CHARACTERIZATION OF GROUND-WATER FLOW AND CHEMICAL TRANSPORT BENEATH TWO IRRIGATED FIELDS IN SOUTH-CENTRAL KANSAS, 1988

By A.T. Rutledge and J.O. Helgesen

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 90-4065

Prepared as part of the
TOXIC WASTE--GROUND-WATER
CONTAMINATION PROGRAM,
U.S. GEOLOGICAL SURVEY

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

Lawrence, Kansas
1990

U.S. DEPARTMENT OF THE INTERIOR
MANUAL LUJAN, JR., Secretary
U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
4821 Quail Crest Place
Lawrence, Kansas 66049

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center, Building 810
Box 25425
Denver, Colorado 80225

CONTENTS

ILLUSTRATIONS

CONTENTS--Continued

Figure **Page**

21-26. Graphs showing:

CONTENTS--Continued

Figure **Page**

TABLES

Table **Page**

CONVERSION FACTORS

For those readers who may prefer metric units (International System), the inch-pound units of this report may be converted using the following factors:

Multiply inch-pound unit	*By*	*To obtain metric unit*
inch	2.54	centimeter
foot	0.3048	meter
mile	1.609	kilometer
acre	4,047	square meter
quart	0.9464	liter
gallon per minute	0.06308	liter per second
cubic foot	28.32	liter
ounce	0.02957	liter
pound	453.6	gram
cubic foot per pound	62.43	cubic centimeter per gram
pound per cubic foot	0.01602	gram per cubic centimeter
pound per acre	0.112	gram per square meter
degree Fahrenheit (°F)	°C = 5/9 (°F-32)	degree Celsius (°C)

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

CHARACTERIZATION OF GROUND-WATER FLOW AND CHEMICAL TRANSPORT BENEATH TWO IRRIGATED FIELDS IN SOUTH-CENTRAL KANSAS, 1988

by A.T. Rutledge and J.O. Helgesen

ABSTRACT

Hydrologic and chemical data were collected at two irrigated fields in south-central Kansas during 1988. These data pertain to ground-water flow and chemical transport in the unsaturated and saturated zones with particular emphasis on the movement of the herbicide atrazine. One field was irrigated by using an overhead center-pivot sprinkler system (S field), and the second field was irrigated by using flood-irrigation techniques (F field).

Soil-moisture profiles indicated that the available water capacity of the unsaturated zone was approximately 1 inch at the S field and 2 inches at the F field. A mathematical scheme that calculates water balance on a weekly basis was used to estimate that, between January 10, 1988 and January 31, 1989, 7.7 inches of water were available for recharge at the S field. On the basis of a chloride tracer test, the seepage velocity through a depth interval of about 6 to 10 feet at the S field was estimated to be about 4.6 feet per year, and the estimated maximum recharge during 1988 was 5 inches. Lithologic and water-level data indicate that water flow in the saturated zone beneath the S field acts as a two-unit ground-water system, with the irrigation well extracting more water out of the more-permeable lower sand unit, and that water flow beneath the F field acts as a one-unit ground-water system exhibiting the effects of partial penetration of the aquifer by the pumping irrigation well.

Soil-water samples collected in 1988 from the unsaturated zone at depths from about 6 to 10 feet showed no definitive movement of atrazine. A possible explanation is that the atrazine detected was applied before 1988, and that the 1988 atrazine application had not reached the 6-foot depth during 1988 because of retardation. This interpretation is supported by analyses of soil samples that showed the largest concentrations of atrazine in the top 0.3 foot at a time when chloride (which had been applied at the same time as the atrazine) had already reached a depth of 6 feet. A mathematical model shows that, below the root zone, atrazine follows a nonsorbing tracer, such as chloride, by approximately 1.2 years.

There is a greater decrease in chemical concentrations, from the land surface to the subsurface, for atrazine as compared to nitrite plus nitrate. On the basis of 1988 data, the fraction of chemical applied at land surface that remains in water that reaches the top of the saturated zone is 0.15 to 0.3 for nitrogen, but the fraction of atrazine remaining is less than 0.0002 for the S field or 0.004 for the F field. Additional avenues of atrazine loss are suggested. The chemical variables of chloride, nitrite plus nitrate, and atrazine show stratification in concentrations in the saturated zone; concentrations decrease with increasing depth. Concentrations of chloride and nitrite plus nitrate in the saturated zone show the effects of deep circulation at the S field and the predominance of shallow circulation at the F field; concentrations in water from deep test wells are larger at the S field than at the F field.

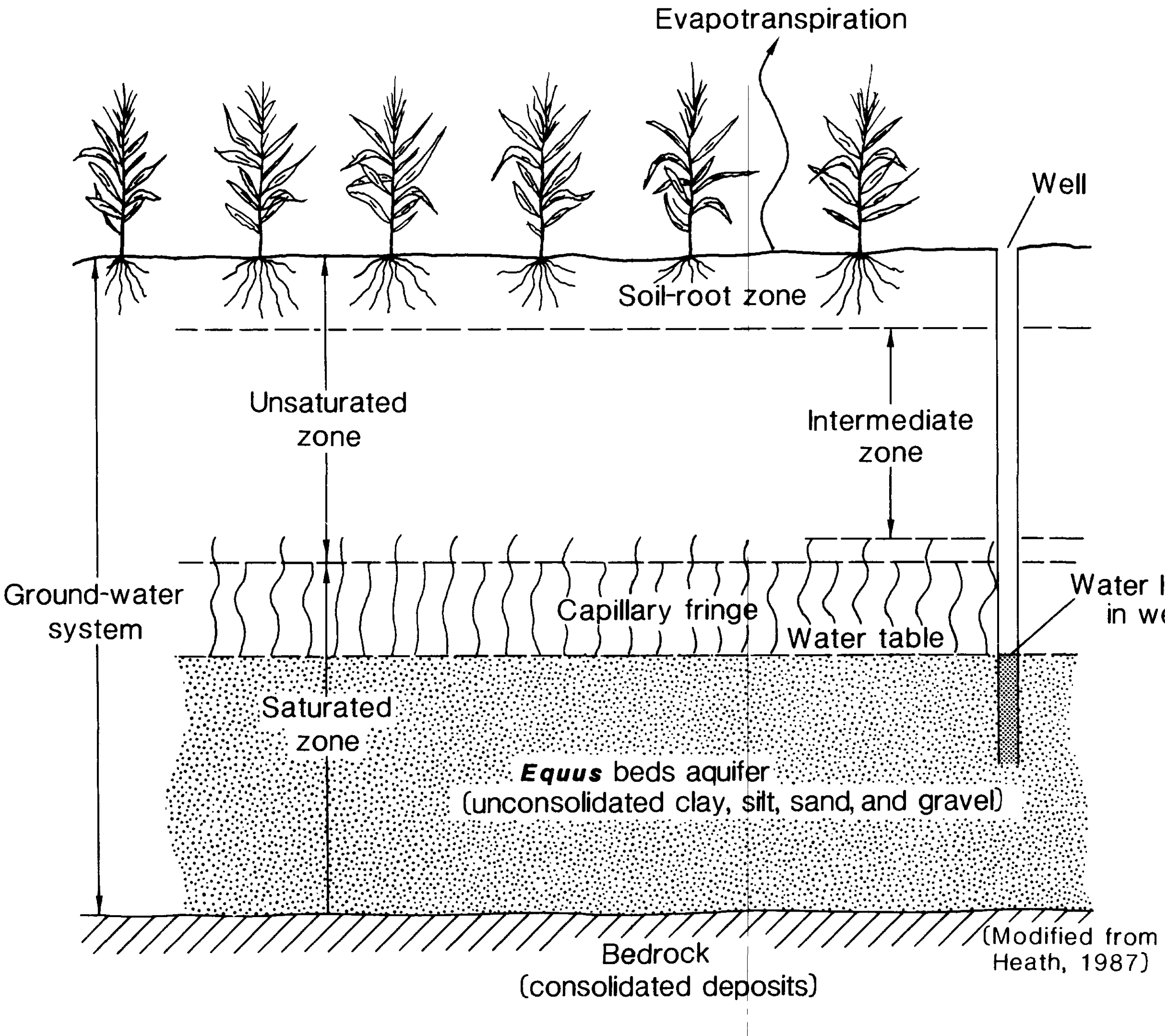
INTRODUCTION

The widespread use of agricultural chemicals poses a possible threat to ground-water quality under cropland in south-central Kansas. This threat may be of particular concern where the potential for downward movement of pesticides and fertilizers is increased by irrigation.

The herbicide atrazine has been detected in ground water beneath irrigated cropland in south-central Kansas, but not at the frequency or in the concentrations that might be expected in view of the widespread use of this chemical. Among 13 ground-water samples collected in areas of irrigated cropland in 1984, atrazine was detected only twice, and the maximum concentration was only 0.2 µg/L (micrograms per liter) (Stullken and others, 1987). Among 60 ground-water samples collected in 1987, atrazine was detected seven times, and the maximum concentration was 3.8 µg/L (Helgesen and Rutledge, 1989). Greater frequencies of atrazine occurrence in ground water Nebraska and Iowa have been reported (Chen and Druliner, 1987; Hallberg and others, 1987).

The need exists to describe and better understand the movement and fate of agricultural chemicals beneath irrigated cropland. Of particular concern are the processes in the unsaturated zone because chemicals must be transported through the unsaturated zone to reach the saturated zone (fig. 1).

As part of the U.S. Geological Survey's Toxic Substances Hydrology Program (Helsel and Ragone, 1984), two fields of irrigated crops in south-central Kansas were equipped with monitoring devices. The data obtained will help describe the physical processes of water and chemical movement in the subsurface. This information could then be used for mathematical modeling of ground-water flow and chemical transport.



(Modified from Heath, 1987)

Figure 1. Schematic diagram of ground-water system.

Purpose and Scope

The fields were instrumented in March 1988, with the intention to monitor soil-moisture content, water levels, and chemical concentrations for a minimum of 2 years. Multiple-year data collection was chosen to account for (1) yearly variations in climate, thus reducing the likelihood of misrepresenting long-term conditions with only 1 year of data; and (2) anticipated slow transport times, which may require long-term monitoring to define the migration of surface-applied chemicals to the water table. The purpose of this report is to provide interpretation of data collected from March 1988 through February 1989.

Acknowledgments

The authors acknowledge the cooperation of Larry Williams, O'Dell McCurry, and Regier Farms, Inc., owners and operators of the fields where data were collected.

DESCRIPTION OF TEST FIELDS

The two irrigated fields used in this study are located on privately owned land in south-central Kansas between the cities of Hutchinson and Wichita (fig. 2). The test fields are in the

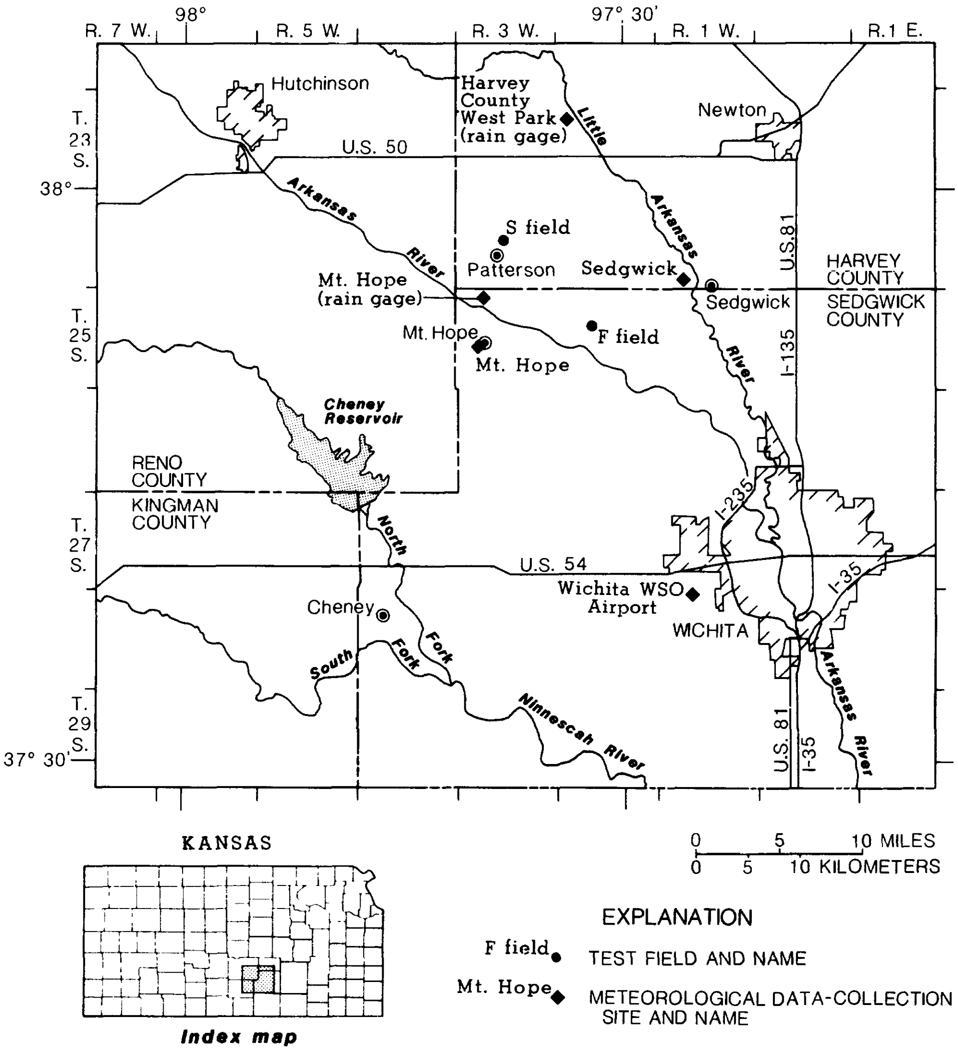


Figure 2. Location of test fields and meteorological data-collection sites in study area.

Arkansas River Lowlands physiographic region identified by Merriam (1963, p. 164-165). Both fields are relatively flat and are irrigated by using ground water from the underlying *Equus* beds aquifer, which consists of unconsolidated deposits of clay, silt, sand, and gravel of Pliocene to Pleistocene age. The S field is irrigated by use of a center-pivot sprinkler system, and the F field is irrigated by use of flood (furrow) irrigation. During the 1988 growing season (May through September), corn was grown at both fields.

Monitoring equipment in each field was installed near an irrigation well that was in place prior to the study. Monitoring equipment at the S field is located at one of two locations--site SA or site SB (fig. 3). Similarly, equipment at the F field is located at site FA or site FB (fig. 4). Monitoring equipment at each field includes two clusters of test wells located approximately 200 feet and 590 feet, respectively, from the irrigation well. The SB and FB sites are also equipped with suction lysimeters for extracting water samples from the unsaturated zone and aluminum access pipes for neutron logging to determine soil-moisture content of the unsaturated zone. Table 1 gives information about the depths of completion of the test wells and suction lysimeters. Site SB is equipped also with a recording rain gage and a cumulative rain

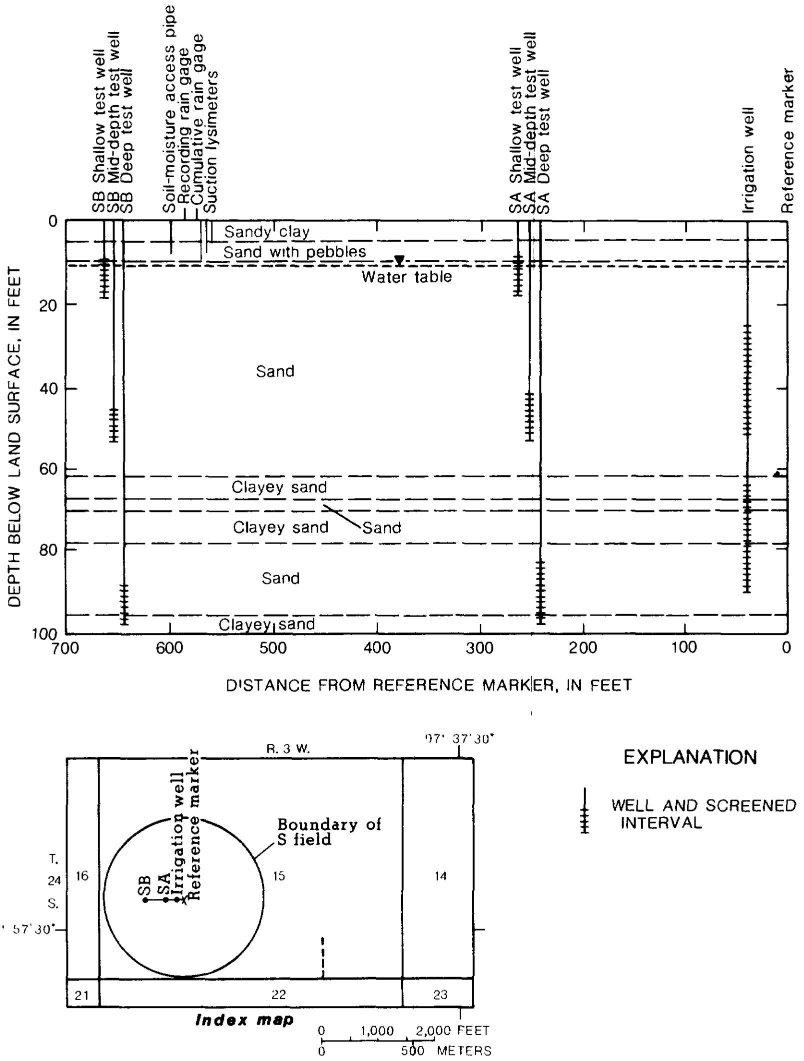


Figure 3. Placement of monitoring equipment and generalized lithology at S field.

