EASTERN YOLO COUNTY GROUNDWATER INVESTIGATION SUMMARY REPORT

January 1992

By

WEST YOST & ASSOCIATES

Project/File No: 003-91-04

TABLE OF CONTENTS
EASTERN YOLO COUNTY GROUNDWATER INVESTIGATION
SUMMARY REPORT

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

SECTION 1 - INTRODUCTION

PURPOSE OF SUMMARY REPORT

This report provides a description and a general summary of the findings of the Eastern Yolo County Groundwater Investigation as of December 1991. Only data necessary to support or illustrate the findings of this study are included herein. A more complete compilation of the data collected during the course of this investigation was included in the report titled " Eastern Yolo County Groundwater Investigation Update Report 2," dated September 26, 1991.

STUDY AREA DESCRIPTION

The study area is located in eastern Yolo County, east of the cities of Woodland and Davis and west of the Sacramento River and the city of West Sacramento. The majority of the information collected during the investigation was obtained on the Conaway, Cowell, Swanston, and S&F Ranches (see Figure 2-1).

The study area is bordered or crossed by several major water ways. The Sacramento River borders the area on the north and east, and the majority of the study area is within the Yolo Bypass of the Sacramento River. Cache Creek terminates in the Cache Creek settling basin at the north edge of Conaway Ranch. Putah Creek flows into the Toe Drain of the Yolo Bypass near the southern edge of Cowell Ranch. The main water ways within the Yolo Bypass, the Tule Canal and the Toe Drain, border the east side of the Conaway, Swanston, and Cowell Ranches.

Generally the study area is very flat and low. The area slopes from northwest to southeast, with surface elevations ranging from about 25 feet on the S&F Ranch to the north to about 10 feet on the Cowell Ranch on the south. Most of the area is used to grow crops including rice, sugar beets, alfalfa, corn, wheat, and tomatoes.

PURPOSE OF INVESTIGATION

In 1991 California experienced a fifth consecutive drought year. Surface water deliveries by both the U. S. Bureau of Reclamation and the California Department of Water Resources were reduced. Water transfers occurred, facilitated by the State Emergency Drought Water Bank. The Conaway, Cowell, and Swanston Ranches sold water to the State Emergency Drought Water Bank. Due to both reduced surface water deliveries and water transfers, groundwater pumping in Yolo County, as well as other areas, reached what may have been historic high levels.

This investigation was implemented to assess the impact of groundwater pumping in the study area and vicinity during 1991, and to obtain information that will assist in the future management of the groundwater resources of the area. The overall purpose of this investigation is outlined in a memorandum of understanding (MOU) between the County of Yolo and Conaway Conservancy Group dated February 27, 1991. In this MOU Yolo County and Conaway agreed to plan and implement a program to monitor the behavior of groundwater in the vicinity of Conaway Ranch, to facilitate more effective management of the water resources of Conaway Ranch and adjacent properties in the County in the future.

INVESTIGATION ACTIVITIES

The various activities which comprise this groundwater investigation are briefly described below. Information derived from these activities and conclusions drawn from this information are discussed in detail in subsequent sections of this report.

Production Well Rehabilitation

Many of the wells on these properties that were activated in 1991 had not been active for several years. The electric motors and electrical panels had been removed from many of the wells in the Yolo Bypass, and had to be reinstalled. Several electrical panels were damaged and had to be replaced, and several motors required rewinding. The screens on some of the wells were encrusted, and vibratory explosives were used to rehabilitate these wells.

Propeller type flowmeters were installed on the discharge piping of all of the wells. Many of the wells did not have openings large enough to insert a water level probe, and sounding tubes were installed on these wells to allow the measurement of water levels within the wells.

Monitoring of Groundwater Pumping

Each of these agricultural wells were visited on friday of each week and on the last day of each month, and totalized flowmeter readings were recorded. The groundwater pumping monitoring results are summarized in Table 1-1.

Construction of Groundwater Monitoring Wells

A total of thirteen monitoring wells were constructed within the study area to monitor groundwater levels. Locations of these wells are shown on Figure 2-1.

These wells consist of 12 inch bore holes drilled to a depth of between 250 and 400 feet. The wells were generally completed by inserting two casings within each well, a 5½ inch diameter casing to a bottom depth of between 150 and 400 feet, and a 2 inch casing to a bottom depth generally less than 110 feet. Screened sections were installed in both casings opposite sand and gravel layers. Gravel pack was placed in the annular space between the casings and the bore hole. A grout plug was installed between the bottom of the 2 inch casing and the first screened section in the 5½ inch casing.

Well Pumping Tests

Prior to continuous pumping of the water wells on the Conaway, Cowell, Swanston, and S&F Ranches, each water well was test pumped for an 8-hour period. Water levels were measured in the test well and in nearby irrigation and domestic wells before starting the pump, and periodically during the pumping test. Pumping flow rates and readings on the electric meter supplying each pump were also recorded periodically during the pumping test. The objective of these tests was to determine the yield and efficiency of each pumping well, and to estimate the aquifer characteristics in the vicinity of each well.

Groundwater Level Monitoring

Water levels have been measured periodically in the monitoring wells (both shallow and deep casings), in the water wells on each ranch, and in several nearby domestic wells. Measurements began

Table 1 - 1
1991 Groundwater Extraction Monitoring Summary Report
Eastern Yolo County Groundwater Investigation

Conaway Ranch

Groundwater Pumping (Pumping Between May 17 and September 30, 1991):

Well	Begin Period Meter Reading	End Period Meter Reading	Water Pumped During Period	Water Used For Agriculture	Water Discharged To Tule Canal
OW-1	0.0	1,231.5	1,231.5	1,231.5	
OW-2	0.0	1,581.7	1,581.7	1,581.7	
OW-3	0.0	1,475.9	1,475.9	1,475.9	
OW-4	0.0	720.6	720.6	720.6	
OW-5	0.0	904.1	904.1	904.1	
3W-1	0.0	1,095.6	1,095.6	10.7	1,084.9
7W-1	0.0	791.4	791.4	791.4	
10W-1	0.0	726.1	726.1	73.2	652.9
31W-1	0.0	399.1	399.1	399.1	
31W-2	0.0	1,139.4	1,139.4	1,139.4	
32NW-1	0.0	282.9	282.9	282.9	
33NW-1	0.0	574.2	574.2	574.2	
33NW-2	0.0	634.3	634.3	339.7	294.6
33NW-3	0.0	738.4	738.4	438.6	299.8
33NW-4	0.0	1,033.5	1,033.5	297.0	736.5
33NW-5	0.0	1,109.6	1,109.6	0.0	1,109.6
33NW-6	0.0	1,051.4	1,051.4	0.0	1,051.4
33NW-7	0.0	872.4	872.4	0.0	872.4
33NW-8	0.0	1,188.3	1,188.3	0.0	1,188.3
TOTALS			17,550.4	10,260.0	7,290.4

Swanston Ranch

Groundwater Pumping (Pumping Between June 28 and October 17, 1991):

Well	Begin Period Meter Reading	End Period Meter Reading	Water Pumped During Period	Water Used For Agriculture	Water Discharged To Tule Canal
SW-1	0.0	983.0	983.0	0.0	983.0
SW-2	0.0	1,229.0	1,229.0	0.0	1,229.0
SW-3	0.0	1,995.0	1,995.0	0.0	1,995.0
SW-4	0.0	454.0	454.0	454.0	0.0
SW-5	0.0	1,730.0	1,730.0	0.0	1,730.0
TOTALS			6,391.0	454.0	5,937.0

Cowell Ranch

Groundwater Pumping (Pumping Between July 12 and September 19, 1991):

Well	Begin Period Meter Reading	End Period Meter Reading	Water Pumped During Period	Water Used For Agriculture
M-7	0.0	485.5	485.5	485.5
43SW	0.0	555.5	555.5	555.5
50E	0.0	510.8	510.8	510.8
57NW	0.0	720.8	720.8	720.8
57SW	0.0	857.3	857.3	857.3
TOTALS		3,129.9	3,129.9	3,129.9

S&F Ranch

Groundwater Pumping (Pumping Between July 13 and September 27, 1991):

Well	Begin Period Meter Reading	End Period Meter Reading	Water Pumped During Period	Water Used For Agriculture
S&F-1	0.0	616.7	616.7	616.7
S&F-2	0.0	453.6	453.6	453.6
S&F-3	0.0	433.8	433.8	433.8
TOTALS		1,504.1	1,504.1	1,504.1

on April 1, 1991 and continued on a weekly basis until October 4, 1991, when the monitoring frequency was reduced to once every two weeks. The measurement frequency was further reduced to once a month on November 1, 1991. The measurement of water levels on a monthly basis is planned to continue at least through the spring of 1992.

Groundwater Quality Monitoring

Samples were collected to determine water quality in selected water wells throughout the study area during the initial pumping test, in the middle of the irrigation season, and in the fall following the irrigation season. Samples were analyzed for a variety of constituents to determine the water's suitability for beneficial uses including agricultural and municipal uses, to identify any seasonal variations, and to obtain an understanding of water quality variation geographically.

Subsidence Monuments

A total of 16 new subsidence monuments were constructed during this investigation. These monuments are 8-inch diameter by 10 feet deep reinforced concrete, or 3/4 inch diameter copper clad bars driven to a depth of 10 feet. All new monuments are capped with 4-inch diameter aluminum monument discs.

Four existing monuments were also monitored during this investigation. Three of the existing monuments were U.S Geological Survey monuments, and the fourth was a California Department of Water Resources monument.

The location of all these monuments is shown on Figure 2-1.

Extensometer Construction

An extensometer was constructed to monitor compaction within the upper 716 feet of geologic formations at the site of monitoring well MW-7 (for location see Figure 2-1). The extensometer consists of a 2-inch diameter galvanized steel pipe cemented in the bottom of a 716 foot deep bore hole (Figure 4-7). A recorder at the surface measures any vertical movement of the top of the pipe with respect to the ground surface. The recorder is mounted within a steel building, on a steel reference table supported by two 4-inch steel posts cemented in 20 foot deep bore holes.

Groundwater levels at this site are monitored in nearby monitoring well MW-7, and total surface subsidence is measured at a nearby GPS monument.

This device will enable the differentiation of any quantified subsidence in the area from groundwater pumping, gas well extraction, or tectonic movement by comparing the subsidence measured on the surface (at a nearby subsidence monument described above) with that measured in the extensometer.

Control & GPS Surveys

Surveys were conducted throughout the study area for two purposes: (1) control surveys were conducted to tie all of the water wells, monitoring wells, and subsidence monuments into the California coordinate system, and to determine the surface elevation of water wells and monitoring wells; and (2) Global Positioning System (GPS) surveys were conducted to measure changes in the ground surface elevation of the subsidence monuments. It is assumed that vertical changes of these monuments are representative of vertical changes of the land surface at these locations. These GPS surveys were conducted on five occasions, the first two in early July for replicate confirmation, and the others at the beginning of August, September, and October.

SECTION 2 - GEOLOGY OF STUDY AREA

The Sacramento Valley is a large southeast trending structural trough between the Sierra Nevada on the east and the subdued Coast Ranges on the west. Thousands of feet of interbedded sequences of alluvial and fluvial gravels, sands, silts and clays have been transported into this trough by ancient streams during the past 100 million years of geologic history. Throughout this time, the valley has continued to sink and adjacent mountains continued to rise.

During the early part of this depositional history, a shallow arm of the sea invaded the valley. Marine deposits of this early period are clearly recognized in the deep formations in the valley. Since the Eocene (38 million years ago), however, the valley floor has remained above sea level and continental formations have been deposited in the subsiding valley while the ancestral Sacramento River has reworked the sediments along the valley trough as it maintained a uniform gentle gradient to the sea.

In the vicinity of Conaway Ranch, the depth of the continental formations is about 2,600 feet and the base of fresh water in these formations about 2,400 feet, below the present land surface. The sediments penetrated by water wells in the area were deposited in the past 12 million years and derived from three principal source areas --- shed westward into the valley from the Sierra Nevada, shed eastward into the valley from the Coast Ranges, and transported southward from more distant sources by the ancient Sacramento and Feather Rivers. Throughout this depositional history, ancient streams in the valley changed their channels many times, and the channel of Sacramento River was considerably west of its present location much of the time.

Figure 2-1a shows location of the study area and the complex composite pattern of water-bearing stream channel deposits accumulated in the region during the past 12 million years (500 to 600 foot depth in the study area). Many of these channel deposits are buried by fine-grained silts and clays and frequently hydraulically isolated from other aquifers in the area.

Most of the groundwater pumped for irrigation in the area come from formations less than 500 feet deep, although a few water wells are more than 1,200 feet deep. The Conaway Ranch gas field that underlies much of the area, on the other hand, produces from saline Cretaceous (65 million years ago) formations that are more than 3,000 feet deep.

Figure 2-1 shows the location of 6 geologic cross sections developed for the study area and shown in Figures 2-2 to 2-7. These sections are based on the interpretation of electric logs of recently drilled monitoring wells, older test holes, and existing irrigation and domestic water wells. These interpretive sections have been confirmed by driller's logs where logs are available. In general, the geologic sections differentiate between the principal water-bearing aquifers that supply groundwater to the numerous deep and shallow pumping wells and the more extensive fine-grained aquitards that tend to restrict the downward movement of groundwater in the aquifer system. These geologic sections give a vertical dimension to the aquifers depicted in Figure 2-1a.

Through most of the area, the fine-grained aquitards tend to hydraulically separate shallow unconfined aquifers from underlying semi-confined and confined aquifers. Because the effects of pumping overdraft is so different for compressible deposits in a confined aquifer system from those in an unconfined system, defining the nature of this confinement throughout the study area is an important aspects of this investigation. This definition can best determined by observing pumping interferences in deep and shallow wells.

Figure 2-1 is contained within an envelope
at the back of this report.

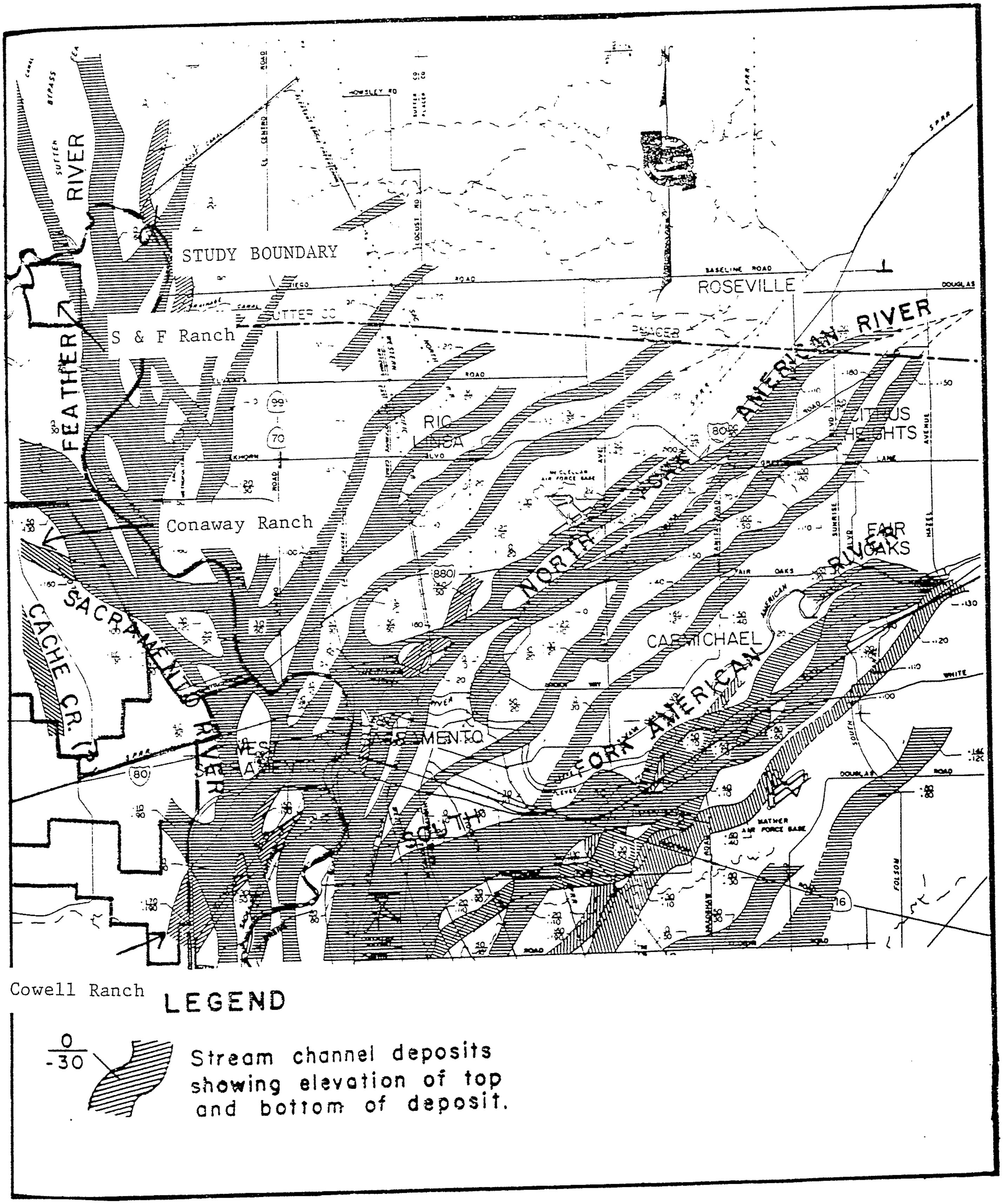


Figure 2-1a. Accumulated Water Bearing Stream Channel Deposits in the Region.
(From DWR Bulletin No. 118-3.)

SECTION 3 - RESULTS OF GROUNDWATER LEVEL MONITORING

The results of the groundwater level monitoring program, which ran from April of 1991 through the present, are summarized in hydrographs, which show groundwater levels in wells over time. These hydrographs are discussed below.

LONG TERM WATER LEVEL MEASUREMENTS

The Yolo County Flood Control and Water Conservation District (YCFCWCD) measured water levels in three of the wells on Conaway Ranch (13N1, 31W1, and 33NW4) prior to the beginning of this groundwater monitoring program. The location of these wells is shown on Figure 2-1. Figures 3-1, 3-2, and 3-3 are hydrographs for these wells. The water levels measurements prior to 1991 were taken by the YCFCWCD. These data were usually collected in the spring during March or April, and again in the fall during October or November.

Well 13N1 is an abandoned domestic well located at the old ranch headquarters at the intersection of county roads 27 and 103. Water level measurements at this location began in the spring of 1973 and continued through 1985. Figure 3-1 presents this historic data, and a water level measurement taken during the fall of 1991 in conjunction with this investigation. The lowest spring or fall water levels observed at this location were recorded during 1977. Water levels gradually recovered between 1978 and 1985. No data is available between the period from 1985 to the fall of 1991. During the fall of 1991 the water level in this well was about 29 feet below the fall 1985 measurement, but about 24 feet above the fall 1977 measurement. This is an agricultural well that is pumped during summer months. Water level measurements during 1991 while the well was being pumped are not shown on this figure.

Well 31W1 is an irrigation well located near the intersection of the west levee of the Yolo Bypass and Interstate 5. Water levels have been measured at this location in the spring and fall of each year since 1963. Figure 3-2 presents this historic data, and a water level measurement taken during the fall of 1991 in conjunction with this investigation. The low water levels recorded during the spring of 1976 and 1977 were probably the result of early irrigation pumping. The lowest fall water level measurements were recorded during the fall of 1977. Both spring and fall water levels in this well gradually recovered from these historic low levels between the period from 1977 to 1983, and have gradually declined since 1983. The fall 1991 water level measurement in this well is only slightly above the historic low level observed in 1977.

Well 33NW4 is located near the junction of the Tule Canal with county road 16. The majority of the agricultural wells on Conaway Ranch are clustered around this well; 13 of the 19 agricultural wells on Conaway Ranch are within a one mile radius. Figure 3-3 presents this historic data, and a water level measurement taken during the fall of 1991 in conjunction with this investigation. The low water levels recorded during the spring of 1976 and 1977 were probably the result of early irrigation pumping. Water levels have been measured at this location in the spring and fall since 1970, but were not recorded during the fall of 1977, which is when maximum low levels were observed in other wells in the region. The water level recorded during the fall of 1991 is the lowest that has been recorded in this well. This level is about 24 feet below the level recorded during the fall of 1976.

1991 WATER LEVEL MEASUREMENTS IN MONITORING WELLS

A total of 13 groundwater monitoring wells were constructed in conjunction with the monitoring program. The locations of these wells are shown on Figure 2-1. These wells were completed during July and August, after nearby irrigation wells had been pumped for several months.

As discussed in Section 1, these wells were generally completed by inserting two casings within each well, a deep casing to a bottom depth of between 150 and 400 feet, and a shallow casing to a bottom depth generally less than 110 feet. Screened sections were installed in both casings opposite sand and gravel layers. Figure 3-4 shows the measured deep (MW1D) and shallow (MW1S) water levels (in blue on the left axis) in these wells, and also the changing ground-surface elevations (in red and right axis) of the nearby subsidence monument (SM12) during the 1991 period of monitoring. Corresponding data for other monitoring sites are shown in Figures 3-5 and 3-14. The water-level trends in these wells are discussed below; the changes in surface elevation , as measured by the GPS surveys, are discussed in Section 4. Also shown on Figures 3-4 through 3-14 are the periods during which nearby agricultural wells were in operation.

Monitoring wells MW-1 and MW-2 are situated near the western boundary of Conaway Ranch. Water levels in these wells are probably affected more by pumping in the region to the west of Conaway Ranch than by pumping within the study area. Shallow groundwater levels remained relatively constant in both wells during the monitoring period, while the deep groundwater levels gradually rose during most of the period. Water levels in both the shallow and deep piezometers within MW-2 appear to have stabilized in the fall. Throughout the period , a downward hydraulic head differential of 52 to 30 feet persisted at MW-1, and half this amount was observed at MW-2.

Monitoring wells MW-4 and MW-5 are located along the southern boundary of Conaway Ranch, near the City of Davis Wastewater Treatment Plant and the Yolo County Landfill. A slight drop occurred in the deep groundwater level during the pumping period, and levels quickly recovered once pumping stopped. Groundwater levels in monitoring well MW-6, which is located along the eastern border of Swanston Ranch, responded in a similar fashion.

Monitoring well MW-8 is located between closely-spaced, highly productive water wells near the Sacramento River. While the wells on Conaway Ranch west of the Tule Canal continued to be pumped, the 5 wells west of the Tule Canal, nearest monitoring well MW-8, were only operated for brief periods after the end of August. The deep groundwater level in this well reflects this reduced level of pumping. By December 1991 the water level in both the shallow and deep wells had recovered to within 13 feet of the land surface in this monitoring well.

Monitoring wells MW-9 and MW-10 are located near Highway 16 (the River Road) at the eastern and western edge of the Yolo Bypass, respectively. MW-9 is approximately in the center of the Conaway Ranch well field. The water levels in these wells were greatly affected by groundwater pumping. These wells were completed during July, when the greatest rate of groundwater pumping and the lowest groundwater levels of the year occurred. Groundwater levels gradually rose during the late summer and fall. By December the water levels in both shallow and deep wells at these sites had recovered to within approximately 20 feet of the surface.

Monitoring well 11 is located on S&F Ranch, at the northern edge of the Yolo Bypass, near the Fremont Weir. The wells on S&F Ranch were pumped intermittently during the early summer of 1991, and more heavily during August and September. Groundwater levels showed little effect and recovered rapidly from this pumping.

Monitoring well MW-12 is at the western edge of Cowell Ranch. This monitoring well was completed with 3 piezometers, a deep piezometer screened between 210 and 290 feet, an intermediate piezometer screened between 90 and 120 feet, and a shallow piezometer screened between 30 and 60 feet. The groundwater levels at this location are probably heavily affected by pumping of City of Davis wells to the west of the monitoring well. Water levels in both the deep and intermediate piezometers have gradually risen since early August, while water levels in the shallow piezometer have gradually fallen. Seepage between the shallow and deep aquifer apparently caused the water levels in the shallow aquifer to continue to drop after groundwater pumping stopped.

Monitoring wells MW-13 and MW-14 are located in the middle of the Yolo Bypass, in the vicinity of agricultural wells that were heavily pumped during the summer of 1991. Groundwater levels in both the shallow and deep piezometers were moderately affected, but had recovered by the December measurement.

GROUNDWATER CONTOUR MAPS

General

Groundwater contour maps have been prepared for the Conaway Ranch portion of the study area for the different aquifer zones (shallow and deep as previously described) under both non-pumping and pumping conditions. The groundwater elevations shown on these maps are in feet with respect to mean sea level.

Spring Water Levels

Groundwater elevations in the spring are presented to illustrate groundwater flow directions prior to the start of irrigation (and water bank) pumping in the study area.

Groundwater contour maps of the study area for the spring of 1961, 1980, and 1986 were presented in the Update on Eastern Yolo County Groundwater Investigation report dated August 1, 1991. These maps were reproduced from DWR regional maps and show similar patterns and elevations of groundwater levels across Eastern Yolo County in the spring of each year. The general direction of groundwater flow indicated by these maps is generally eastward and southeastward. The contours in the study area represent water levels in wells that are generally perforated in the 150 to 300 feet depth range, and are therefore representative of the deep aquifer zone.

Figure 3-16 shows groundwater contours from YCFCWCD and DWR wells in Eastern Yolo County during the spring of 1989. These patterns are similar to the patterns observed during 1961, 1980, and 1986. These data indicate that in the vicinity of Conaway Ranch, under pre-pumping conditions, the average slope of the groundwater surface is about 0.0004 ft/ft (2 feet per mile) to the east and southeast.

The average March 1989 Sacramento River stage at two locations (at the Fremont Weir (west) and at the Bryte Lab gauging station) are also plotted on Figure 3-16. The March 1989 average river stage at these locations was much higher than the average 1989 water year values of 13.93 and 5.55 at Fremont and Bryte, respectively. Because the water surface elevation in the river was above the groundwater elevations in March 1989, some recharge probably occurred from the river to the adjacent aquifer.

Groundwater probably discharged to the river during January and February, 1989, when the river elevations were closer to the annual water year average. During the irrigation season groundwater levels reach their annual lows and recharge from the river probably occurs.

Figure 3-17 is a vector plot showing the approximate direction of groundwater flow during April, 1989. Arrows point in the direction of flow and their length is an indicator of the relative magnitude of the gradient. Longer arrows are shown in areas of steeper gradients, as indicated by closely spaced groundwater contours lines.

Figure 3-18 shows groundwater contours on April 15, 1991. These were derived from data collected at Conaway Ranch irrigation wells before pumping began on May 1, 1991. These wells are completed in the semiconfined aquifer. These water levels may have also been near the water table in the eastern part of Conaway Ranch because the data were collected under non-pumping conditions, and the elevations were near the surface elevation of Tule Canal. Water levels in the area shown range from about 9 to 10 ft in elevation.

