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GROUND-WATER FLOW AND SOLUTE MOVEMENT TO DRAIN LATERALS, WESTERN SAN JOAQUIN VALLEY, CALIFORNIA

I. GEOCHEMICAL ASSESSMENT

U.S. GEOLOGICAL SURVEY

Open-File Report 90-136

REGIONAL AQUIFER-SYSTEM ANALYSIS

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

Prepared in cooperation with the
SAN JOAQUIN VALLEY DRAINAGE PROGRAM

This report was prepared by the U.S. Geological Survey in cooperation with the San Joaquin Valley Drainage Program and as part of the Regional Aquifer-System Analysis (RASA) Program of the U.S. Geological Survey.

The San Joaquin Valley Drainage Program was established in mid-1984 and is a cooperative effort of the U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, California Department of Fish and Game, and California Department of Water Resources. The purposes of the program are to investigate the problems associated with the drainage of agricultural lands in the San Joaquin Valley and to develop solutions to those problems. Consistent with these purposes, program objectives address the following key concerns: (1) public health, (2) surface- and ground-water resources, (3) agricultural productivity, and (4) fish and wildlife resources.

Inquiries concerning the San Joaquin Valley Drainage Program may be directed to:

San Joaquin Valley Drainage Program
Federal-State Interagency Study Team
2800 Cottage Way, Room W-2143
Sacramento, California 95825-1898

The RASA Program of the U.S. Geological Survey was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system, and accordingly transcend the political subdivisions to which investigations were often arbitrarily limited in the past. The broad objectives for each study are to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The Central Valley RASA study, which focused on the hydrology and geochemistry of ground water in the Central Valley of California, began in 1979. Phase II of the Central Valley RASA began in 1984 and is in progress. The focus during this second phase is on more detailed study of the hydrology and geochemistry of ground water in the San Joaquin Valley, which is the southern half of the Central Valley.

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CONTENTS

ILLUSTRATIONS

CONVERSION FACTORS

For readers who prefer inch-pound units, conversion factors for terms used in this report are listed below.

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic meter (m^3)	35.31	cubic foot
cubic meter per minute (m^3/min)	264.2	gallon per minute
hectare (ha)	2.471	acre
kilogram (kg)	2.2046	pound
kilogram per minute (kg/min)	2.2046	pound per minute
meter (m)	3.281	foot
meter per second (m/s)	3.281	foot per second
meter per year (m/yr)	3.281	foot per year

Abbreviations used:

µg/L	microgram per liter
µm	micrometer
mg/L	milligram per liter
µS/cm	microsiemen per centimeter
TU	tritium unit

GROUND-WATER FLOW AND SOLUTE MOVEMENT TO DRAIN LATERALS, WESTERN SAN JOAQUIN VALLEY, CALIFORNIA

I. GEOCHEMICAL ASSESSMENT

By *S.J. Deverel* and *John L. Fio*

ABSTRACT

A study was undertaken to quantitatively evaluate the hydrologic processes affecting the chemical and isotopic composition of drain-lateral water in a drained agricultural field in the western San Joaquin Valley, California. The results of chemical and isotopic analysis of the samples and analysis of hydraulic-head data and drain-lateral flow data elucidate the process of mixing of deep and shallow ground water entering the drain laterals. The deep ground water was subject to partial evaporation prior to drainage-system installation and has been displaced downward (at depths greater than 6 meters) in the ground-water system. This ground water is flowing toward the drain laterals. The percentage of the deep, isotopically enriched ground water entering the drain laterals varies with time and between drain laterals. The percentage of the total drain-lateral flow, which is deep ground-water flow, is about 30 percent for the shallow drain lateral (1.8 meters below land surface) and 60 percent for the deep drain lateral (2.7 meters below land surface). During irrigation, the percentages decrease to 0 and 30 percent for the shallow and deep drain laterals, respectively.

Selenium loads in the drain laterals vary with time and between drain laterals. The selenium load for the shallow drain lateral (68 kilograms) during 1 year is 21 percent of the load for the deep drain lateral (332 kilograms) because it collects less deep, high-selenium ground water and does not flow continuously. Although selenium concentrations in the drain-lateral water decreased during irrigation, selenium loads increased substantially during a preplant irrigation because of increased flow into the drain laterals. The selenium loads during 8 days of irrigation represented a substantial percentage (25 percent for the shallow drain lateral and 11 percent for the deep drain lateral) of the total selenium load for 1 year.

INTRODUCTION

About 100,000 ha of irrigated agricultural land in the western San Joaquin Valley, California, are affected by shallow water tables and inadequate drainage (U.S. Bureau of Reclamation, 1984). Subsurface drainage systems have been installed in some low-lying areas of the western valley where a shallow water table can be detrimental to crop production. These drainage systems generally maintain the water table below 1.5 m of land surface. Evapotranspiration from a water table within 1.5 m of land surface can lead to accumulation of salts in the unsaturated zone. Soil and ground-water salinity have caused agricultural water-management concern in the western San Joaquin Valley for decades. The discovery of high selenium concentrations in saline drain water in this area (Deverel and others, 1984; Presser and Barnes, 1984, 1985) and the associated detrimental effects on waterfowl (Ohlendorf and others, 1986) has increased environmental concern in this area.

Saline soil is naturally prevalent in the low-lying areas of the western valley (Harradine, 1950). The soil salinity is the result of low rainfall, high evapotranspiration rates, and the erosion of saline, sedimentary deposits from the Diablo Range that form the alluvial fans of this area. The areas of highest naturally occurring soil salinity are coincident with the areas of high ground-water salinity and selenium concentrations (Deverel and Gallanthine, 1989). Leaching of soil salts and associated selenium is the primary factor that has led to high concentrations of dissolved solids and selenium in shallow ground water.

Irrigation of this area and the importation of water from northern California caused the water table to rise. The percentage of the area characterized by a water table within 6 m of land surface has increased substantially since 1952 (Belitz and Heimes, 1990). The rise in the water table resulted in evapotranspiration from a shallow water table, further concentrating the dissolved solutes in the ground water and resulting in the highest selenium concentrations (Deverel and Gallanthine, 1989).

The highly mobile selenate ion ($SeO_4^=$) is the predominant selenium species in the oxidized and alkaline, regional shallow ground water (Deverel and Millard, 1988; Deverel and Gallanthine, 1989). Saline, high-selenium ground water is being displaced from the shallow aquifer to agricultural drainage systems by less saline water that has percolated past the crop root zone. The extent of this displacement is proportional to the length of time since installation of the drainage system (Pillsbury and others, 1965; Jury, 1975a, 1975b; and Deverel and Fujii, 1988). Because of low hydraulic conductivities and gradients, ground-water velocities generally are less than 2 m/yr. Given the lateral spacing of subsurface drains from 30 to 100 m, the time required for complete displacement of saline ground water to a drainage system can be as long as several decades.

Development of effective water-management practices in the San Joaquin Valley will rely on a quantitative understanding of the factors affecting the chemical composition of drain water. The chemistry of drain water is affected by hydrologic and geochemical factors related to the distribution of chemical constituents in the ground water and ground-water flow to drain laterals. This paper and a companion paper (Fio and Deverel, 1990) describes the results of the study of geochemistry, ground-water flow, and advective solute movement in ground water underlying an artificially drained field studied by Deverel and Fujii (1988).

In 1985, at the time of the study by Deverel and Fujii (1988), the field had been artificially drained for 15 years and was denoted as the 15-year field. The field was first irrigated in the 1930's. Deverel and Fujii (1988) evaluated geochemical and isotopic data for shallow ground-water samples and hydrologic measurements in the 15-year field and two other fields that had been drained for 6 and 1.5 years. In the 15-year field, these authors concluded that ground water was moving to drain laterals from a sand layer at a depth greater than 9 m below land surface. Stable-isotope data indicated that the water reaching the drain laterals was relatively old, partially evaporated water that had been displaced by more recently recharged water subject to less evaporation.

The objectives of this study are: (1) to better quantify the hydrologic and geochemical relations described in Deverel and Fujii (1988); (2) to evaluate the transient changes in ground-water hydraulics and drain-lateral flow and chemistry during irrigation; and (3) to quantitatively assess steady-state ground-water flow and advective solute movement to drain laterals. This paper describes the geochemical and hydrologic relations and the evaluation of transient changes during irrigation. A companion paper (Fio and Deverel, 1990) describes steady-state ground-water flow and advective solute movement. The primary focus of these two papers is a quantitative description of the processes affecting the mobility and distribution of salinity and selenium in ground water and drain water. These studies are a part of a comprehensive investigation of the hydrology and geochemistry of the San Joaquin Valley by the U.S. Geological Survey. The studies are being done in cooperation with the San Joaquin Valley Drainage Program and as part of the Regional Aquifer-System Analysis Program of the U.S. Geological Survey.

The approach was to use geochemical and physical data to develop a better understanding of the movement of ground water and transport of dissolved constituents in ground water associated with agricultural drainage in the western San Joaquin Valley. Physical and geochemical data were collected from January 1987 through September 1989 in observation wells installed in the field and at the edge of the field and drain laterals. To gain insight into the processes operating during irrigation, hydrologic and geochemical data were collected at short intervals before, during, and after irrigations in November 1988 and June/July 1989. Physical measurements included ground-water hydraulic gradients, flow in the drain laterals and sump, and soil moisture tension and soil moisture content. Samples were collected from the drain laterals and sump and analyzed for pH, specific conductance, and various chemical constituents and isotopic (oxygen-18 and deuterium) composition.

DESCRIPTION OF STUDY SITE

The location of the 15-year field studied by Deverel and Fujii (1988) is shown in figure 1. Additional data were collected in this field during this study. The drainage system was installed in 1969 when ground-water levels and soil salinity adversely affected crop

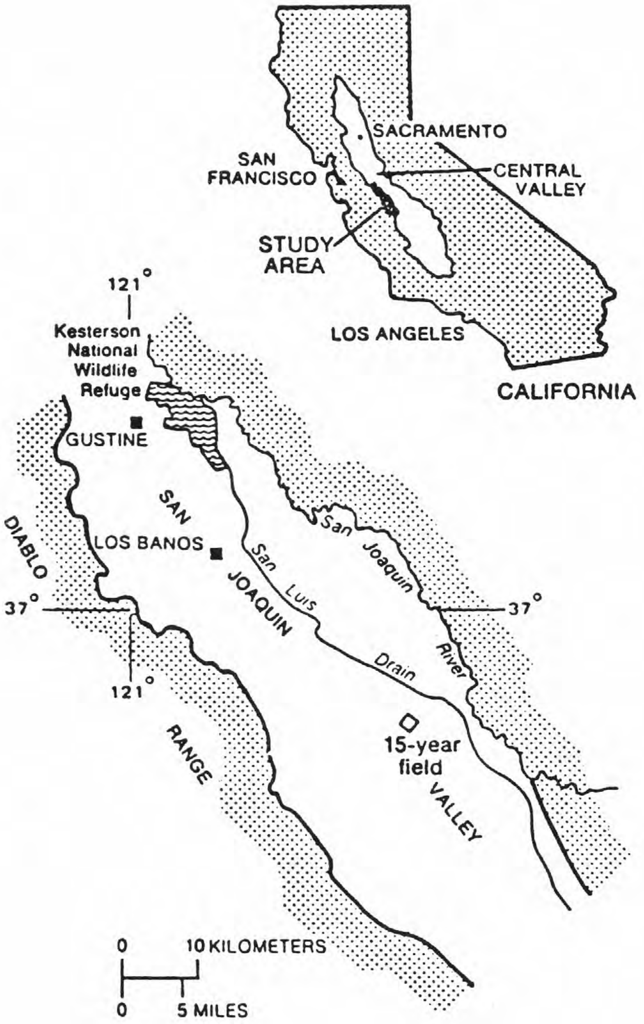

Figure 1. Location of study area and drained agricultural field.

yields (Willardson and others, 1970). The drainage system consists of six 0.15-meter diameter concrete drain laterals installed 1.8, 2.7, and 2.3 m below land surface and spaced laterally from a minimum distance of 38 m to a maximum distance of 76 m.