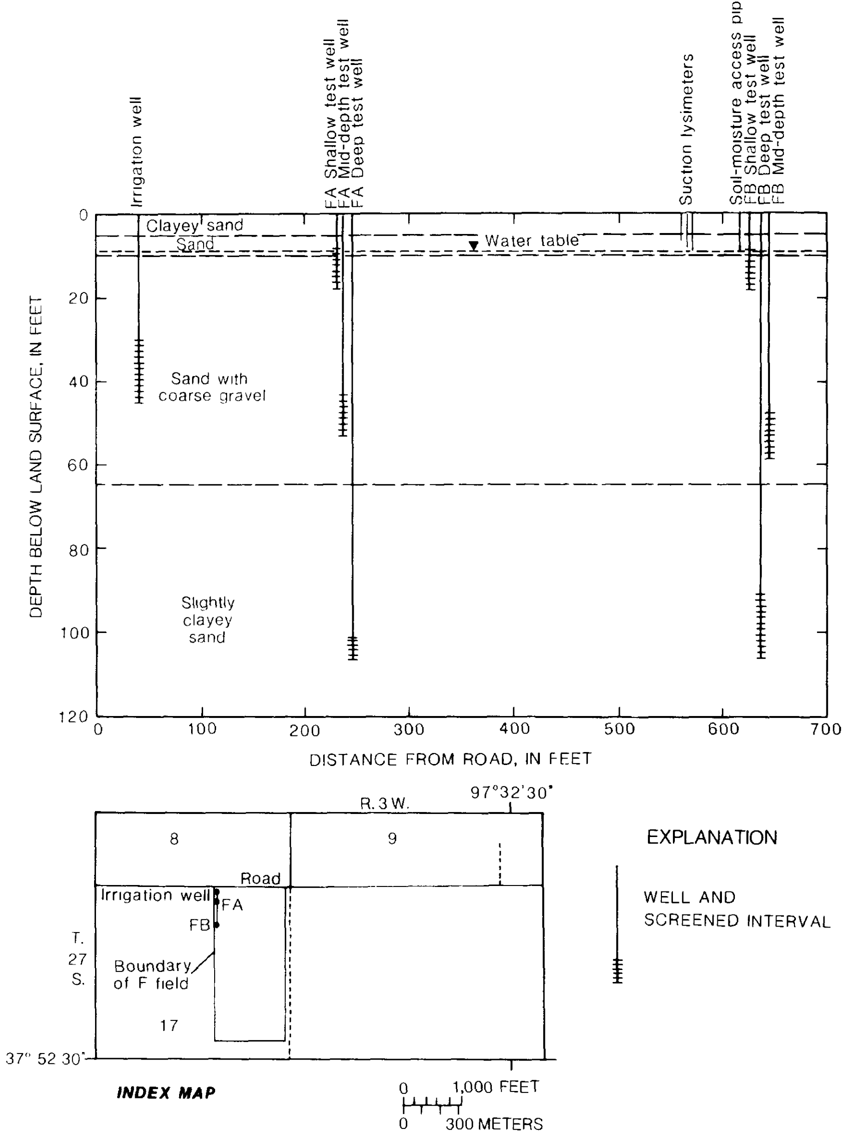


Figure 4. Placement of monitoring equipment and generalized lithology at F field.

gage that measure rainfall plus irrigation. An additional cumulative rain gage (not shown in fig. 3) was installed adjacent to the S field to measure rainfall only.

Generalized lithology (figs. 3 and 4) show that ground-water conditions probably are unconfined to semiconfined. At the S field, two zones of clayey sand occur between the depths of 62 and 78 feet. The irrigation well is open to sand units above, between, and below these zones. Two test wells are open to the sand unit below, and four are open to the sand unit above these zones of clayey sand (fig. 3). At the F field, the lithology becomes slightly clayey at a depth of 65 feet. The irrigation well is open from 30 to 45 feet below land surface, and the test wells are open to depth intervals above and below this (fig. 4).

Events pertinent to the study of the two fields are summarized in figures 5 and 6. Chemical applications, as noted, consisted of anhydrous ammonia, alachlor, atrazine, and 2,4-D on the S field and anhydrous ammonia, atrazine, and metolachlor on the F field.

Table 1. *Depth intervals for suction lysimeters and test-well screens*

Suction lysimeter (fig. 3 or 4)	Depth interval of porous cup (feet below land surface)
SB 5.9	5.7-5.9
SB 7.9	7.7-7.9
SB 9.7	9.5-9.7
FB 5.7	5.5-5.7
FB 7.7	7.5-7.7
FB 8.3	8.1-8.3
Test well (fig. 3 or 4)	**Depth interval of screen (feet below land surface)**
SA shallow	8-18
SA mid-depth	43-53
SA deep	83-98
SB shallow	8-18
SB mid-depth	45-53
SB deep	88-98
FA shallow	8-18
FA mid-depth	43-53
FA deep	102-107
FB shallow	8-18
FB mid-depth	48-58
FB deep	91-106

COLLECTION AND ANALYSIS OF WATER-QUANTITY AND WATER-LEVEL DATA

Rainfall and Irrigation

The test fields received water from both rainfall and irrigation. This water influx was measured at the S field but not at the F field, as discussed below.

S Field

The S field (fig. 3), which is a circular area 0.5 mile in diameter (125 acres), was irrigated with water from one well located near the center of the field. Pumping from the well, at a reported rate of 750 gallons per minute, generally is continuous throughout the irrigation season, although the pump is turned off during exceptionally rainy periods. Water is conveyed from the irrigation well to a junction at the pivotal end of the center-pivot system and then is conveyed to sprinklers along the length of the system. During the 1988 irrigation season, this pivot system made a circular traverse of the field once every 9 days. Therefore, during continuous pumping, water is applied only periodically at any one location in the field.

The irrigation season at the S field was from June 7 to approximately August 15, 1988

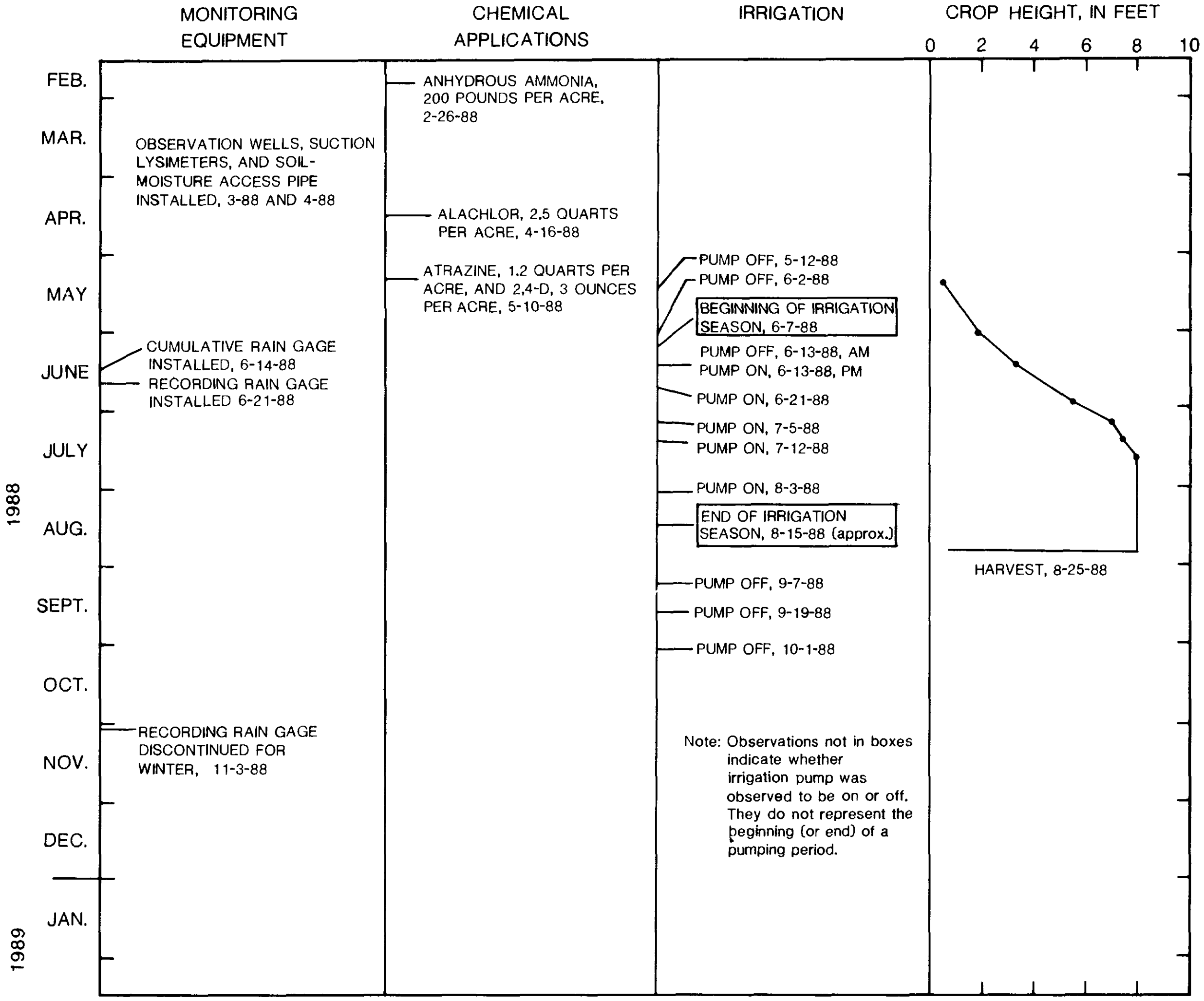


Figure 5. Schedule of events and crop-height record at S field.

(fig. 5). Records of rainfall plus irrigation at the SB site and records of rainfall adjacent to the S field for various time intervals (fig. 7) are during periods of nonirrigation, but differ during the irrigation season. The difference indicates a total irrigation of 9 inches at the SB site in 1988. A daily record of rainfall plus irrigation (fig. 8) was obtained from the recording rain gage at the SB site. Days when all or part of the total amount was irrigation are indicated by asterisks. The gap between irrigation on July 11 and July 27 is 7 days longer than gaps between other irrigation periods. This indicates a 7-day break in pumping, which probably occurred because of the rainfall on July 16 and 17. Figure 7 indicates more than 3 inches of rain fell between July 12 and July 19.

F Field

Flood irrigation was used at the F field. The irrigated area (fig. 4) is 0.25 mile by 0.5 mile (80 acres). This rectangular area is comprised of two fields--a northern half where corn was grown, and a southern half where soybeans were grown (in 1988). The irrigation well and the monitoring sites are located in the northern half of the field, and the irrigation well is located at the northwest corner. Water from the irrigation well (reported to yield about 900 gallons per

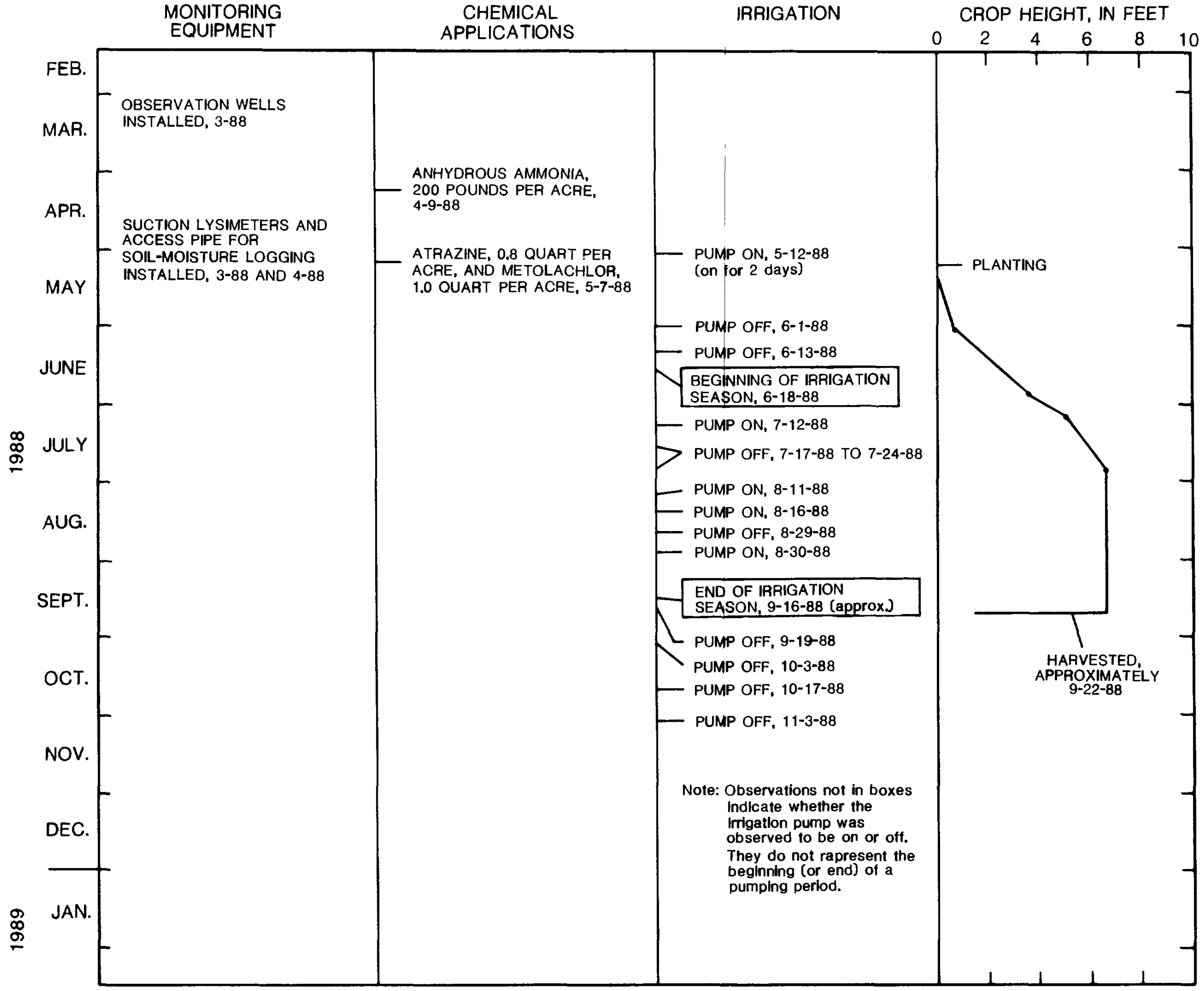


Figure 6. Schedule of events and crop-height record at F field.

minute) is conveyed either to a perforated discharge pipe that extends along the northern end of the corn field or to another pipe that extends along the northern end of the soybean field, and then flows southward through furrows in either field. A time of pumping from the irrigation well may not necessarily be a time of inundation in the furrows at the test sites because:

(1) water from the pump may have been conveyed to the soybean field, or

(2) although water may have been conveyed to the discharge pipe along the northern end of the corn field, the perforations in the segment of the discharge pipe that are located at the furrows that traverse the test sites may have been closed temporarily.

Pumping at the F field was monitored by observing electrical energy consumption at the pump (fig. 9). Pumping was not continuous throughout the irrigation season, which lasted approximately 90 days (June 18 to September 16, 1988); there were 63 days of pumping, 27 days of no pumping, and 5 interruptions in pumping.

