# LONG-TERM EFFECTS OF SURFACE COAL MINING ON GROUND-WATER LEVELS AND QUALITY IN TWO SMALL WATERSHEDS IN EASTERN OHIO

By William L. Cunningham and Rick L. Jones

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## CONVERSION FACTORS AND ABBREVIATIONS

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| acre | 0.4047 | square hectometer ($hm^2$) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |

Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligram) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Temperature in degrees Fahrenheit ( F) can be converted to degrees Celsius ( C) as follows:

$$F = 1.8 \times C + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD 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."

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## ABSTRACT

Two small watersheds in eastern Ohio that were surface mined for coal and reclaimed were studied during 1986-89. Water-level and water-quality data were compared with similar data collected during previous investigations conducted during 1976-83 to determine long-term effects of surface mining on the hydrologic system. Before mining, the watersheds were characterized by sequences of flat-lying sedimentary rocks containing two major coal seams and underclays. An aquifer was present above each of the underclays. Surface mining removed the upper aquifer, stripped the coal seam, and replaced the sediments. This created a new upper aquifer with different hydraulic and chemical characteristics. Mining did not disturb the middle aquifer. A third, deeper aquifer in each watershed was not studied.

Water levels were continuously recorded in one well in each aquifer. Other wells were measured every 2 months. Water levels in the upper aquifers reached hydraulic equilibrium from 2 to 5 years after mining ceased. Water levels in the middle aquifers increased more than 5 feet during mining and reached equilibrium almost immediately thereafter.

Water samples were collected from three upper-aquifer wells, one middle-aquifer well, a seep from the upper aquifer, and the stream in each watershed. Two samples were collected in 1986 and 1987, and one each in 1988 and 1989. In both watersheds, sulfate replaced bicarbonate as the dominant upper-aquifer and surface-water anion after mining.

For the upper aquifer of a watershed located in Muskingum County, water-quality data were grouped into premining and late postmining time periods (1986-89). The premining median pH and concentration of dissolved solids and sulfate were 7.6, 378 mg/L (milligrams per liter), and 41 mg/L, respectively. The premining median concentrations of iron and manganese were 10 µg/L (micrograms per liter) and 25 µg/L, respectively. The postmining median values of pH, dissolved solids, and sulfate were 6.7, 1,150 mg/L, and 560 mg/L, respectively. The postmining median concentrations of iron and manganese were 3,900 µg/L and 1,900 µg/L, respectively.

For the upper aquifer of a watershed located in Jefferson County, the water-quality data were grouped into three time periods of premining, early postmining, and late postmining. The premining median pH and concentrations of dissolved solids and sulfate were 7.0, 335 mg/L, and 85 mg/L, respectively. The premining median concentrations of iron and manganese were 30 µg/L for each constituent. Late postmining median pH and

concentrations of dissolved solids and sulfate were 6.7, 1,495 mg/L, and 825 mg/L, respectively. The postmining median concentrations of iron and manganese were 31 µg/L and 1,015 µg/L, respectively. Chemistry of water in the middle aquifer in each watershed underwent similar changes.

In general, statistically significant increases in concentrations of dissolved constituents occurred because of surface mining. In some constituents, concentrations increased by more than an order of magnitude. The continued decrease in pH indicated that ground water had not reached geochemical equilibrium in either watershed more than 8 years after mining.

# INTRODUCTION

Surface mining consists of the removal of topsoil, removal of overburden, extraction of coal, and reclamation. The overburden removed to expose the coal is called spoil. Removal of overburden commonly eliminates the shallowest saturated zone in a ground-water system. Reclamation involves replacement of overburden and topsoil followed by final grading and seeding. Replaced spoil may contain a new saturated zone that has different hydraulic and chemical characteristics than the saturated zone that existed before mining.

Few analytical data are available on the long-term effects of surface mining on the ground-water hydrology of small watersheds. Some hydrologic processes necessary to evaluate long-term effects are not fully understood. These processes include the changes in hydraulic head and ground-water quality resulting from mining and the time required for these changes to reach equilibrium in a mined watershed.

Previous studies in eastern Ohio by the U.S. Geological Survey (USGS), the U.S. Bureau of Mines, the Ohio Agricultural Research and Development Center, and the U.S. Department of Agriculture, Agricultural Research Service, have described the premining and early postmining ground-water hydrology of small watersheds. Helgesen and Razem (1981) determined the hydrologic conditions during mining of one watershed in both Coshocton and Muskingum Counties. Razem (1984) and Hren (1986) studied the changes in ground-water hydrology and quality of a small watershed in Jefferson County. All of the reports indicated that the ground-water chemistry and hydraulic heads within the watersheds had not reached equilibrium as much as 4 years after mining.

The watersheds discussed in this report (fig. 1) are the above-mentioned watersheds in Muskingum and Jefferson Counties. The watersheds are identified by the first letter of the county in which they are located and a two-digit number that indicates the number of the coal seam mined. The Meigs Creek No. 9 coal was mined at watershed M09 beginning in January 1977. The watershed was reclaimed by August 1978 (Helgesen and Razem, 1981). Ground-water levels and ground-water-quality data available for water-

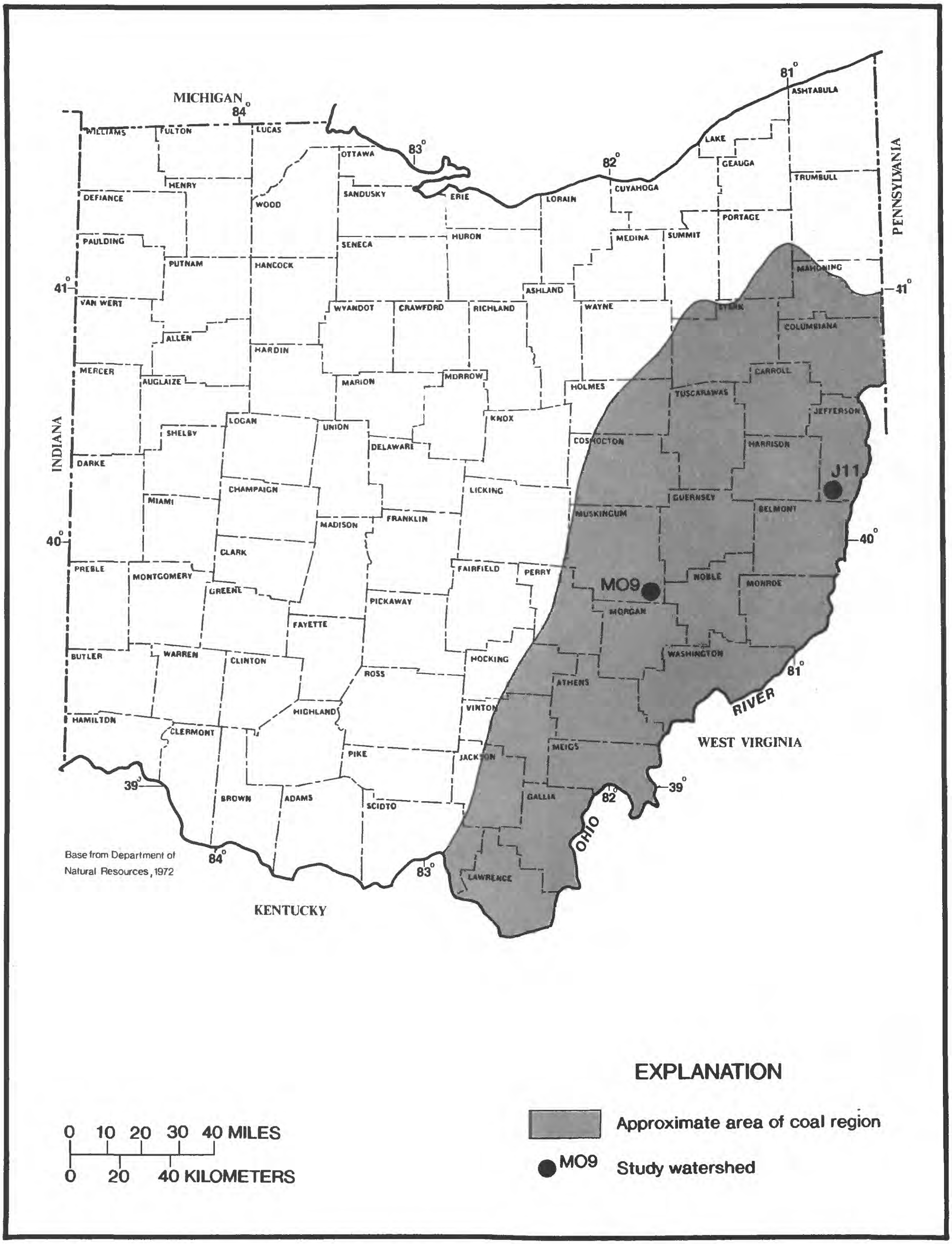

Figure 1.--Location of the study watersheds.

shed M09 were collected from March 1976 through April 1983. The Waynesburg No. 11 coal was mined at watershed J11 from May 1980 through October 1980 (Hren, 1986). Final reclamation of the watershed was completed in June 1982. Previous data are available from May 1976 through June 1984 for watershed J11.

### Purpose and Scope

This report describes changes in ground-water conditions in two watersheds representative of small watersheds of the region over periods of 8 and 10 years since mining and reclamation ended. Specifically, this report describes the (1) occurrence of ground water in and beneath the overburden spoil, (2) resaturation rates of the spoil material, (3) chemical changes in the water quality of the aquifers and ground-water discharge, and (4) the equilibrium state of ground water in each watershed.

The report is based on data obtained by measurement of hydraulic head and water-quality sampling in each watershed. Data were collected from October 1985 through July 1989. These data were analyzed in concert with the data collected in the previously mentioned studies to describe the long-term changes within each watershed.

### Acknowledgments

The authors appreciate the assistance provided by Eric Perry, Office of Surface Mining and James Bonta, U.S. Department of Agriculture, Agricultural Research Service. Access to wells was provided by the Ohio Power Company at watershed MO9 and by Bedway Land Management at watershed J11.

## METHODS OF STUDY

Data collection for this study included continuous recording of ground-water levels, periodic measurements of ground-water levels, and chemical analyses of surface water (if flow was sufficient) and ground water in each watershed. During the first year of the study, two water-level recorders were installed in each watershed, one in the upper aquifer and one in the middle aquifer. For the remainder of the study, one observation well in the upper aquifer of each watershed was equipped with a continuous water-level recorder. Water levels in all other observation wells were measured every 2 months.

Water levels measured before 1985 were compared with water levels measured during this study. Water levels were measured monthly in watershed MO9 from March 1976 through May 1982 and in watershed J11 from May 1976 through August 1982.

Water samples for chemical analysis were collected semi-annually during the first 2 years and annually thereafter from four wells in each watershed. Wells sampled included three wells from the upper aquifer and one well from the middle aquifer in each watershed. In addition, one surface-water site and one seep in each watershed were sampled for chemical analysis when flow was sufficient. All ground-water and surface-water samples were analyzed in the field for pH, specific conductance, temperature, and alkalinity. Acidity also was measured if the pH was less than 6.5. Samples were analyzed in the USGS National Water Quality Laboratory for concentrations of dissolved sulfate, iron, manganese, aluminum, chloride, calcium, sodium, magnesium, potassium, and dissolved solids.

Sampling procedures for the observation wells were designed to collect samples representative of water from the aquifers. All observation wells were pumped until approximately three casing volumes were purged from the well, and pH, specific conductance, dissolved-oxygen concentration, and temperature had stabilized. Waters were sampled from the upper aquifer by use of a Johnson-Keck SP-81[1] submersible pump at a rate of approximately 1 gallon per minute (gal/min). Waters were sampled from the middle aquifer by use of a submersible pump at a rate of approximately 10 gal/min. Samples for laboratory analysis of dissolved constituents were filtered at the field sites through a membrane having a pore size of 0.45 micrometer. Samples for metals analysis were preserved with nitric acid. Dissolved-solids concentration was determined by weighing the residue left after evaporation at 180 degrees Celsius of a filtered sample.

## DESCRIPTION OF THE STUDY WATERSHEDS

Watersheds M09 and J11 are in the unglaciated eastern coal region of Ohio along the western edge of the Allegheny Plateau. The region is characterized by hilly terrain with winding rivers and streams. The study areas are typical of the small (less than 40 acres) watersheds of the region. Each watershed is drained by a small intermittent stream. Base flow to each stream is by discharge from the upper aquifer as seeps and the middle aquifer as ground-water discharge. The stratigraphy of the watersheds is shown in figures 2 and 3. A detailed description of the geology and soils of each watershed is given by the U.S. Bureau of Mines (1982, 1983).

Watershed M09 is located in Meigs Township in southeastern Muskingum County. Figure 4 is a map of the M09 watershed showing the premining and postmining watershed boundary, the premining Meigs Creek (No. 9) coal-seam outcrop, and locations of the stream and seep.

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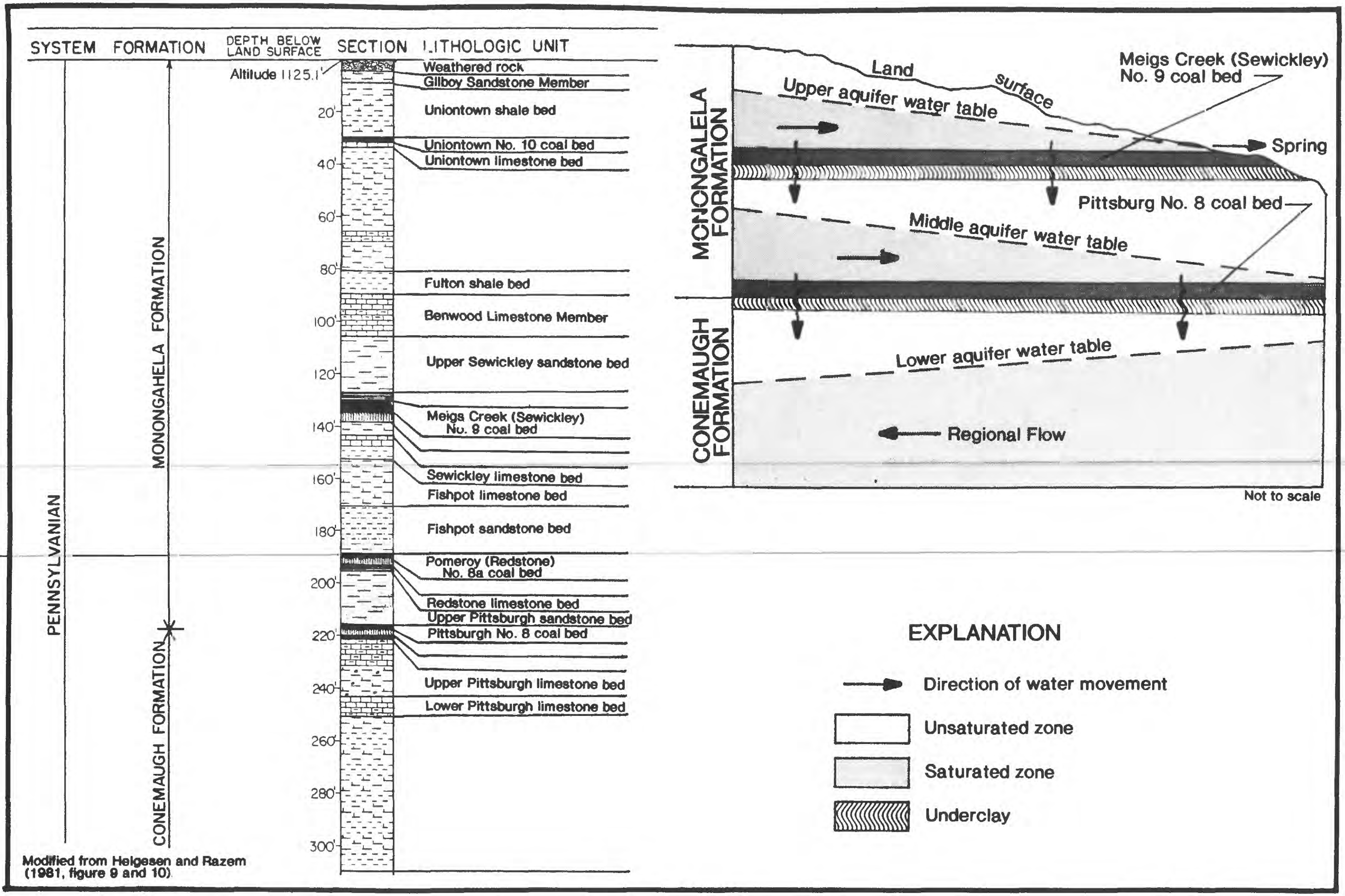
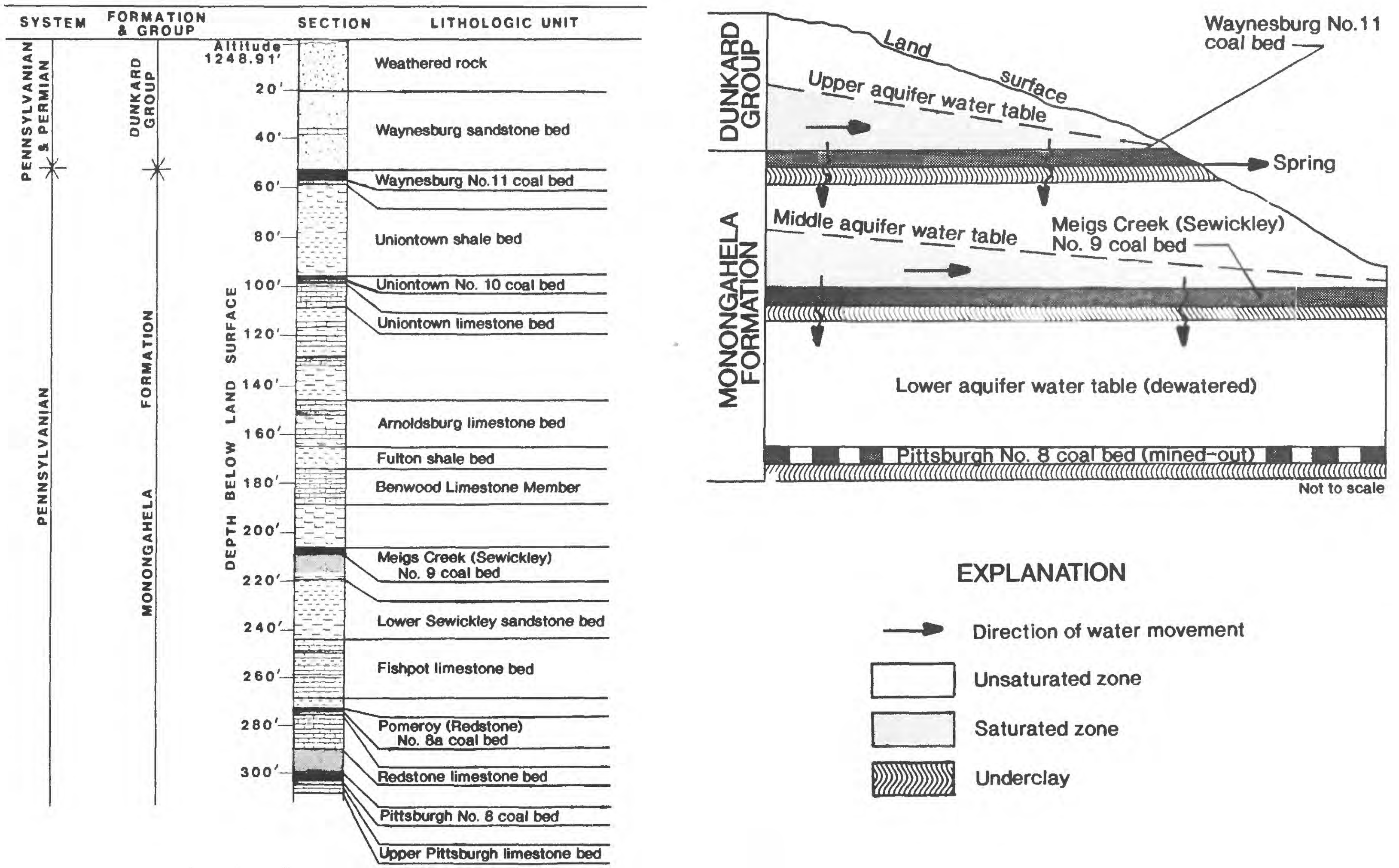
[1] Use of firm or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.



Modified from Helgesen and Razem (1981, figure 9 and 10)

Figure 2.--Stratigraphic column and schematic cross section of watershed MO9.



Modified from Razem (1984, figure 2 and 4)

Figure 3.--Stratigraphic column and schematic cross section of watershed J11.