A schematic of the part of the drainage system where data were collected for this study is shown in figure 2. Flow was measured in the 1.8-meter and 2.7-meter drain laterals denoted as drain laterals 1 and 2, respectively. Geohydrologic section A-A' shown in figure 2 is used to represent the distribution of isotopic and chemical composition of ground-water samples and hydraulic head at sites 1 through 4.

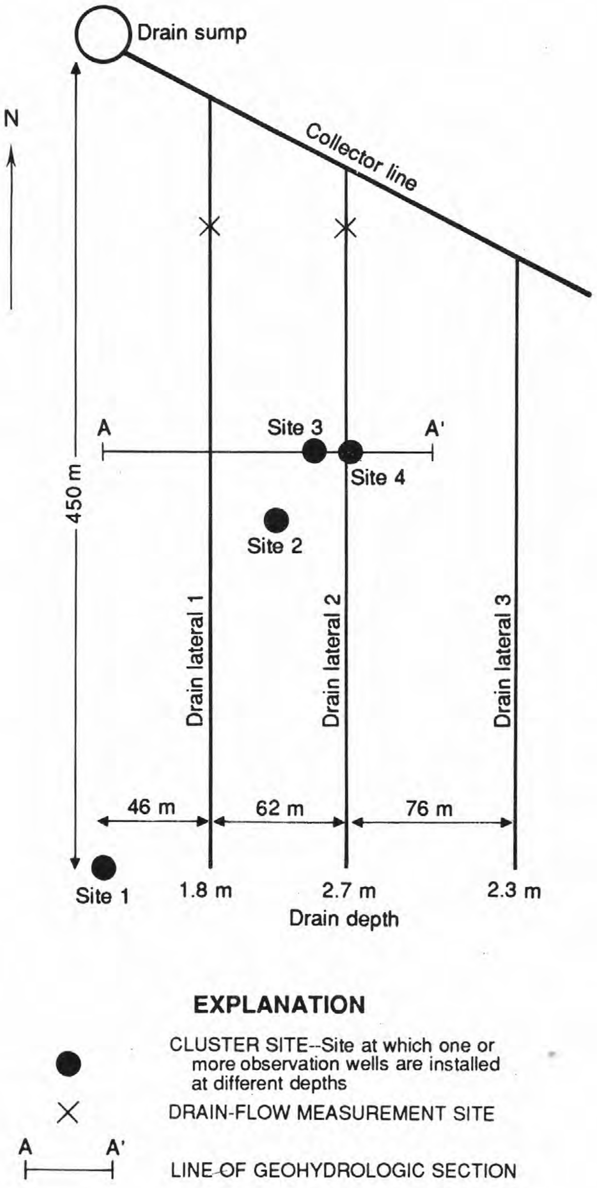

Figure 2. Drainage system in the 15-year field and locations of cluster sites, drain-flow measurement sites, and geohydrologic section A-A'.

The study area has a semiarid climate. Recharge to the water table primarily is from irrigation water applied prior to and during the agricultural growing season. The estimated net rate of recharge to the water table in areas of the central part of the western San Joaquin Valley with drain laterals is between 0.16 and 0.41 m/yr (Phillips and Belitz, 1989). Regional ground water in the shallow (within 30 m of land surface) semiconfined aquifer flows from southwest to northeast.

METHODS

FIELD

Observation wells were installed at four cluster sites (sites 1, 2, 3, and 4) in the field (fig. 2). Four wells each were installed with screened intervals centered at 3, 6, 12, and 15 m below land surface at sites 2, 3, and 4. At site 1, five wells were installed with screened intervals centered at 3, 6, 12, 15, and 27 m below land surface. The 0.20-meter diameter boreholes for the observation wells were drilled using a hollow-stemmed auger. Borehole samples were collected in 0.91-meter increments with a steel sampling tube, and a sample of the profile was analyzed at the U.S. Geological Survey sediment laboratory in Salinas, California, for determination of the proportion of sand, silt, and clay (Guy, 1969).

The polyvinyl-chloride well casings (0.05-meter diameter) with 0.60-meter perforated intervals were installed in the boreholes. The perforated intervals were surrounded by sand, and the annular spacing from the top of the sand to land surface was sealed with bentonite grout.

Ground-water samples collected from the observation wells in March 1987 and July 1988 and drain-lateral and drain-sump samples collected from March 1988 through May 1989 were analyzed for various chemical constituents, stable oxygen- and hydrogen-isotopic composition, and tritium. The ground-water samples were collected through Teflon[1] tubing with bladder pumps placed down the wells. Prior to sampling, the well was pumped until several well-casing volumes were removed, and the electrical conductivity of consecutive well volumes did not vary more than 10 percent. Samples to be analyzed for selenium were pressure filtered through filters having a nominal pore size of 0.45 μm and collected in acid-washed bottles and preserved with nitric acid (HNO_3) to a pH of less than 2. All sampling and filter apparatus were rinsed thoroughly with well water prior to sample collection. Unfiltered samples (for analysis of the stable isotopes and tritium) were collected in glass bottles with polyethylene lids so that there was no air space. Drain-lateral and drain-sump samples were collected through Teflon tubing placed in the drain lateral or sump and attached to a peristaltic pump.

The flow velocity in the drain laterals and sump was measured with an electromagnetic velocity meter (the velocity meters have an accuracy of ±0.0030 m/s). The cross-sectional area of flow was calculated from the internal drain-lateral inside geometry and the measured height of flow in the drain lateral. The flow was calculated as the product of the velocity and cross-sectional area.

Hydraulic head was calculated from water-level and pressure measurements with pressure transducers placed in the wells. Field data loggers buried in the field and flooded in June 1989 were not discovered to be inoperative until September 1989, therefore, hydraulic head values are not reported after June 1989.

LABORATORY

Selenium in water samples was determined by hydride-generation atomic-absorption spectrophotometry (Fishman and Bradford, 1982). The method is designed to determine the total concentration of all forms of selenium present in a water sample. The oxygen-18 isotope composition of the water samples was determined using a modification of the carbon dioxide equilibration method of Epstein and Mayeda (1953). The results are reported relative to Vienna Standard Mean Ocean Water (V-SMOW) in the delta notation where:

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{V-SMOW}}{(^{18}O/^{16}O)_{V-SMOW}} \times 1{,}000. \quad (1)$$

The stable hydrogen-isotopic composition (expressed as delta deuterium or δD) was determined by analyzing hydrogen quantitatively extracted from water (Kendall and Coplen, 1985). Hydrogen results are reported relative to V-SMOW in the per mil notation. The standard deviations of the oxygen- and hydrogen-isotopic compositions are 0.10 and 1.00 per mil, respectively. The hydrogen- and oxygen-isotopic compositions were determined in the Isotope Fractionation Project Laboratory of the U.S. Geological Survey, Reston, Virginia.

Tritium was determined by scintillation counting after electrolytic enrichment (International Atomic Energy Agency, 1976). Tritium concentrations are expressed

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[1] The use of brand, firm, or trade names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

in tritium units (TU), where 1 TU is equal to 1 tritium atom in 10^{18} hydrogen atoms. All tritium analyses were done by the Environmental Isotope Laboratory at the University of Waterloo, Ontario, Canada. Standard deviation for tritium concentrations is about 0.8 TU.

RESULTS AND DISCUSSION

GENERAL RELATIONS

As the water table in the 15-year field rose to within 1.5 m of land surface in the mid-1960's, substantial evapotranspiration from the shallow ground water caused increased soil and ground-water salinity. The installation of a drainage system in 1969 prevented further evapoconcentration of solutes in the shallow ground water by lowering the water table to below 1.5 m where there is negligible evapotranspiration. Prior to the drainage-system installation, ground-water hydraulic gradients primarily were vertically downward. Partially evaporated ground water that was near land surface prior to the drainage-system installation was displaced downward in the aquifer.

When the drainage system was installed, hydraulic gradients were changed so that ground water flowed upward and horizontally toward the drain laterals. Willardson and others (1970) reported that the specific conductance of the drain-sump water was 14,000 µS/cm in 1969. This value is substantially higher than the value of about 9,000 µS/cm measured during this study. Ground-water-flow paths and chemistry and isotopic composition of ground-water samples indicate that partially evaporated, saline ground water within about 6 m of land surface probably was displaced toward the drain laterals by recently recharged non-saline ground water within the first decade after drainage-system installation. This caused a decrease in the specific conductance of water from the drain sump. Saline ground water at deeper depths and less saline ground water at shallower depths flow into the drain laterals.

The relative proportions of low-salinity water within 6 m below land surface and deeper saline water that flow into the drain laterals are dependent on the depth of the drain laterals and the amount of recharge. Selenium concentrations in ground-water and drain-lateral samples are correlated with dissolved solids. These general relations are illustrated by (1) the distribution of ground-water hydraulic head; (2) the distribution of tritium, oxygen-18, deuterium, and selenium concentrations in the ground water; and (3) drain flow and the chemical and isotopic composition of drain-lateral samples.

HYDRAULIC HEAD

The median hydraulic head for each well during the study period and the general direction of ground-water flow in geohydrologic section A-A' is shown in figure 3. From visual inspection of core material collected during drilling, a continuous sand layer was identified about 9 m below land surface. Above the sand layer, the texture of the aquifer material is clay loam. Numerous sand strata ranging from a few centimeters to 7 cm in thickness were identified in the clay-loam strata. Ground water flows horizontally in the sand layer and vertically upward toward the drain laterals in the sand layer and the clay loam overlying the sand layer. Although the lithologic and hydraulic conductivity (Fio and Deverel, 1990) data indicate substantial heterogeneity in the clay loam and sand layers, our inability to adequately quantify this heterogeneity has led us to simplify our conceptual and quantitative models of the system to two layers.

The changes in hydraulic head in nine observation wells at sites 1 and 4 (center of perforated intervals 3, 6, 12, 15, and 27 m below land surface) from January 1987 to June 1989 are shown in figure 4. The field was irrigated four times in 1987, a preplant irrigation in early January and three irrigations during the summer months (late June to September). The field was then fallow and was not irrigated until November 1988. Recharge to the water table from irrigation caused increasing hydraulic heads in 1987 and November 1988. Removal of ground water by the drain laterals and evapotranspiration caused decreasing heads after irrigation. Hydraulic heads increased during January and February 1988 and 1989 because of irrigation of areas upgradient from the field.

The median hydraulic gradients were different for irrigated conditions (1987) and nonirrigated conditions (October 1987 through October 1988). The median upward vertical gradient from 15 m below land surface to drain lateral 2 was 0.011 during the irrigated period. The median horizontal gradient from the western boundary of the geohydrologic section to drain lateral 2 was 0.0016 during the nonirrigated period and 0.0032 during the irrigated period. The gradients were calculated from hydraulic head measured in the observation wells. At site 4, the 3-meter well is within 1 m of drain lateral 2 and the hydraulic head in this well is similar to that in the drain lateral.