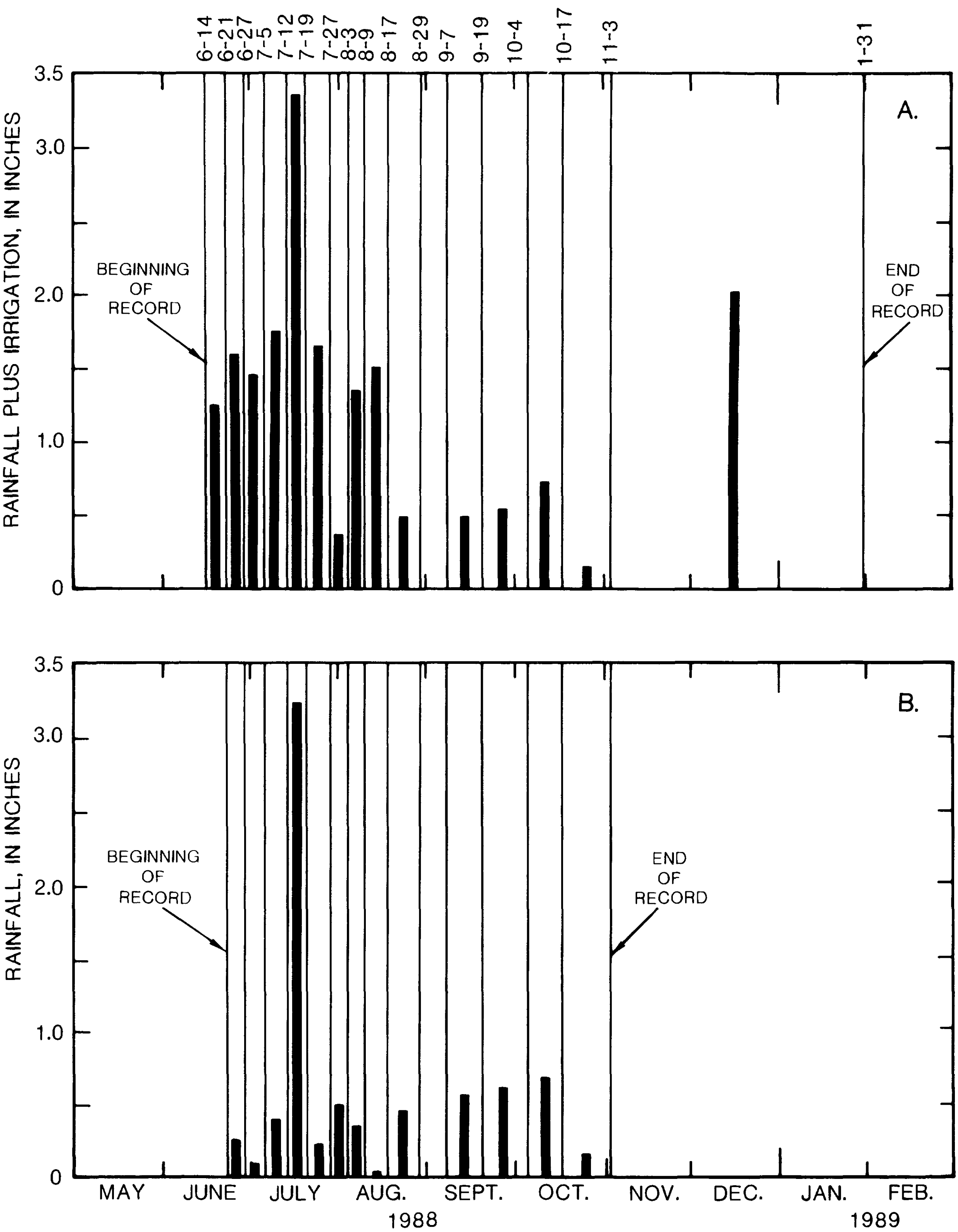


Figure 7. Rainfall plus irrigation at SB site (A) and rainfall adjacent to S field (B) for various time intervals. (Time intervals are indicated by vertical lines, and beginning and ending dates of these intervals are shown on top of graph A.)

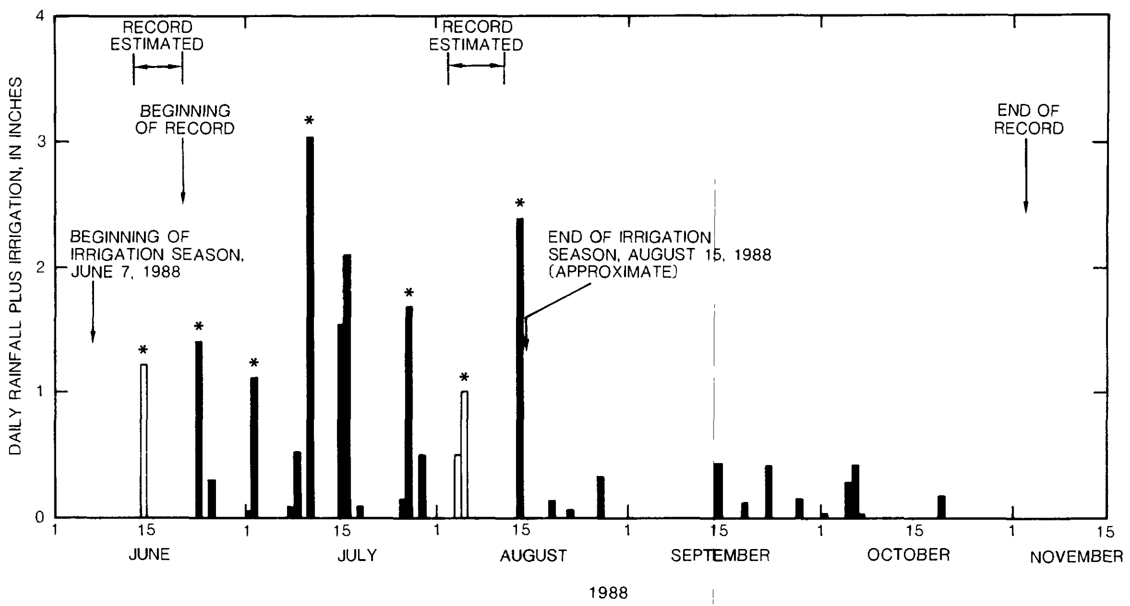


Figure 8. Daily rainfall plus irrigation for SB recording rain gage, June 19 to November 2, 1988. (Asterisks indicate days when all or part of total was irrigation. Estimated parts of record were inferred from total rainfall plus irrigation at SB site and rainfall adjacent to S field, figure 7 and from rainfall records from other sites, figure 2. Estimated quantities are shown as open bars.)

Measurements of rainfall and irrigation at the F field were not made in 1988. Measurement of irrigation in the F field would be difficult and subject to considerable error because of the use of flood irrigation. However, potentially useful information might include a continuous record of furrow inundation at the FB site during the irrigation season and percolation tests in the furrows.

Soil Moisture

Soil-moisture profiles were obtained by use of a neutron probe at the SB and FB sites to: (1) aid in describing the lithology of the unsaturated zone, (2) determine the available water capacity in the root zone (field capacity minus residual moisture content), (3) measure evapotranspiration, and (4) obtain the relation between the seepage velocity (v) and the volume flux (q) in the unsaturated zone. This information can be used in the application of various mathematical models to estimate recharge.

Apparent soil-moisture content (instrument not calibrated specifically to the test sites) was measured on 10 different occasions at eight different depths at the SB site (fig. 10) and at nine different depths at the FB site (fig. 11) from August 1988 to January 1989. The relatively large apparent soil-moisture content between the depths of 1.0 and 4.5 feet is characteristic of the large water-retention capacity of the clay that occurs within this depth interval, and the small apparent soil-moisture content at depths greater than 4.5 feet is characteristic of sand layers that occur there (figs. 3 and 4). Changes through time are due partially to the random error associated with moisture-profile data and partially to change in actual soil-moisture content. The latter is especially the case for the larger variations that occur at shallow depths (less than 2.5 feet).

Relatively large soil-moisture content generally occurs after periods when rainfall plus irrigation exceeds evapotranspiration, and relatively small soil-moisture content occurs when evapotranspiration exceeds rainfall plus irrigation. The wettest and driest observed apparent soil-moisture profiles for the SB site were on August 1 and September 7, respectively (fig. 12). The 6-day antecedent rainfall plus irrigation for these two dates was 2.3 and 0 inches, respectively (fig. 8). The wettest and driest observed soil-moisture profiles for the FB site are shown in figure 13.

The difference in total apparent soil-

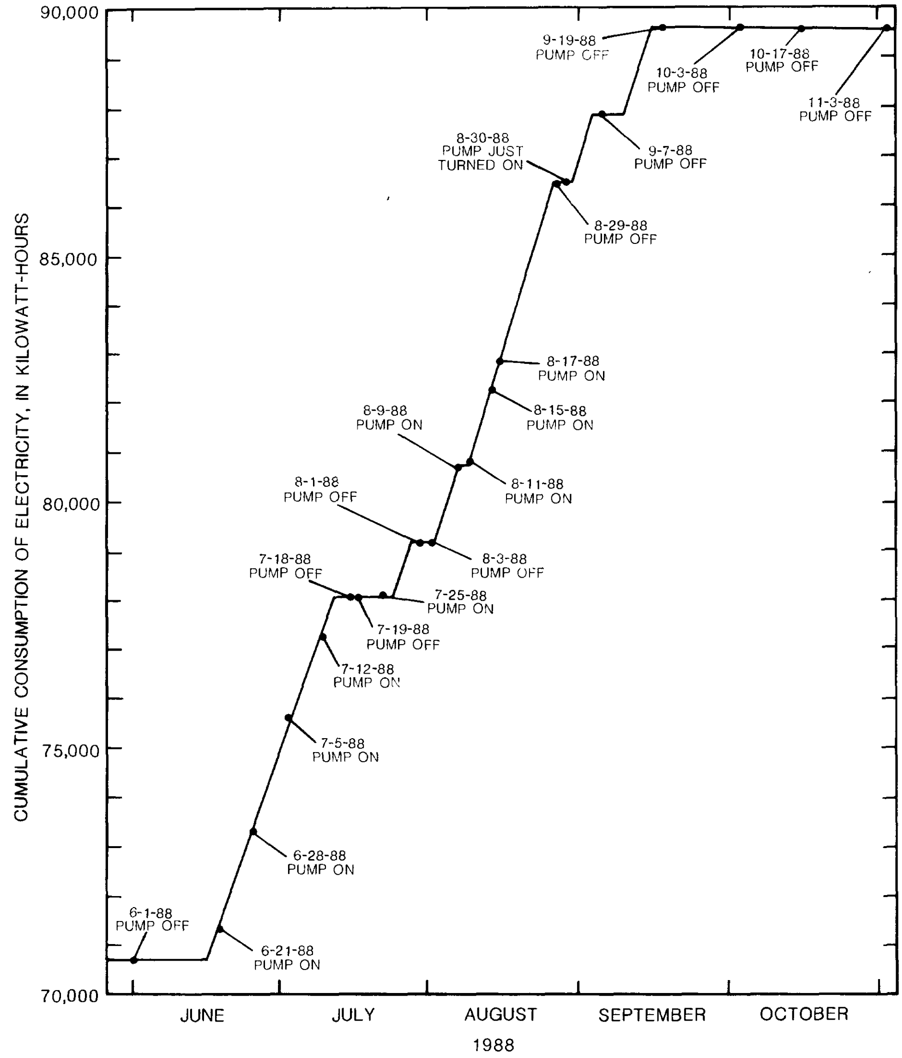


Figure 9. Consumption of electricity by the pump in the irrigation well at F field during 1988 irrigation season.

moisture content between the wettest and the driest soil profiles may indicate the available water capacity of the unsaturated zone. The wettest profile may approach the water-holding capacity, and the driest profile may approximate residual-moisture conditions after gravity drainage and evapotranspiration are negligible (Sophocleous and Perry, 1987). The available water capacity can be calculated using the following equation:

$$\Delta W = (12/100) \sum_{i=1}^{n} (WCWi - WCDi)\ Ti, \qquad (1)$$

where

ΔW = total change in soil-moisture content (inches);

n = number of layers, which is the number of different depths of soil-moisture measurement;

i = layer counter;

$WCWi$ = soil-moisture content under wet conditions for layer i (percent by volume);

$WCDi$ = soil-moisture content under dry conditions for layer i (percent by volume);

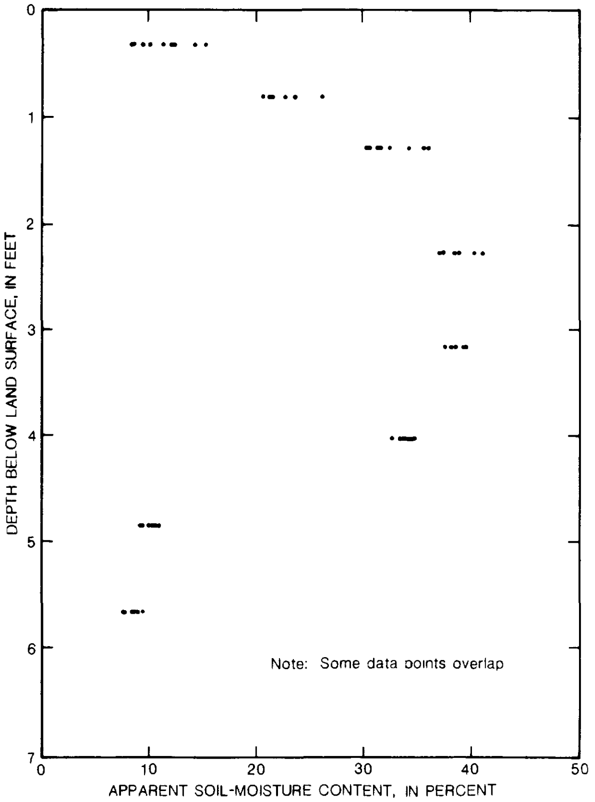


Figure 10. Apparent soil-moisture content at SB site on 10 different occasions from August 1988 to January 1989.

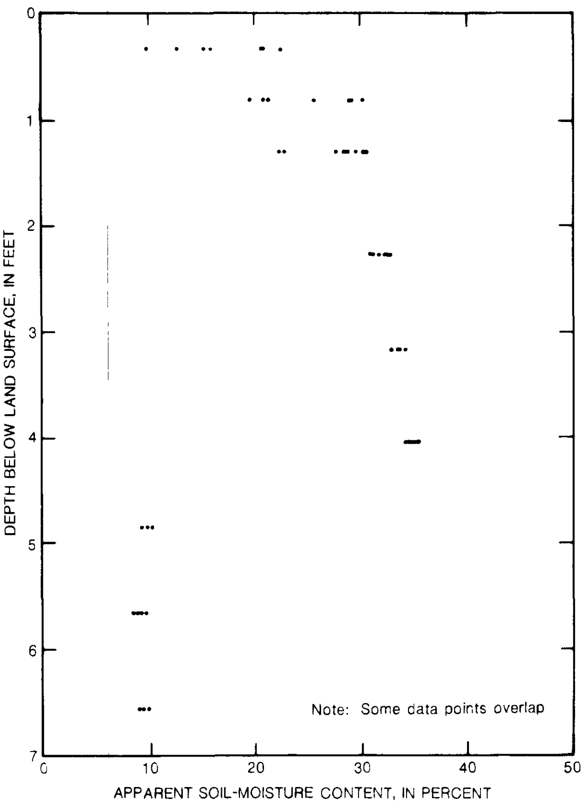


Figure 11. Apparent soil-moisture content at FB site on 10 different occasions from August 1988 to January 1989.

and

Ti = thickness of layer *i* (feet).

By using the wettest and driest soil profiles for each site (figs. 12 and 13), equation 1 results in the following:

	Available water capacity of soil profile (inches)
SB site	1.0
FB site	2.0

Under extremely dry conditions, the available water-capacity values may be equal to the maximum possible moisture deficiencies at each site. When moisture deficiency reaches these levels, further evapotranspiration is near zero.

Moisture profiles may be used to measure evapotranspiration by obtaining two profiles at the same site separated by a small time interval. The time interval can be as short as 1 day, when evapotranspiration is expected to be large, or as long as 1 or 2 weeks. During this time interval, there should be no rainfall or irrigation, so that no infiltration or deep percolation (gravity drainage) occurs. The change in apparent soil-moisture content then is assumed to be a function of evapotranspiration only. The amount of water lost to evapotranspiration during the time period between the two profiles is calculated by using an equation of the form of equation 1 and by substituting the soil-moisture contents of the first profile for the array *WCWi* and those of the second profile for the array *WCDi*. The change in total soil moisture, ΔW, then is divided by the number of days between the profiles to obtain evapotranspiration in inches per day. This procedure was applied by using profiles from the SB site for August 1 and August 3, 1988 (fig. 14), and evapotranspiration was calculated as 0.34 inch per day for the 2-day period. The procedure may be used in the future to corroborate estimates of evapotranspiration in water-balance models that simulate soil-moisture dynamics.

