive belt of phreatophyte growth.

Assumptions:

Discharge of the well = 5 cfs.

Transmissivity of alluvium = 100,000 gpd/ft.

S = 0.1.

Ratio of hydraulic conductivities, K/K' = 10000.

Distance from well to fault = 200 ft.

Distance from fault to desired area to be dewatered on the other side of the fault = 1000 ft.

Assumed thickness of semi-pervious fault, b' = 1 ft.

The first step is to find the time required for quasi-steady state to be established. Quasi-steady state conditions are assumed to exist when the rate of drop at the fault is less than 0.1 ft/day.

Using image-well theory, the time required to establish quasi-steady state conditions is 50 days. Also, the drawdown at the face of the fault due to pumping 5 cfs for 50 days is 30 ft.

Choosing the desired drawdown to be 10 ft with the differential water level across the fault δ = 30 ft, s/δ = 10/30 = 0.33.

Also, $a = \frac{K}{K'/b'}$ = 10000 feet.

The desired distance downstream, x = 1000 ft.

Then x/a = 1000/10000 = .10.

Referring to Fig. 23, (plot of s/δ vs. $1/U^2$ for different values of x/a), we find that for a value of s/δ = 0.33 and on the x/a = .10 curve, $1/U^2$ = 100.

Since $1/U^2 = 4Tt/x^2S = 100$, solving for time t, we find t = 187 days.

This means that after quasi-steady state conditions are established, it will take 187 days for the water surface to be lowered 10 ft at a distance of 1000 ft downstream from the fault. Or, the total time required to dewater this area since pumping of the well began, would be 237 days.

This value is a mathematical estimate and will be compared to the actual observed value once the operational phase of the second aqueduct system has begun. As of now (1969), pumps are not installed in the newly drilled supply wells.

A mathematical estimate of the hydraulic conductivity of the fault gouge layer (K') can be obtained from continuity considerations.

By equating volume-rates of flow into and out of the fault zone, the following approximation is obtained:

$$K' = K \frac{b'}{\xi} \; (dh/dx)$$

where: K = hydraulic conductivity of aquifer

b' = thickness of fault gouge layer

ξ = differential water level across the fault

(dh/dx) = upstream hydraulic gradient

An investigation is presently underway by the writer to test this relation by obtaining field values of b' and ξ.

SUMMARY AND CONCLUSIONS

This report represents an attempt to explain the ground-water hydrology of the southern Owens Basin. The main effort was oriented towards predicting the behavior of the basin under various pumping and spreading conditions.

Detailed geologic mapping in the field, coupled with actual aerial reconnaissance, was used to formulate an up-to-date geologic map of the study area. Photogeologic mapping techniques, integrated with petrographic analysis, were employed to obtain more comprehensive knowledge concerning the geology of the area.

The hydrologic cycle in the Owens Valley was studied with regard to the role of precipitation, evaporation, and runoff. This knowledge was gained through the averaging of records over a chosen base period.

The different ground-water regions, or provinces, were then delineated in the study area on the basis of all available geohydrologic knowledge. Hydrologic familiarity with these different regions was gained through aquifer tests performed on different wells and well fields in the area. One major ground-water region was chosen for its immediate importance in future aqueduct operations. The geohydrologic properties of this particular area were simulated mathematically with a digital computer. Future aqueduct operations consisting of extractions, artificial recharge, and optimum salvage of ground water were imposed upon the area in order to gain insight into the behavior of the reservoir.

The factors making up the hydrologic cycle in the study area were incorporated into a hydrologic budget consisting of all inflow, outflow and storage changes. From the balance of this budget the important quantity of ground-water safe yield was established for the study area.

The results of this investigation yield the following conclusions:

1. The ground-water reservoirs in the study area comprise basically the area from the base of the Sierra Nevada on the west, to the toe of the alluvial fans on the east. The central portions of the valley, in general, contain lacustrine and other fine-grained deposits and are not considered aquifers.

The eastern portion of the valley yields small amounts of runoff and is insignificant as far as the water supply is concerned.

2. The ground-water reservoirs in the study area are recharged from percolation of runoff from the melting sierran snowpack. A lesser amount of recharge occurs as the result of direct precipitation on the alluvium and volcanics.

The ground-water reservoirs in the study area discharge in the form of springs, seeps and large, high ground-water areas at the lower peripheral zones of the alluvial detritus cones and lava flows. It is in these lower zones that the eastward-moving ground water is forced to the surface by relatively impermeable lacustrine and fine-grained sediments.

3. Over 1 million acre-feet of ground water is presently stored in the valley's aquifers.

4. The ground-water safe yield of the study area, as determined from ground-water discharge, is 221 cfs.

The ground-water discharge in the Bajada region (Sawmill to Hogback creeks inclusive), as determined from Darcy's law and using formation parameters obtained in the well-field analyses, is 112 cfs.

5. Optimization of the ground-water resources in the study area can be gained in a controlled and integrated RECHARGE-EXTRACTION-SALVAGE SYSTEM. In a system of this type artificial recharge is induced into the valley's aquifers by impounding and diverting the flow from creeks tributary to the areas. Extraction of the ground water is accomplished by means of properly designed and developed drainage wells located near the toe, or discharge zone of the fans. Salvage of water in high ground-water areas is accomplished by lowering the water table in those areas causing water-consuming phreatophyte growth to die out. This lowering of the water table is the direct result of pumping high-capacity drainage wells.

6. Tests in the area indicate that the aquifers generally are very transmissive. Transmissivities of over 200,000 gpd/ft can be expected in the deep Bajada regions, while much higher values can be expected in the volcanic areas.

Storativities average about 0.01 for the alluvial-fan areas and range in order of magnitude higher for the volcanic regions.

7. The results of the computer study in the Bajada region shows the need for improved artificial recharge techniques as well as extraction techniques. This modification involves selective operation of the existing wells coupled with operation of additional new wells.

8. Natural subsurface barriers exist in several areas in the form of semi-pervious or "leaky" alluvial faults. These faults have the effect of temporarily blocking or impounding the water which otherwise would continue to lower points of discharge.

It is in these areas that the writer feels excellent opportunity is afforded for storing large amounts of surplus water by impounding tributary stream flows in periods of excessive or surplus runoff.

When predicting water-level declines in the vicinity of these faults, due to discharging wells, the theory of semi-pervious faults developed herein should be used to avoid erroneous results.

9. Properly designed and developed wells can be expected to produce high sustained yields. These would typically range from 3 to 5 cfs in the alluvial areas, to 7 to 10 cfs in the volcanic regions.

RECOMMENDATIONS FOR FURTHER STUDY

Geologic and hydrologic control is noticeably lacking in the areas away from the center of the valley. Deep wells preferably 1000 feet or more in depth should be drilled with a small-diameter rotary rig starting near the base of the mountains and continuing to the valley floor. East-west profiles of this type should be run on regular intervals to gain maximum geologic and hydrologic knowledge of the area. These wells should be carefully analyzed, preferably with well-logging techniques.

Pumping tests should be conducted on all wells considered for production. Step-drawdown tests should be run on these wells and well efficiencies calculated and recorded. Periodically, during the pumping life of the well, a step-drawdown test should be run and its then efficiency compared with its initial or optimum efficiency. It can then be determined if redevelopment is necessary.

Standard interference tests should be run of all new production wells and selected neighboring wells as an aid to obtaining knowledge regarding the hydraulic characteristics of the basin.

Use should be made of the new infrared aerial-photographic techniques as an aid in studying the valley. By using this new geohydrologic tool, insight as to ground-water flow paths, areas of recharge and discharge can be gained.

Finally, after complete geohydrologic control is gained concerning all phases of the area, an expansion of the digital model should be made. This expansion would take into account the complete study area, from Owens Lake on the south, to the southern boundary of the Bishop Cone on the north.

A complete revamping of the current artificial-recharge program should be undertaken. Storage of underground water in the Owens Valley should be carefully studied, especially as to practices and techniques.

APPENDIX I (Tables)

TABLE 1

Runoff Tributary to the Study Area (Base Period 1937/38 - 1959/60)

CREEK or AREA	DRAINAGE AREA (acres)	BASE OF MTS. RUNOFF (ac-ft)
Baker Creek	2800	5060
Big & Little Pine Creek	24890	31120
Birch Creek	3290	5960
Tinemaha Creek	7880	13550
Taboose Creek	4650	7900
Area between Taboose & Goodale	2860	2930
Armstrong Canyon Area	2690	4620
Goodale Creek	3190	5020
Division Creek	3030	6700
Area between Sawmill & Division	1070	970
Sawmill Creek	4800	3660
Area between Sawmill & Thibaut	4240	3110
Thibaut Creek	1550	1620
Area between North Fork Oak & Thibaut	540	330
North Fork Oak Creek	7230	7980
Area betwen North & South Fork Oak	1180	630
South Fork Oak Creek	5170	5180
Area between South Fork Oak Creek & Independence Creek	1570	830
Independence Creek	7190	10240
Pinyon Creek	3020	2690
Area between Pinyon & Symmes	1420	750
Symmes Creek	4510	3120
Area between Symmes & Shepherd	160	90
Shepherds Creek	8220	8050
Area between North Fork Bairs & Shepherd	1150	700
North Fork Bairs Creek	2510	1960
Area between North & South Forks	450	270
South Fork Bairs Creek	1890	1590
Area between Georges & South Fork Bairs	1090	730
Georges Creek	5950	6180
Area between Georges & Hogback	1040	790
Hogback Creek	3000	2780
Area between Hogback & Lone Pine Creek	1290	920
Papoose Flat Area	8320	560
Mazourka Canyon Area	38870	2430
Reward Area	25040	1680

TABLE 1 (Cont.)

CREEK or AREA	AREA (acres)	BASE OF MTS. RUNOFF (ac-ft)
Lone Pine Creek	10550	8570
Tuttle Creek	5180	3970
Diaz Creek	4300	2960
Lubkin Creek	3940	2090
Long John Canyon Area	18840	1180
Carroll Creek	2070	270
Area between Carroll & Cottonwood	4700	1980
Cottonwood Creek	27100	16960
Area between Ash & Cottonwood	1680	240
Ash Creek	9540	3160
Area between Ash & Braley	2890	500
Braley Creek	3490	1060
Cartago Olancha Area	12970	3850
Falls-Walker Summit Area	10360	2910
Cerro Gordo Area	50460	2780
Centennial Flats	29910	1500
Vermillion Canyon	15920	890

Sum = 207570 AF/Yr.

(286 cfs)

TABLE 2

WATER BUDGET (Bishop Cone - Owens Lake)
for base period 1937/38 - 1959/60

General equation:

INFLOW = OUTFLOW + STORAGE GAIN

Assumption is that the storage gain for both surface and ground water equals zero for the base period.

	cfs
INFLOW	
Tributary inflow from creeks at base of mountains.	286
Effective precipitation on alluvium and volcanics.	82
Surface inflow imported (Owens River at Zurich Bridge).	348
Subsurface inflow across so. bound. of cone.	15
TOTAL INFLOW	731
OUTFLOW	
Waste Gates (Owens River at Keeler Bridge).	28
Surface outflow via aqueduct to Haiwee Reservoir.	436
Consumptive use of irrigated lands.	16
Excessive spreading (water wasted by evaporation).	30
Subsurface outflow from basin.	0
Ground-water discharge (Evapotranspiration from areas of high ground water plus unknown springs and seep areas).	221
TOTAL OUTFLOW	731
STORAGE GAIN	
Tinemaha Reservoir	0
Ground water	0
TOTAL STORAGE GAIN	0

Total ground-water discharge = 221

(OPTIMIZED SAFE YIELD)

TABLE 3 POTENTIAL EVAPOTRANSPIRATION

Area Independence** Year 1965 Latitude 36° 59' N

Elevation 3840' Longitude 118° 14' W

Thornwaite's Formula*

$PE = (b/30)UPE$ -- Potential evapotranspiration

where:

$UPE = 1.6(10T/I)^a$ -- Unadjusted PE

$a = 6.75 \times 10^{-7} \; I^3 - 7.71 \times 10^{-5} \; I^2 + 1.79 \times 10^{-2} \; I + 0.49$

$I = {}^{12}_{n=1} \; i_n$

$i = (Tm/5)^{1.514}$

Tm = mean monthly temperature

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T, in °F	43.3	45.6	49.8	54.1	62.2	69.6	77.1	76.8	66.2	64.1	50.0	38.7
T, in °C	6.28	7.56	9.89	12.28	16.78	20.89	25.05	24.88	19.00	17.84	10.00	3.72
i	1.41	1.87	2.81	3.89	6.25	8.71	11.47	11.35	7.55	6.85	2.86	0.63

I = i 65.65

a 1.524

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
10T/I	.958	1.150	1.505	1.870	2.555	3.185	3.815	3.790	2.895	2.718	1.524	0.566
$(10T/I)^a$	.937	1.237	1.865	2.60	4.16	5.85	7.70	7.62	5.05	4.60	1.898	0.420
UPE in cm	1.50	1.98	2.98	4.16	6.66	9.36	12.32	12.19	8.08	7.36	3.04	0.67
b	25.8	25.5	30.9	33.0	36.6	36.9	37.5	35.1	30.9	29.1	25.5	24.9
PE in cm	1.29	1.68	3.07	4.58	8.13	11.52	15.45	14.28	8.33	7.14	2.58	0.56

Yearly PE 78.61 cm = 2.58 ft

*--Refer to Reference for Tables and Other Data.
**-Independence mean monthly temperatures were used.
REFERENCE: Hantush, M.S., Potential Evapotranspiration in Areas Along the Rivers of New Mexico, Professional Paper 101, N. M. Inst. of Mining & Tech.

TABLE 4

Summary of Underground Storage

Ground-Water Reservoir	Surface area A (acres)	Assumed saturated thickness, b(ft)	Storativity S	Volume of water in storage V = A x b x S (acre-ft)
Big Pine alluvial fan	5161	200	0.001	1000
Crater Mt.-Fish Springs Volcanic area	25807	150	0.10	390000
Taboose-Aberdeen Volcanic area	23226	150	0.10	350000
Bajada area	65032	500	0.01	330000
Lone Pine alluvial veneer area	20645	200	0.01	41000
Lone Pine alluvial fan	5150	200	0.01	10000
Owens Lake perepheral alluvium	15484	100	0.01	15000

Total Volume Stored in Aquifers . . . . 1,100,000 A-F

TABLE 5

Summary of Aquifer Tests

Well Number and Location	Type of Aquifer Tested	Type of Test(s) Conducted	Transmissivity T (gpd/ft)	Storativity S	Well Loss CQ^n(ft)	Formation Loss BQ (ft)
341 Big Pine Area	Glacial outwash and mudflows	Step-drawdown and recovery	7000*	---	$62Q^{.3}$*	60Q
342 Taboose Cr. area	Recent volcanic flows and alluvium	Step-drawdown	838000	---	$0.0067Q^{3.4}$	1.1Q
344 Lone Pine Area	Small alluvial fan type	Step-drawdown and time-drawdown	154000	---	$0.1Q^{4.5}$	3.0Q
105 Thibaut-Sawmill area	Large coalesced alluvial fans "Bajada type"	Multiple-well field analysis. "Composite drawdown"	115000	0.024	---	---
7 Independence Oak Cr. area	Bajada type	Multiple-well field "Composite drawdown"	318000	0.006	---	---
24 Symmes-Shepards area	Bajada type	Multiple-well field "Composite drawdown"	255000	0.005	---	---
98 Bairs-Georges Cr. area	Bajada type	Multiple-well field "Composite drawdown"	146000	0.004	---	---

* NOTE: Well 341 was tested in an undeveloped state.

TABLE 6

AQUIFER TEST DATA

Well 341 Big Pine

Drawdown s(ft)	Discharge Q(cfs)	Time t(min)	Comments
81	0.5	60	Step-Drawdown Test
101	0.75	120	
143	1.25	300	

Recovery s(ft)	Discharge Q(cfs)	Time t(min)	Comments
30.0	0.53	5	
33.0		8	
35.0		13	Recovery Test Data
36.5		16	
39.9		26	
42.1		37	
43.6		47	
45.3		67	
47.0	0.53	97	

Well 342 Taboose Creek

Drawdown s(ft)	Discharge Q(cfs)	Time t(min)	Comments
7.6	4.31	35	
13.6	6.22	70	Step-Drawdown Test (Lower Aquifer)
15.6	6.81	185	

TABLE 6 (Continued)

Drawdown s(ft)	Discharge Q(cfs)	Time t(min)	Comments
4.9	3.91	200	
7.0	4.95	400	Step-Drawdown Test (Both Aquifers)
10.0	6.07	800	
16.0	7.78	1200	
20.0	8.62	1400	(Virtually Non-Measurable Stabilization Times)
24.0	9.55	1900	
26.0	10.05	2500	
30.0	10.95	3000	

Well 344 Lone Pine

Drawdown s(ft)	Discharge Q(cfs)	Time t(min)	Comments
5.31	1.54	140	
11.06	2.30	280	Step-Drawdown Test
23.0	3.03	420	

Recovery s(ft)	Discharge Q(cfs)	Time t(min)	Comments
13.7	3.07	10	
14.2		20	
14.9		60	
15.3		90	Time-Drawdown Data
15.8		150	
16.2		210	
16.5		265	
16.9	3.07	390	

ANALYSIS OF RECOVERY DATA IN THIBAUT CREEK AREA| FEB"| =(

COMPUTATIONS OF SPECIFIC DRAWDOWN AND WEIGHTED LOGARITHMIC MEAN $\overline{(RXR/T)}$ FOR WELL 105

TIME	K	N	DIS CHARGE WELL	R	T	RXR/T	LOG(RXR/T)	Q	(9)X(8)	LOG(RXR/T)	$\overline{(RXR/T)}$	S	(S/Q)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
M D				FT.	SEC			CFS	CFS			FT.	FT/CFS
2 28	1		103	1056	691200	1.6	.204	1.88	.38				
	2		104	2218	691200	7.1	.851	1.41	1.20				
		2						3.29	1.58	.480	3.02	2.20	.669
3 10	1		103	1056	1555200	.7	-.154	1.88	-.28				
	2		104	2218	1555200	3.2	.505	1.41	.71				
		2						3.29	.43	.131	1.36	3.80	1.156
3 20	1		103	1056	2419200	.5	-.300	1.88	-.55				
	2		104	2218	2419200	2.0	.301	1.41	.42				
		2						3.29	-.13	-.039	.92	4.40	1.338
3 30	1		103	1056	3283200	.3	-.522	1.88	-.97				
	2		104	2218	3283200	1.5	.176	1.41	.25				
		2						3.29	-.72	-.218	.61	4.80	1.459

ANALYSIS OF RECOVERY DATA IN THE INDEPENDENCE AREA, FEB., 1962

COMPUTATIONS OF SPECIFIC DRAWDOWN AND WEIGHTED LOGARITHMIC MEAN $\overline{(RXR/T)}$ FOR WELL 7

TIME	K	N	DISCHARGE WELL	R	T	RXR/T	LOG(RXR/T)	Q	(9)X(8)	LOG(RXR/T)	$\overline{(RXR/T)}$	S	(S/Q)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
M D				FT.	SEC			CFS	CFS			FT.	FT/CFS
2 28	1		39	8712	691200	109.8	2.041	1.20	2.45				
	2		16	6072	691200	53.3	1.727	1.24	2.14				
	3		15	6336	691200	58.1	1.764	1.96	3.46				
	4		77	5544	691200	44.5	1.648	3.00	4.94				
	5		61	5016	691200	36.4	1.561	1.96	3.06				
	6		59	4330	691200	27.1	1.433	1.76	2.52				
	7		65	4224	691200	25.8	1.412	4.50	6.35				
	8		57	4171	691200	25.2	1.401	3.96	5.55				
	9		60	4699	691200	31.9	1.504	2.10	3.16				
	10		63	5544	691200	44.5	1.648	2.10	3.46				
		10						23.78	37.09	1.560	36.31	6.60	.278
3 10	1		39	8712	1555200	48.8	1.688	1.20	2.03				
	2		16	6072	1555200	23.7	1.375	1.24	1.70				
	3		15	6336	1555200	25.8	1.412	1.96	2.77				
	4		77	5544	1555200	19.8	1.297	3.00	3.89				
	5		61	5016	1555200	16.2	1.210	1.96	2.37				
	6		59	4330	1555200	12.1	1.083	1.76	1.91				
	7		65	4224	1555200	11.5	1.061	4.50	4.77				
	8		57	4171	1555200	11.2	1.049	3.96	4.15				
	9		60	4699	1555200	14.2	1.152	3.20	3.69				
	10		63	5544	1555200	19.8	1.297	2.10	2.72				
		10						24.88	30.00	1.206	16.07	9.70	.390
3 20	1		39	8712	2419200	31.4	1.497	1.20	1.80				
	2		16	6072	2419200	15.2	1.182	1.24	1.47				
	3		15	6336	2419200	16.6	1.220	1.96	2.39				
	4		77	5544	2419200	12.7	1.104	3.00	3.31				
	5		61	5016	2419200	10.4	1.017	1.96	1.99				
	6		59	4330	2419200	7.8	.892	1.76	1.57				
	7		65	4224	2419200	7.4	.869	4.50	3.91				
	8		57	4171	2419200	7.2	.857	3.96	3.39				
	9		60	4699	2419200	9.1	.959	3.20	3.07				
	10		63	5544	2419200	12.7	1.104	2.10	2.32				
		10						24.88	25.22	1.014	10.00	11.50	.463
3 30	1		39	8712	3283200	23.1	1.364	1.20	1.64				
	2		16	6072	3283200	11.2	1.049	1.24	1.30				
	3		15	6336	3283200	12.2	1.086	1.96	2.13				
	4		77	5544	3283200	9.4	.973	3.00	2.92				
	5		61	5016	3283200	7.7	.886	1.96	1.74				
	6		59	4330	3283200	5.7	.756	1.76	1.33				
	7		65	4224	3283200	5.4	.732	4.50	3.29				
	8		57	4171	3283200	5.3	.724	3.96	2.87				
	9		60	4699	3283200	6.7	.826	3.20	2.64				
	10		63	5544	3283200	9.4	.973	2.10	2.04				
		10						24.88	21.90	.880	7.59	12.90	.519

ANALYSIS OF THE RECOVERY DATA IN THE SYMMES AREA, FEB., 1962

COMPUTATIONS OF SPECIFIC DRAWDOWN AND WEIGHTED LOGARITHMIC MEAN $\overline{(RXR/T)}$ FOR WELL 24

TIME	K	N	DIS CHARGE WELL	R	T	RXR/T	LOG(RXR/T)	Q	(9)X(8)	LOG(RXR/T)	$\overline{(RXR/T)}$	S	(S/Q)
(1) M D	(2)	(3)	(4)	(5) FT.	(6) SEC.	(7)	(8)	(9) CFS	(10) CFS	(11)	(12)	(13) FT.	(14) FT/CFS
2 28	1		27	2640	691200	10.1	1.004	1.28	1.29				
	2		31	2112	691200	6.5	.813	1.61	1.31				
	3		67	2640	691200	10.1	1.004	3.38	3.39				
	4		68	2640	691200	10.1	1.004	1.86	1.87				
	5		69	4118	691200	24.5	1.389	4.44	6.17				
	6		74	4752	691200	32.7	1.515	3.16	4.79				
	7		92	7656	691200	84.8	1.928	3.30	6.36				
	8		96	6230	691200	56.2	1.750	4.40	7.70				
	9		99	9768	691200	138.0	2.140	2.49	5.33				
		9						25.92	38.21	1.474	29.79	9.20	.355
3 10	1		27	2640	1555200	4.5	.653	1.28	.84				
	2		31	2112	1555200	2.9	.462	1.61	.74				
	3		67	2640	1555200	4.5	.653	3.38	2.21				
	4		68	2640	1555200	4.5	.653	1.86	1.21				
	5		69	4118	1555200	10.9	1.037	4.44	4.60				
	6		74	4752	1555200	14.5	1.161	3.16	3.67				
	7		92	7656	1555200	37.7	1.576	3.30	5.20				
	8		96	6230	1555200	25.0	1.398	4.40	6.15				
	9		99	9768	1555200	61.4	1.788	2.49	4.45				
		9						25.92	29.07	1.122	13.25	13.20	.510
3 20	1		27	2640	2419200	2.9	.462	1.28	.59				
	2		31	2112	2419200	1.8	.255	1.61	.41				
	3		67	2640	2419200	2.9	.462	3.38	1.56				
	4		68	2640	2419200	2.9	.462	1.86	.86				
	5		69	4118	2419200	7.0	.845	4.44	3.75				
	6		74	4752	2419200	9.3	.968	3.16	3.06				
	7		92	7656	2419200	24.2	1.384	3.30	4.57				
	8		96	6230	2419200	16.0	1.204	4.40	5.30				
	9		99	9768	2419200	39.4	1.595	2.49	3.97				
		9						25.92	24.07	.929	8.50	15.50	.598
3 30	1		27	2640	3283200	2.1	.322	1.28	.41				
	2		31	2112	3283200	1.4	.146	1.61	.24				
	3		67	2640	3283200	2.1	.322	3.38	1.09				
	4		68	2640	3283200	2.1	.322	1.86	.60				
	5		69	4118	3283200	5.2	.716	4.44	3.18				
	6		74	4752	3283200	6.9	.839	3.16	2.65				
	7		92	7656	3283200	17.9	1.253	3.30	4.13				
	8		96	6230	3283200	11.8	1.072	4.40	4.72				
	9		99	9768	3283200	29.1	1.464	2.49	3.65				
		9						25.92	20.67	.797	6.27	17.30	.668

ANALYSIS OF RECOVERY DATA IN GEORGES CREEK AREA, FEB., 1962

COMPUTATIONS OF SPECIFIC DRAWDOWN AND WEIGHTED LOGARITHMIC MEAN $\overline{(RXR/T)}$ FOR WELL 98

TIME	K	N	DIS CHARGE WELL	R	T	RXR/T	LOG(RXR/T)	Q	(9)X(8)	LOG(RXR/T)	$\overline{(RXR/T)}$	S	(S/Q)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
M D				FT.	SEC			CFS	CFS			FT.	FT/CFS
2 28	1		75	5016	691200	36.4	1.561	3.16	4.93				
	2		86	2112	691200	6.5	.813	1.05	.85				
	3		76	4752	691200	32.7	1.515	2.35	3.56				
	4		89	9768	691200	138.0	2.140	1.19	2.55				
	5		95	5966	691200	51.5	1.712	1.23	2.11				
	6		87	8606	691200	107.2	2.030	1.12	2.27				
		6						10.10	16.27	1.611	40.84	4.30	.426
3 10	1		75	5016	1555200	16.2	1.210	3.16	3.82				
	2		86	2112	1555200	2.9	.462	1.05	.49				
	3		76	4752	1555200	14.5	1.161	2.35	2.73				
	4		89	9768	1555200	61.4	1.788	1.19	2.13				
	5		95	5966	1555200	22.9	1.360	1.23	1.67				
	6		87	8606	1555200	47.6	1.678	1.12	1.88				
		6						10.10	12.72	1.259	18.16	7.20	.713
3 20	1		75	5016	2419200	10.4	1.017	3.16	3.21				
	2		86	2112	2419200	1.8	.255	1.05	.27				
	3		76	4752	2419200	9.3	.968	2.35	2.27				
	4		89	9768	2419200	39.4	1.595	1.19	1.90				
	5		95	5966	2419200	14.7	1.167	1.23	1.44				
	6		87	8606	2419200	30.6	1.486	1.12	1.66				
		6						10.10	10.75	1.064	11.59	8.60	.852
3 30	1		75	5016	3283200	7.7	.886	3.16	2.80				
	2		86	2112	3283200	1.4	.146	1.05	.15				
	3		76	4752	3283200	6.9	.839	2.35	1.97				
	4		89	9768	3283200	29.1	1.464	1.19	1.74				
	5		95	5966	3283200	10.8	1.033	1.23	1.27				
	6		87	8606	3283200	22.6	1.354	1.12	1.52				
		6						10.10	9.45	.936	8.63	9.60	.951