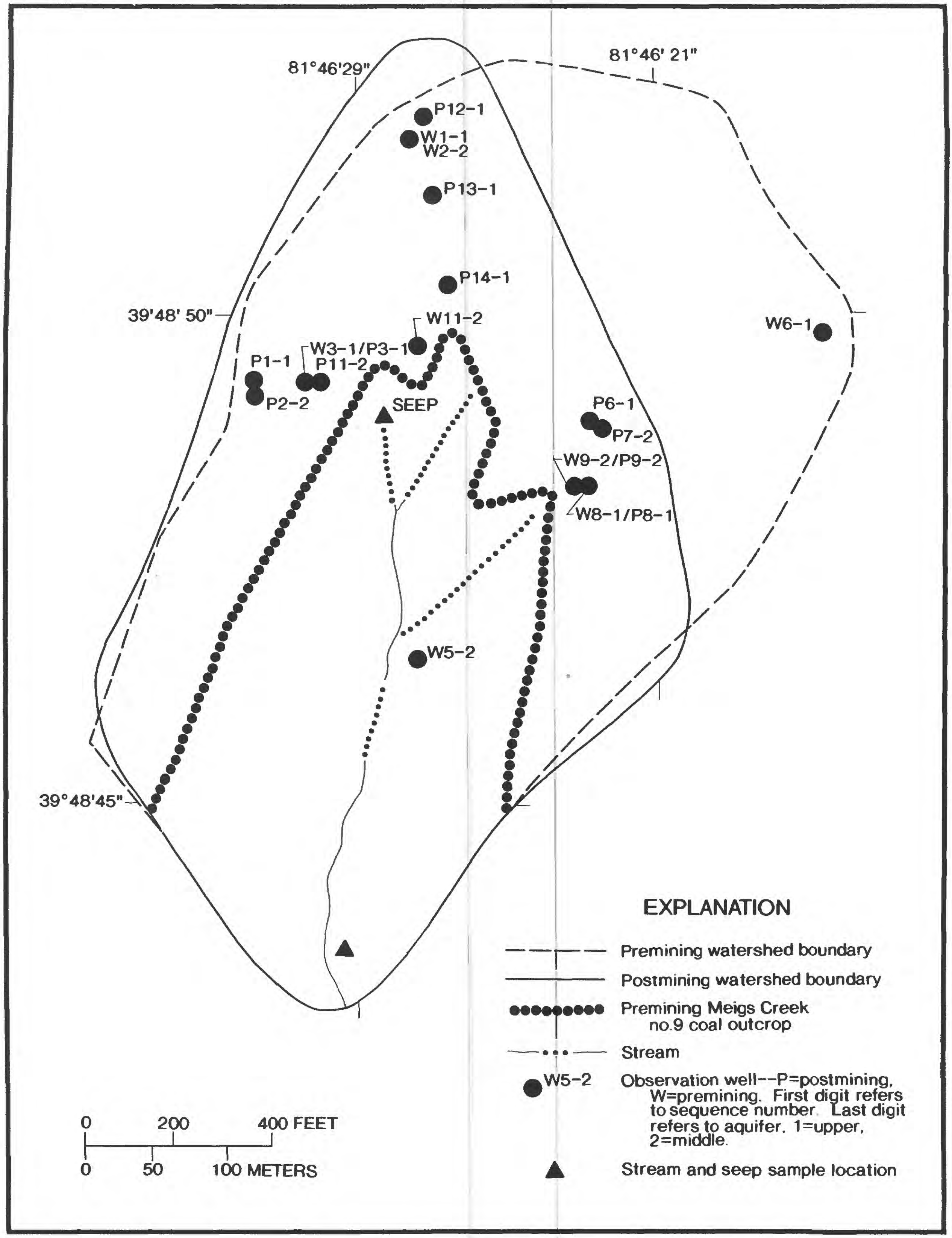


Figure 4.--Locations of observation wells, seep, and stream at watershed M09 (modified from Helgesen and Razem, 1981, page 11).

Watershed J11 is located in Mt. Pleasant Township in southwestern Jefferson County. Figure 5 is a map of the watershed showing the premining and postmining watershed boundary, Waynesburg (No. 11) coal-seam outcrop, extent of the spoil material, and locations of the stream and seep.

The observation wells shown in figures 4 and 5 are identified alphanumerically. The letter "W" indicates a premining well, whereas the letter "P" refers to a postmining well. The first digit of the hyphenated observation-well number is a sequence number. The last digit refers to the aquifer in which the well was completed, with "1" representing the upper aquifer and "2" the middle aquifer. The observation-well network and details of well construction are addressed in reports by the U.S. Bureau of Mines (1978), Helgesen and Razem (1981), and Razem (1984). All wells completed into the middle aquifer were cased through the upper aquifer and into the clay layer. Most of the premining observation wells were destroyed by mining. At least one well in each watershed was installed outside the mined area and was not destroyed. These wells retain the "W" prefix into the postmining period. A postmining well with the same sequence number as the premining well it replaced was installed as close as possible to the premining well location.

The ground-water-flow system in each watershed is affected by the underclays present beneath the mined coal seams. The underclay beneath the mined coal seam and the underlying geologic units were to be left intact throughout the mining process. It is likely, however, that the underclay was disturbed somewhat during mining. This relatively impermeable underclay allows the spoil and undisturbed material to saturate as perched zones above the clays. The saturated spoil and rock is referred to as an aquifer, although the typical yields to wells may be less than 1 gal/min.

In each watershed, the source of ground-water recharge to the upper aquifer is precipitation. Discharge from the upper aquifer is by vertical leakage through the underclay to the middle aquifer, by lateral discharge as springs and seeps, and by evapotranspiration. Recharge to the middle aquifer is by vertical leakage through the overlying clay and by precipitation where the clay is absent. Discharge from the middle aquifer is by vertical leakage through the underclay to the deep aquifer, by evapotranspiration, and as base flow to the stream. The deep aquifer beneath watershed M09 is a part of the regional-flow system. The aquifer is recharged and discharged from outside the watershed except for the leakage it receives from the middle aquifer (Helgesen and others, 1982). The deep aquifer beneath watershed J11 is dry because of previous deep-mine activities.

Eastern Ohio receives approximately 38 in./yr (inches per year) of precipitation and has a mean annual temperature of 51 degrees Fahrenheit (National Oceanic and Atmospheric Administration, 1987). Precipitation in this part of the State is highest in April and lowest in October. Summer precipitation is characterized by intermittent rainstorms.

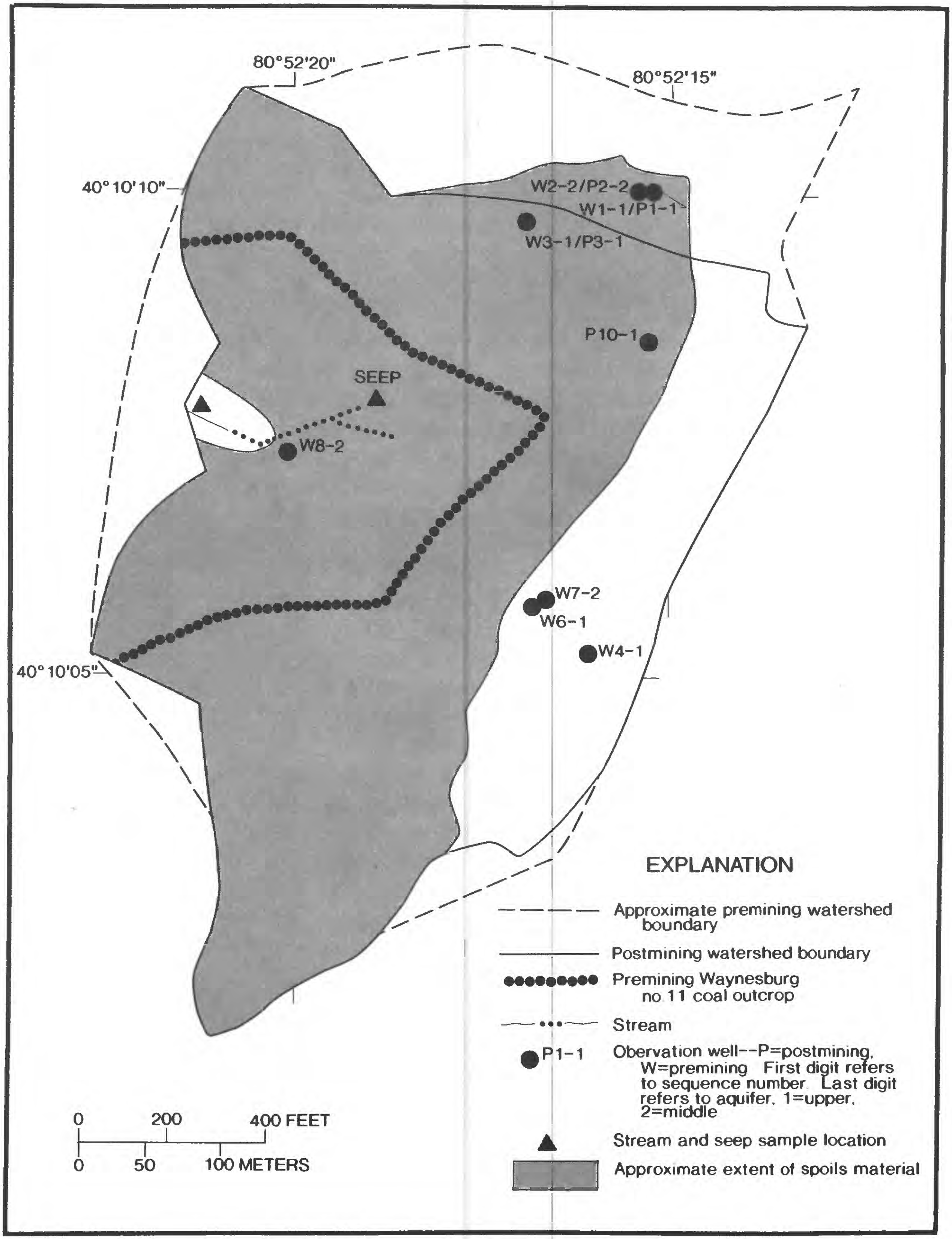


Figure 5.--Locations of observation wells, seep, and stream at watershed J11 (modifed from Razem, 1984, figure 3).

# LONG-TERM EFFECTS OF SURFACE MINING

## Watershed M09

### Ground-Water Levels

Ground-water-flow direction in watershed MO9 is shown by the hydraulic gradients along the generalized flow lines A, B, and C in figure 6. The anomalously high water level in well P14-1 indicates localized ground-water mounding. The gradients range from 0.003 in the upper basin to 0.05 near the premining coal outcrop. Water in the upper aquifer generally flows from the watershed divide to the premining coal outcrop, discharging as a seep above the underclay. The flow paths in the middle aquifer appear to be similar to those in the upper aquifer.

Water levels for selected wells in the upper aquifer are shown in figure 7. The water levels in wells not represented in figure 7 are between the levels shown for wells P3-1 and P14-1. Water levels declined as the aquifer was removed. This illustration shows the resaturation of the aquifer after mining over time.

The variability of the water levels soon after mining illustrates the response of each well to aquifer resaturation. A stable water level was reached as early as 3 months (at well P3-1) and as late as 2 1/2 years (at well P8-1) after reclamation. Water levels in the upper aquifer reached an overall steady state sometime in 1981, approximately 2 1/2 years after reclamation. From October 1985 through September 1989 water levels were fairly stable and had similar seasonal responses. These characteristics indicate a flow system in hydraulic equilibrium.

Water levels in the middle aquifer are shown in figure 8. The hydrograph of well W5-2 characterizes the response of the middle aquifer to mining. The well was not destroyed by mining, thus, continuous record is available. The water level in well W5-2 rose 5.8 ft (feet) from April through May 1977 near the beginning of mining. After that time, the water level remained fairly stable except for seasonal fluctuations. The changes in water level in wells P2-2 and P9-2, compared with wells W2-2 and W9-2, probably were caused by a slight change in location of the wells to a point downgradient from the original premining well site. Equilibrium was reached at well W5-2, and possibly at well P9-2, before mining was completed. The water level in well P2-2 increased throughout the initial period of record following mining but was fairly stable through July 1989.

Water levels in paired wells completed in different aquifers indicate the vertical hydraulic gradient between the upper and middle aquifers, which ranges from 0.3 to 0.6 ft of head loss per vertical foot of aquifer (calculated from February 1989 water levels, figs. 9 and 10). This difference in water-level altitude between the upper and middle aquifers

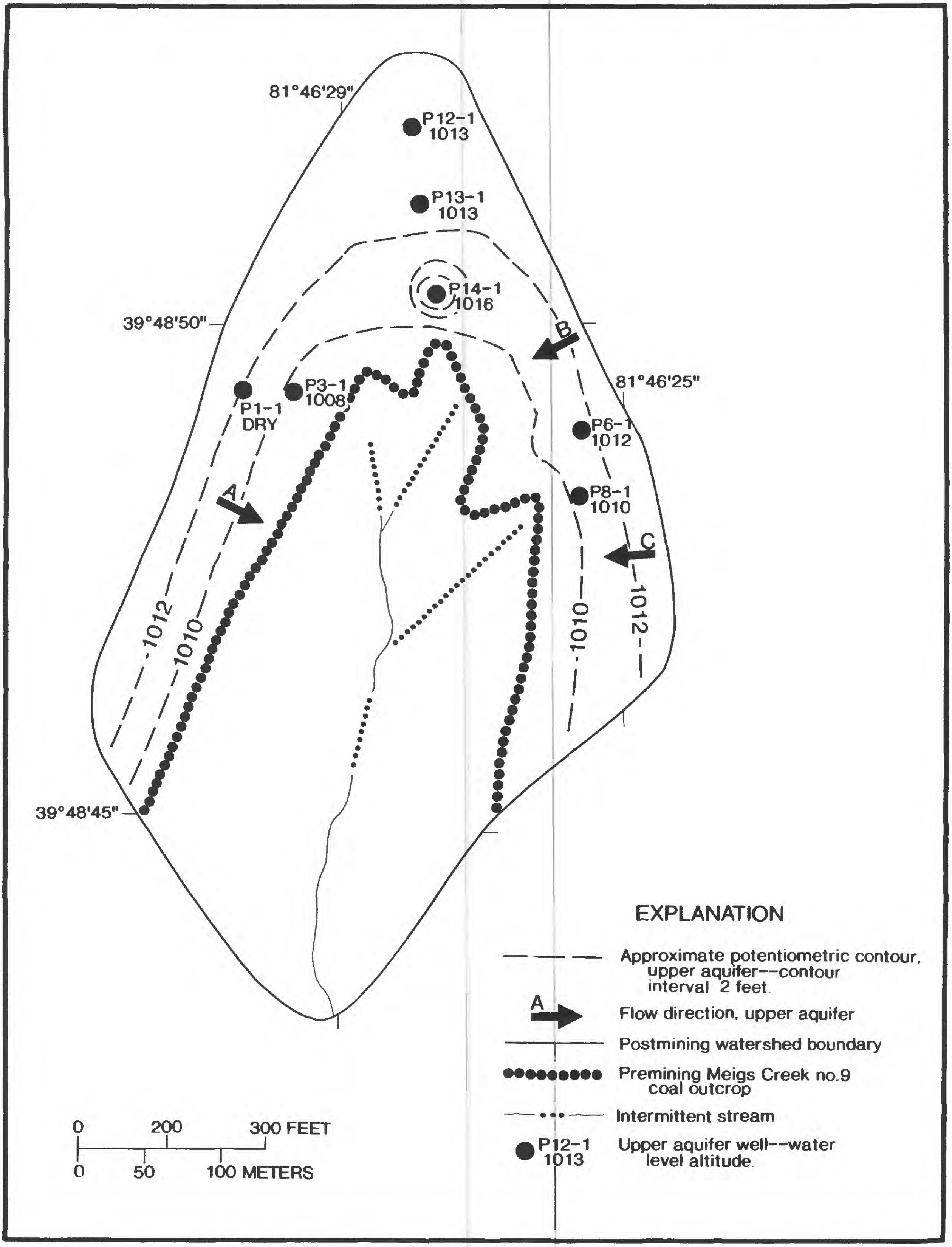


Figure 6.--Generalized flow map of watershed M09, February 1989.

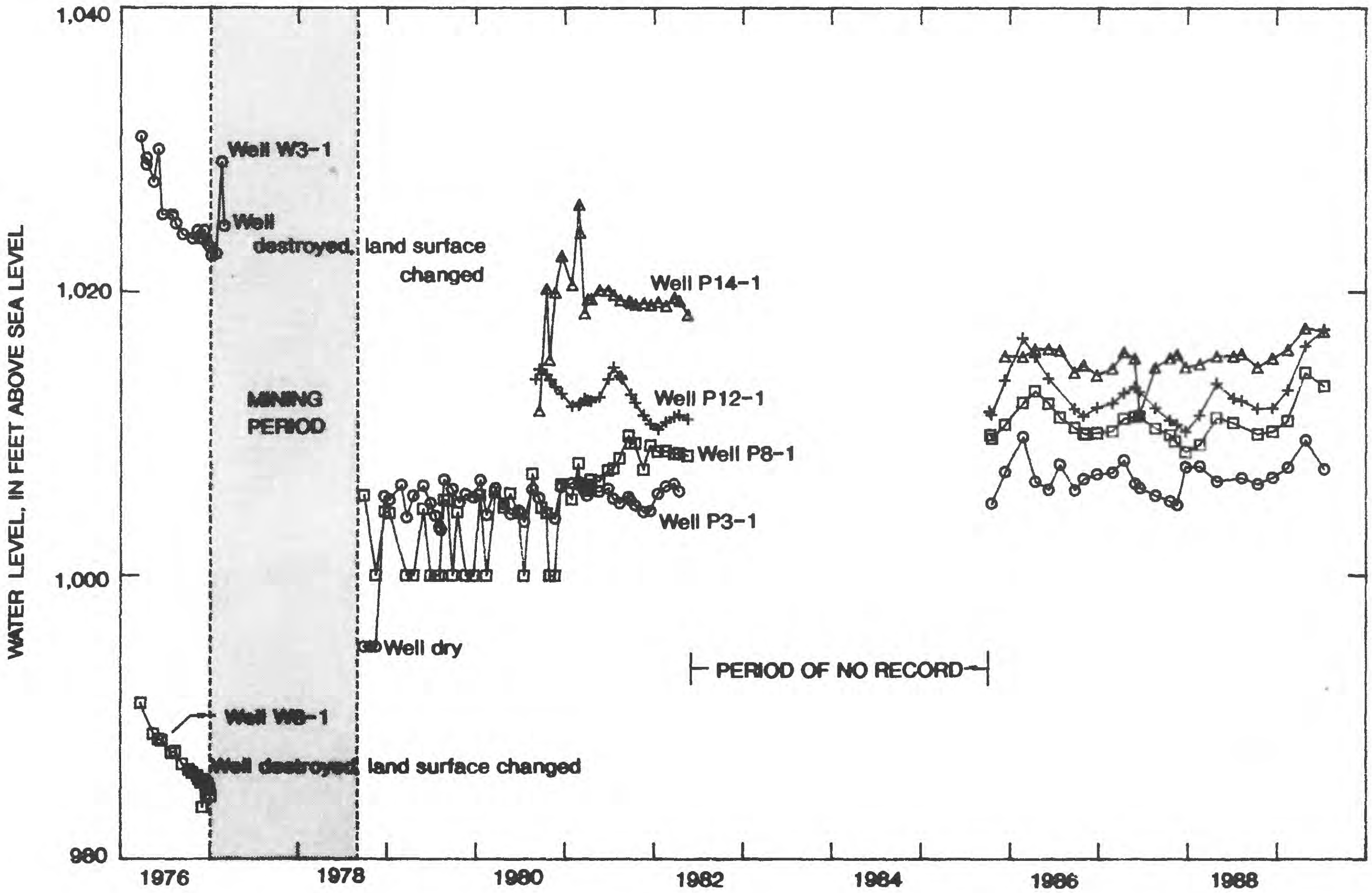


Figure 7.--Water levels of selected wells at watershed MO9, upper aquifer.