Water Levels

Water levels were monitored in all 12 test

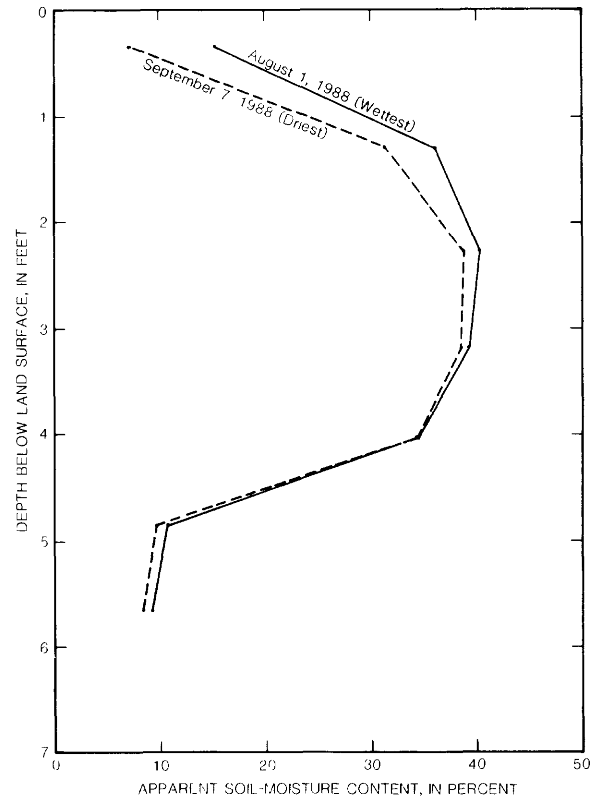


Figure 12. Driest and wettest measured apparent soil-moisture profiles during August 1988 to January 1989 for SB site.

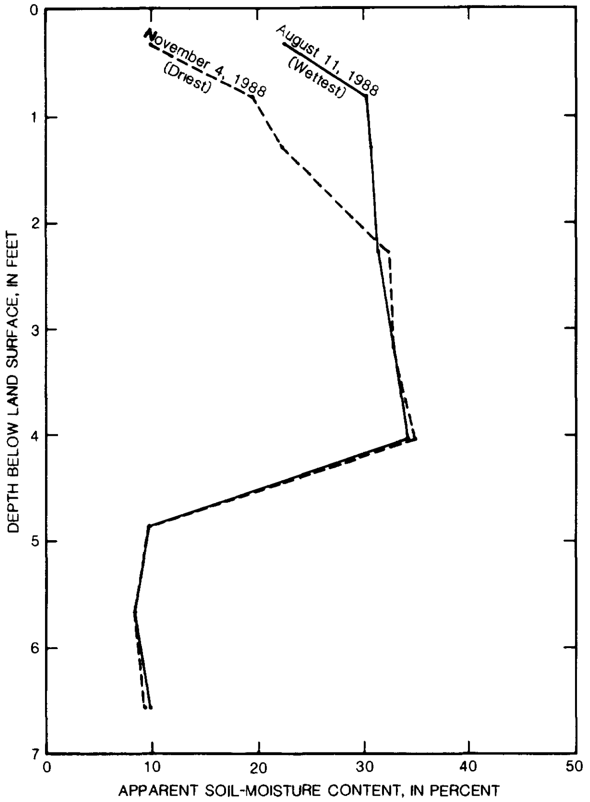


Figure 13. Driest and wettest measured apparent soil-moisture profiles during August 1988 to January 1989 for FB site.

wells (figs. 3 and 4) throughout the year. Prior to the irrigation season, the depth below land surface to the water level in all wells was approximately 10.5 feet at the S field (on June 2, 1988) and 8.5 feet at the F field (on June 1, 1988). These water levels were used as reference water levels during the rest of the year.

S Field

At the S field, water-level changes in the shallow test wells were similar to water-level changes in the mid-depth wells (fig. 15) because both well types are open to the same lithologic unit and because the pumped irrigation well extracts water from a large section of this unit. Water-level declines in shallow and mid-depth test wells after prolonged pumping were about 0.7 foot larger at the SA site than at the SB site (July 5). In late 1988, water levels in all wells recovered to a position 2.6 feet below their preirrigation season levels (fig. 15), then showed little change during a 3-month period.

During the irrigation season, water levels in the deep test wells (fig. 16) exhibit considerably larger declines than shallow and mid-depth test wells (fig. 15). On July 5, 1988, the difference between the shallow and mid-depth and the deep test wells was 4.38 feet at the SA site and 1.85 feet at the SB site. A possible explanation for this is that the lower sand unit (deeper than 78 feet below land surface) is separated from the upper sand unit by clayey sand units of smaller permeability, which retard flow between the two sand units (fig. 3). The lower sand unit appears to be of greater permeability than the upper sand unit; the irrigation well, which is open to both sand units (fig. 3), thus extracts a larger fraction of its total discharge from the lower sand unit, and drawdown in the lower sand unit exceeds that of the upper unit.

Water-level records indicate a large hydraulic-head drop (greater than 4 feet at the SA site) from the upper sand unit to the lower sand unit during periods of pumping. The vertical hydraulic-head gradients under the S field may induce downward flow of chemicals

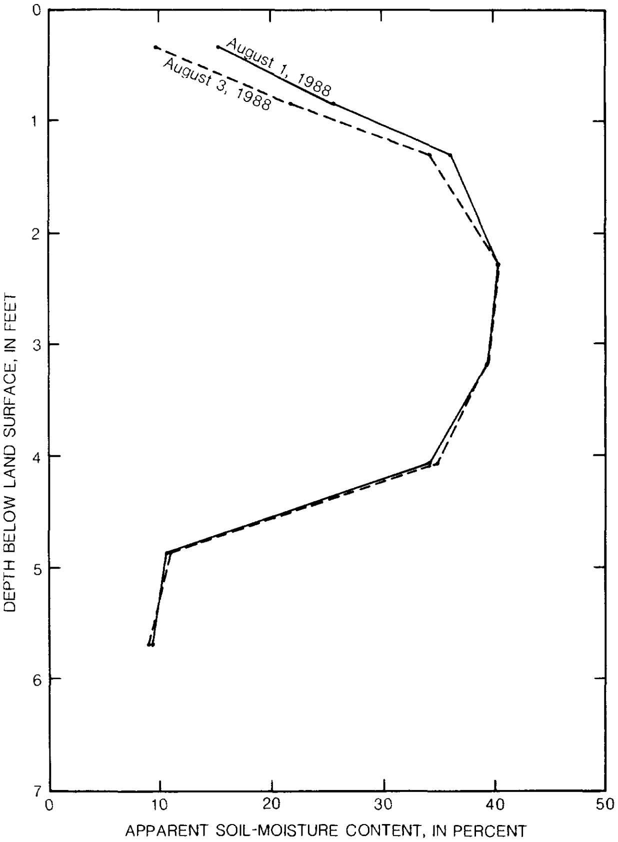


Figure 14. Apparent soil-moisture profiles for August 1 and 3, 1988.

that enter the aquifer at the water table.

The lowest water levels in the SA deep and SB deep wells were observed on August 9 (fig. 16), close to the end of the irrigation season, which was approximately 6 days later. Water levels later in August exhibit considerable recovery in the deep wells (fig. 16) but show continued decline in the shallow and mid-depth wells (fig. 15). This is because water levels in the lower sand unit remained lower than those of the upper sand unit until late August (figs. 15 and 16) and thus induce continued declines in the upper sand unit due to downward flow of water to the lower unit.

F Field

At the FA site, the water levels in the deep test well showed slightly smaller declines during pumping than did those in the shallow and mid-depth wells, but at the FB site all water levels were similar (fig. 17). The smaller declines in the FA deep well are due to partial penetration of the aquifer by the pumping irrigation well (fig. 4). The effects of this partial penetration become small at the FB site. McWhorter and Sunada (1985, p. 134) note that vertical components of flow caused by a pumping well that is partially penetrating are negligible for distances from the well that exceed approximately 1.5(b), where b is the thickness of the aquifer. Estimating saturated thickness at the F field to be 186 feet (Williams and Lohman, 1949, plate 7), then 1.5(b) = about 280 feet. The distances of the test wells from the pumping well are about 200 feet for the FA site and about 590 feet for the FB site. Therefore, vertical flow may be significant at FA and not significant at FB.

CHARACTERIZATION OF GROUND-WATER FLOW THROUGH UNSATURATED ZONE

Because of the interest in potential contamination of ground water by agricultural chemicals, an understanding is required of the downward movement of water from land surface to the water table. The description of the average water particle's position in the unsaturated zone as a function of time is of particular importance because it may be requisite to a description of the average pesticide molecule's position through time. Pesticides, such as atrazine, undergo decay processes, the rate of which may depend on depth below land surface (Perry, 1990). This section discusses some of the methods that are being used to describe or estimate the downward movement of water from land surface to the water table.

Tracer Tests

Conservative-tracer tests may provide useful information for describing downward movement of contaminants through the unsaturated zone because they can provide a description of the actual movement of water molecules through time. Tracer tests were begun on May 13, 1988, by applying potassium chloride to the land surface directly above the two clusters of suction lysimeters that were installed at the SB and FB sites (figs. 3 and 4). Water samples were withdrawn from the suction lysimeters periodically during the study and, when sample volume was adequate, were analyzed for chloride concentration at the U.S. Geological Survey laboratory in Lawrence,

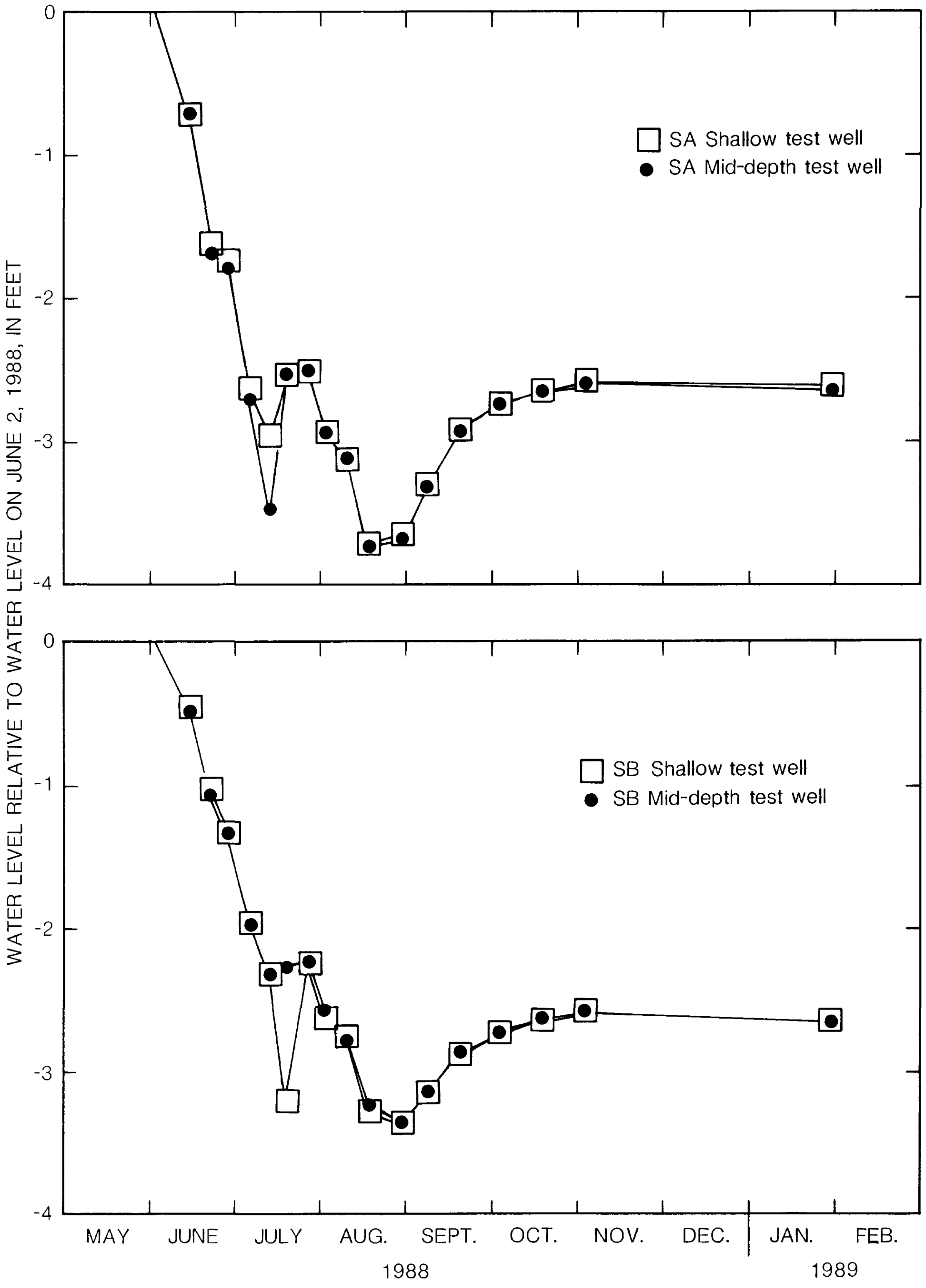


Figure 15. Water levels in shallow and mid-depth test wells at S field.

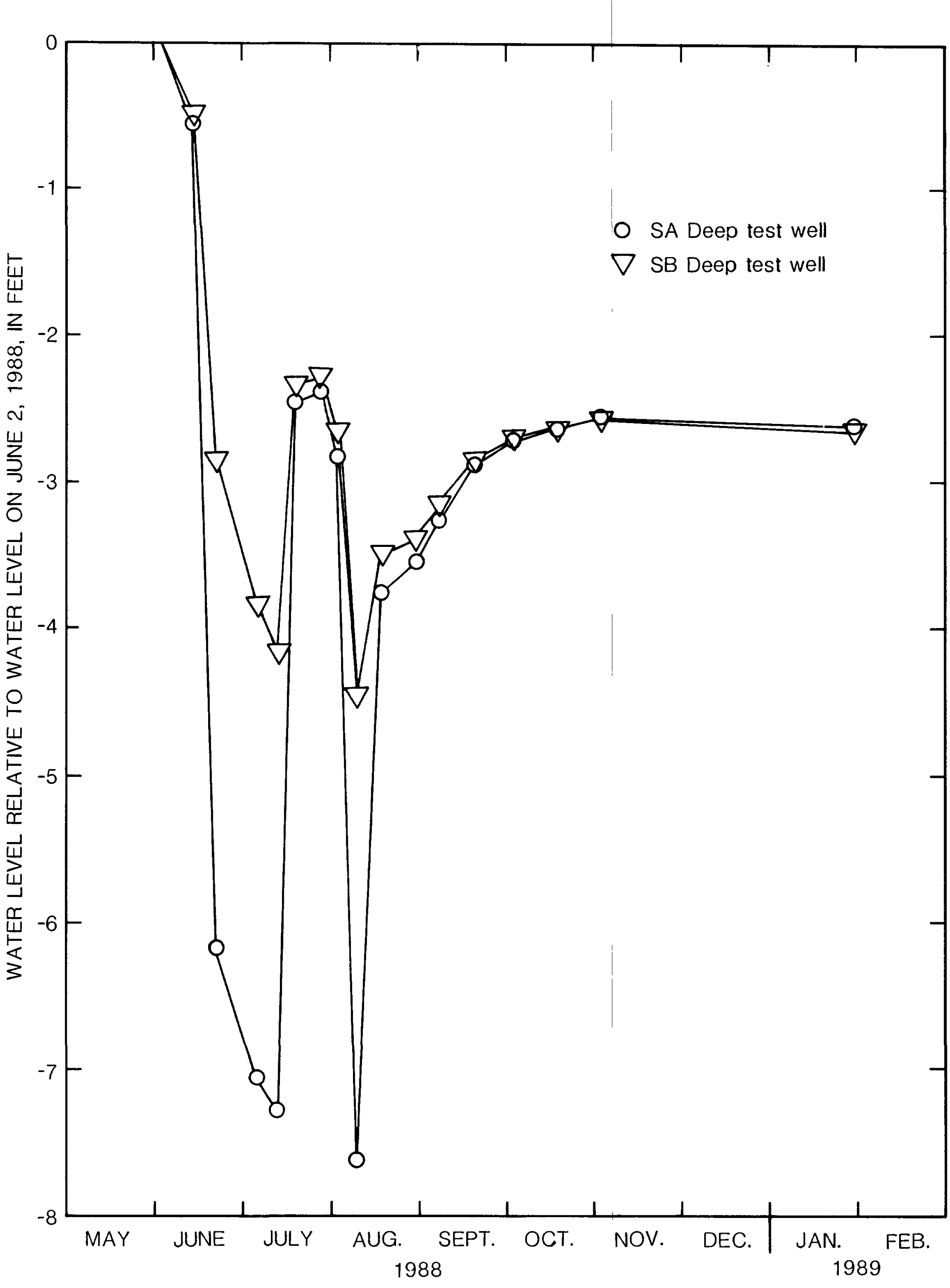


Figure 16. Water levels in deep test wells at S field.