The contours on Figure 3-18 indicate a gradient of about 0.0002 ft/ft to the southeast along the general direction of the Tule Canal and Sacramento River. This pattern is similar to that observed during the spring of 1989 (see Figure 3-15). Heavy rains fell during March 1991, and water overflowed the Cache Creek settling basin weir and entered the Yolo Bypass. During the first week of April the area around the wells on Conaway Ranch within the Yolo bypass was still flooded by the Tule Canal, and groundwater levels were near the ground surface.

Groundwater Levels Under 1991 Pumping Conditions

Groundwater Elevations on July 26, 1991 - Figures 3-19 and 3-20 show groundwater contours below Conaway Ranch on July 26, 1991 in the shallow zone and deep zone, respectively. At this time most of the wells on Conaway Ranch were in operation and groundwater levels were about at their lowest.

The direction of groundwater flow was to the east and northeast across Conaway Ranch, toward the areas of concentrated pumping on Conaway and Swanston Ranch. Sacramento River stage data at Fremont Weir and Bryte on July 26 are shown on Figures 3-19 and 3-20. The Sacramento River and Tule Canal water level were higher than that in the underlying aquifers, and likely recharged the aquifers to some extent.

Between May 1 and July 6, 1991 the groundwater level in the shallow aquifer declined about 10 feet. The agricultural wells on Conaway Ranch primarily draw water from the deep aquifer, so the decline observed in the groundwater level in the shallow aquifer was probably caused largely by leakage or downward movement between the shallow and deeper aquifer. This is reflected by many of the hydrographs, which show a decline in the shallow aquifer water level while the deeper aquifer water level is rising.

Figure 3-20 shows groundwater elevations on July 26, 1991 in wells perforated in the deeper pumped zone. The average drawdown in the vicinity of the pumping wells was about 50 feet.

Figure 3-21 is a plot of the difference in groundwater elevations between the shallow and deeper zones on July 26 1991. Although the data are incomplete, the average head differences across Conaway Ranch appear to have ranged from about 60 ft along the western boundary to about 20 ft near the Tule Canal.

Groundwater Levels on October 18 - Figure 3-22 shows groundwater contours in the shallow aquifer below Conaway Ranch on October 18, 1991. The pattern was similar to that on July 26, shown in Figure 3-19. Between July 26 and October 18 water levels rose nearly uniformly about 5 feet across the ranch. Groundwater elevations in the shallow zone remain lower than Sacramento River stage.

Figure 3-23 shows groundwater contours from "deep" monitoring wells on Conaway Ranch on October 18, 1991. A "-12" groundwater elevation contour encompasses much of the ranch. However, because MW-7D at the extensometer site was not yet completed, there were no deep measurements in the central ranch area. Water levels in the area apparently rose more than 20 feet between July 26 and October 18.

Figure 3-24 shows contours of the difference between groundwater elevations in the shallow and deeper zones on October 18, 1991. This also resembles Figure 3-21 for the July 26 data, but the difference had lessened. The difference ranged from about 30 to about 10 ft across Conaway Ranch, about half that shown on Figure 3-20 for July 26.

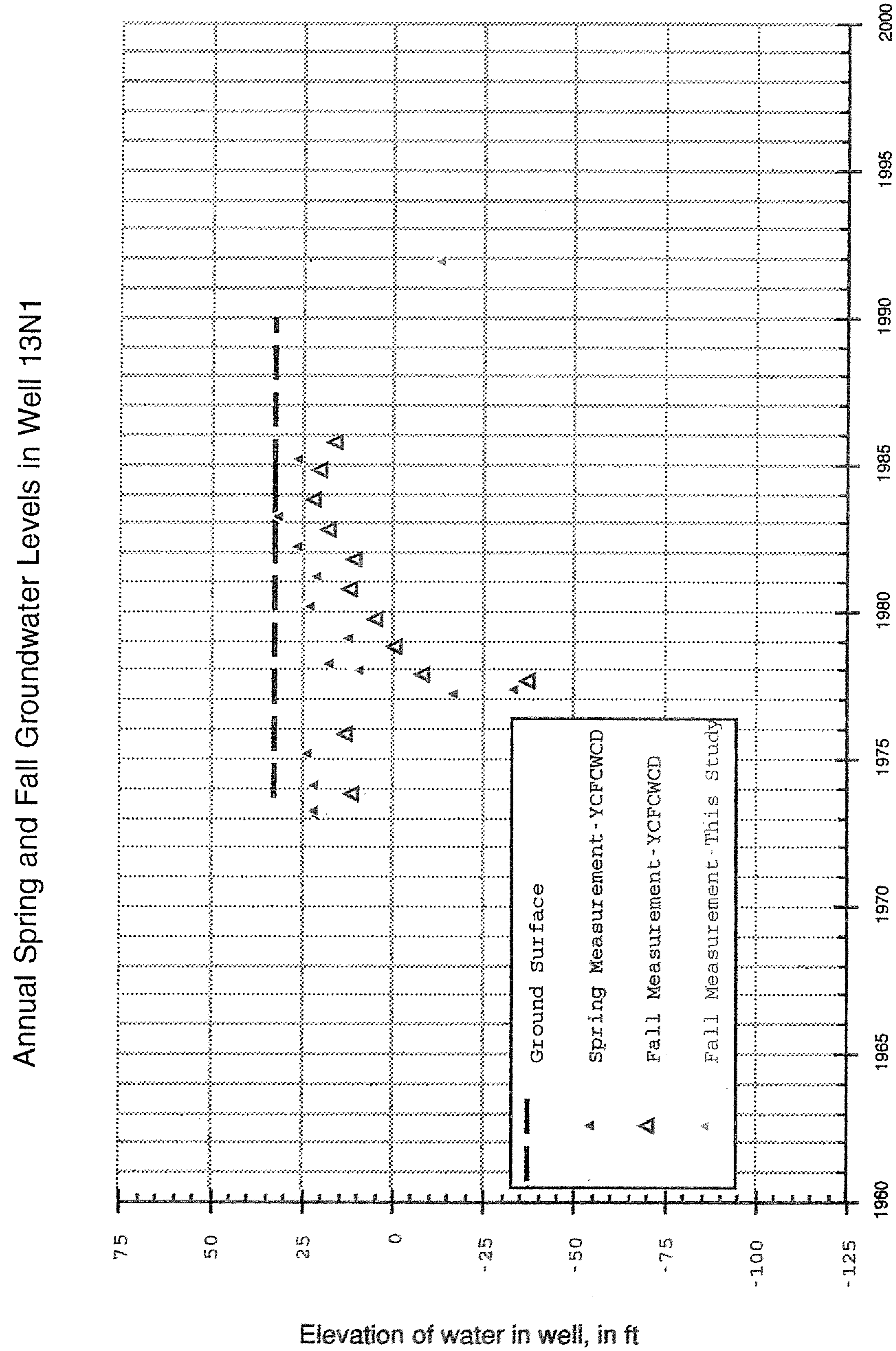
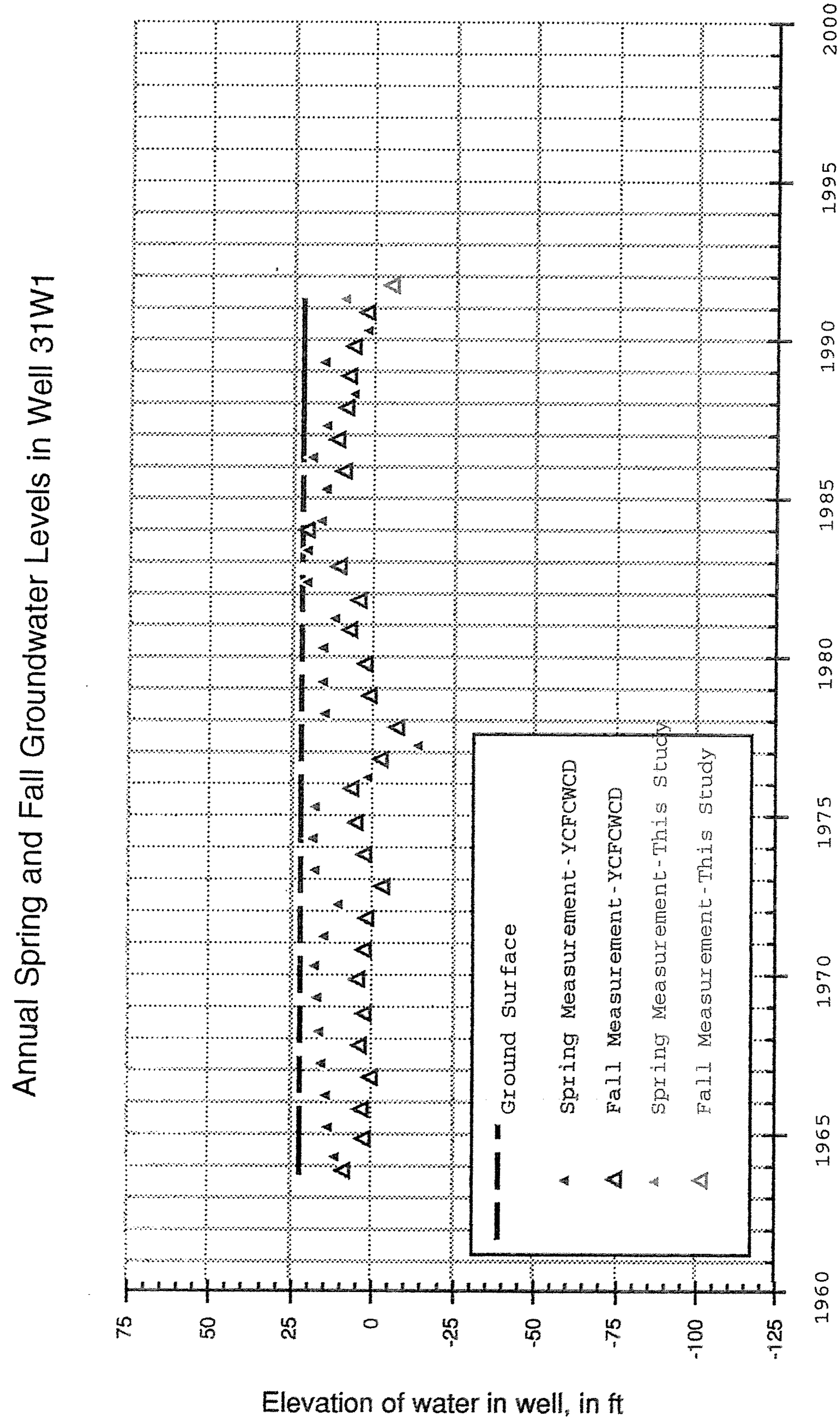

Annual Spring and Fall Groundwater Levels in Well 13N1
Elevation of water in well, in ft
75
50
25
0
-25
-50
-75
-100
-125
1960
1965
1970
1975
1980
1985
1990
1995
2000
Ground Surface
Spring Measurement-YCFCWCD
Fall Measurement-YCFCWCD
Fall Measurement-This Study

Figure 3-1



Annual Spring and Fall Groundwater Levels in Well 31W1
Elevation of water in well, in ft
75
50
25
0
-25
-50
-75
-100
-125
1960
1965
1970
1975
1980
1985
1990
1995
2000
Ground Surface
Spring Measurement-YCFCWCD
Fall Measurement-YCFCWCD
Spring Measurement-This Study
Fall Measurement-This Study

Figure 3-2

Annual Spring and Fall Groundwater Levels in Well 33NW4

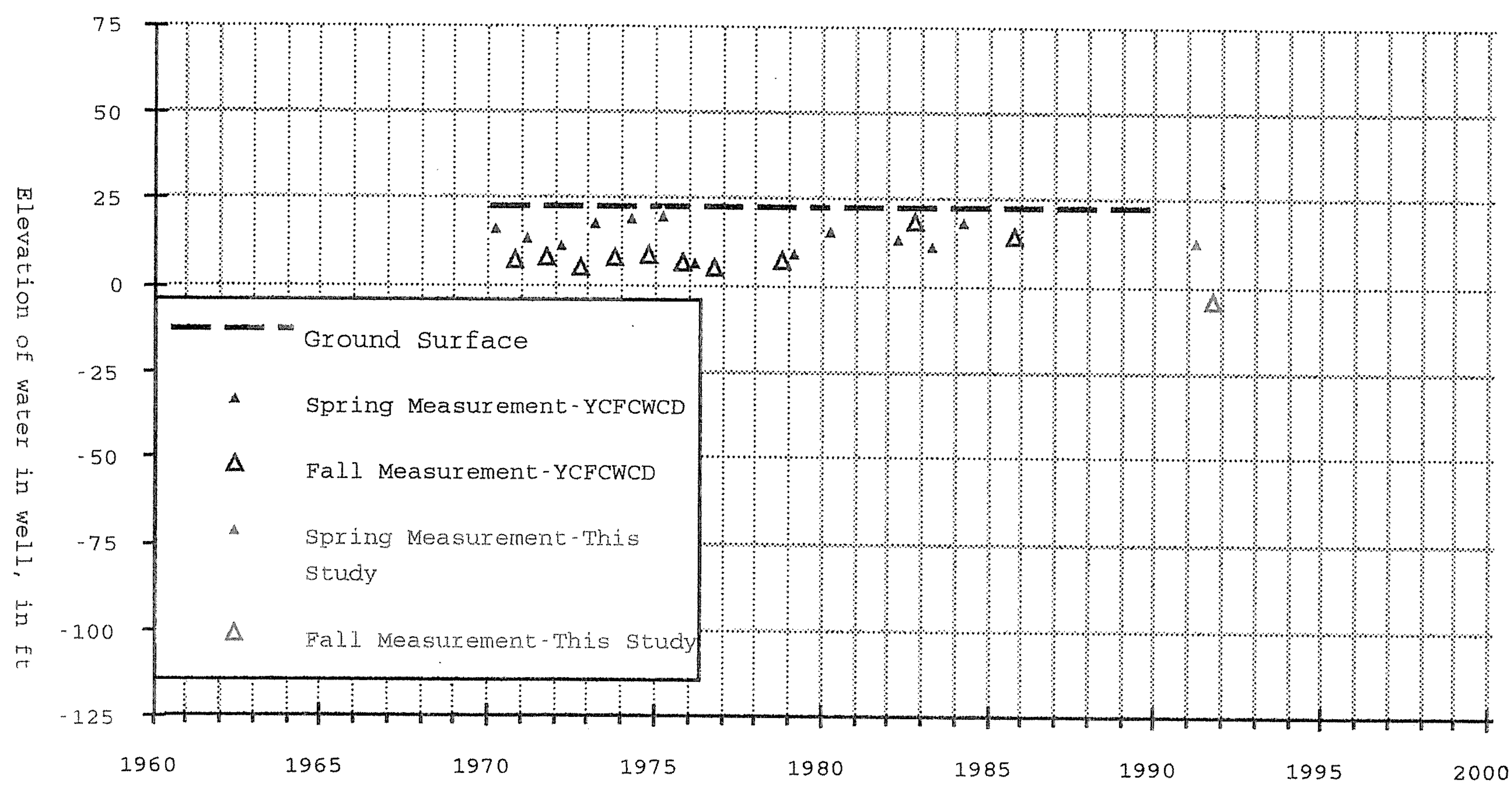
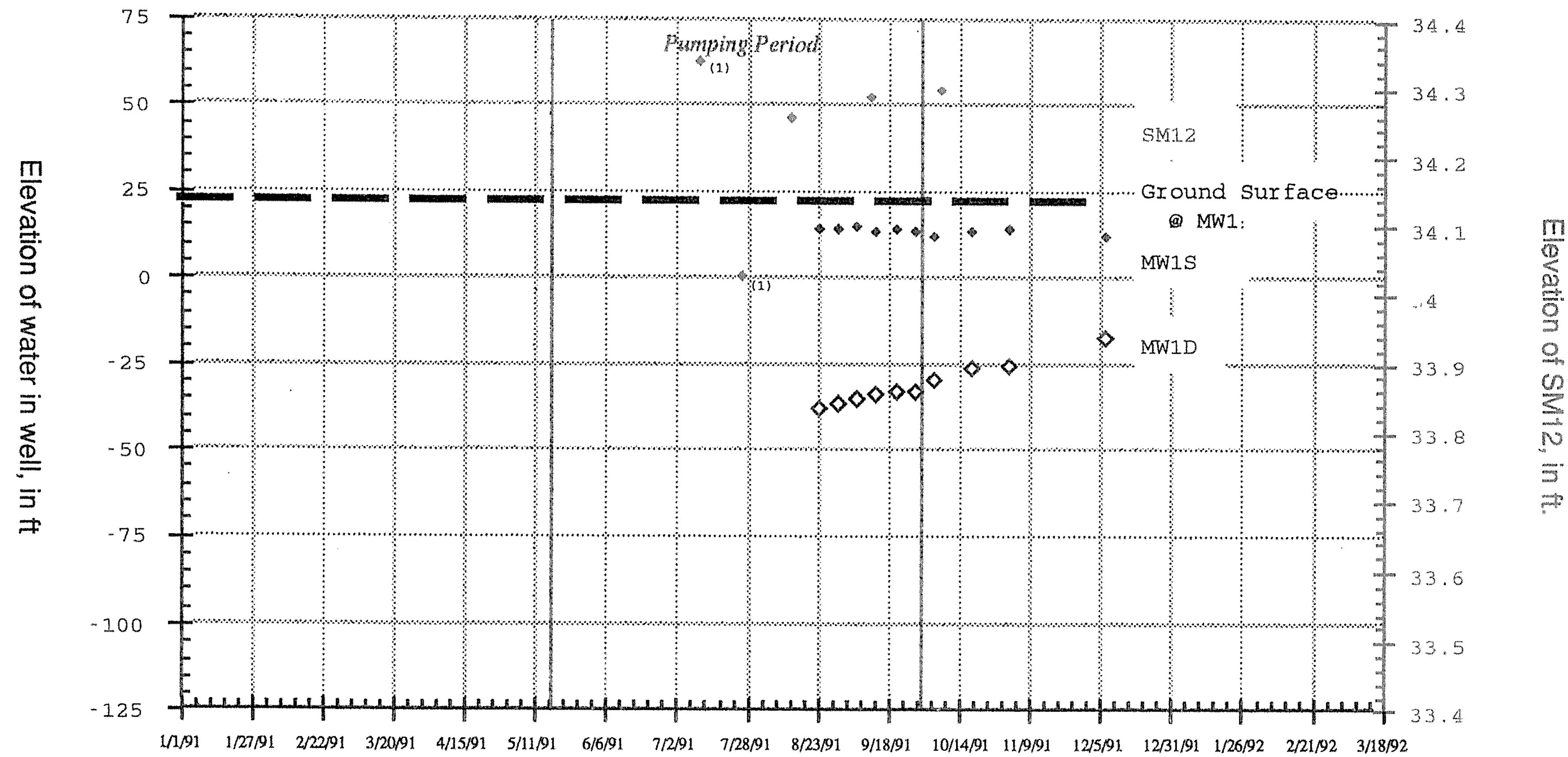


Figure 3-3

1991 Groundwater Levels in Monitoring Well MW1 and Elevation of Subsidence Monitor SM12



Notes:

(1) Unusually high solar and geomagnetic field activity appears to have had an affect on the accuracy of these observations.

Figure 3-4

1991 Groundwater Levels in Monitoring Well MW12 and Elevation of Subsidence Monitor SM3

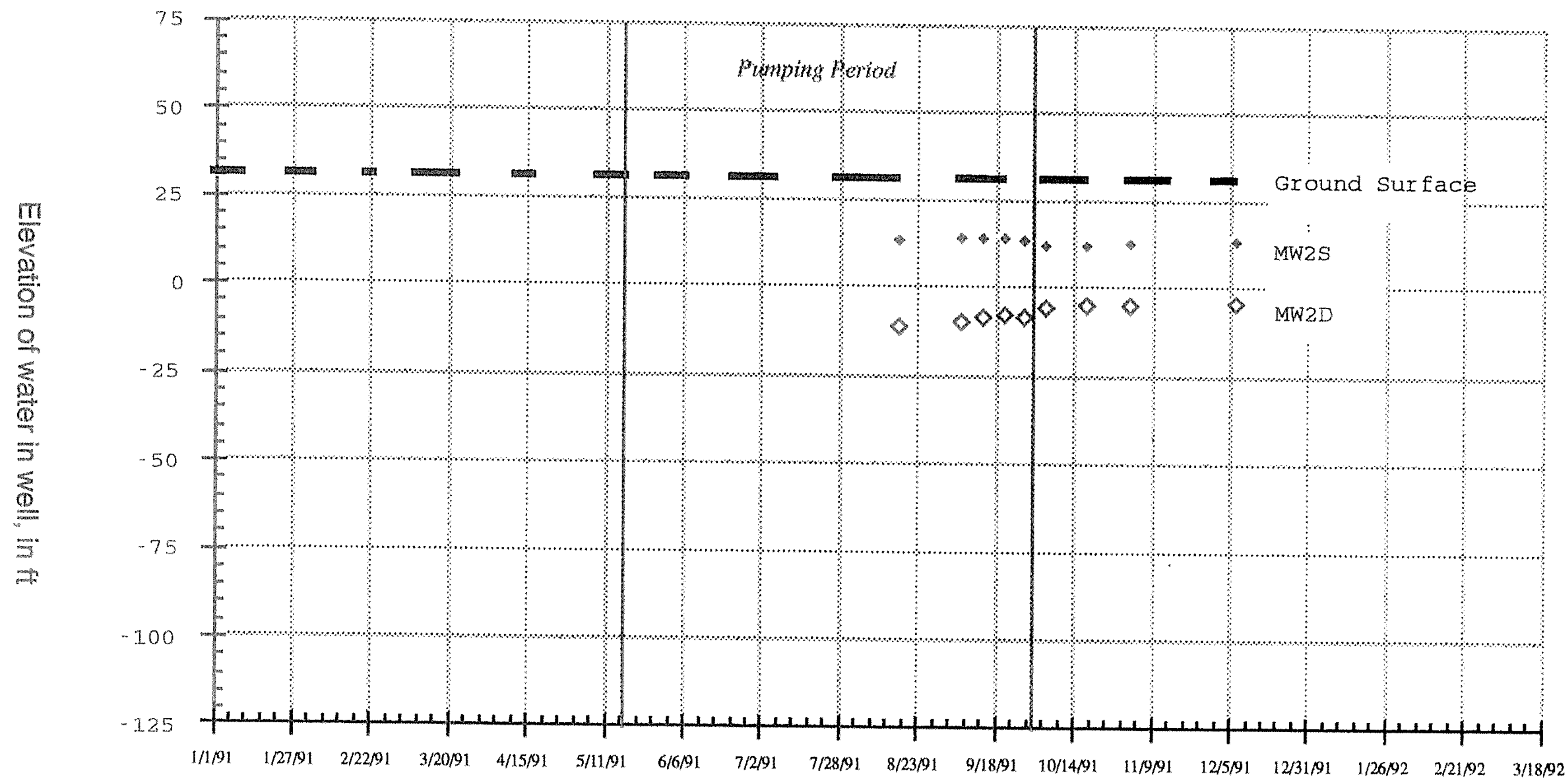


Figure 3-5

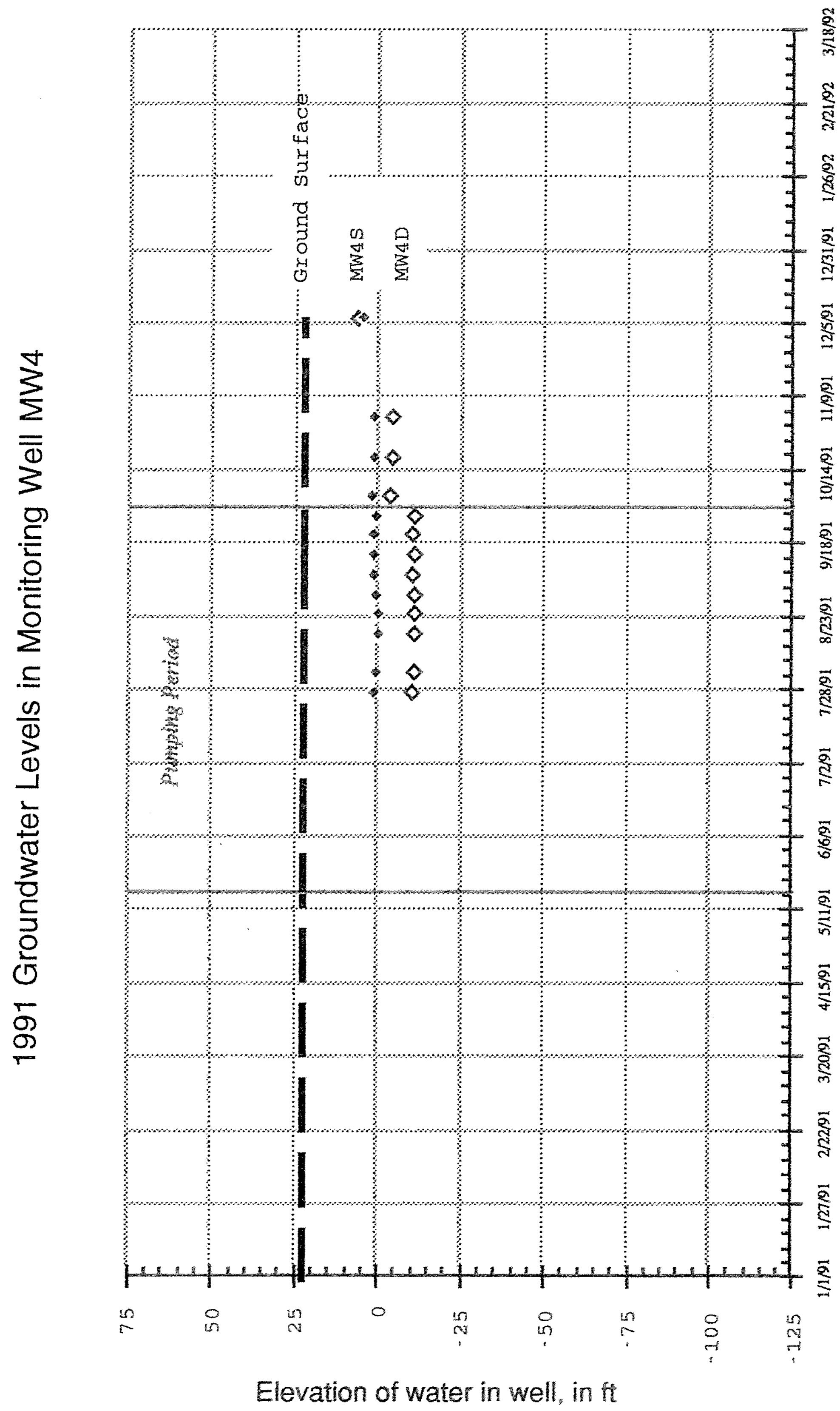

1991 Groundwater Levels in Monitoring Well MW4
Ground Surface
MW4S
MW4D
Pumping Period
75
50
25
0
-25
-50
-75
-100
-125
Elevation of water in well, in ft
1/1/91
1/27/91
2/22/91
3/20/91
4/15/91
5/11/91
6/6/91
7/2/91
7/28/91
8/23/91
9/18/91
10/14/91
11/9/91
12/5/91
12/31/91
1/26/92
2/21/92
3/18/92