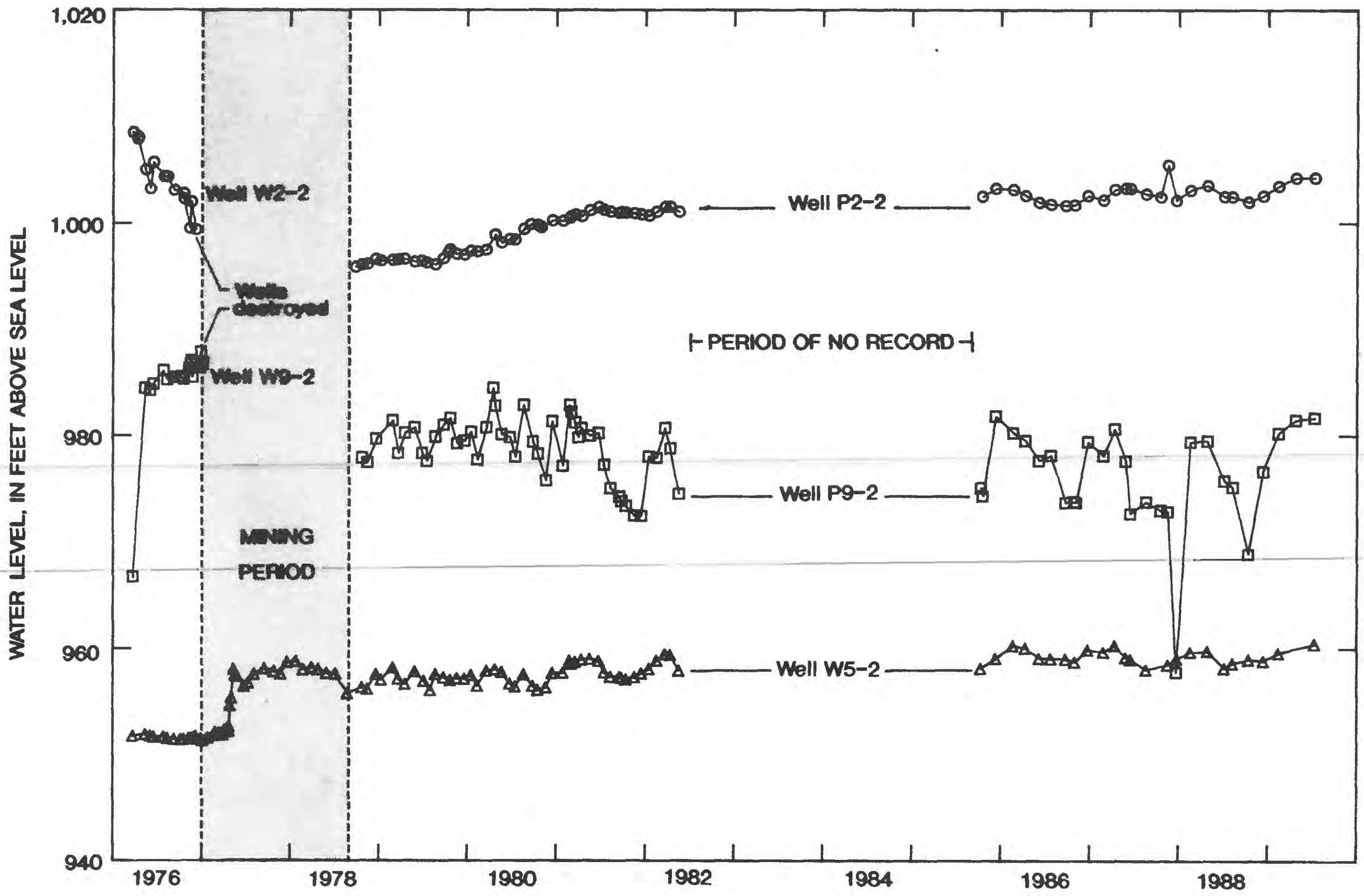


Figure 8.--Water levels of selected wells at watershed MO9, middle aquifer.

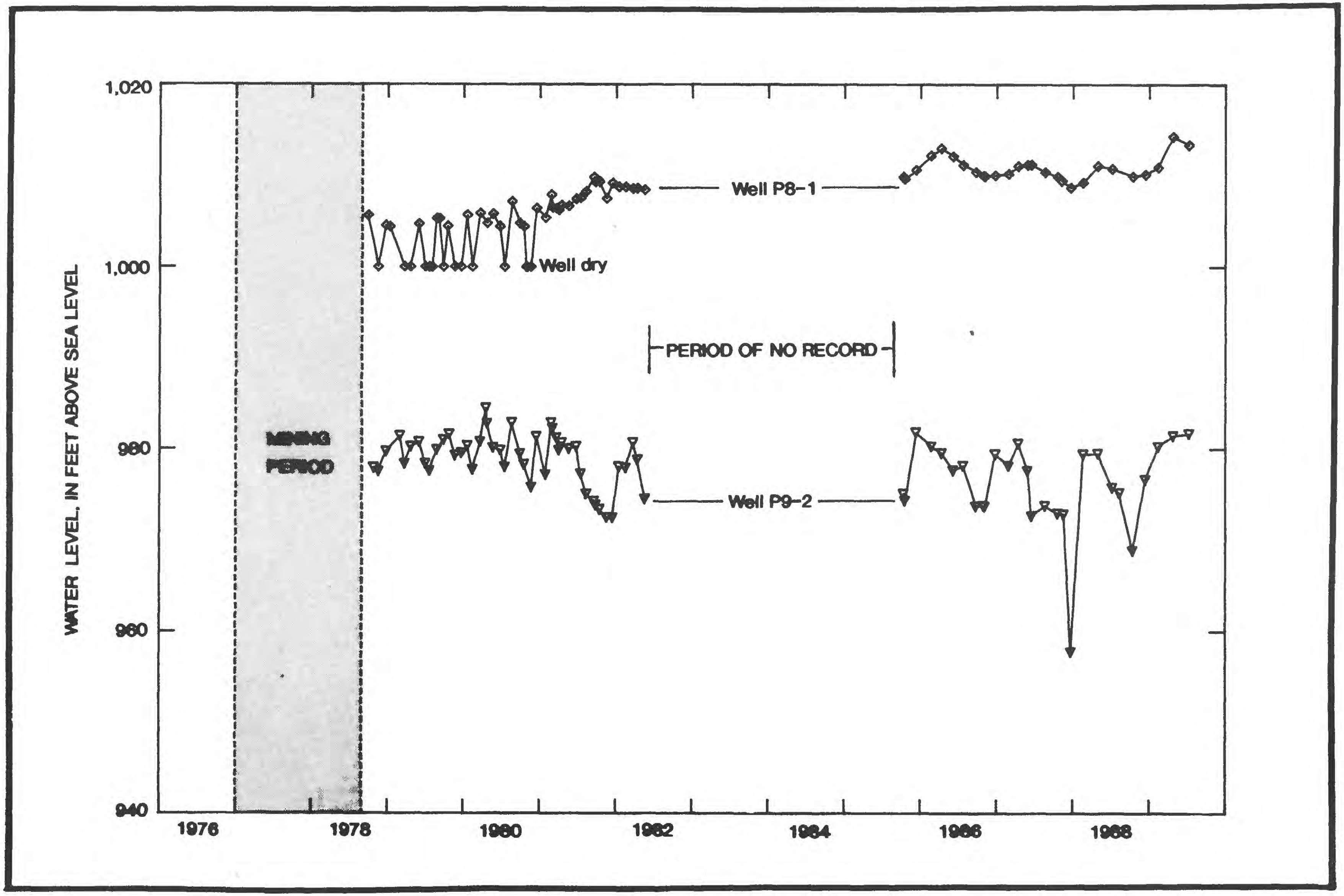


Figure 9.--Water levels in upper and middle aquifers in paired wells P8-1 and P9-2 (watershed MO9).

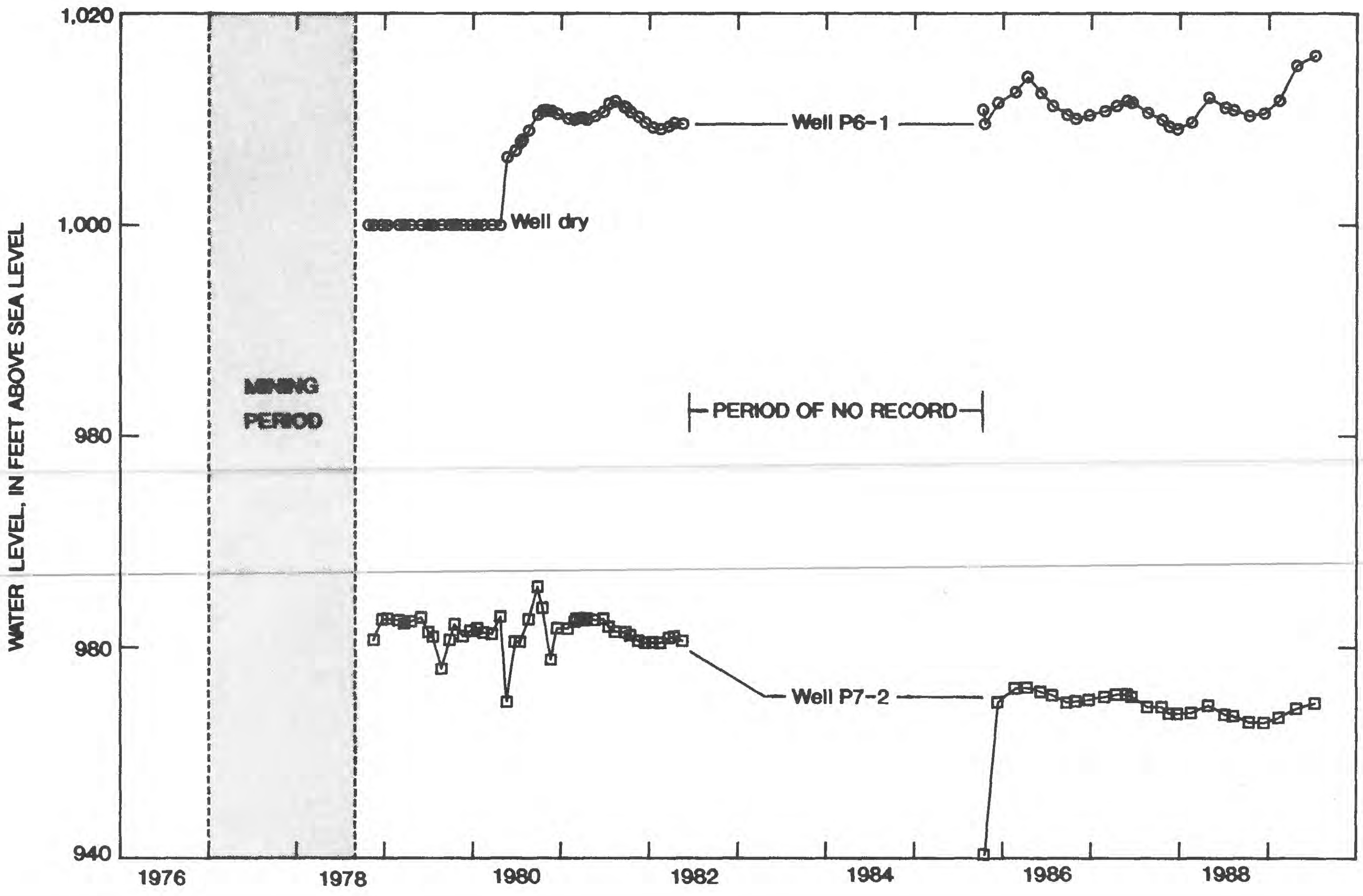


Figure 10.--Water levels in upper and middle aquifers in paired wells P6-1 and P7-2 (watershed MO9).

indicates that the direction of potential vertical flow is downward. Any mixing of water from the upper aquifer with water in the underlying aquifer would be a function of the seepage rate through the clay layer and would be accelerated if the clay layer were absent or disturbed.

The hydraulic characteristics of the upper aquifer are different in the postmining period than before mining. As previously discussed, reclamation of a surface-mined area involves replacing the spoil material, regrading, applying topsoil, and seeding. Razem (1984) discussed artificial infiltration tests which indicated that recharge rates in the area covered by spoils decreased because of the destruction of the soil structure and compaction of the soil. Razem also stated that storage capacity and hydraulic conductivity also increased because the broken overburden material creates many more openings, pores, and voids than are present in the premining consolidated rocks.

A well hydrograph can be used to estimate the changes in the aquifer's response to recharge; however, data available before mining in watershed MO9 are limited, and clear comparison of upper-aquifer water-level changes before and after mining cannot be made. The expected response would be a subdued hydrograph caused by a decreased recharge rate (because of surface-soil compaction) and increases in the storativity and hydraulic conductivity (because of the porous nature of the spoil).

The response of the middle aquifer to recharge is shown by well W5-2 (fig. 11). Water-level response to recharge increased slightly after mining. This increased response is due to (1) disturbance of the clay layer during mining, and (2) increased fracture development caused by blasting during mining, both of which would increase flow of water from the upper to the middle aquifer.

## Water Quality

In previous studies, ground-water samples were collected from wells in the upper, middle, and deep saturated zones. These data were collected from July 1976 through November 1977 (Helgesen and Razem, 1981). Premining data for watershed M09 are limited, as only two samples were analyzed for each well before mining began in 1977.

The wells sampled for this study were wells P8-1, P12-1, and P14-1 from the upper aquifer and well P9-2 from the middle aquifer (fig. 4). Samples were collected twice a year in 1986 and 1987 and annually thereafter. These data are compared with all the premining data and with early postmining data collected at the same wells during a previous study.

An important factor in the interpretation of these data is the relation between precipitation and water quality. The quality of the ground water in spoil is influenced by the

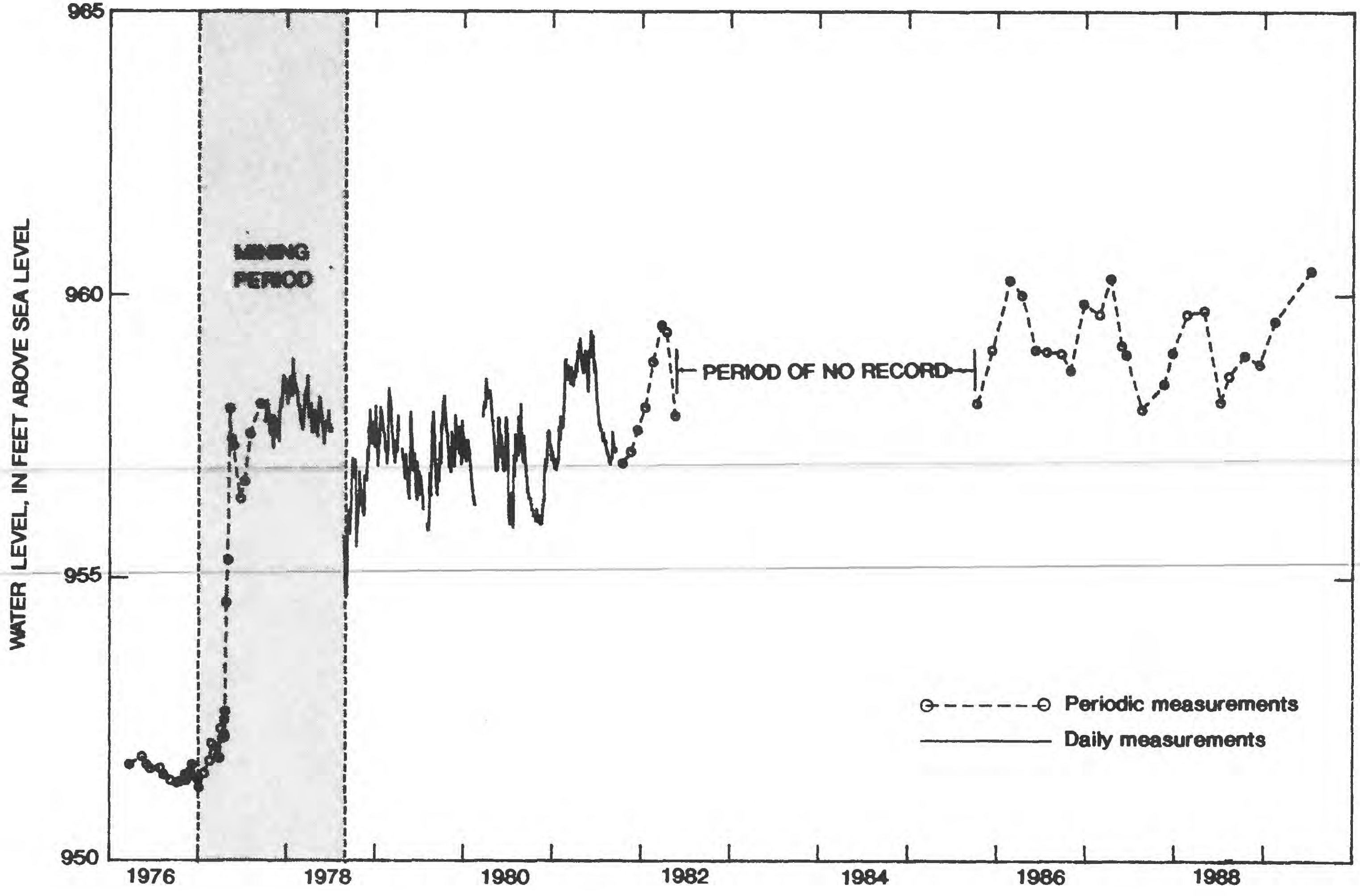


Figure 11.--Hydrograph showing increase in water-level fluctuation after mining in well W5-2, (watershed MO9).

duration of dry periods between precipitation events and the volume of those precipitation events. Metallic salts in the spoil produced by pyrite oxidation and clay-mineral dissolution build up in the unsaturated zone during periods of low precipitation and recharge. These metallic salts are then flushed into the saturated zone by infiltrating water during storms (Williams and others, 1990, in press). Thus, the chemistry of the ground water and ground-water runoff can depend on the frequency and volume of precipitation and resulting recharge before sampling.

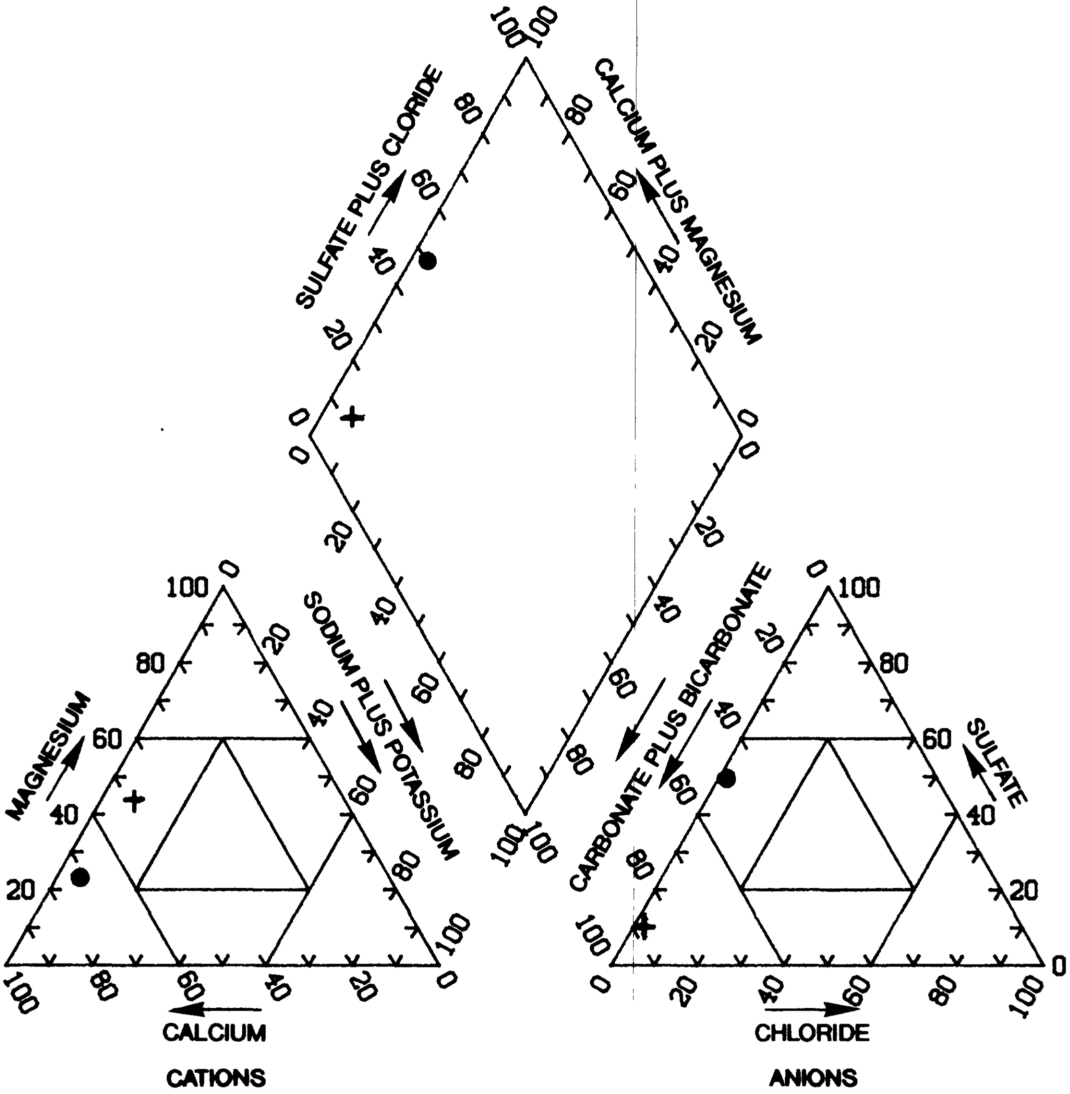
The water in the premined upper aquifer in watershed M09 was classified as a calcium magnesium bicarbonate type (Helgesen and Razem, 1981). The changes in median water type from premining to postmining for this study are shown in the trilinear diagram in figure 12. Calcium and magnesium remained the major cations after mining, but sulfate concentration increased substantially in water from wells P8-1 and P12-1. Water from well P14-1 remains a calcium bicarbonate type. The median water type in the postmining aquifer is classified as calcium sulfate bicarbonate. The different chemistry of well P14-1, along with the anomalous water level noted in figure 6, indicates two possible interpretations; the chemistry of the spoil in the vicinity of the well may differ from the overall site conditions, or the well also may be receiving significant inflow of water from a source outside the spoil zone.

The structural changes in the upper-aquifer materials are responsible for the changes in ground-water type. Mining and reclamation have decreased the grain sizes of aquifer materials, thereby increasing the surface area available for chemical weathering. Mining and reclamation also facilitate introduction of oxygen into the system. This oxygen can readily oxidize pyrite, which commonly is found in and near coal seams. This weathering process is responsible for increases in concentrations of sulfate and other dissolved solids, as well as an increase in acidity (Eberle and Razem, 1985).