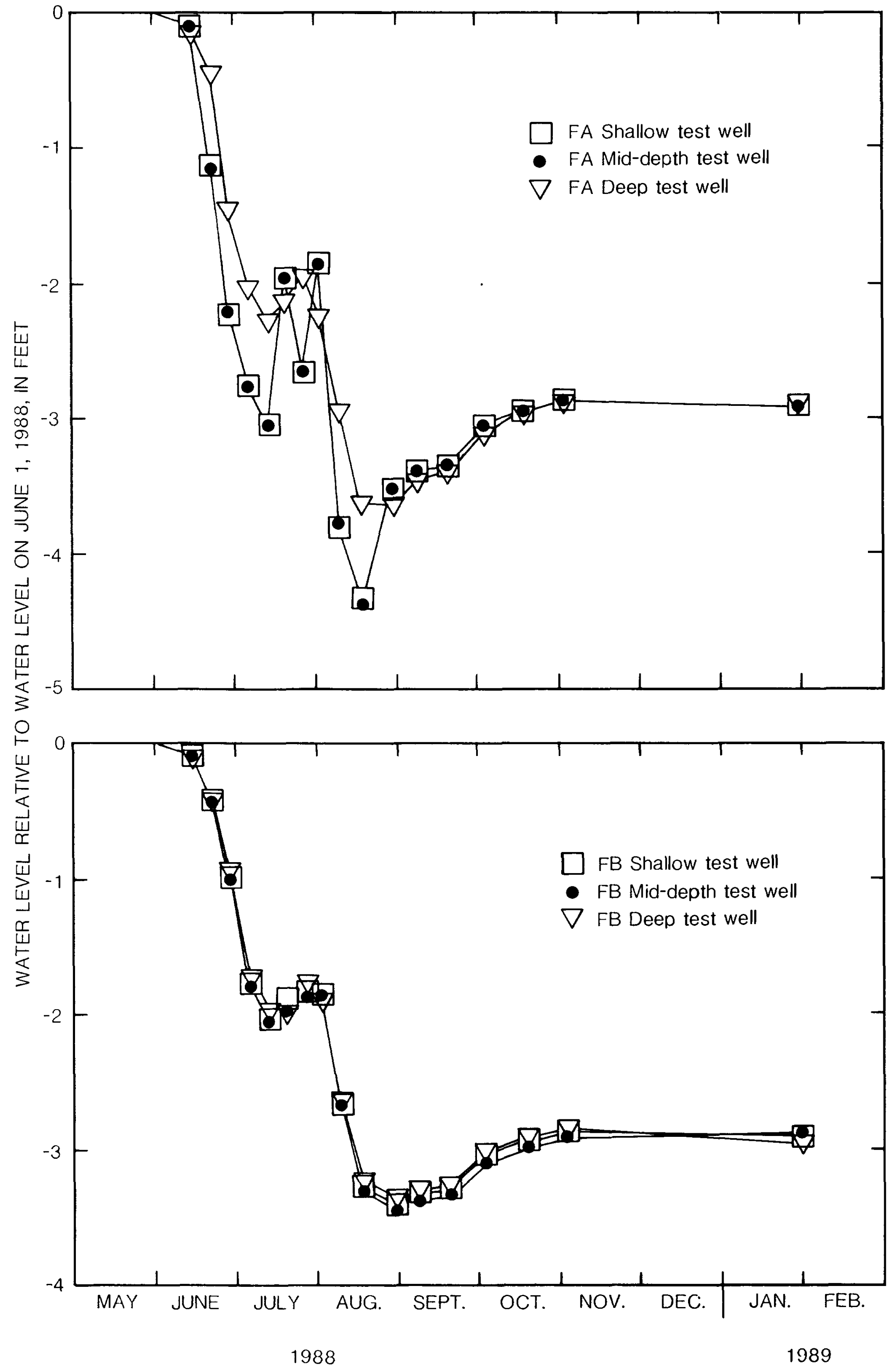


Figure 17. Water levels in test wells at F field.

Kansas. Background chloride concentrations are indicated approximately by the values for May 1988 (available for samples from some of the lysimeters) shown in figures 18 and 19.

Results of the tracer test at the SB site (fig. 18) show:

(1) the largest chloride concentration prior to mid-June at a depth of 5.9 feet;

(2) a slow decrease in chloride concentration during the subsequent months at the 5.9-foot depth; and

(3) slow increases in chloride concentrations through the fall of 1988 and into the subsequent winter, at depths of 7.9 and 9.7 feet.

Results indicate relatively rapid transport through the root zone (from land surface to a depth of 4 to 6 feet) followed by slower vertical transport below the root zone.

The times of peak chloride concentrations cannot be determined conclusively from figure 18. However, if it is assumed that the maximum chloride concentrations for the depths of 5.9 and 9.7 feet occurred on June 1, 1988, and February 1, 1989, respectively, then the transport time between these depths is 8 months. Thus, the downward vertical rate of chloride-ion transport is about 5.7 feet per year. If the retardation factor for chloride is 0.8 because of the anion exclusion effect (Wierenga and Van Genuchten, 1989), then the seepage velocity between the depths of 5.9 and 9.7 feet is about 4.6 feet per year.

If it is assumed for estimation purposes that all water in the unsaturated zone participates in flow, then the downward volumetric water flux (ultimately to become recharge to the saturated zone) is, according to McWhorter and Sunada (1985, p.66):

$$q = \theta(v) \quad , \qquad (2)$$

where

q = downward volumetric water flux (inches per year);

θ = soil-moisture content (dimensionless); and

v = mean downward seepage velocity (inches per year).

When considering soil-moisture content below the root zone to be 0.09, from figure 10, and assuming the mean downward seepage velocity to be 4.6 feet per year (55 inches per year), then q = 5 inches per year. Because not all water participates in flow and because the velocity of the peak chloride concentration is probably larger than the mean velocity of all chloride ions, this may be the maximum downward volumetric water flux below the root zone, for the time of interest.

Results of the tracer test at the FB site (fig. 19) show:

(1) a peak in chloride concentration at the end of August 1988, at a depth of 5.7 feet;

(2) a slight decrease in chloride concentration during the subsequent months at the 5.7-foot depth;

(3) an increase in chloride concentration to a plateau in late September, after which there is no decrease in concentration, at a depth of 7.7 feet; and

(4) little change in chloride concentration at a depth of 8.3 feet.

Results indicate slow transport through the root zone. The transport time from the land surface to a depth of 5.7 feet is approximately 3.5 months, more than 3.5 times that of the SB site (fig. 18).

The leveling-off of chloride concentrations at depths of 5.7 and 7.7 feet may indicate a stagnation of vertical flow from October 1988 to January 1989 because of the scarceness of precipitation (figs. 7 and 8) but also may represent residual chloride ions that remain in the interstitial water after the chloride-tracer pulse has moved past.

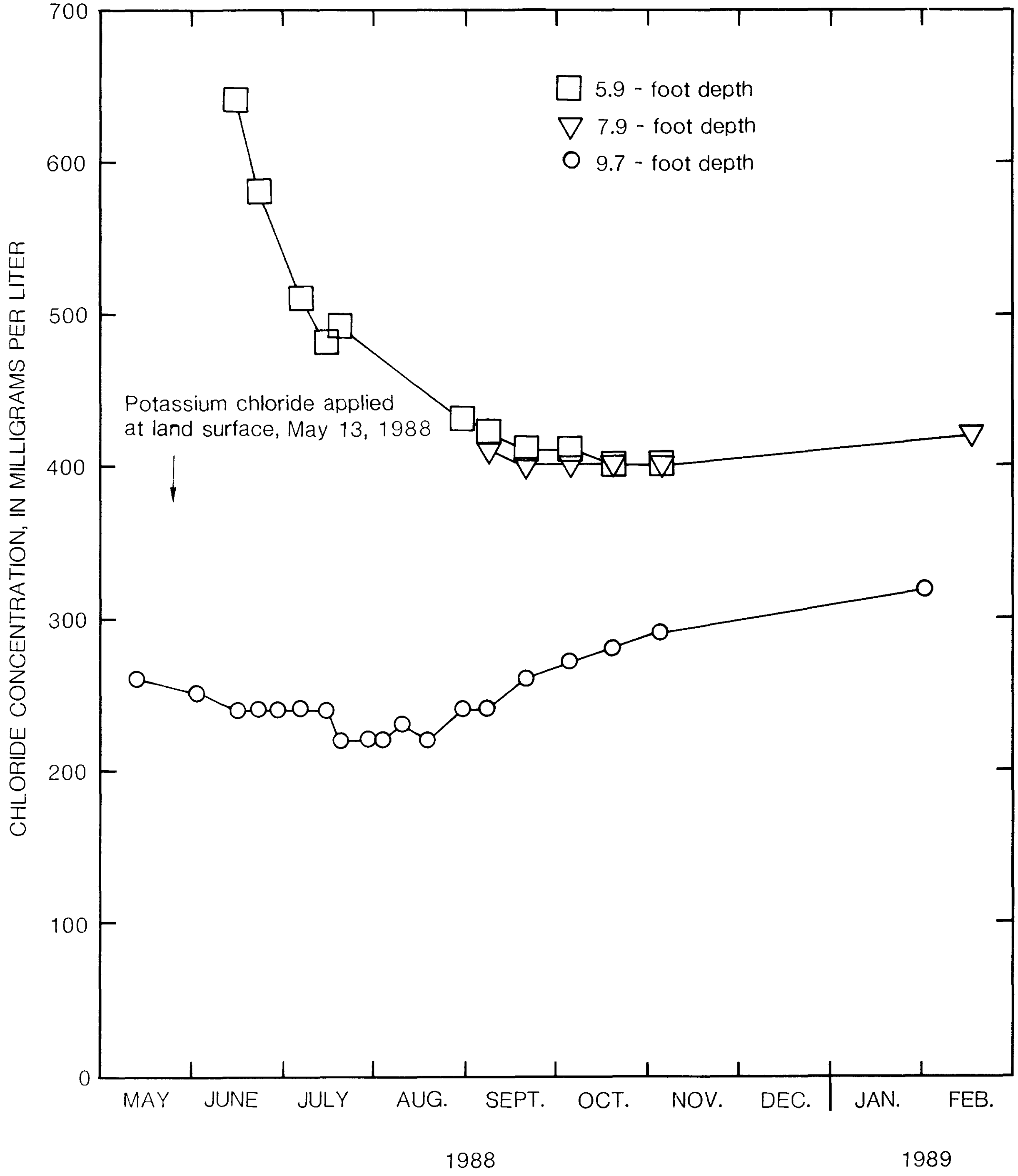


Figure 18. Chloride concentrations in water from suction lysimeters at SB site after application of potassium chloride at land surface.

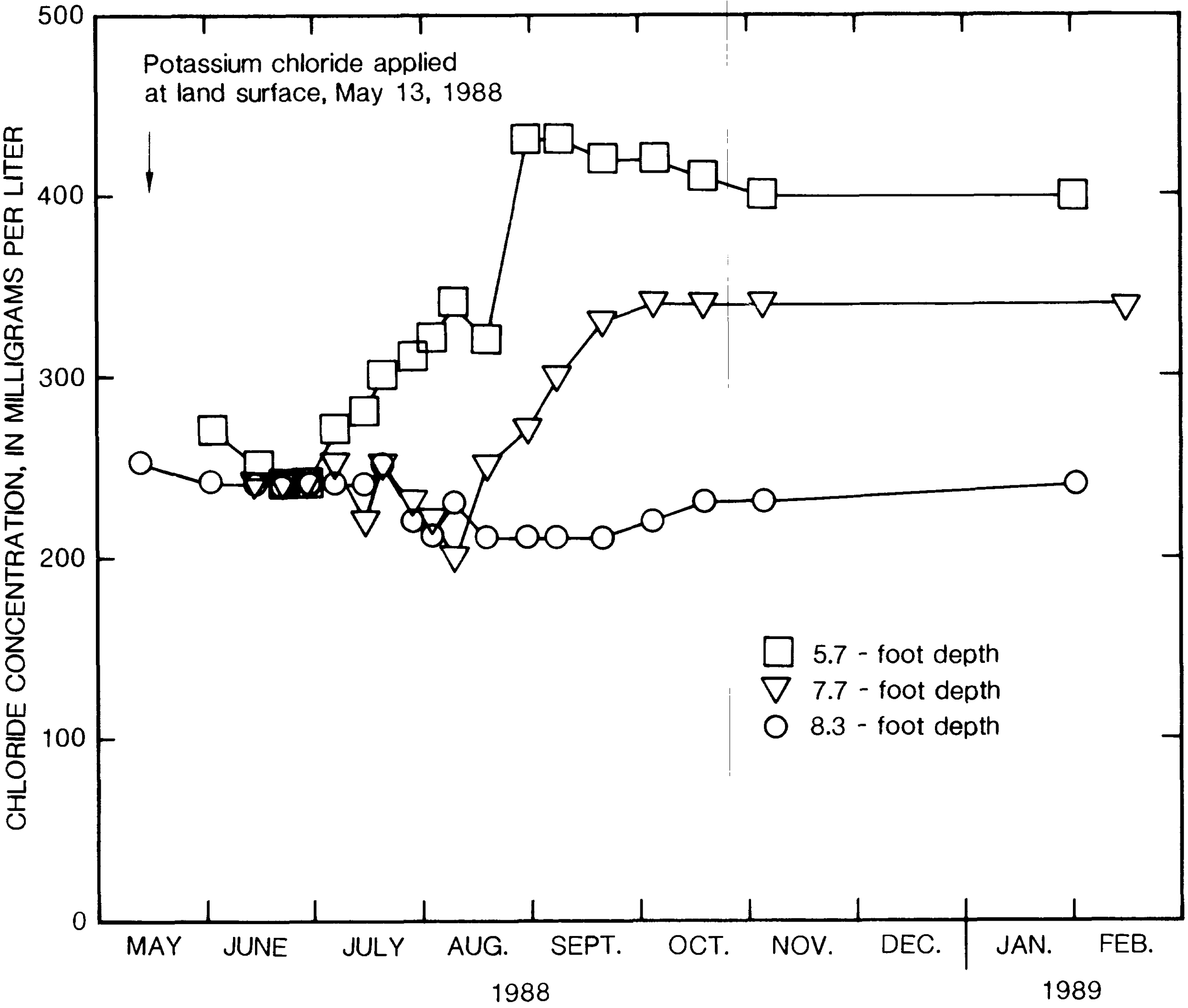


Figure 19. Chloride concentrations in water from suction lysimeters at FB site after application of potassium chloride at land surface.

Water-Level Changes

At times of substantial recharge of short duration, water-level changes can be used to estimate recharge. This technique can be applied in combination with other techniques to estimate the vertical movement of surface-applied chemicals.

The amount of recharge that occurs during a period of recharge can be estimated by the equation:

$$R = Sya = (\Delta h) \ , \qquad (3)$$

where

R = amount of recharge (inches);

Sya = apparent specific yield (dimensionless); and

Δh = increase in water level at the water table (inches).

To avoid errors caused by interference, this calculation should be applied only for time periods when water levels are not changing for other reasons, such as drawdown due to pumping or recovery after drawdown. Thus, use of this equation is precluded during June-October at the test fields (figs. 15-17). For the data obtained in 1988, no period of recharge was identifiable by use of this method.

Water-Balance Methods

Water-balance methods can be used to estimate recharge during an extended length of time, such as several years. Calculations are based on a relatively smaller time step (for example: 1 hour, 1 day, or 1 week), depending on the availability of data, the precision required, and the resources available. Critical elements of a water-balance calculation of recharge include the determination of evapotranspiration and the accounting of changes in soil moisture.

A simple mathematical scheme was employed to estimate the water available for recharge at the SB site. This scheme considers rainfall, irrigation, evapotranspiration, and soil-moisture deficiency. Elements of this mathematical scheme (fig. 20), which is executed using a 1-week time interval, are:

(1) Use of the Jensen-Haise equation for estimating potential evapotranspiration (Jensen and Haise, 1963).

(2) The ratio of adjusted evapotranspiration (the calculated evapotranspiration before crop effects are considered) to potential evapotranspiration is a function of rainfall plus irrigation minus the initial soil-moisture deficiency (fig. 20).

(3) The evapotranspiration after crop effects is equal to the previously calculated evapotranspiration multiplied by the crop factor (Jensen, 1973). Crop factors are set arbitrarily at 0.2 during the nongrowing season.

(4) The soil-moisture deficiency at the end of the present time interval is equal to the previous deficiency plus adjusted evapotranspiration for the week minus rainfall and irrigation but is not allowed to exceed 1 inch (see "Soil Moisture" section).

(5) If the calculated soil-moisture deficiency is less than zero, then the water available for recharge is equal to that value, and the soil moisture is reset to zero. Otherwise, recharge is zero, and soil-moisture deficiency is not changed.