Figure 3-6

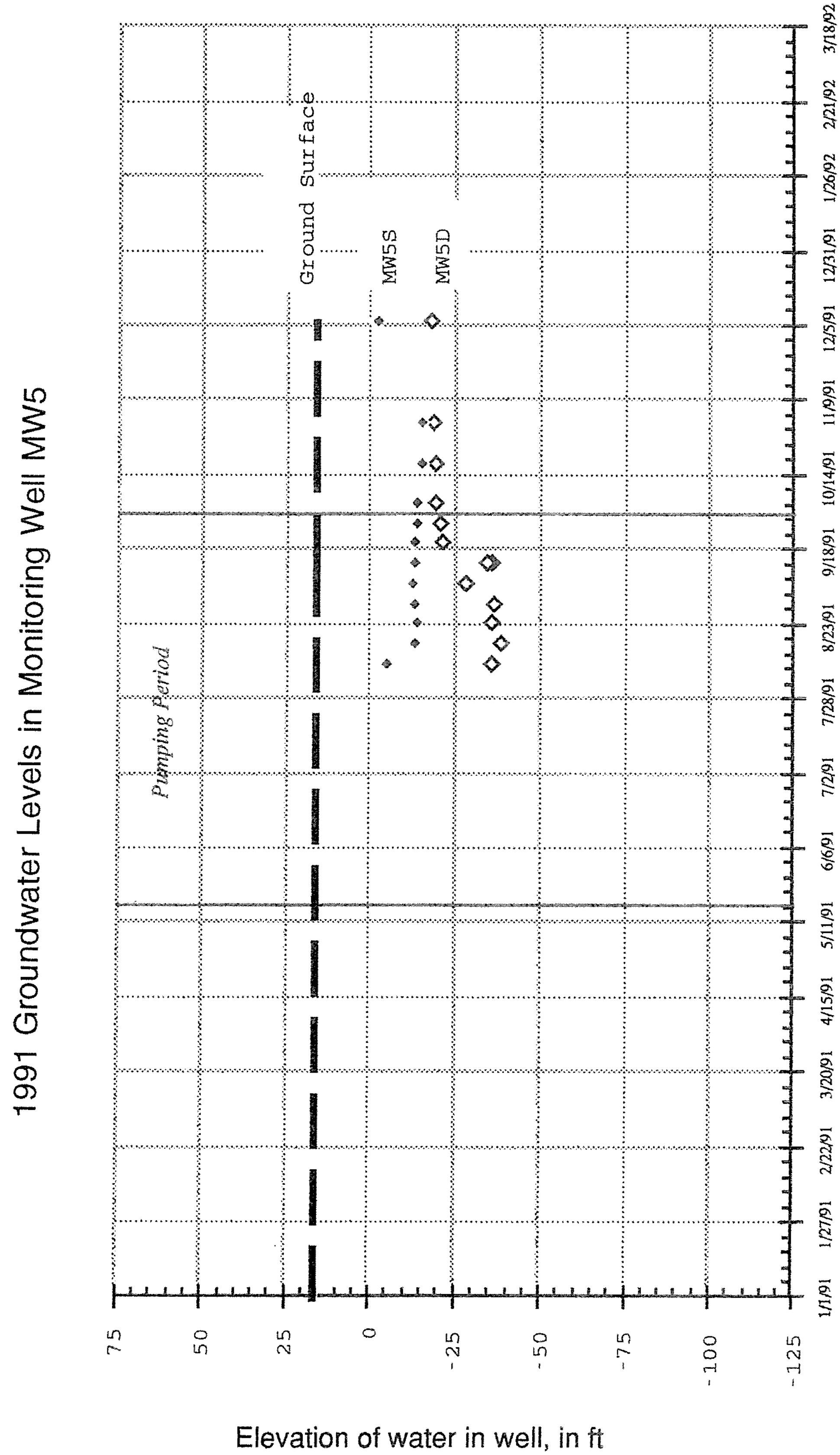
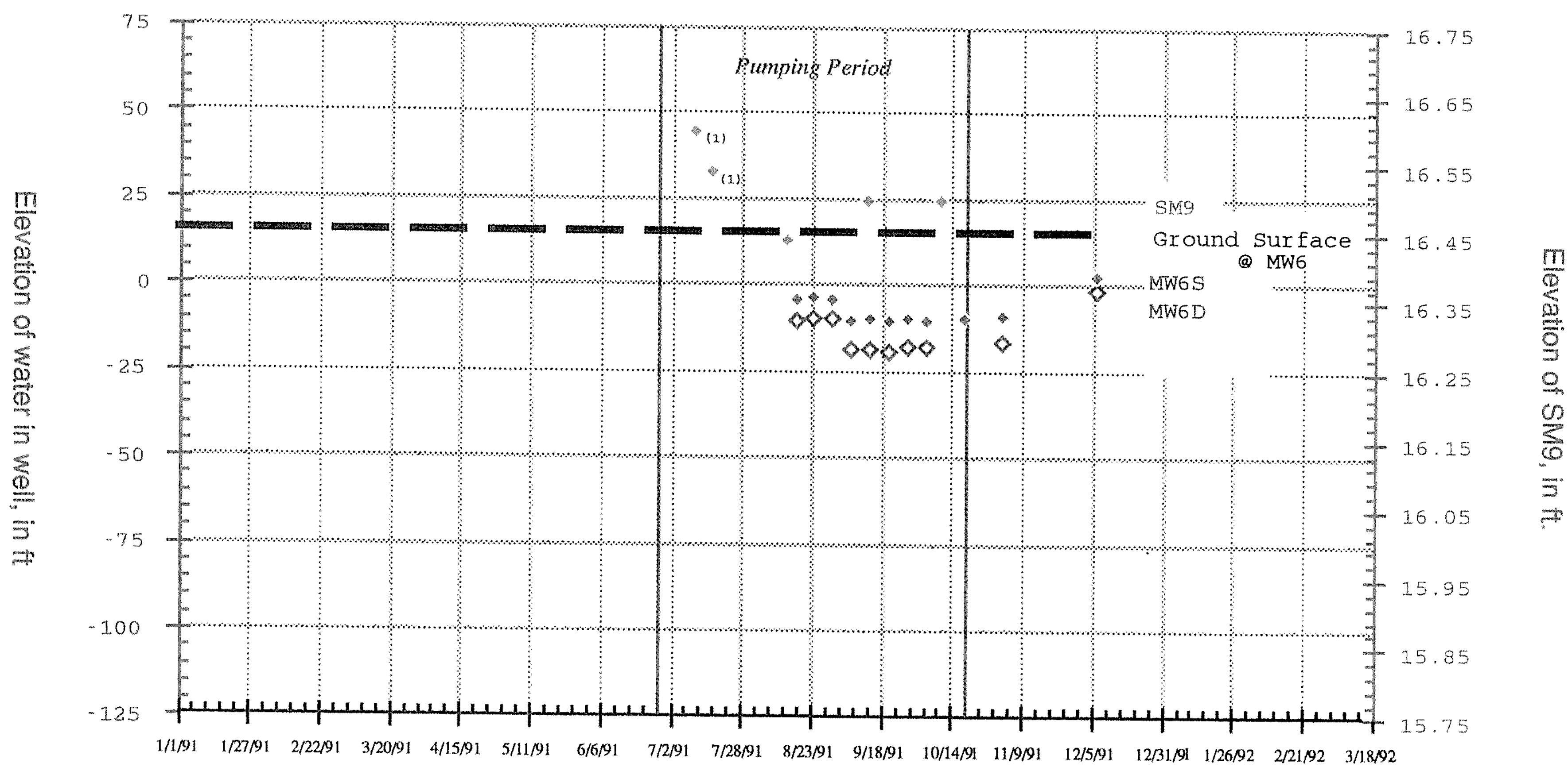

1991 Groundwater Levels in Monitoring Well MW5
Ground Surface
MW5S
MW5D
Pumping Period
75
50
25
0
-25
-50
-75
-100
-125
1/1/91
1/27/91
2/22/91
3/20/91
4/15/91
5/11/91
6/6/91
7/2/91
7/28/91
8/23/91
9/18/91
10/14/91
11/9/91
12/5/91
12/31/91
1/26/92
2/21/92
3/18/92
Elevation of water in well, in ft

Figure 3-7

1991 Groundwater Levels in Monitoring Well MW6 and Elevation of Subsidence Monitor SM9

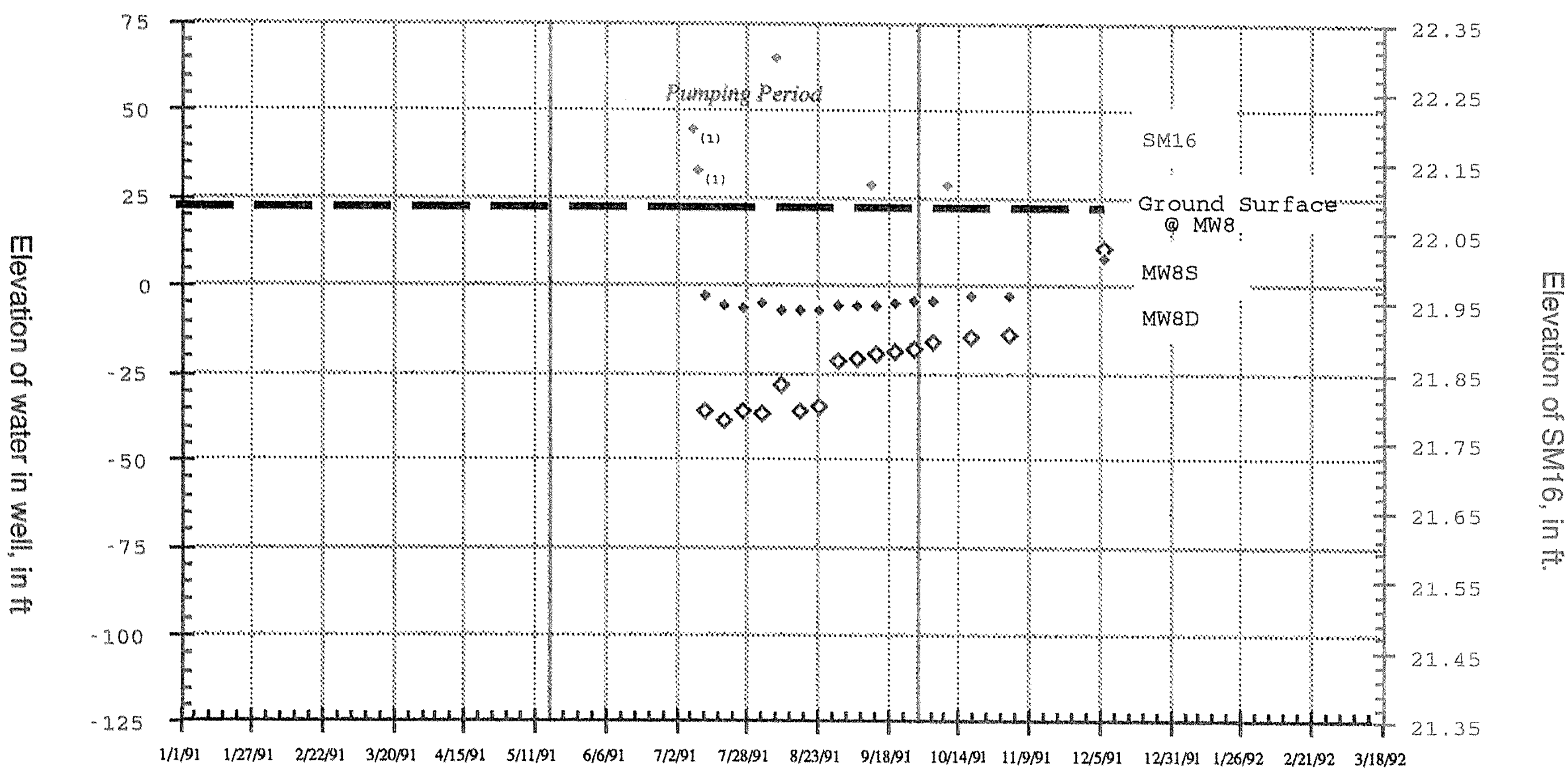


Notes:

(1) Unusually high solar and geomagnetic field activity appears to have had an affect on the accuracy of these observations.

Figure 3-8

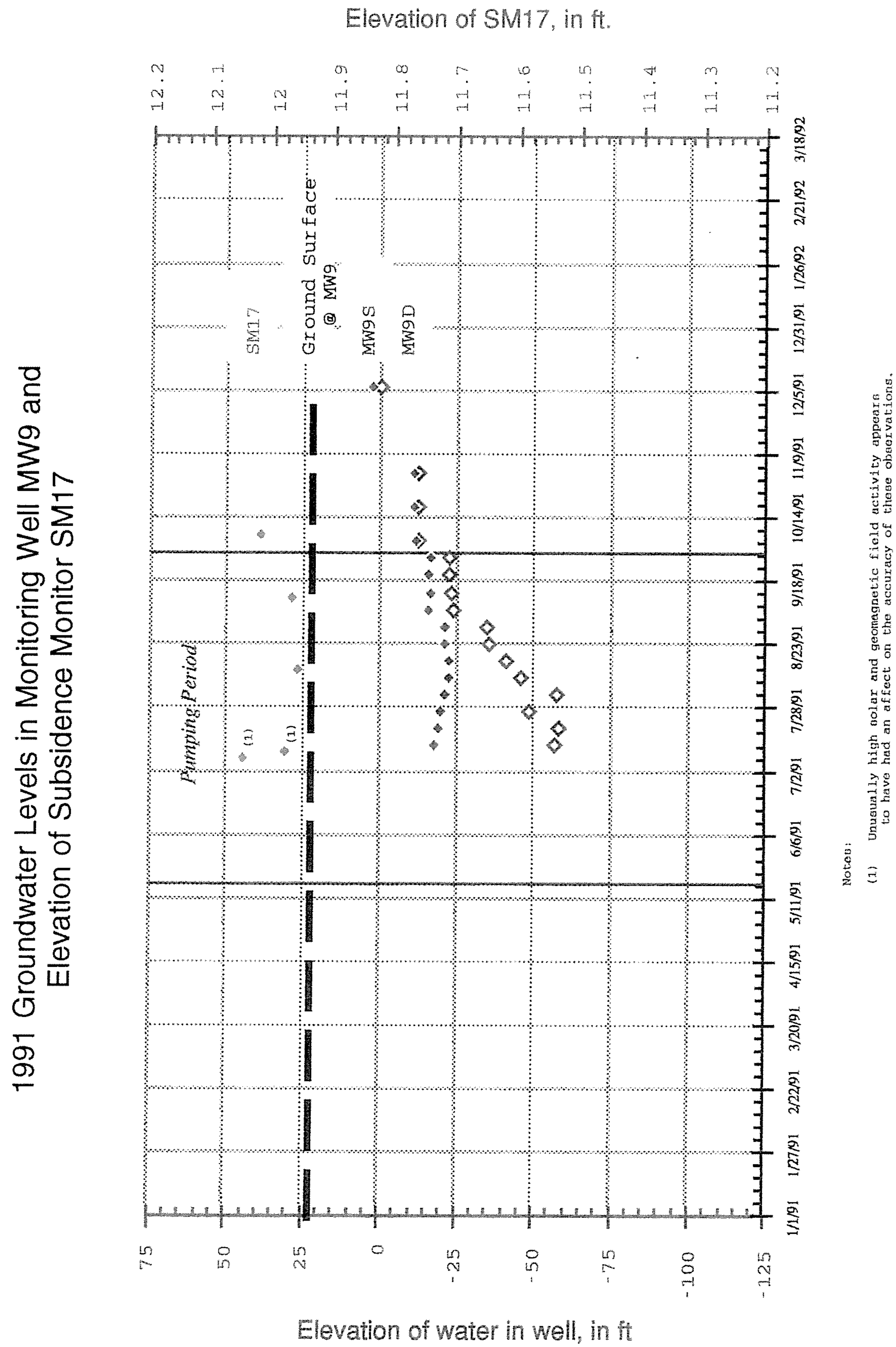
1991 Groundwater Levels in Monitoring Well MW8 and Elevation of Subsidence Monitor SM16



Notes:

(1) Unusually high solar and geomagnetic field activity appears to have had an affect on the accuracy of these observations.

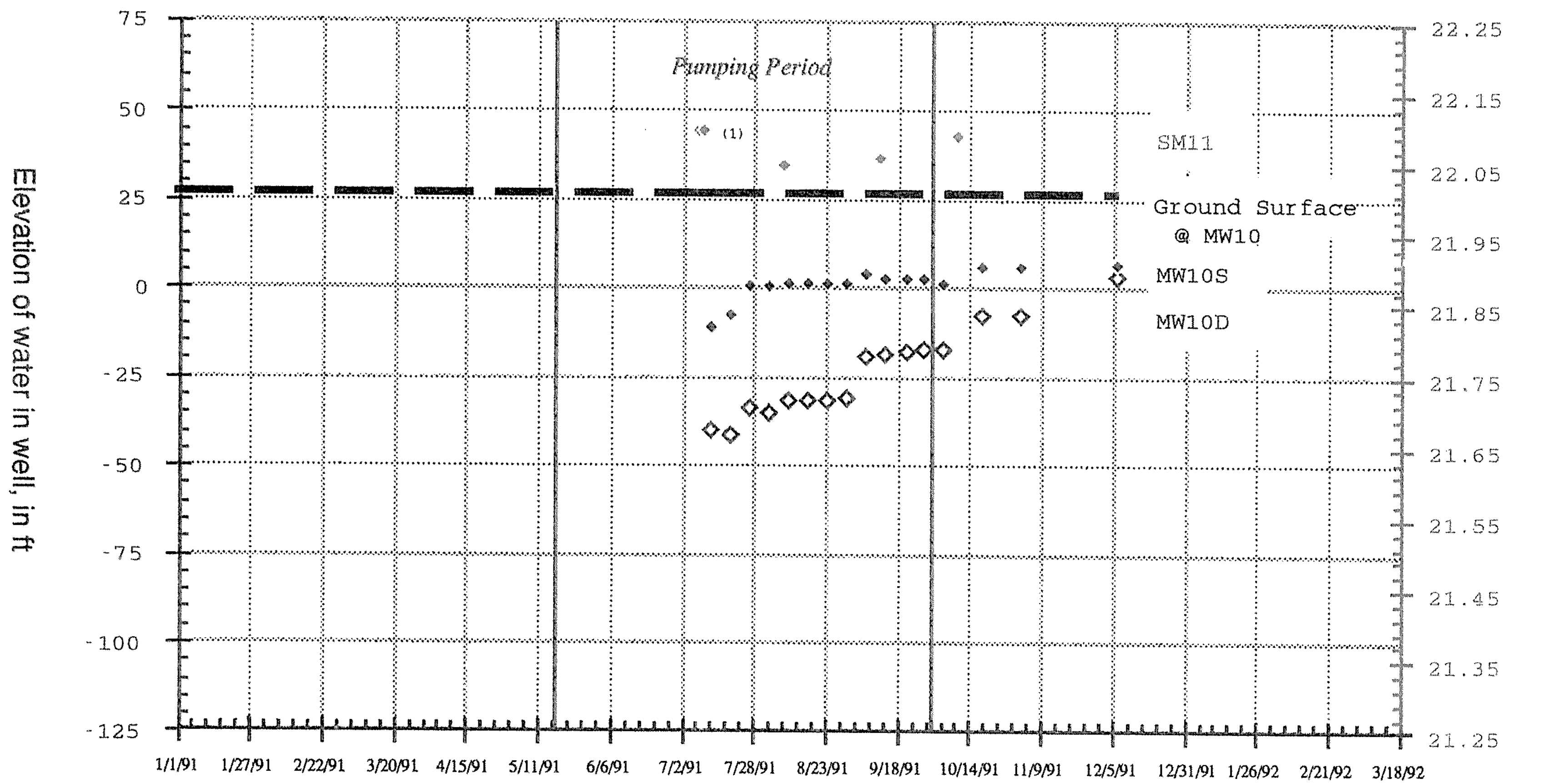
Figure 3-9



1991 Groundwater Levels in Monitoring Well MW9 and Elevation of Subsidence Monitor SM17
Elevation of SM17, in ft.
Elevation of water in well, in ft
SM17
Ground Surface @ MW9
MW9S
MW9D
Pumping Period
(1)
Notes:
(1) Unusually high solar and geomagnetic field activity appears to have had an affect on the accuracy of these observations.

Figure 3-10

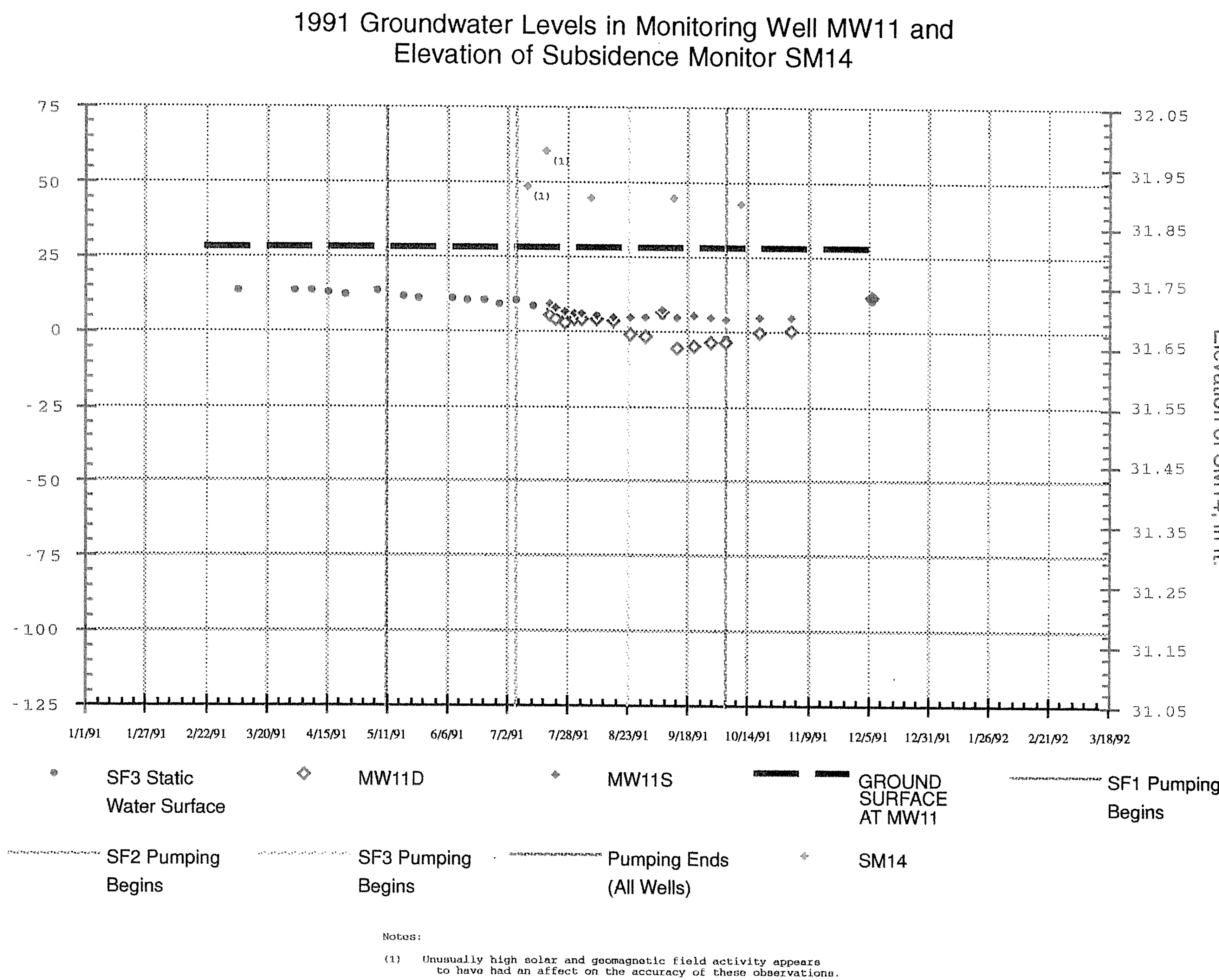
1991 Groundwater Levels in Monitoring Well MW10 and Elevation of Subsidence Monitor SM11



Notes:

(1) Unusually high solar and geomagnetic field activity appears to have had an affect on the accuracy of these observations.

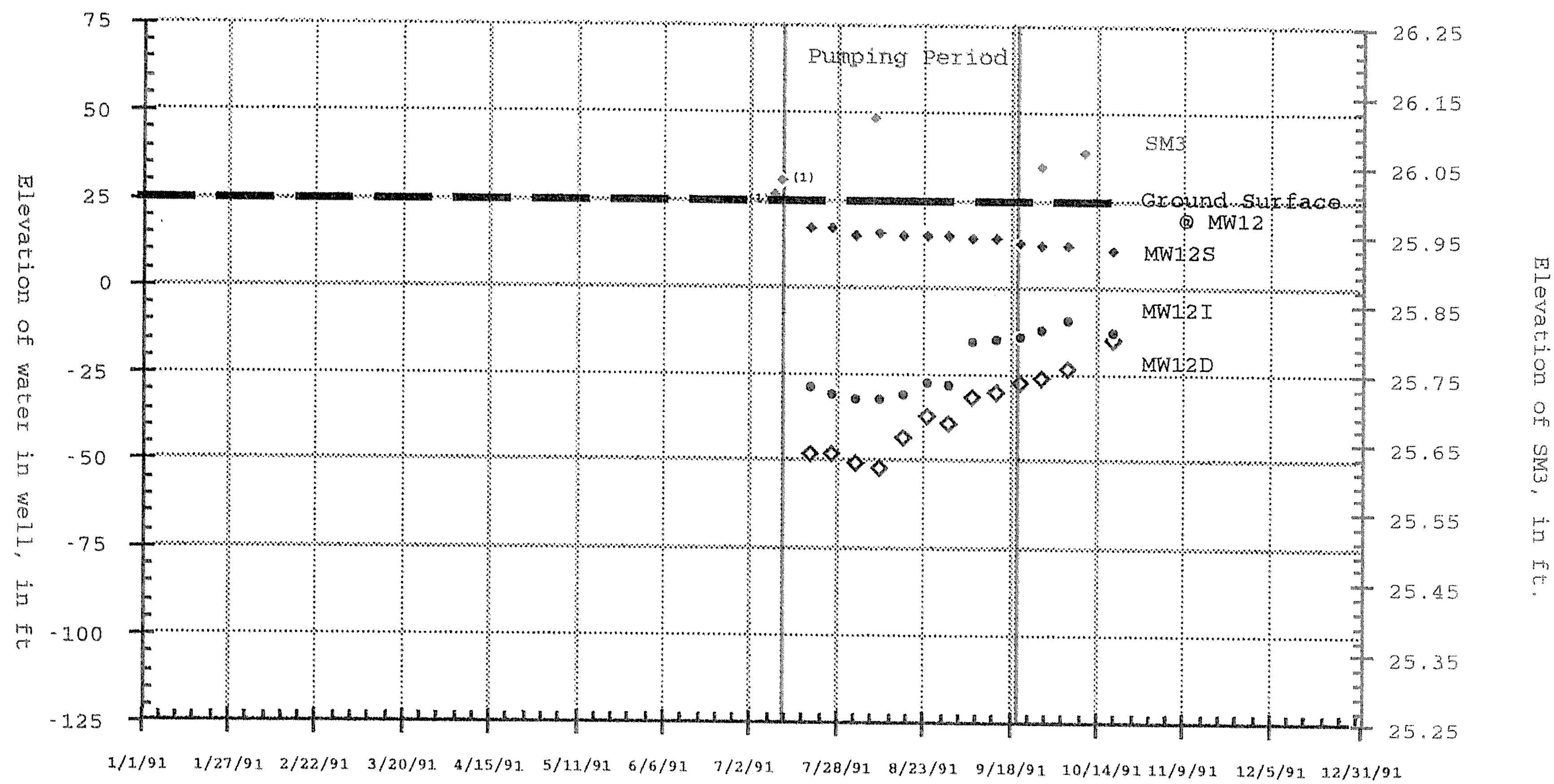
Figure 3-11



1991 Groundwater Levels in Monitoring Well MW11 and
Elevation of Subsidence Monitor SM14
Elevation of water in well, in ft
Elevation of SM14, in ft.
75
50
25
0
-25
-50
-75
-100
-125
32.05
31.95
31.85
31.75
31.65
31.55
31.45
31.35
31.25
31.15
31.05
1/1/91
1/27/91
2/22/91
3/20/91
4/15/91
5/11/91
6/6/91
7/2/91
7/28/91
8/23/91
9/18/91
10/14/91
11/9/91
12/5/91
12/31/91
1/26/92
2/21/92
3/18/92
(1)
(1)
SF3 Static Water Surface
MW11D
MW11S
GROUND SURFACE AT MW11
SF1 Pumping Begins
SF2 Pumping Begins
SF3 Pumping Begins
Pumping Ends (All Wells)
SM14
Notes:
(1) Unusually high solar and geomagnetic field activity appears to have had an affect on the accuracy of these observations.