TABLE 7

Computer Model Parameters

(Refer to Fig. 24 for node and side location)

Node	Area (acres)	Storativity	Ave. AQ (acre-ft/yr)	Side	J/L	Transmissivity (acre-ft/yr/ft)
1	6236	.10	- 8508	1	1739	100
2	4797	.025	3309	2	2063	18
3	3187	.05	2886	3	554	9
4	3118	.10	9394	4	585	50
5	3255	.025	- 6476	5	613	10
6	3735	.10	- 5426	6	1582	77
7	3906	.035	- 1855	7	1561	74
8	4214	.08	- 1723	8	561	10
9	4317	.04	2345	9	532	10
10	3851	.025	4942	10	484	10
11	3118	.05	2567	11	2439	6
12	2947	.075	1122	12	2015	40
13	3159	.035	296	13	2149	29
14	3015	.15	524	14	531	10
15	2501	.05	- 1022	15	571	20
16	2022	.05	- 3577	16	523	3
17	2645	.025	- 157	17	435	10
18	2775	.10	1093	18	1847	5
19	2604	.075	1154	19	1510	38
20	2810	.05	3320	20	1617	29
21	5208	.05	3567	21	1482	23
22	3906	.075	1533	22	806	10
23	4112	.10	4880	23	677	10
24	3803	.10	- 3997	24	729	10
25	2810	.05	- 6286	25	695	10
				26	556	10
				27	1599	22
				28	1281	44
				29	1379	42
				30	1268	34
				31	652	10
				32	569	10
				33	609	22
				34	549	10
				35	429	10
				36	2390	54
				37	1974	77
				38	2016	38
				39	1865	6

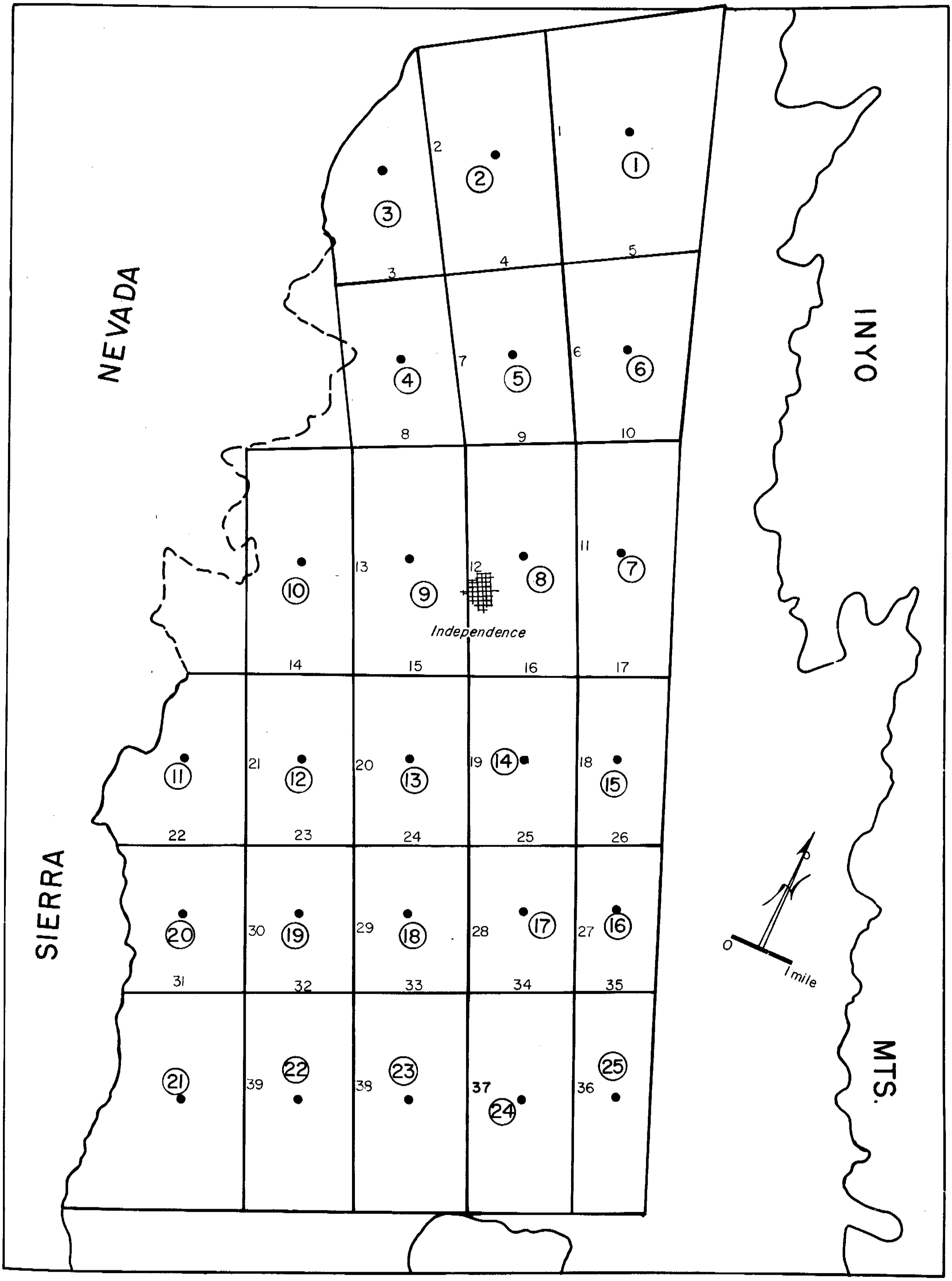


Fig. 24 NODAL POLYGONS FOR THE INDEPENDENCE GROUND-WATER BASIN

TABLE 8

CALIBRATION RUN

Hydrographic years (Oct. 1 to Sept. 30) 1958/59 - 1962/63

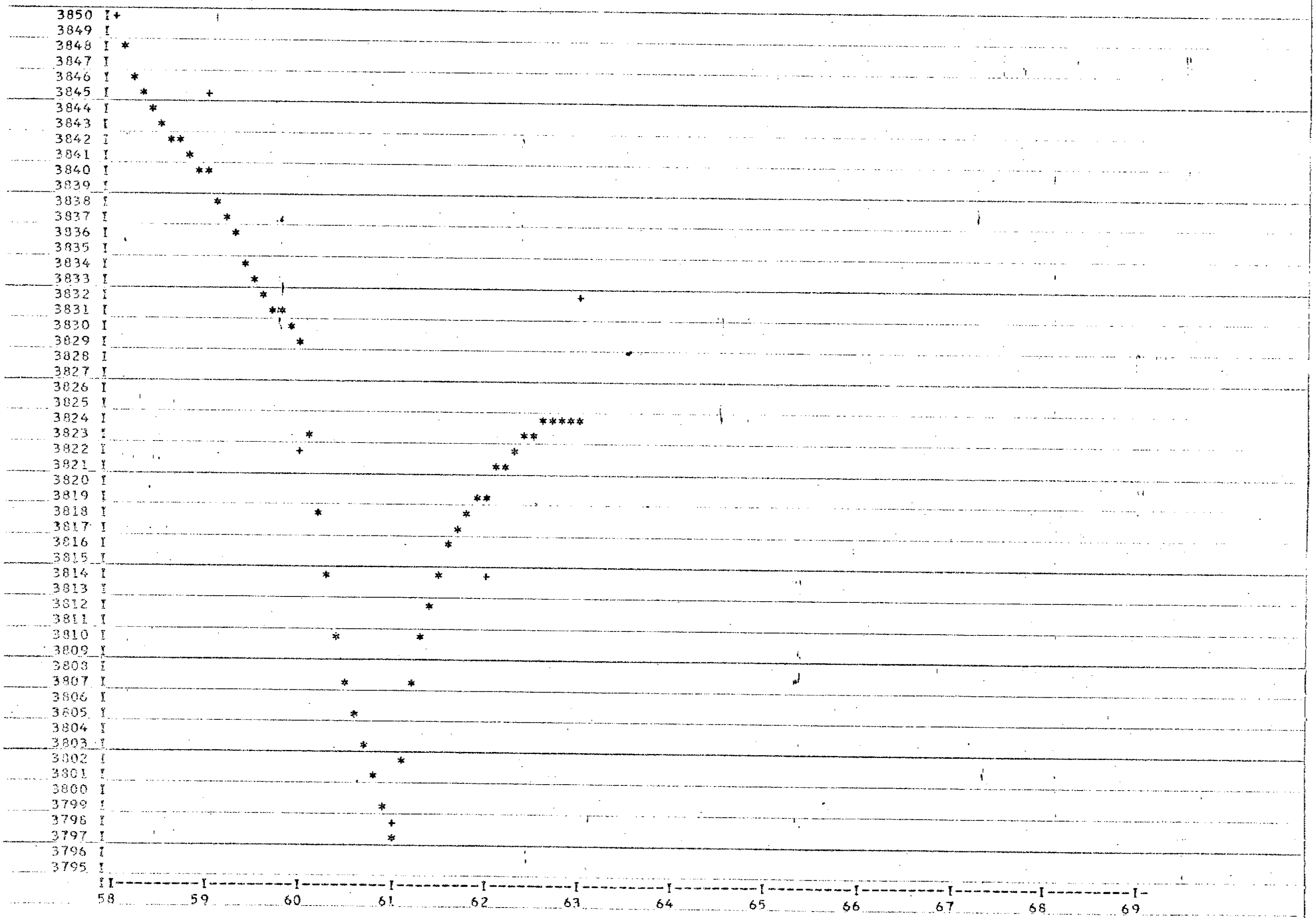
All water levels taken on or about November 1

Only the nodes with pumping or spreading are shown for simplicity.

NODE	Pumping Acre-ft/yr	Artificial Recharge By Spreading Acre-ft/yr	Comments
		1958-59	
All nodes	0	0	No spreading No pumping
		1959-60	
2	191	0	
8	5645	0	No spreading
14	7047	0	
17	938	0	
24	1695	0	
		1960-61	
2	5226	0	
8	17945	0	
14	19986	0	No spreading
17	3216	0	Maximum pumping
24	4370	0	
		1961-62	
8	7034	0	
14	7275	0	
17	1145	0	
24	1614	0	
		1962-63	
			No spreading No pumping

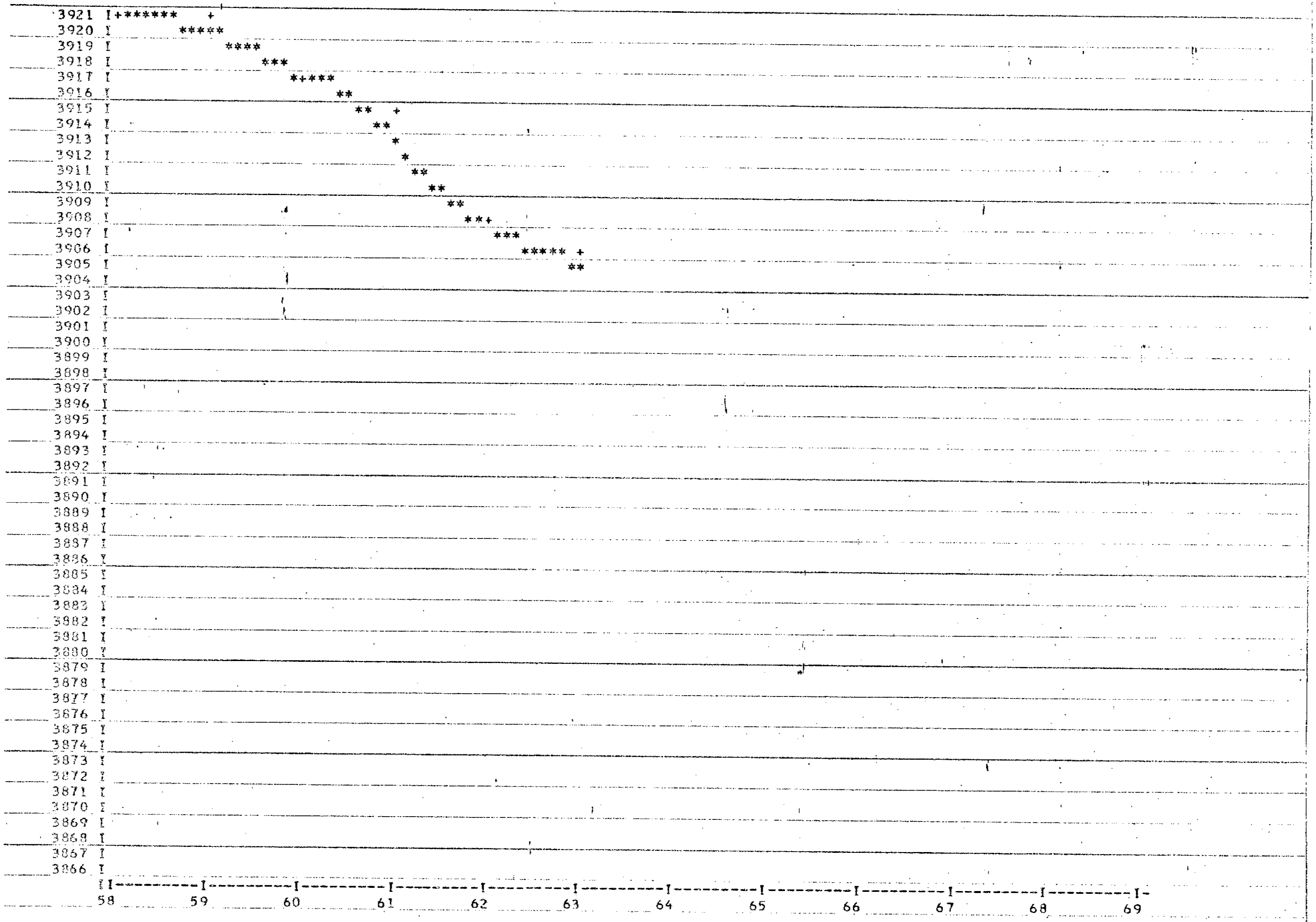
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 2   + HISTORIC ELEVATION   * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEAR'S

NODE 3 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



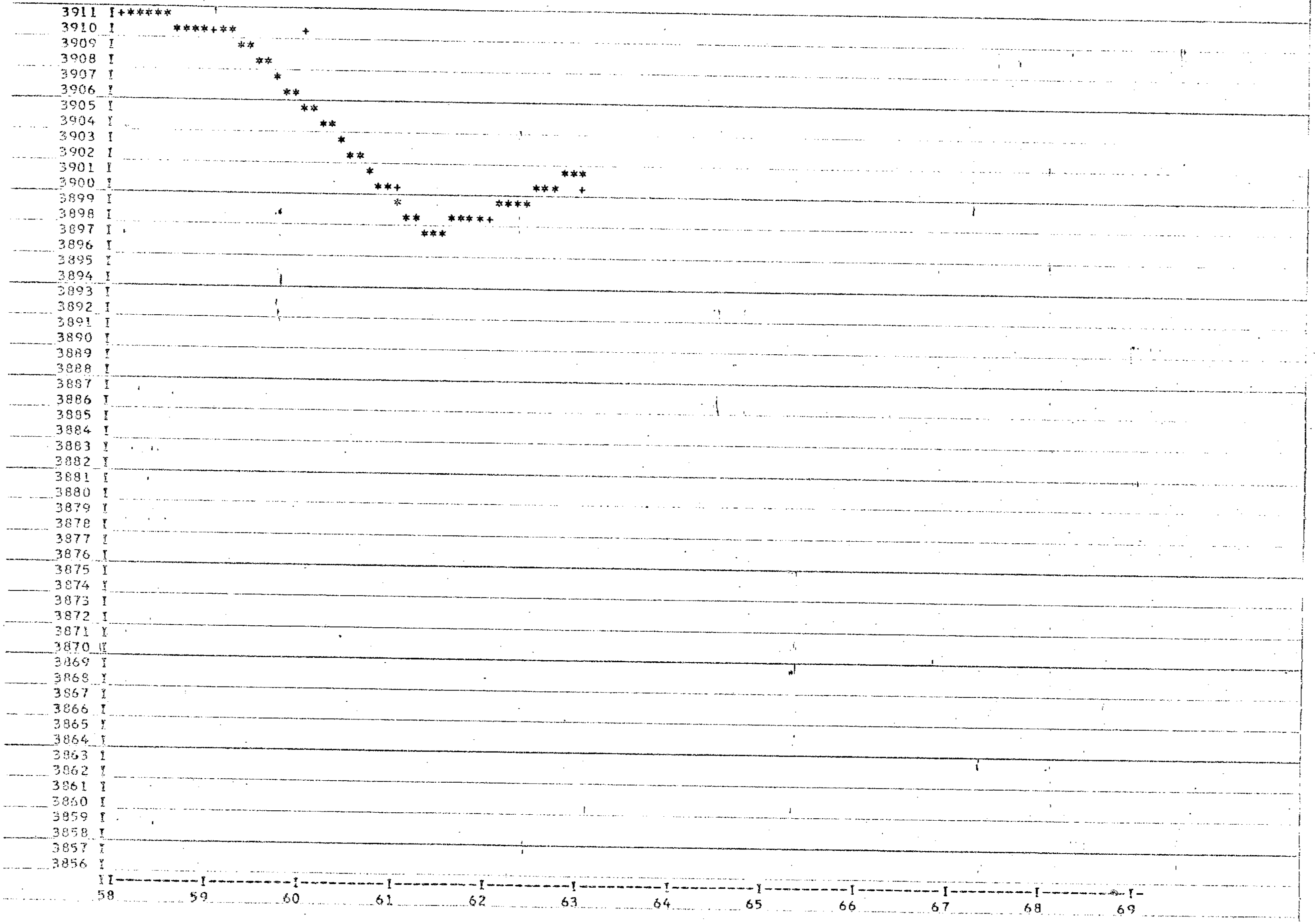
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA

WATER SURFACE ELEVATION VS. WATER YEARS

NODE 4

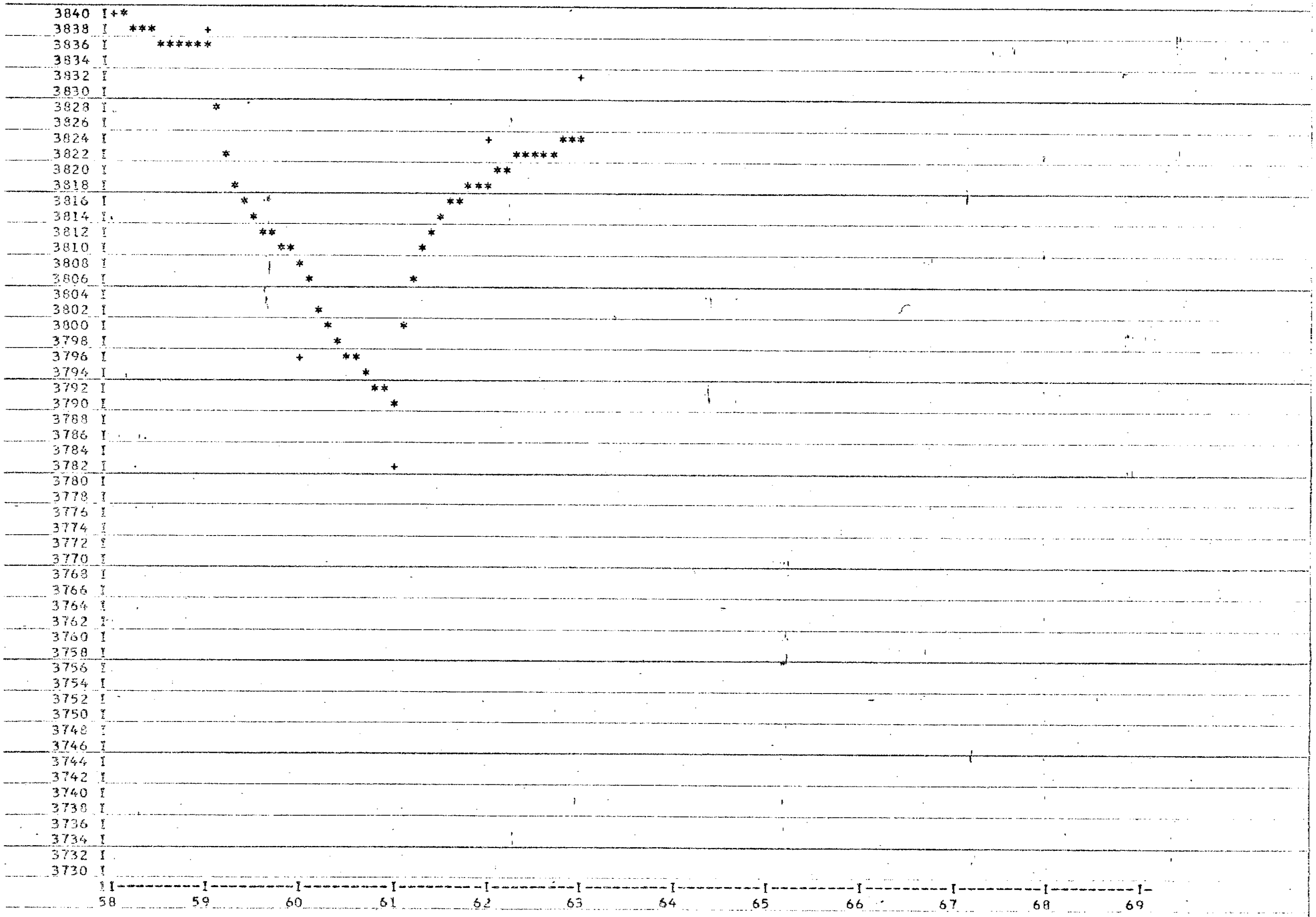
+ HISTORIC ELEVATION

* CALCULATED ELEVATION



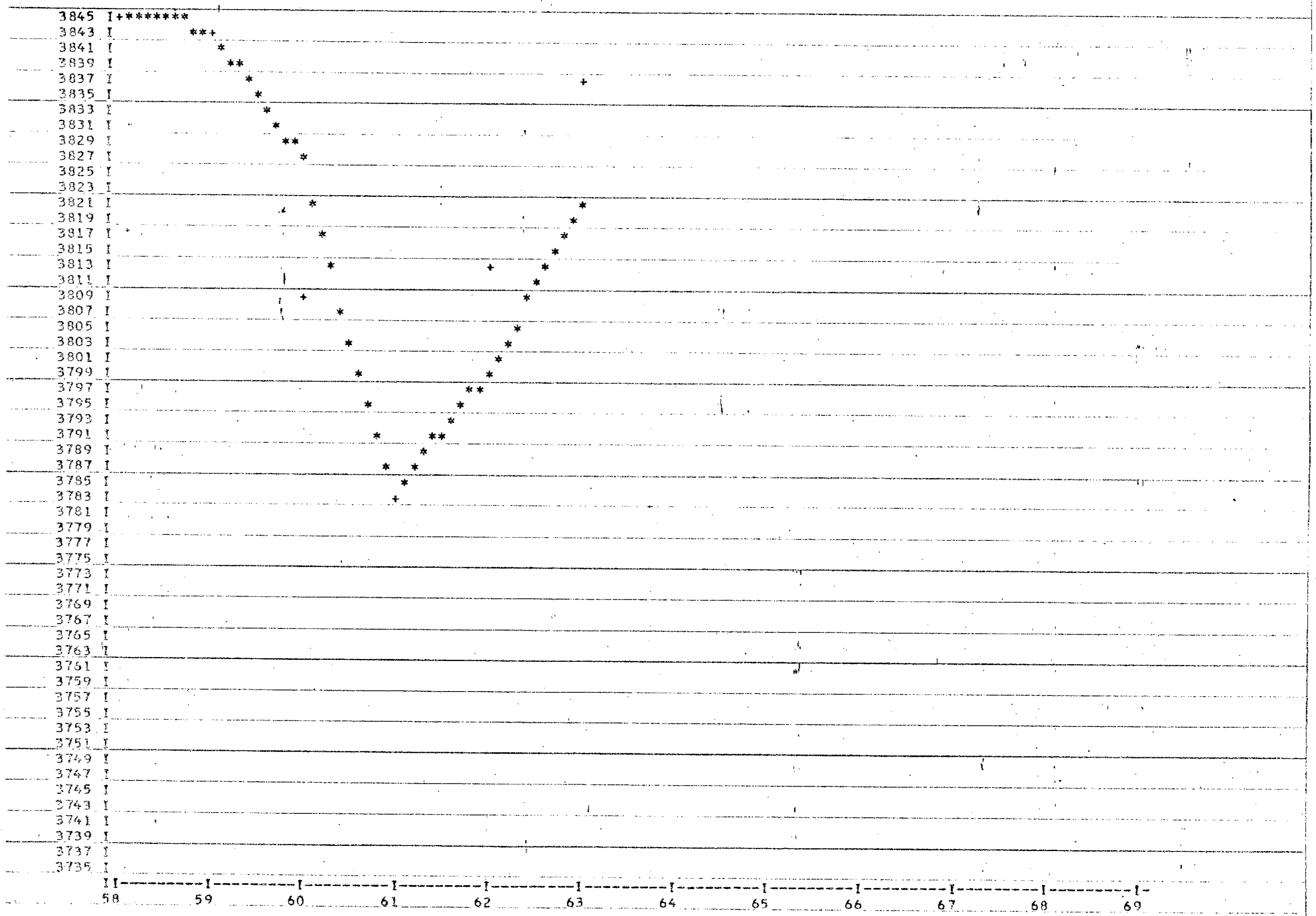
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 5 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