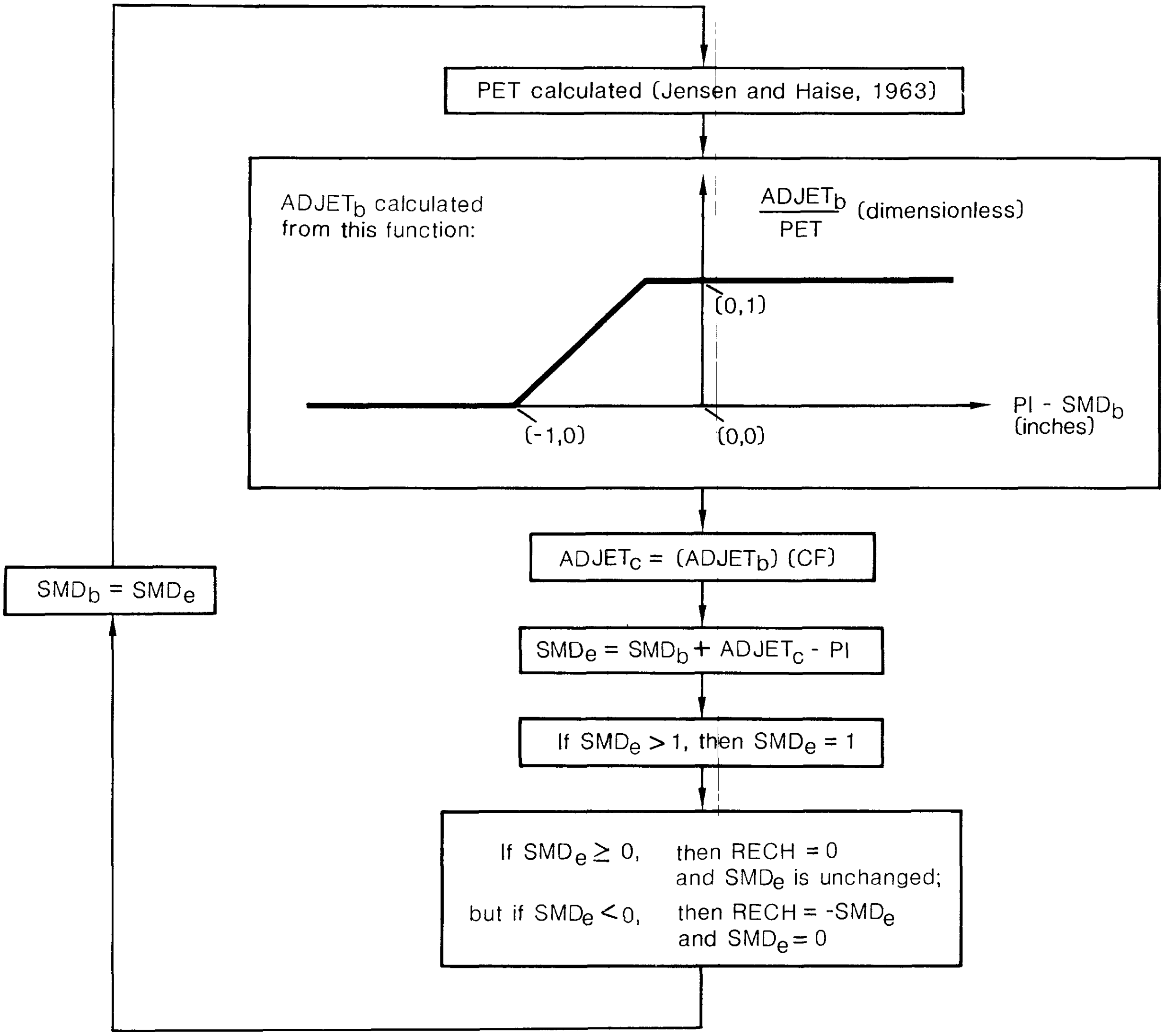
(6) The final soil-moisture deficiency at the end of a time increment is retained as the beginning deficiency for the next increment.

The result of using this mathematical scheme for the SB site is illustrated in figure 21. The initial moisture content was set at 0.5 inch, and the first week of calculations was January 10-16, 1988. Average weekly temperatures were all above 32 °F. Potential recharge is calculated to be approximately 7.7 inches between January 10, 1988, and the end of January 1989. Most of the potential for recharge was during the spring of 1988.

Models exist for estimating ground-water recharge using a mathematical structure that is similar to the just-described scheme, but using more data, such as soil properties, and applying calculations using a smaller time step. An example of such a model is documented by Bauer and Vaccaro (1987).

CHARACTERIZATION OF GROUND-WATER QUALITY AND CHEMICAL TRANSPORT

In addition to the sampling that was done for tracer-test analysis of flow in the unsaturated zone (already discussed), sampling also was carried out to characterize the ground-water quality in the unsaturated and saturated zones and to relate ground-water quality to agriculture. This water-quality characterization included three indicator chemical variables--chloride, nitrite plus nitrate, and atrazine. Chloride is conservative (nondegrading and nonsorbing) and may be an effective indicator of transport from the surface to the saturated zone. Nitrite plus nitrate is analyzed as one chemical variable. Neither ion is retained by the



EXPLANATION

PET = Potential evapotranspiration (inches)
ADJET$_b$ = Adjusted evapotranspiration before crop effects are considered (inches)
ADJET$_c$ = Adjusted evapotranspiration after crop effects are considered (inches)
CF = Crop factor (dimensionless)
SMD$_b$ = Soil-moisture deficiency before this time increment (inches)
SMD$_e$ = Soil-moisture deficiency after this time increment (inches)
PI = Rainfall plus irrigation (inches)
RECH = Potential for recharge (inches)

Figure 20. Mathematical scheme for calculating amount of water available for recharge. (The diagram shows steps during one time increment, 1-week long.)

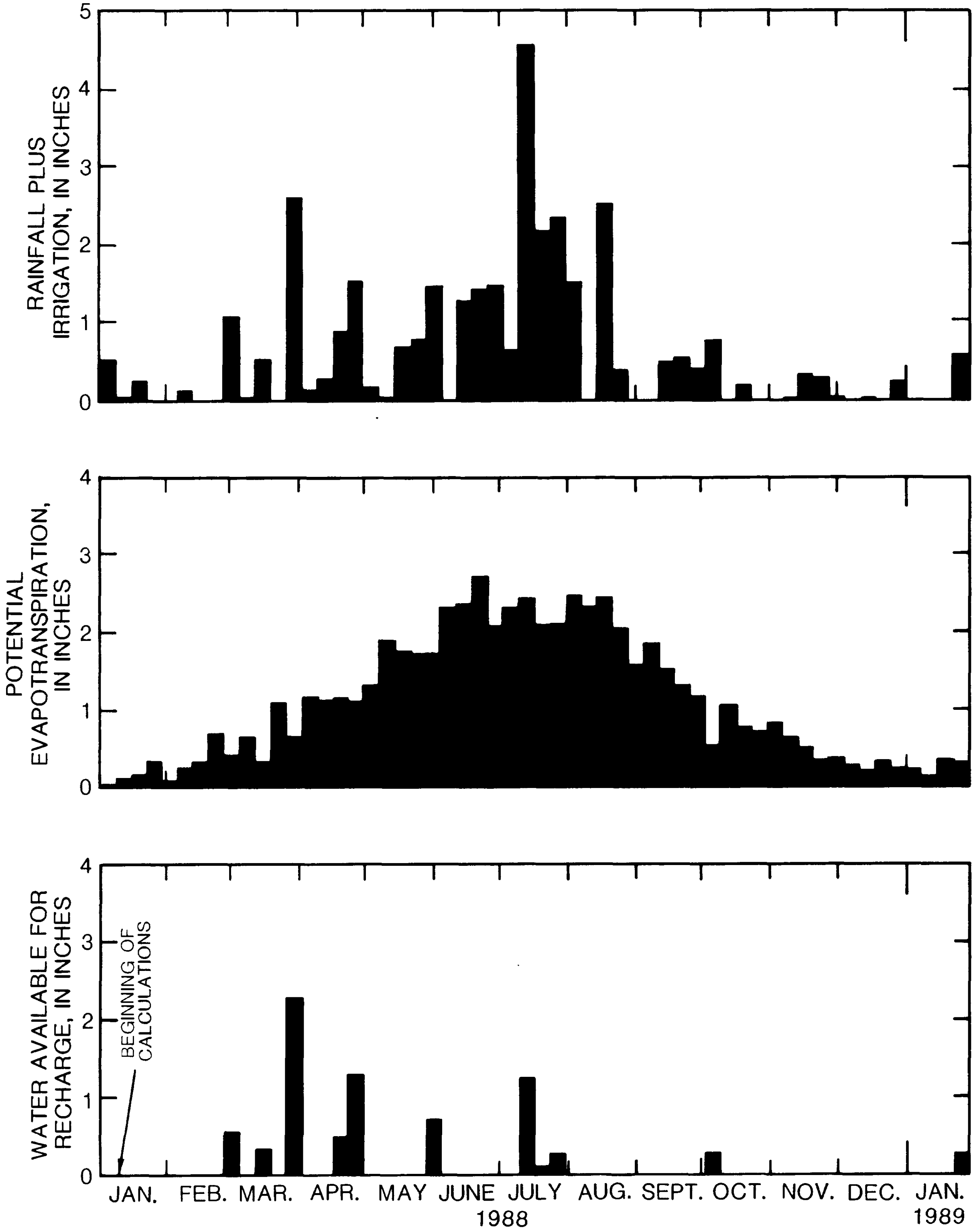


Figure 21. Weekly rainfall plus irrigation at SB site (record prior to June 21 and after November 3 was calculated as average of rainfall records from four sites north of Wichita, figure 2), weekly potential evapotranspiration calculated using Jensen-Haise equation and climatological data from Wichita WSO Airport meteorological station (figure 2), and weekly water available for recharge (calculated by using simple mathematical scheme, figure 20).

solid phase (soil materials), but both are subject to degradation. An advantage of nitrite plus nitrate relative to chloride is that the former occurs at very small background (prior to agriculture) concentrations, so the detection of change induced by agriculture can be accomplished with greater ease. Atrazine is the chemical of particular concern to this study. It is retained by solid-phase interactions and is subject to decay.

Chloride

Chloride concentrations in the unsaturated zone were discussed in the section on "Characterization of Ground-Water Flow Through Unsaturated Zone." Chloride concentrations in the saturated zone show considerable variation through time (fig. 22).

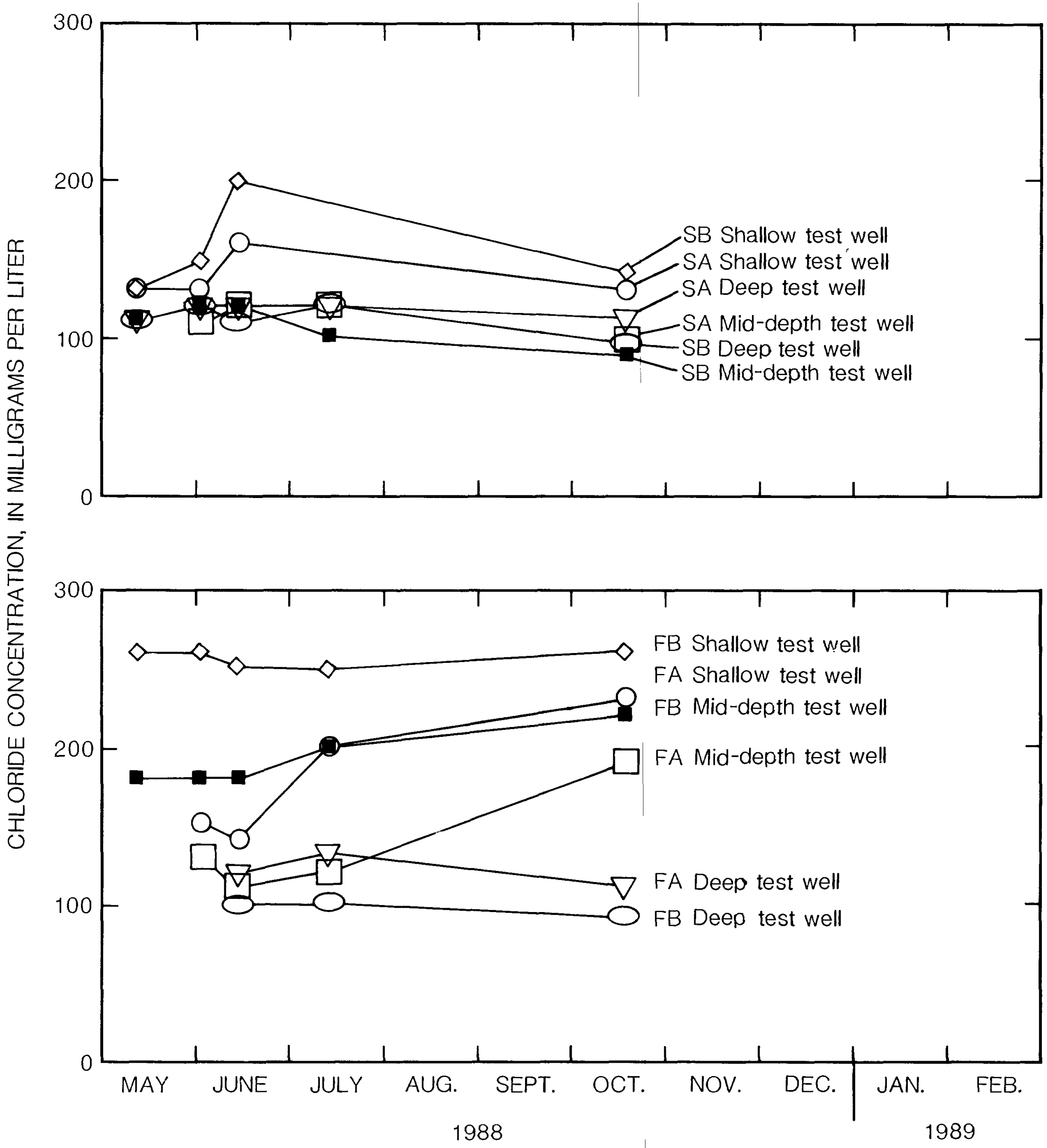


Figure 22. Chloride concentrations in water from test wells.

Chloride concentrations in samples from the deep test wells at the S field indicate that the lower sand unit may not be as isolated from the upper sand unit as the lithology (fig. 3) might indicate. The chloride concentrations in water from the deep test wells are similar to those in water from the mid-depth wells at the S field. A possible reason may be the downward flow induced by large drawdown in the lower sand unit (fig. 16) relative to that in the upper unit (fig. 15).

In the F field, differences in chloride concentrations in samples from test wells at different depths indicate relative isolation of the slightly clayey sand unit to which the deep wells are open (fig. 23). Under the F field, the irrigation well is open to shallower depths, inducing a shallower circulation in the saturated zone as compared to the S field. Chloride concentrations in water from the FA shallow and mid-depth test wells exhibit a possible increase through time (fig. 22). There is a stratification in

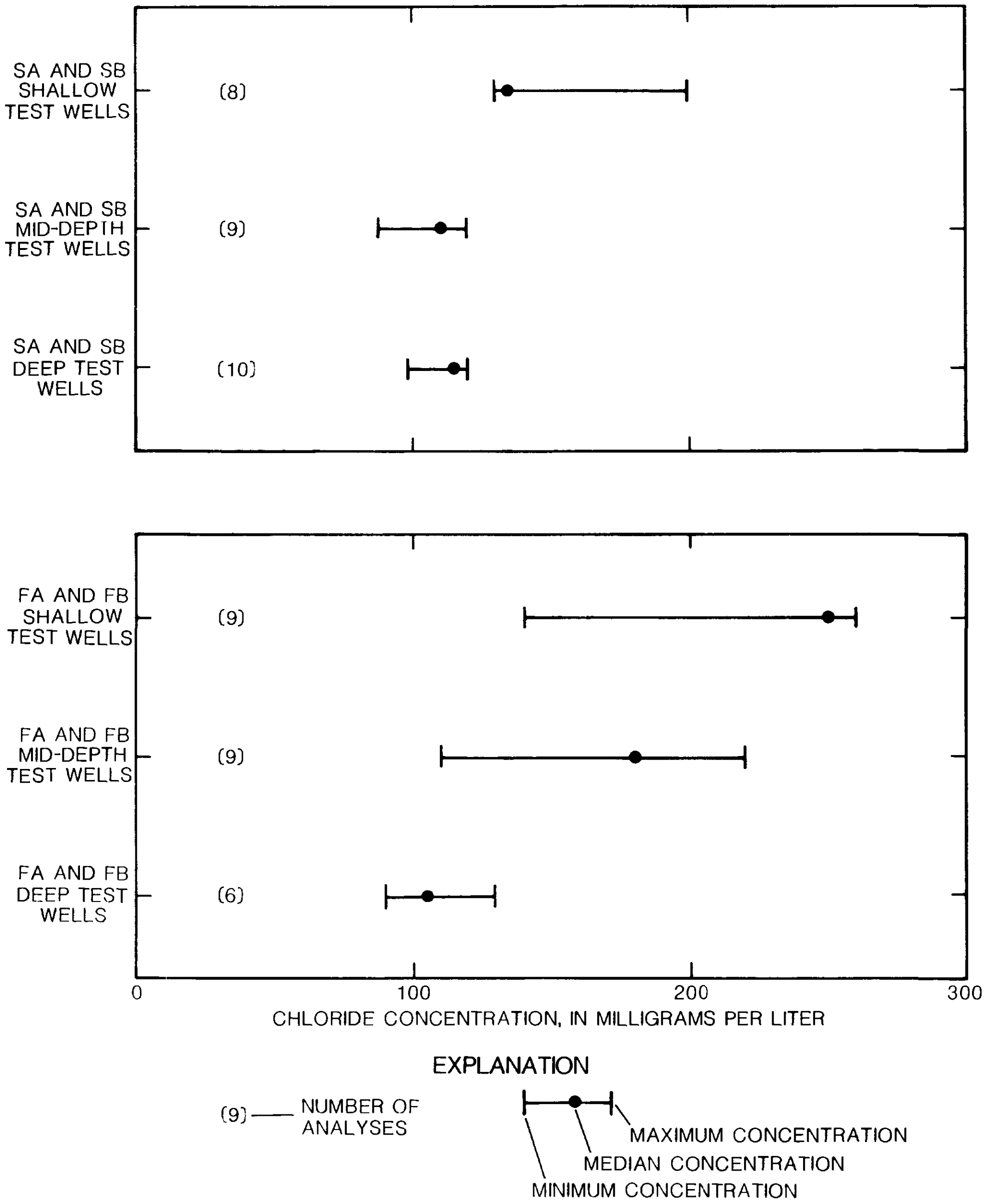


Figure 23. Distribution of chloride concentrations in water from test wells.

chloride concentrations, with water from shallow wells showing larger concentrations than water from the deep wells. Larger concentrations in water from shallow wells (fig. 23) possibly occur because the shallow wells are extracting water from a zone which is closer to the source of the chloride (land surface).