Figure 3-12

1991 Groundwater Levels in Monitoring Well MW2

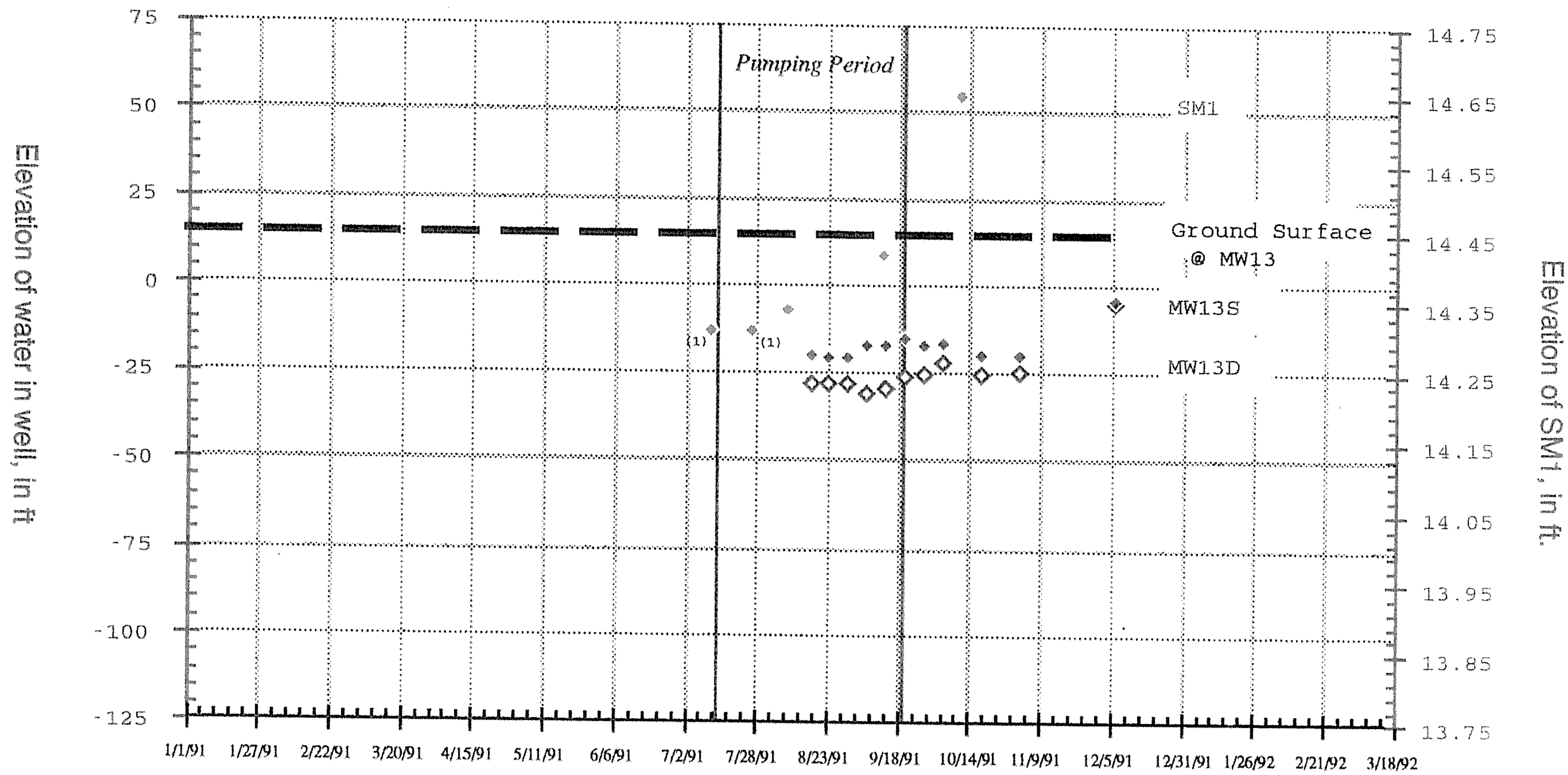


Notes:

(1) Unusually high solar and geomagnetic field activity appears to have had an affect on the accuracy of these observations.

Figure 3-13

1991 Groundwater Levels in Monitoring Well MW13



Notes:

(1) Unusually high solar and geomagnetic field activity appears to have had an affect on the accuracy of these observations.

Figure 3-14

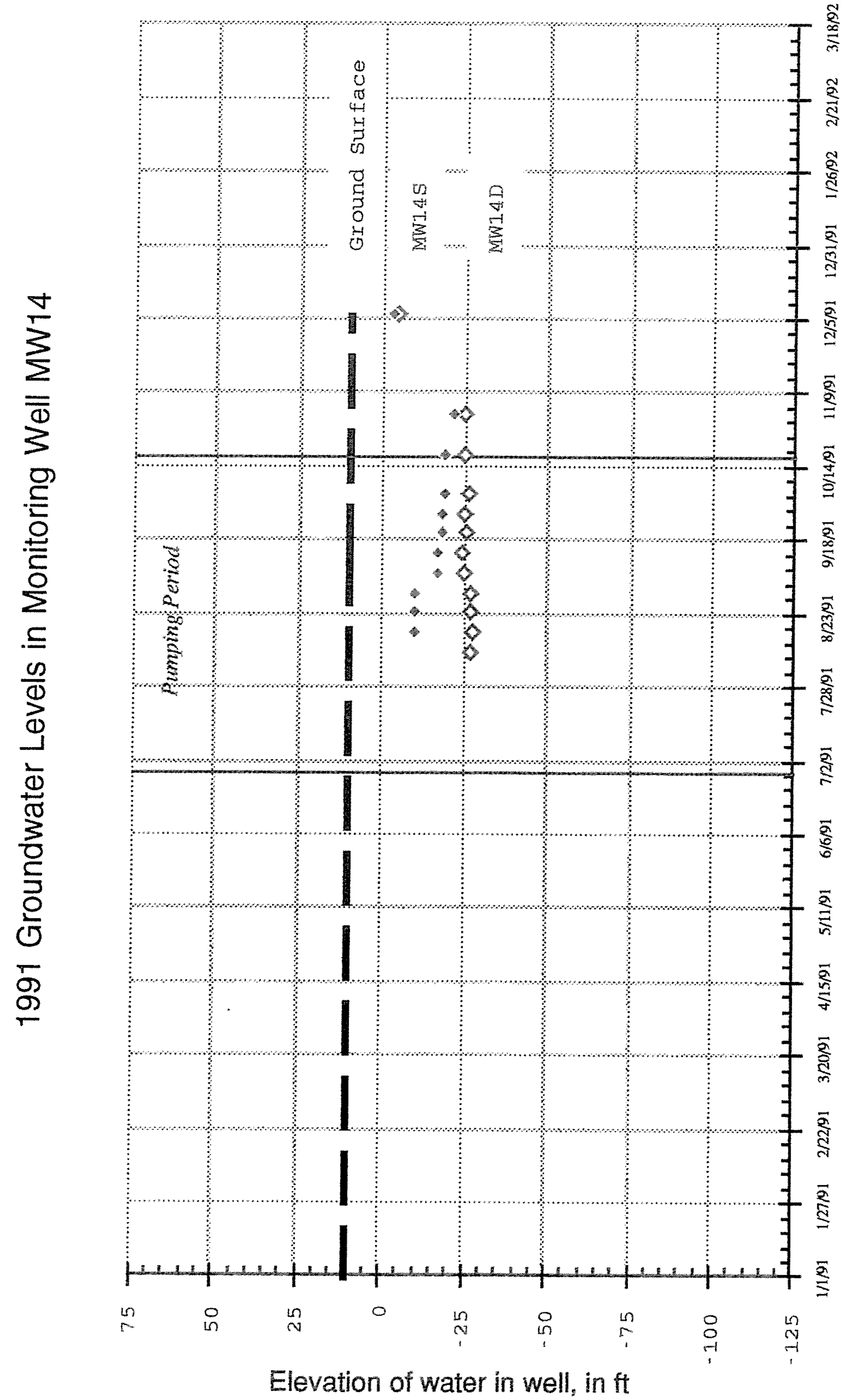

1991 Groundwater Levels in Monitoring Well MW14
Ground Surface
MW14S
MW14D
Pumping Period
75
50
25
0
-25
-50
-75
-100
-125
Elevation of water in well, in ft
1/1/91
1/27/91
2/22/91
3/20/91
4/15/91
5/11/91
6/6/91
7/2/91
7/28/91
8/23/91
9/18/91
10/14/91
11/9/91
12/5/91
12/31/91
1/26/92
2/21/92
3/18/92

Figure 3-15

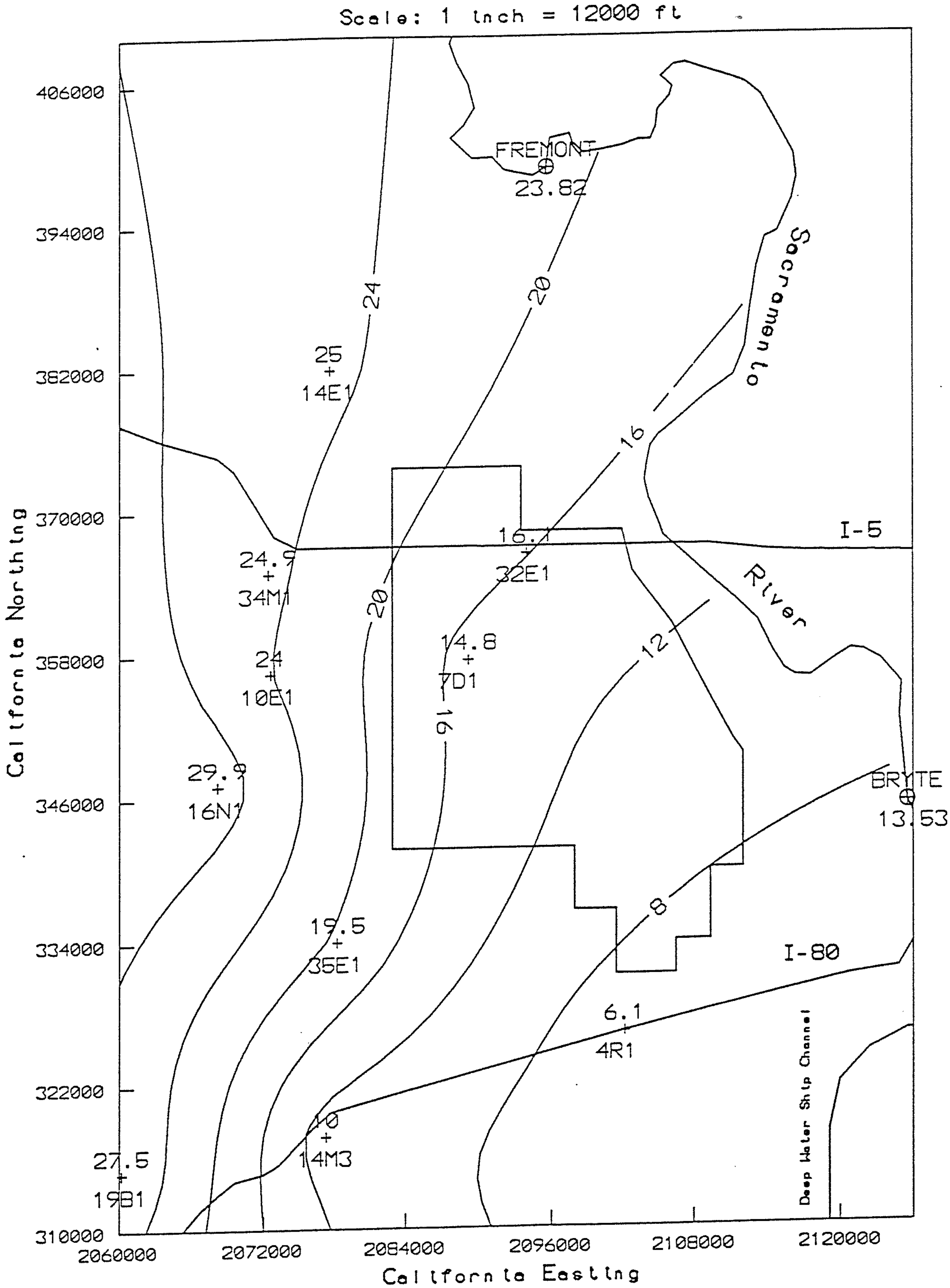


Figure 3-16. Groundwater Elevation Contours.
Eastern Yolo County, April, 1989.

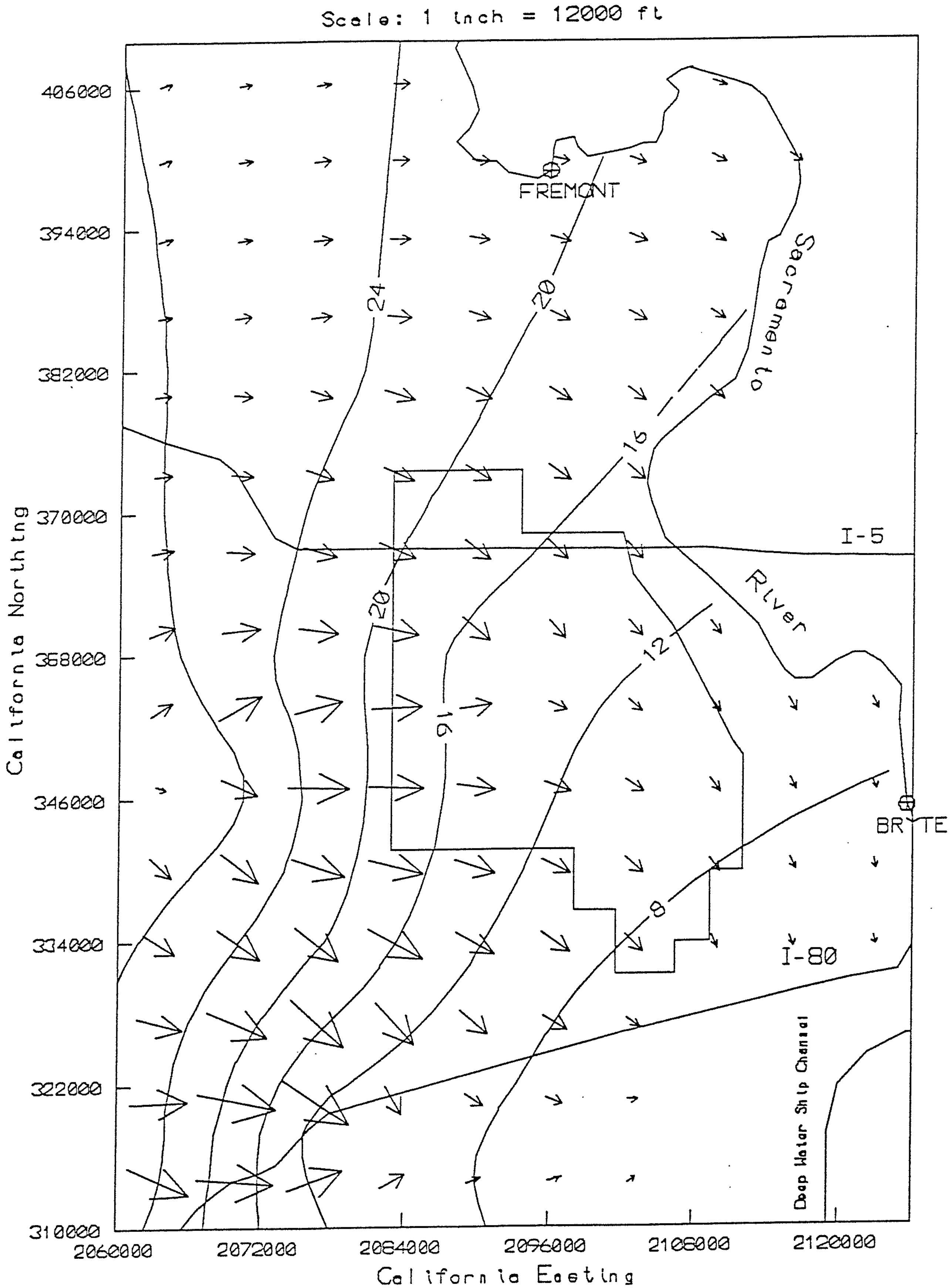


Figure 3-17. Approximate Directions of Groundwater Flow. Eastern Yolo County, April, 1989.

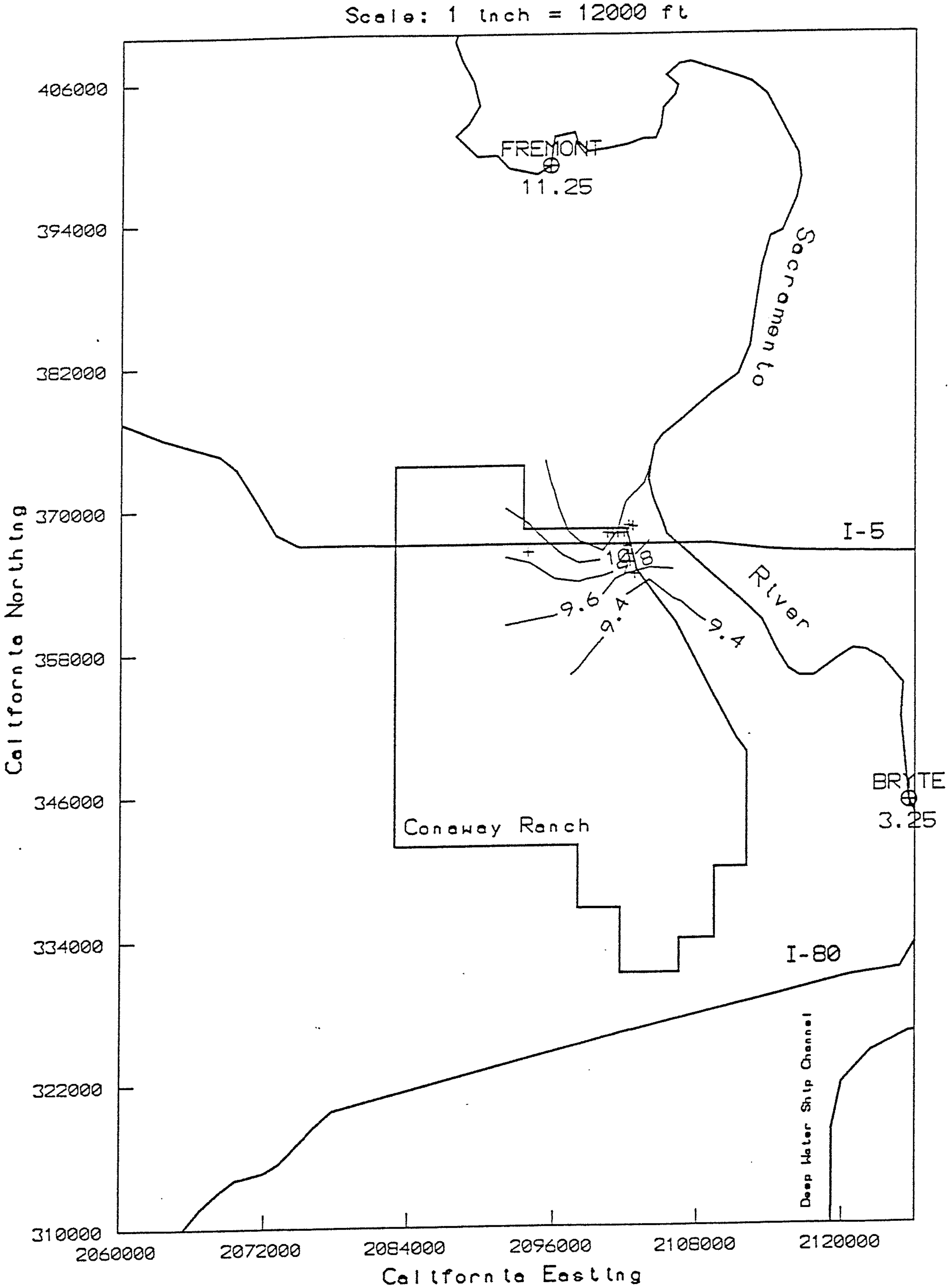


Figure 3-18. Groundwater Elevation Contours.
Eastern Yolo County, April 15, 1991.

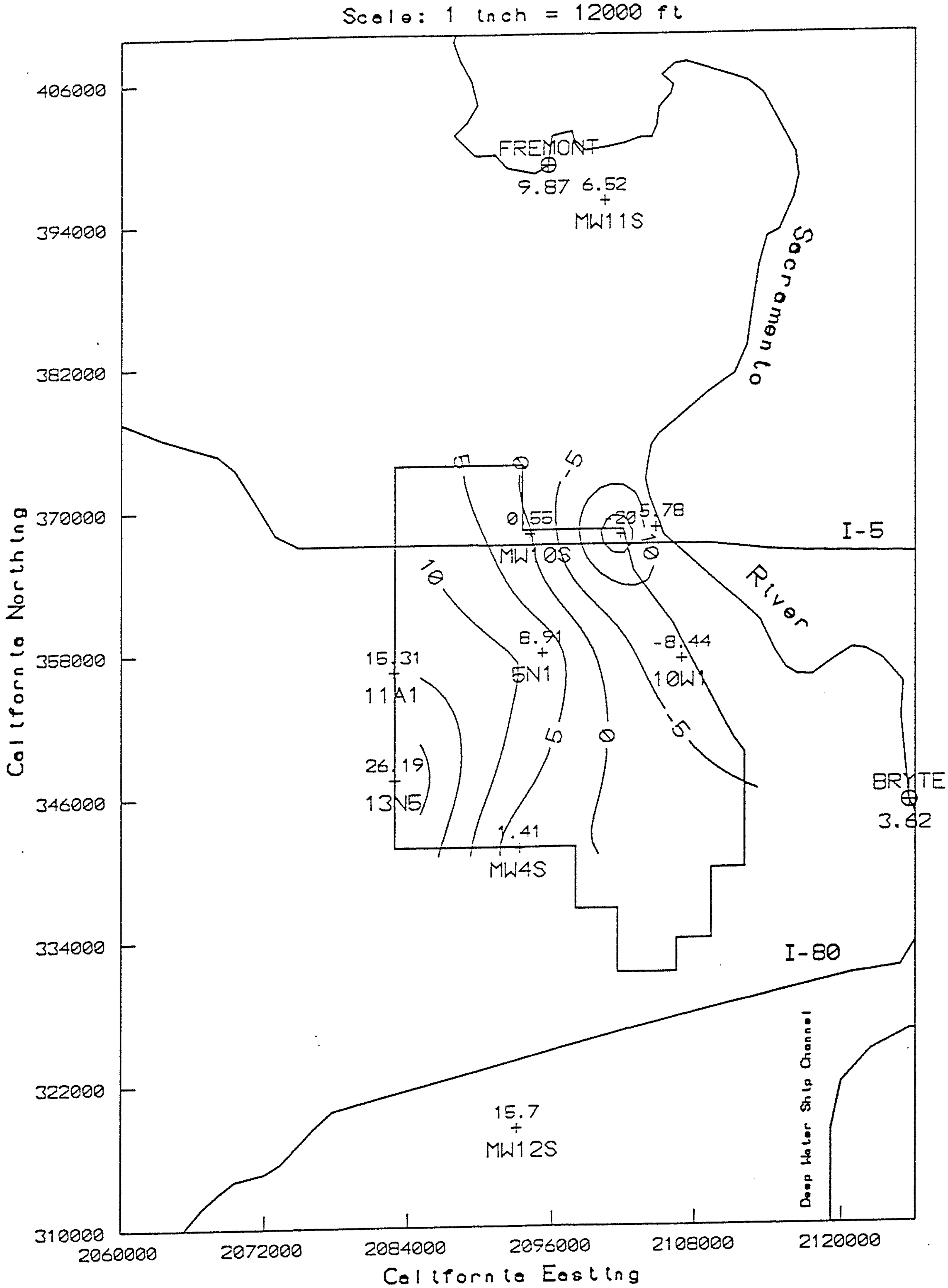


Figure 3-19. Shallow Zone Groundwater Elevation Contours.
Eastern Yolo County, July 26, 1991.