The water-quality tables at the back of the report summarize all water-quality data used in this study. Only pH and concentrations of dissolved solids, sulfate, iron, and manganese are discussed in detail within this report. The supplemental data section includes time-series plots of dissolved constituents that are not discussed in detail.

It was not possible to use the same wells for the statistical comparison of water quality because most of the upper aquifer was destroyed by mining. Because of the small areal size of the watershed and the limited amount of data, data from all sampled wells were combined for statistical analysis. Postmining wells P8-1 and P9-2 were completed in the same locations as premining wells W8-1 and W9-2, respectively. Data from these wells also are compared for a "single-site" analysis.

All water-quality data were analyzed nonparametrically by use of Minitab statistical software (Minitab, 1986) to determine statistically significant differences in data sets. The Mann-Whitney test was used to compare all premining data with all data collected



**EXPLANATION**

+ Median percentage of premining samples

● Median percentage of postmining samples

Figure 12.--Trilinear diagram for water sampled from the upper aquifer in watershed MO9.

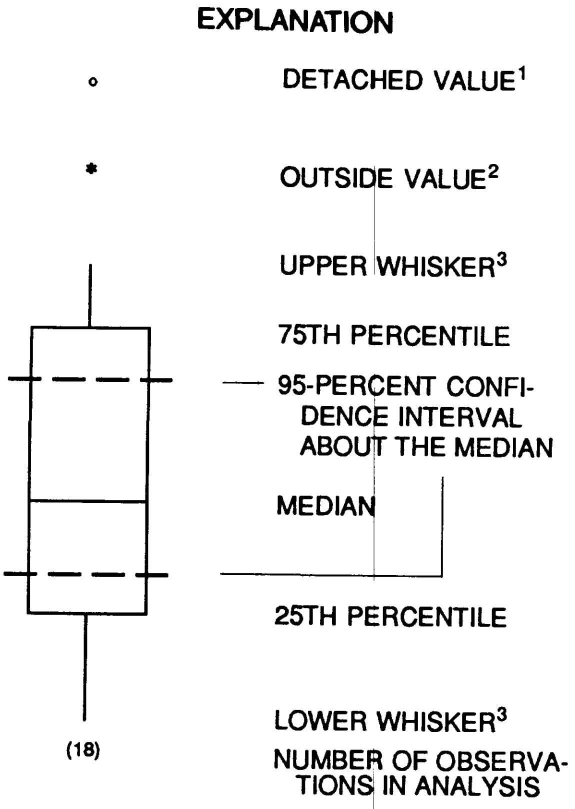
during this study (termed late postmining) for each aquifer. Each water-quality characteristic is discussed in relation to its median value; significant deviations from median values were determined by the Mann-Whitney test. A box plot with 95-percent confidence intervals also is presented to help show the differences among data sets. The data sets are significantly different when the 95-percent confidence intervals do not overlap. An explanation of the parts of a box plot is shown in figure 13. The data sets represented by box plots include (1) all premining samples, (2) all late postmining samples, (3) premining wells W8-1 and W9-2, and (4) postmining wells P8-1 and P9-2.

Changes in pH in the upper aquifer over time are illustrated in figure 14. The box plot shows a significant decrease in pH from a premining median pH of 7.6 to the postmining median pH of 6.7. At the end of the study (1989), the pH of upper-aquifer waters continued on a downward trend, indicating equilibrium had not yet been reached. The largest decrease in pH occurred within the 2 years following mining.

Although the classification of water type in the upper aquifer changed only slightly, the concentration of dissolved constituents increased significantly. Figure 15 shows the large variation in dissolved-solids concentrations in water from upper-aquifer wells. The median dissolved-solids concentration increased threefold from 378 mg/L before mining to 1,150 mg/L after mining. The concentration of dissolved solids in the upper aquifer after mining was fairly stable until the final sample, which was about 1,000 mg/L higher than previous samples in wells P12-1 and P8-1.

Changes in sulfate concentration are shown in figure 16. Sulfate concentrations in the upper aquifer are highly variable. Water from well P14-1 shows little change in sulfate concentration over the period of record. The high concentrations of sulfate in water from well P12-1 (2,800 to 3,500 mg/L) probably were caused by a pocket of pyritic spoil material. The sulfate concentrations in 1989 samples collected in wells P8-1 and P12-1 exceeded concentrations in the previous samples by at least 600 mg/L, and the highest concentration previously measured by at least 200 mg/L. This increase may result from the flushing of accumulated salts from a relatively dry year in 1988 by above-average precipitation in 1989. The median postmining concentration of dissolved sulfate in water from the three wells (560 mg/L) was more than 10 times the premining concentration (41 mg/L).

Dissolved-iron concentrations were extremely variable in the upper aquifer (fig. 17). For example, the dissolved-iron concentrations in well P8-1 range from 5 µg/L to 20,000 µg/L within the same year (1987). One reason for this variability could be the sensitivity of sampling for dissolved iron. The reduced form of iron ($Fe^{+2}$) found in ground water precipitates out of solution (as $Fe^{+3}$) if the sample is oxygenated during collection. The median concentration of dissolved iron in the upper aquifer increased from 10 µg/L before mining to 3,900 µg/L after mining. The box plot indicates a statistically significant difference between premining data and data obtained during this study.



[1] A detached value is defined as a value that is greater than 3 times the interquartile range (beyond the box)

[2] An outside value is defined as >1.5 and ≤3 interquartile ranges from the box

[3] Upper whisker is defined as the largest data point less than or equal to the uper quartile plus 1.5 times the interquartile range. Lower whisker is minus 1.5 times the interquartile range

**Figure 13.--Explanation of box plot diagrams used in this report.**

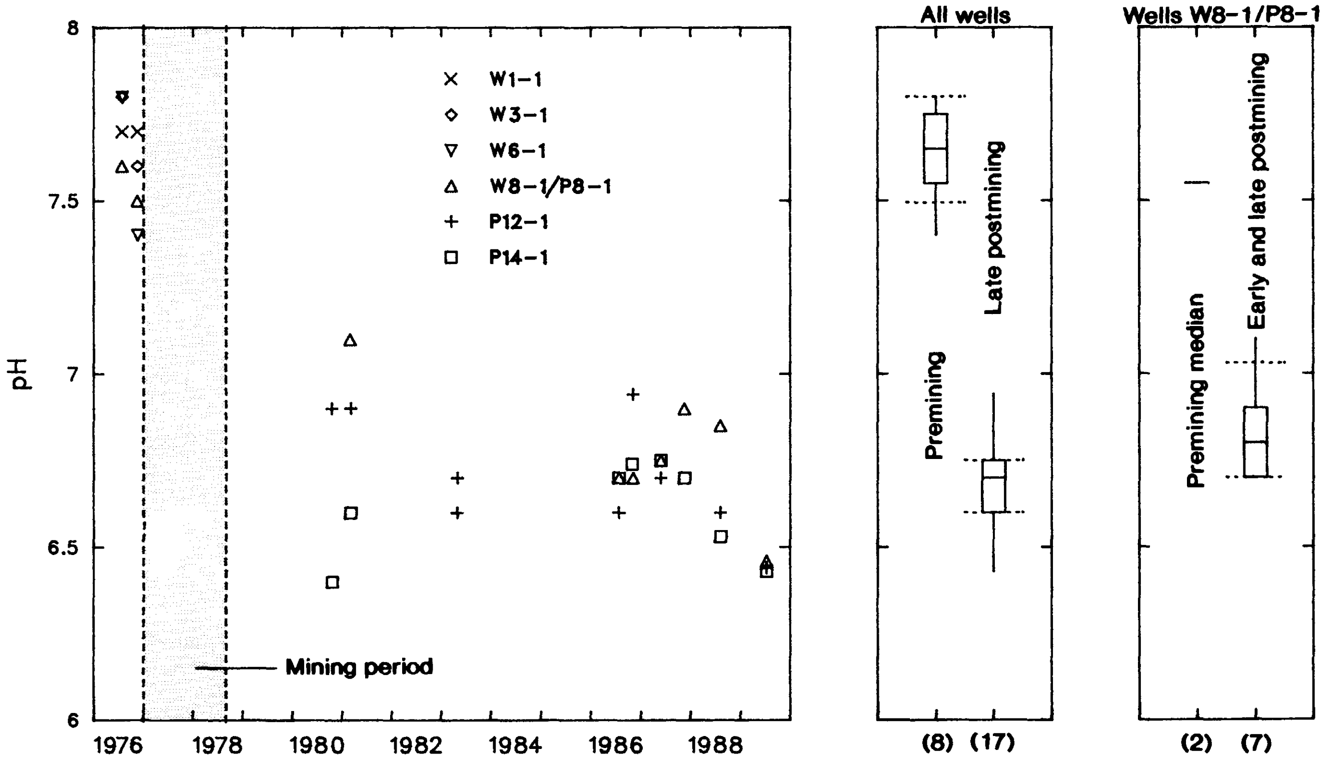


Figure 14.—Comparison of pH of the waters from the upper aquifer in watershed MO9.

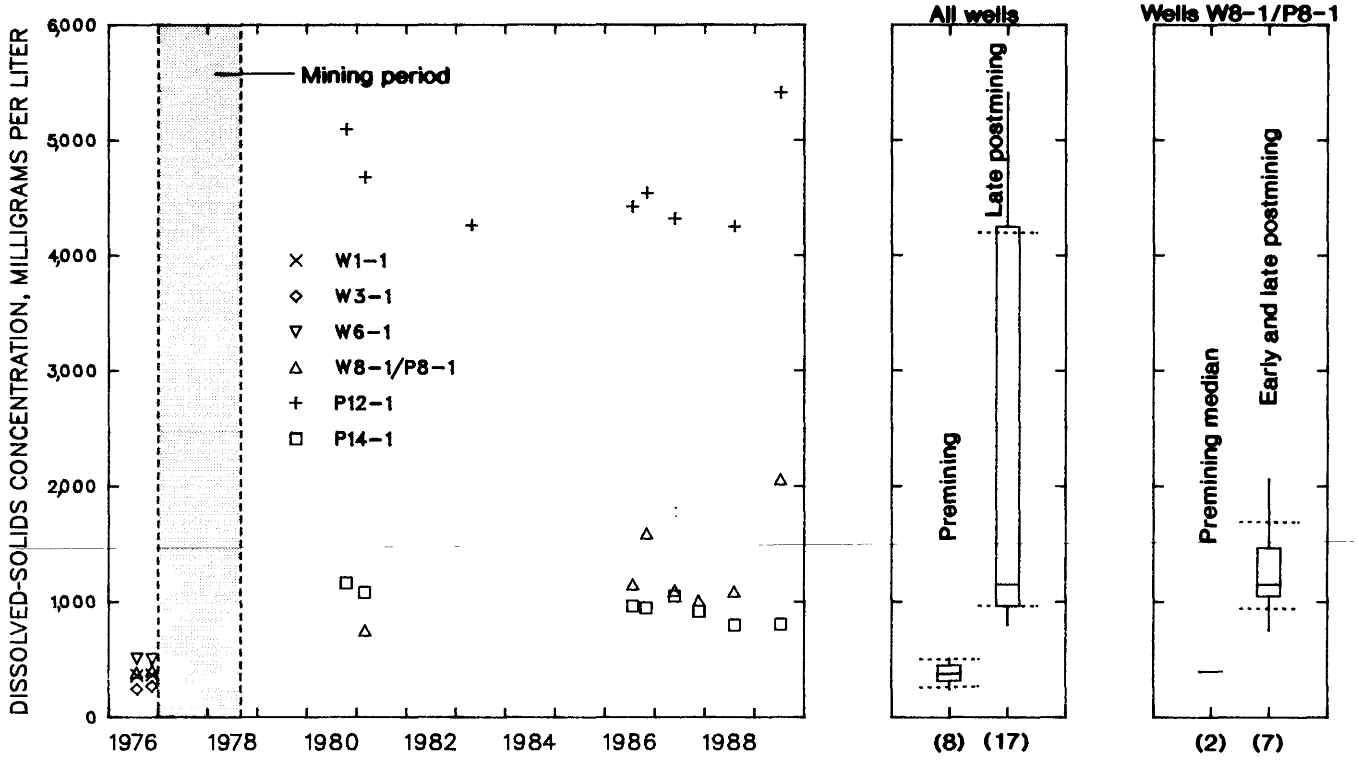


Figure 15.--Comparison of dissolved-solids concentrations of the waters from the upper aquifer in watershed MO9.

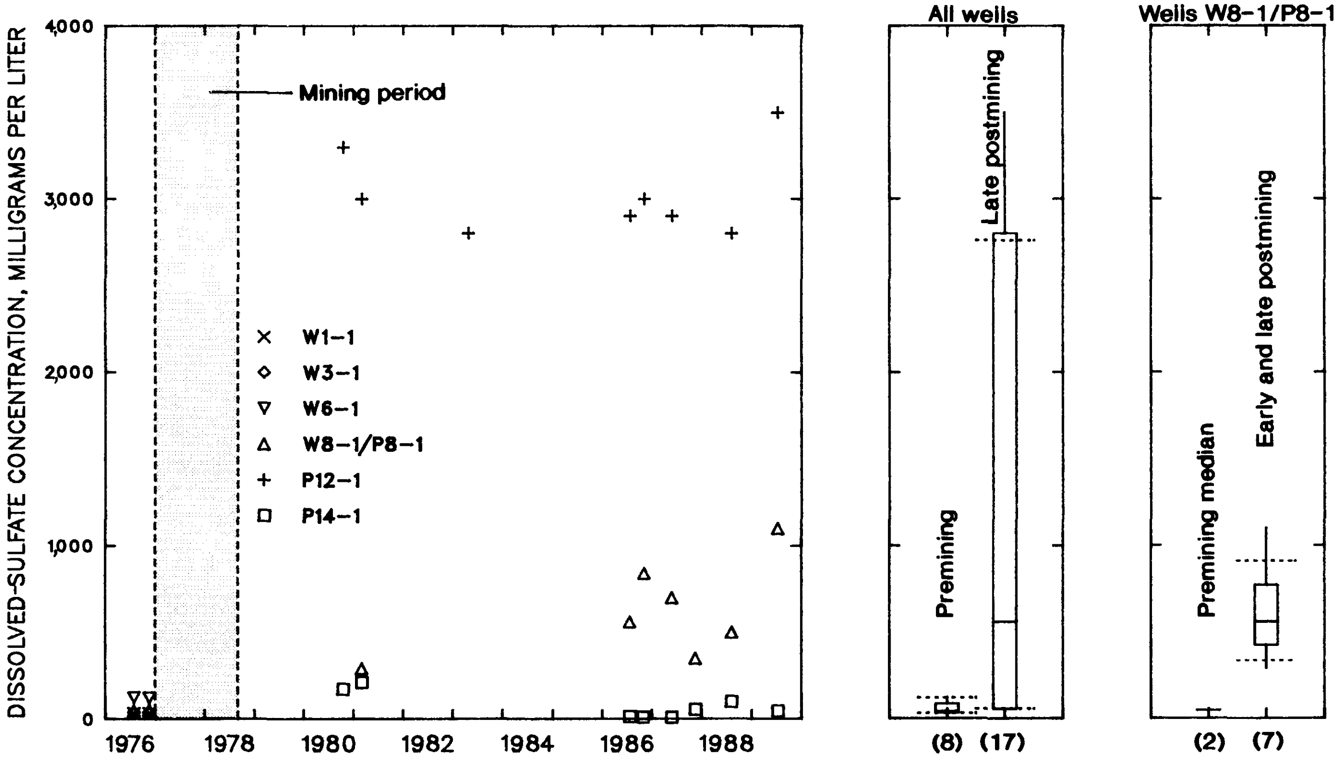


Figure 16.—Comparison of dissolved-sulfate concentrations of the waters from the upper aquifer in watershed MO9.

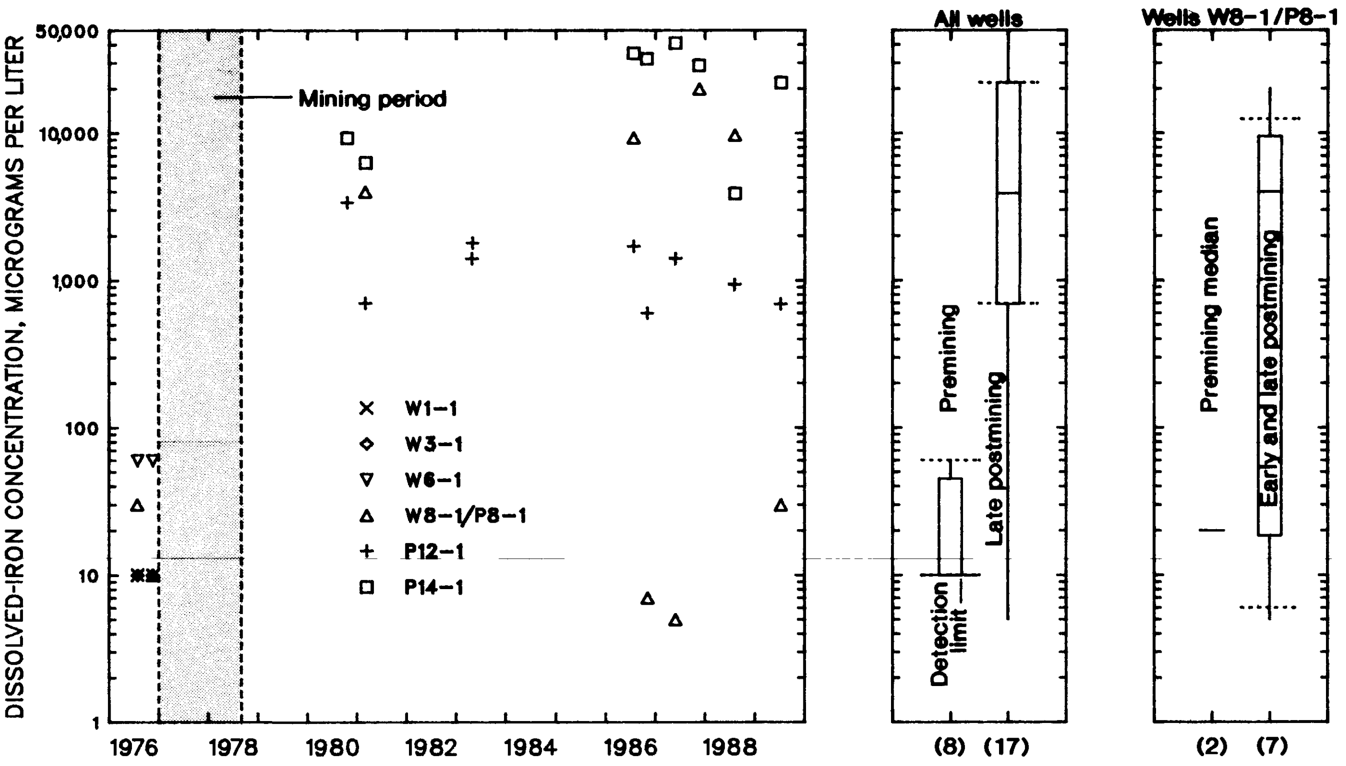


Figure 17.--Comparison of dissolved-iron concentrations of the waters from the upper aquifer in watershed MO9.

Manganese does not precipitate from solution as readily as does iron, so it can be a useful constituent for determining trends in water quality. The concentration of dissolved manganese in upper-aquifer wells increased from a premining median of 25 µg/L to a median concentration of 1,900 µg/L during this study (fig. 18). The box plot shows a significant statistical difference between these data sets. Although dissolved-manganese concentrations were significantly elevated after mining, the trend in wells P12-1 and P14-1 during this study appeared to be decreasing.

The premining water type of the middle aquifer differed by well. Helgesen and Razem (1981) classified the premining water as sodium chloride and sodium bicarbonate types. The median premining water type was sodium bicarbonate. The change in median water type from premining to postmining is shown in the trilinear diagram (fig. 19). Calcium and magnesium percentages increased enough to change the character of the water to a calcium magnesium sodium bicarbonate type. Sulfate percentage also increased slightly. Because only well P9-2 was sampled after mining, middle-aquifer characteristics must be inferred from this well.

The pH of water in the middle aquifer is described in figure 20. The box plot indicates a significant decrease in pH because of mining. The premining median pH of 8.0 has decreased to a postmining median of 7.4, possibly indicating leakage from the upper aquifer, in which the median pH was 6.7. The pH did not change significantly during the study period and may have reached equilibrium between 1981 and 1986, from 2 to 7 years following the end of active mining.

Figure 21 illustrates anomalously high, premining dissolved-solids concentrations in water from well W9-2. Most of the ions were sodium and chloride having a combined concentration of about 1,200 mg/L. Well W9-2 waters were the only waters to be classified as a sodium chloride type. Waters from all other premining wells sampled were a sodium bicarbonate type. Although median dissolved-solid concentrations indicate a significant change in water from wells W9-2 and P9-2 from premining (median, 1,590 mg/L to postmining (median, 549 mg/L), there is no significant difference between well P9-2 after mining and the other middle-aquifer wells before mining.

Another influence of the upper aquifer on the middle aquifer after mining is shown in figure 22. Sulfate concentrations increased almost fivefold, from a premining median of 26.5 mg/L to a postmining median of 130 mg/L. This postmining median, although less than the median concentration of 630 mg/L for well P8-1 (which overlies well P9-2), indicates some mixing with upper-aquifer waters. During the study period, sulfate concentrations fluctuated from 130 to 170 mg/L.