Nitrite Plus Nitrate

Results describing nitrite-plus-nitrate concentrations are very limited, especially in water collected from suction lysimeters, due to small sample volumes and unsuccessful use of a field test kit. Use of the field test kit was attempted because it requires only about 10 milliliters of sample. However, comparisons between field-test-kit results and laboratory results were poor, and no field-test-kit results are given in this report.

Only two laboratory analyses of nitrite plus nitrate in soil water from suction lysimeters were obtained in 1988:

	Concentration of nitrite plus nitrate as nitrogen (milligrams per liter)
SB 9.7-foot deep lysimeter	70
FB 8.3-foot deep lysimeter	19

These samples were collected on June 14, 1988, and analyzed by the U.S. Geological Survey laboratory in Arvada, Colorado. The relatively large concentrations indicate a substantial effect of fertilizer application on water quality in the unsaturated zone. Tracking of the movement of nitrite plus nitrate through the unsaturated zone may provide useful information pertaining to the movement of water and the transport of nutrients and pesticides in the unsaturated zone.

Results of laboratory analyses of water from test wells indicate a stratification in nitrite-plus-nitrate concentrations, similar to that of chloride concentrations, in the saturated zone (fig. 24). Shallower test wells generally yield water having larger concentrations of nitrite plus nitrate than water from deeper wells because the depth intervals to which they are open are closer to the source. Median nitrite-plus-nitrate concentrations in water from the shallow wells were 40 and 20 mg/L (milligrams per liter) for the S field and F field, respectively. At the S field, the nitrite-plus-nitrate concentrations were considerably larger in water from the shallow wells than they were in water from the mid-depth and deep wells, whereas at the F field there was a more gradual decrease in concentrations from the shallow to the mid-depth to the deep wells. The nitrite-plus-nitrate concentrations in the water from the deep wells at the S field may be a further manifestation of downward flow of water to the lower sand unit induced by larger drawdown in the lower unit (fig. 16) as compared to the upper unit (fig. 15). At the F field, the smaller nitrite-plus-nitrate concentrations in samples from the deep test wells probably reflect the shallower circulation that prevails there.

Atrazine

To reduce laboratory costs, enable analysis of small sample volumes, and provide rapid turnaround time for analytical results, a field test kit designed for detecting atrazine was used. In 1988, more than 100 analyses were conducted, and because most samples were from suction lysimeters, many measured less than 50 milliliters in total volume.

To verify results of field test kits, comparisons were made between some results obtained with the field test kit and chemical analyses conducted in the U.S. Geological Survey laboratory (Lawrence, Kansas) using gas chromatography (table 2). The test-kit results are in reasonable agreement with the laboratory results.

Water from the suction lysimeters was sampled several times to characterize the atrazine concentration in the unsaturated zone and to attempt to track the movement of specific pulses of the chemical as it migrated through the unsaturated zone below the root zone. Atrazine has been applied once per year for several consecutive years at both the S and F fields. The time of applications in 1988 was in May (figs. 5 and 6).

Data obtained in 1988 show no discernable trend through time (table 3), unlike the data obtained for chloride concentration, which indicated movement of a particular chloride pulse through the unsaturated zone (figs. 18 and 19). A possible explanation is that the atrazine concentrations detected in 1988 result from the residuals of pre-1988 applications of atrazine, similar to the residuals of chloride (figs. 18 and 19), and that the atrazine applied in 1988 had not reached the suction lysimeters during 1988 because of retardation.

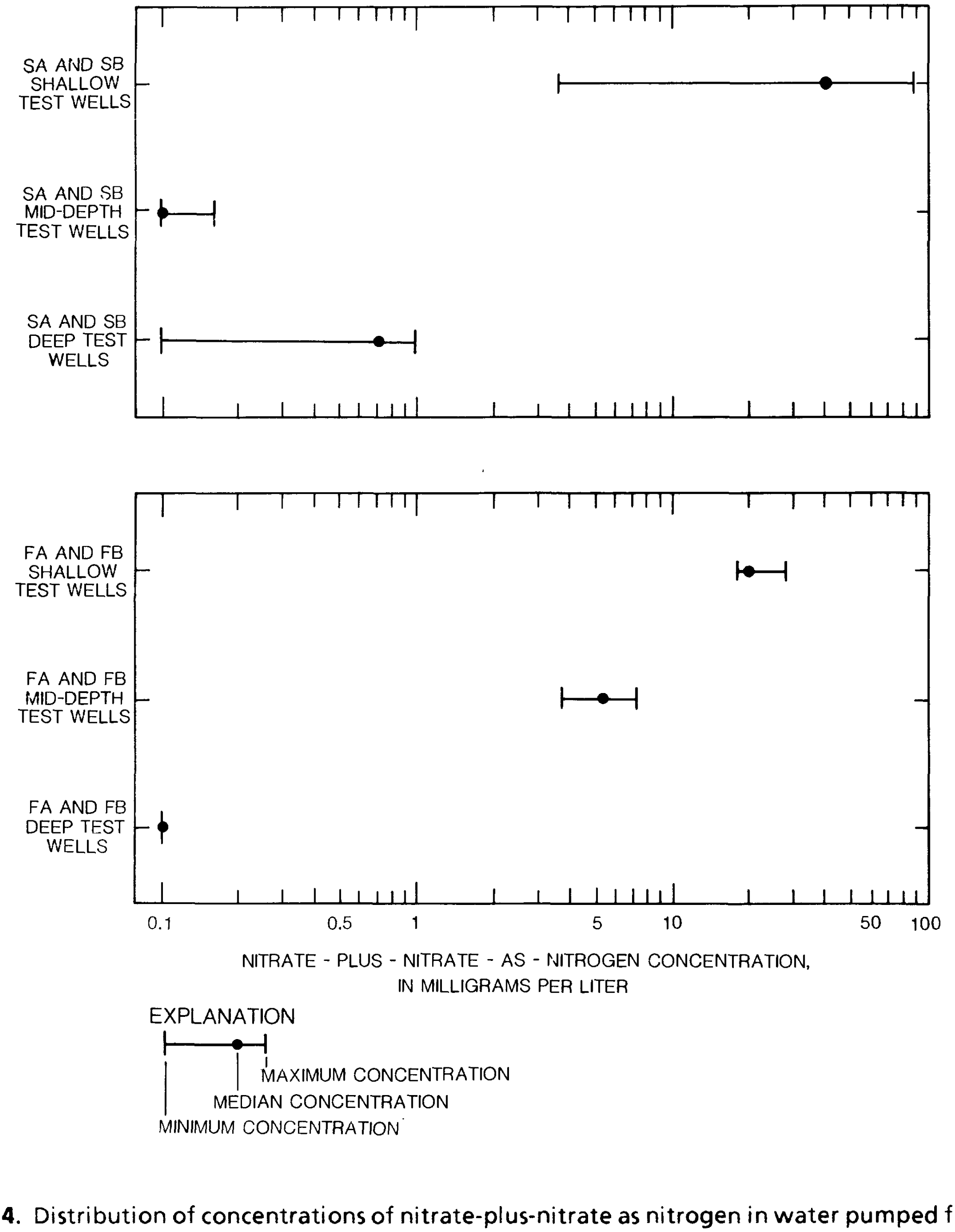


Figure 24. Distribution of concentrations of nitrate-plus-nitrate as nitrogen in water pumped from test wells. (Each set of minimum, median, and maximum concentrations was based on four laboratory analyses.)

Table 2. *Comparison of atrazine field-test kit results with laboratory gas-chromatography results*

Source of sample (figs. 3 and 4)	Date of sample	Atrazine concentration, in micrograms per liter	
		Field test kit	Laboratory
Lysimeter depth			
SB 9.7 feet	June 22, 1988	0.1	<0.2
FB 8.3 feet	June 22, 1988	9	7.5
FB 8.3 feet	June 28, 1988	5	7.0
FB 8.3 feet	July 13, 1988	2	2.5
Test wells			
FB shallow	October 18, 1988	2	2.0
FB mid-depth	October 18, 1988	< .2	< .2
FB deep	October 18, 1988	< .2	< .2

A simple mathematical model (Rutledge and Helgesen, 1989) that can be used to compare the transport of a chemical that is retarded due to chemical sorption, with that of a nonsorbed chemical, is:

$$ti = \int_{0}^{zi} \frac{1}{q}[\theta + pb(Kd)]\,dz\,, \qquad (4)$$

where

ti = time of travel, for transport from land surface to a depth of interest (years);

zi = depth of interest below land surface (feet);

q = downward volumetric water flux (inches per year);

θ = soil-moisture content (dimensionless);

pb = bulk density of the soil (pounds per cubic foot);

Kd = distribution coefficient of the chemical in the soil-water system (cubic feet per pound); and

dz = depth below land surface (feet).

The chemical's distribution coefficient is calculated as:

$$Kd = Koc(Poc)/100\,, \qquad (5)$$

where

Koc = organic-carbon partition coefficient of the chemical (cubic feet per pound); and

and

Poc = percentage of organic carbon in the soil.

The value of *Koc* is a standardized measure of the chemical's sorption. For atrazine, the value of *Koc* is 2.56 cubic feet per pound.

The term *pb* in equation 4 is assumed to be constant, 107 pounds per cubic foot, but q, θ, and *Poc* vary considerably with depth. Their distributions, in a hypothetical example, are

Table 3. *Atrazine test-kit results for water samples from suction lysimeters, 1988*

[Concentrations in micrograms per liter]

Lysimeter depth (figs. 3 and 4)	June 2	June 14	June 22	June 28	July 6	July 13	July 19	July 27	Aug. 3	Aug. 9	Aug. 17	Aug. 30	Sept. 7	Sept. 20	Oct. 18	Nov. 4
SB 5.9 feet	--	0.4	<0.1	--	0.1	0.2	0.4	--	--	--	--	0.3	0.1	<0.1	0.5	0.3
SB 7.9 feet	--	--	--	--	--	--	--	--	--	--	--	--	.1	.2	.4	.2
SB 9.7 feet	0.2	.2	.1	0.2	.1	.2	.2	0.2	0.2	0.2	0.2	.2	<.1	.2	.5	.2
FB 5.7 feet	1	.9	1	5	3	.9	2	2	.8	3	4	2	2	4	2	2
FB 7.7 feet	3	4	3	9	8	3	4	8	4	10	3	1	6	10	4	10
FB 8.3 feet	>10	>10	9	5	4	2	2	4	2	4	6	3	4	4	3	5

shown in figure 25. Volumetric water flux (q) is based on an infiltration rate of 40 inches per year, a deep percolation rate of 5 inches per year, and gradual loss of flow in the root zone, which is 5 feet thick. Soil-moisture (θ) is similar to that at the SB site (fig. 10), and percentage of organic carbon (Poc) is estimated.

Solution of equation 4, using data from figure 25, shows considerable retardation of atrazine relative to a nonsorbing tracer, especially in the organic-rich upper 1 foot of soil (fig. 26). The tracer moves at a velocity equal to that of the water seepage velocity. According to this hypothetical example, the arrival of atrazine at a given point below the root zone follows that of a nonsorbing tracer by approximately 1.2 years. Transport velocities of atrazine and the nonsorbing tracer become equal at depths where the organic-carbon content is zero.

Concentrations of atrazine, alachlor, and metolachlor in soil material (table 4) demonstrate considerable retention of these pesticides due to sorption. Detection of atrazine in March 1988 probably results from atrazine application in 1987. Before the soil sampling in June 1988, this atrazine probably was transported beyond the depth range sampled in June because of recharge in late March and April (fig. 21) and because the transport velocity of atrazine was approaching that of a nonsorbed tracer (fig. 26). The atrazine detected near the surface in June 1988 (table 4) probably resulted from the atrazine applications of mid-May 1988 (figs. 5 and 6). The transport of the atrazine applied at the SB site in 1988 was retarded with respect to the nonretained chloride, which showed considerable movement between mid-May and mid-June (fig. 18).

Atrazine concentrations in ground water generally are larger at the F field than at the S field. Concentrations in water from the suction lysimeters generally are an order of magnitude larger at the F field (table 5). Similarily, concentrations in water from the test wells generally are greater than the detection limit at the F field and less than the detection limit at the S field (table 6).

Both test fields show decreasing atrazine concentrations in water from the suction lysimeters to the test wells; this condition probably results from the lysimeters being closer to the atrazine source (land surface). For the F field, there is a stratification of atrazine concentrations, similar to that of chloride and nitrite plus nitrate, with concentrations decreasing in water from shallow wells to mid-depth wells to deep wells (table 6). Furthermore, atrazine concentrations in water from the suction lysimeters are larger than concentrations in water from shallow test wells.

There is a greater decrease in chemical concentrations from the land surface to the subsurface for atrazine as compared to nitrite plus nitrate. If, for purposes of estimation, it is assumed that the quality of water from the shallow test wells is representative of recharge water, that chemicals applied at the land surface are not lost and become evenly distributed in this recharge water, and that recharge is 5 inches per

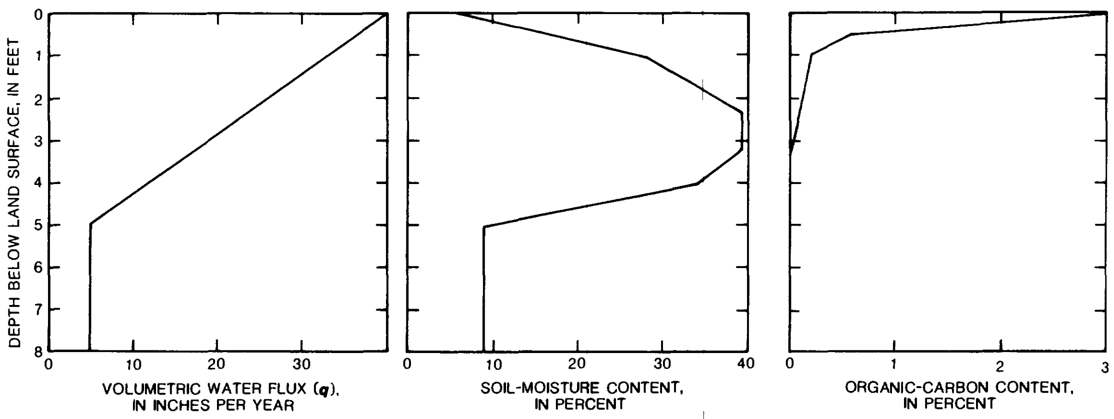


Figure 25. Distribution of volumetric water flux, soil-moisture content, and organic-carbon content with depth in a hypothetical example.