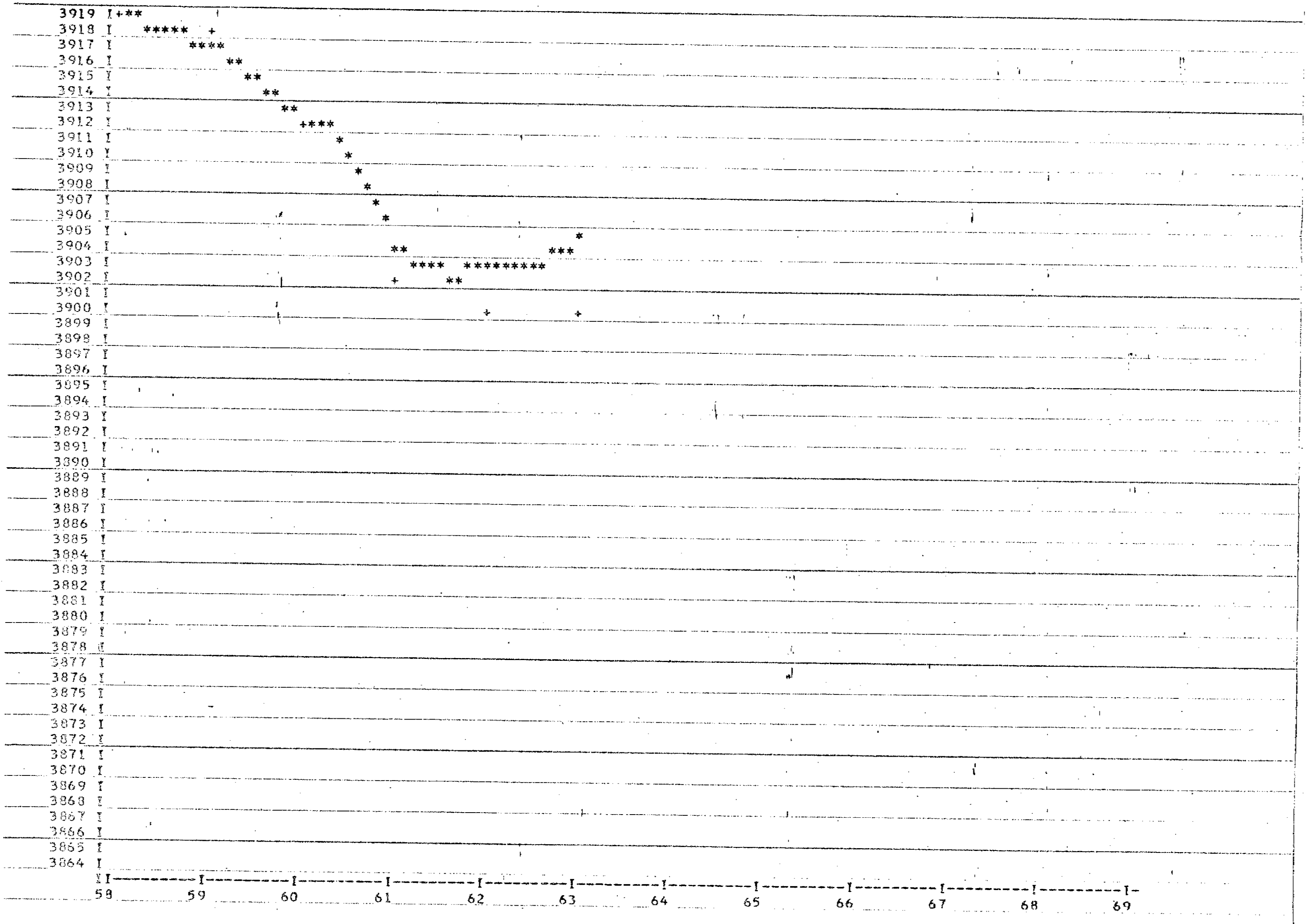
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE . 8 + HISTORIC ELEVATION * CALCULATED ELEVATION



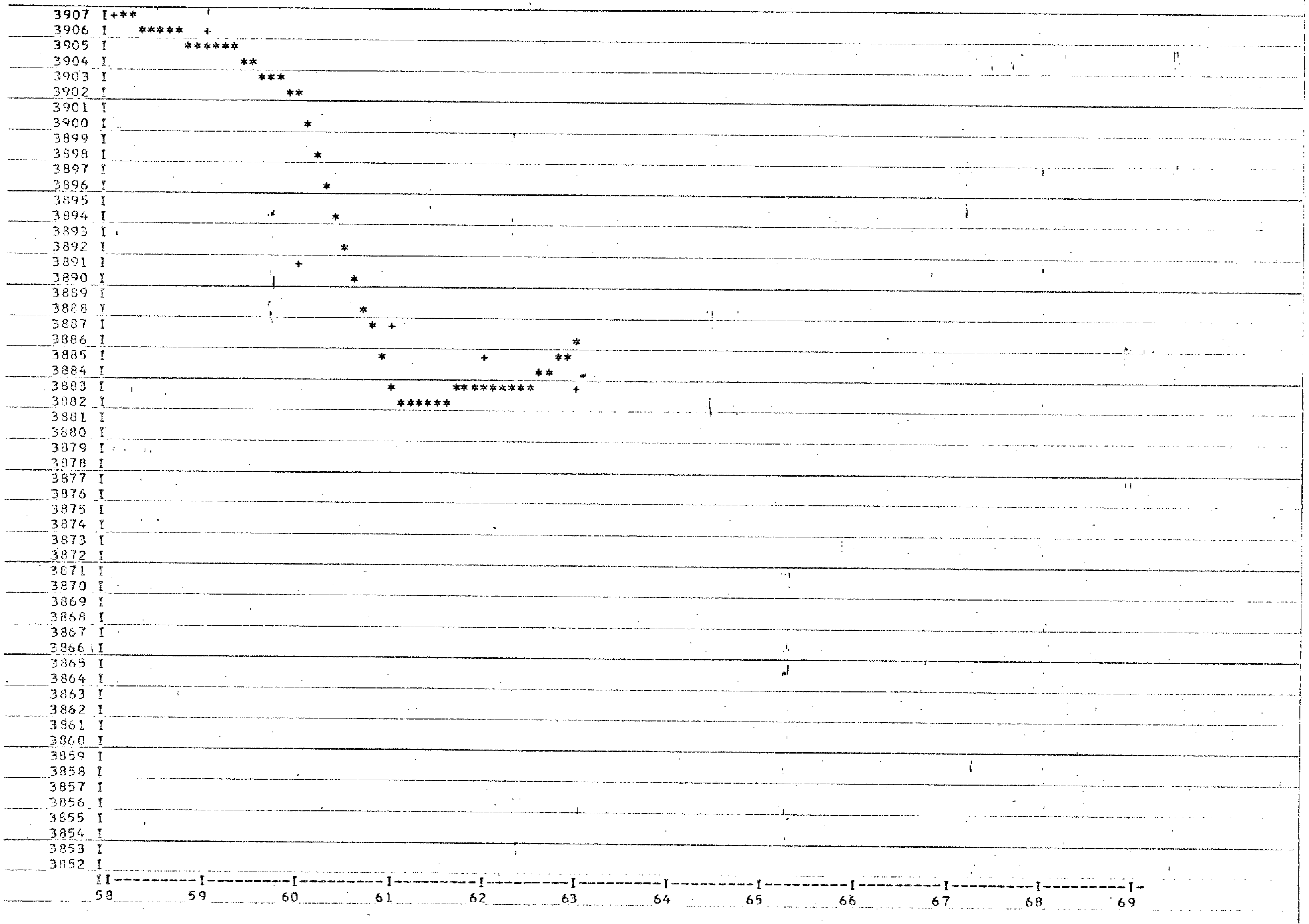
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 9   + HISTORIC ELEVATION   * CALCULATED ELEVATION



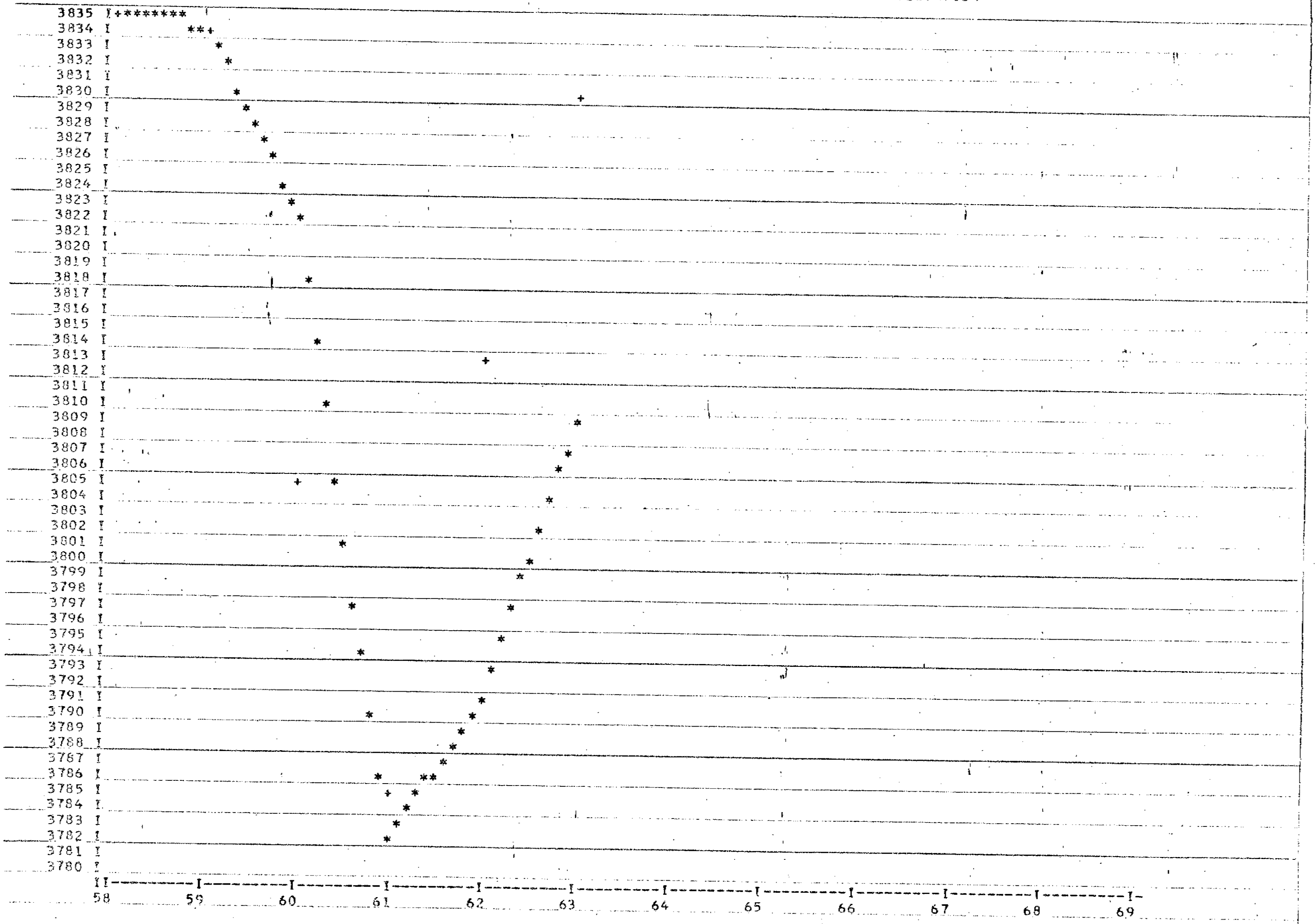
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA WATER SURFACE ELEVATION VS. WATER YEARS

NODE 13 + HISTORIC ELEVATION * CALCULATED ELEVATION



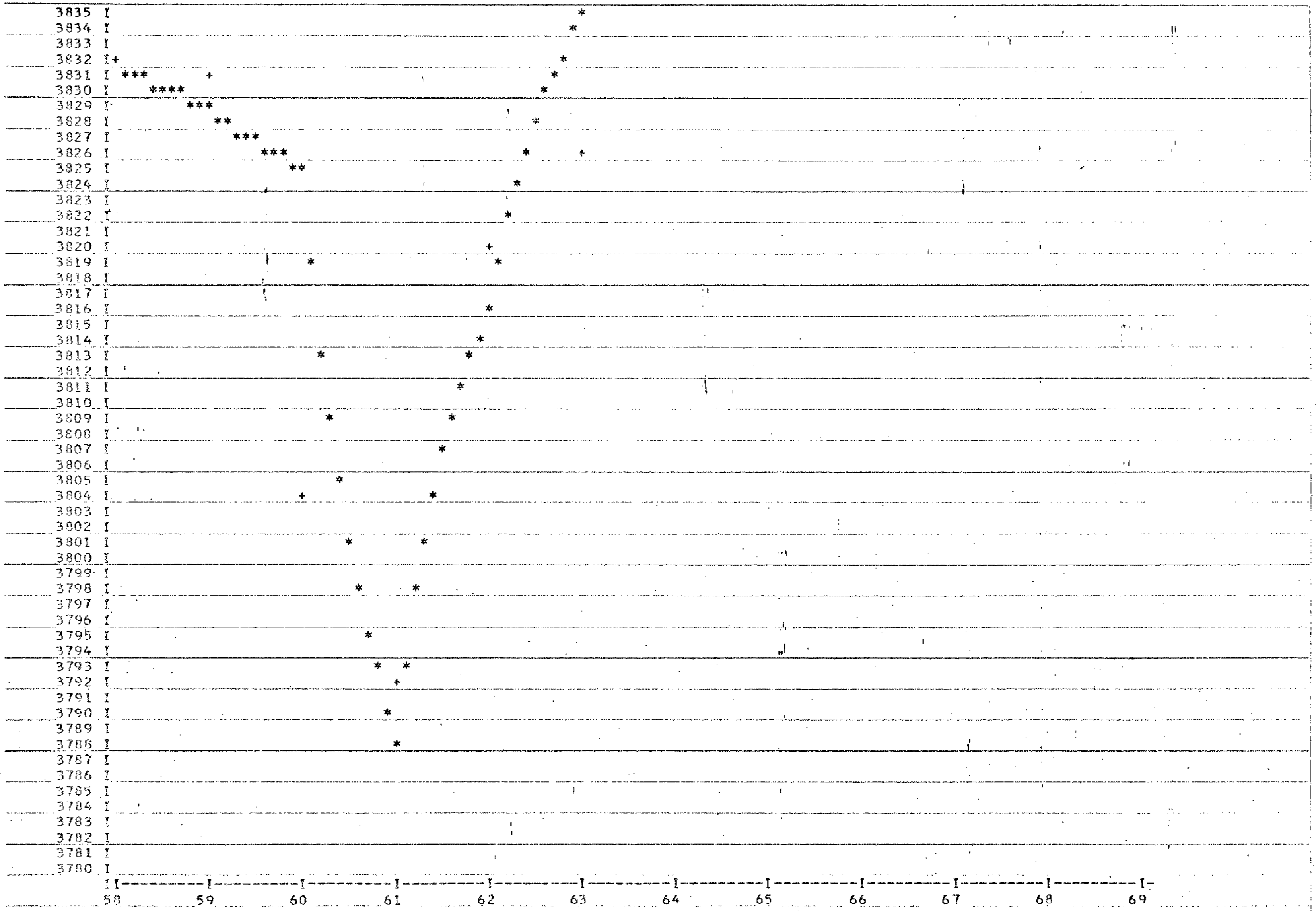
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA WATER SURFACE ELEVATION VS. WATER YEARS

NODE 14 + HISTORIC ELEVATION * CALCULATED ELEVATION



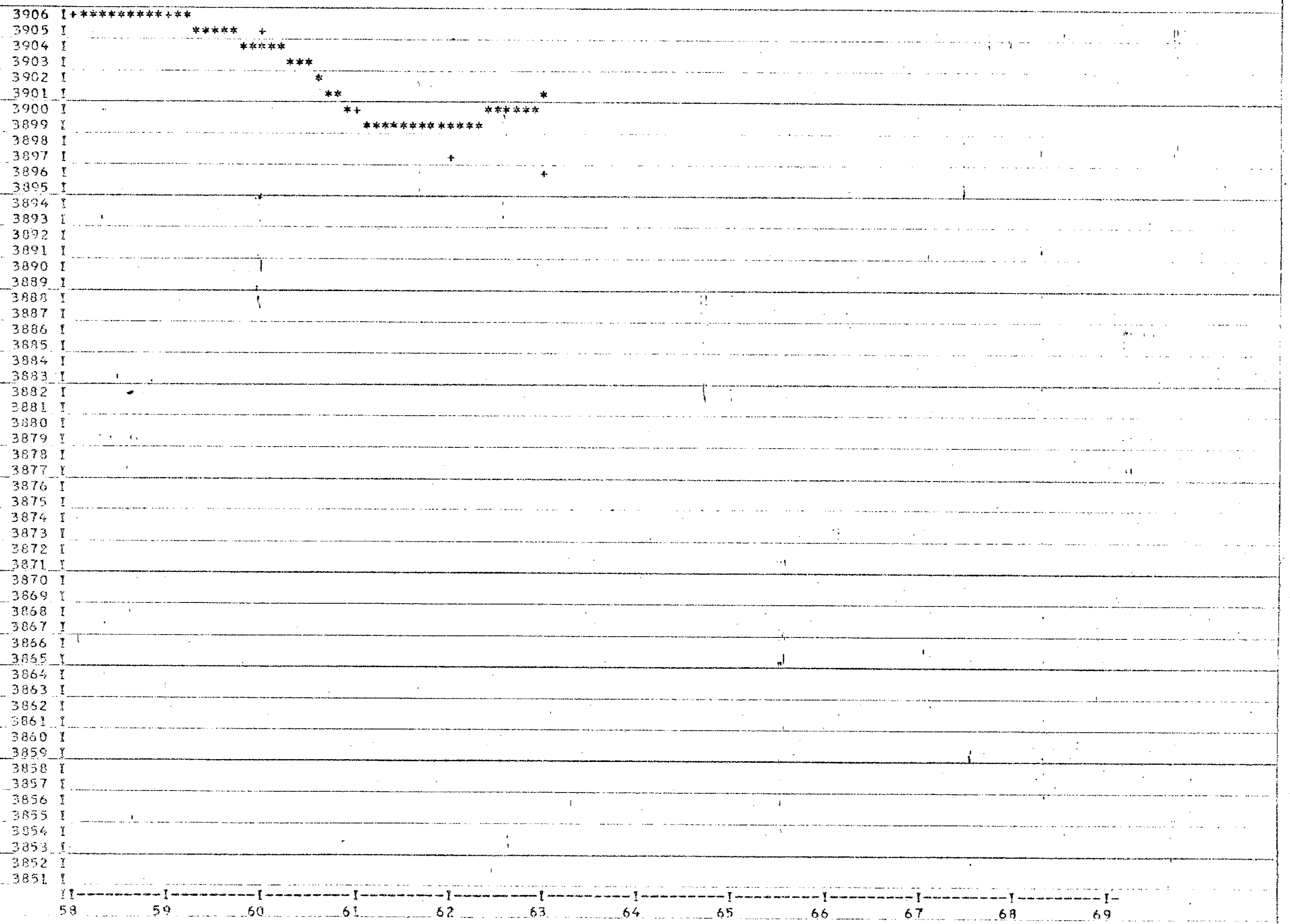
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 17   + HISTORIC ELEVATION   * CALCULATED ELEVATION



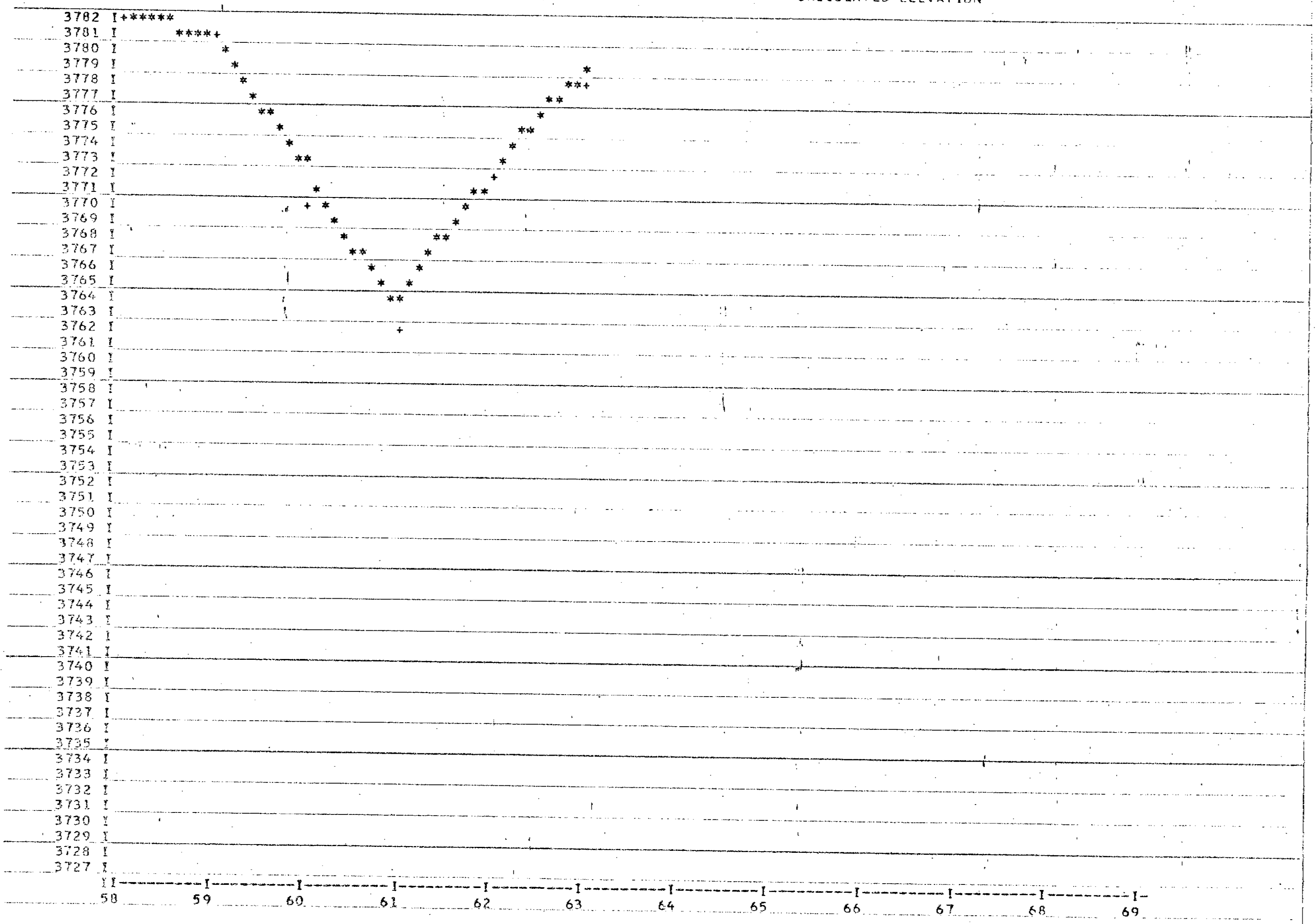
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 18 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 24   + HISTORIC ELEVATION   * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 25 — + HISTORIC ELEVATION — * CALCULATED ELEVATION

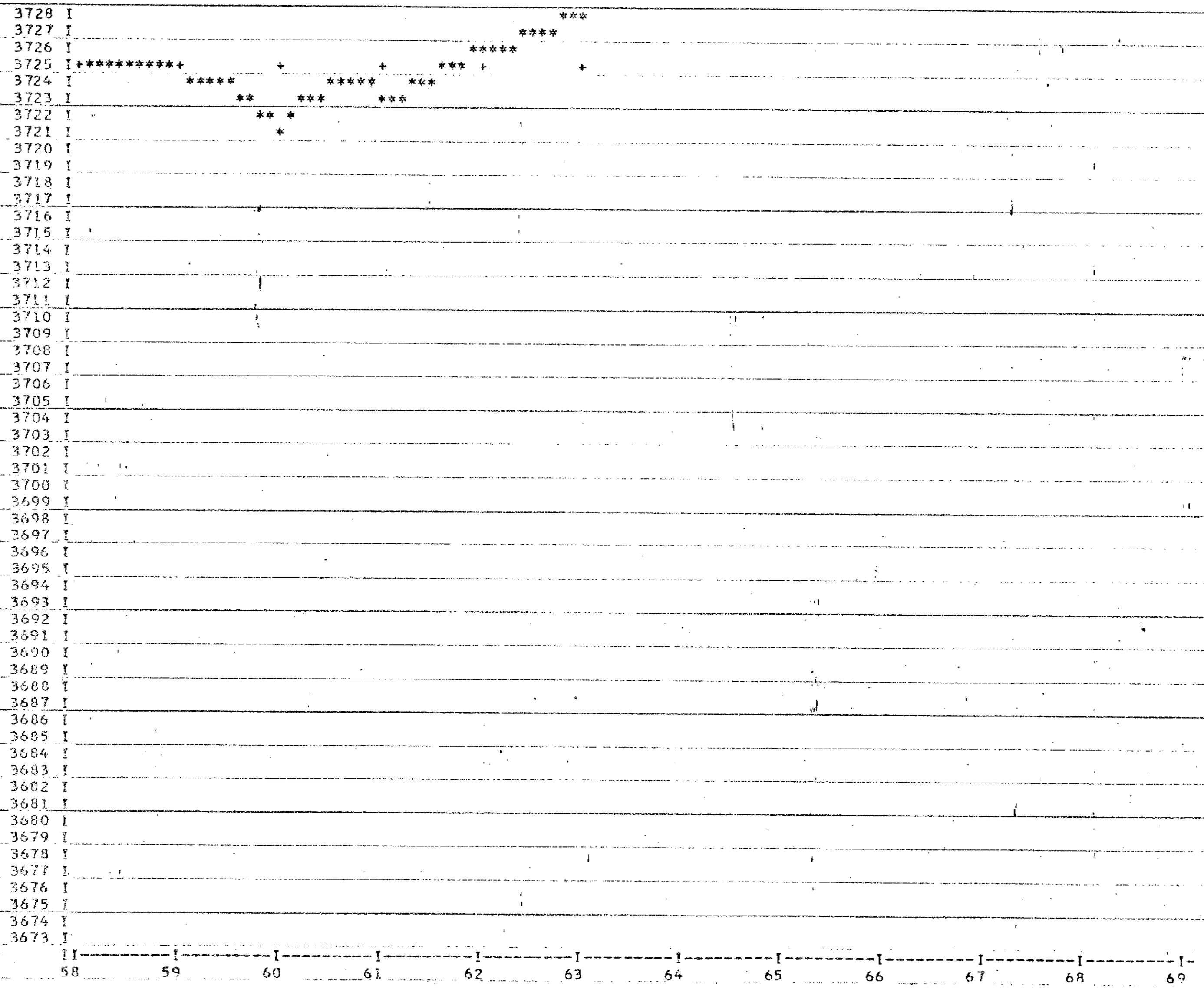


TABLE 9

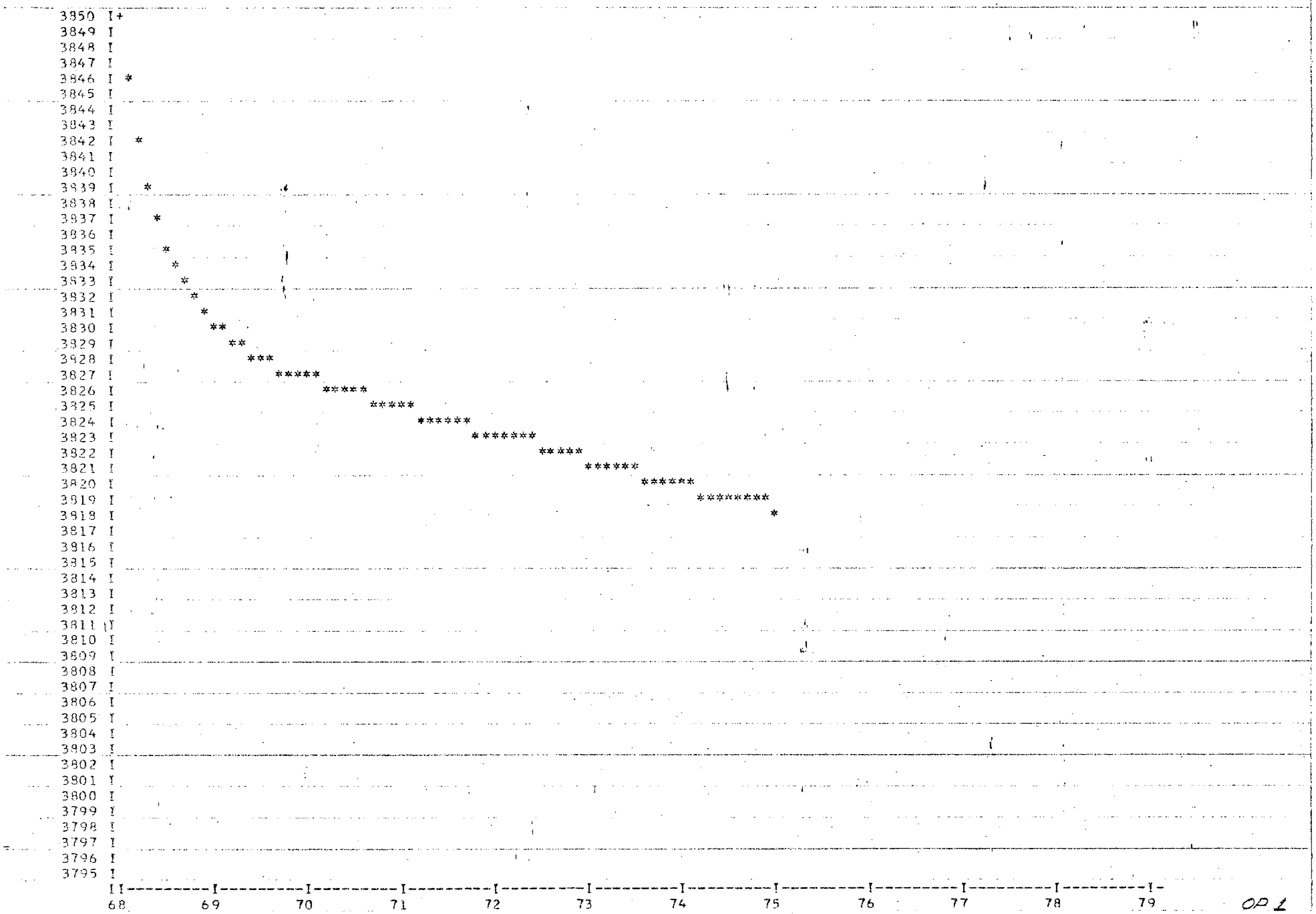
OPERATION RUN 1

HYDROGRAPHIC YEARS 1968/69 - 1974/75

NODE	PUMPING Acre-Ft/Yr	ARTIFICIAL RECHARGE by spreading (Acre-Ft/Yr)	COMMENTS
2	5226	1119	
3		2963	100% of the mean annual creek flow spread according to present diversion patterns.
4		2852	
8	17945		
9		4009	
10		3719	
14	19986	2662	
17	3216		maximum existing pumping facilities based on 1960-62 pumping period.
18		269	
19		632	
20		269	
21		298	
22		1015	
23		1305	
24	4370		