Differences between premining and postmining dissolved-iron concentrations are not statistically significant. The premining median concentration of 30 µg/L decreased to 23 µg/L after mining; however, dissolved-iron concentration increased rapidly during the first year after mining (fig. 23). The concentration decreased in late 1980 and remained near 15 µg/L through the end of the study.

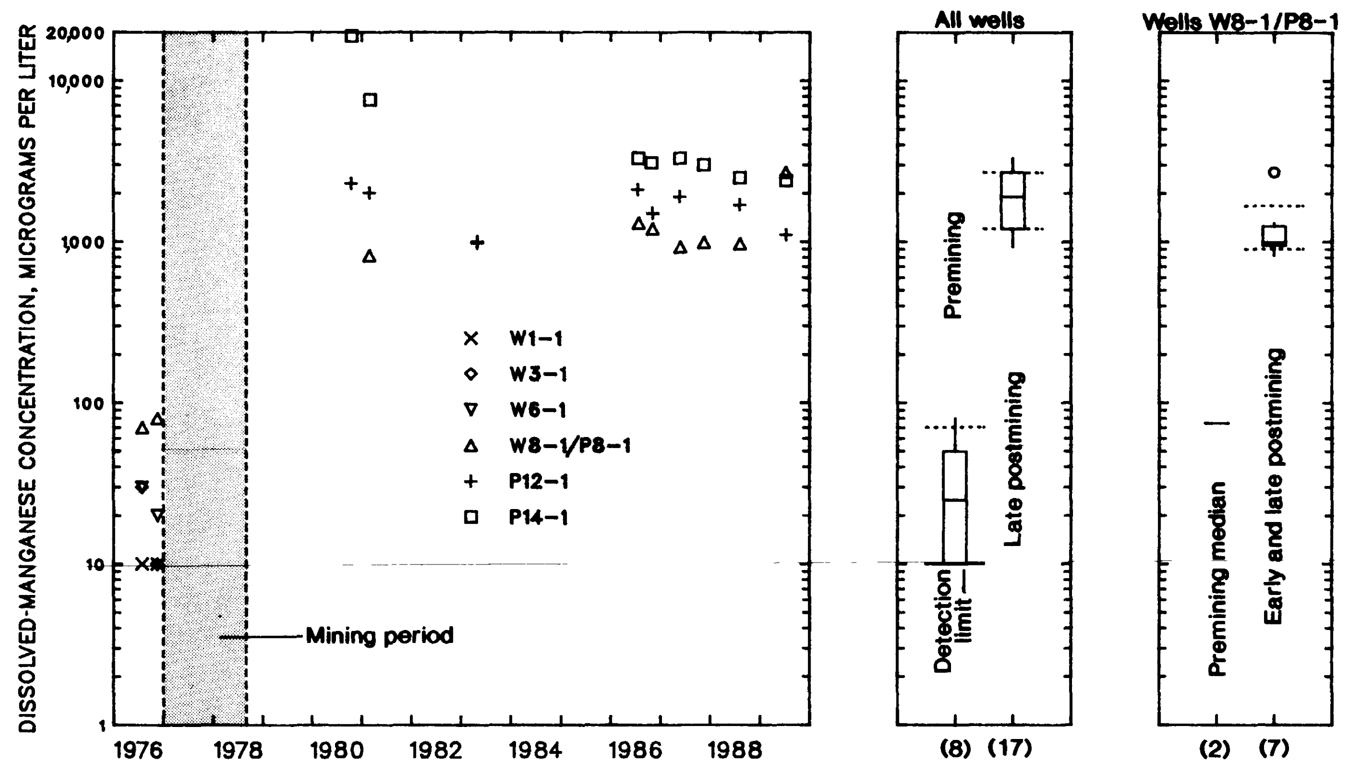


Figure 18.--Comparison of dissolved-manganese concentrations of the waters from the upper aquifer in watershed MO9

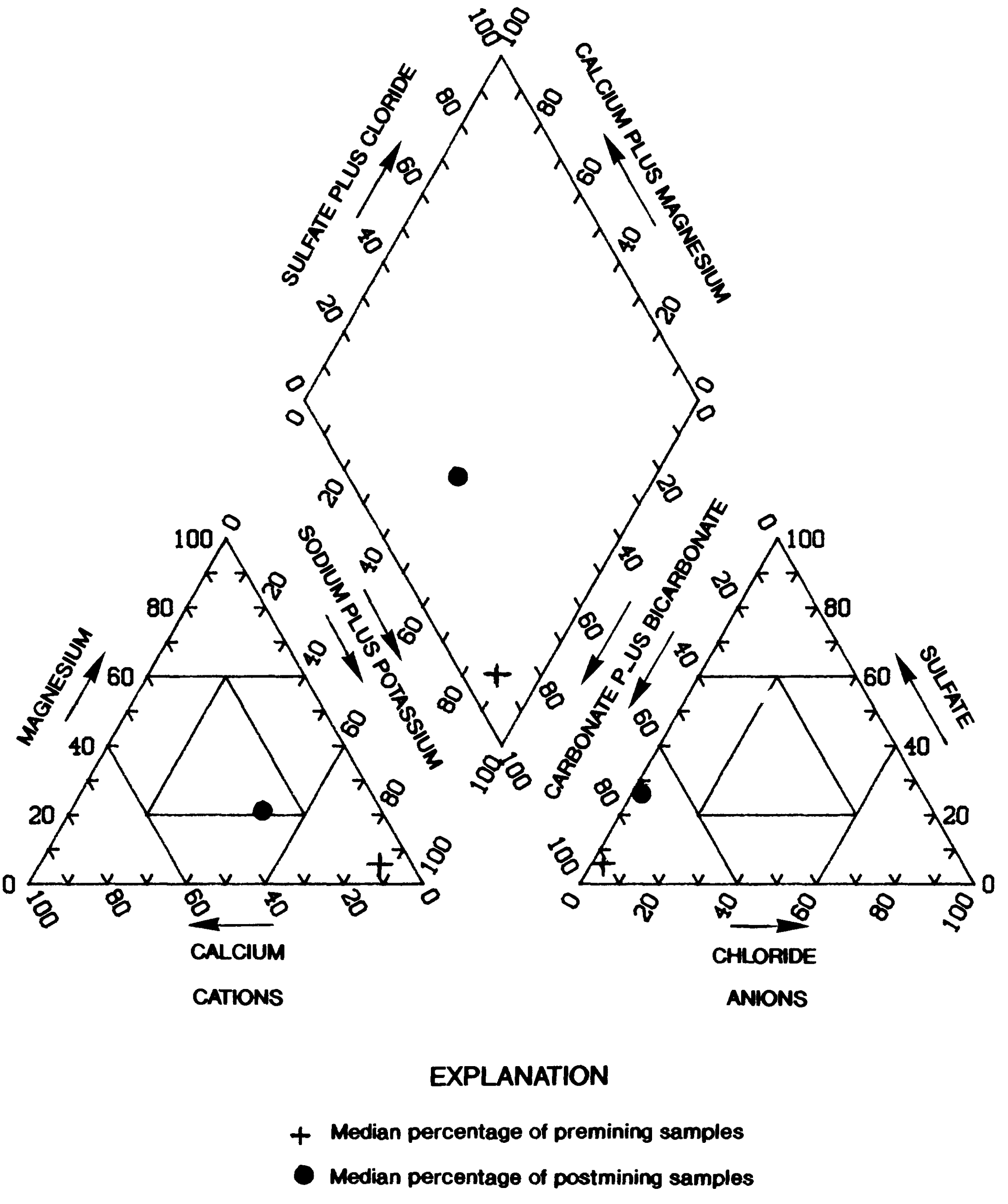


Figure 19.--Trilinear diagram for water sampled from the middle aquifer in watershed MO9.

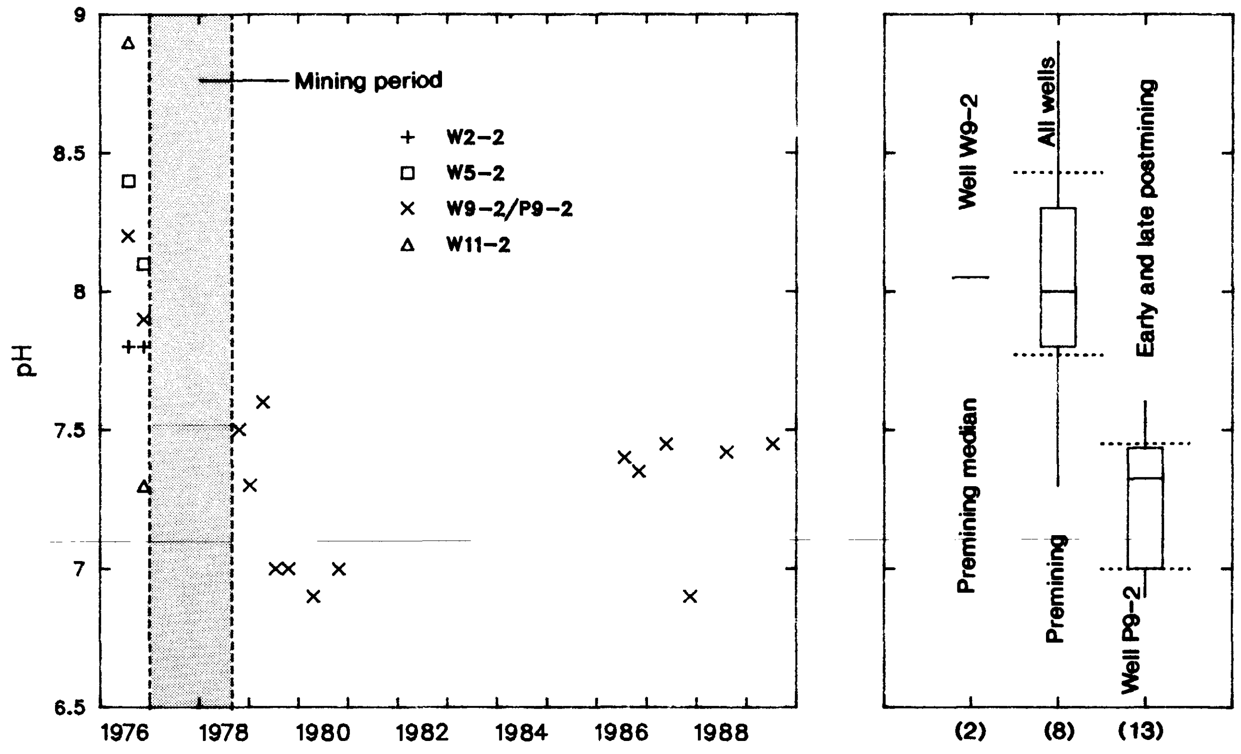


Figure 20.--Comparison of pH of the waters from the middle aquifer in watershed MO9.

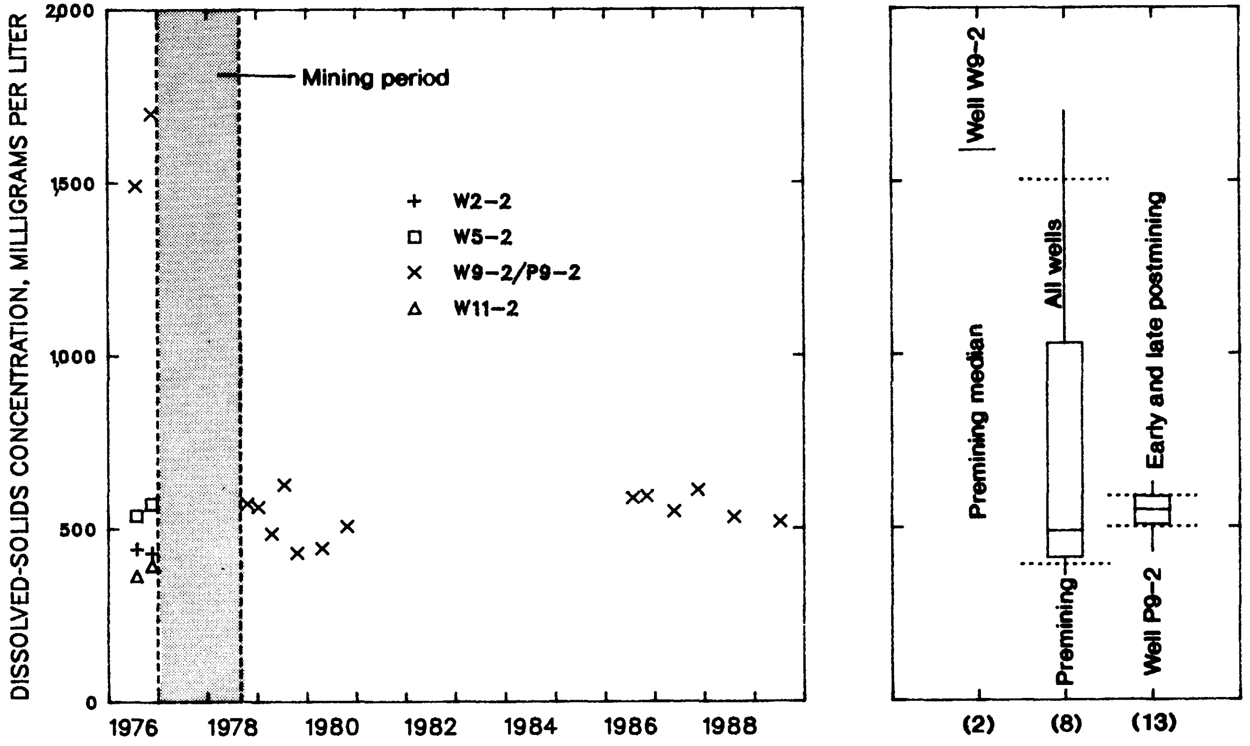


Figure 21.—Comparison of dissolved-solids concentrations of the waters from the middle aquifer in watershed MO9.

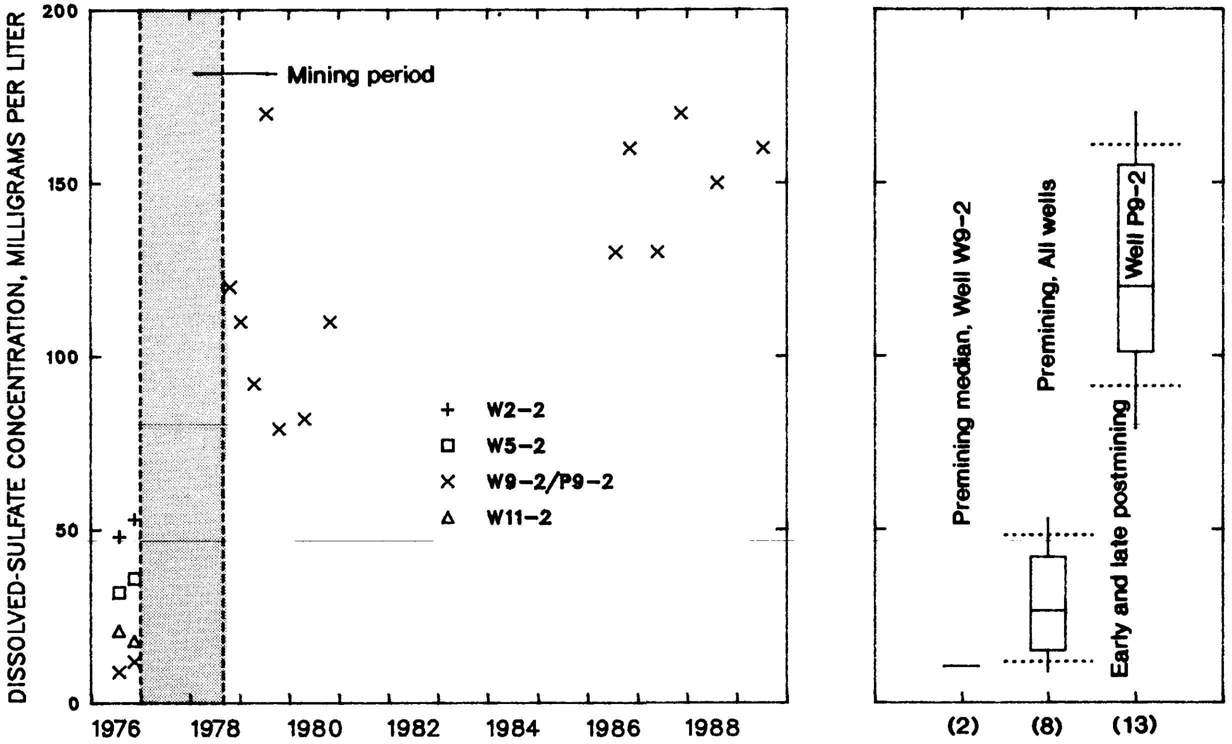


Figure 22.--Comparison of dissolved-sulfate concentrations of the waters from the middle aquifer in watershed MO9.

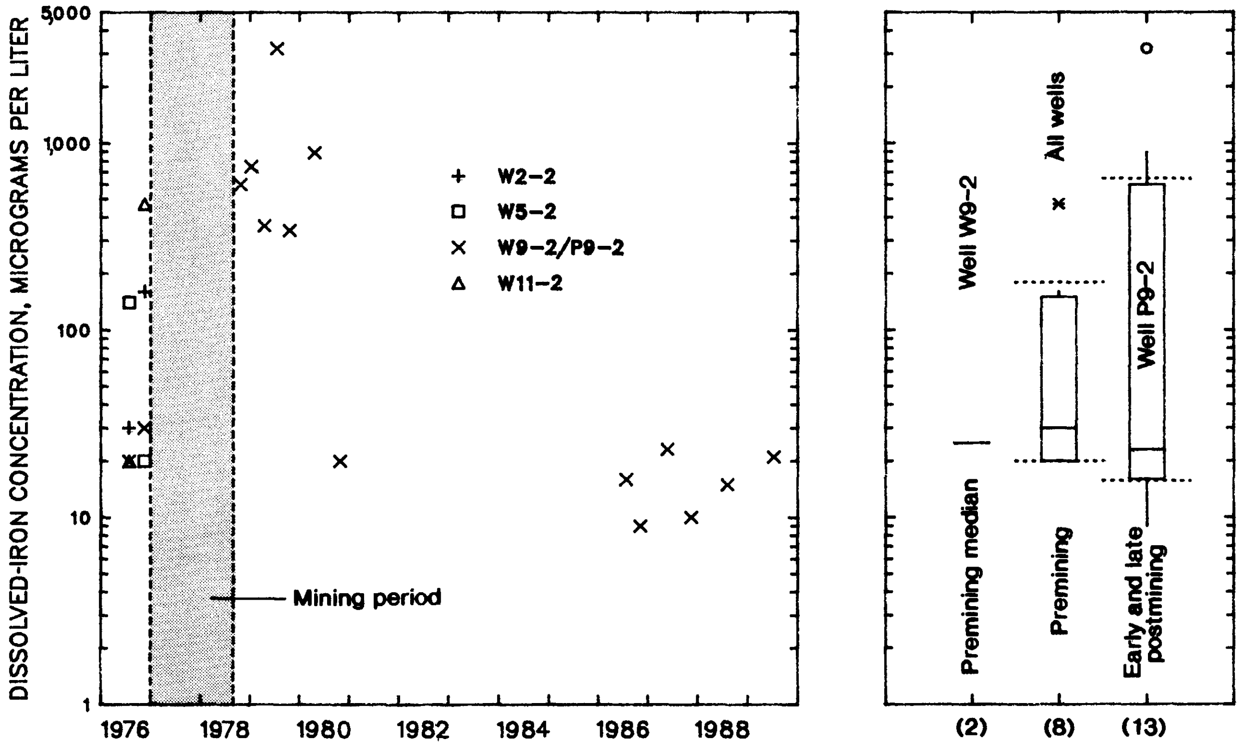


Figure 23.--Comparison of dissolved-iron concentrations of the waters from the middle aquifer in watershed MO9.

Dissolved-manganese concentrations in the middle aquifer increased from a premining median of 15 µg/L to a postmining median of 80 µg/L (fig. 24). The box plots indicate a significant difference between premining and postmining concentrations. The median dissolved-manganese concentrations increased more than fivefold; however, dissolved-manganese concentrations decreased during the last 2 years of data collection.

The stream and the seep also were sampled in watershed M09 (fig. 3). Surface water leaving the basin before mining was classified as a calcium bicarbonate type (U.S. Bureau of Mines, 1982). All stream waters sampled from 1986 through 1988 were classified as calcium sulfate or calcium magnesium sulfate types. The relation between ground-water and surface-water quality at the end of the study (July 1989) is shown in figure 25. This graph compares the pH and dissolved constituents in waters from the upper aquifer, the seep, and the stream. The upper-aquifer pH and concentration of dissolved constituents are represented by the median value of the three wells sampled. The concentration of iron and manganese decreases as the pH is buffered by carbonate riprap in the stream. The elevated sulfate concentrations in the ground water contribute to elevated concentrations in the stream. Because neutralization of pH does not change the concentration of sulfate, sulfate is the primary constituent with an elevated concentration as the water leaves the watershed.

## Watershed J11

Watershed J11 has been studied more extensively than has watershed M09. Water-level and water-quality data from water-shed J11 are available as long as 3 years after reclamation. The following discussion of watershed J11 focuses primarily on the late postmining trends in water levels and water quality.