The hydraulic-head gradient at site 4 generally was upward from the 15-meter well to the 3-meter well adjacent to drain lateral 2 (fig. 4). Hydraulic gradients

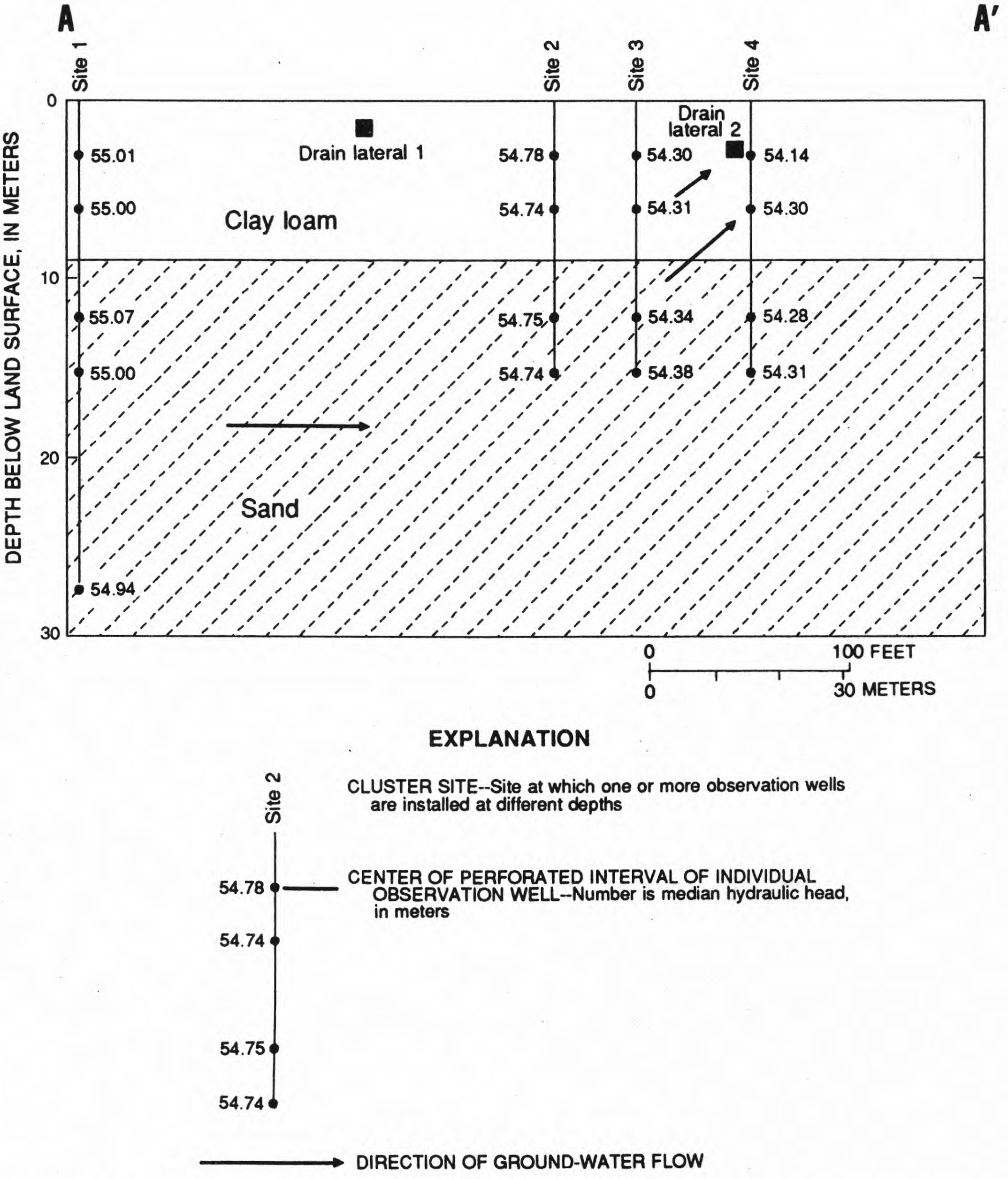


Figure 3. Median hydraulic head for observation wells at cluster sites 1, 2, 3, and 4 and general direction of ground-water flow along geohydrologic section A-A' in the 15-year field.

were largest during irrigation periods during the summer of 1987 and the winters of 1988 and 1989. In January and February of 1988 and 1989, no water was applied in the 15-year field, but adjacent fields were irrigated causing hydraulic heads to increase in this field. The differences in hydraulic head between wells at site 4 are larger than the other sites because of the proximity to drain lateral 2.

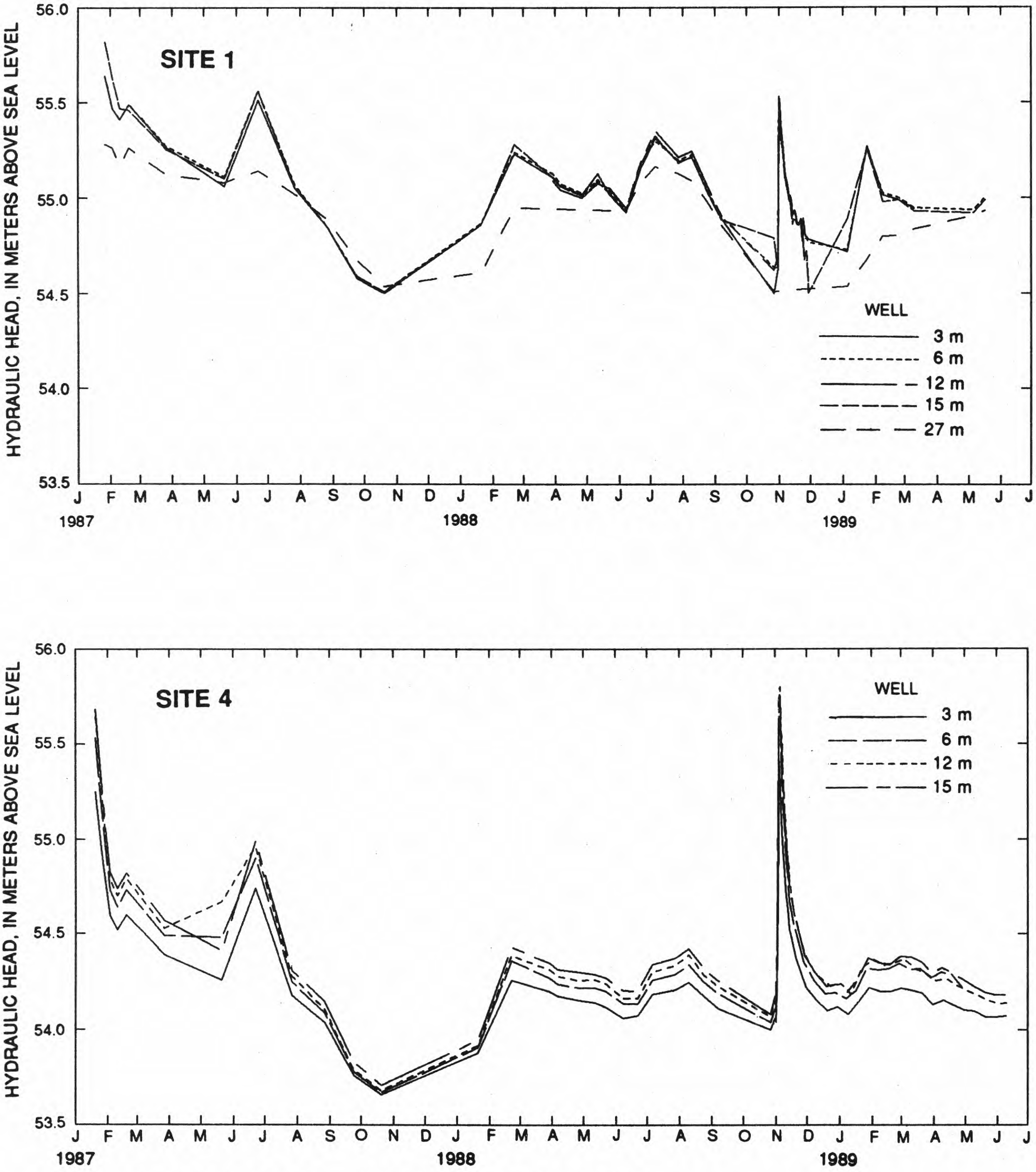


Figure 4. Changes in hydraulic head with time at cluster sites 1 and 4.

In contrast to the other sites, a well was placed at the 27-meter depth at site 1. The temporal variability of the hydraulic heads and gradients in the 3-, 6-, 12-, and 15-meter wells at site 1 is similar to that measured at sites 2 and 3. Hydraulic gradients generally are upward from 15 m below land surface. From 15 to 27 m, the hydraulic gradient is almost always downward.

The direction of the median horizontal component of ground-water flow in the geohydrologic section was estimated from the median hydraulic heads in wells at cluster sites 2, 3, and 4. The median horizontal-flow directions in the clay loam and sand layers are shown in figure 5. Horizontal flow in the clay loam is perpendicular to the drain laterals. In the sand layer, horizontal flow is to the northeast. Ground-water flow in the clay loam is affected more by the drain laterals, and horizontal flow in the sand layer is affected more by the regional-flow system. Beyond the influence of the drainage system, the direction of the horizontal flow in the clay loam and sand layers probably will be the same and determined by the regional-flow system.

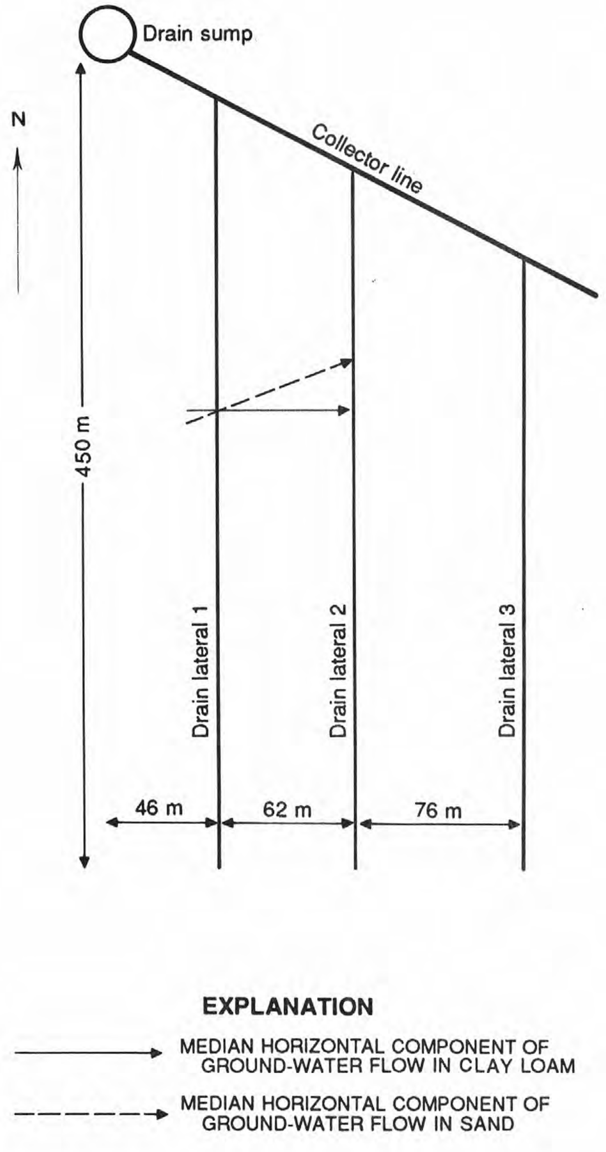


Figure 5. Direction of median horizontal components of ground-water flow in clay loam and sand.

ISOTOPIC AND CHEMICAL COMPOSITION OF GROUND WATER

The distribution of tritium, oxygen-18, and selenium in samples collected in the observation wells provides information about the processes affecting the chemical and isotopic composition of drain water. The distribution of tritium in ground water provides information about historical ground-water recharge and flow to drain laterals. Figure 6 shows the distribution of tritium in samples collected in 1987 and 1988.