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

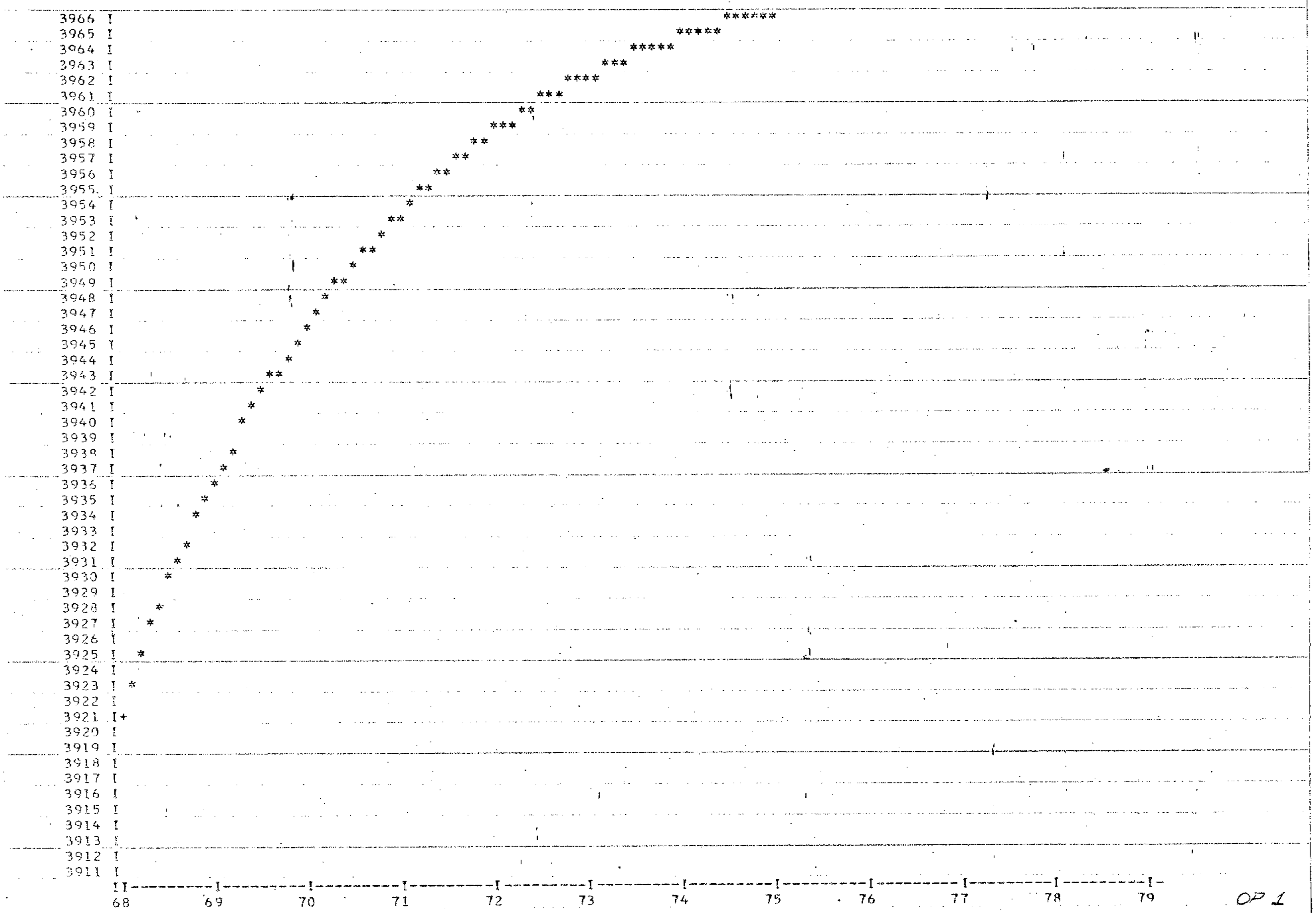
NODE 2   + HISTORIC ELEVATION   * CALCULATED ELEVATION



OP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

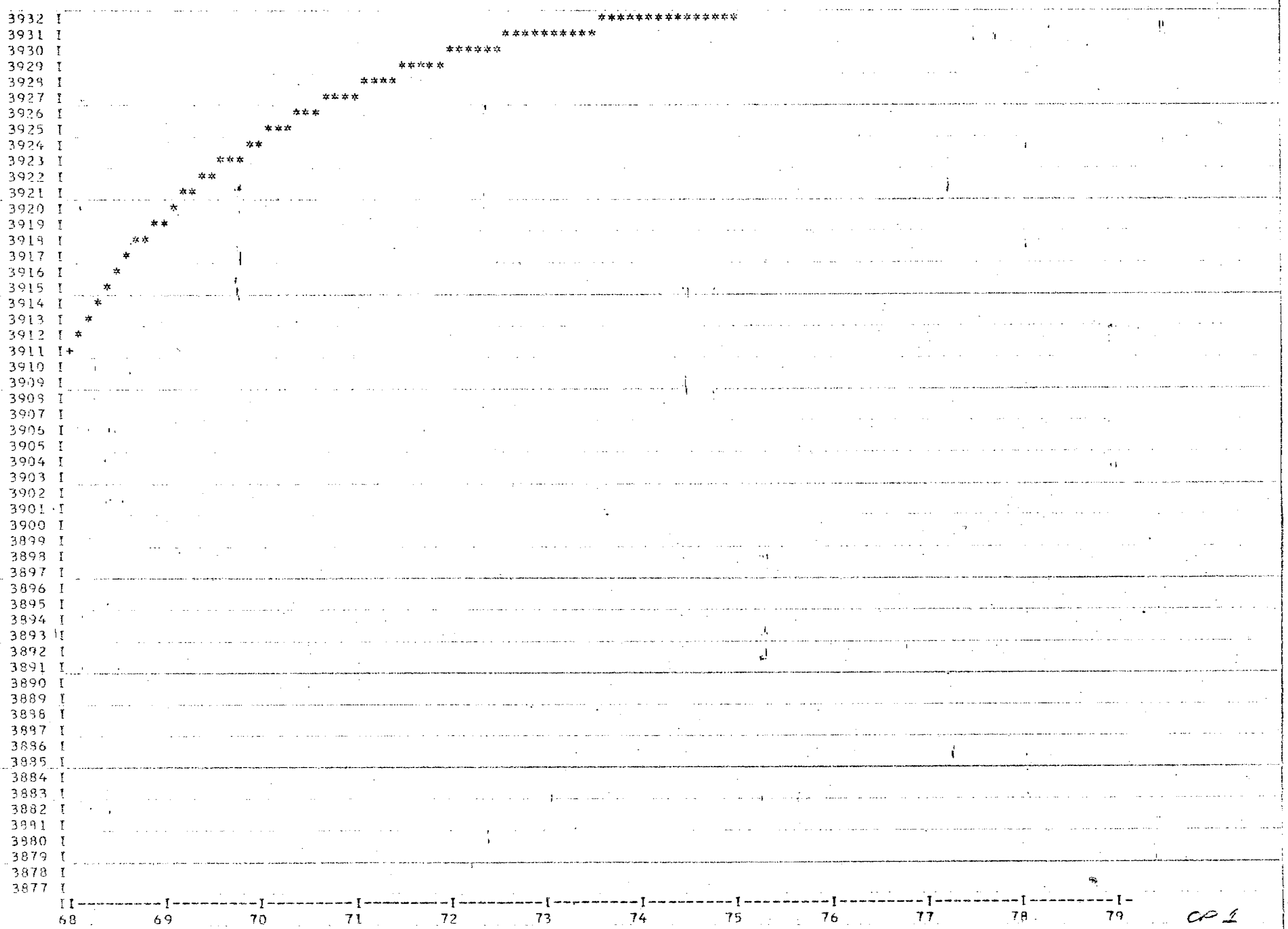
NODE 3 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



OP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

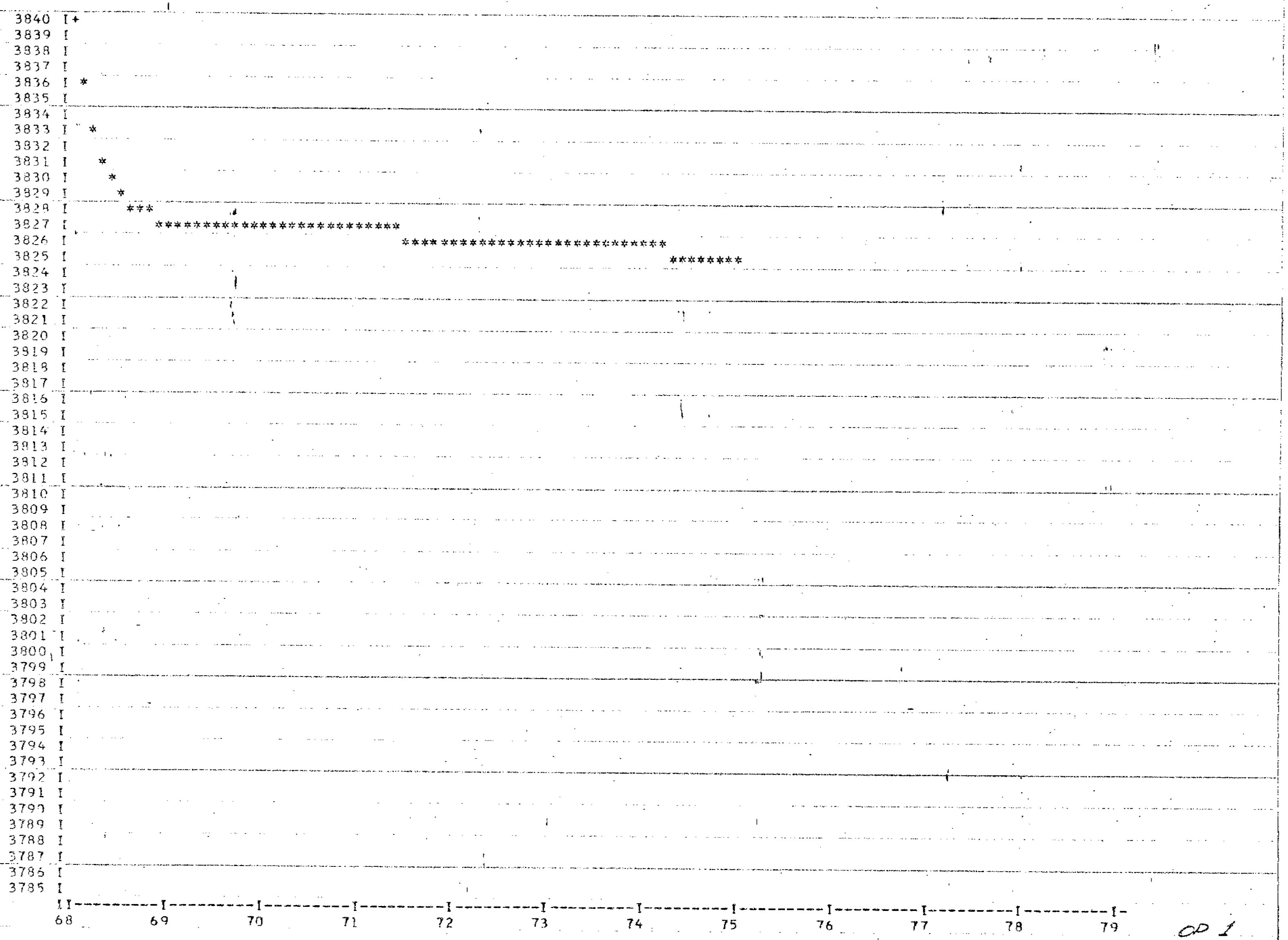
NODE 4   + HISTORIC ELEVATION   * CALCULATED ELEVATION



CP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

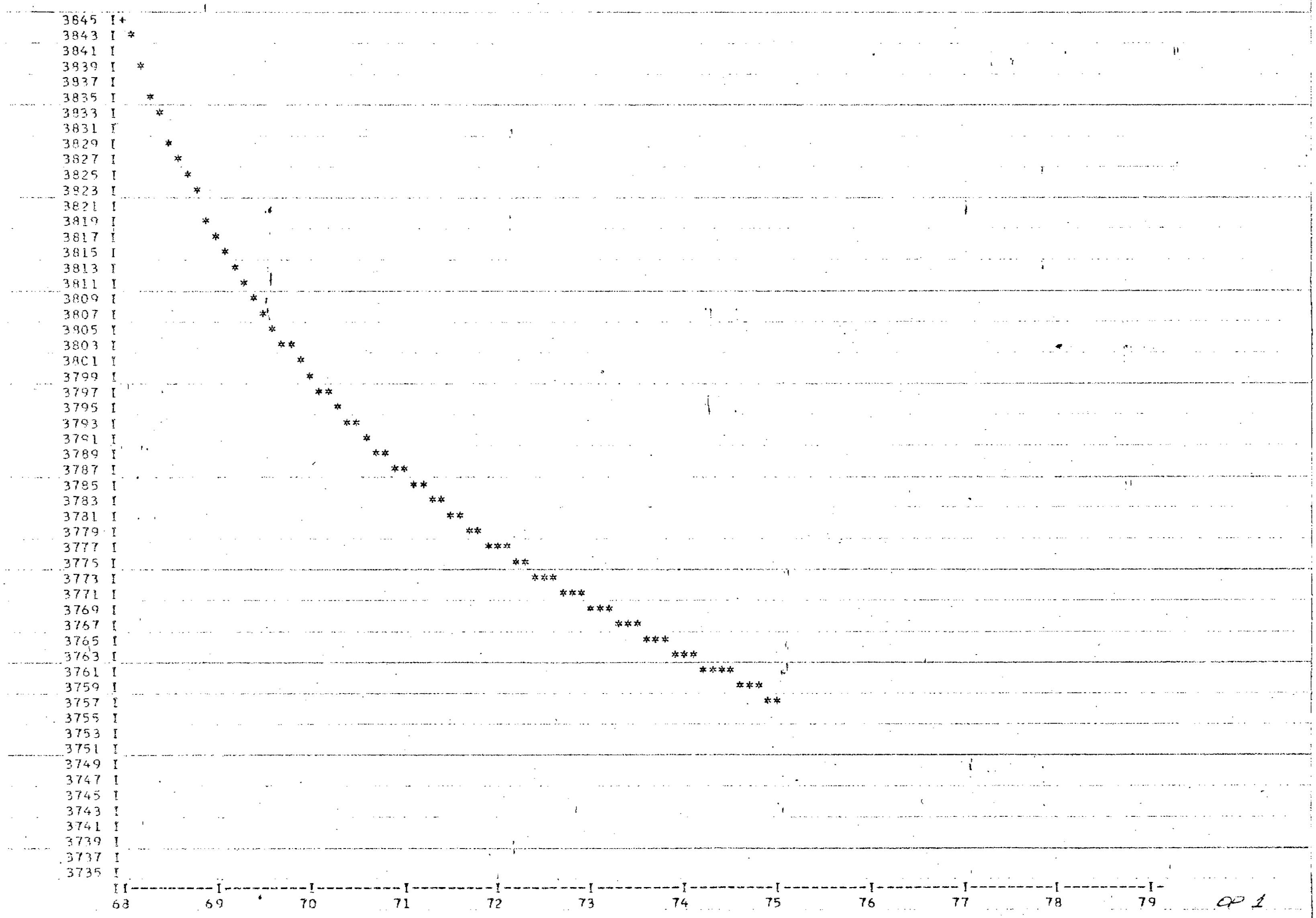
NODE 5   + HISTORIC ELEVATION   * CALCULATED ELEVATION



OP 1

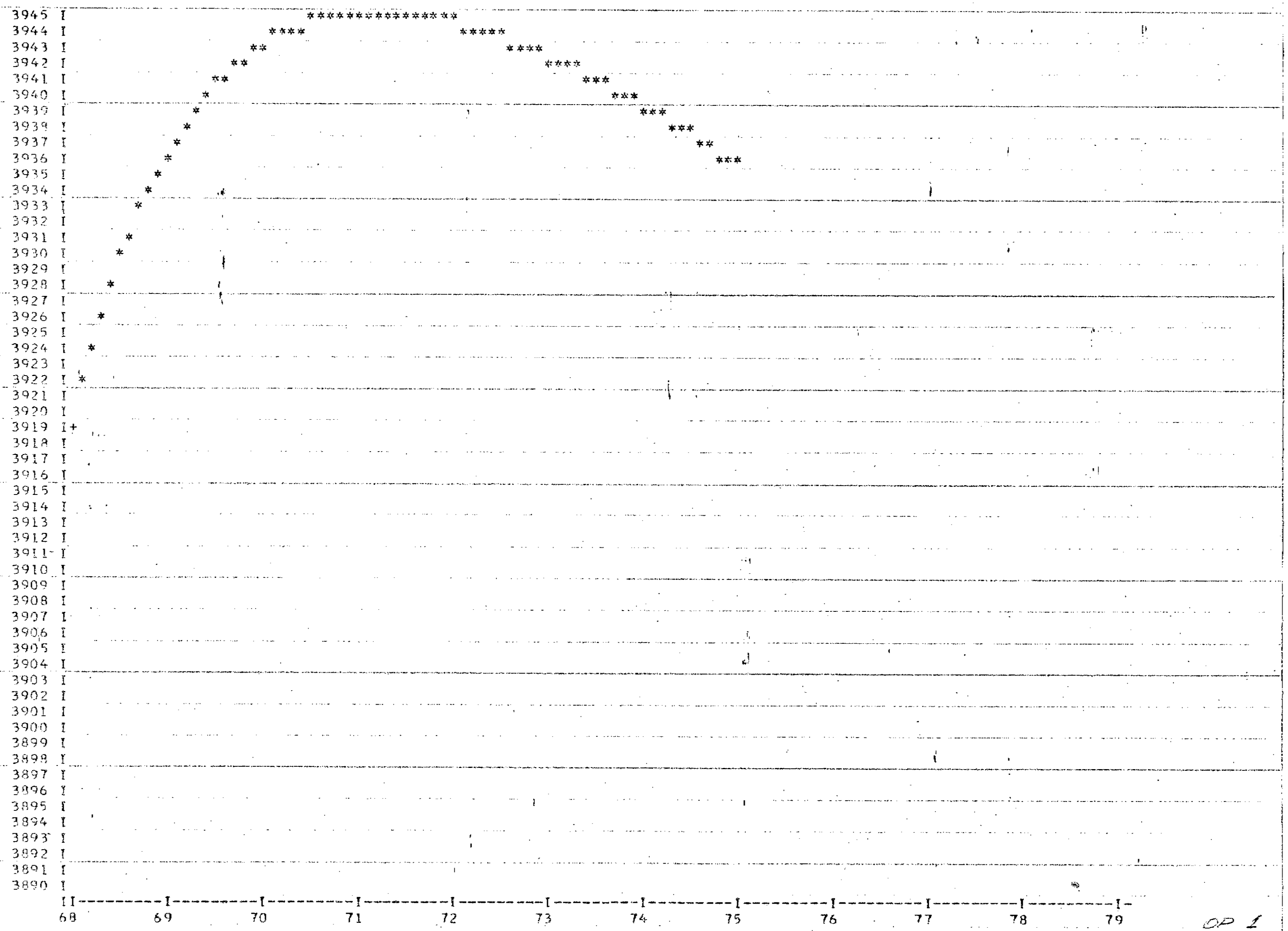
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 8 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