### Ground-Water Levels

Ground-water flow in the upper aquifer is estimated by use of the hydraulic gradients along the generalized flow lines A and B shown in figure 26. The approximate hydraulic gradient is 0.007. Flow is from the watershed divide to the west, where it discharges as flow from a seep. Flow in the middle aquifer is also toward the west.

Water levels in the upper aquifer declined almost immediately after mining began (fig. 27). Water levels in upper-aquifer wells that were not disturbed by mining (wells W1-1 and W6-1) declined more than 10 ft. Recharge to the upper aquifer reached wells from 5 to 15 months after reclamation. Water levels in wells installed in the spoil were increasing slightly at the end of a previous study in 1982. The water levels probably stabilized sometime between late 1982 and 1986, from 2 to 5 years after reclamation.

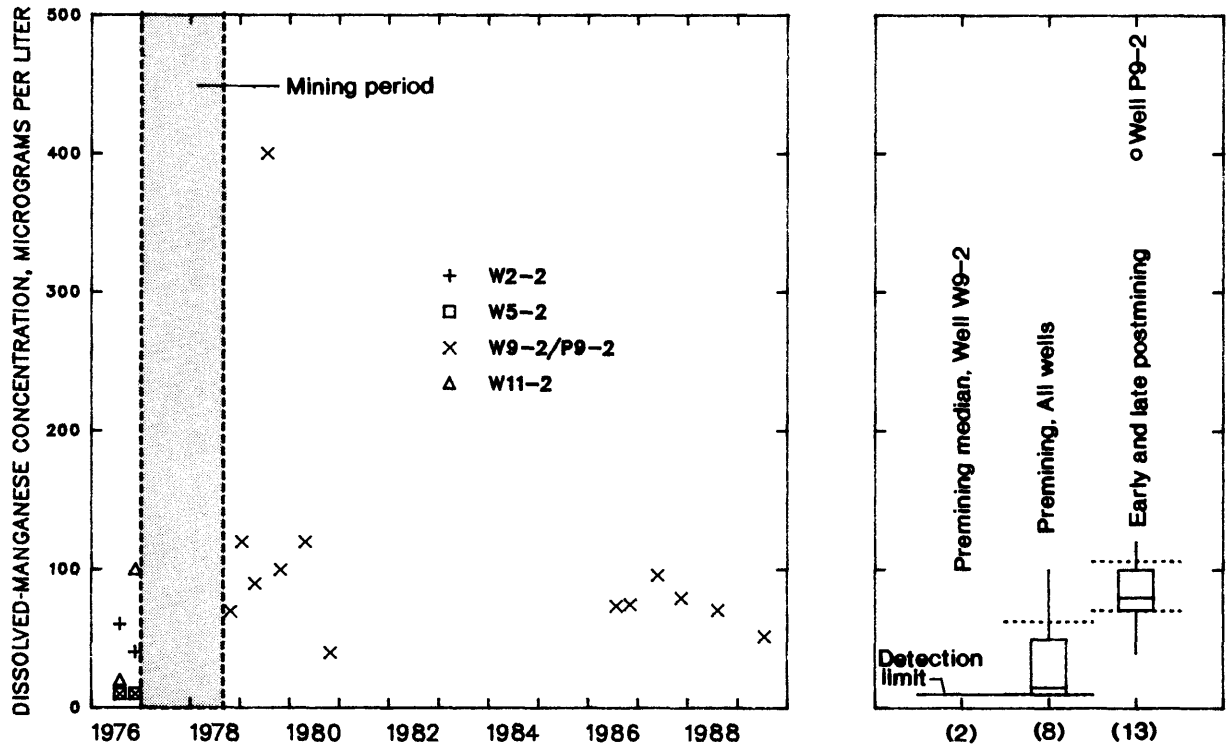


Figure 24.—Comparison of dissolved-manganese concentrations of the waters from the middle aquifer in watershed MO9.

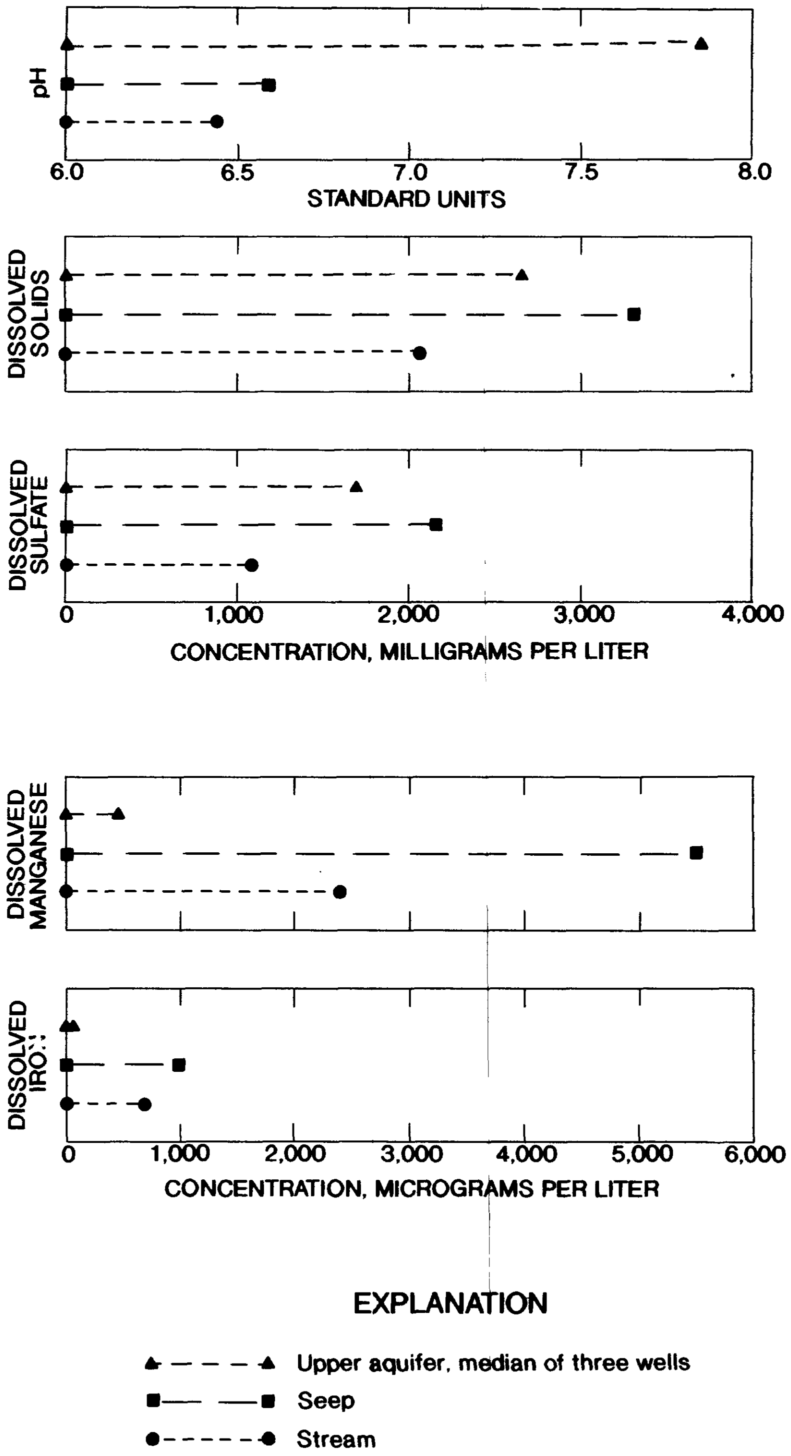


Figure 25.--Selected water-quality characteristics in upper aquifer, seep, and stream in watershed M09, July 1989.

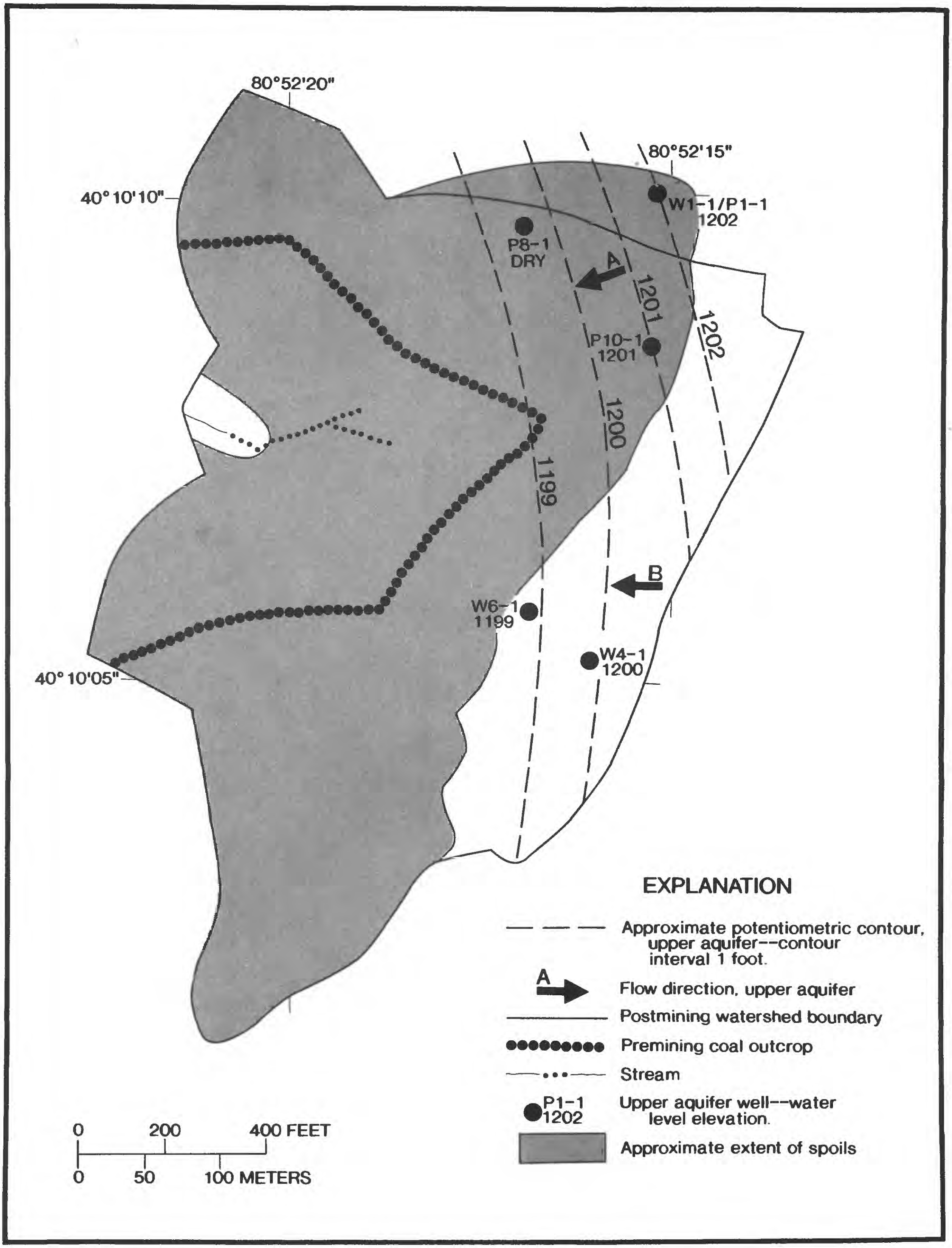


Figure 26.--Generalized flow map of watershed J11, February 1989

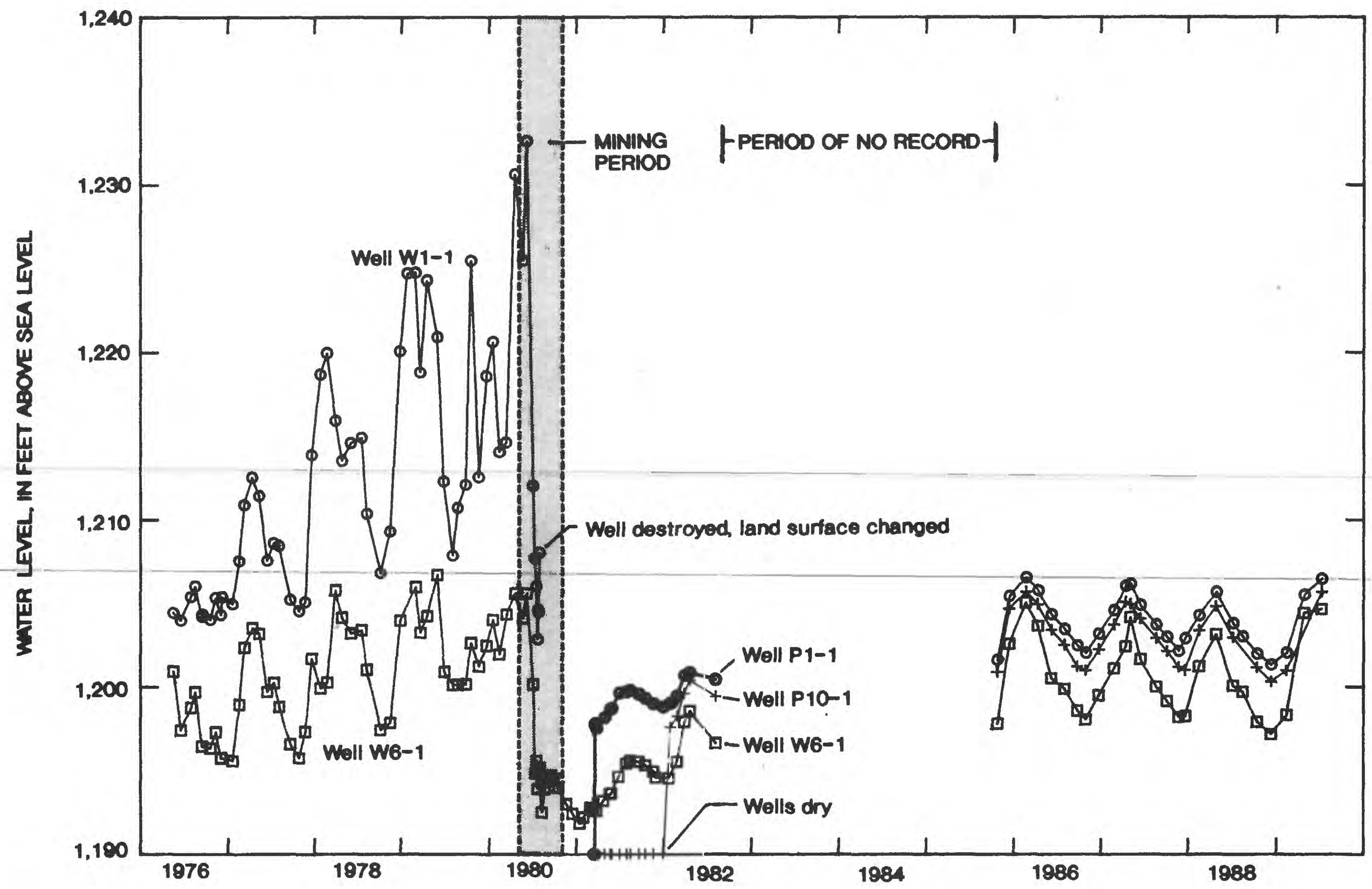


Figure 27.--Water levels of selected wells at watershed J11, upper aquifer.

Water levels in the middle aquifer are shown in figure 28. Wells W7-2 and W8-2 were not destroyed by mining and indicate the response of the aquifer to mining. Water levels in well W8-2 increased aproximately 5 ft because of mining. Because of the large fluctuations in well W7-2, the effect of mining on water levels in this well is not easily determined. Since the initial water-level changes caused by mining, the water levels have remained stable, indicating hydraulic equilibrium.

An example of the vertical hydraulic gradient in watershed J11 is shown in figure 29. The vertical hydraulic gradient (calculated from February 1989 water levels) between the upper aquifer and middle aquifer at this location is approximately 1.2 ft of head loss per vertical foot of aquifer. Changes in the water quality in the upper aquifer have an effect on the middle aquifer. The effects on water quality and water levels in the underlying aquifer would depend on the rate of seepage through the clay layer and would be accelerated if the clay layer were absent or disturbed.

Figure 30 illustrates the response of several wells to precipitation as determined from continuous-recorder records. The left-hand part of the figure represents the water-level responses just before, during, and just after mining. The right-hand part of the figure represents water-level responses in 1987 and 1988. Some periods of record are missing for well W8-2. Figure 28 can be referred to for a general indication of the water-level fluctuations during these periods. Early precipitation data are from a gage at the watershed. The precipitation data from 1987 and 1988 were collected at a National Oceanic and Atmospheric Administration weather station approximately 10 mi (miles) northwest in Cadiz, Ohio.

Well W6-1 indicates the changes in upper-aquifer response to recharge. This well was not destroyed by mining and is adjacent to the spoil zone. Mining caused a sharp drop in water level, as well as a subdued response to precipitation after mining. This subdued response is also indicated long after mining in well P10-1, a well completed within the spoil after mining. The decline in responsiveness of the postmining hydrograph shown by these two wells is a result of the destruction of the soil structure and compaction of the soil above the new aquifer, as well as the increase in storativity and hydraulic conductivity of the porous spoil.

The fluctuations of water level in the middle aquifer are represented by the hydrograph for well W8-2. Although a large increase in hydraulic head occurred between periods of continuous record, no other inferences can be made. The well hydrograph shows a possible decrease in aquifer responsiveness to precipitation, but the changes are not definitive.

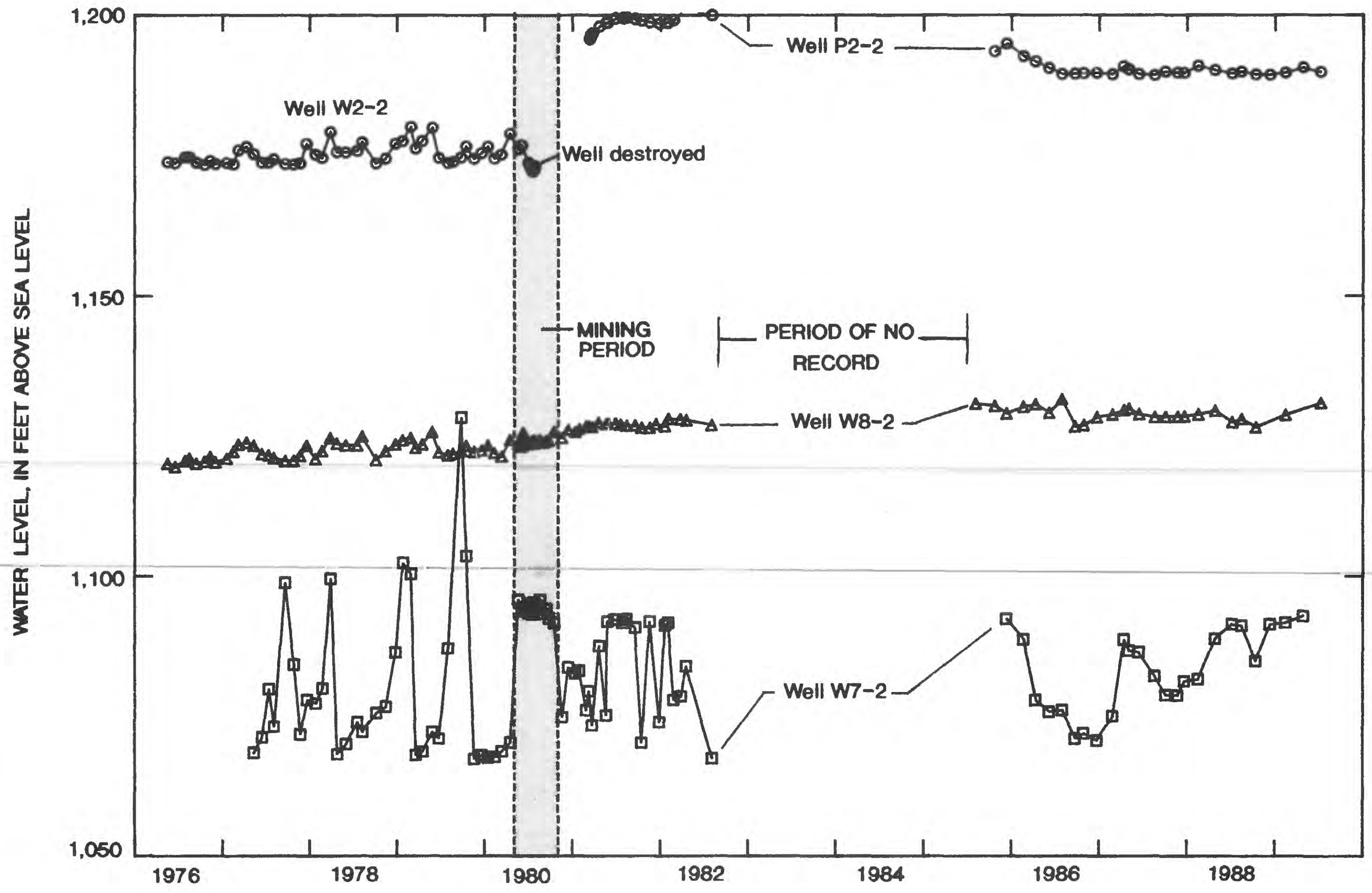


Figure 28.--Water levels of selected wells at watershed J11, middle aquifer.