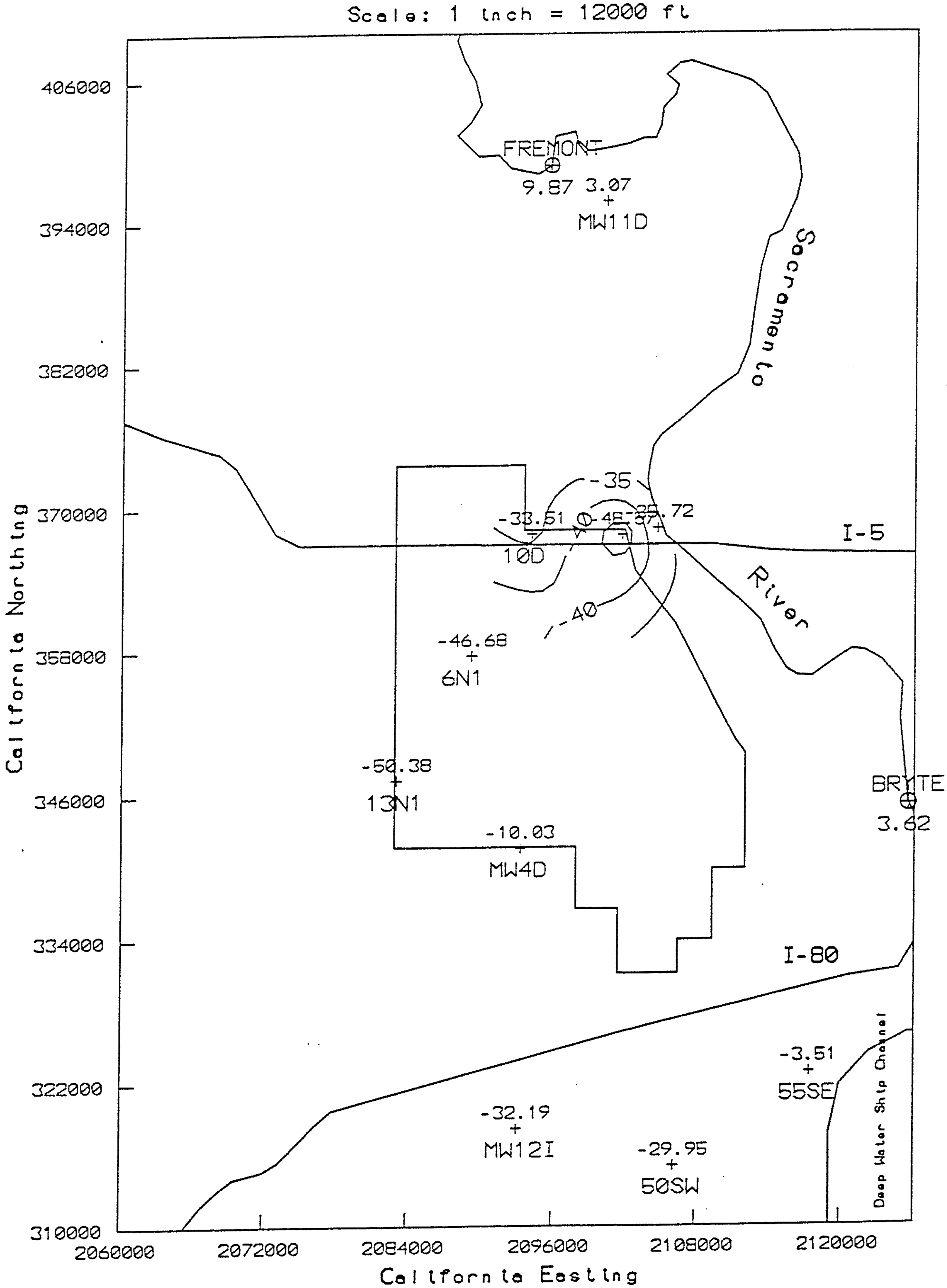


Figure 3-20. Deeper Zone Groundwater Elevation Contours.
Eastern Yolo County, July 26, 1991.

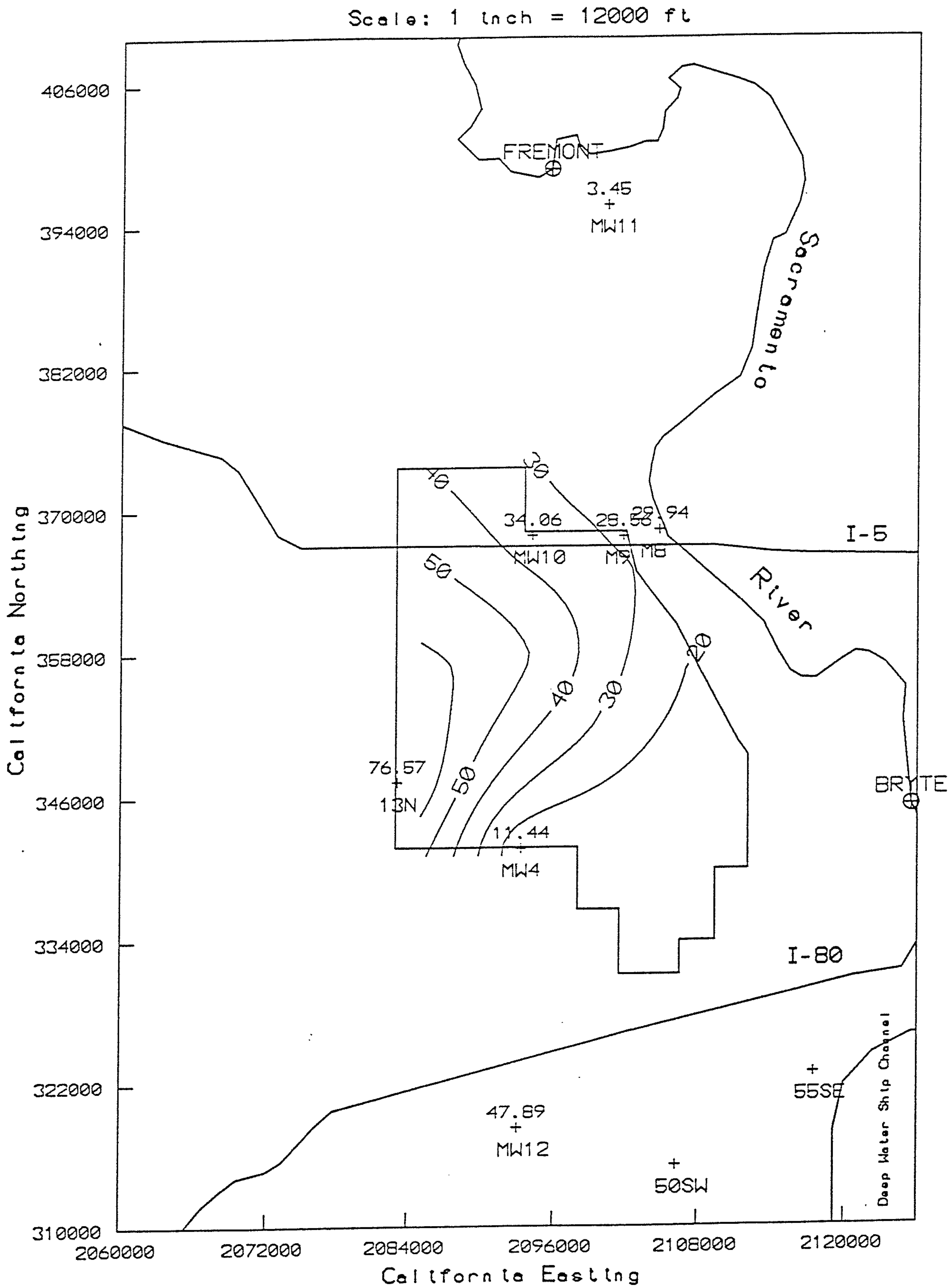


Figure 3-21. Difference in Groundwater Elevations. Between Shallow and Deeper Zones, July 26, 1991.

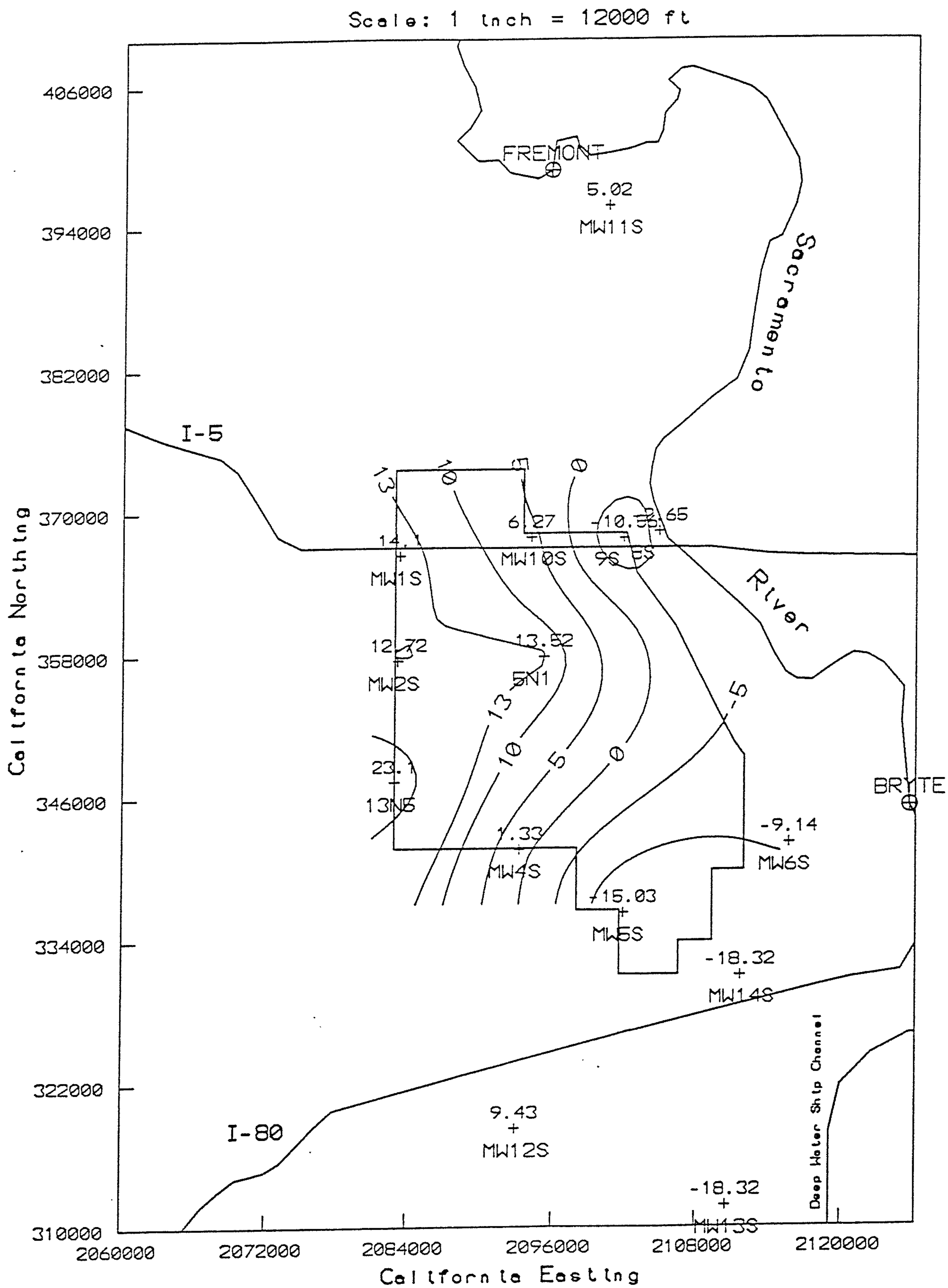


Figure 3-22. Shallow Zone Groundwater Elevation Contours.
Eastern Yolo County, October 18, 1991.

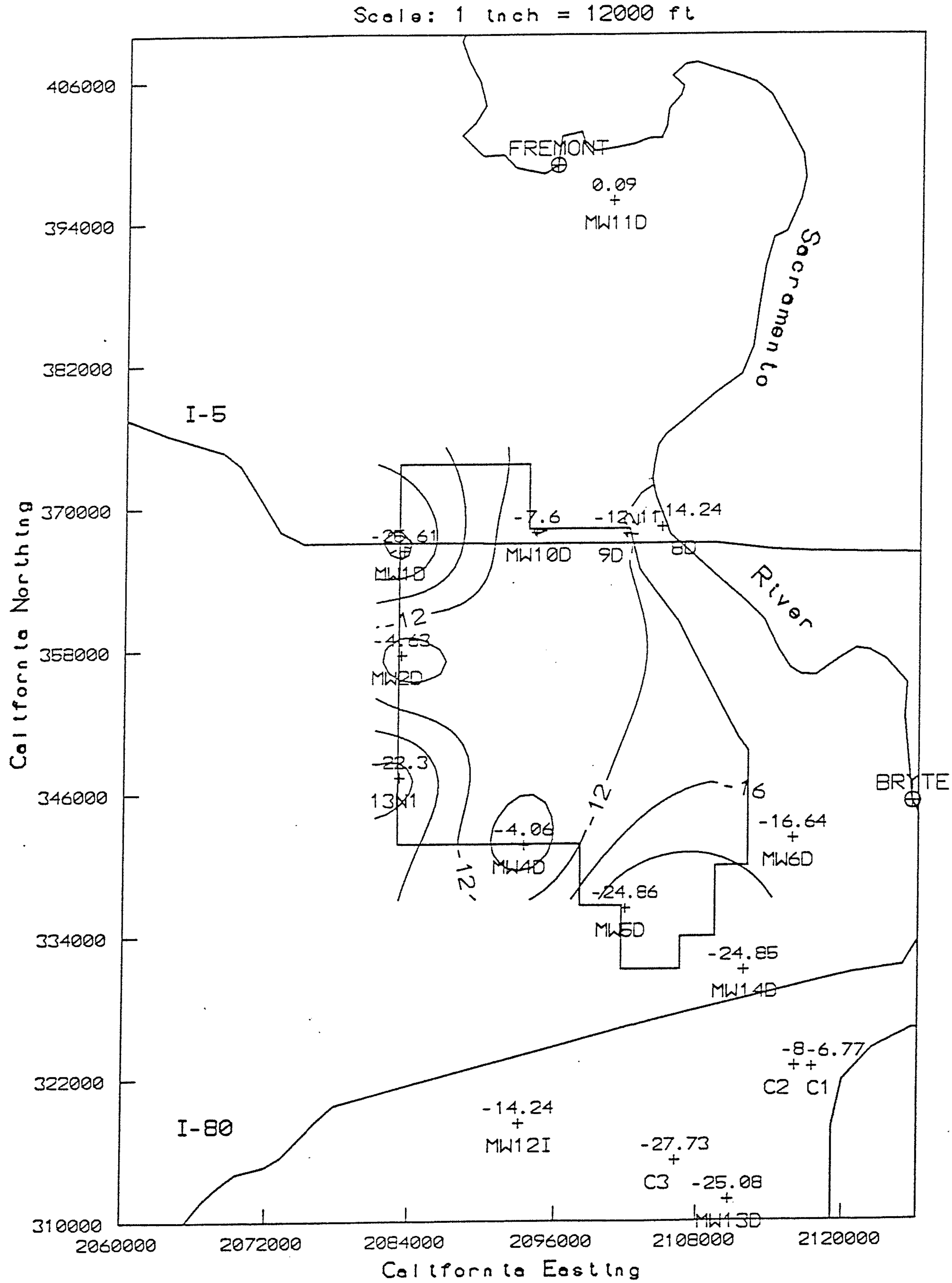


Figure 3-23. Deeper Zone Groundwater Elevation Contours.
Eastern Yolo County, October 18, 1991.

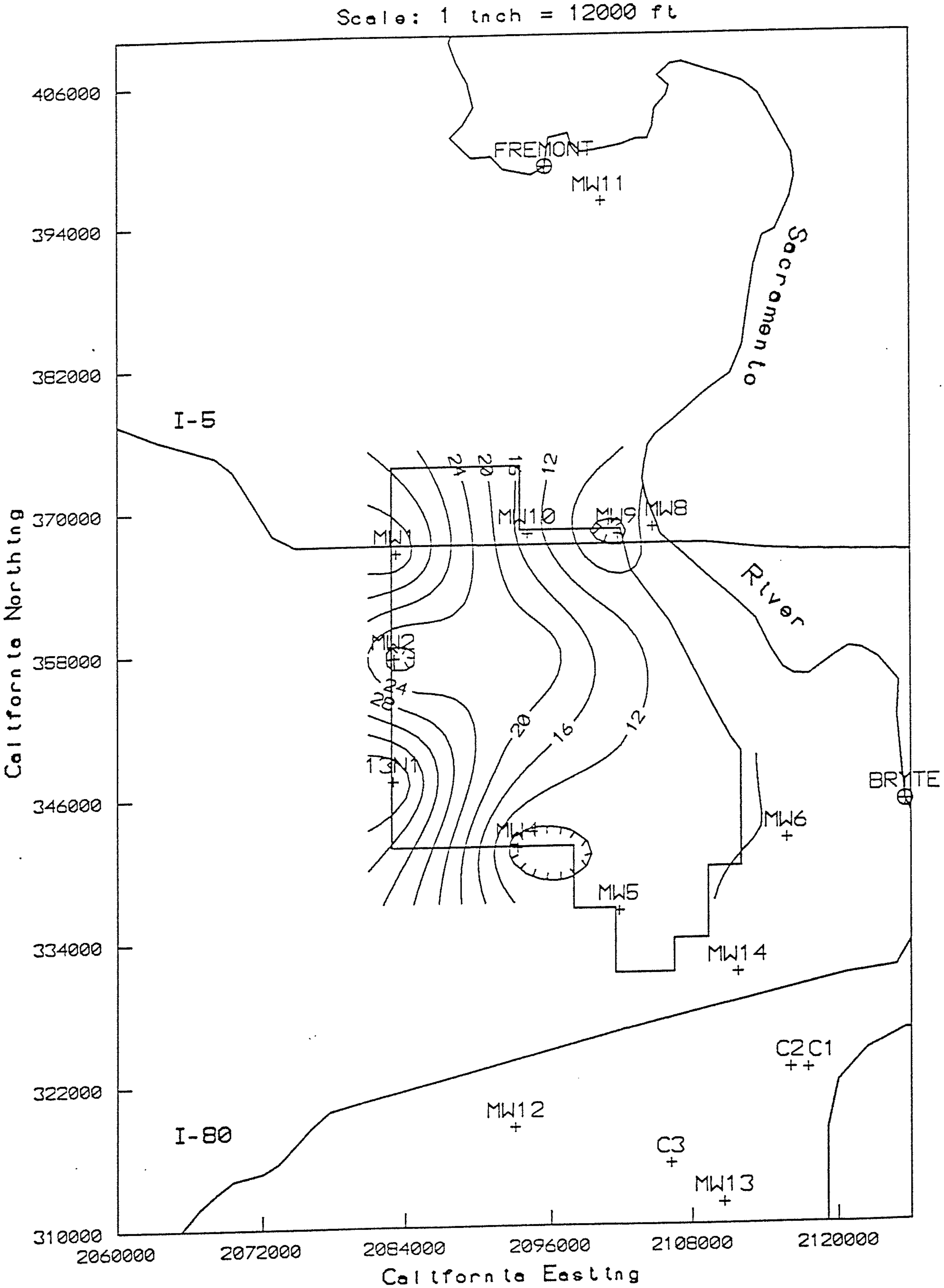


Figure 3-24. Difference in Groundwater Elevation Contours.
Eastern Yolo County, October 18, 1991

SECTION 4 - SUBSIDENCE

Based on data available to date, four quite unrelated types of land subsidence probably are occurring in the area of this investigation in eastern Yolo County. One of the important objectives of this study is to differentiate these types of subsidence and define the probable causes of each. Listed in descending order of magnitude and depth of occurrence, these types of subsidence and probable causes are:

(1) The compaction of compressible water-bearing beds in the relatively shallow unconfined or semi-confined aquifer system, due to shallow water-level declines. These beds often expand significantly when the shallow water levels recover.

(2) The compaction of deeper formations in the semi-confined and confined aquifer system due to water-level declines caused by ground-water pumping. Usually there is little rebound when water levels in these semi-confined and confined formations recover.

(3) Compaction of deep formations due to the extraction of fluids from deep gas-field.

(4) Tectonic down-warping of the bedrock basement along the valley trough.

The combined effect of these processes results in a change in elevation of bench marks on the land surface, which may reflect subsidence or rebound. In the area of this study only the first three of the above processes are: (a) induced by man's activities, and thus can be regulated and controlled, and (b) believed of sufficient magnitude and rates of change to be of significance in this study.

The mechanics of aquifer systems and processes of land subsidence caused by heavy groundwater pumping in California have been studied by the U.S. Geological Survey for more than thirty years. Precise field measurement to study these processes began in the San Joaquin Valley in the mid-1950's, in the Sacramento Valley in the early 1970's, and in the Conaway Ranch study area in mid-1991. Many of the techniques of data collection and interpretation being used in this Conaway Ranch investigation have been adopted from these earlier USGS studies. For additional background information on these and other areas, numerous published USGS reports are available.

CONCEPTS DERIVED IN EARLIER SUBSIDENCE STUDIES

After years of experimentation, three types of field measurements in a heavily pumped groundwater basin have proved most effective in obtaining the data needed to: (1) differentiate the various types of natural and induced subsidence, (2) define the relationship between water-level change and subsidence, and (3) calculate the formation parameters needed to evaluate past and future subsidence in an area. These types of measurements, all now in progress in eastern Yolo County, are:

(1) Periodic surveys of change in elevation of a network of surface bench marks, referenced to a datum outside the subsidence area. Prior to this study, most of the vertical-control surveys were by spirit leveling. In this study, satellite surveys (GPS) proved to be the most cost effective.

(2) Frequent water-level measurements in an array of observation wells, preferably of deep, intermediate and shallow depth, from which changes in vertical compressive stresses in the formation can be calculated.

(3) Continuous extensometer records (described later), from which the progressive change in vertical thickness of a sequence of beds, from the surface to some predetermined depth, can be calculated.

The net change in thickness of all beds from the land surface to a predetermined depth at a location is effectively measured by an extensometer of the type shown in Figure 4-1. Modified versions of this type extensometer have been maintained by the USGS east of Zamora since mid-1988. A version, constructed by the California Department of Water Resources, is now operating at the Conaway Ranch headquarters. When functioning properly, an extensometer of this type can accurately measure formation-thickness changes, during both the compaction and expansion, of a few thousandths of a foot.

In each of the areas studied, a close correlation has been observed between water-level fluctuations in deeper pumped aquifers and the subsidence observed on the land surface. This correlation is particularly meaningful and the surface changes most significant whenever groundwater levels are pumped below prior historic low levels. Depending on the compressibility, depth, degree of confinement, and reconsolidation stress-range of the deposits, the compaction that occurs may be: (1) largely elastic, independent of time, and reversible, or (2) principally nonelastic and non-recoverable, and apparently resulting from a rearrangement and densification of the granular structure of the deposits.

As an example of the results obtained during a 6-year period in the San Joaquin Valley, Figure 4-2 shows a correlation between land subsidence, compaction, water-level fluctuations, and change in effective stress at a recorder site near Pixley. The lower graph shows the hydrographs of the confined (lower) and overlying unconfined aquifers from which the changes in effective stress (in feet of water head) in the confined aquifer system are calculated (see center graph; from Lofgren, 1968, p.B219-B225). The record of subsidence of bench mark Q945 at the Pixley site, as measured by spirit leveling from a distant stable reference bench mark, is shown in the top graph. During this 6-year period, measured compaction to a depth of 740 feet--deeper than most irrigation wells in the area--accounted for about 75 percent of the total subsidence. Thus, 25 percent of the subsidence was due to compaction of water-bearing deposits below 740 feet, or even deeper effects.

A comparison of the compaction rate with water-level fluctuations in Figure 4-2 indicates that compaction begins each year during the period of rapid water-level decline, continues through the pumping season, and ceases during the early stages of head recovery. Although the causal relationship of compaction to water-level fluctuations is apparent, the relationship between compaction and the calculated changes in effective stress is most revealing. Of special interest is the position of the straight line C-C'(center graph). During each seasonal cycle of pumping, most of the compaction occurred when the effective-stress curve was below the C-C' line (that is, when the effective stress was greater). Little or no compaction or rebound occurred when the effective stress curve was above (stress less than) the C-C' line. Compaction continued each year for several weeks after the date of maximum effective stress and, in all instances, ceased before the effective stress in recovery reached the line C-C'. In this context, the C-C'line, seen here to increase with time as seasonal water-level lows continue to decline, represents a preconsolidation stress which must be exceeded before significant permanent compaction occurs.

As indicated above, at locations where several years of water-level and extensometer records are available, as at a site east of Zamora since 1988 and soon at the Conaway Ranch site, the compressibility and storage parameters of the aquifer system can be calculated, and also the unit compressibilities of the various aquifers and aquitards can be approximated. Also, at these sites, by subtracting the measured compaction from the measured subsidence, the amount of subsidence occurring due to changes below the bottom-hole anchor can be approximated.

SUBSIDENCE IN EASTERN YOLO COUNTY

During the 1960's it was recognized that significant subsidence had occurred in several areas of heavy groundwater pumping in eastern Yolo County. However these early surveys gave little definition of the areal extent or rates of subsidence in these areas. Also, during the 1970's and again in 1981, local leveling along a line east from Zamora, indicated as much as 4.5 feet of subsidence had occurred in an area between Zamora and Knights Landing (Figure 4-3).

In 1987 a reach of a first-order level line between Madison, Woodland, and Davis, was resurveyed. Also, the graph shown in Figure 4-4 was prepared showing profiles of subsidence of bench marks along this line between various surveys between 1935 and 1987. As shown, little subsidence has occurred in areas where the Tehama Formation outcrops and the effects of ground-water pumping are minimal. Between Woodland and Davis, however, 2.0 to 2.5 feet of subsidence has been measured, probably due largely to the continuing decline of ground-water levels.

At a few bench-mark locations where water-level data were available, a correlation was made between subsidence trends and water-level changes. Figure 4-5 shows such a correlation in the town of Davis. Here a lack of leveling data from 1938 to 1963 and 1969 to 1987 makes defining the subsidence trend imprecise. It appears, however, that the rate of subsidence has continued to slow since 1979 while the water level in Well C has continued to rise.

ANALYSIS OF EXTENSOMETER DATA FROM A SITE EAST OF ZAMORA

A sensitive recording borehole extensometer, a modified version of the type shown in Figure 4-6 and anchored at a depth of 1,000 feet, has been maintained by the U.S. Geological Survey since mid-1988 at a site 3 miles southeast of Zamora (11N/1E-24Q). This Zamora site is about 12 miles northwest of the State's newly installed Conaway Ranch extensometer (9N/3E-8C) discussed later. Although the hydrogeologic conditions and pumping regime at the Zamora site are different, it is believed that the Zamora aquifer system characteristics, as observed in the water-level and compaction records, are typical of the conditions at the Conaway Ranch site and that similar records will be recorded at the Conaway site during the next several years.

Figure 4-7 shows the three-year correlation of measured compaction (in the 18-1,000 foot depth zone) and water-level fluctuations (in the 180-200 foot depth zone) at the Zamora site, based on provisional data collected and plotted by the USGS. As shown, the compaction of the aquifer system at the Zamora site closely parallels the water-level fluctuations, during both the pumping-drawdown and non-pumping/recovery limbs of the annual water-level cycle. This is in marked contrast to conditions at Pixley (Figure 4-2), where virtually no expansion or rebound of the aquifer system occurred during the period of water-level recovery each year.