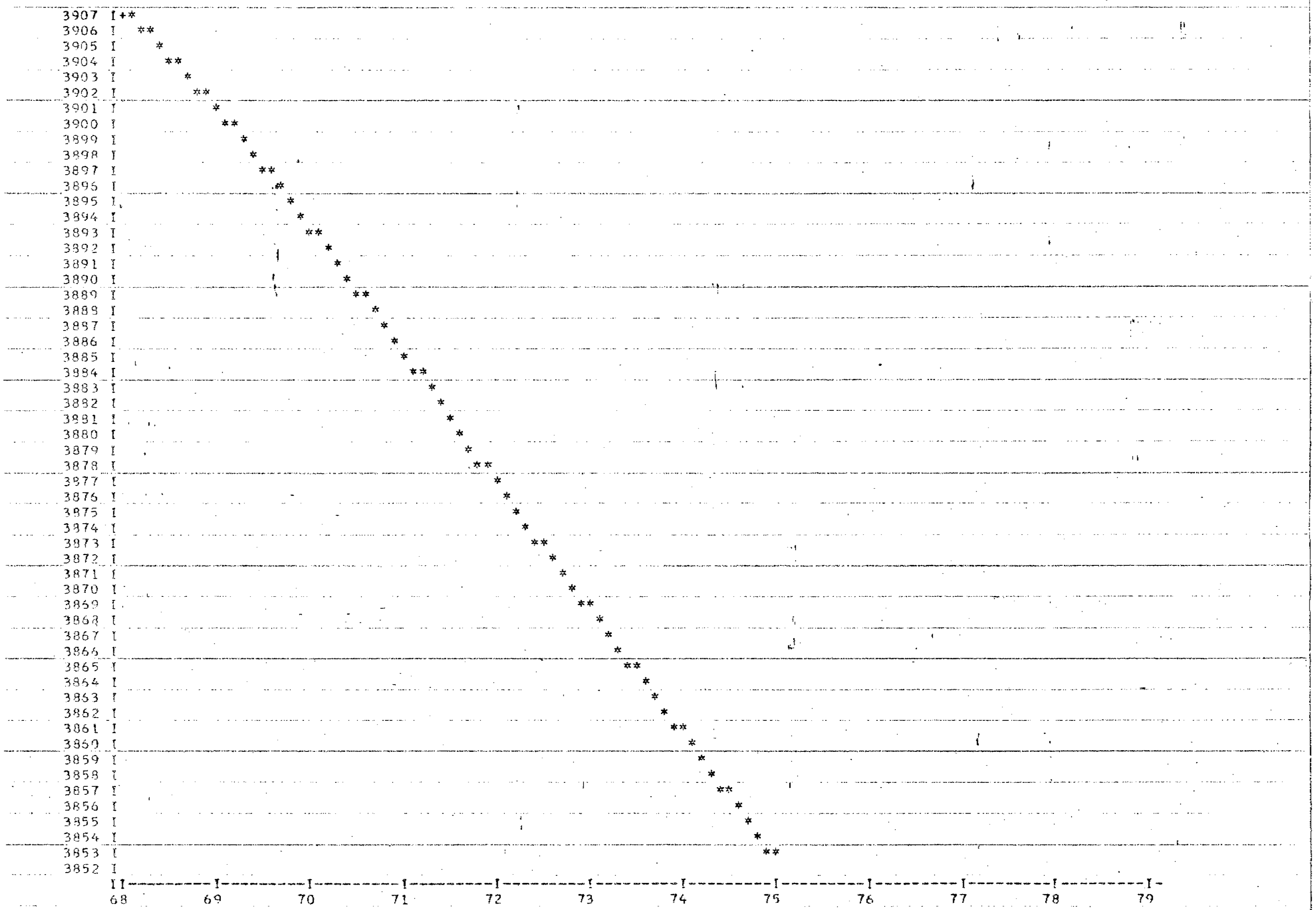
NODE 9   + HISTORIC ELEVATION   * CALCULATED ELEVATION



OP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

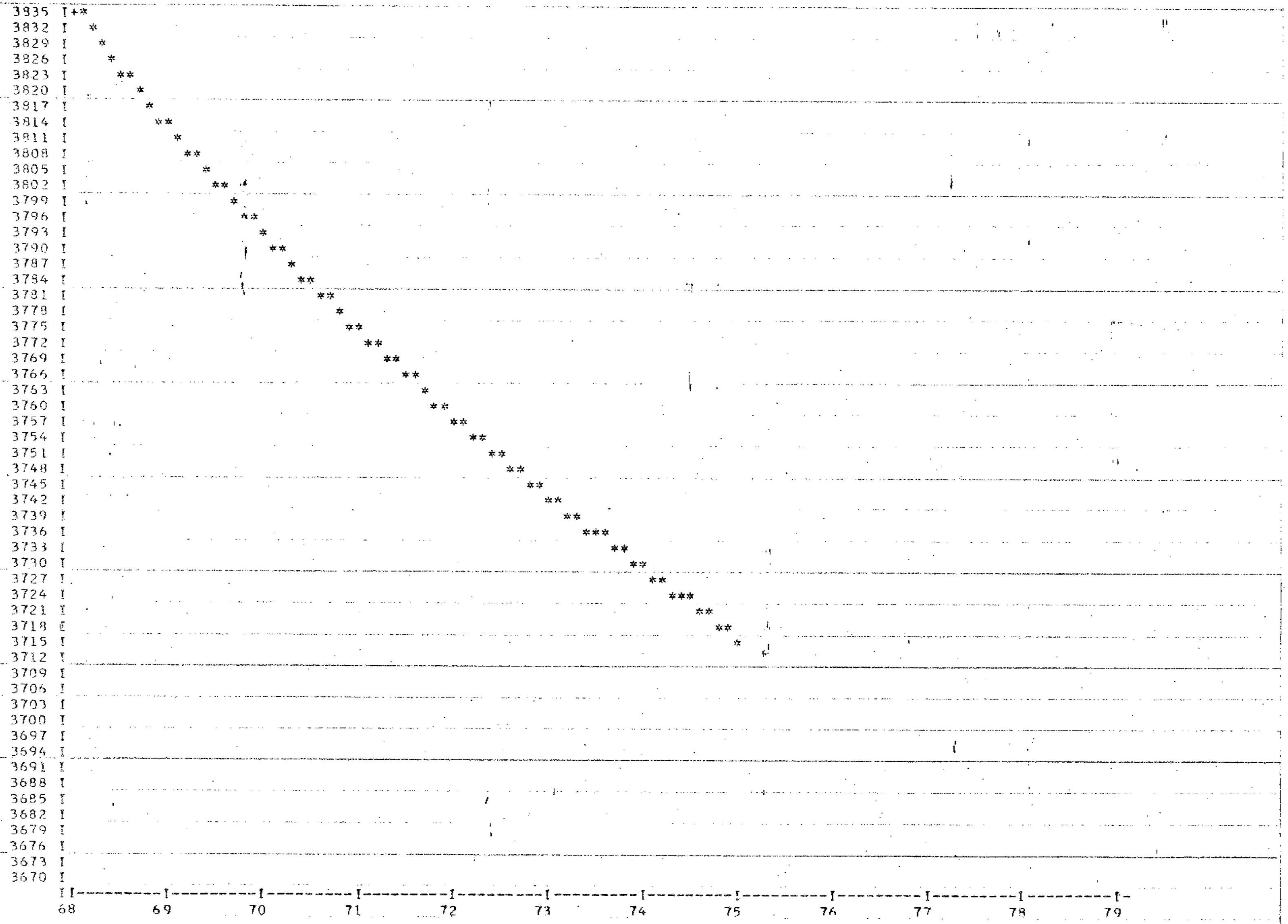
NODE 13 + HISTORIC ELEVATION * CALCULATED ELEVATION



OP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

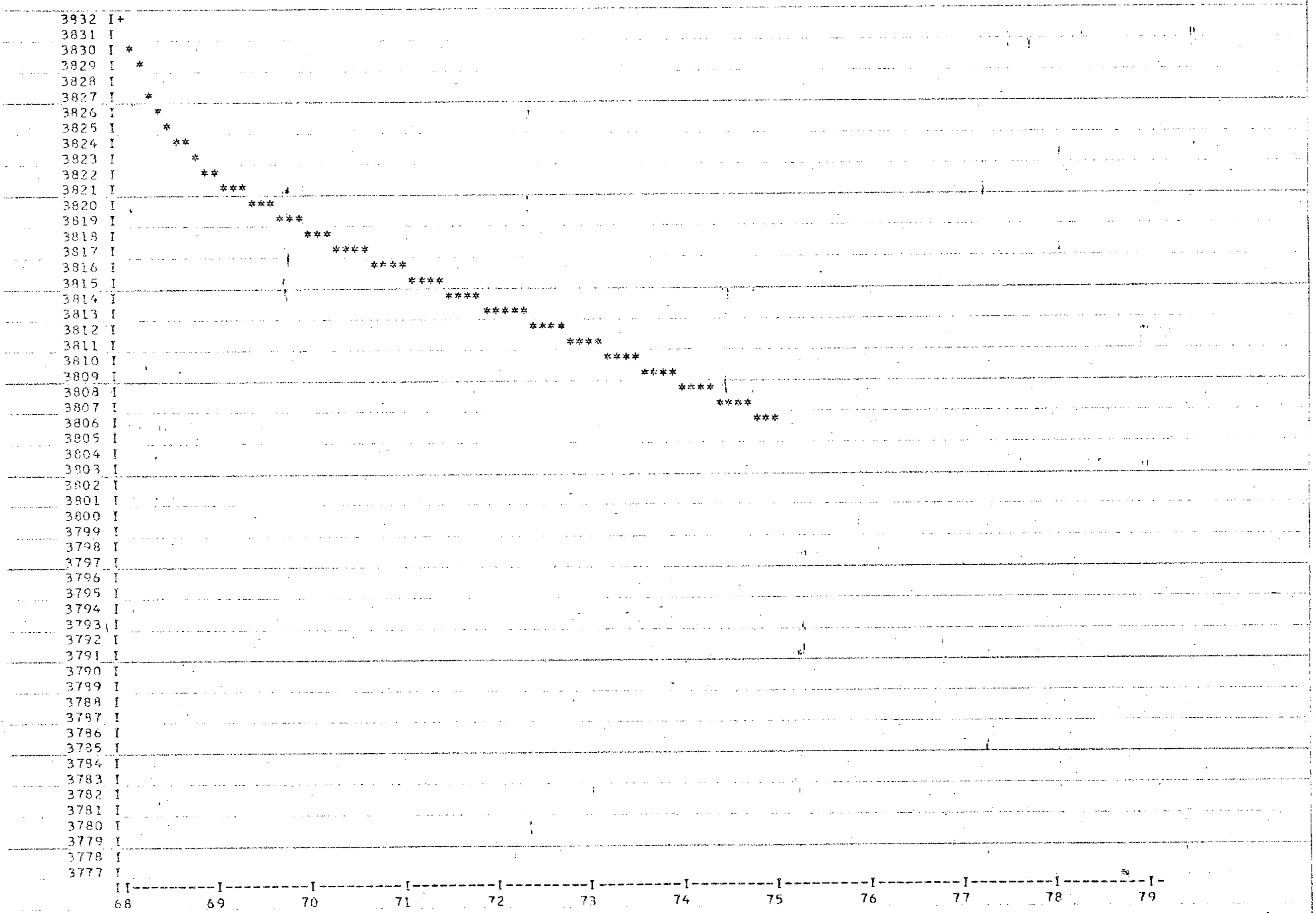
NODE 14   + HISTORIC ELEVATION   * CALCULATED ELEVATION



OP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

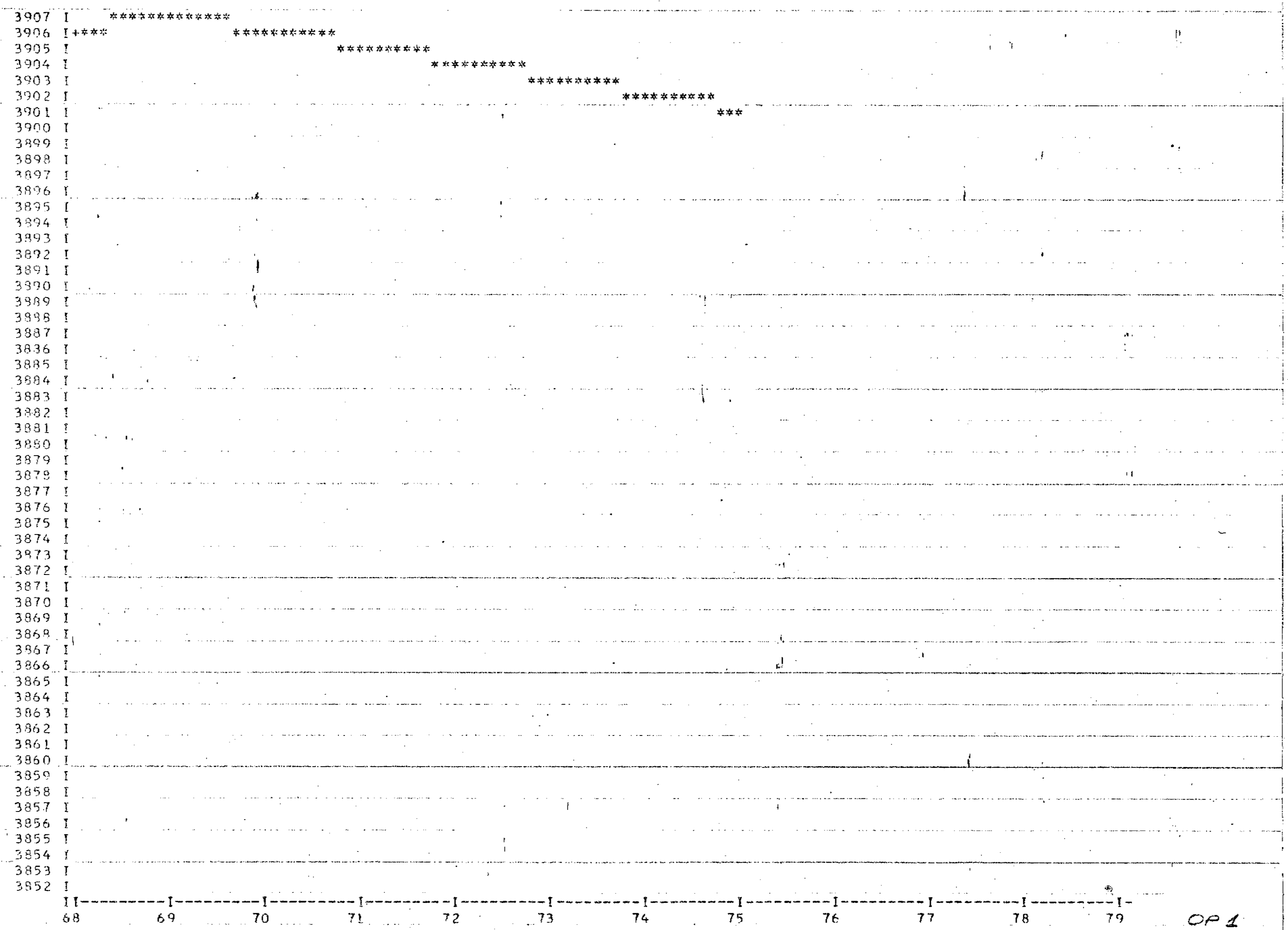
NODE 17   + HISTORIC ELEVATION   * CALCULATED ELEVATION



OP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

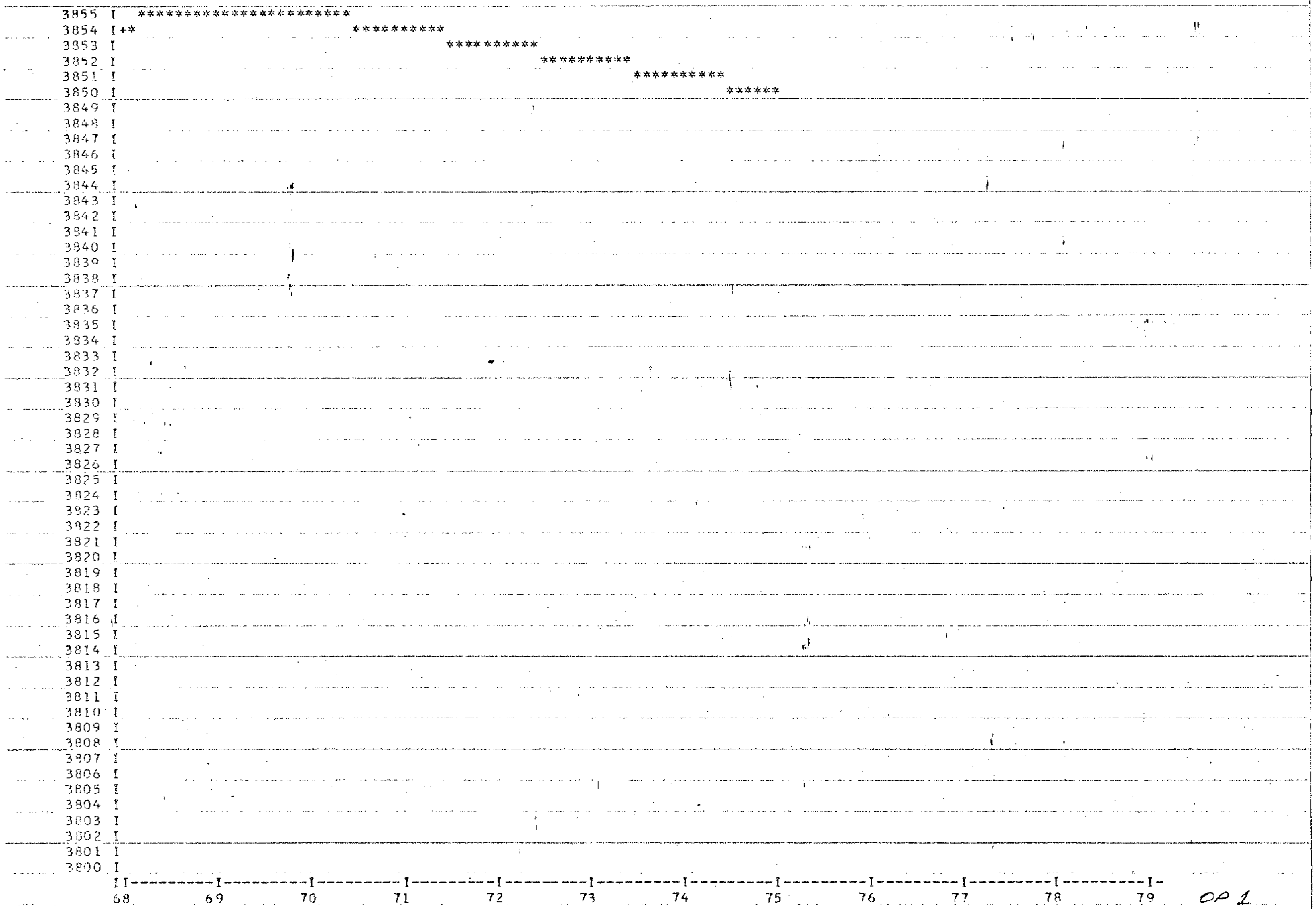
NODE 18 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



OP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

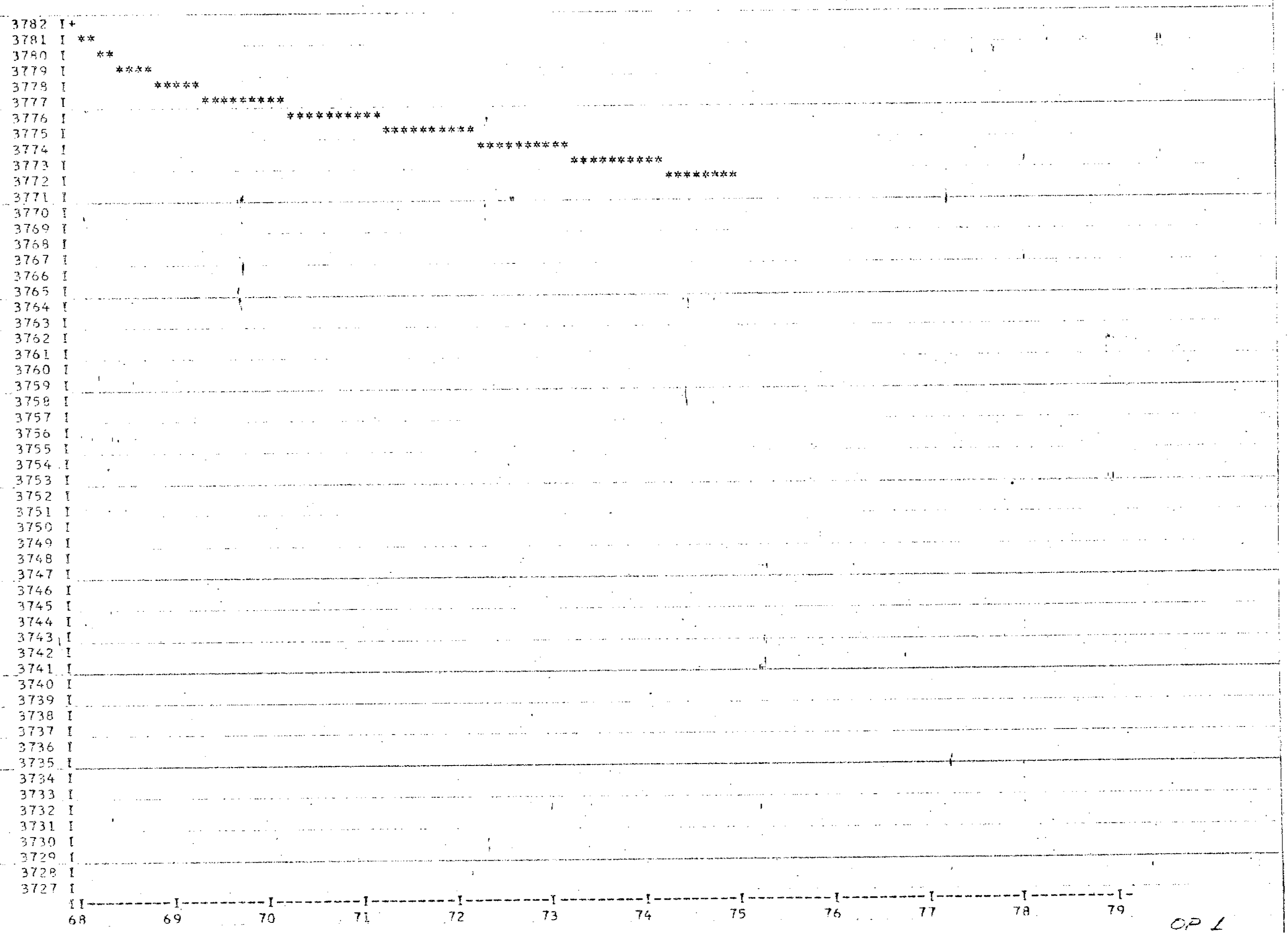
NODE 23 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



OP 1

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 24   + HISTORIC ELEVATION   * CALCULATED ELEVATION



OP 1

TABLE 10

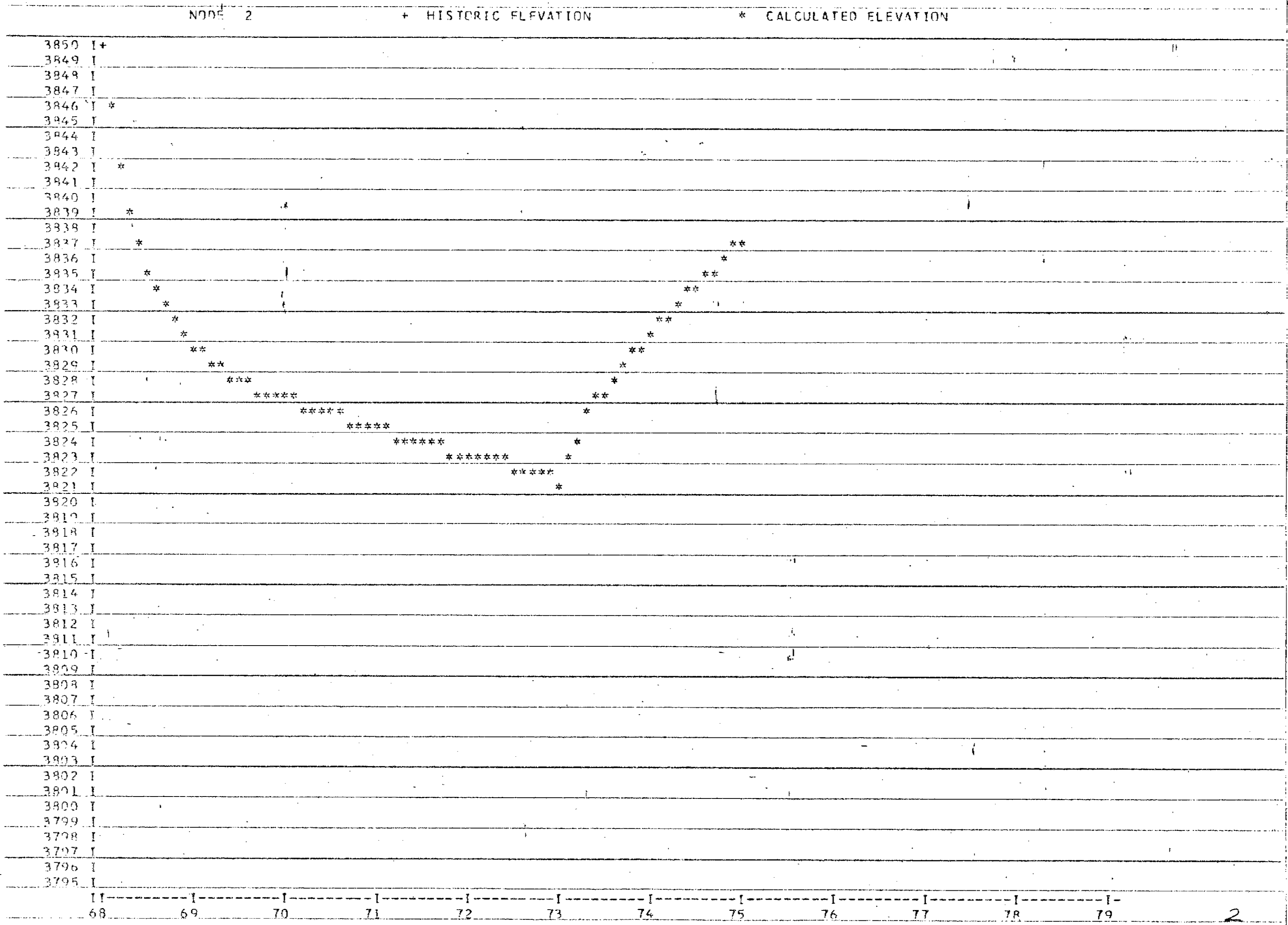
OPERATION RUN 2

HYDROGRAPHIC YEARS 1968/69 - 1974/75

Note: Same as Operation Run 1 for 1st 5 years

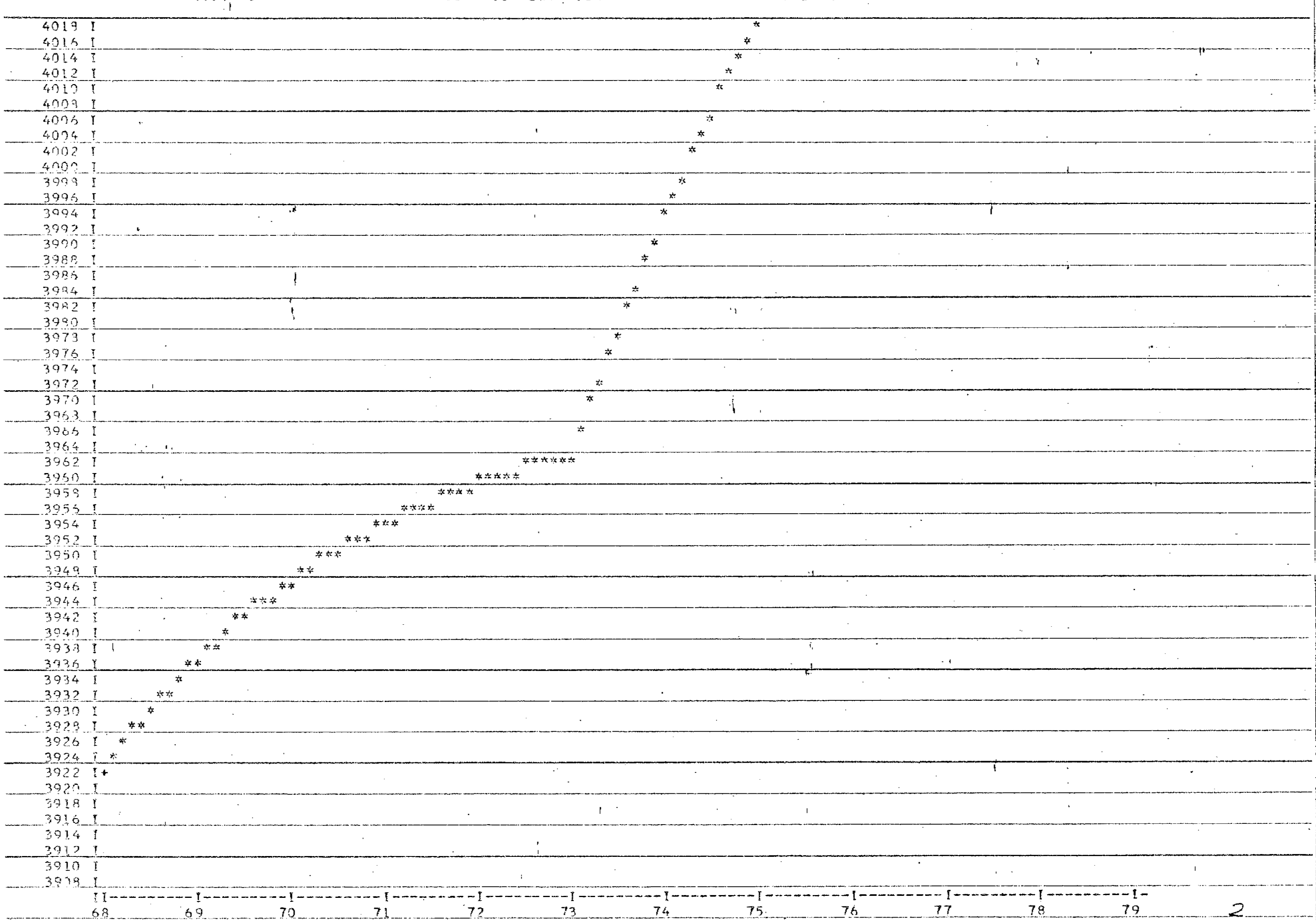
NODE	PUMPING Acre-Ft/Yr	ARTIFICIAL RECHARGE by spreading (acre-ft/yr)	COMMENTS
3		7975	for last 2 yrs. maximum recorded flow from creeks spread in a selective pattern to optimize storage.
4		19575	
9		7250	
10		14500	
11		7250	
12		7250	
13		2900	
19		3625	
20		4350	
21		3625	no pumping
22		7250	

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA WATER SURFACE ELEVATION VS. WATER YEARS