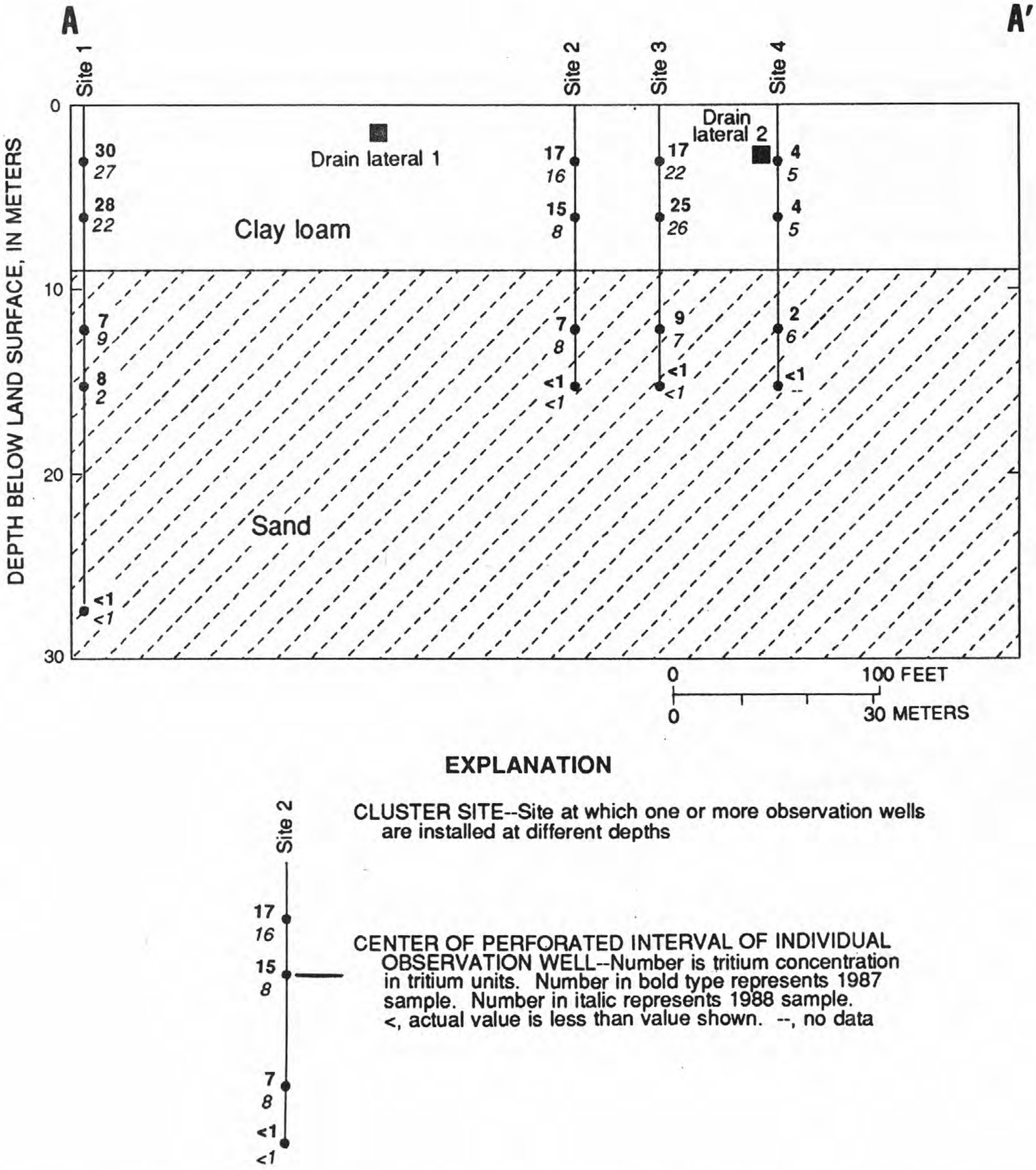
In the three cluster sites in the 15-year field (sites 2, 3, and 4), tritium was not detected in the samples collected from the 15-meter wells indicating that ground water at this depth infiltrated prior to 1952. All samples collected above 15 m had tritium and therefore infiltrated after 1952. Because tritium was detected in ground water from the 12-meter depth at sites 2, 3, and 4, a boundary between the 12- and 15-meter depths divides ground water that infiltrated before and after 1952. Hydraulic influence of the drain laterals at sites 2, 3, and 4 probably caused the presence of bomb-era tritium at a shallower depth than at site 1.

Stable hydrogen- and oxygen-isotope data confirm the historical information provided by the tritium data. The relation between delta deuterium (δD) and delta oxygen-18 ($\delta^{18}O$) is shown in figure 7. The equation representing all ground-water samples, including the samples collected by Deverel and Fujii (1988), is similar to the slope of the evaporative trend line reported by Deverel and Fujii (1988):

$$\delta D = -31.3 + 4.09\,\delta^{18}O \;(r^2 = 0.91). \qquad (2)$$

The slope of the line represented by this equation indicates the samples have been subject to partial evaporation (Deverel and Fujii, 1988).

Delta D and $\delta^{18}O$ for samples with and without detectable tritium indicate the different origins of the infiltrating water. The isotopic composition of samples collected during 1987 and 1988 from the irrigation canal that has supplied irrigation water to this field since 1952 is shown in figure 7. Points representing these samples and isotopically nonenriched ground-water samples collected by Deverel and Fujii (1988) and during this study, are on or close to a local



CLUSTER SITE--Site at which one or more observation wells are installed at different depths

CENTER OF PERFORATED INTERVAL OF INDIVIDUAL OBSERVATION WELL--Number is tritium concentration in tritium units. Number in bold type represents 1987 sample. Number in italic represents 1988 sample. <, actual value is less than value shown. --, no data

Figure 6. Tritium in samples collected in observation wells at cluster sites 1, 2, 3, and 4.

ground-water line (Davis and Coplen, 1989). The similarity in isotopic composition of the shallow ground-water samples collected by Deverel and Fujii (1988) and the samples collected from the 3-meter wells at sites 1, 2, and 3 and the irrigation canal indicates a common source of water. The equation of the evaporative trend line representing the samples with detectable tritium is:

$$\delta D = -29.4 + 4.31\ \delta^{18}O\ (r^2 = 0.91). \qquad (3)$$

Analysis of covariance (Draper and Smith, 1981) shows that the equation of the line representing the samples without detectable tritium,

$$\delta D = -24.9 + 5.10\ \delta^{18}O\ (r^2 = 0.60) \qquad (4)$$

is significantly different (α=0.01) from the equation representing the samples with detectable tritium. The intercept of this line with a line representing the local ground-water line, $\delta D = -2.58 + 7.39\ \delta^{18}O$ (Davis and Coplen, 1989), is -9.75 per mil and close to the mean $\delta^{18}O$ of -9.24 per mil reported by Davis and Coplen (1989) for the northern lower water-bearing zone. This water-bearing zone probably was the primary source of irrigation water for this field prior to 1952. Irrigation

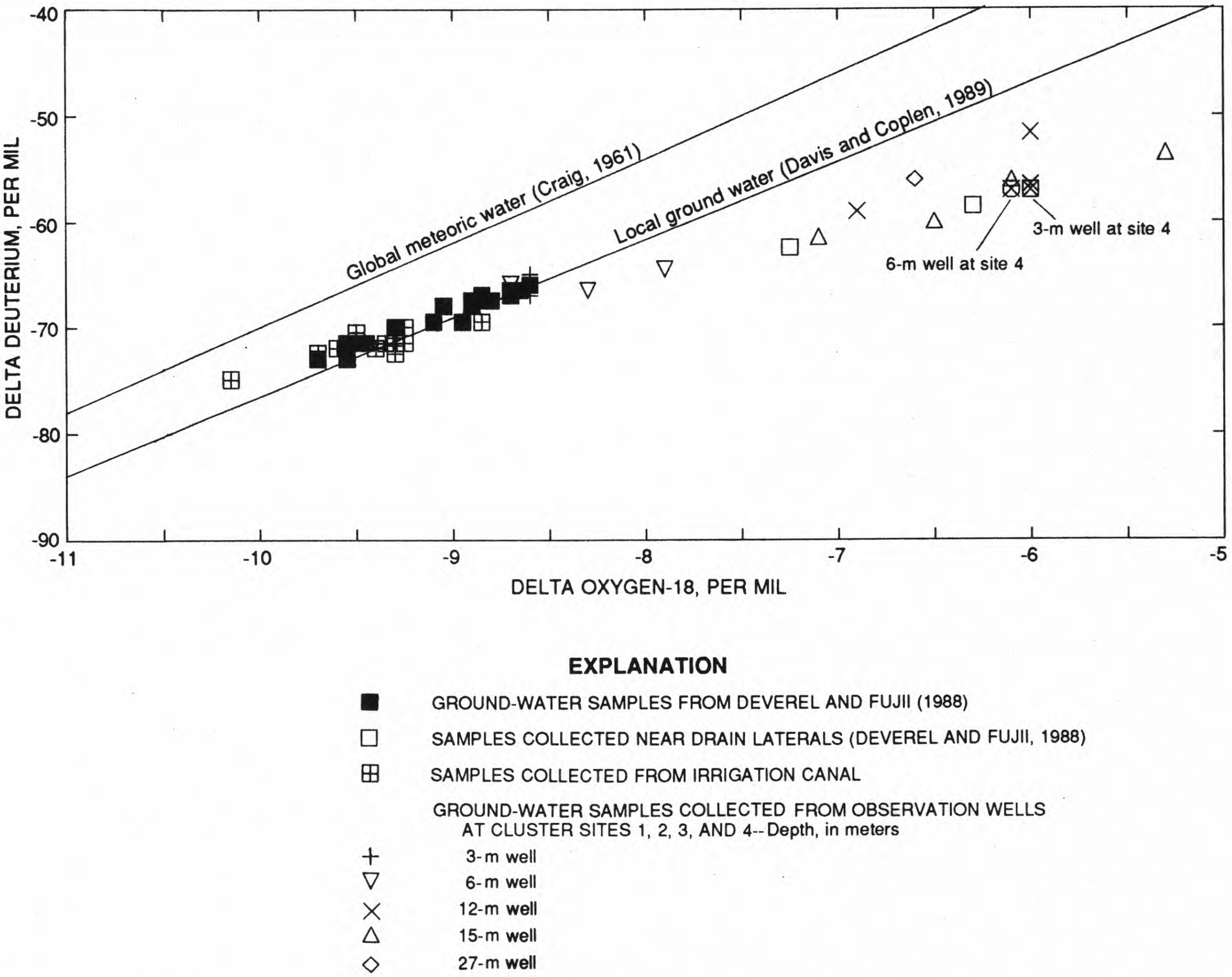


Figure 7. Relation of delta deuterium and delta oxygen-18 for ground-water and irrigation-water samples.

water also was pumped from the upper water-bearing zone. The $\delta^{18}O$ value for this ground water ranges from about -7 to -9 per mil (Davis and Coplen, 1989).

The distribution of $\delta^{18}O$ in the ground-water samples is shown in figure 8. In general, ground-water samples collected at the shallow depths (at and less than 6 m below land surface) are not enriched and represent water infiltrated after drainage-system installation. Samples collected at the deeper depths (greater than 6 m below land surface) are isotopically enriched and were subject to evaporative enrichment near land surface prior to the drainage-system installation. Samples collected at the shallow depths next to and directly below drain lateral 2 also are isotopically enriched.

The isotopic composition of the ground water can be divided into two groups. Group 1 (median $\delta^{18}O$=-8.9 per mil) includes water samples collected at sites 1, 2, and 3 at and less than 6 m below land surface during this study and samples collected in shallow wells by Deverel and Fujii (1988). These samples represent ground water that is not isotopically enriched and infiltrated after drainage-system installation. Group 2 (median $\delta^{18}O$=-6.3 per mil) includes samples collected at depths greater than 6 m below land surface. These samples represent isotopically enriched ground water that has been subject to more evaporation than the shallow ground water. This ground water infiltrated prior to drainage-system installation.