As noted in Figure 4-7, the amount of compaction during the pumping season increased from about 0.35 foot in 1989 to 0.46 foot in 1990, while the expansion of the aquifer system these years after nearby pumps turned off decreased from 0.19 foot (54 percent of compaction) in 1989 to 0.16 foot (35 percent of the compaction) in 1990. Thus, the non-recovered compaction (compaction minus rebound) increased from 0.16 foot in 1989 to 0.32 foot in 1990, while winter high water-levels each year declined only 2 feet and 12 feet, respectively. The 0.48 foot of non-recovered compaction, represents the net changes in formations thickness to a depth of 1,000 feet, and does not consider possible changes that might be occurring at depths greater than 1,000 feet.

As noted in Figure 4-7, the 0.48 foot of non-recovered compaction at the Zamora site occurred during the pumping season, and probably mostly during the few weeks each year when pumping drawdowns were greatest. This 0.48 foot of non-recovered compaction represents groundwater squeezed from the aquifer system by increased loading stresses caused by the water-level decline. It is commonly referred to as "water of compaction". Thus, 0.48 foot of "water of compaction", or 0.48 acre-foot of groundwater per acre of land, was mined from the aquifer system in these two years. This is a non-renewable one-time source of groundwater supply. It also represents permanent, non-recoverable subsidence of the land surface at this site.

Figure 4-7 suggests little or no time delay between the applied stress (water level) and the resulting strain (compaction or rebound). This is most easily observed during the winter highs and the summer lows of the respective curves each year. This close correlation and the large percentage of rebound (discussed above), suggests that the effects of dewatering and refilling of rapid-draining, shallow, unconfined deposits of the aquifer system dominate the extensometer record at the Zamora site during this 3-year period of record. This is not unexpected at the Zamora site, because a heavily pumped nearby irrigation well is relative shallow.

Most of the non-recovered compaction at the Zamora site is probably caused by drawdown effects of deeper wells and the compaction of deeper fine-grained water-bearing beds. Thick, fine-grained beds in the deeper confined aquifers can compact only as rapidly as water can drain from the formation. Frequently these fine-grained beds are still compacting months and even years after pumping stresses are applied. No attempt has been made in this review, however, to correlate the non-recovered compaction of Figure 4-7 with water levels in the deeper aquifers.

SUBSIDENCE DUE TO DEEP GAS-FIELD WITHDRAWALS

The Conaway Ranch Gas Field underlies an area of about 10 square miles around the Conaway Ranch headquarters. It is irregularly shaped, and centers at about the Conaway Ranch extensometer site. Gas production comes from depths of 3,800 to 5,400 feet. From 1973 through 1989, the total field production was roughly 32 billion cubic feet of natural gas and about 5895 barrels of brine. None of this was injected back into the deep reservoir. Although roughly three-quarters depleted, the field is still producing at about the average rate of this period.

To get a rough estimate of the rate of subsidence that might be occurring at the extensometer site due to these gas-field withdrawals, the following gross assumptions were made: 1) that the volume of gas, when converted to the temperature and pressure of the deep reservoir, occupied space in the reservoir the same as an equal volume of brine, and 2) the subsidence at the land surface caused by the withdrawal of this volume was volumetrically equal to the withdrawal and was uniform over the 10 square-mile area. The volume of gas produced in the 16 years converts to an equivalent volume of 7850 acre-feet of fluid, and the brine produced in the 16 years converts to 12 acre-feet.

This suggests that at the Conaway Ranch extensometer site and surrounding area, the subsidence rate due to these gas-field withdrawals probably averages about 0.08 foot per year. Although difficult to detect in one year, a foot of subsidence in just 15 years is highly significant, especially along drainage canals and levees designed to control flood waters.

TECTONIC DOWNWARPING OF THE VALLEY TROUGH

In the vicinity of the Conaway Ranch extensometer site, the top of the Fair Oaks Formation (2 million years old) is roughly 100 feet below land surface, the top of the Mehrton Formation (10 million years old) is about 550 feet below land surface, and the top of the gas-bearing Cretaceous formations (65 million years old) are 3,000 feet deep.

For each of these depths, the average rate of downwarping of that location in the valley trough for elapsed span of geologic time, calculated by dividing the depth by the spanned years, is roughly 0.00005 foot per year. This suggests that even though tectonic subsidence probably still continues in the study area, the rate of change is far too small to be of concern in this investigation.

EXTENSOMETER AT CONAWAY RANCH HEADQUARTERS (9N/3E-8C)

In close coordination with the Conaway Ranch subsidence monitoring program, the California Department of Water Resources constructed and placed in operation in late 1991 a bore-hole extensometer of the type shown in Figure 4-6. The extensometer site is located south of the Conaway Ranch headquarters buildings and immediately south of a deep drainage canal, in the NE1/4 of NW1/4 of section 8, T.9 N.,R.3 E. (see SM10, Figure 2-1).

The Conaway Ranch extensometer is anchored at a depth of 716 feet, and has nearby piezometers monitoring water-levels in the 80-90, 140-150, 240-280 and 530-540 foot depth zones. Recorders on the extensometer and all piezometers are designed to provide continuous records of change. Also a reference bench mark SM10 is located near the extensometer and is scheduled to be resurveyed periodically with other bench marks in the GPS subsidence monitoring network.

With the extensometer, piezometers, and bench mark now functioning at the Conaway site, it should be possible to differentiate the effects of shallow and deep groundwater pumping, and the effects of very deep gas-field extractions on the surface elevation of the Conaway site. As now planned, the Department of Water Resources will continue to maintain and operate the extensometer and nearby piezometers for the foreseeable future and the Conaway Ranch interests will continue the monthly water-level monitoring program for at least the coming year. The future of the subsidence monitoring program, using repeated satellite surveys, is indefinite, however.

RESULTS OF 1991 SUBSIDENCE MONITORING

As discussed in Section 1, the elevation of 16 new bench marks and 4 existing bench marks in the Conaway Ranch study area were measured five times in the 4 month period July - October, 1991 by GPS surveys. The first two surveys, in early and mid-July, were scheduled close together to establish a verified base from which future changes could be referenced. The other three surveys were in the early part of August, September and October. The changes in elevation for six of these bench marks are shown in Figures 3-4 and 3-8 through 3-12. For each of these five surveys a relatively stable bench mark west of Woodland was considered to be a stable reference datum.

Pumping in 1991 outside the Conaway ranch began in January, and on the Conaway Ranch in early May. By August groundwater levels had already experienced the bulk of their seasonal declines, and in some areas were recovering from historic lows. Based on records from Zamora, there probably is a close correlation between water-level trends and subsidence in the Conaway Ranch study area. If so, much of the subsidence that probably occurred during the 1991 season had occurred before the

GPS surveys of vertical control began. As shown in the six subsidence graphs, noted above, the last three data points indicate a gradual rebounding of the land surface.

Early records indicate that during most years groundwater levels continue to recover for months after wells stop pumping. Frequently the recovery is interrupted by the next years pumping. It is expected, therefore, that in the study area the rebound of the land surface will probably continue for several months after the October 1991 satellite survey. Thus, it is apparent that the 1991 satellite survey data gives little or no basis for estimating the amounts of either subsidence or rebound that occurred during 1991.

It is essential, therefore, that GPS surveys be continued in 1992 with sufficient frequency to measure the winter high elevation and the summer low elevation of each of the subsidence monitoring bench marks. Of particular concern is the inclusion of the newly set bench mark at the Conaway Ranch extensometer site in the 1992 survey network.

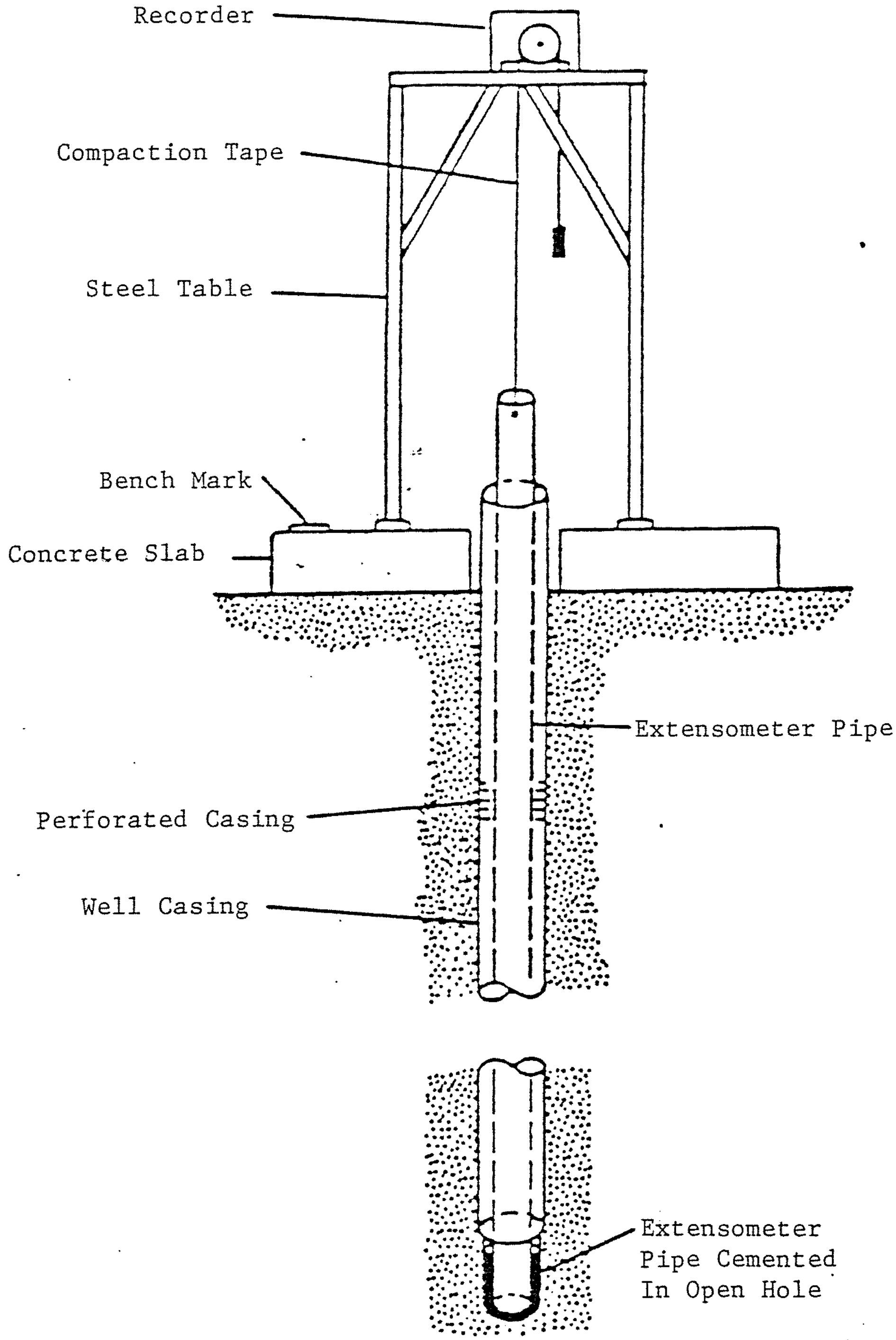


Figure 4-1. Recording extensometer installation.

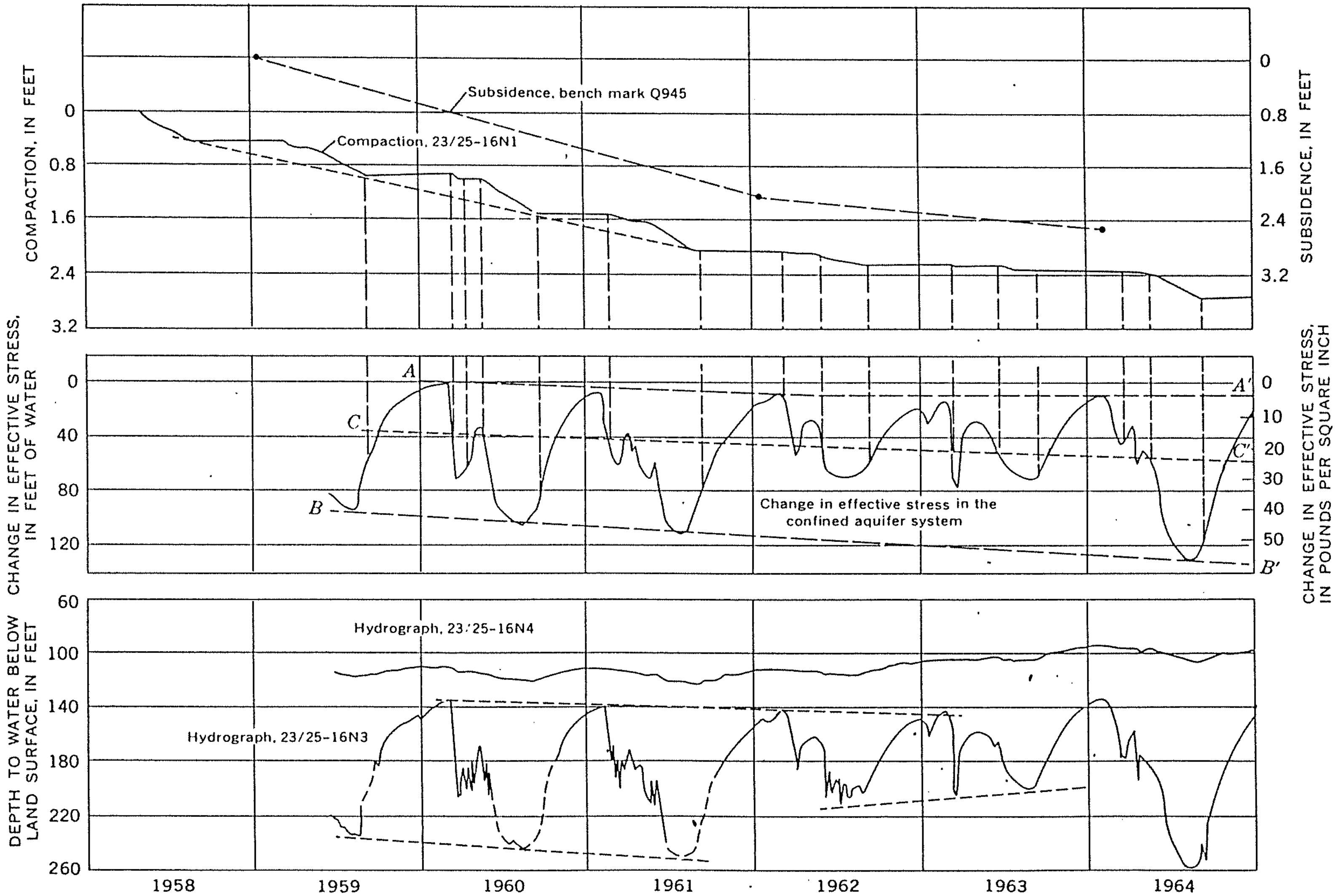


Figure 4-2. Six year correlation of land subsidence, compaction, water-level fluctuations, and change in effective, stress near Pixley, California. (From Lofgren, 1968, Figure 3.)

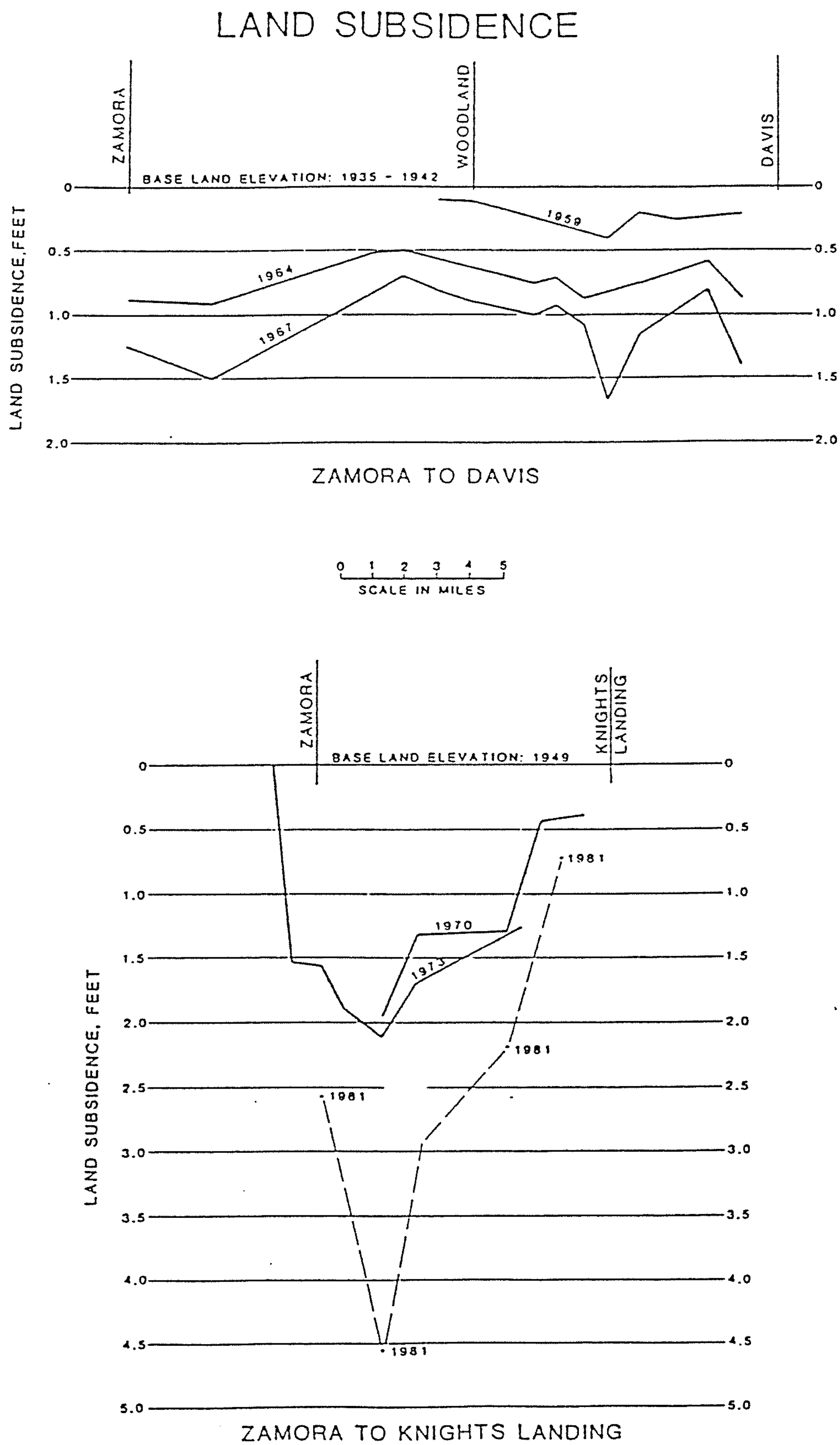


Figure 4-3. Profiles of differential subsidence between Zamora, Woodland, and Davis, 1935-67; and between Zamora and Knights Landing, 1949-81.

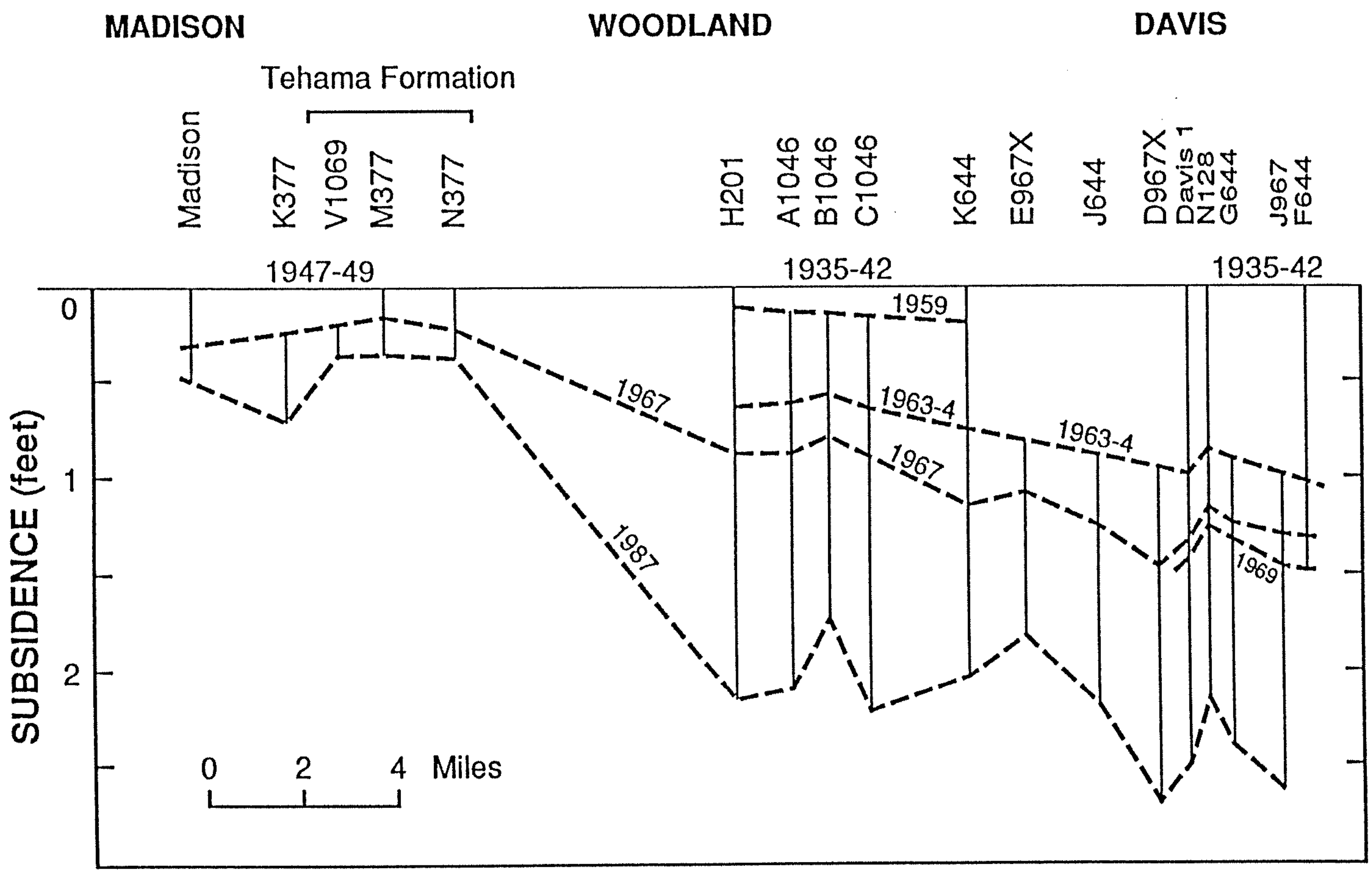


Figure 4-4. Profiles of land subsidence along leveling-control line between Madison, Woodland, and Davis from 1935 to 1987. (Lofgren, 1987.)

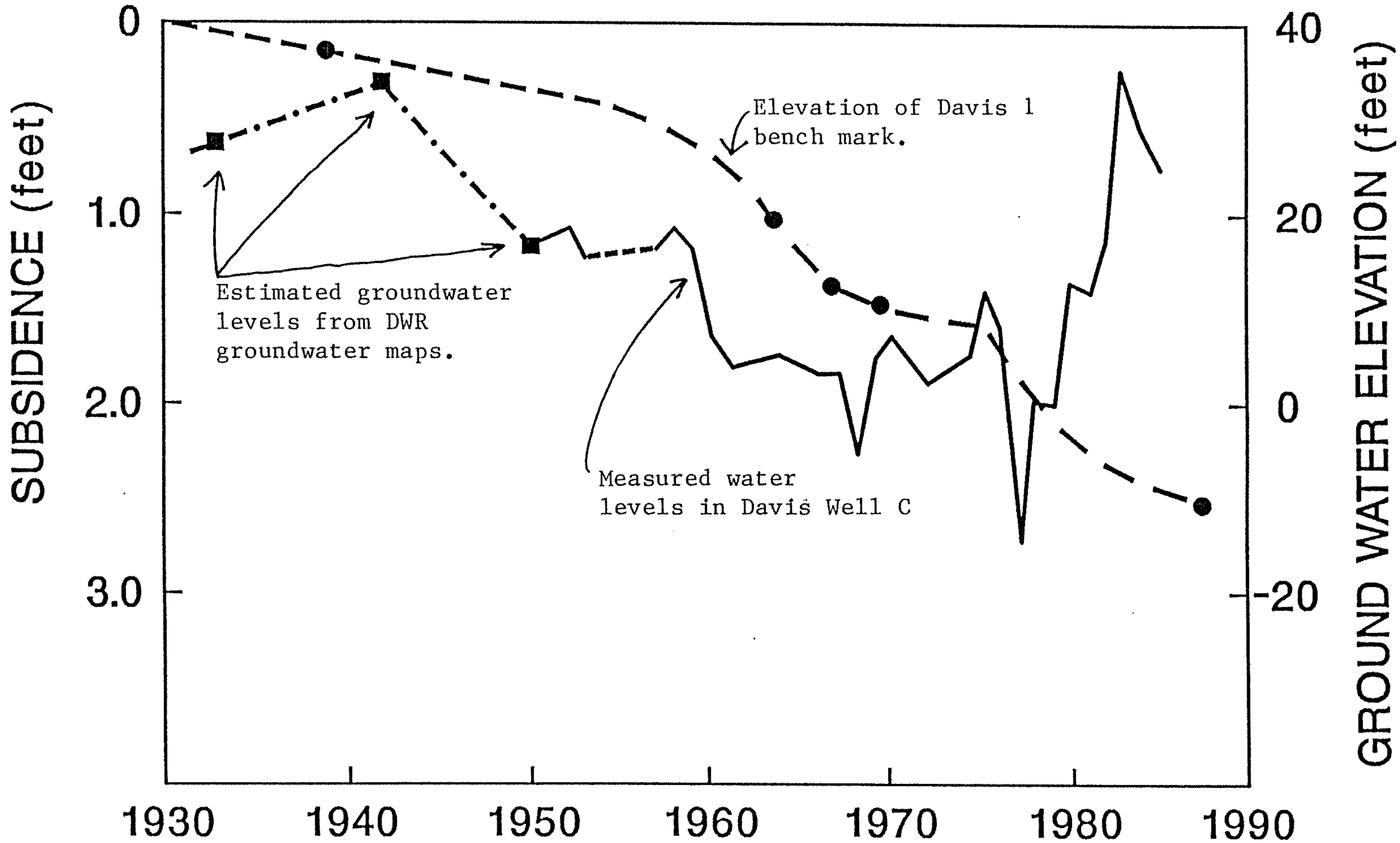


Figure 4-5. Graphs showing correlation between bench mark Davis 1, in Davis, and water levels from maps and nearby water well. (Lofgren, 1987.)