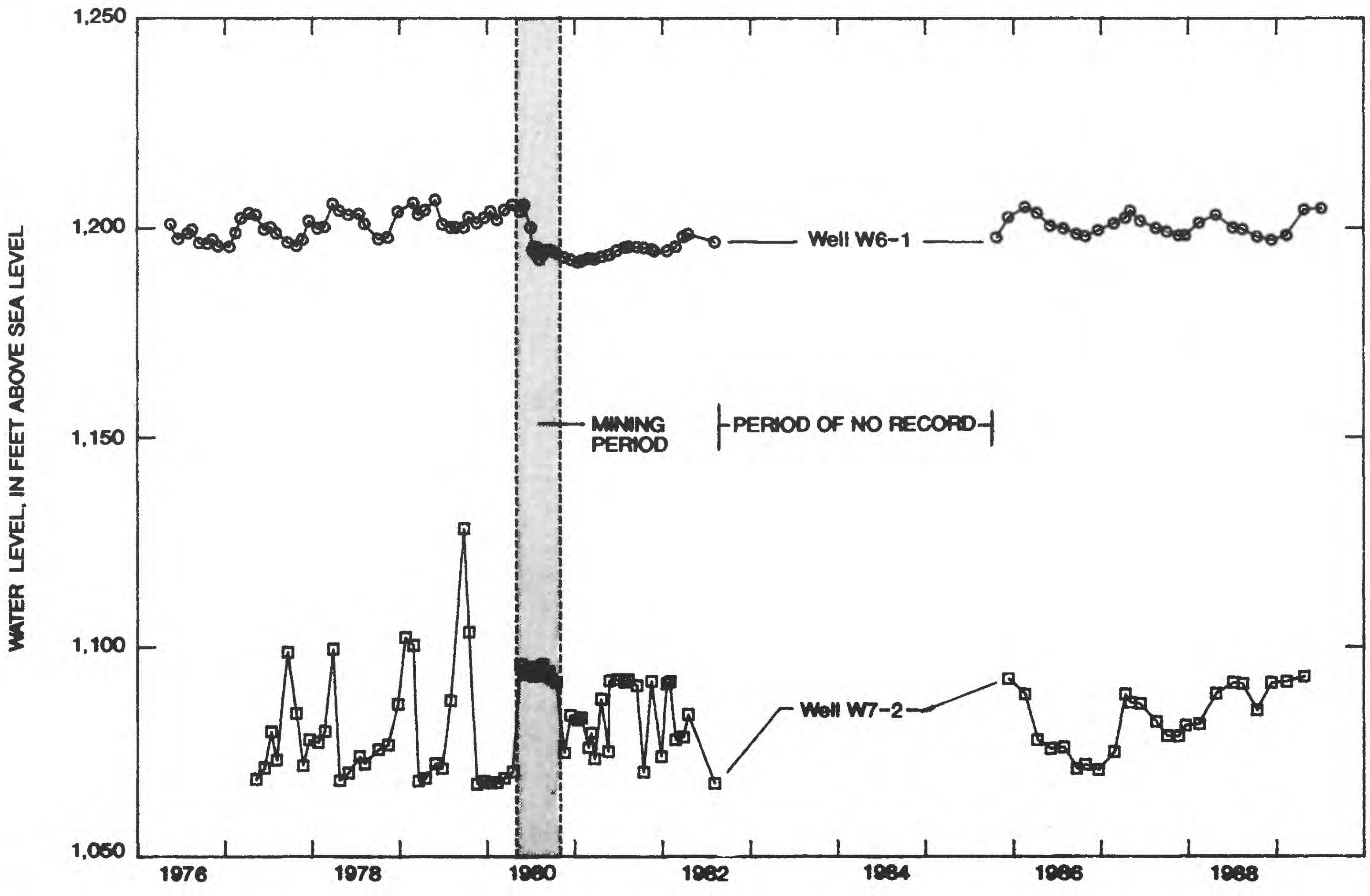
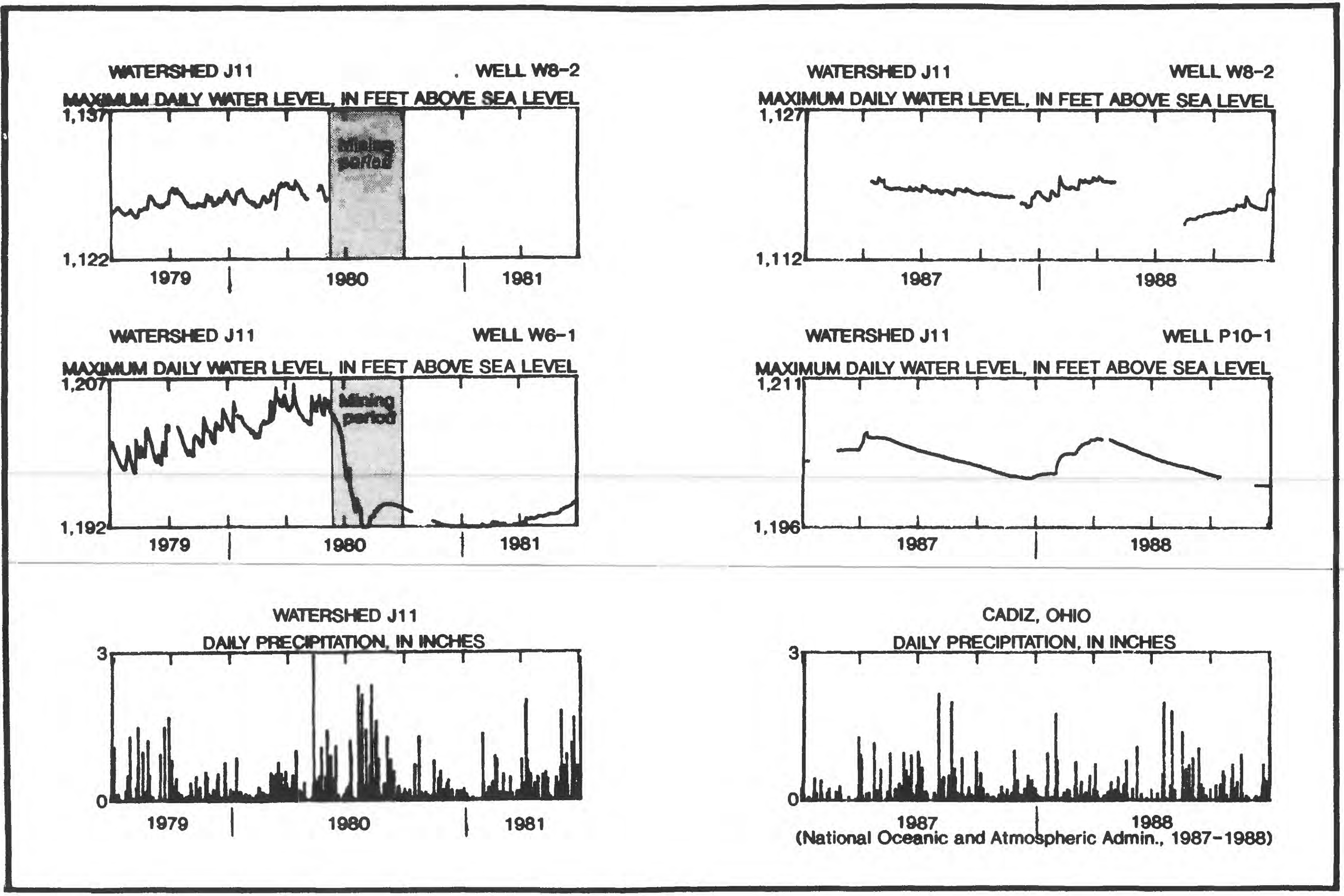


Figure 29.--Water levels in upper and middle aquifers in paired wells W6-1 and W7-2 (watershed J11).



(National Oceanic and Atmospheric Admin., 1987-1988)

Figure 30.--Aquifer response to precipitation at watershed J11.

## Water Quality

In previous studies, ground-water samples were collected from August 1976 through May 1983 from wells in the upper and middle saturated zones. The wells sampled for this study were wells P1-1, P3-1, and P10-1 from the upper aquifer and well W8-2 from the middle aquifer. Samples were collected twice a year in 1986 and 1987 and annually thereafter. These data are compared with all of the premining data available and with early post- mining data collected at the same wells during a previous study.

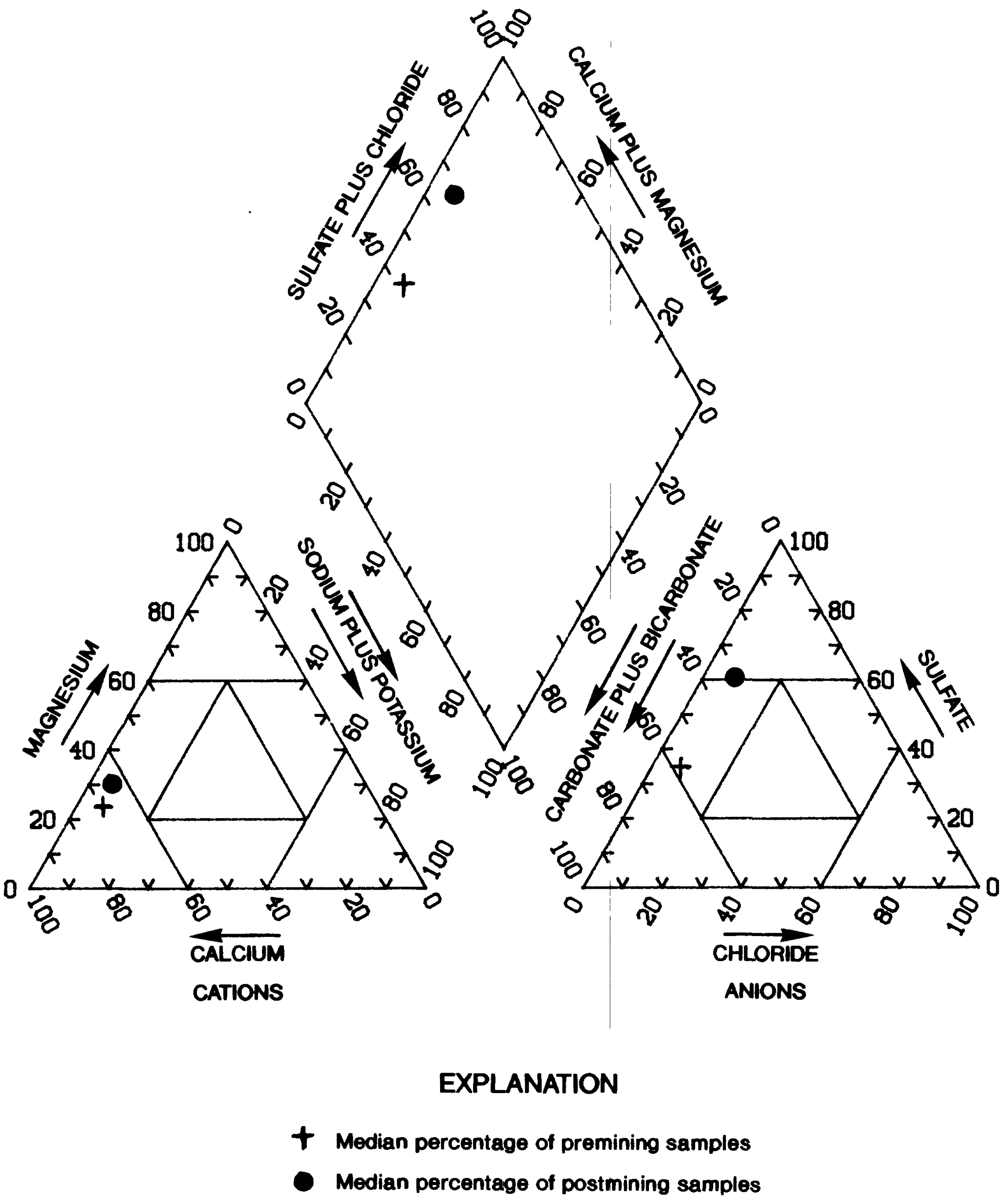
The premining upper aquifer in watershed J11 contained calcium bicarbonate and calcium sulfate-type waters (Razem, 1984). The changes in water type from premining to postmining are shown by the median percentages plotted in the trilinear diagram in figure 31. Calcium remained the major cation, but sulfate gradually replaced bicarbonate as the major anion in the system. The water is now uniformly classified as calcium sulfate type.

As with the discussion of water quality in watershed MO9, only pH, and concentrations of dissolved solids, sulfate, iron, and manganese are discussed in detail. Time-series plots for other dissolved constituents analyzed are in the supplemental data section at the back of the report.

The water-quality data were compared statistically by use of the Mann-Whitney test as described in the watershed MO9 section. Each water-quality characteristic is discussed in relation to median values, as well as the significant deviations from median values determined by the Mann-Whitney test. A box plot with 95-percent confidence intervals also is presented to help show the differences among data sets. An explanation of the box-plot graphic is shown in figure 13.

As with watershed MO9, the nature of the mining process prevented comparison of the data from the same well, but because more water-quality data are available for watershed J11 than for watershed MO9, box plots are presented of premining, early postmining, and late postmining data for wells W1-1 and P1-1 and W8-2. The early postmining data include data from 1980 through the first sample collected in 1986. Late-postmining data include data obtained during 1986-89. This method of data presentation is an attempt to show graphically that the constituents are either in equilibrium or that the rate of changes in concentration has increased or decreased substantially after mining. The degree of variation of data is illustrated by the quartile ranges of the box plot.

Changes in pH in the upper aquifer through time are illustrated in figure 32. The box plot shows a statistically significant decrease in pH from a premining median of 7.0 to a late postmining median of 6.7. Wells W1-1 and P1-1 indicate that the difference between early and late postmining data is not significant. However, the time-series plot appears to show an overall downward trend in pH over time.



EXPLANATION

+ Median percentage of premining samples

● Median percentage of postmining samples

Figure 31.--Trilinear diagram for water sampled from the upper aquifer in watershed J11.

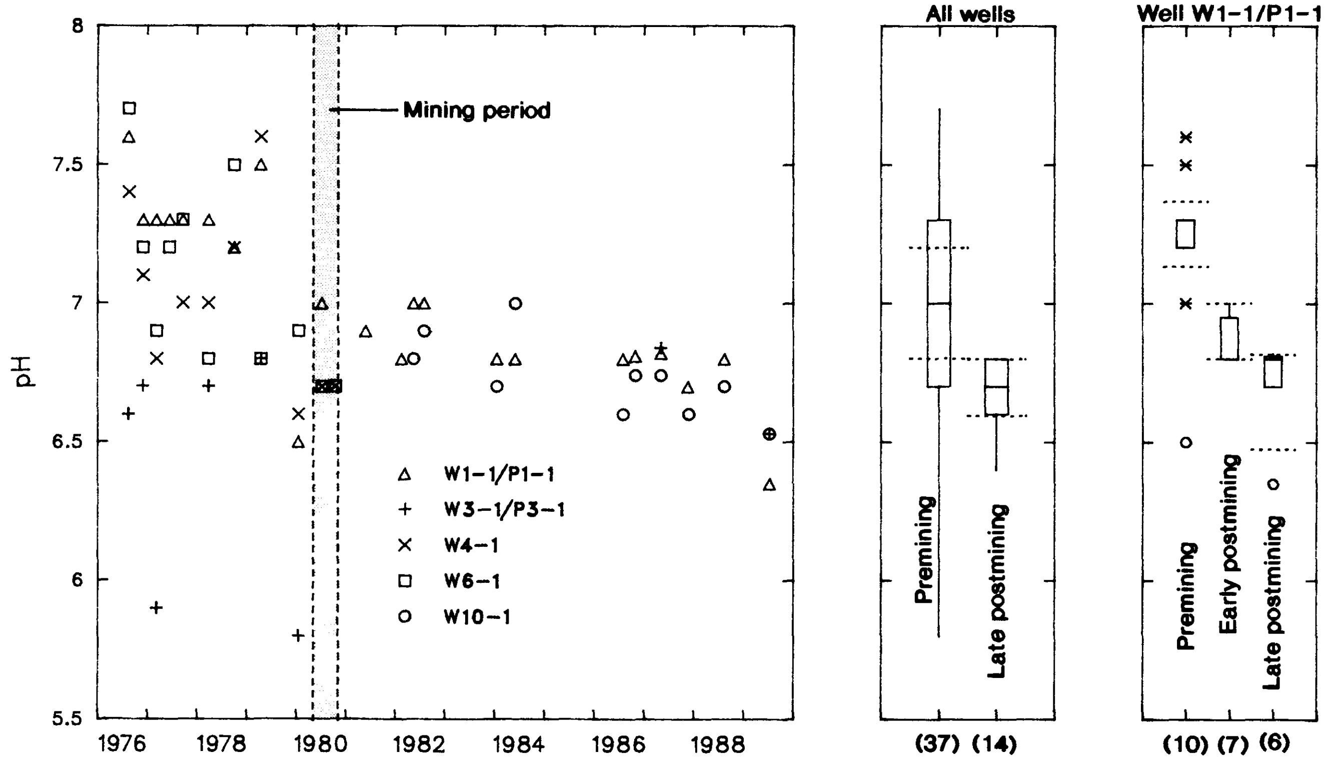


Figure 32.--Comparison of pH of the waters from the upper aquifer in watershed J11.

Concentrations of dissolved solids were stable during premining conditions; the median concentration was 335 mg/L (fig. 33). The late postmining median dissolved-solid concentration increased by about 4.5 times to 1,495 mg/L. Water from well P1-1 also indicated a significant increase in dissolved-solid concentration after mining. The median dissolved-solids concentration increased from 1,100 mg/L to 1,650 mg/L from early to late postmining. The data indicate a continued increasing trend in dissolved-solid concentrations within the watershed.

Because sulfate is the primary component in the dissolved-solids concentrations in this aquifer, the trends in sulfate concentration (fig. 34) are similar to those of dissolved solids discussed above. Concentrations of sulfate were fairly stable during premining conditions; the median concentration was 85 mg/L. The late postmining median sulfate concentration increased by almost an order of magnitude to 825 mg/L. The data indicate a continued increasing trend in sulfate concentration.

Dissolved-iron concentrations are shown in figure 35. Because of variability in premining and postmining concentrations, the differences in dissolved-iron concentration for the upper aquifer are not significant.

Dissolved-manganese concentration in the upper aquifer was highly variable before mining (fig. 36). The median concentration for all data was 30 µg/L. After mining, the median concentration for all wells sampled increased by more than one order of magnitude to 1,015 µg/L. The analysis of wells W1-1 and P1-1 show a postmining increase of more than two orders of magnitude from premining (median = <10 µg/L) to early postmining (median = 740 µg/L) to late postmining (median = 5,850 µg/L). Upper-aquifer waters were not in equilibrium with respect to manganese.

The premining water of the middle aquifer was classified as calcium bicarbonate by Razem (1984) and Hren (1986). The median premining water was a calcium magnesium sodium bicarbonate type. The changes in median water type from premining to postmining are shown in the trilinear diagram in figure 37. After mining, sulfate replaced bicarbonate as the dominant anion. The postmining water is classified as a calcium sulfate bicarbonate type.

The premining water quality of the middle aquifer is represented by wells W2-2, W7-2, and W8-2. Only one well (W8-2) was consistently sampled during the postmining period, thus, data for well W8-2 are used to characterize the middle aquifer after mining.

Figure 38 indicates a significant decrease in pH from premining (median = 7.5) to late postmining (median = 6.6). The time-series plot and well W8-2 box plot show that a downward trend continued through the end of the study. This is similar to the decline noted in the upper aquifer.

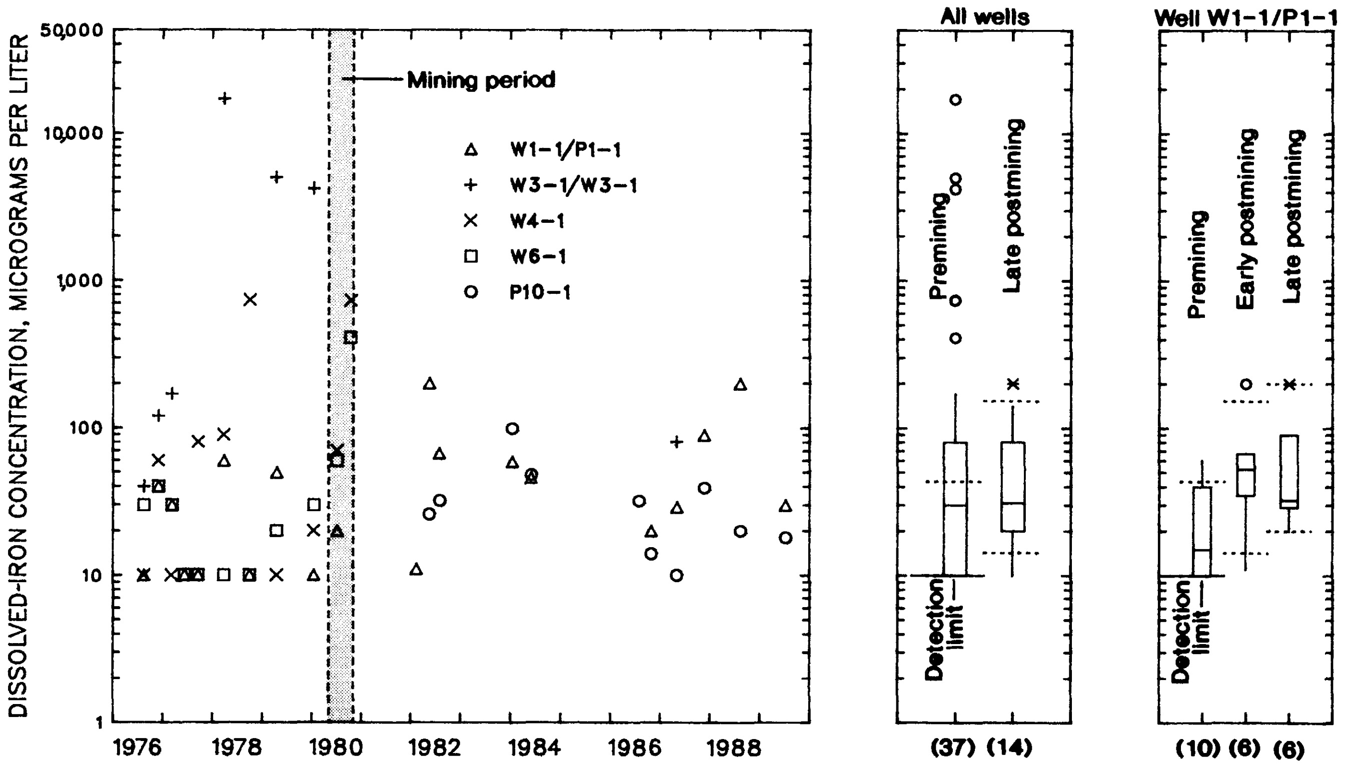


Figure 35.—Comparison of dissolved-iron concentrations of the waters from the upper aquifer in watershed J11.