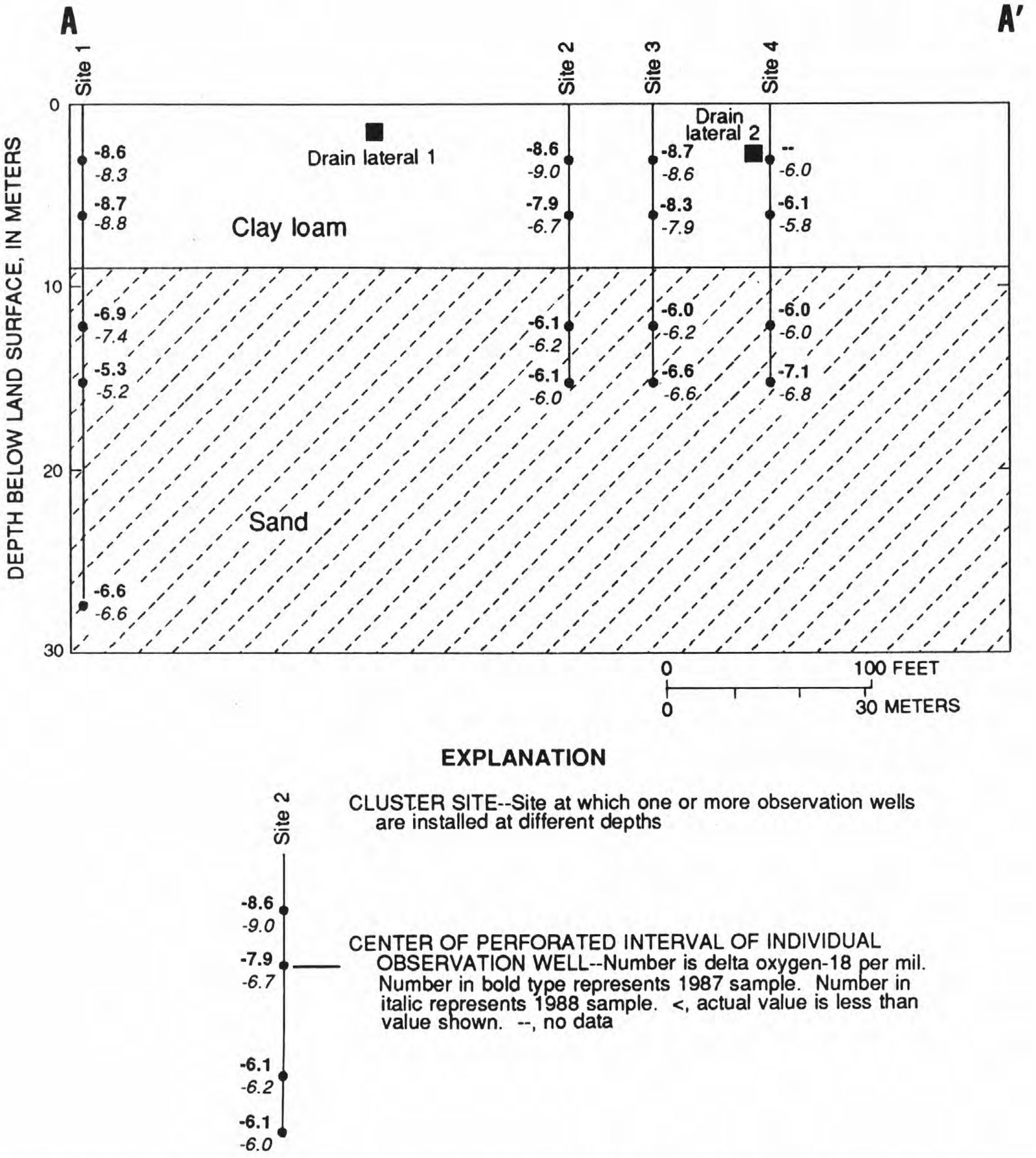


Figure 8. Delta oxygen-18 in samples collected in observation wells at cluster sites 1, 2, 3, and 4.

In separating isotopic composition of ground-water samples into two groups, we have assumed that the variability in isotopic composition within each group is due to spatial variability of the evaporative process and the mixing of waters that recharged at different times. In the calculation of median values, the points representing the samples collected at the 6-meter depths at sites 2, 3, and 4 and the 3-meter depth at site 4 were eliminated. The ground water in these wells probably is affected by ground water flowing from deeper depths toward drain lateral 2 (Fio and Deverel, 1990). The innerquartile ranges for groups 1 and 2 are -9.4 to -8.7 per mil and -6.5 to -6.0 per mil, respectively. Because of the separation in space of the samples representing each group and the small variability within each group relative to the difference between the groups, the isotopic composition of samples in each group probably has not been influenced by the other group, except at the 6-meter depths at sites 2, 3, and 4 and the 3-meter depth at site 4.

The relation of δD to $\delta^{18}O$ for drain-lateral samples collected during the study period and the median isotopic composition for the two ground-water groups is shown in figure 9. The points representing the isotopic compositions of the drain-lateral samples are in between the two ground-water groups and represent a mixture of the two groups. The samples collected in drain lateral 1 are less enriched than those collected in drain lateral 2. Drain lateral 2 is deeper and collects more of the isotopically enriched ground water. The isotopic compositions of the drain-lateral samples vary substantially over time (fig. 9). The temporal variability of the isotopic composition of the drain-lateral samples is due to the varying influx of the proportions of shallow and deep ground water.

The distribution of selenium in the ground water is similar to the distribution of $\delta^{18}O$. High selenium concentrations are the result of evapoconcentration of shallow ground water and dissolution of soluble salts and are associated with oxygen-18 enrichment and dissolved solids in ground water. The distribution of selenium concentrations in ground-water samples collected during this study is shown in figure 10. Selenium concentrations were greater than 700 µg/L for samples collected directly beneath and adjacent to drain lateral 2 and at depths greater than 6 m. The six samples collected at and less than the 6-meter depth and the shallow samples collected by Deverel and Fujii (1988) had lower selenium concentrations. The geometric mean of selenium concentrations for the shallow ground-water samples collected by Deverel and Fujii (1988) was 108 µg/L. Their data showed that selenium concentrations for samples collected near drain lateral 2 were four to six times greater than the geometric mean.

Selenium concentrations and $\delta^{18}O$ were substantially larger in the 1988 sample collected at the 6-meter well at site 2 relative to the 1987 sample (figs. 8 and 10). The greater isotopic enrichment and higher selenium concentration in the most recent sample indicate the arrival of more evaporated, high-selenium ground water from the west. Steady-state ground-water modeling results simulating nonirrigated conditions described in Fio and Deverel (1990) indicate the existence of a flow path originating at the edge of the field, flowing upward toward drain lateral 2, and across the clay-loam/sand boundary. Ground water flowing along this flow path or other adjacent flow paths calculated by the

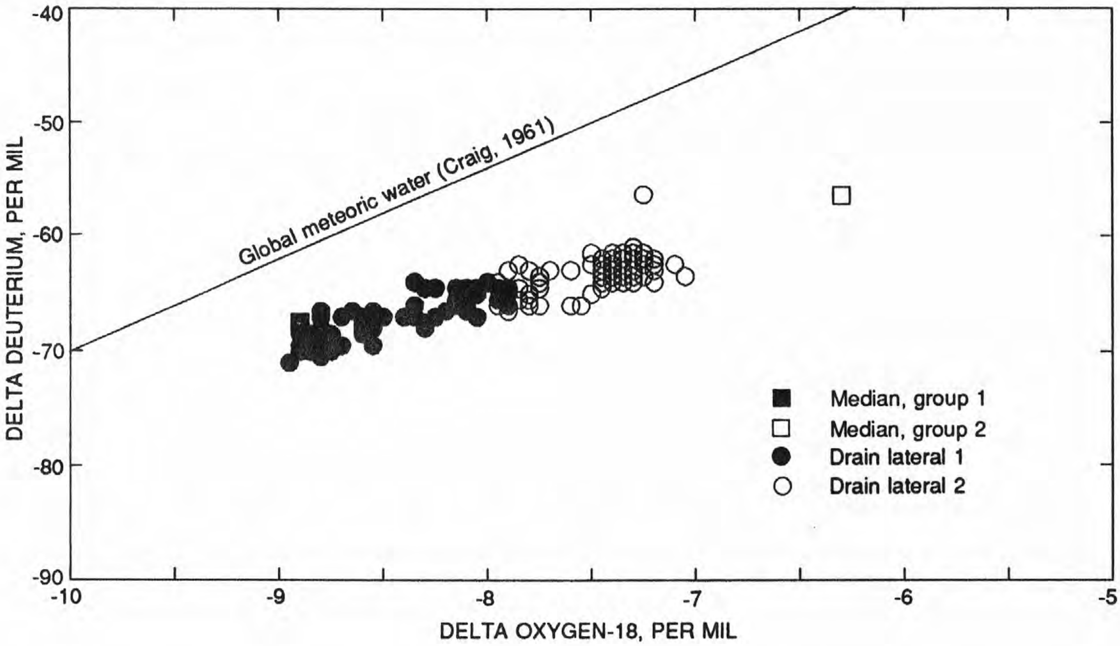


Figure 9. Relation of delta deuterium to delta oxygen-18 for drain-lateral samples and median isotopic composition for two ground-water groups (see text for explanation).

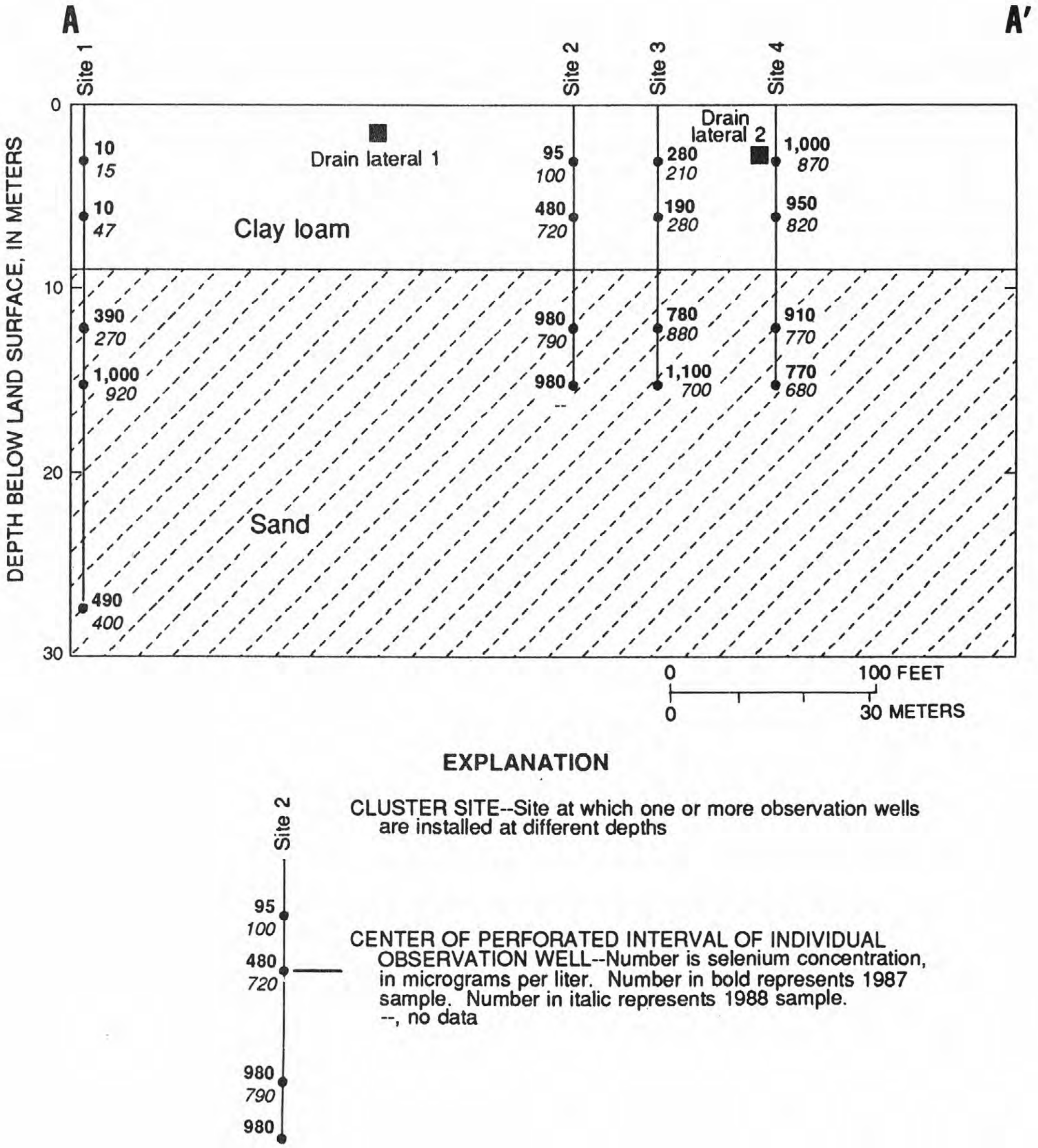


Figure 10. Selenium concentrations for samples collected in observation wells at cluster sites 1, 2, 3, and 4.

steady-state simulation and originating west of site 2 had apparently not reached the 6-meter well at site 3 in 1988. Ground-water flow during irrigation also influences the chemical composition of samples collected from observation wells. Concentric flow paths extending from the water table to drain lateral 2 intersect the 6-meter wells at sites 2 and 3 (Fio and Deverel, 1990, fig. 9). The high-selenium isotopically enriched ground water reaching the 6-meter well at site 2 probably is ground water that has moved from the sand layer toward drain lateral 2. The actual traveltime is affected by dispersion and interaction of irrigated and nonirrigated flow paths (Fio and Deverel, 1990).