NODE 3 + HISTORIC ELEVATION * CALCULATED ELEVATION



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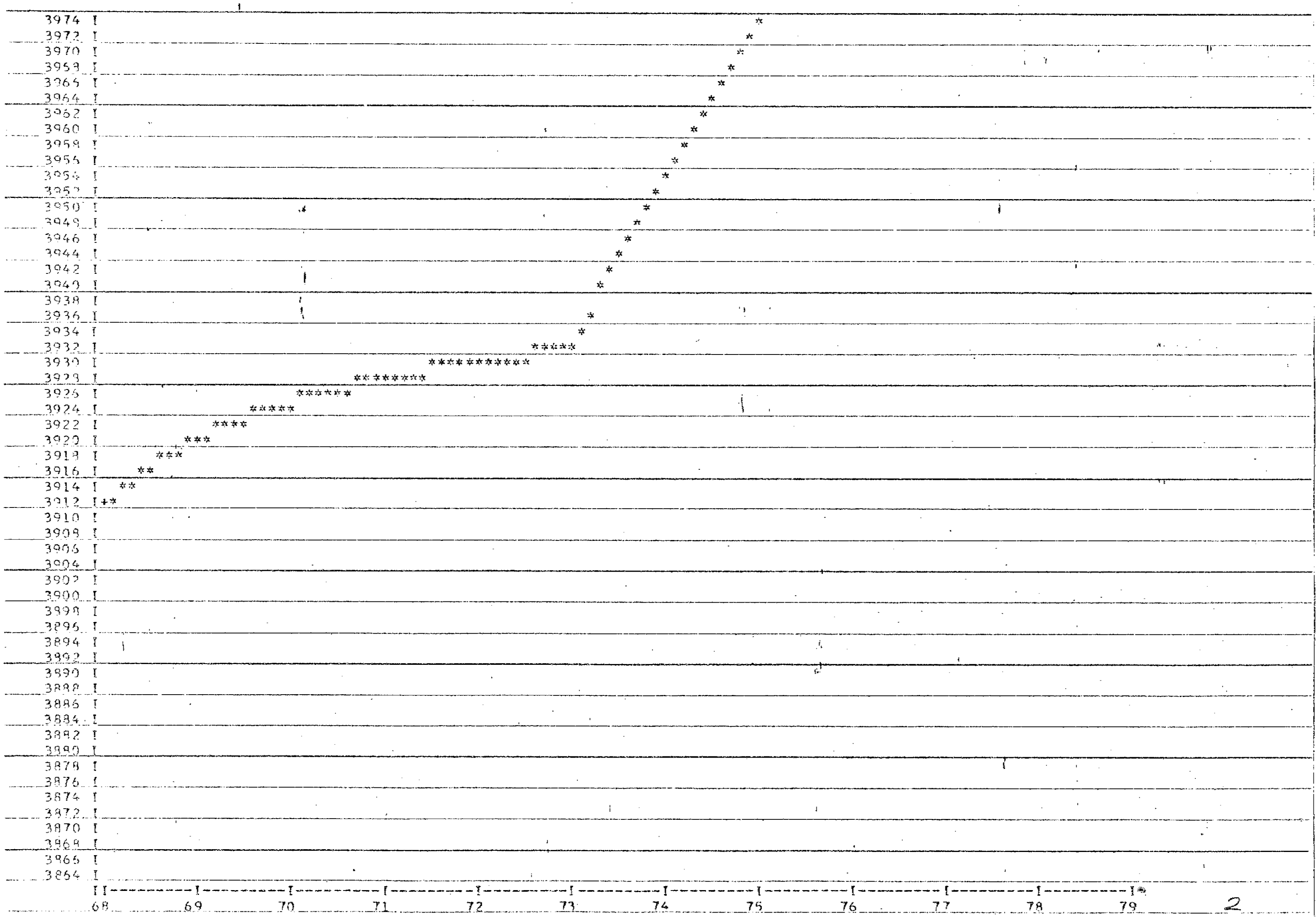
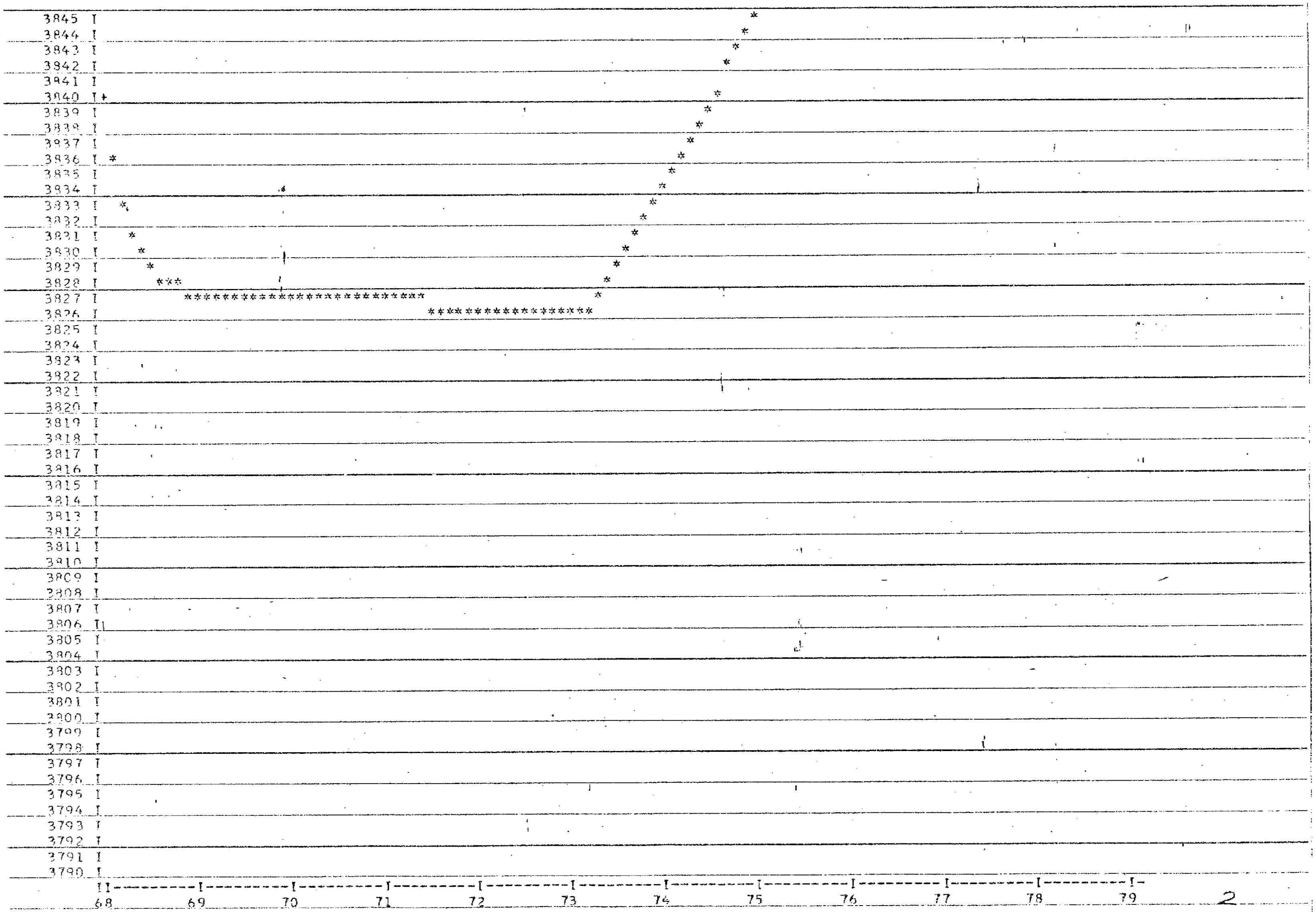
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 4   + HISTORIC ELEVATION   * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 5 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



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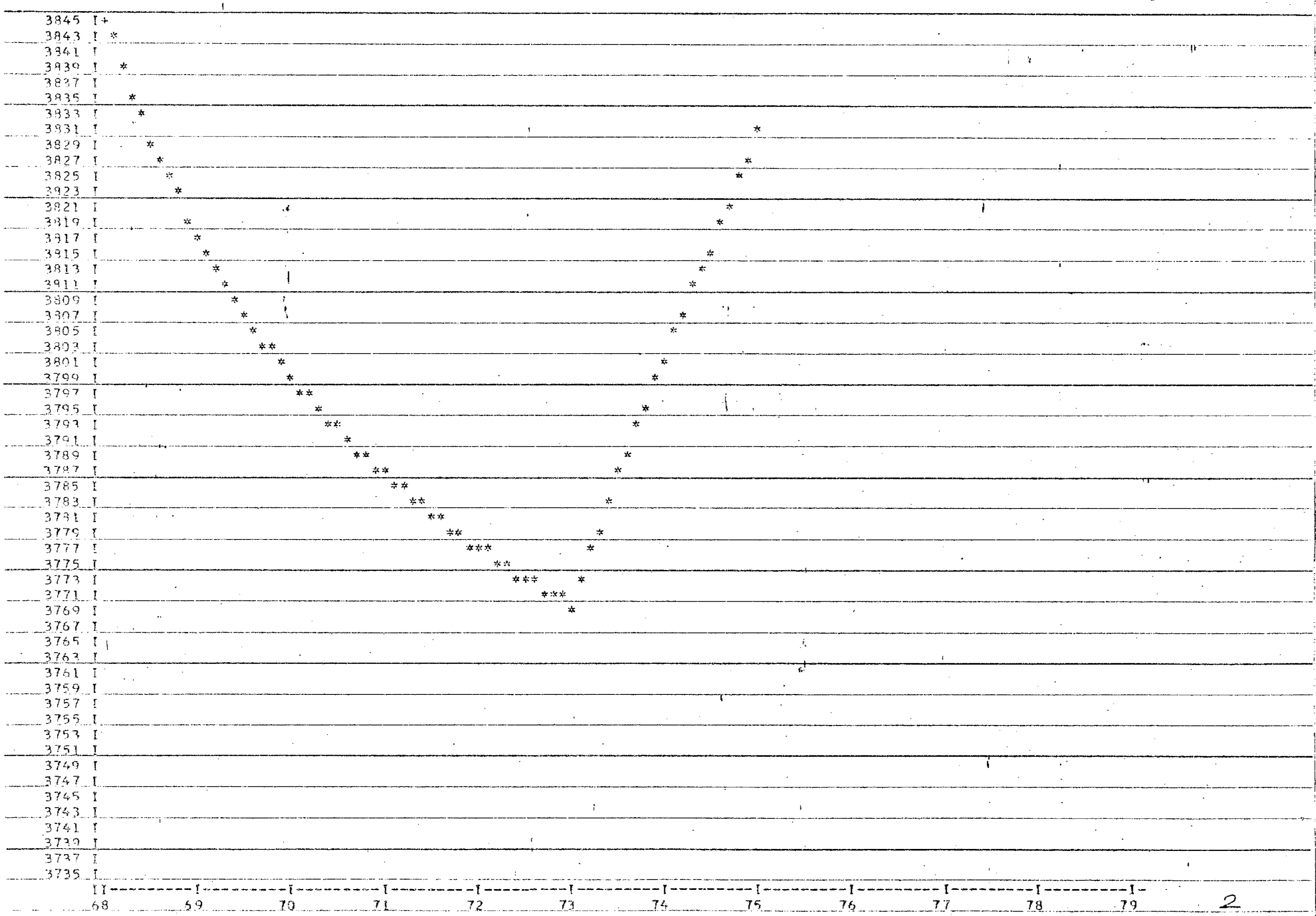
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 8   + HISTORIC ELEVATION   * CALCULATED ELEVATION



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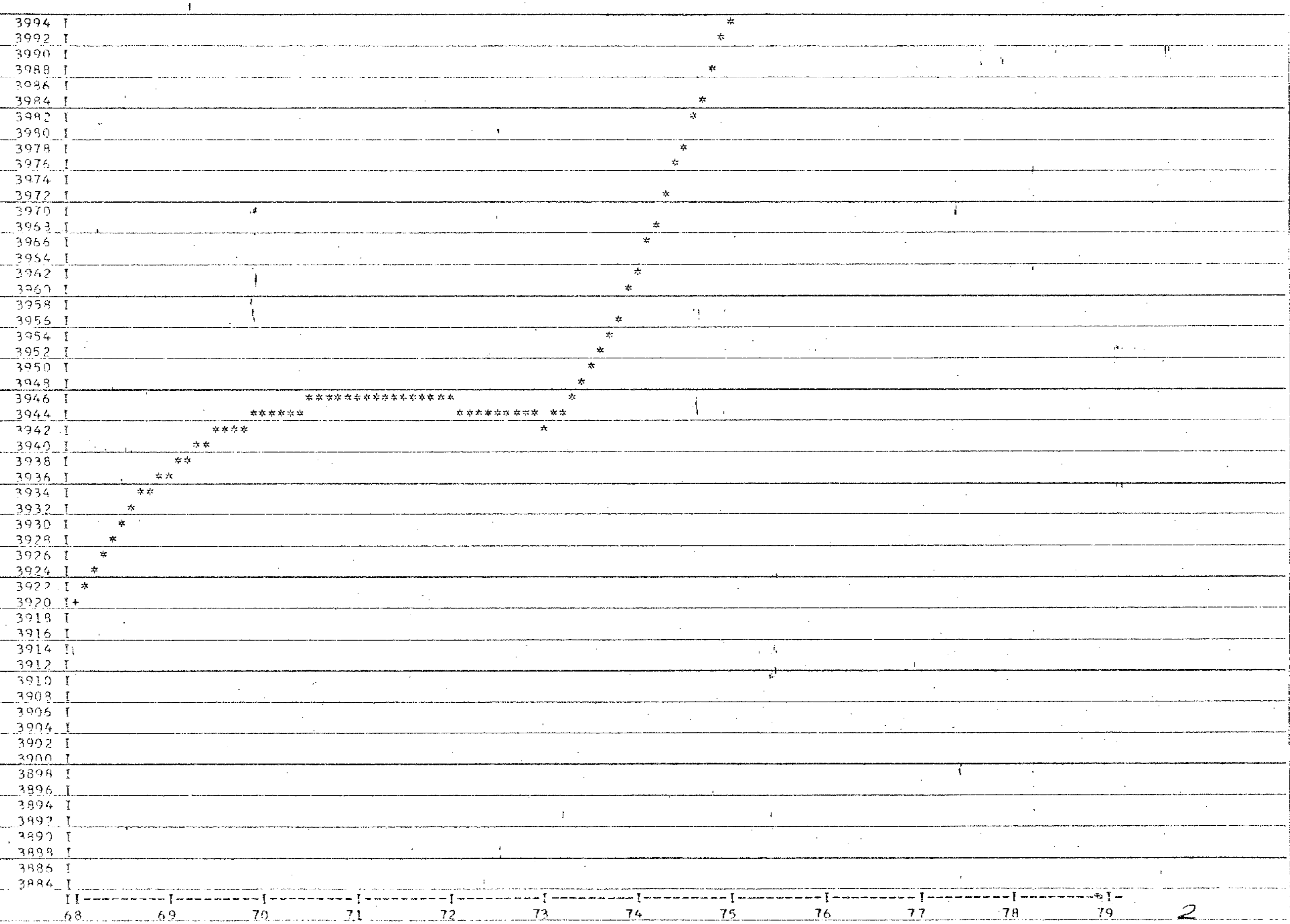
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 9 + HISTORIC ELEVATION * CALCULATED ELEVATION



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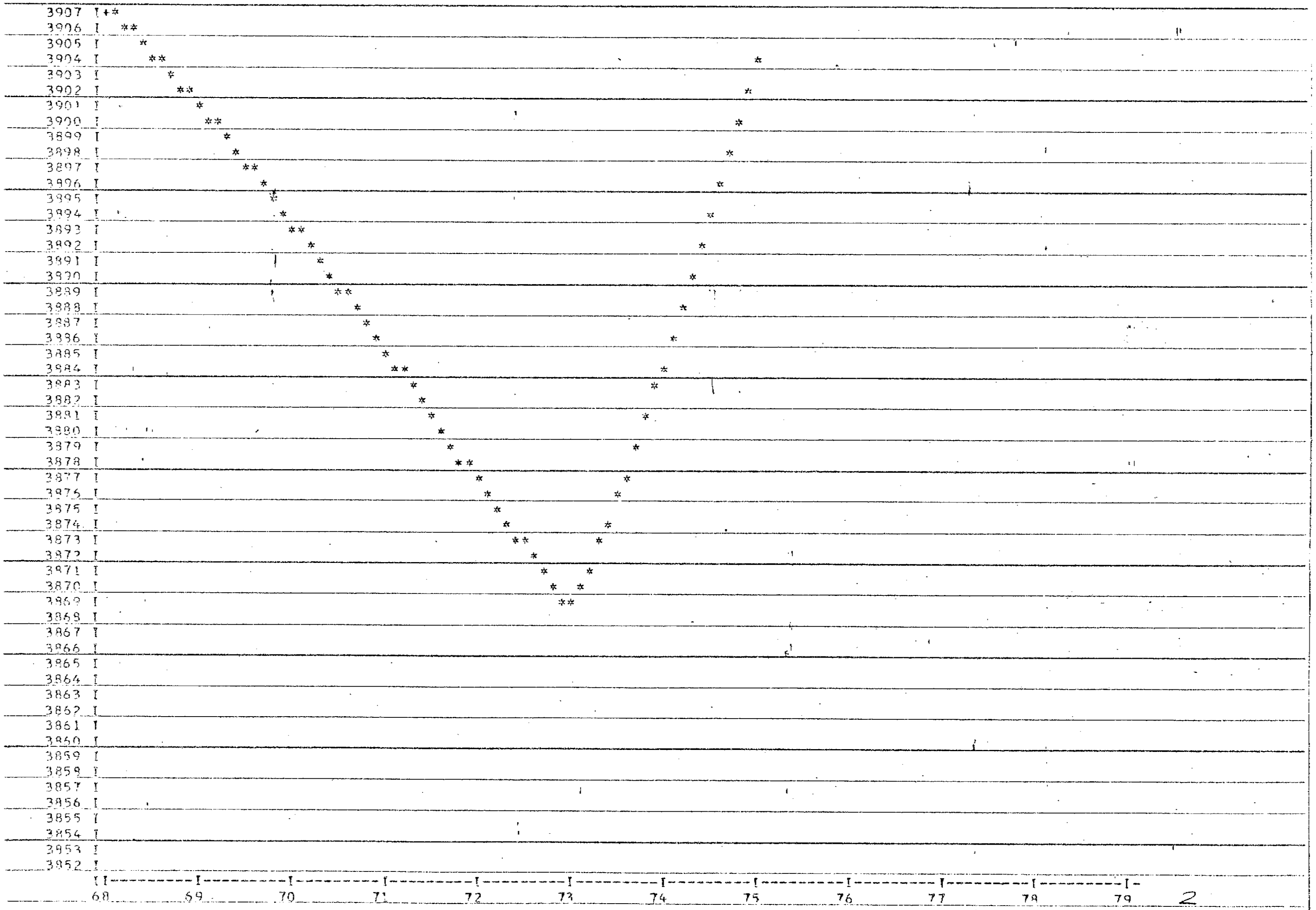
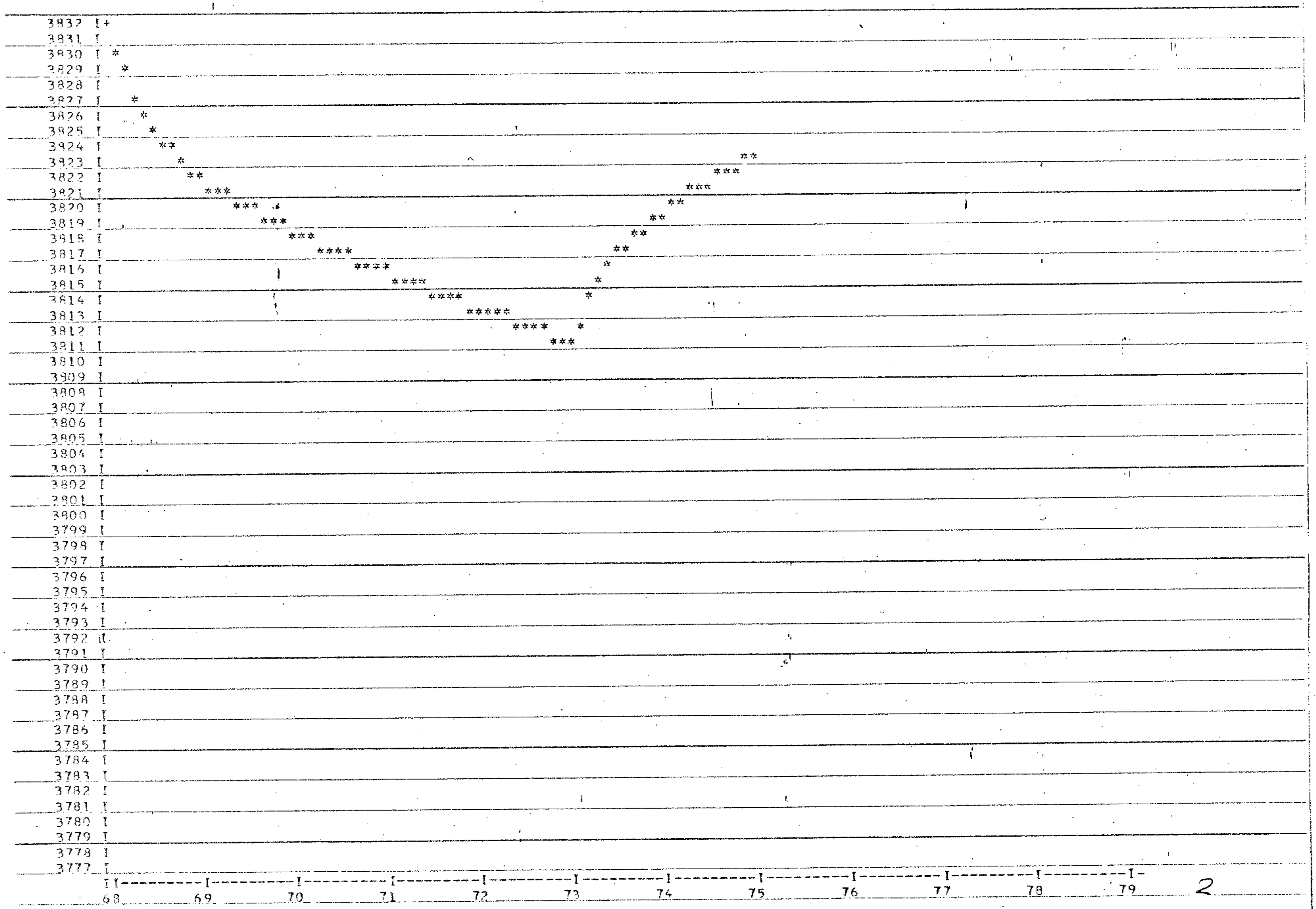
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 13 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 17 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



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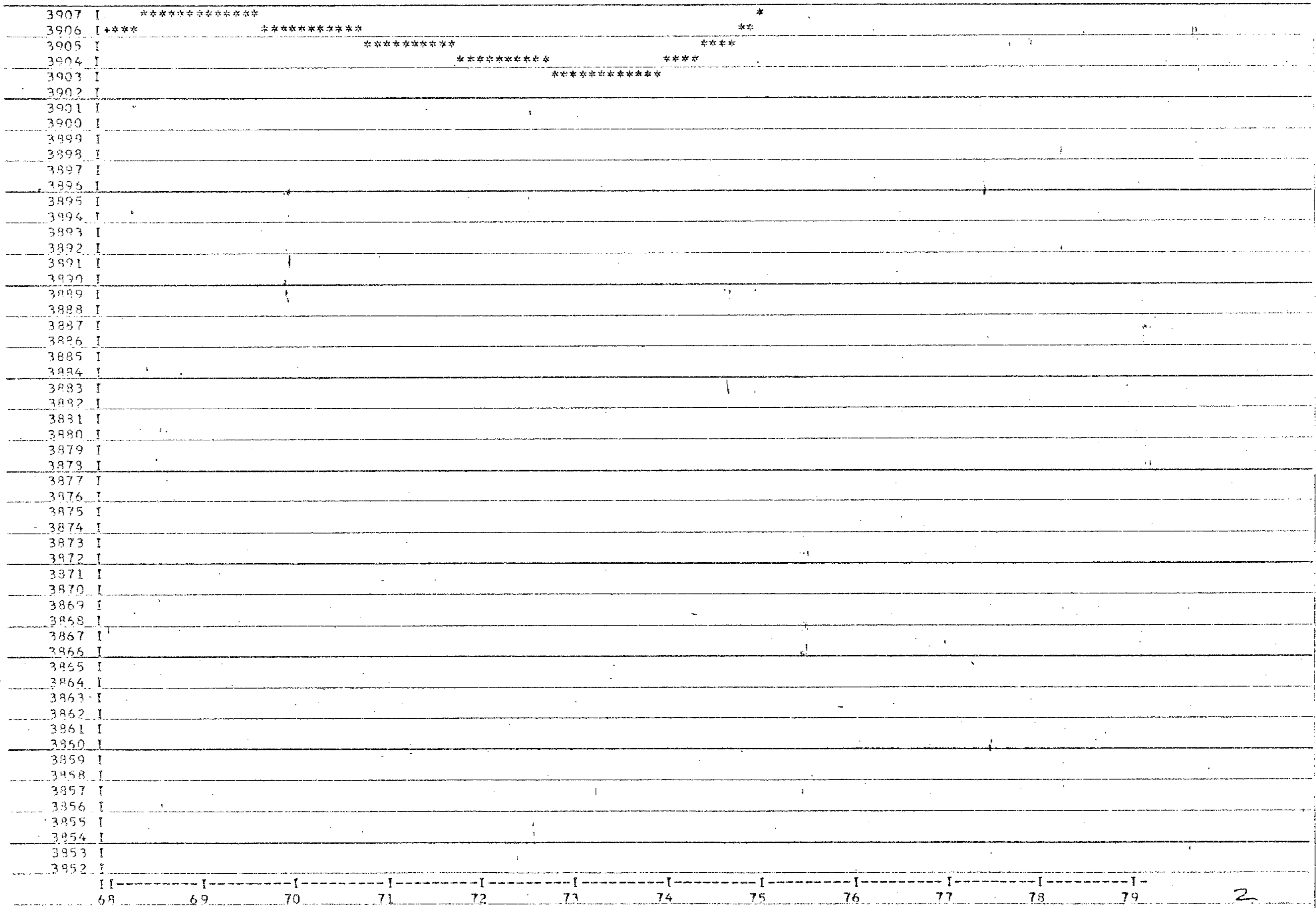
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA WATER SURFACE ELEVATION VS. WATER YEARS