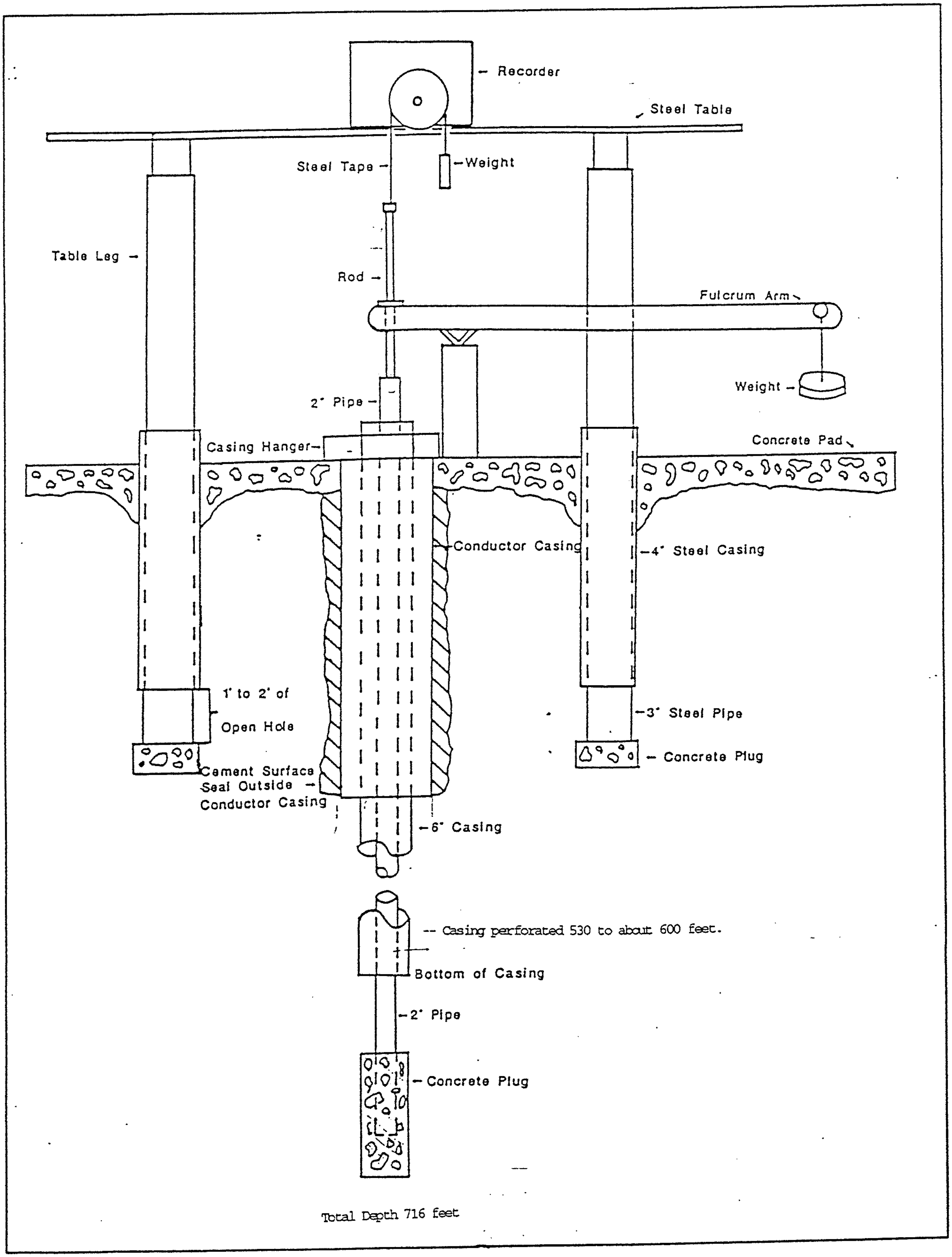


Figure 4-6. Simplified Schematic of Conaway Ranch Extensometer. Not to scale. Prepared by California Department of Water Resources.

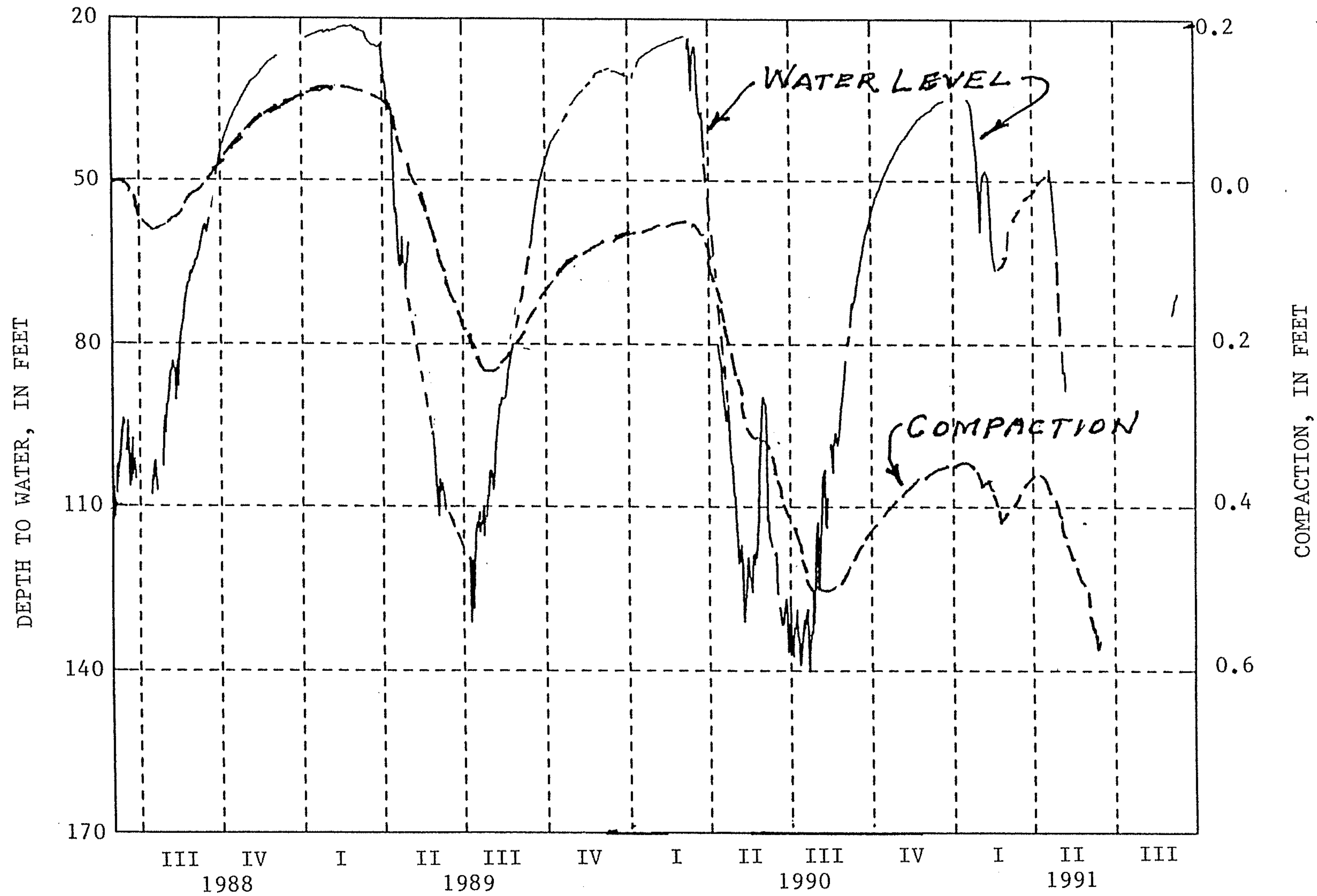


Figure 4-7. Three year correlation between compaction (18 to 1,000 ft. depth) and water-level fluctuations (180 to 200 ft. depth zone), east of Zamora, California. (Based on provisional data in the U.S. Geological Survey ADAPS data base.)

SECTION 5 - GROUNDWATER QUALITY

The results of both prior and 1991 groundwater quality sampling within the study area are discussed in this section.

PRIOR GROUNDWATER SAMPLING PROGRAMS

The quality of groundwater in eastern Yolo County has been evaluated in previous or ongoing investigations by the United States Geological Survey (USGS) and the Cities of Davis, Woodland, and West Sacramento.

The most comprehensive groundwater quality study previously conducted for Yolo County is the USGS study "Chemical Quality of Ground Water in Yolo and Solano Counties, California" (1985). Additional USGS studies were conducted in neighboring counties including "Chemical Quality of Groundwater In the Tehama-Colusa Canal Service Area, Sacramento Valley, California," (1976) and "Chemical Quality of Groundwater in the Central Sacramento Valley, California," (1978).

The 1985 USGS study is based upon groundwater samples collected in 1980 and 1981. A total of 188 domestic and agricultural wells within Yolo County were sampled to determine concentrations of general mineral and inorganic constituents. Seventeen of these wells were also sampled to determine levels of radioactive elements (cobalt, lithium, strontium, and vanadium). This report found that groundwater in the area is suitable for domestic and most agricultural uses. Water from wells near the Sacramento River generally had lower concentrations of dissolved solids and higher concentrations of trace elements than the rest of the study area. Fifty-seven percent of the groundwater samples had dissolved solids concentrations less than 500 milligrams per liter. Many of the wells sampled had boron concentrations that exceeded tolerance levels for many crops. Other trace elements were present in negligible amounts.

Ongoing monitoring of municipal supply wells for the Cities of Davis, Woodland and West Sacramento also provides data regarding groundwater quality in eastern Yolo county. These data are applicable to areas bordering the study area of this report, and are not addressed herein; however, an expanded monitoring and evaluation program is suggested that would include these data.

1991 GROUNDWATER SAMPLING PROGRAM

Schedule and Description

In conjunction with this study, a total of 36 wells were selectively sampled during May, July, October, and December of 1991. These wells are distributed throughout the study area, allowing spatial variations in water quality to be identified. Many of these wells were sampled at three different times to identify water quality variations over time. In December seven monitoring wells were sampled that contain two or three casings screened at different levels, allowing a comparison of water quality variations with depth. The water quality sampling schedule is summarized in Table 5-1.

Table 5-1 Groundwater Quality Sampling Schedule

Well Number	Initial	July 24,25	October 11,15	December 3,4
OW1	5/23 (1)	7/24 (2)	---	---
OW4	5/9 (1) no Se,B	---	---	---
OW5	5/8 (1)	7/24 (2)	---	---
3W1	6/28 (1)	7/24 (2)	10/11 (3)	---
7W1	5/2 (1)	7/3 (4), 7/24 (2)	10/11 (3)	---
10W1	6/4 (1)	7/24 (2)	10/11 (3)	---
31W1	5/3 (1) no Se, N	---	10/11(3)	---
31W2	6/28 (1)	7/24 (2)	---	---
32NW1	5/7 (1)	---	10/11 (3)	---
33NW3	6/17 (1)	---	10/11 (3)	---
33NW4	---	7/3 (4)	---	---
33NW5	6/28 (1)	---	---	---
33NW6	6/19 (1)	---	---	---
33NW7	6/18 (1)	7/24 (2)	10/11 (3)	---
33NW8	6/11 (1)	---	---	---
SW1	5/22 (1)	7/3 (4),7/24 (2)	---	---
SW2	6/3 GM, IC	7/24 (2)	10/11 (3)	---
SW3	---	7/24 (2)	---	---
SW4	5/21 (1)	7/24 (2)	---	---
SF1	---	---	10/15 (3)	---
SF2	5/13 (1)	7/16 (2,4)no AB,GO	---	---
MW1	5/20 (1)	---	---	---
MW3	---	---	---	12/3 (5)
MW4	---	---	---	12/3(5,7)
MW7	6/12 (1)	7/24 (2)	10/15 (3)	---
MW8	---	---	---	12/4 (5,7)
MW9	---	---	---	12/3 (5,7)
MW10	---	---	---	12/4 (5,6)
MW12	---	---	---	12/4 (5,7)
MW13	---	---	---	12/4 (5,6)
MW14	---	---	---	12/4 (5,6)
43SW	6/13 (1)	7/24 (2)	---	---
55N	---	7/24 (1)	---	---
55SE	---	7/24(1),7/25(2)	---	---
57NW	---	7/16 (2*,4)	---	---
57SW	---	7/16(1),7/24(2**)	10/15 (3)	---

(1) This analysis included General Mineral (GM), selenium (Se), boron (B), nitrates (N), and inorganic chemicals (IC).
(2) This analysis included GM, IC, B, Gross alpha and beta (AB), radon (R), and grease and oil (GO). In 2* GM and B were omitted. In 2** Se and NO_3 were sampled in place of IC.
(3) This analysis included GM, B, Se, N, Title 22 pesticides and herbicides (PH), DBCP, and EDB.
(4) This analysis included EPA 602 organics.
(5) This analysis included GM, B, Se, NO_3, Al, As, Ba.
(6) Sampled at 2 depths.
(7) Sampled at 3 depths.

Water Quality Results and Discussion

Only those constituents found in concentrations that may be detrimental to agricultural or municipal uses are discussed herein.

Total Dissolved Solids - Total dissolved solids (TDS) consist primarily of inorganic salts. The TDS in groundwater is generally a product of reactions during rock weathering, and soil and sediment leaching. Municipal water supplies with high TDS concentrations can stain fixtures and have objectional taste or odor. The recommended State Secondary Drinking Water Standard for TDS is 500 mg/l, and the maximum State Secondary Drinking Water Standard for TDS is 1,000 mg/l. The effect of high dissolved solids concentrations on agricultural crops is discussed under specific conductance.

The majority of the wells sampled in this investigation had TDS concentrations in excess of 500 mg/l, which agrees with the findings of the USGS 1985 study. TDS concentrations that were measured in water sampled from wells during this study are summarized in Figure 5-1. These measured TDS concentrations ranged from 250 to 8,200 mg/L. The highest concentrations were measured in wells MW 14, 55W and 55SE in the southeastern part of the study area near Interstate 80. Wells 55W and 55SE had been capped and were not being used for agricultural purposes because of poor water quality. Excluding these wells the maximum concentration measured was 1900 mg/L.

The spatial variation of TDS concentrations was somewhat random. This may be due to the spatial variation of deposited minerals in the underlying geologic formations. Generally the highest TDS concentrations were measured in three locations, near Highway 16 and the old City of Woodland wastewater ponds, adjacent to the Tule Canal, and in the southeastern part of the study area south of Interstate 80. Some of the highest TDS concentrations were observed in wells on Conaway Ranch that are clustered together, resulting in a localized cone of depression. The lowest TDS concentrations were measured in wells near the Sacramento River. In the series of wells near the Sacramento River (OW-1 through OW-5) the TDS concentration increases with the distance from the Sacramento River. TDS concentrations in these wells also decreased from early to late summer, and increased with depth.

Specific Conductance - The measurement of the specific conductance (commonly referred to as EC for electrical conductance) of a water is a rapid way to measure the dissolved solids concentration. The EC measures the capacity of the sample to carry an electric current, which is related to the concentration of ionized substances in the water. The recommended State Secondary Drinking Water Standard for EC is 900 micromhos, and the maximum State Secondary Drinking Water Standard for EC is 1,600 micromhos. High salinity, as measured by EC concentrations, can stress crops and reduce yields. There is a wide range in salt tolerance of agricultural crops. The salt tolerance of the major crops grown within the study area is indicated in Table 5-2.

Table 5-2 Yield Potential of Selected Crops as a Function of Specific Conductance(EC)

Crop	Yield Potential With Respect to EC(1) (umho/cm)		
	100%	90%	75%
Alfalfa	1,300	2,200	3,600
Corn	1,100	1,700	2,500
Rice	2,000	2,600	3,400
Sugarbeet	4,700	5,800	7,500
Tomatoes	1,700	2,300	3,400
Wheat	4,000	4,900	6,300

(1) Source: "Water Quality for Agriculture," FAO Irrigation Paper 29

Figure 5-2 summarizes the results of the EC measurements collected in this investigation. These measurements ranged from 415 to 5860 umho/cm (excluding wells 55W and 55SE which had been capped, the maximum was 3210 umho/cm). These results were distributed in the same patterns as the TDS concentrations.

As indicated by Table 5-2, alfalfa, corn, tomatoes and rice are moderately salt sensitive. The EC levels in many of the wells within the study area are sufficiently high that potential yields of these crops could be reduced by more than 10 percent. Salinity reduces crop yield by causing a build-up in soluble salts in the soil. Providing the soil is sufficiently permeable, this build-up can be mitigated to some extent by applying excess water to leach these soluble salts. Salinity problems may not be experienced because ranches within the study area use surface water in conjunction with groundwater, water from different wells is often blended, and tolerant crops may be planted in affected areas.

Iron and Manganese - Iron and manganese are objectionable in municipal water supplies because they can interfere with laundering operations, impart stains to plumbing fixtures, and cause difficulties in the distribution system by supporting growths of iron bacteria. Iron also imparts a taste to water which is detectable at very low concentrations. The State Secondary Drinking Water Standard maximum contaminant level for iron is 0.3 mg/l, and the maximum contaminant level for manganese is 0.05 mg/l. Excessive iron and manganese may be removed from municipal water supplies by oxidation and filtration.

The 1985 USGS study concluded in general that iron concentrations greater than 0.3 mg/l occurred in groundwater west of Woodland along Cache Creek, groundwater north of Knights Landing, and groundwater in the vicinity of West Sacramento and extending south along the Sacramento River.

The data collected in conjunction with this study indicates that the iron concentration in groundwaters varies widely, and that wells with iron concentrations greater than 0.3 mg/l are scattered throughout the study area. Generally the highest iron concentrations were measured when the wells were first operated in the early summer, and concentrations declined during the summer. High iron concentrations were also measured in the monitoring wells. Measured iron concentrations ranged from 0.03 to 1.4 mg/L. Iron and manganese concentrations measured during this investigation are summarized in Figures 5-3 and 5-4.

The 1985 USGS study found that wells bordering the Sacramento River produced water with the highest manganese concentrations, and that manganese concentrations decreased as the distance from the Sacramento River increased. The USGS study found that wells adjacent to the Sacramento River generally produced water with manganese concentrations greater than 0.1 mg/l; that wells further to the west, to roughly the area of Woodland and Davis generally produced water with manganese concentrations between 0.01 and 0.1 mg/l; and that wells west of Woodland and Davis generally produced water with less than 0.01 mg/l of manganese.

The data regarding manganese concentrations collected in this study is generally in agreement with findings of the 1985 USGS study. Manganese concentrations generally ranged from less than 0.01 to 0.027 mg/L, with the exception of three areas. Water from one of the wells at the extreme north end of the study area near the Sacramento River (well S&F1) had a manganese concentration of 0.440 mg/l; water from a strip of wells in the east-central portion of the study area near the Tule Canal (including wells 10W1, 3W1, 33NW7, SW1, SW2, and SW4) had relatively high manganese concentrations (0.14 to 0.37 mg/L); and water from several wells in the eastern portion of Cowell Ranch, at the southern end of the study area, had high manganese concentrations (wells 57SW, MW14, 55W, and 55SE). Six of the wells with high concentrations of manganese showed significant decreases in concentration with time. Manganese concentrations were generally higher in shallow groundwaters and decreased with depth.

Boron - Boron is an essential element for plant growth, however if it is present in quantities appreciably greater than needed it becomes toxic. The boron tolerance of the major crops grown within the study area is indicated in Table 5-3, a significant loss in yield can be expected at boron concentrations above the range indicated in this table for each crop.

Table 5-3 Boron Tolerance of Selected Crops

Sensitive(0.75 - 1.0 mg/l)
- Rice
- Wheat

Moderately Tolerant (2.0 - 4.0 mg/l)
- Corn

Tolerant (4.0 to 6.0 mg/l)
- Alfalfa
- Sugarbeets
- Tomatoes

(1) Source: "Water Quality for Agriculture," FAO Irrigation Paper 29

Boron concentrations of water samples collected from wells within the study area during this study are summarized in Figure 5-5. The boron concentrations measured during this study were similar to those reported in the 1985 USGS study. Both studies found boron concentrations equal to or greater than 2 mg/l in an area near Cache Creek extending northward to the Sacramento River. The USGS study generally found boron concentrations between 1 and 2 mg/l in the southern part of this study area.

Boron concentrations measured in this study (see Figure 5-5) ranged from 0.87 mg/L (Maupin well) to 8 mg/L (well MW14). In the series of wells near the Sacramento River (OW-1 through OW-5) the boron concentration increases with the distance from the Sacramento River, from 1.3 to 2.1 mg/l. The highest boron concentrations were generally found in the wells bordering the Tule Canal.

Radon and Other Radioactive Elements - The doses of radiation that a body accrues from drinking water is quite small as compared to natural background radiation, however the EPA's policy has been to permit only very low levels of radiation in drinking water on the basis that there is potential for harm from any level of radiation dose. The State Primary Drinking Water Standard maximum contaminant level (MCL) for alpha particles is 5 pCi/l, and the MCL for beta particles is 50 pCi/l. On July 18, 1991 the U.S. Environmental Protection Agency (EPA) issued proposed regulations that would establish a MCL for radon of 300 pCi/l.

As part of this investigation, the total concentrations of total alpha emitters, total beta emitters, and radon gas were measured in 17 wells during July, 1991. All wells had concentrations of both total alpha and beta emitters well below the maximum contaminant levels; total alpha ranged between 0-0.42 pCi/L (MCL = 5 pCi/L) and total beta was 0-17 pCi/L (MCL = 50 pCi/L). However, some of the radon concentrations were at or above the proposed MCL for drinking water (300 pCi/L). Figure 5-6 summarizes the radon levels detected in water from wells within the study area. Measured radon concentrations ranged from 200 to 500 pCi/L.

Radon may easily be removed from groundwater in aeration towers which strip the radon from the water, however this increases the cost of the water supply. The EPA has received numerous criticisms of it's proposed MCL for radon, and is considering increasing the proposed MCL to 1,000 pCi/L. If this were the final MCL, all the wells wold fall within it.

Conclusions

Water Quality Limitations With Respect to Municipal Uses - Many of the wells in the study area produced water with concentrations of dissolved minerals (or TDS) such that this water may be poorly suited for municipal water supplies of aesthetic reasons. However groundwater with similar TDS concentrations is currently used by the nearby cities of Woodland and Davis. Some of the wells within the study area also produce water with iron and manganese concentrations that would cause aesthetic problems in municipal supplies. Excessive iron and manganese may be removed from municipal water supplies by oxidation and filtration. If the proposed MCL for radon of 300 pCi/l is adopted, aeration may be required prior to the use of groundwater for municipal purposes.

Water Quality Limitations With Respect to Agricultural Use - The salinity of water produced by many of the wells within the study area is such that the yield of salt sensitive crops may be affected if groundwater from that individual well is the sole supply of irrigation water. Boron concentrations in wells within the northern portion of the study area are also such that yield of sensitive crops may be affected. Providing the soil is sufficiently permeable, harmful effects of high salinity and boron concentrations may be mitigated by applying excess irrigation water to leach toxic ions from the crop root zone. Salinity problems may not be experienced because ranches within the study area use surface water in conjunction with groundwater, water from different wells is often blended, and tolerant crops may be planted in affected areas.

Water Quality Variations - The following significant variations in water quality were observed:

(1) Higher boron concentrations were generally observed in the vicinity of the Tule Canal. Geothermal springs in the Coast Range that contribute to Cache Creek are thought to be the original source of this boron, and agricultural drainage is thought to contribute to the high concentrations near the Tule Canal.

(2) Some of the highest dissolved mineral concentrations were observed in water from wells on Conaway Ranch that are clustered together, resulting in a localized cone of depression near Highway 16 and the Tule Canal, and in a strip of wells to the south parallel with the Tule Canal. The old City of Woodland sewer farm is directly north of this cluster of wells. The City of Woodland currently discharges treated wastewater with a TDS concentration of about 1,500 mg/l through this area to the Tule Canal. The Tule Canal also receives agricultural drainage water high in dissolved minerals. Recharge by this high TDS water is one possible explanation for the high concentration of dissolved minerals in the groundwater in this area. Another possible explanation is that the water is being withdrawn from fine-grained materials as a result of the localized cone of depression. Because these materials transmit water slowly, they allow longer residence times for water to dissolve minerals than coarse-grained materials.

(3) Two wells in the southwestern portion of the study area produced very poor quality water. This area was referred to as the "Putah Sink" prior to construction of reclamation levees, which indicates that the area was historically a place where salts accumulated in the soil.

(4) In the series of wells near the Sacramento River (OW-1 through OW-5) the TDS concentration increases with distance from the Sacramento River. TDS concentrations in these wells also decreased from early to late summer, and increased with depth. These results indicate that groundwater in this area is being at least partially recharged by water from the Sacramento River, and that wells nearest the river are producing recent groundwater that has not accumulated dissolved minerals.