Selenium concentrations in ground water generally are correlated with dissolved solids in ground water; however, the correlation between selenium and dissolved solids is different for samples with detectable tritium than for samples without detectable tritium. The equation representing the data for samples with detectable tritium is:

$$\log_{10} \text{selenium } (\mu\text{g/L}) = -21.1 + 5.29 \times \log_{10} \text{dissolved solids (mg/L)} \quad (r^2=0.82) \qquad (5)$$

The equation representing the data for the four samples collected in 1987 without detectable tritium is:

$$\log_{10} \text{selenium } (\mu\text{g/L}) = -6.32 + 1.63 \times \log_{10} \text{dissolved solids (mg/L)} \quad (r^2=0.90) \qquad (6)$$

The predominant anion in the ground-water samples was sulfate. There was no predominant cation in most samples except for those with the highest dissolved-solids concentrations where sodium was predominant. Dissolved-solids concentrations are limited by gypsum precipitation as the ground water becomes more concentrated by evaporation, and selenium to sulfate ratios increase with increasing evaporation of ground water (Deverel and Fujii, 1988). The large slope of the regression line for the relation of selenium and dissolved solids for samples with tritium apparently is the result of partial evaporation of samples with the highest selenium concentrations. The slope of this regression line is disproportionately influenced by the points representing the samples from the 12-meter wells. Evapoconcentration causes selenium concentrations to increase relative to sulfate and therefore dissolved-solids concentrations.

In contrast, the small slope of the relation of selenium and dissolved solids for the samples without detectable tritium probably is the result of salt dissolution. The samples collected at the 15- and 27-meter depths represent ground water that was near land surface soon after the onset of irrigation and was subject to less evaporation (fig. 6) than the samples collected at the 12-meter depth, which have the highest dissolved-solids concentrations. Furthermore, the irrigation water applied to the field prior to 1952 probably had higher $\delta^{18}O$ values than the irrigation water applied after 1952. The high selenium probably is the result of the dissolution of sodium and magnesium sulfate salts that contained selenium that was present in the soil prior to irrigation.

Evaluation of chloride concentrations (in milligrams per liter) relative to selenium concentrations (in micrograms per liter) at different depths further elucidates the relation of selenium and dissolved solids because chloride concentrations are not limited by mineral solubility. Selenium to chloride ratios are less than 1 for samples collected at the 3-, 6-, and 12-meter depths that represent ground water with detectable tritium. Median selenium to chloride ratios are 0.33, 0.38, and 0.57 for the 3-, 6-, and 12-meter depths, respectively. The median ratios for selenium and chloride are 1.38 and 1.6 for the 15- and 27-meter depths, respectively. Chloride concentrations vary with depth, median values are 725, 1,097, 1,250, 652, and 250 mg/L for samples collected at the 3-, 6-, 12-, 15-, and 27-meter depths, respectively.

The ground-water samples collected at the 15- and 27-meter depths have lower chloride concentrations than the samples collected at the 12-meter depth because they have been subject to less evaporation. As the water table rose, chloride became concentrated by evapotranspiration in the shallow ground water as represented by samples collected at 12 m. This ground water was near land surface in the late 1950's and originated as irrigation water from the Federal Central Valley Project. The lower selenium to chloride ratio in this ground water is the result of a limitation of selenium solubility relative to the samples from the 15- and 27-meter depths.

The concentrations of selenium, tritium, and the isotopic enrichment in samples collected in the drain laterals provide evidence that ground water reaching the drain laterals is a mixture of deep and shallow ground water. The deep ground water, represented by samples collected at depths greater than 6 m, infiltrated before drainage-system installation and has the highest selenium concentrations and greatest isotopic enrichment. The recently recharged shallow ground water is low in selenium concentrations and is not isotopically enriched.

Data collected at another field in the study area shows a similar pattern in the distribution of ground-water constituents. Isotopic and geochemical data on ground water collected for a field that was drained for 6 years at the time of sampling (Deverel and Gallanthine, 1989) show that the ground-water samples with the highest salinity and selenium concentrations and greatest isotopic enrichment were collected at the 6- and 9-meter depth below land surface. This ground water infiltrated prior to drainage-system installation and was subject to partial evaporation when the water table was within 1.5 m of land surface. The samples collected at depths greater than 6 m and less than 9 m were less isotopically enriched and salinity and selenium concentrations were lower. The ground water at the 3-meter depth infiltrated after drainage-system installation and displaced the more saline water at the 6- and 9-meter depths.

The isotopic composition of ground-water samples collected from wells installed and sampled in 1987 in the 1-year field originally studied by Deverel and Fujii (1988) in 1985 showed a pattern that is consistent with the above discussion. The shallowest (3 m) ground-water samples were isotopically enriched relative to the samples collected at the 6-, 12-, and 15-meter depths. Because this field had been drained only for 3 years at the time of sampling, the shallowest ground water that was subject to partial evaporation prior to drainage-system installation has not been substantially displaced.

CHEMISTRY AND FLOW OF DRAIN-LATERAL WATER

Isotopic Composition and Flow

The isotopic composition of the water flowing in the drain laterals further elucidates the ground-water mixing process in the drain laterals. The proportions of isotopically enriched deep ground water entering from depths greater than 6 m below land surface and isotopically depleted shallow ground water entering from areas at depths less than 6 m to the drain lateral varies with time and is different for the two drain laterals.

The $\delta^{18}O$ values for samples collected from March 1988 through September 1989 and during irrigations in November 1988 and June and July 1989 are shown in figure 11. The $\delta^{18}O$ values for samples collected from March through October 1988 are relatively constant and are enriched relative to the values for samples collected during irrigations in November 1988 and June and July 1989. During irrigation in November 1988 and June and July 1989, the $\delta^{18}O$ values decreased substantially because of the increased influx of shallow, nonenriched ground water in drain lateral 2 (fig. 11). Shallow isotopically nonenriched ground water began flowing into the drain lateral 1 during irrigation. As irrigation water shifted further east in the field and later during drainage, $\delta^{18}O$ increased in the drain-lateral samples as proportionally more deep ground water flowed into the drain laterals.

Less water was applied during irrigation in June and July 1989 relative to irrigation in November 1988. Hydraulic gradients were presumably lower and less shallow ground water flowed into the drain lateral during irrigation.

We assumed that the isotopic composition of water in the drain laterals is the result of conservative mixing of the two ground-water groups (fig. 9). The medians of $\delta^{18}O$ values for the two ground-water groups were used to represent the end-member values for calculating the proportions of shallow and deep ground water flowing to the drain laterals. Because the observation wells were installed close to drain lateral 2, the calculations for drain lateral 1 are subject to greater uncertainty. The changes in flow in the drain laterals and the flow derived from the deep ground water during the study are shown in figure 12. As flow increased because of increased hydraulic gradients during irrigations in November 1988 and June and July 1989, proportionally more ground water flowed from the shallow part of the aquifer to the drain laterals. In November 1988, irrigation moved across the field from west to east in furrows over drain lateral 1 on November 1 and drain lateral 2 on November 3. The irrigation ended on November 8. Similarly in June and July 1989, irrigation moved across the field such that water flowed in furrows over drain lateral 1 on June 27 and drain lateral 2 on June 28. The irrigation ended on July 2.

Although a substantial part of the total flow in drain lateral 1 (about 30 percent) is from deep ground-water flow, the increase in flow during irrigations (fig. 12) almost entirely is derived from flow from the shallow ground water. Less water flows in drain lateral 1 than in drain lateral 2. Drain lateral 1 stopped flowing in October 1988 but resumed in November 1988 during irrigation.

In contrast, drain lateral 2 collects more deep ground water than drain lateral 1 and flows continuously (fig. 12). From March through October 1988, about 60 percent of the water flowing in drain lateral 2 was deep ground water. During irrigation in November 1988 and June and July 1989, the increase in flow in drain lateral 2 primarily was due to an increase in flow from the shallow ground water. The percentage of deep ground-water flow in the drain lateral decreased to about 30 and 37 percent during irrigation in November 1988 and June and July 1989. For both laterals, the increase in

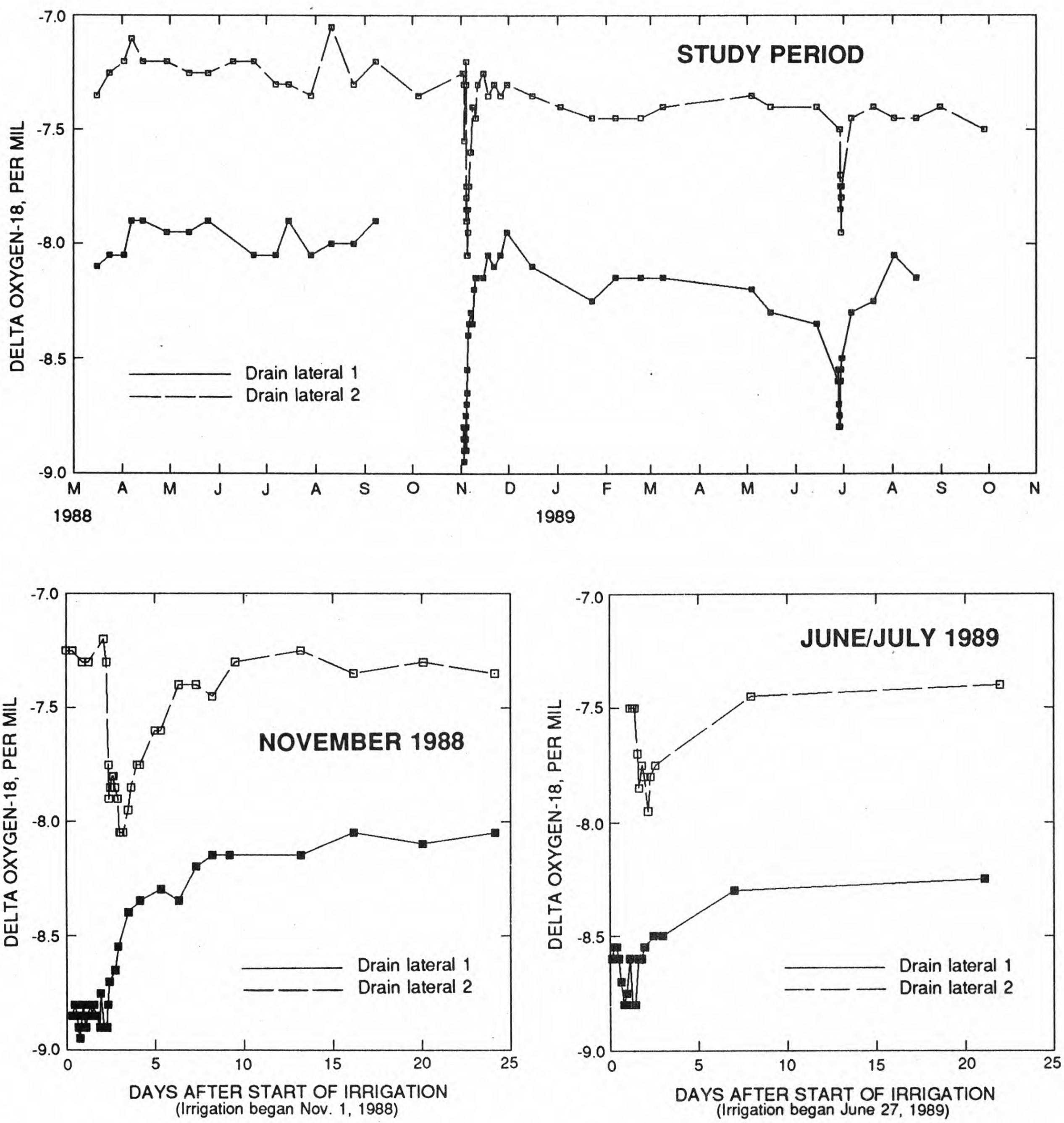


Figure 11. Changes in delta oxygen-18 in drain-lateral samples for the study period and during irrigation.