NODE 18 + HISTORIC ELEVATION * CALCULATED ELEVATION



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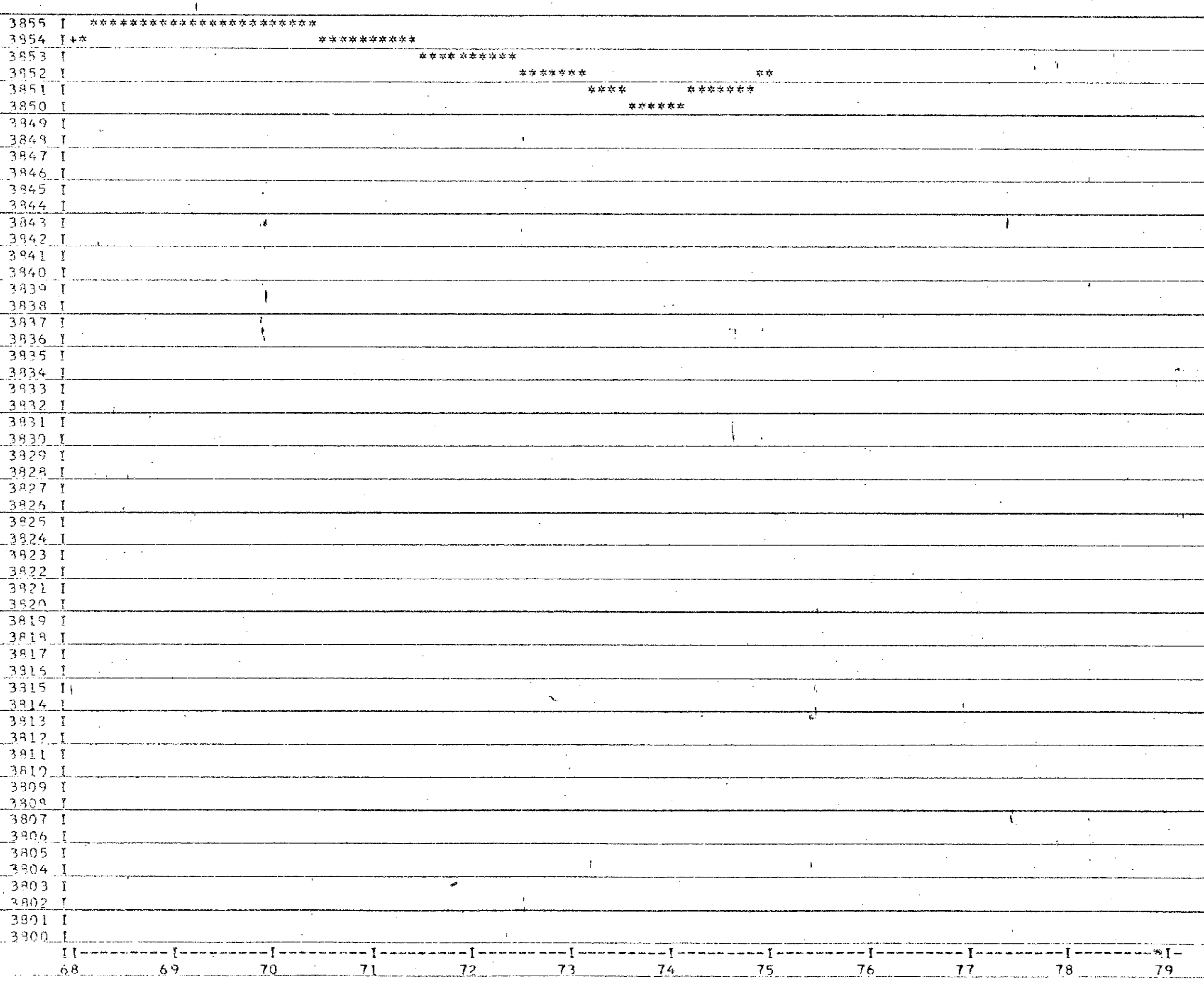
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 23   + HISTORIC ELEVATION   * CALCULATED ELEVATION



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DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 24 — + HISTORIC ELEVATION — * CALCULATED ELEVATION

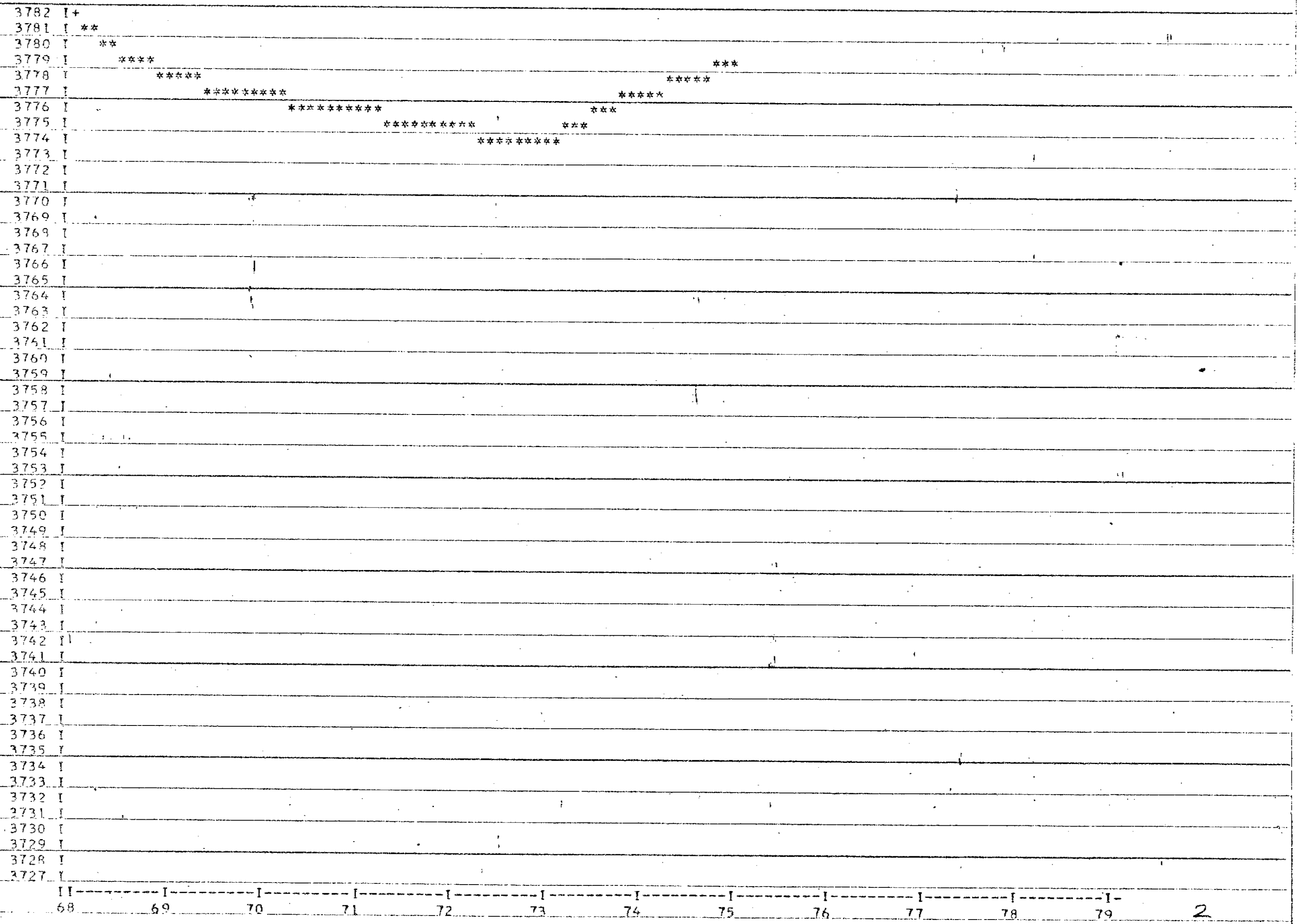

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TABLE 11

OPERATION RUN 3

HYDROGRAPHIC YEARS 1968/69 - 1974/75

NODE	PUMPING Existing Wells Acre-ft/yr	New Wells Needed	ARTIFICIAL RECHARGE by Spreading Acre-ft/yr	Comments
2	5226	16283		
3			5075	Optimization of spreading - extractions and salvage of high ground-water areas
4			11600	
5	0	21509		
8	17945	3564		
9			6000	
10			4875	
13			10150	
14	19986	1523		
17	3216	14293		
18			2000	
19			1625	
22			1800	
23	0	15509	4000	
24	4370	0		
TOTAL	69 cfs	100 cfs	65 cfs	

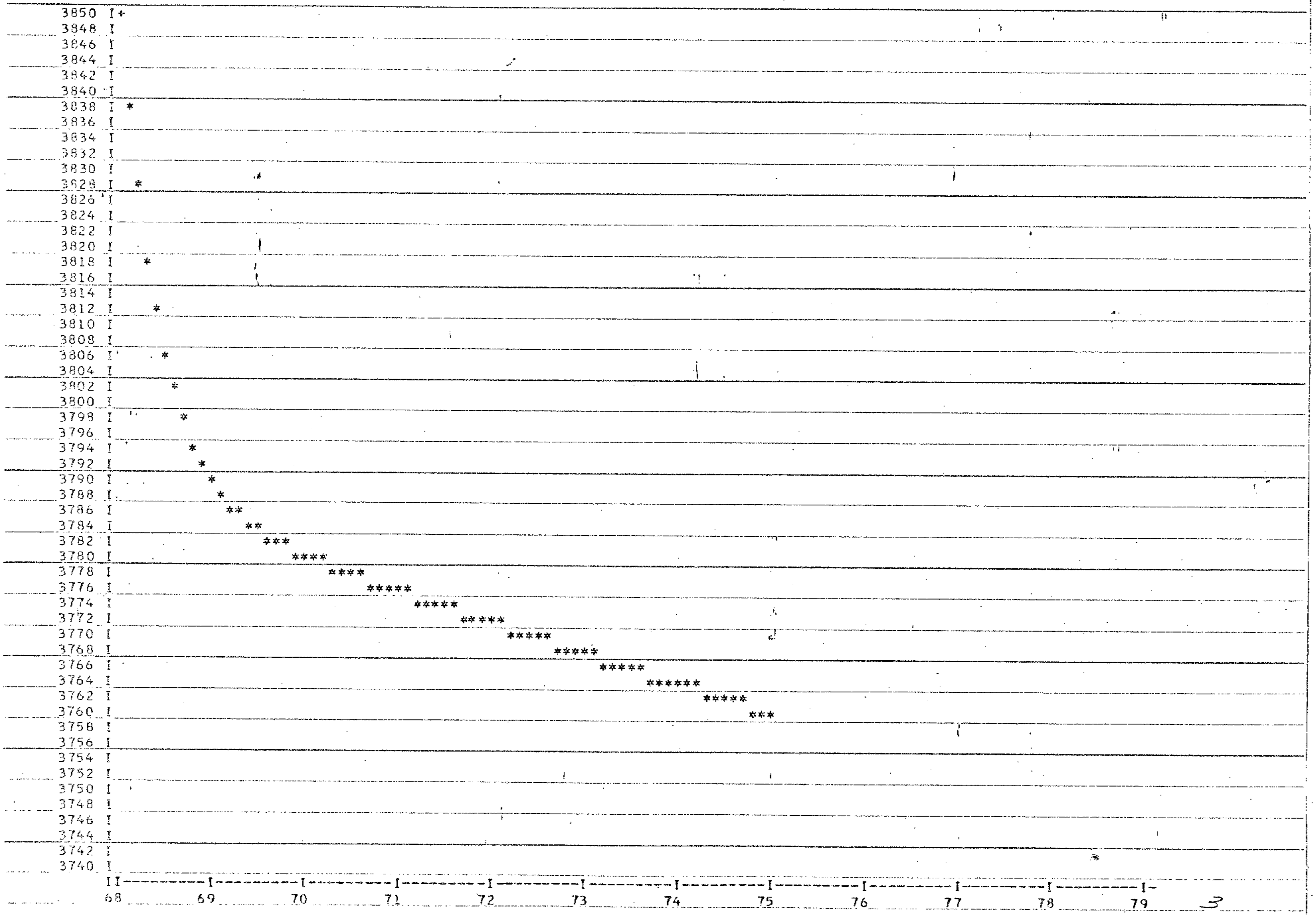
SAFE YIELD = 113 cfs

SAFE YIELD + ARTIFICIAL RECHARGE = 178 cfs

PRACTICABLE PUMPING 169 cfs

DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA WATER SURFACE ELEVATION VS. WATER YEARS

NODE 2 + HISTORIC ELEVATION * CALCULATED ELEVATION



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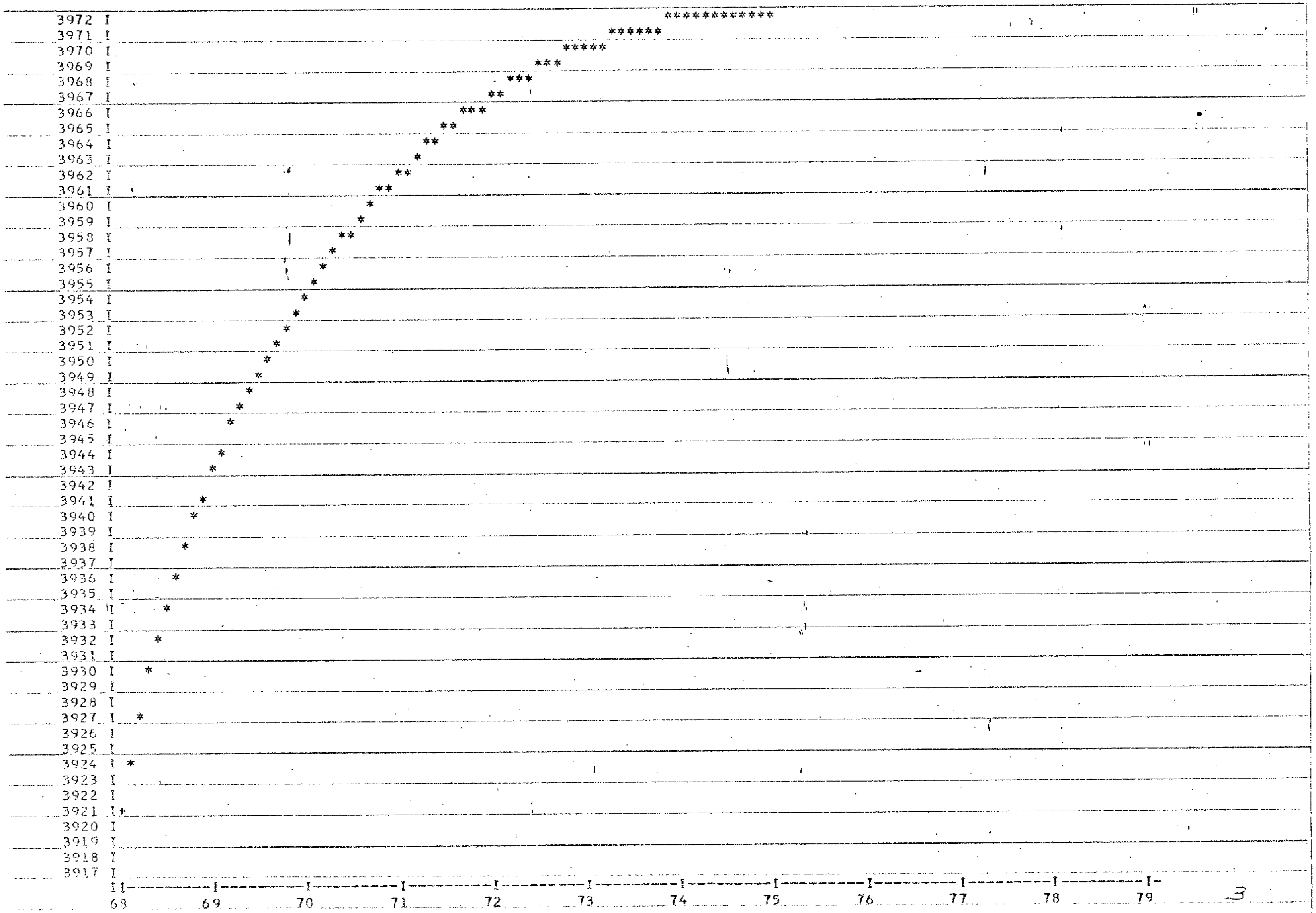
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 3 + HISTORIC ELEVATION * CALCULATED ELEVATION



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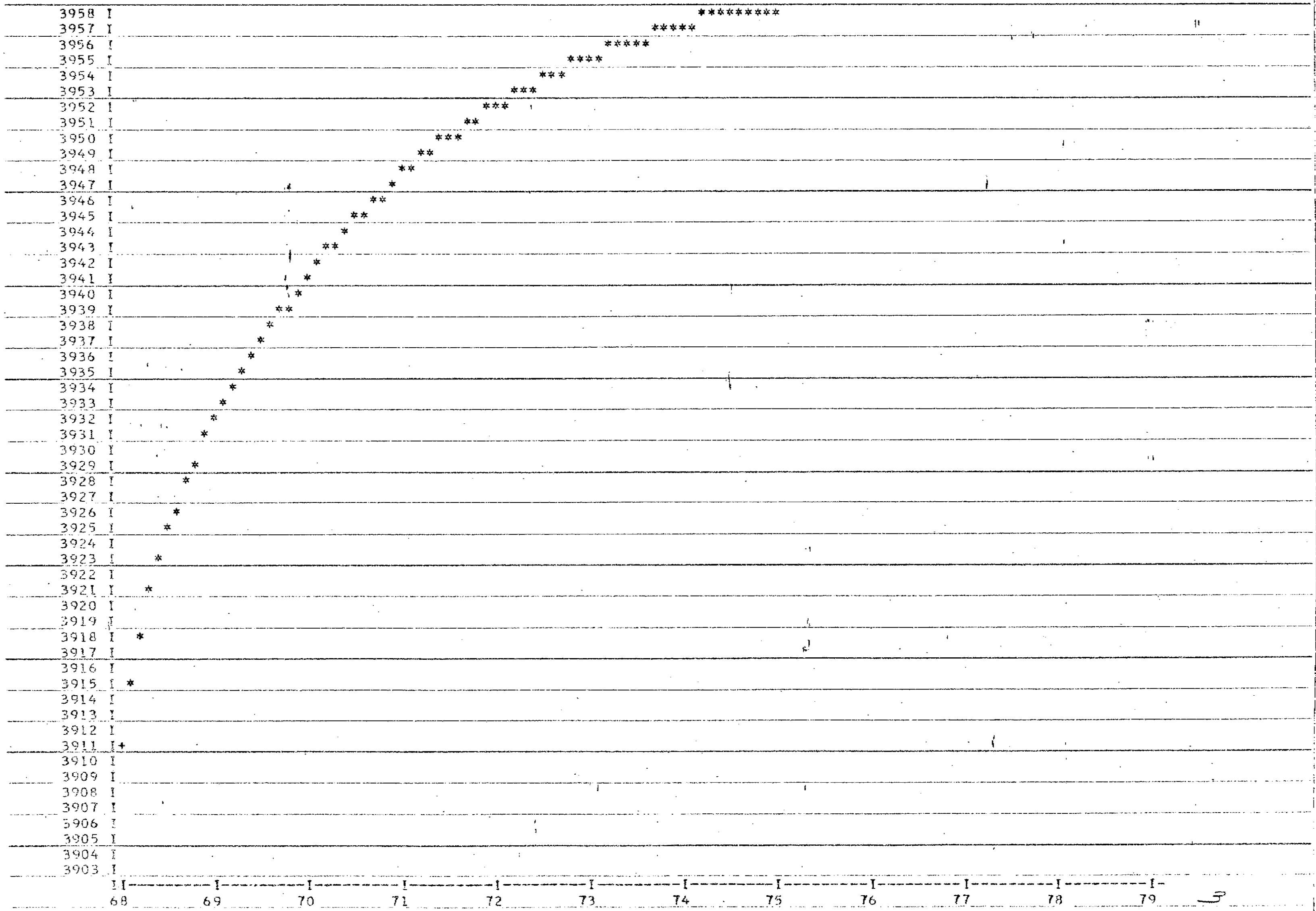
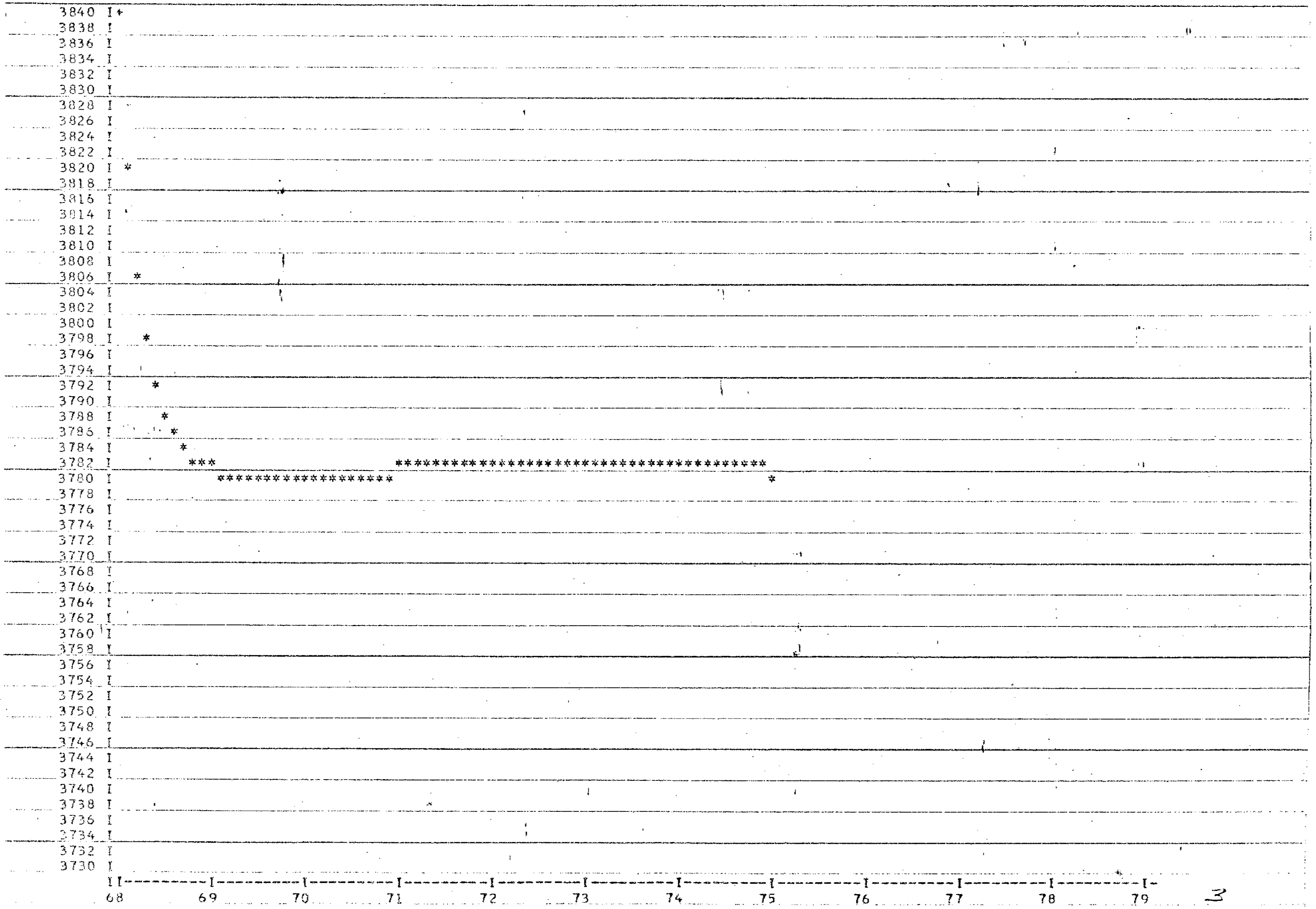
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 4 + HISTORIC ELEVATION * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA WATER SURFACE ELEVATION VS. WATER YEARS

NODE 5 + HISTORIC ELEVATION * CALCULATED ELEVATION



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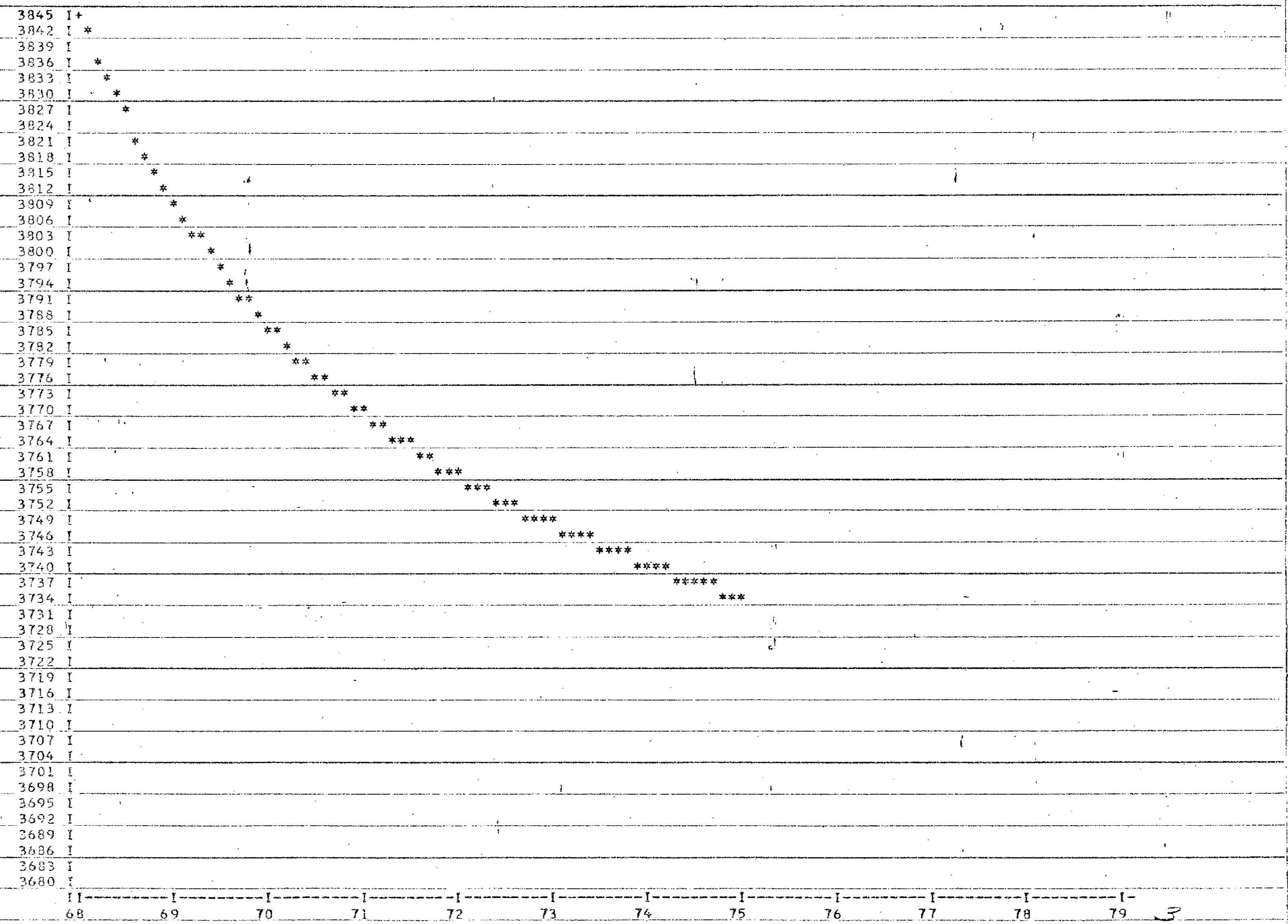
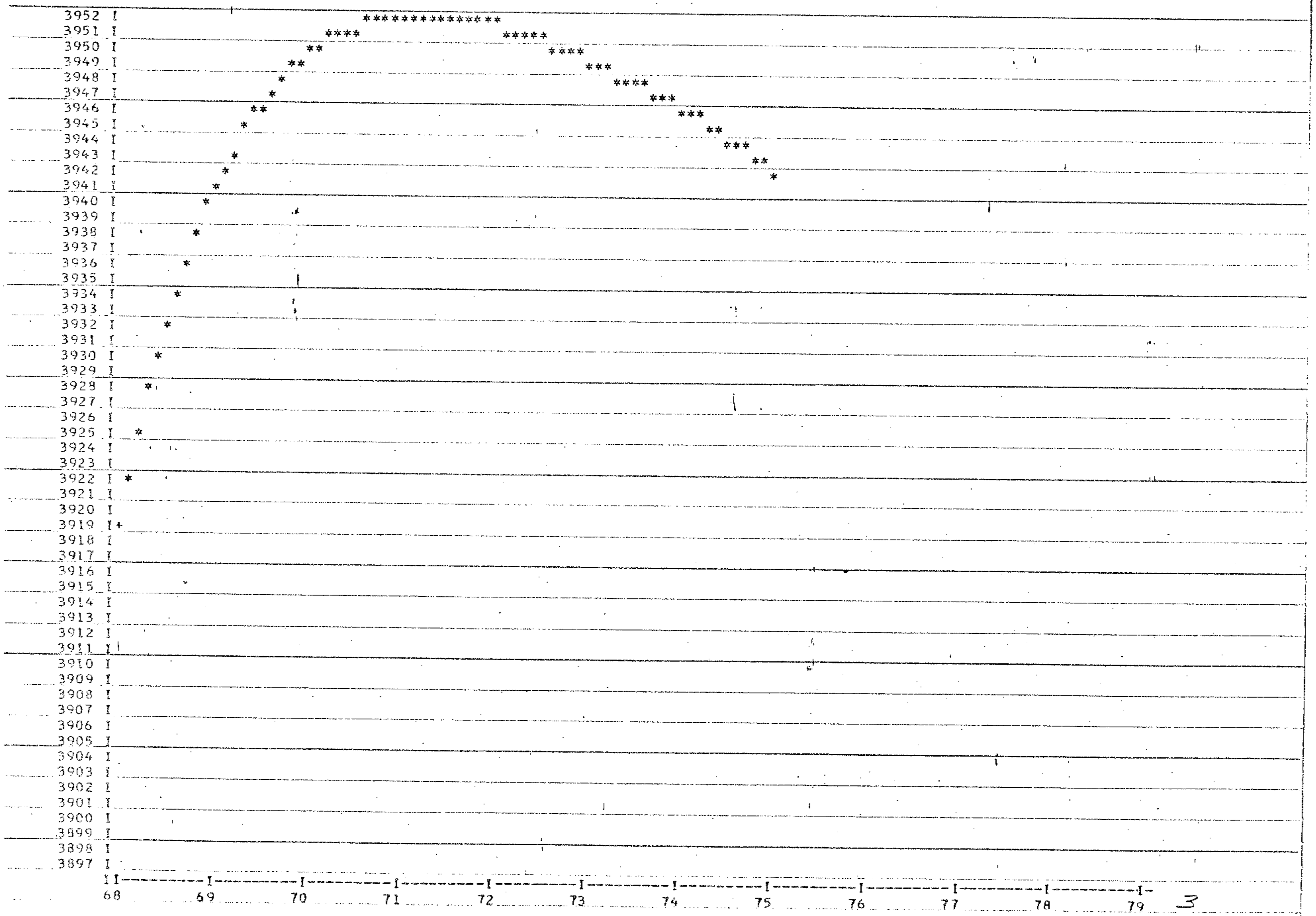
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 8   + HISTORIC ELEVATION   * CALCULATED ELEVATION