Figure 5-1 Total Dissolved Solids

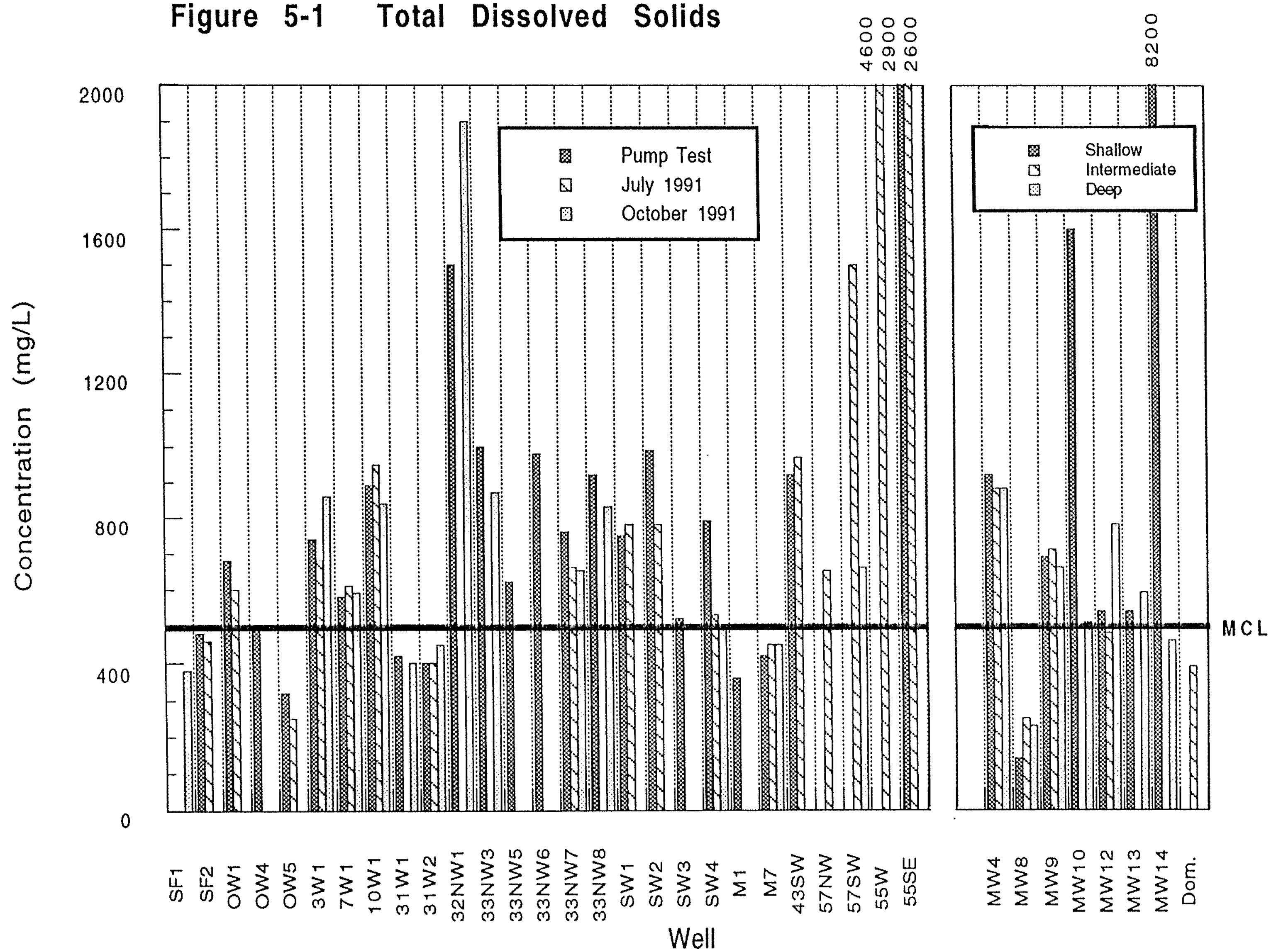
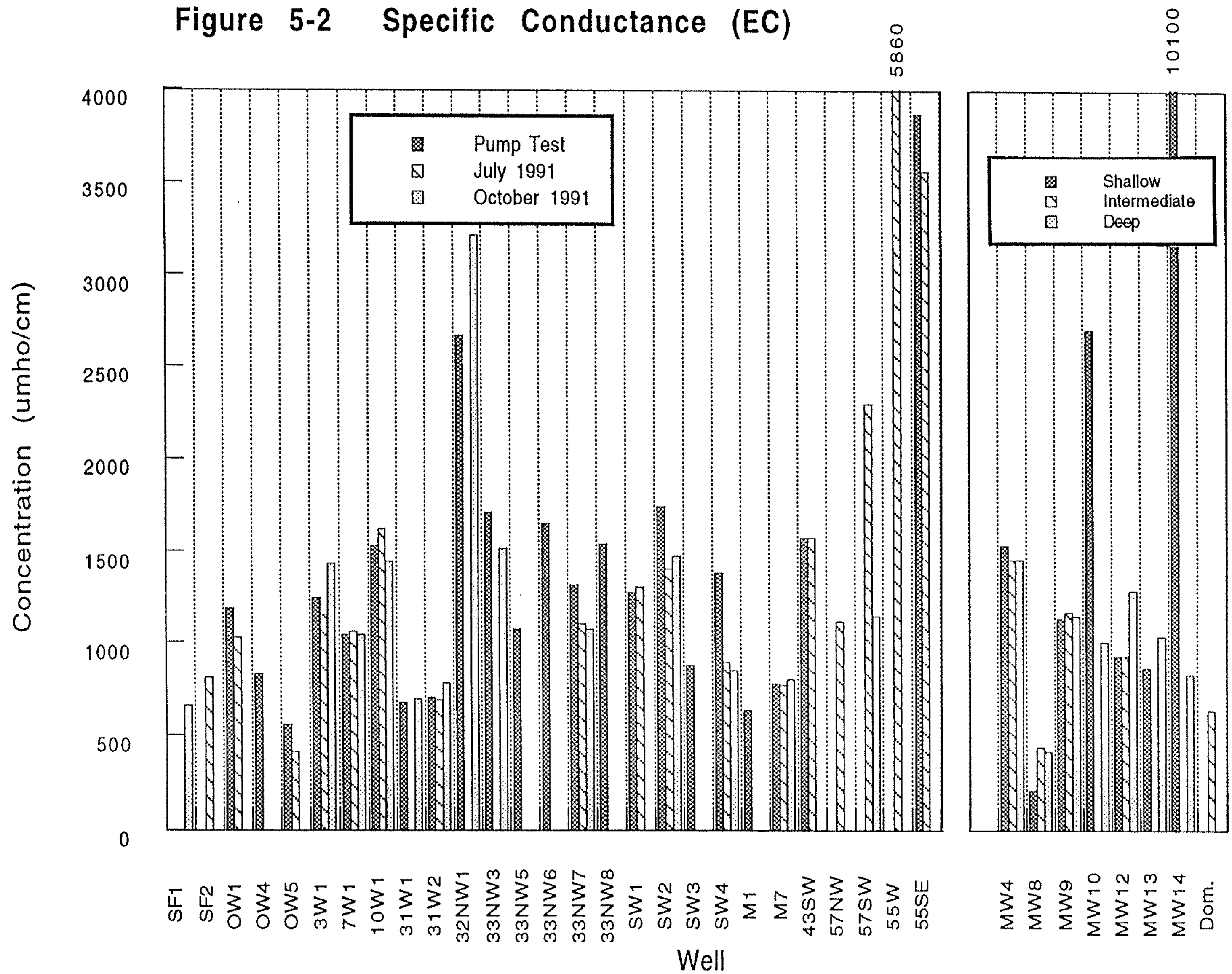


Figure 5-2 Specific Conductance (EC)



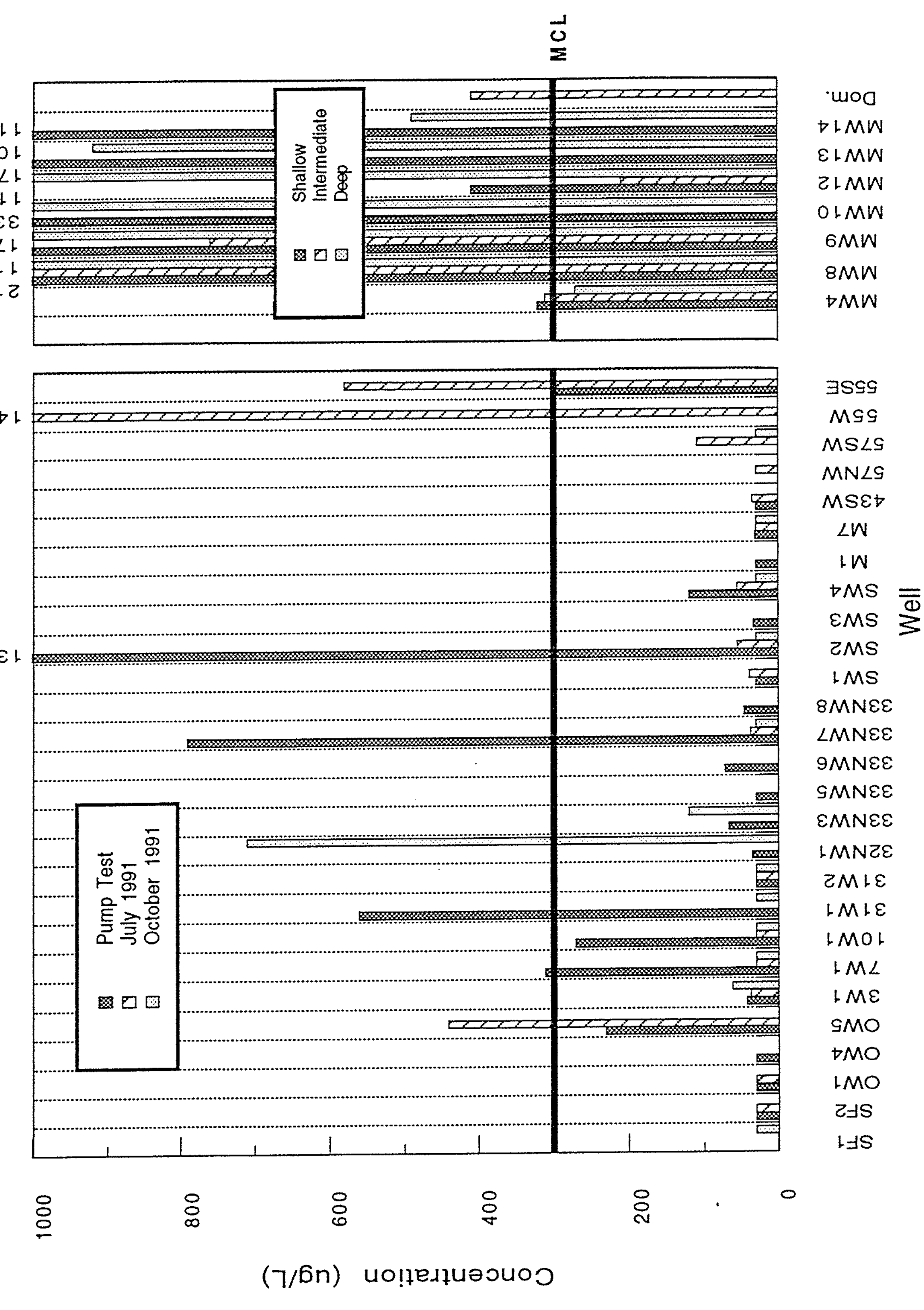


Figure 5-3 Iron

Figure 5-4 Manganese

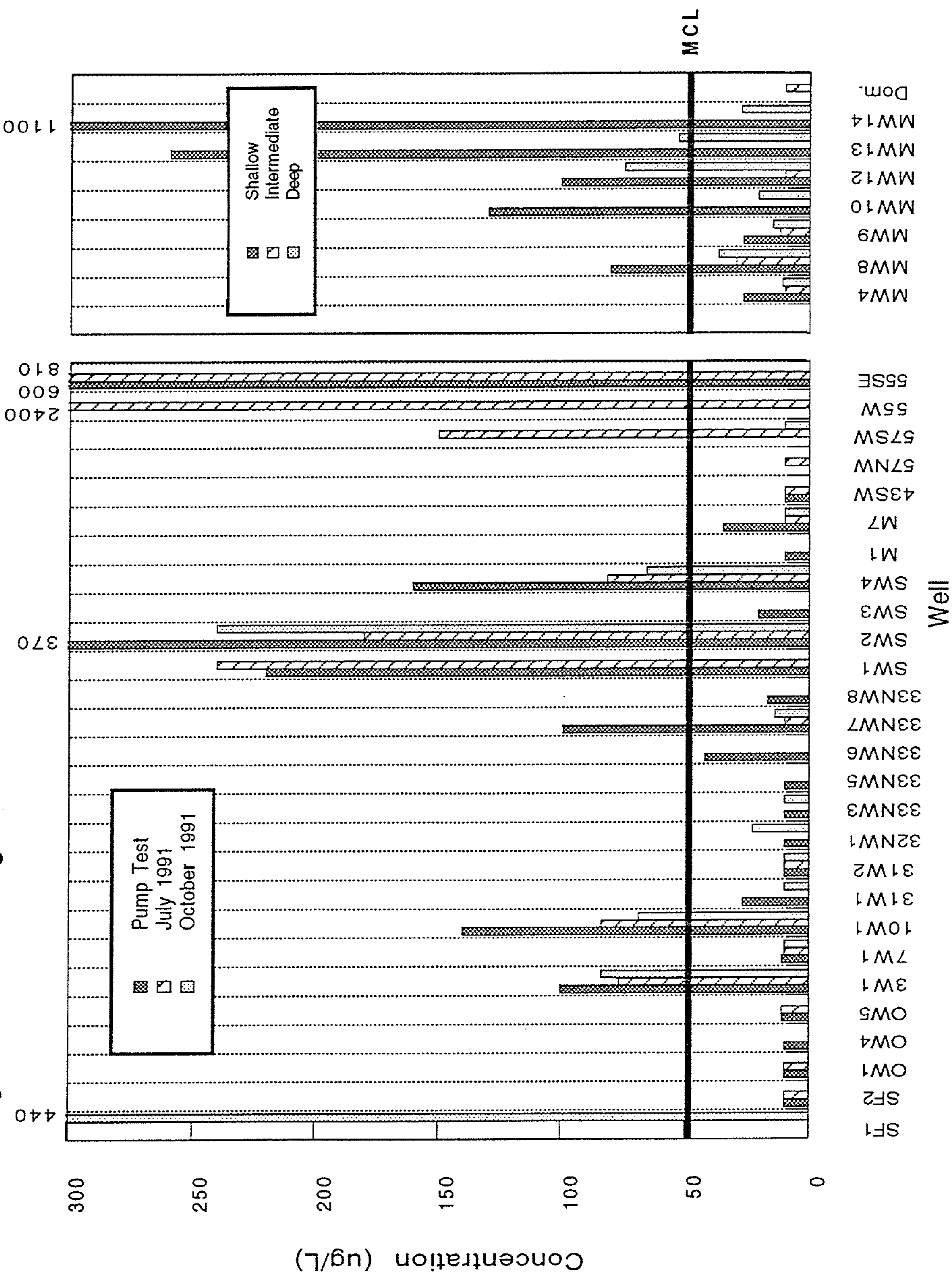


Figure 5-5 Boron

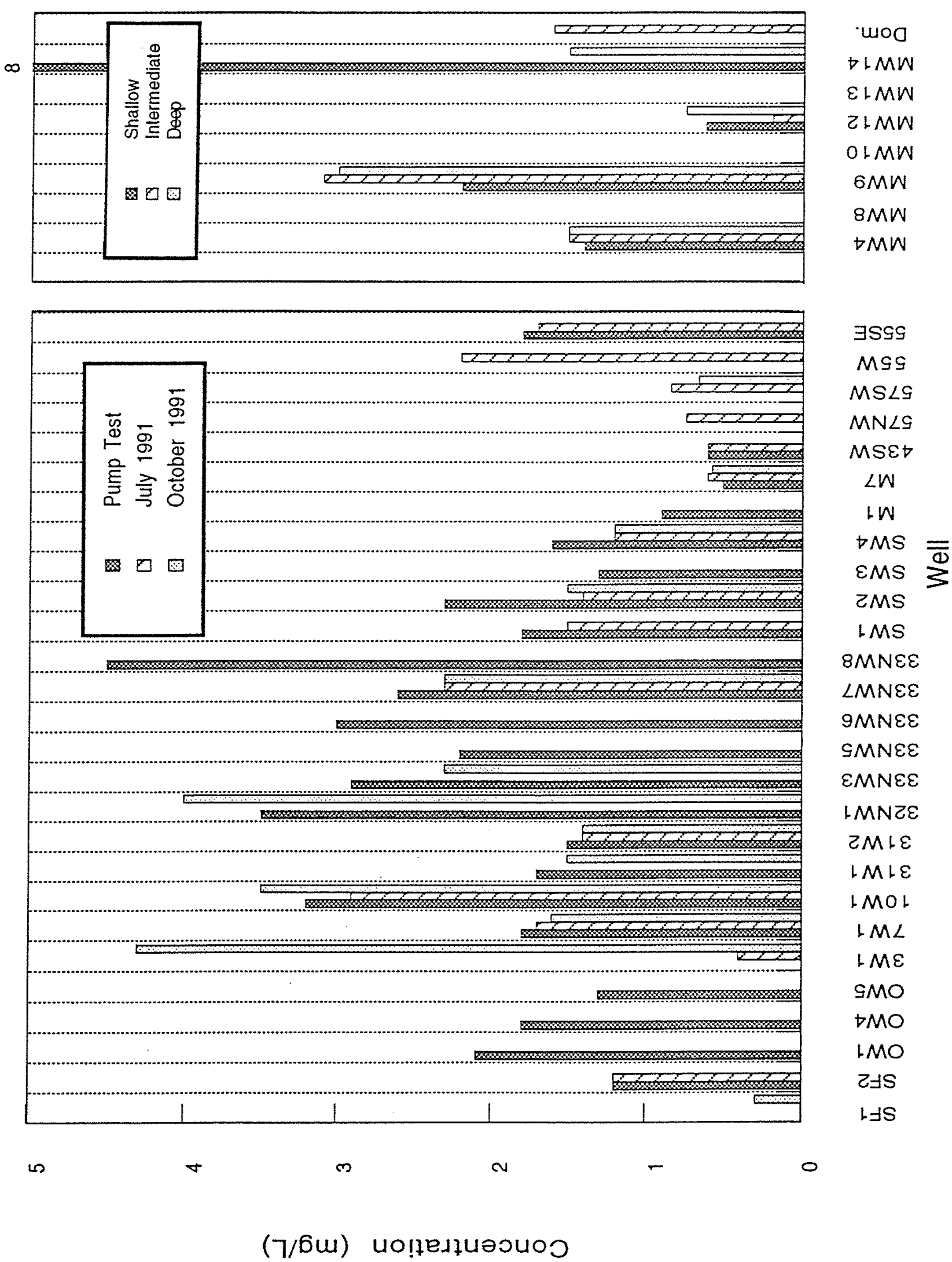
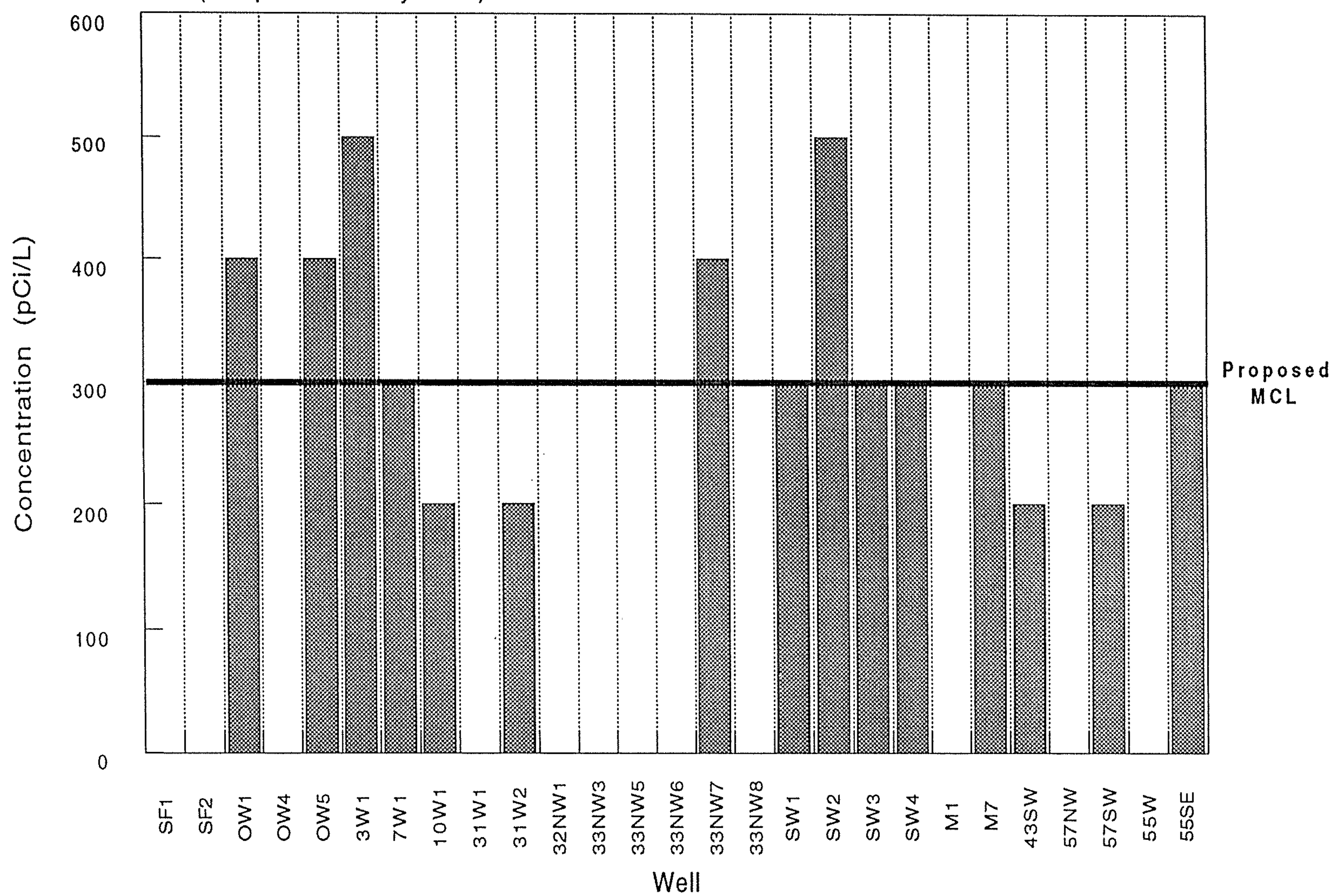


Figure 5-6 Radon

(Sample Date: July 1991)



SECTION 6 - SUMMARY OF CONCLUSIONS

The major conclusion that can be derived from the analysis of the data collected during this investigation are summarized herein:

(1) The study area is underlain by alternating coarse-grained sand and gravel aquifers, which are separated by fine-grained aquitards of silt and clay. Through most of the area, the fine-grained aquitards tend to hydraulically separate shallow unconfined aquifers from underlying semi-confined and confined aquifers. Because the effects of pumping overdraft is so different for compressible deposits in a confined aquifer system from those in an unconfined system, defining the nature of this confinement throughout the study area is an important aspects of this investigation. This definition can best determined by observing pumping interferences in deep and shallow wells.

(2) Long term spring and fall groundwater level monitoring indicates that groundwater levels in the area have gradually declined since 1983. Groundwater levels appear to generally be above the historic low levels recorded in 1977.

(3) The 1991 groundwater level and subsidence monitoring programs observed only a part of the full seasonal cycles of water-level change and subsidence. Subsidence monitoring during 1991 indicates a gradual rebounding of the land surface. A full year of measurements are needed to record the magnitude of seasonal change of both water levels and subsidence throughout the area, and to approximate the stress-strain parameters of the aquifer system. Although the hydrogeologic conditions and pumping regime at the Zamora site are different, it is believed that the Zamora aquifer system characteristics, as observed in the water-level and compaction records, are typical of the conditions at the Conaway Ranch site and that similar records will be recorded at the Conaway site during the next several years.

(4) Groundwater beneath the study area contains dissolved minerals that may affect it's suitability for both municipal and agricultural uses. Groundwater quality varies between wells, but generally the best water quality occurs near the Sacramento River and the worst water quality occurs in the area of the old "Putah Sink", in areas of the greatest pumping, and near Cache Creek. Water quality problems may be avoided by conjunctive use with surface water, or blending water from several wells. The results of the 1991 monitoring indicates that many potentially problematic constituents are not present in the area, and that future samples should be analyzed for only general mineral constituents, boron, and manganese.

SECTION 7 - RECOMMENDATIONS FOR FUTURE INVESTIGATION

At this time it appears that California is entering a sixth consecutive year of drought, and that extensive groundwater pumping will occur in Yolo County during 1992. During 1991 facilities were constructed to monitor the affect of groundwater pumping, however the 1991 monitoring observed only a part of the full seasonal cycles of water-level change and subsidence throughout the area. It is suggested that groundwater pumping, water-level, subsidence, and water quality monitoring programs established during 1991 be continued throughout 1992, and that these programs be expanded to include a larger area.

The objectives of this monitoring would be to:

(1) Observe the full seasonal cycles of water-level change and subsidence throughout the area.

(2) Develop a mass balance of withdrawals and recharge to the groundwater basin.

(2) Better define spatial variations in water quality and detect possible adverse water quality impacts of withdrawals.

There is little question that the type of groundwater monitoring now continuing in the Conaway Ranch study area would be of tremendous benefit to all parties concerned if it were expanded to include the remainder of Yolo County, and were integrated with monitoring by various municipalities and districts of the area. The continuation of the Conaway Ranch study area monitoring program established in 1991 and the expansion of this study to a larger area are discussed below in greater detail under separate topic headings.

SUGGESTED 1992 MONITORING PROGRAM IN CONAWAY RANCH STUDY AREA

The Department of Water Resource plans to record water-level changes and extensometer measurements at the Conaway Ranch extensometer site throughout 1992 and beyond. This will define the drawdown effects of seasonal pumping on water level in various depth intervals at this one site, and will measure the net compaction and expansion of the aquifer system to a depth of 740 feet throughout the year.

Measurements of water levels within all piezometers and observation wells has continued on a monthly basis throughout the 1991-1992 winter. To quantify and define the effects of groundwater pumping during 1992 within the Conaway Ranch study area, and to better understand the aquifer system in this area, the following monitoring is recommended during 1992:

(1) The measurements of water levels within all piezometers and observation wells should continued on at least a monthly basis throughout 1992. Once groundwater pumping in the area initiates, the frequency of measurements should be increased to biweekly measurements.

(2) GPS surveys of all bench marks in the GPS net, 3 times to measure the winter highs and 3 times to measure the summer lows. The suggested schedule for these surveys is as follows:

1st 1992 GPS Survey - Approximately Feb 1	To measure high
2nd 1992 GPS Survey - Approximately March 1	To measure high
3rd 1992 GPS Survey - Approximately April 1	To measure high
4th 1992 GPS Survey - Approximately July 1	To measure low
5th 1992 GPS Survey - Approximately August 1	To measure low
6th 1992 GPS Survey - Approximately Sept 1	To measure low

(3) Water quality monitoring consisting of:

(a) Sampling of each of the agricultural water wells that had been sampled during 1991. The 1992 sampling would occur once in April or May, at the initiation of groundwater pumping, and once in September or October at the end of the pumping season. Samples would be analyzed for general minerals, boron, and selenium. The intent of this sampling would be to identify any change in water quality either between the 1991/1992, or between the spring and fall of 1992.

(b) The sampling of each of the series of wells near the Sacramento River (OW-1 through OW-5) and the Sacramento River on a monthly basis to further define the extent to which groundwater in this area is recharged by the Sacramento River. Samples would be analyzed for conductivity and iron concentrations.

(4) Develop estimates of the total amount of groundwater pumpage in the area from farming, municipal, water bank sales, etc. This data would be used to develop a mass balance for the groundwater reservoir.

SUGGESTED INTEGRATED YOLO COUNTY MONITORING AND EVALUATION PROGRAM

In 1984 the Yolo County Board of Supervisors adopted the Yolo County Water Resources Plan. This plan was prepared under the direction of an Inter-Agency Water Management Coordinating Group (ICOR), consisting of representatives from Yolo County, the Cities of Woodland and Davis, Yolo County Flood Control and Conservation District, East Yolo Community Services District, Dunnigan Water District, Yolo-Zamora Water District, the University of California at Davis, and Reclamation District 900. The plan recommended the formulation of a comprehensive water quality monitoring and evaluation program, and groundwater monitoring and evaluation program within the county.

At the time the Water Resources Plan was adopted the awareness of the need for these programs was such that these activities did not get implemented. However there now seems to be the requisite awareness of need and general interest among the various agencies to implement these programs.

We suggest that the ICOR be invited to coordinate their efforts in 1992 with the ongoing Conaway Ranch study. Potential goals of this integrated effort include:

(1) Develop a Yolo County groundwater data base that includes maps showing wells being monitored, and water level and quality data.

(2) Coordinate data collection so the various monitoring programs examine uniform parameters, and are based upon the same datum.

(3) Develop annual estimates of the total amount of groundwater pumpage in the County from farming, municipal, water bank sales, etc.

(4) Expand the GPS monument and monitoring network to include selected areas throughout the county.

Most of the members of the ICOR are also members of represented in the technical advisory committee for this study. Mr. Fran Borcalli, Yolo County's water consultant, should probably coordinate and manage this integrated monitoring and evaluation effort. We suggest that, subsequent to the technical advisory committee meeting of January 28, 1992, a meeting be scheduled of the ICOR to establish goals and a schedule for this integrated effort.