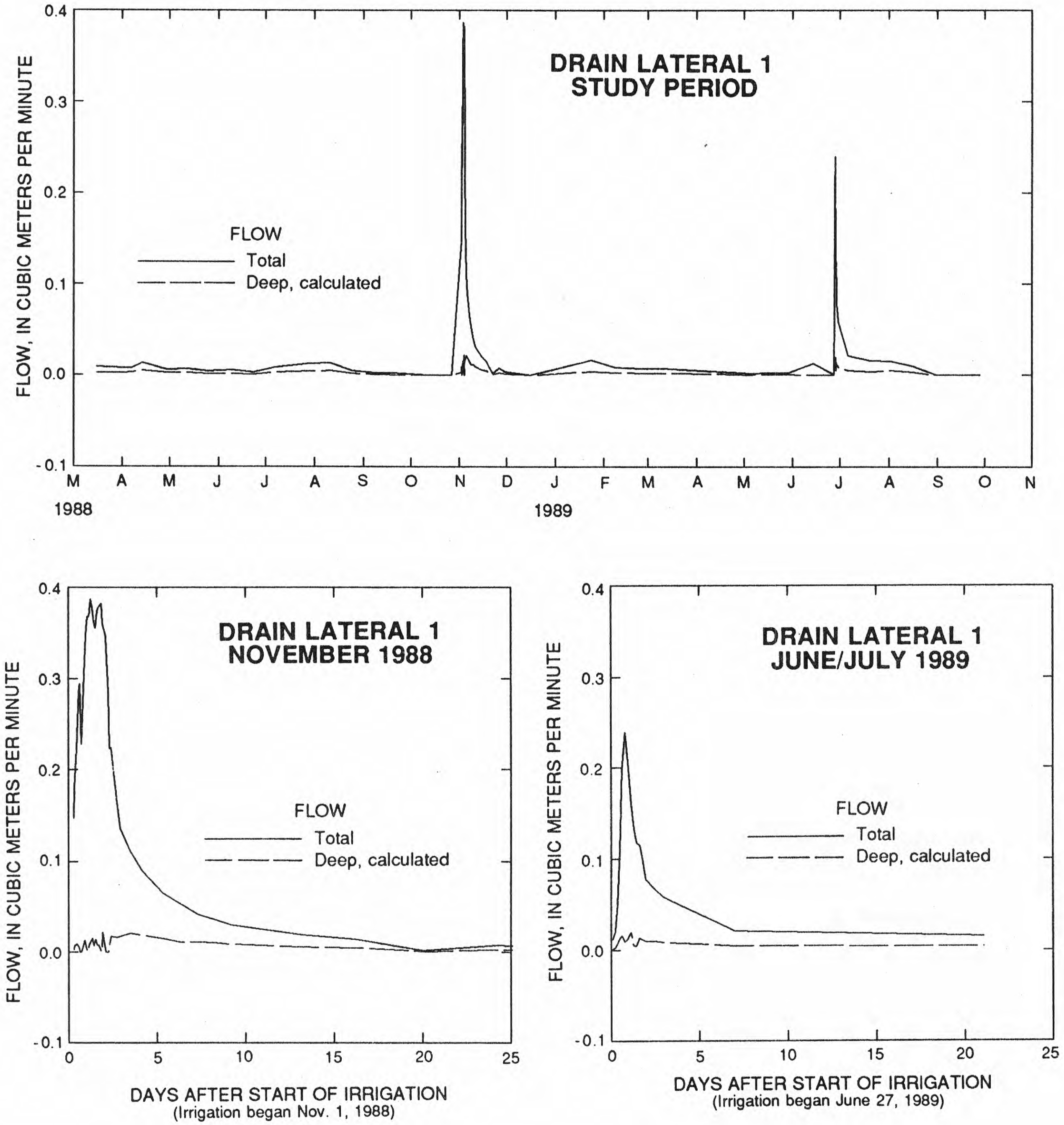


Figure 12. Changes in flow in drain laterals for the study period and during irrigation.

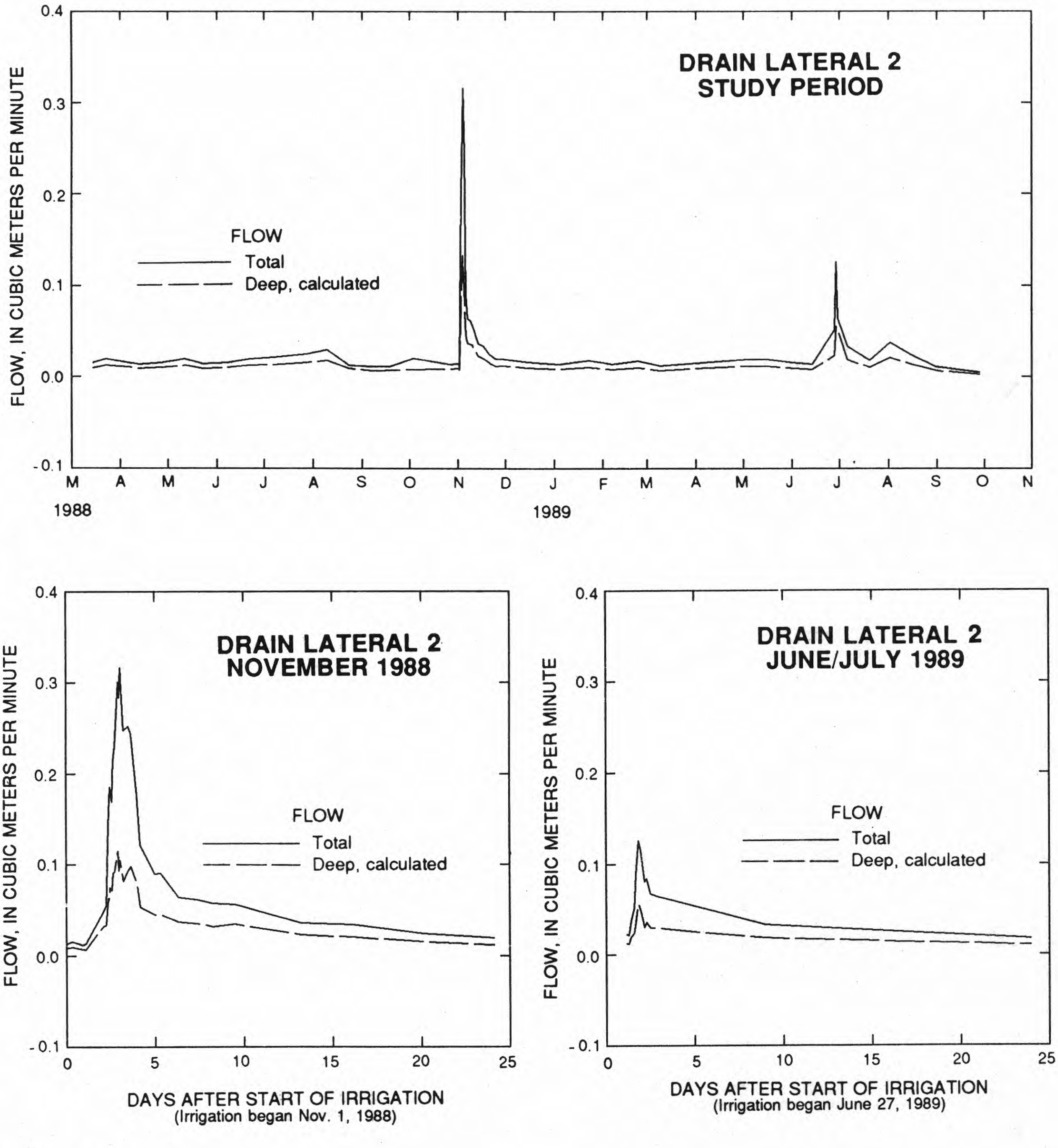


Figure 12. Continued.

flow during irrigations is due to increased outflow of shallow ground water and direct recharge moving into the drain lateral. The isotopic compositions of both shallow ground water and direct recharge are about the same (fig. 7).

Salinity and Selenium

The changes in salinity as determined by specific conductance in the drain laterals during the study are shown in figure 13. Salinity varies similarly to variations in $\delta^{18}O$. Salinity was relatively constant

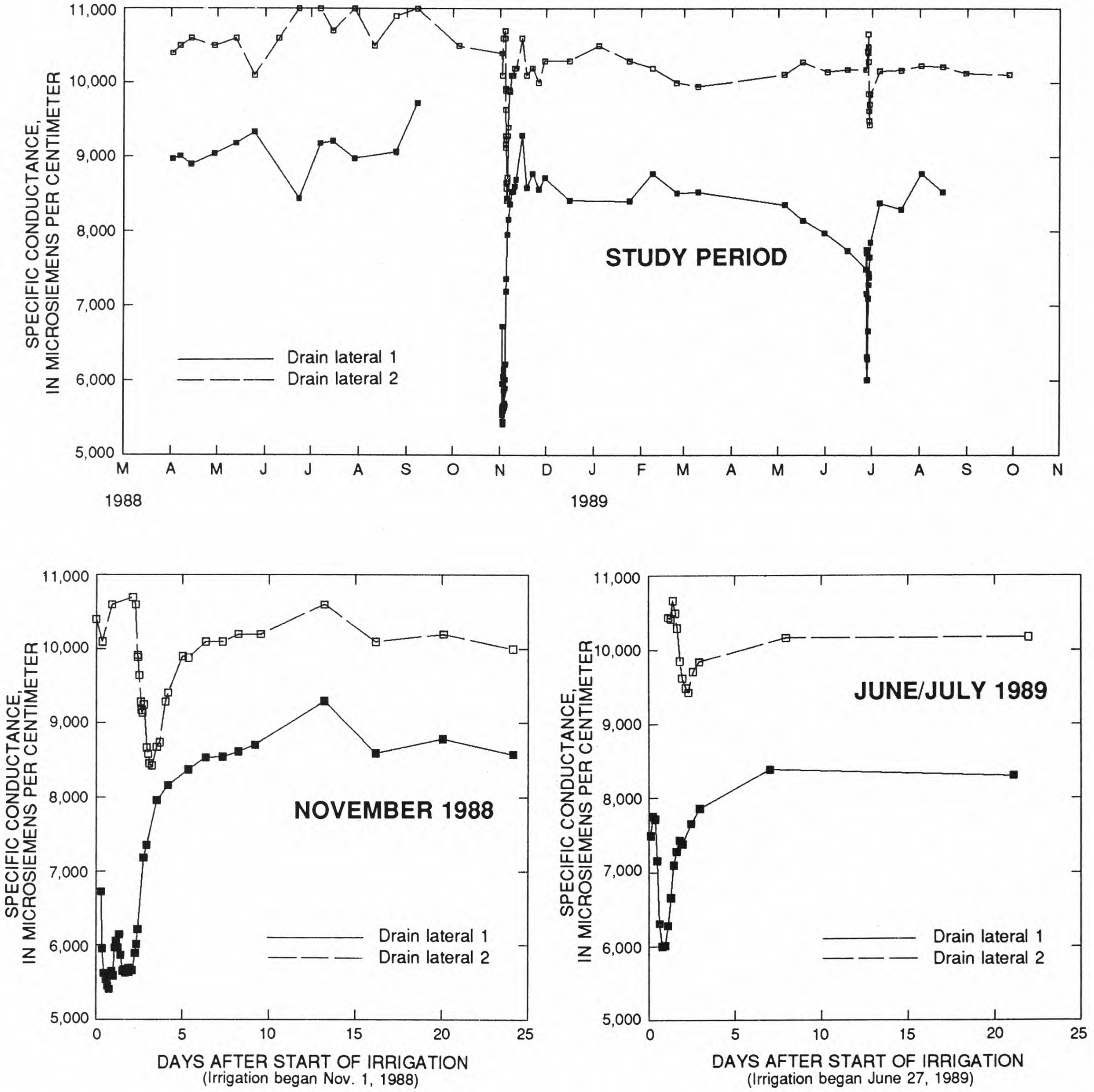


Figure 13. Changes in salinity as determined by specific conductance in the drain-lateral samples for the study period and during irrigation.

from March through October 1988 and January through May 1989. When irrigation water was applied to the field in November 1988 and June and July 1989, the salinity decreased because of an increase influx of more recently recharged shallow ground water that had low salinity relative to the deep ground water. Salinity subsequently increased because of renewed influx of deep ground water after irrigations in both drain laterals. Because drain lateral 1 collects less deep ground water, the salinity of drain lateral 1 samples is lower than drain lateral 2 samples (fig. 13).