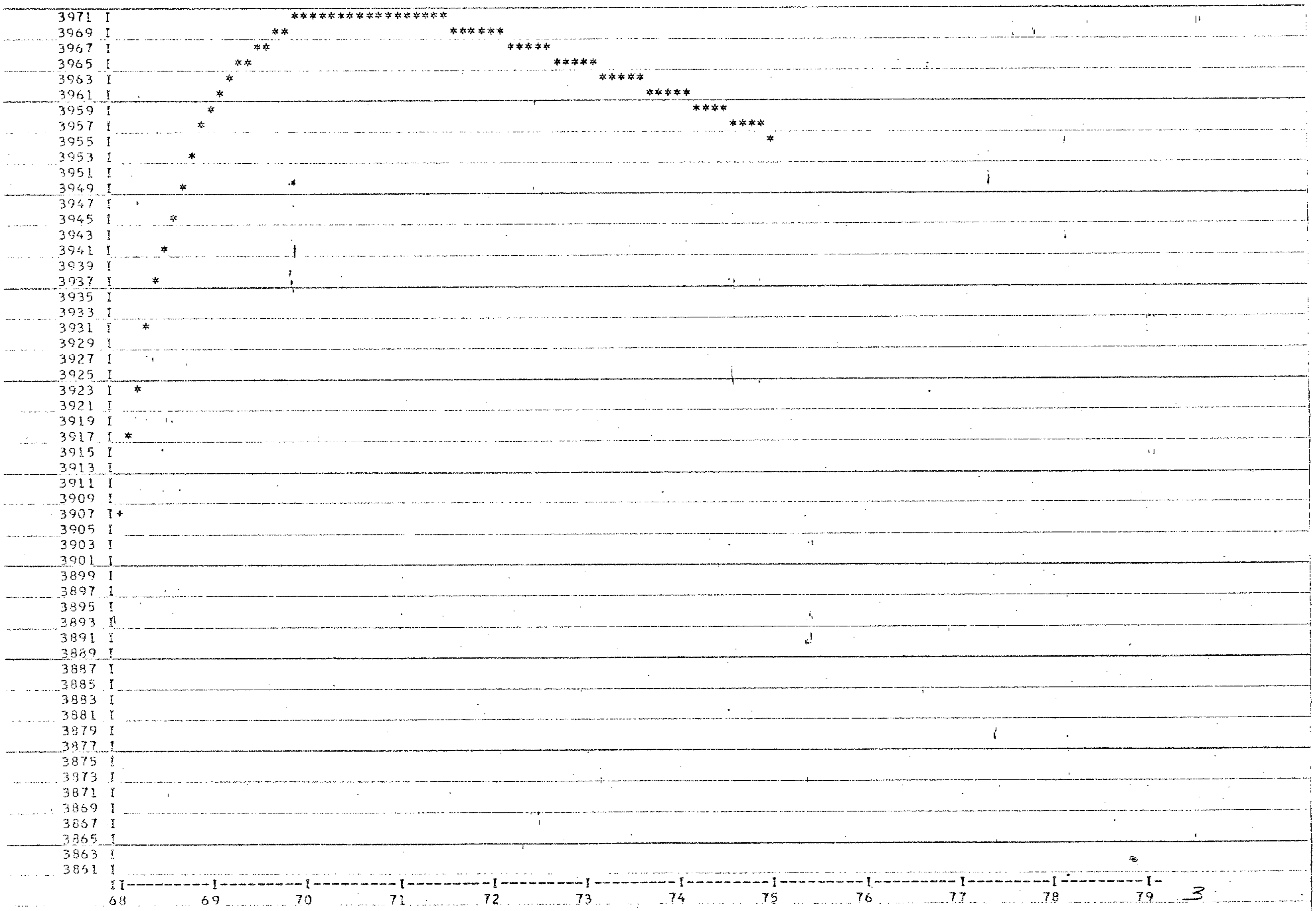
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 9   + HISTORIC ELEVATION   * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 13   + HISTORIC ELEVATION   * CALCULATED ELEVATION



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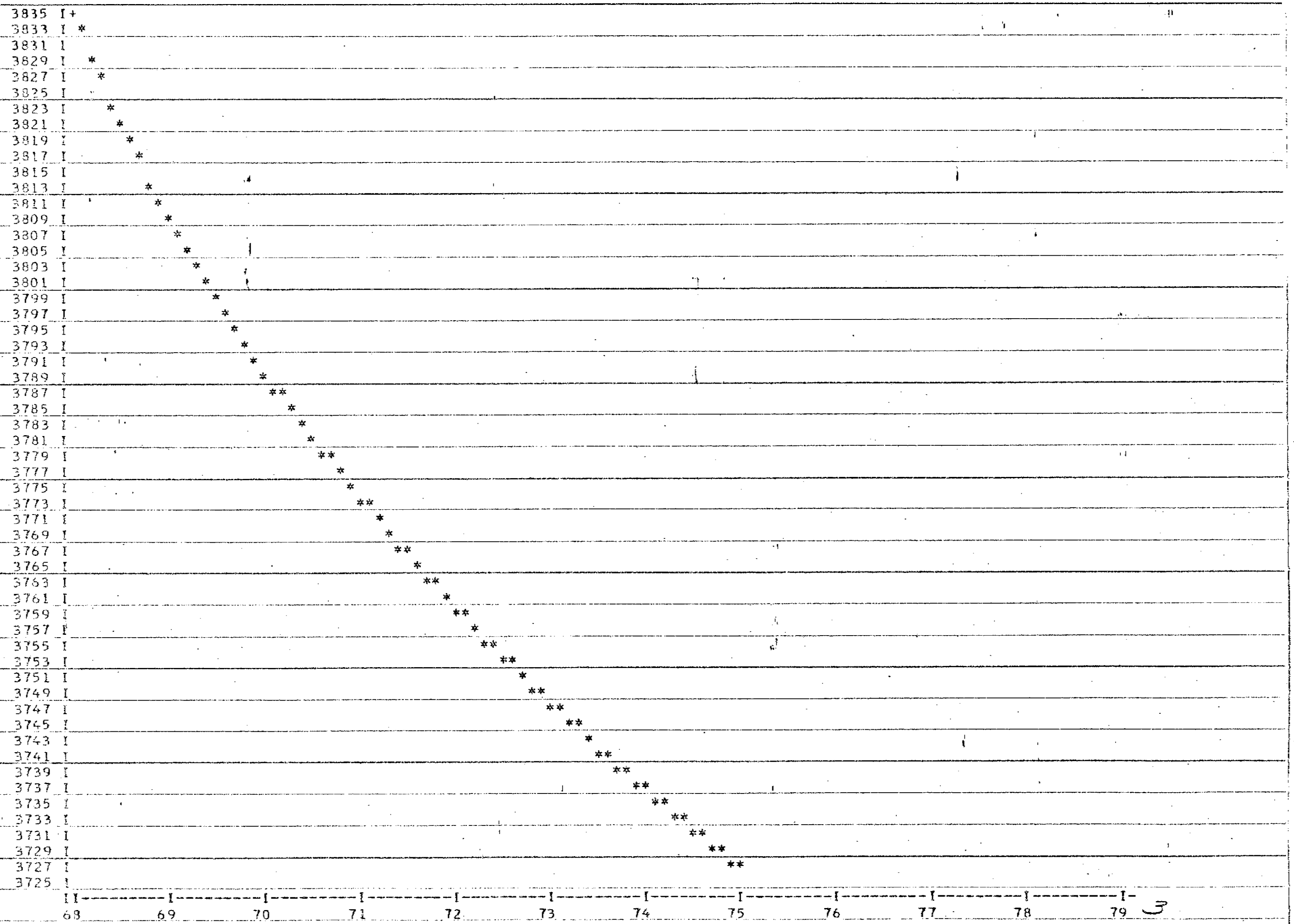
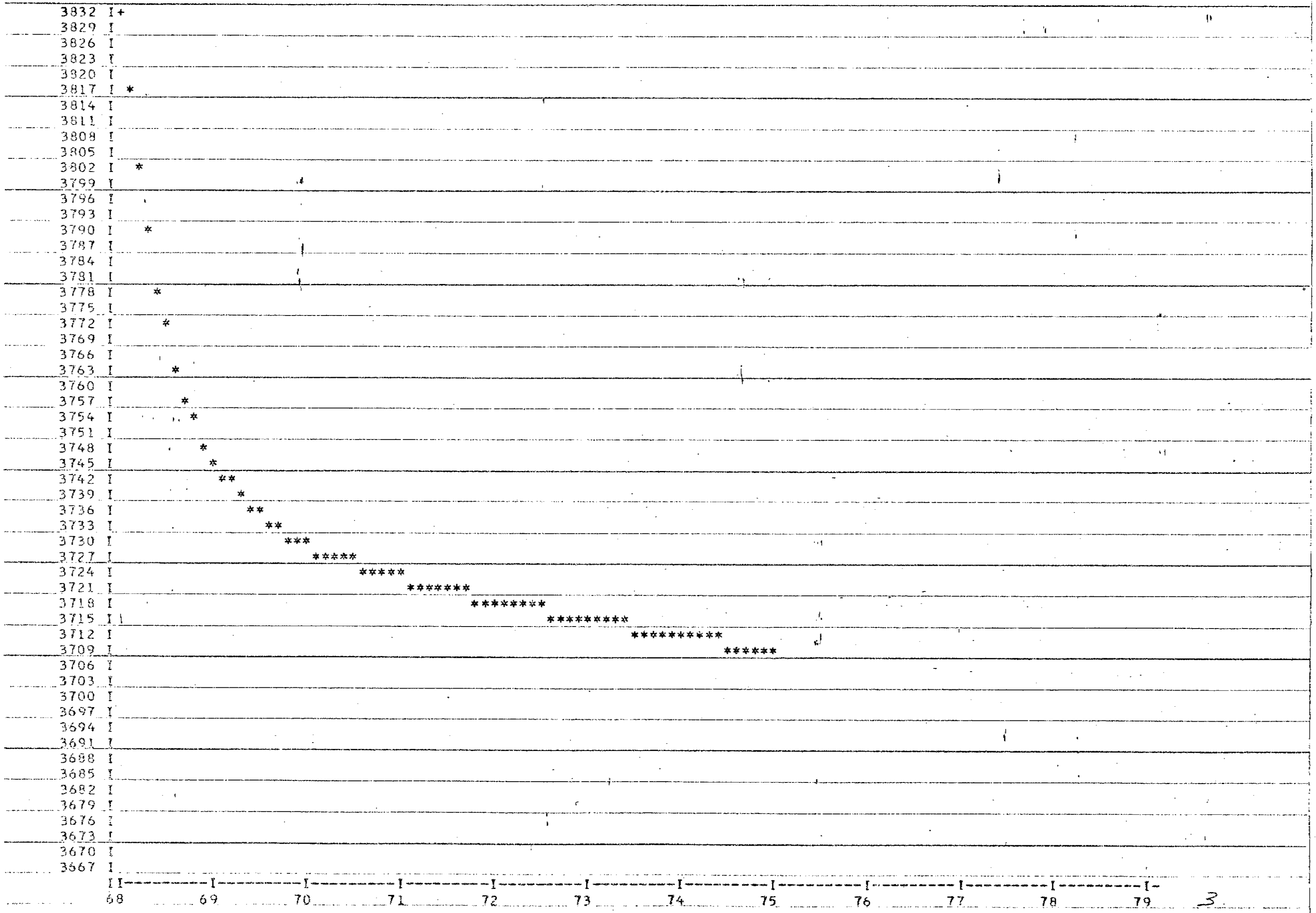
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 14 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 17   + HISTORIC ELEVATION   * CALCULATED ELEVATION



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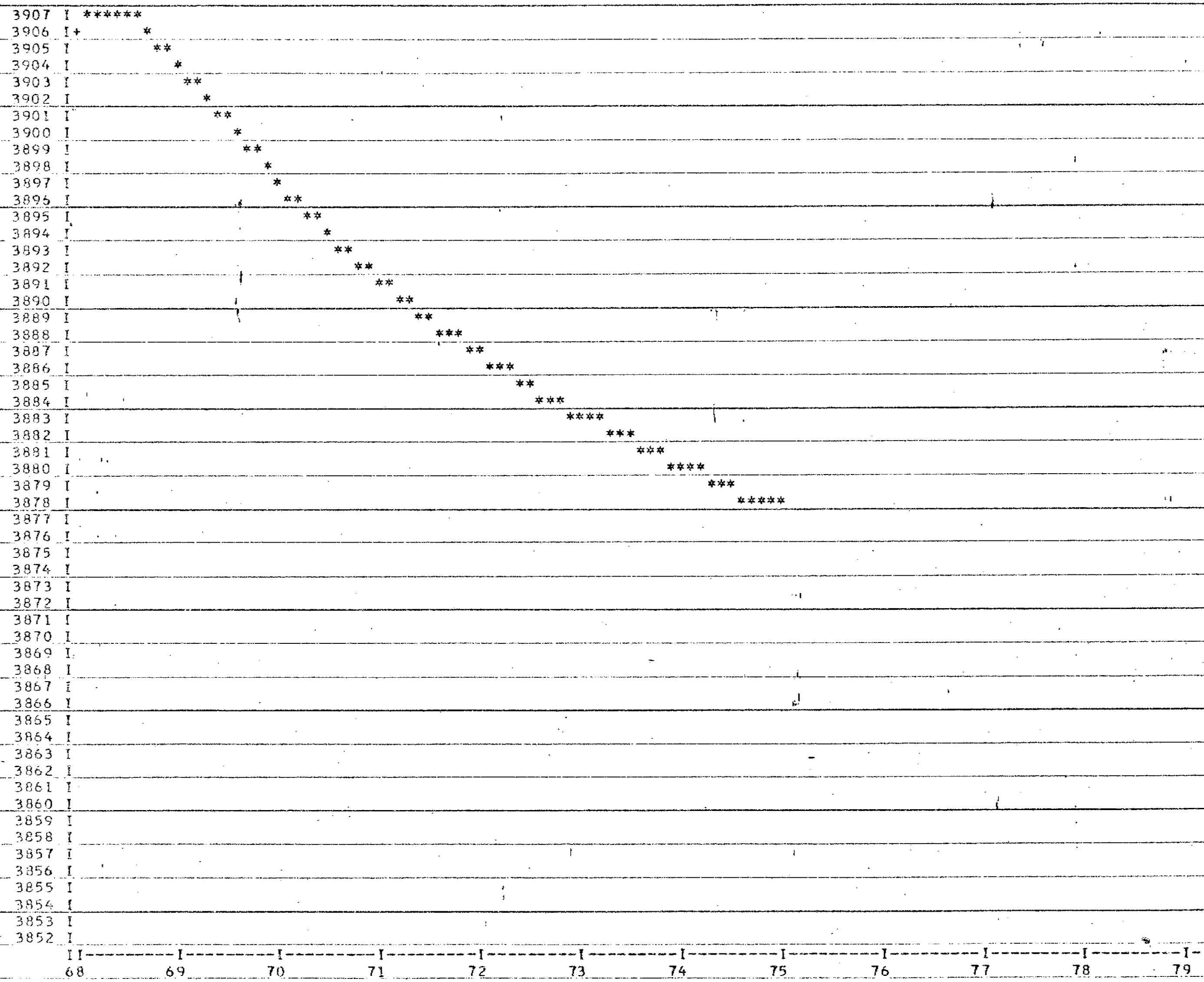
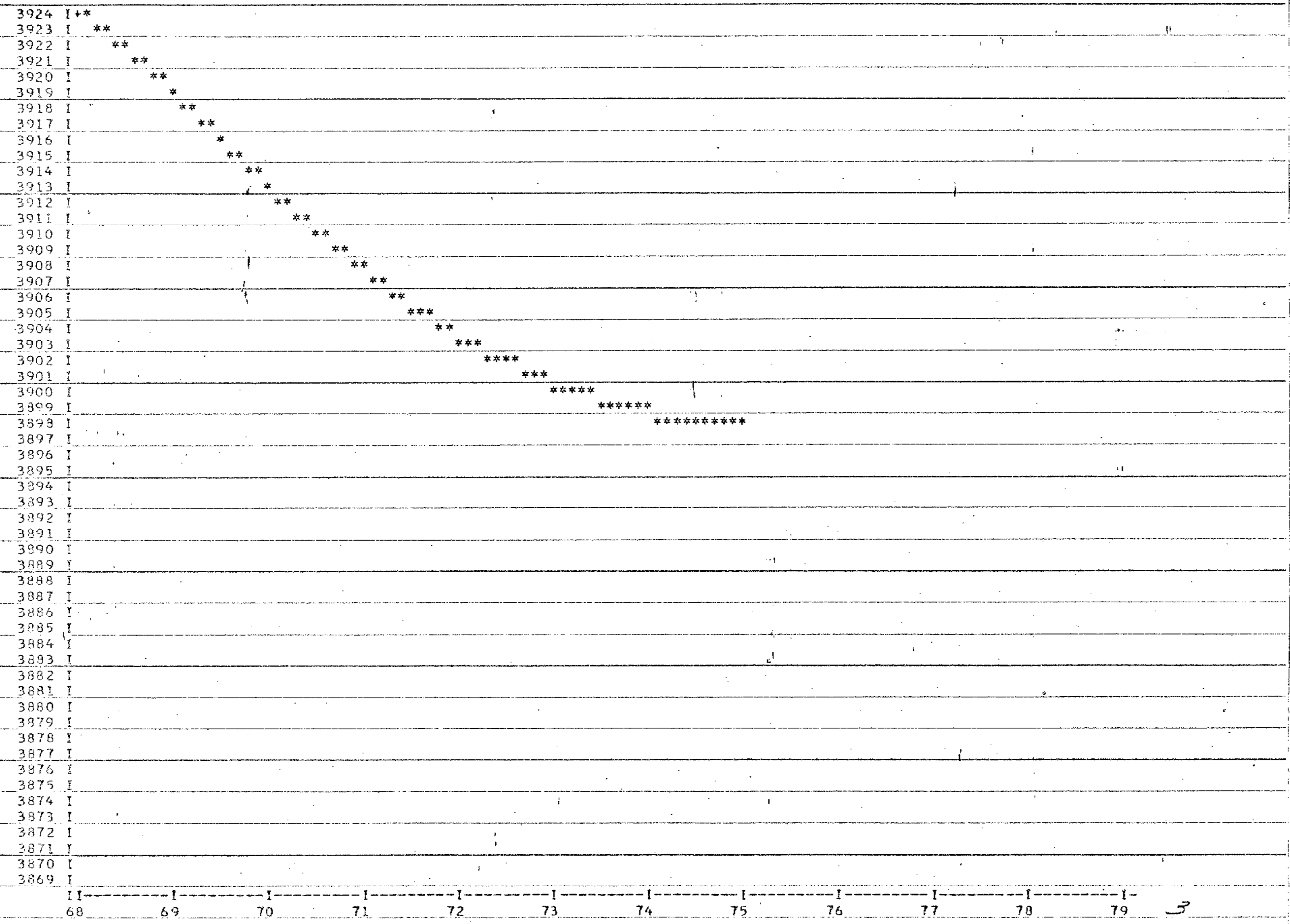
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA   WATER SURFACE ELEVATION VS. WATER YEARS

NODE 18   + HISTORIC ELEVATION   * CALCULATED ELEVATION



DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 22 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



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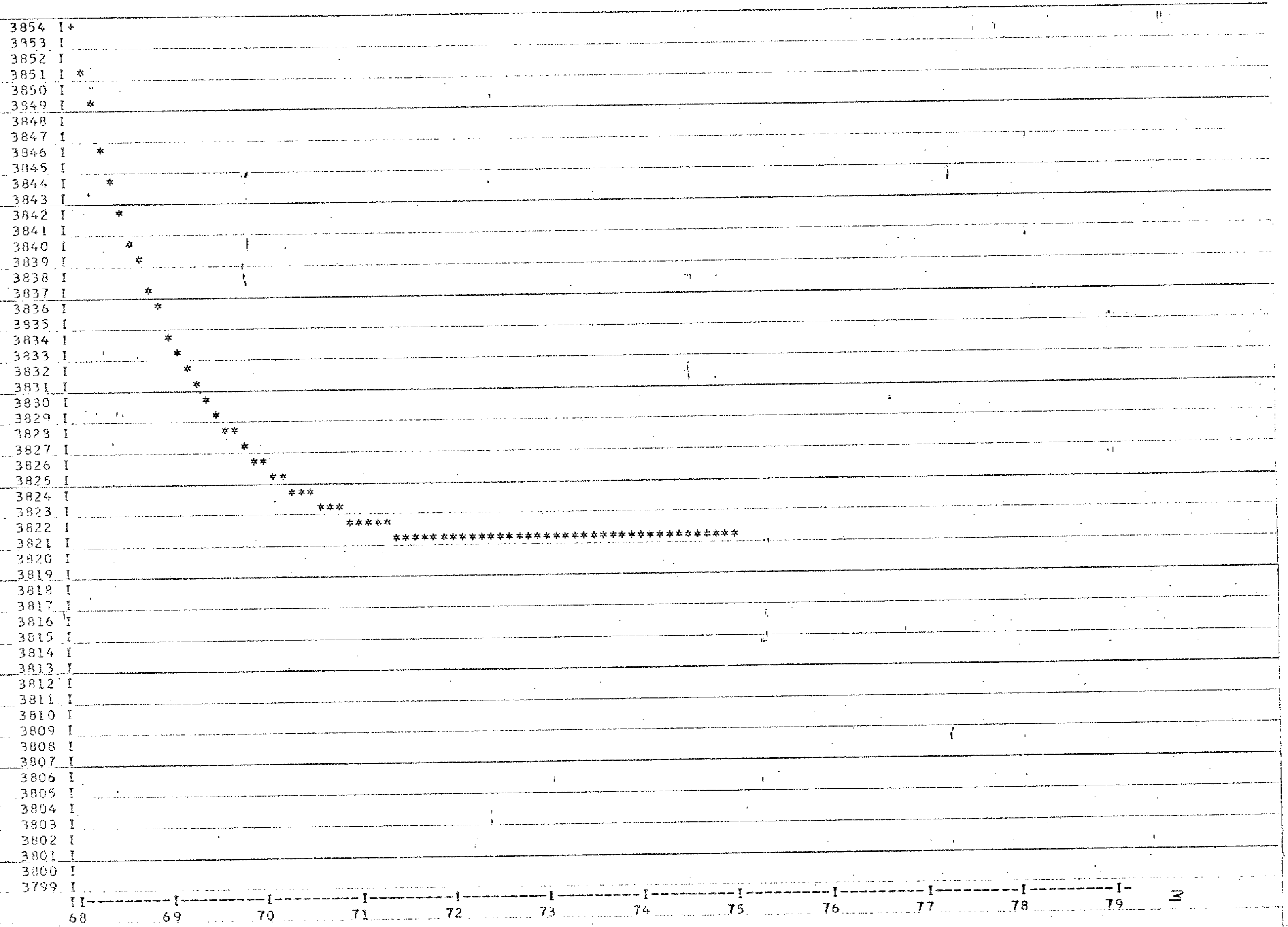
DIGITAL SIMULATION OF THE INDEPENDENCE, CALIFORNIA AREA — WATER SURFACE ELEVATION VS. WATER YEARS

NODE 23 — + HISTORIC ELEVATION — * CALCULATED ELEVATION



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This thesis is accepted on behalf of the faculty of the Institute by the following committee:

Date: 2 May 1969