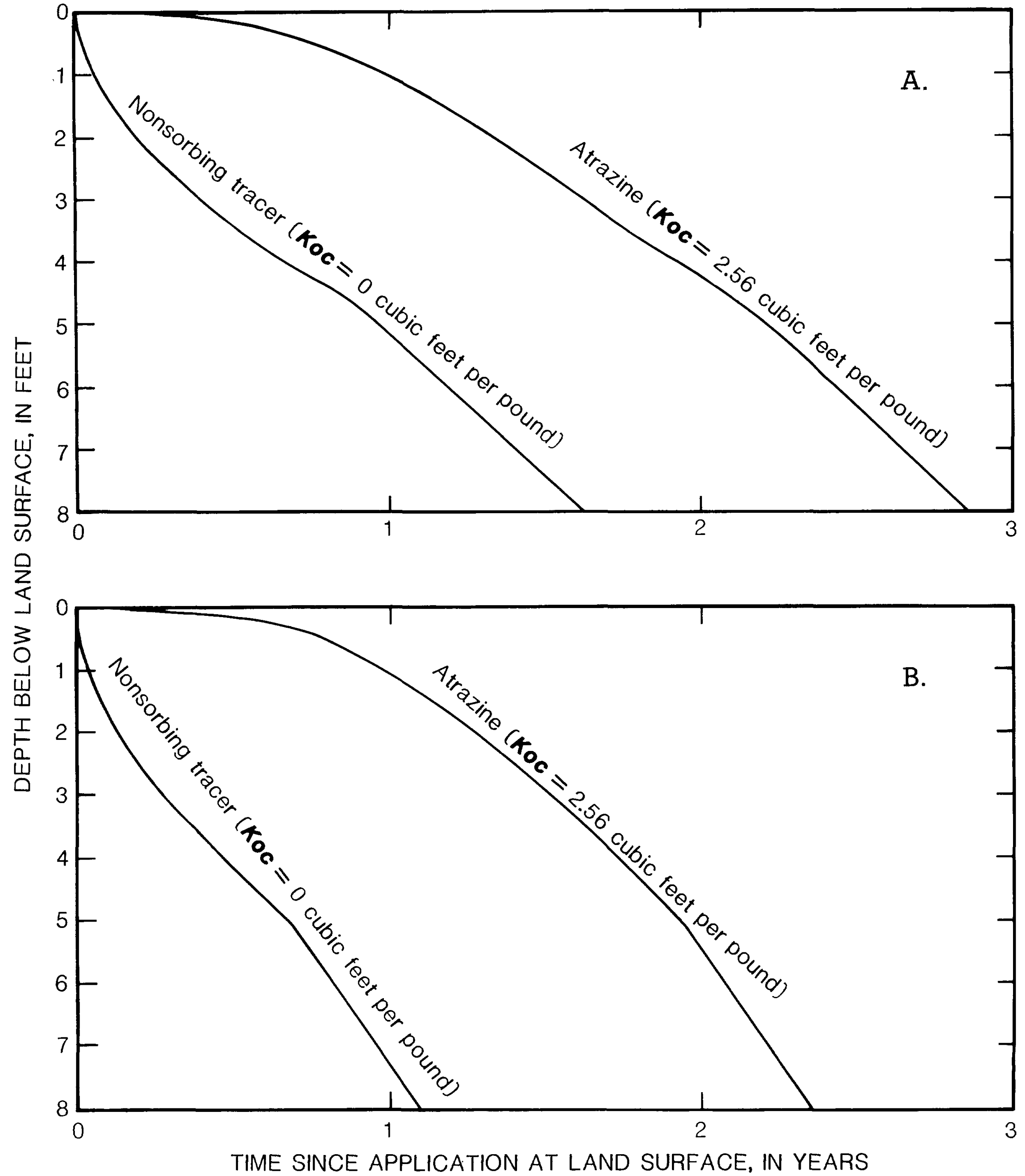


Figure 26. Transport of atrazine and nonsorbing tracer through unsaturated zone as calculated with equation 4: (A) using data from figure 25 and (B) using data from figure 25, assuming that only 70 percent of moisture in unsaturated zone participates in transport. (Organic-carbon partition coefficient (*Koc*) for atrazine and nonsorbing tracer are 2.56 and 0 cubic feet per pound, respectively).

Table 4. *Concentrations of atrazine, alachlor, and metolachlor in soil samples, 1988*

[Concentrations are in micrograms of pesticide per kilogram of total mass of sample, including water. Detection limits are 2 micrograms per kilogram for atrazine and 4 micrograms per kilogram for alachlor and metolachlor. Metolachlor was analyzed for, but not detected, in samples from the SB site. Alachlor was analyzed for, but not detected, in samples from the FB site]

Pesticide (figs. 3 and 4)	March 1988		June 1988		September 1988	
	Depth interval (feet)	Concentration	Depth interval (feet)	Concentration	Depth interval (feet)	Concentration
Atrazine						
SB site	0.1-0.2	2	0.1-0.2	40	0.1-0.3	6
	0.4-0.5	<2	0.5-0.6	<2	0.8-0.9	<2
	0.9-1.0	<2	0.9-1.0	<2	1.4-1.5	<2
	2.5-3.0	<2	1.2-1.3	<2	1.9-2.0	<2
	3.5-4.0	<2	1.9-2.0	<2	2.2-2.3	<2
	5.0-5.5	<2	2.0-2.1	<2	3.4-3.5	<2
			2.4-2.4	<2		
FB site	0.2-0.3	2	0.0-0.3	130	0.1-0.2	5
	0.5-0.6	24	0.5-0.6	5	0.7-0.8	6
	0.9-1.0	2	0.9-1.1	5	1.3-1.4	<2
	1.8-2.0	<2	1.4-1.5	<2	2.0-2.1	<2
	2.8-3.0	<2	2.7-2.8	<2	2.4-2.5	<2
	4.0-5.0	<2			3.3-3.4	<2
	6.0-7.0	<2				

Table 4. *Concentrations of atrazine, alachlor, and metolachlor in soil samples, 1988* --Continued

Pesticide (figs. 3 and 4)	March 1988		June 1988		September 1988	
	Depth interval (feet)	Concentration	Depth interval (feet)	Concentration	Depth interval (feet)	Concentration
Alachlor						
SB site	0.1-0.2	<4	0.1-0.2	6	0.1-0.3	<4
	0.4-0.5	<4	0.5-0.6	<4	0.8-0.9	<4
	0.9-1.0	<4	0.9-1.0	<4	1.4-1.5	<4
	2.5-3.0	<4	1.2-1.3	<4	1.9-2.0	<4
	3.5-4.0	<4	1.9-2.0	<4	2.2-2.3	<4
	5.0-5.5	<4	2.0-2.1	<4	3.4-3.5	<4
			2.3-2.4	<4		
Metolachlor						
FB site	0.2-0.3	<4	0.0-0.3	383	0.1-0.2	15
	0.5-0.6	<4	0.5-0.6	12	0.7-0.8	7
	0.9-1.0	<4	0.9-1.1	10	1.3-1.4	6
	1.8-2.0	<4	1.4-1.5	<4	2.0-2.1	<4
	2.8-3.0	<4	2.7-2.8	<4	2.4-2.5	<4
	4.0-5.0	<4			3.3-3.4	<4
	6.0-7.0	<4				

Table 5. *Summary of atrazine test-kit results for water from three suction lysimeters at SB site and from three suction lysimeters at FB site*

[Concentrations in micrograms per liter]

Group of suction lysimeters (figs. 3 and 4)	Number of analyses	Minimum concentration	Median concentration	Maximum concentration
SB site	30	<0.1	0.2	0.5
FB site	48	.8	4.0	>10

Table 6. *Summary of atrazine test-kit results for water samples from test wells*

[Concentrations in micrograms per liter]

Test wells (figs. 3 and 4)	Number of analyses	Minimum concentration	Median concentration	Maximum concentration
SA and SB shallow wells	6	<0.1	<0.1	0.2
SA and SB mid-depth wells	8	< .1	< .1	< .2
SA and SB deep wells	8	< .1	< .1	.2
FA and FB shallow wells	8	.2	1.5	2.0
FA and FB mid-depth wells	8	< .1	< .15	.3
FA and FB deep wells	6	< .1	< .1	.2

year, then the concentrations in water from shallow wells should be:

Nitrite plus nitrate:	176 milligrams per liter
Atrazine:	882 micrograms per liter

(based upon application rates of 200 pounds per acre per year for nitrogen, and 1 pound per acre per year for atrazine).

Because of biochemical reactions, the actual concentrations are considerably smaller than these. Median concentrations in the shallow test wells (fig. 24, table 5) indicate that, relative to these numbers, the fraction of nitrogen that remains is about 0.15 to 0.3, but that the fraction of atrazine that remains is about 0.0002 for the S field and 0.004 for the F field.

If the decay of atrazine can be expressed as a first-order reaction, then the fraction of atrazine remaining can be expressed as a function of time (Rutledge and Helgesen, 1989):

$$FM = e^{-0.693(t)/(thalf)}, \qquad (6)$$

where

FM = fraction of pesticide remaining (dimensionless);

e = 2.71828;

t = time since application (days); and

$thalf$ = half-life of pesticide (days).

If the half-life of atrazine in the unsaturated zone is 182 days, and the time of transport to the water table is 3 years, then the fraction remaining, according to equation 6, is 0.015. Other avenues of atrazine loss are suggested by the smaller value of the actual fraction remaining. These avenues may include root uptake and irreversible sorption.

SUMMARY

Two fields of irrigated cropland were instrumented in March 1988 to collect data pertaining to water and chemical movement in the unsaturated and saturated zones, with particular emphasis on the movement of the herbicide atrazine. One field was irrigated by using an overhead center-pivot sprinkler system (S field) and was equipped with two monitoring sites--SA and SB. The other field was irrigated by using flood (furrow) irrigation (F field) and was equipped with two monitoring sites--FA and FB. The irrigation season for both fields started in June 1988 and ended in August at the S field and in September at the F field. Irrigation at the S field was measured as 9 inches in 1988.

Apparent soil-moisture content is large (15 to 40 percent by volume) in clayey zones that occur from land surface to a depth of 4.5 feet, and is small (8 to 10 percent by volume) in underlying sand layers. Soil-moisture profiles indicated that the available water capacity for the soil profile was 1 inch at the SB site and 2 inches at the FB site. Profiles obtained in early August 1988 at the SB site allowed for determination of an evapotranspiration rate of 0.34 inch per day.

Lithologic and water-level data indicate that water flow in the saturated zone beneath the S field acts as a two-unit ground-water system with the irrigation well extracting more water out of the more-permeable lower sand unit, and that water flow beneath the F field acts as a one-unit ground-water system and exhibits the effects of partial penetration of the aquifer by the pumping irrigation well.

Chloride tracer tests indicated rapid transport (less than 1 month) at the SB site through the root zone to a depth of 5.9 feet. On the basis of chloride tracing below the root zone from a depth of 5.9 to 9.7 feet, the seepage velocity at the SB site was estimated to be about 4.6 feet per year, and the estimated maximum recharge was 5 inches per year. Results from data collected at the FB site indicate much slower transport through the root zone--approximately 3.5 months. Relative to tracer results at the S field, those at the F field exhibit considerable leveling-off of chloride concentrations after an initial increase, possibly because of stagnation of vertical flow or because of residual chloride ions.

A mathematical scheme that calculates water balance on a weekly basis, considering rainfall, irrigation, evapotranspiration, and soil-moisture deficiency, was used to estimate that, between January 10, 1988, and January 31, 1989, 7.7 inches of water was available for recharge at the SB site. Rigorous models could be used to estimate ground-water recharge using a similar mathematical structure. Use of such models would require more data, such as soil properties.

Two samples of soil water from suction lysimeters indicate large concentrations of nitrite plus nitrate--70 mg/L at the SB site and 19 mg/L at the FB site. The chemical variables of chloride and nitrite plus nitrate showed a tendency of stratification of concentrations in the saturated zone; concentrations decreased in water from the shallow test wells to the deep test wells. Median nitrite-plus-nitrate concentrations in water from the shallow test wells were 40 and 20 mg/L at the S field and F field, respectively. Concentrations of nitrite plus nitrate showed the effects of deep circulation at the S field where concentrations were relatively large in water from deep test wells, and showed the effects of shallow circulation at the F field where concentrations were relatively small in water from the deep test wells.

Analyses of atrazine concentration in soil-water samples collected in 1988 from suction lysimeters placed at depths from about 6 to 10 feet showed no discernable trend through time to indicate the movement of particular atrazine pulses. A possible explanation for this is that the atrazine detected resulted from residuals of pre-1988 applications of atrazine, and that the 1988 application of atrazine had not reached the lysimeters during 1988 because of retardation. A simple mathematical model shows that, below the root zone, atrazine follows a nonsorbing tracer, such as chloride, by approximately 1.2 years. The analyses of soil samples detected atrazine concentrations near land surface in March 1988, before the application of atrazine in May. These concentrations are probably a residual from the application in the previous year. Another soil analysis in June 1988 detected large atrazine concentrations just beneath the land surface at a time when chloride that had been applied in May was already 6 feet below land surface.

Atrazine concentrations in ground water from the unsaturated and saturated zones are generally larger at the F field than at the S field. Both fields show decreasing atrazine concentrations in water from suction lysimeters to water from the test wells. For the F field, there is a stratification of concentrations, with concentrations decreasing in water from shallow wells to mid-depth wells to deep wells.

There is a greater decrease in chemical concentrations, from the land surface to the subsurface, for atrazine as compared to nitrite plus nitrate. Calculations show that the fraction of chemical applied at the land surface that reaches the top of the saturated zone is 0.15 to 0.3 for nitrogen, but the fraction of atrazine remaining is less than 0.0002 for the S field and approximately 0.004 for the F field. Expressing the loss of atrazine as a first-order reaction and using a chemical half-life of 182 days and a transport time to the water table of 3 years, the fraction remaining is calculated as 0.015. Other avenues of atrazine loss are suggested. These avenues may include root uptake and irreversible sorption.

REFERENCES CITED

Bauer, H.H., and Vaccaro, J.J., 1987, Documentation of a deep percolation model for estimating ground-water recharge: U.S. Geological Survey Open-File Report 86-536, 180 p.

Chen, H.H., and Druliner, A.D., 1987, Nonpoint-source agricultural chemicals in ground water in Nebraska--Preliminary results for six areas of the High Plains aquifer: U.S. Geological Survey Water-Resources Investigations Report 86-4338, 68 p.

Hallberg, G.R., Libra, R.D., Long, K.R., and Splinter, R.C., 1987, Pesticides, ground water, and rural drinking water quality in Iowa, *in* Pesticides and ground water--A health concern for the Midwest (Proceedings of conference, St. Paul, Minnesota, October 16-17, 1986): Navarre, Minnesota, Freshwater Foundation, p. 83-104.

Heath, R.C., 1987, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Helgesen, J.O., and Rutledge, A.T., 1989, Relations between land use and water quality in the High Plains aquifer of south-central Kansas, *in* Mallard, G.E., and Ragone, S.E., eds., U.S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the technical meeting, Phoenix, Arizona, September 26-30, 1988: U.S. Geological Survey Water-Resources Investigations Report 88-4220, p. 437-443.

Helsel, D.R., and Ragone, S.E., 1984, Evaluation of regional ground-water quality in relation to land use--U.S. Geological Survey Toxic Waste--Ground-Water Contamination Program: U.S. Geological Survey Water-Resources Investigations Report 84-4217, 33 p.

Jensen, M.E., ed., 1973, Consumptive use of water and irrigation water requirements: New York, American Society of Civil Engineers, 215 p.

Jensen, M.E., and Haise, H.R., 1963, Estimating evapotranspiration from solar radiation: American Society of Civil Engineers, Journal of Irrigation and Drainage Division, v. 89, p. 15-41.

McWhorter, D.B., and Sunada, D.K., 1985, Ground-water hydrology and hydraulics: Fort Collins, Colorado, Water Resources Publications, 290 p.

Merriam, D.F., 1963, The geologic history of Kansas: Kansas Geological Survey Bulletin 162, 317 p.

Perry, C.A., 1990, Source, extent, and degradation of herbicides in a shallow aquifer near Hesston, Kansas: U.S. Geological Survey Water-Resources Investigations Report 90-4019, 24 p.

Rutledge, A.T., and Helgesen, J.O., 1989, Use of a simplified transport model for pesticides in the unsaturated zone, *in* Mallard, G.E., and Ragone, S.E., eds., U.S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the technical meeting, Phoenix, Arizona, September 26-30, 1988: U.S. Geological Survey Water-Resources Investigations Report 88-4220, p. 523-530.

Sophocleous, M.A., and Perry, C.A., 1987, Measuring and computing natural ground-water recharge at sites in south-central Kansas: U.S. Geological Survey Water-Resources Investigations Report 87-4097, 48 p.

Stullken, L.E., Stamer, J.K., and Carr, J.E., 1987, Reconnaissance of water quality in the High Plains aquifer beneath agricultural lands, south-central Kansas: U.S. Geological Survey Water-Resources Investigations Report 87-4003, 25 p.

Wierenga, P.J., and Van Genuchten, M.T., 1989, Solute transport through small and large unsaturated soil columns: Ground Water, v. 27, no. 1, p. 35-42.

Williams, C.C., and Lohman, S.W., 1949, Geology and ground-water resources of a part of south-central Kansas, with special reference to the Wichita municipal water supply: Kansas Geological Survey Bulletin 79, 455 p.

☆ U.S. GOVERNMENT PRINTING OFFICE 1990–555–043/20060