Selenium concentrations in the drain-lateral samples vary similarly to salinity (fig. 14). Selenium concentrations are significantly (α=0.01) correlated with specific conductance values (r^2=0.85) for samples collected in both drain laterals during the study. Because the shallow ground water has relatively low selenium concentrations and flows into the drain laterals in greater proportion during irrigation, selenium concentrations decrease during periods of high flow. Dissolved-oxygen concentrations ranged from 1 to 5 mg/L, and pH was alkaline for all ground-water and drain-lateral samples. Because of the alkaline and

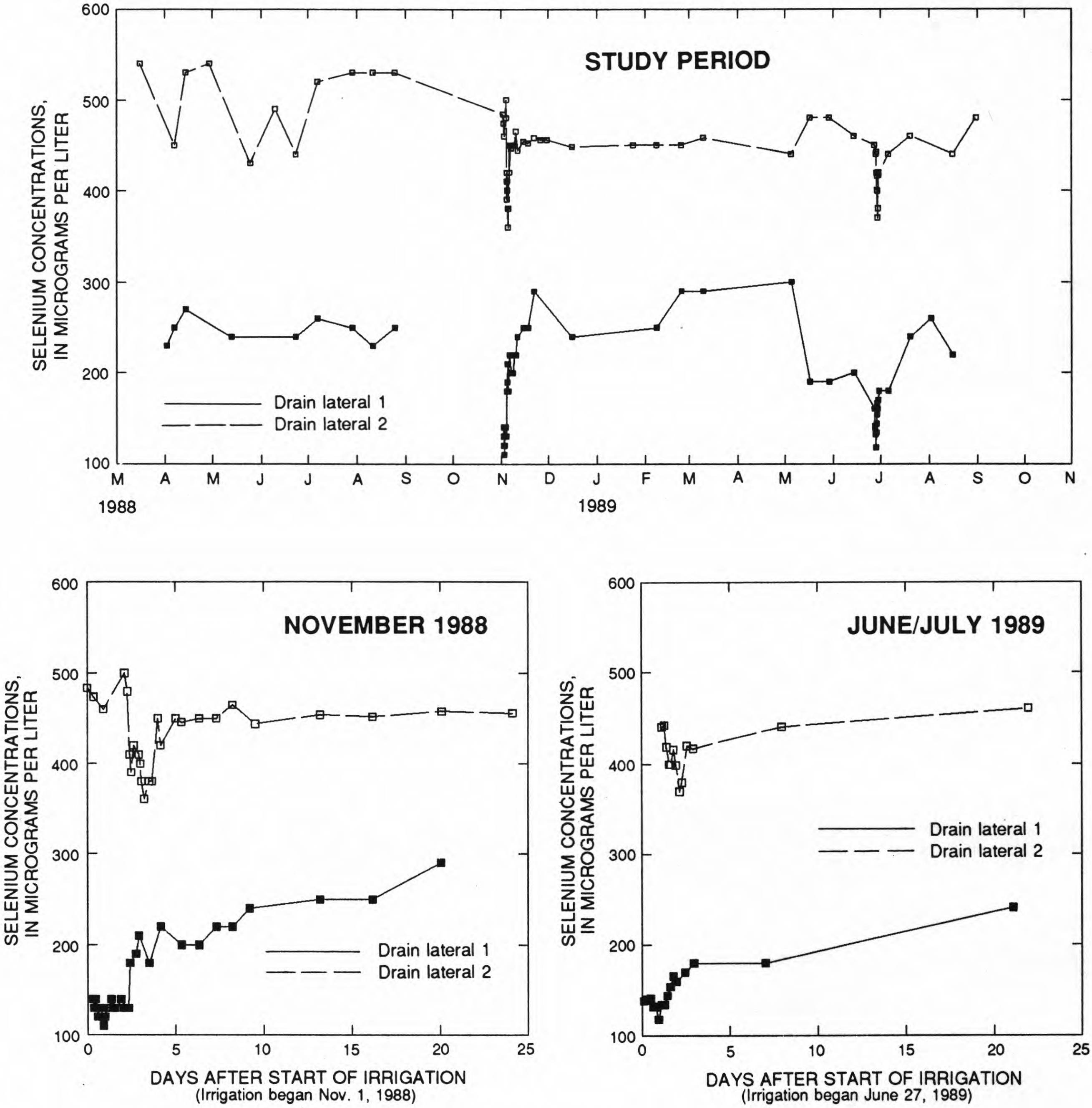


Figure 14. Changes in selenium concentrations in drain-lateral samples for the study period and during irrigation.

oxidized conditions and the high correlation coefficients for selenium and dissolved solids in ground water and drain-lateral samples, it is assumed that selenium predominantly is in the selenate form in the drain-lateral samples. This is consistent with other studies where selenate represents more than 80 percent of the dissolved selenium in ground-water and drain-water samples (Deverel and Millard, 1988; Deverel and Gallanthine, 1989).

Selenium load increases with increases in flow (fig. 15). Increased selenium loads during irrigation and

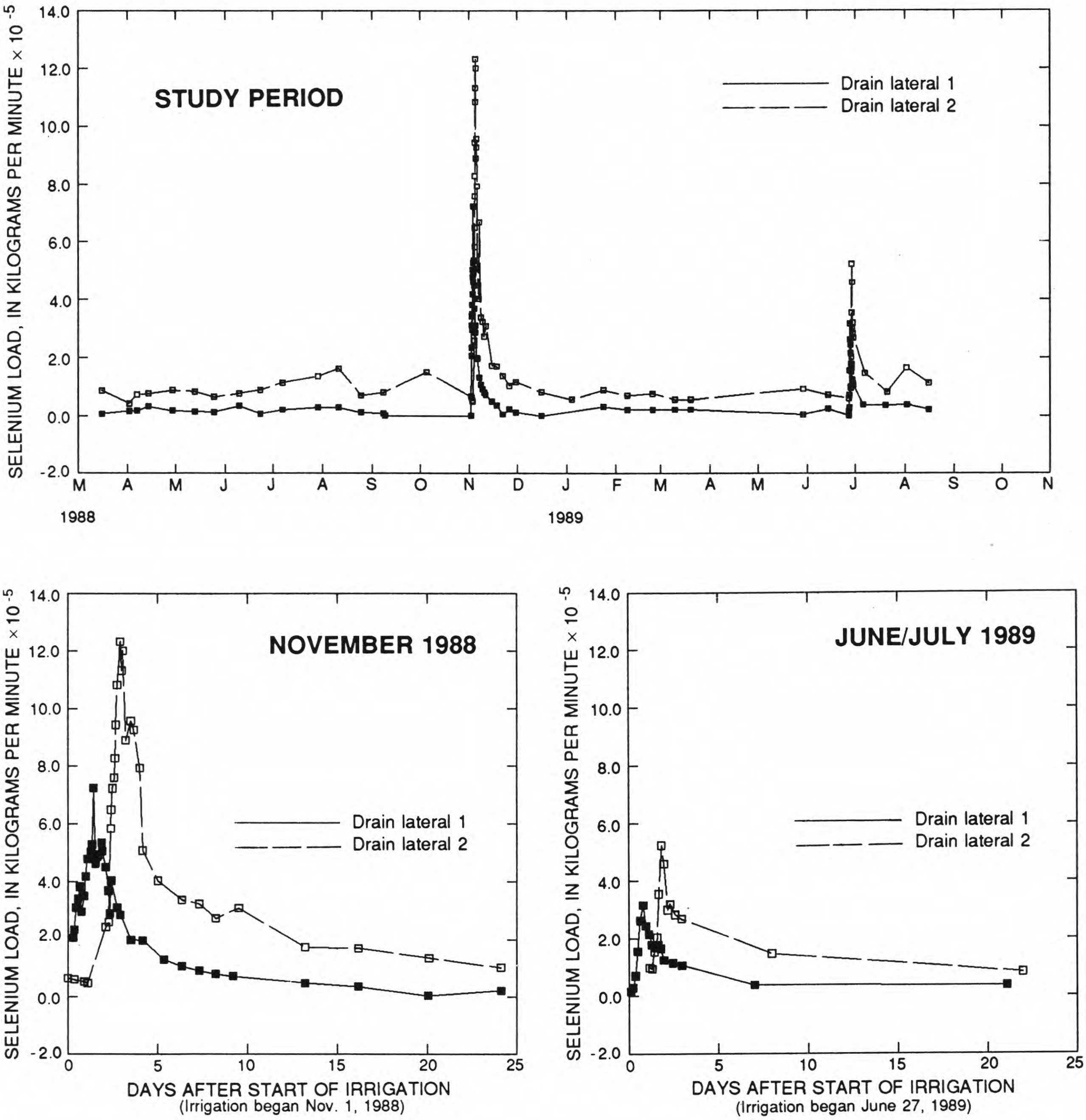


Figure 15. Changes in selenium load in drain laterals for the study period and during irrigation.

periods of increased hydraulic gradients are the result of substantial increases in flow in the drain laterals which compensate for the decrease in selenium concentrations. Because drain lateral 2 collects more deep ground water than drain lateral 1, the selenium loads in drain lateral 2 are substantially larger than drain lateral 1, especially during irrigations. Drain-lateral selenium loads calculated for the drain laterals are significantly correlated ($\alpha=0.01$) with flow ($r^2=0.974$ and 0.964 for drain laterals 1 and 2, respectively). Selenium loads during the November irrigation were substantially more than during the June/July irrigation because more water was applied. During the 8 days of irrigation in November 1988, about 62,550 m^3 of water was applied to the field. During the 5 days of irrigation in June and July 1989, about 40,862 m^3 of water was applied.

Using the calculated selenium loads from March 1988 to March 1989, we integrated the areas under the curves using the trapezoidal rule (Press and others, 1986) to determine cumulative and total selenium loads. For this year of data, the calculated selenium loads were 68 and 322 kg of selenium for drain laterals 1 and 2, respectively. For both laterals, selenium loads during the 8 days of irrigation starting on November 1 represent a substantial proportion of the total selenium load for the year. Because nonirrigation flow and selenium concentrations in drain lateral 1 generally are lower than drain lateral 2, the increased flow during irrigation caused a greater increase in load for drain lateral 1. Twenty-five percent of the total load for drain lateral 1 occurred during the 8 days of irrigation in November. In contrast, 11 percent of the total selenium load for drain lateral 2 occurred during this same period.

SUMMARY AND CONCLUSIONS

The results of this study illustrate the hydrologic processes affecting the chemical and isotopic composition of drain-lateral water in the western San Joaquin Valley. Analysis of geochemical and hydrologic data provide an understanding of the mixture of ground water that enters the drain laterals. Ground water at depths greater than 6 m below land surface (deep ground water) is more saline, has higher selenium concentrations, and is more enriched in oxygen-18 and deuterium than ground water at and less than 6 m below land surface (shallow ground water). The deep and shallow ground water enters the drain laterals in differing proportions.

The proportions of shallow and deep ground water entering the drain laterals varies temporally and by drain-lateral depth. More of the deep ground water enters the drain lateral at 2.7 m below land surface (drain lateral 2) relative to the drain lateral at 1.8 m below land surface (drain lateral 1). More shallow ground water enters the drain laterals during irrigation causing salinity, selenium concentrations, and $\delta^{18}O$ to temporarily decrease. The percentages of deep ground water entering the drain laterals were calculated from $\delta^{18}O$ by using shallow and deep ground-water isotopic compositions as end members. Deep ground water entering the drain laterals ranges from 30 to 60 percent of the total flow in drain lateral 2 and from 0 to 30 percent in drain lateral 1 with minimum proportions occurring during irrigation.

Total selenium loads from March 1988 to March 1989 were 68 and 322 kg for drain laterals 1 and 2, respectively. Selenium concentrations decrease with increases in flow in the drain laterals. Selenium loads, however, increase substantially during irrigation because of more water flowing into the drain laterals. The selenium load during 8 days of irrigation in November 1988 accounted for 25 and 11 percent of the total selenium load for drain lateral 1 and 2, respectively, for the 1-year period between March 1988 and March 1989.

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