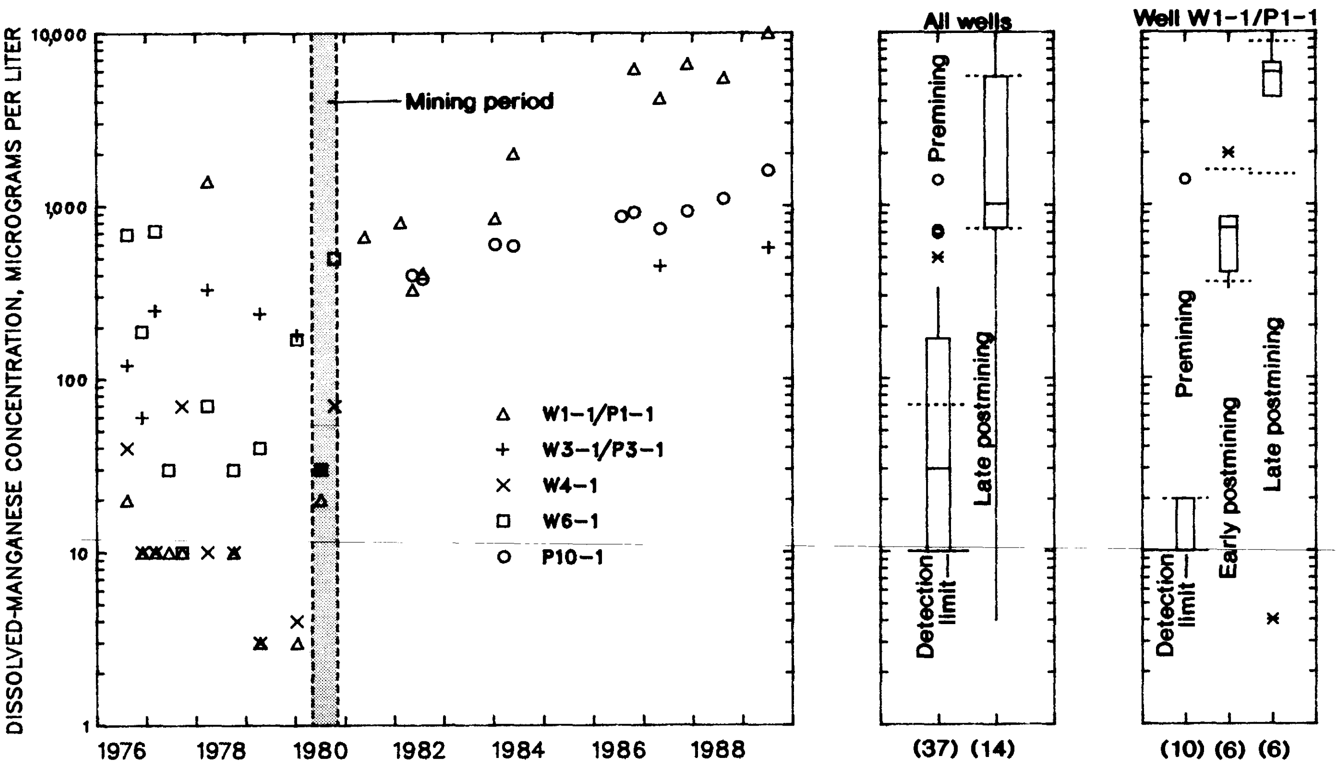


Figure 36.--Comparison of dissolved-manganese concentrations of the waters from the upper aquifer in watershed J11.

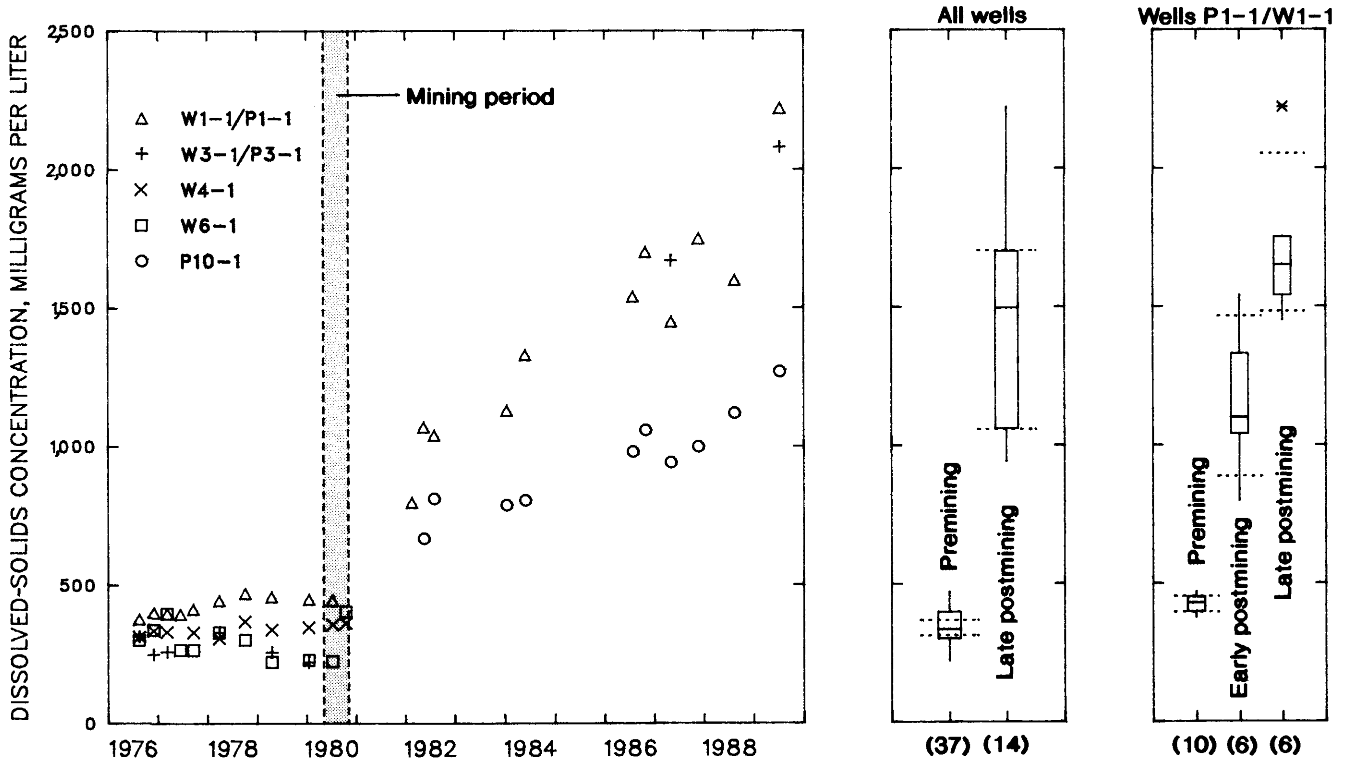


Figure 33.—Comparison of dissolved-solids concentrations of the waters from the upper aquifer in watershed J11.

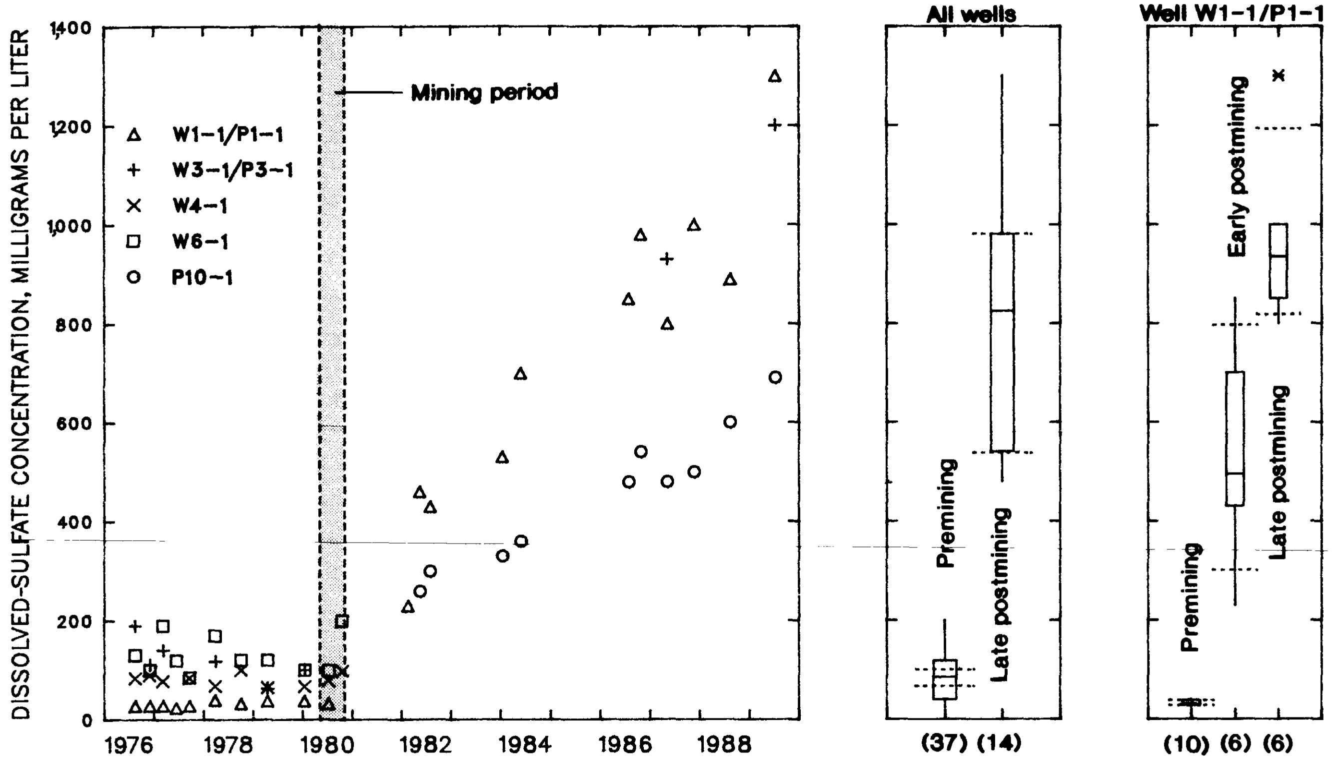


Figure 34.--Comparison of dissolved-sulfate concentrations of the waters from the upper aquifer in watershed J11.

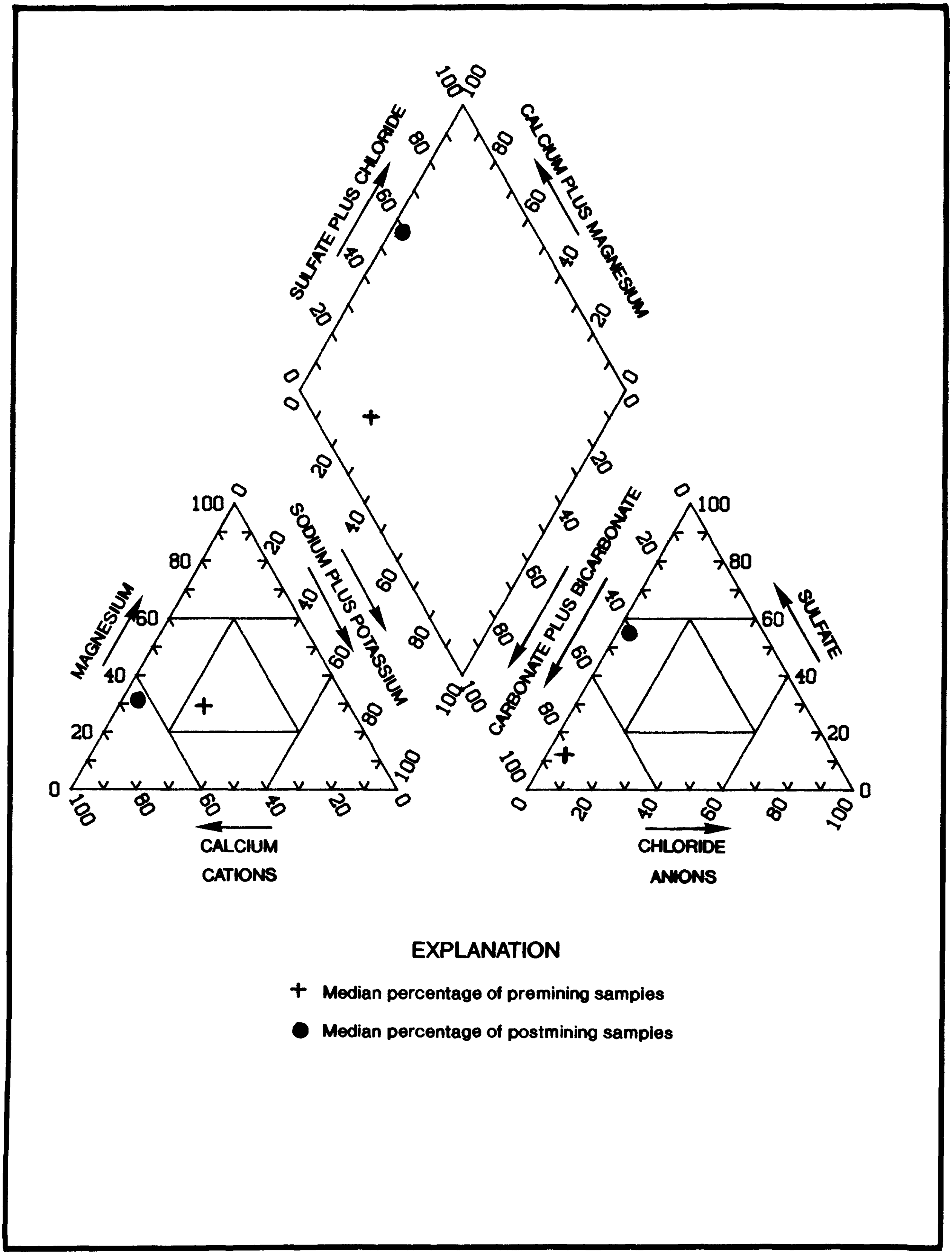


Figure 37.--Trilinear diagram for water sampled from the middle aquifer in watershed J11.

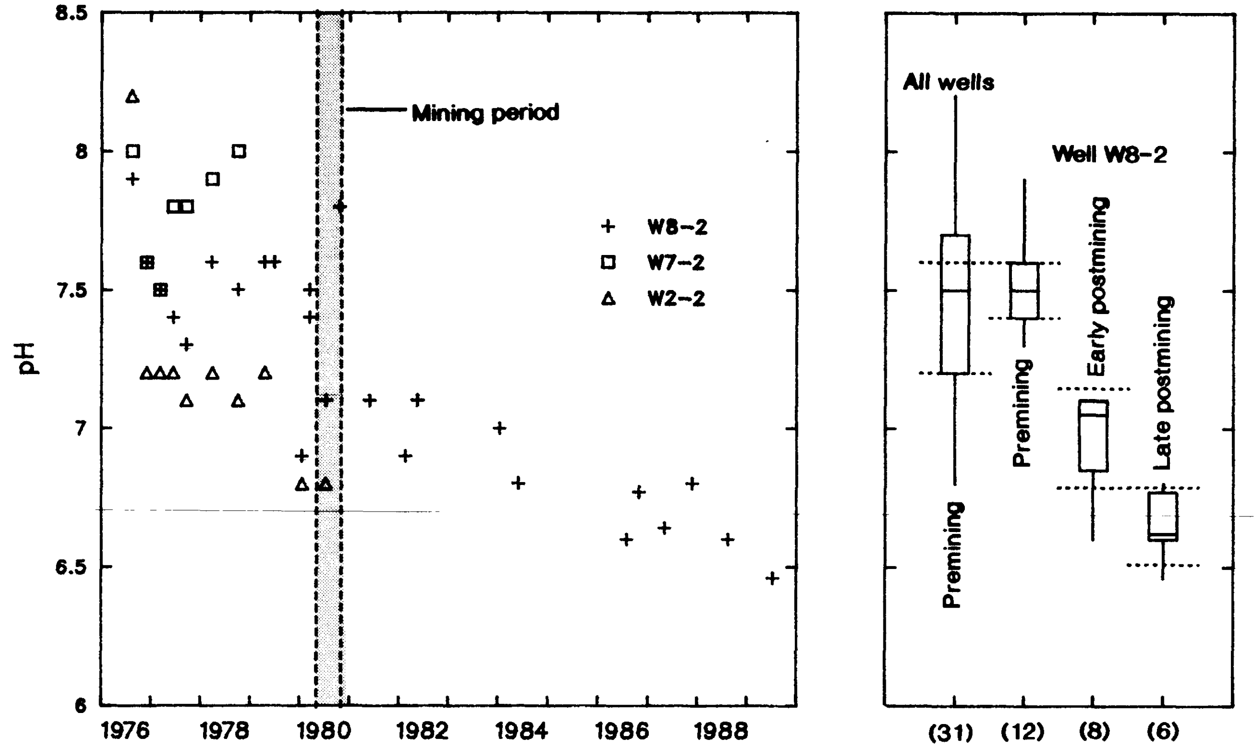


Figure 38.--Comparison of pH concentrations of the waters from the middle aquifer in watershed J11.

The response of dissolved solids in water from the middle aquifer to mining (figure 39) is comparable to that for the upper aquifer. Dissolved-solids concentrations were stable during premining conditions; median concentration was 404 mg/L. Concentrations in water from well W8-2 increased by about 200 mg/L per year during early postmining (355 mg/L in 1980 to 1,420 mg/L in 1986); median concentration was 804 mg/L. During late postmining, the rate of increase slowed (1,420 mg/L in 1986 to 1,740 mg/L in 1989); median concentration was 1,530 mg/L. These medians represent nearly a fourfold increase in dissolved-solid concentration from premining to postmining concentrations.

Premining concentrations for sulfate were stable; the median was 47 mg/L (fig. 40). Sulfate concentrations increased by about 125 mg/L during early postmining (42 mg/L in 1980 to 790 mg/L in 1986); median concentration was 190 mg/L. During late postmining, the rate of increase slowed (790 mg/L in 1986 to 810 mg/L in 1989); median concentration was 770 mg/L. This increase from premining to postmining exceeds an order of magnitude.

Dissolved-iron concentrations are not discussed for the middle aquifer. Dissolved-oxygen concentrations greater than 7 mg/L caused by cascading water in well W8-2 prevent valid comparison of the data because oxygenation of the ground water induces precipitation of iron.

Dissolved-manganese concentrations increased from a premining median concentration below the detection limit (<10 µg/L) to a late postmining median concentration of 3,500 µg/L (fig. 41). This represents more than an order of magnitude increase in manganese concentration after mining ended. However, because of two very low concentrations sampled in 1986 and a limited sample population, the lower quartile range of the data is very large, and a statistically significant difference between premining and postmining concentrations does not exist.

The stream and the seep also were sampled in watershed J11. Surface water flowing out of the basin before mining was classified as a calcium bicarbonate type (U.S. Bureau of Mines, 1984). Late postmining water samples are classified as a calcium sulfate type. As in the aquifers, sulfate has replaced bicarbonate as the dominant anion.

The relation between ground-water and surface-water quality at the end of the study (July 1989) is shown in figure 42. This graph compares the pH and dissolved constituents in waters from the upper aquifer, the seep, and the stream. The upper-aquifer pH and concentration of dissolved constituents are represented by the median value of the three wells sampled. Changes in dissolved solids, sulfate, and manganese concentrations from the aquifer to the seep to the stream are not pronounced; however, pH and dissolved-iron concentration changed considerably. As pH is buffered by carbonate riprap in the stream, iron precipitates, lowering the dissolved-iron concentration as the surface water leaves the watershed.

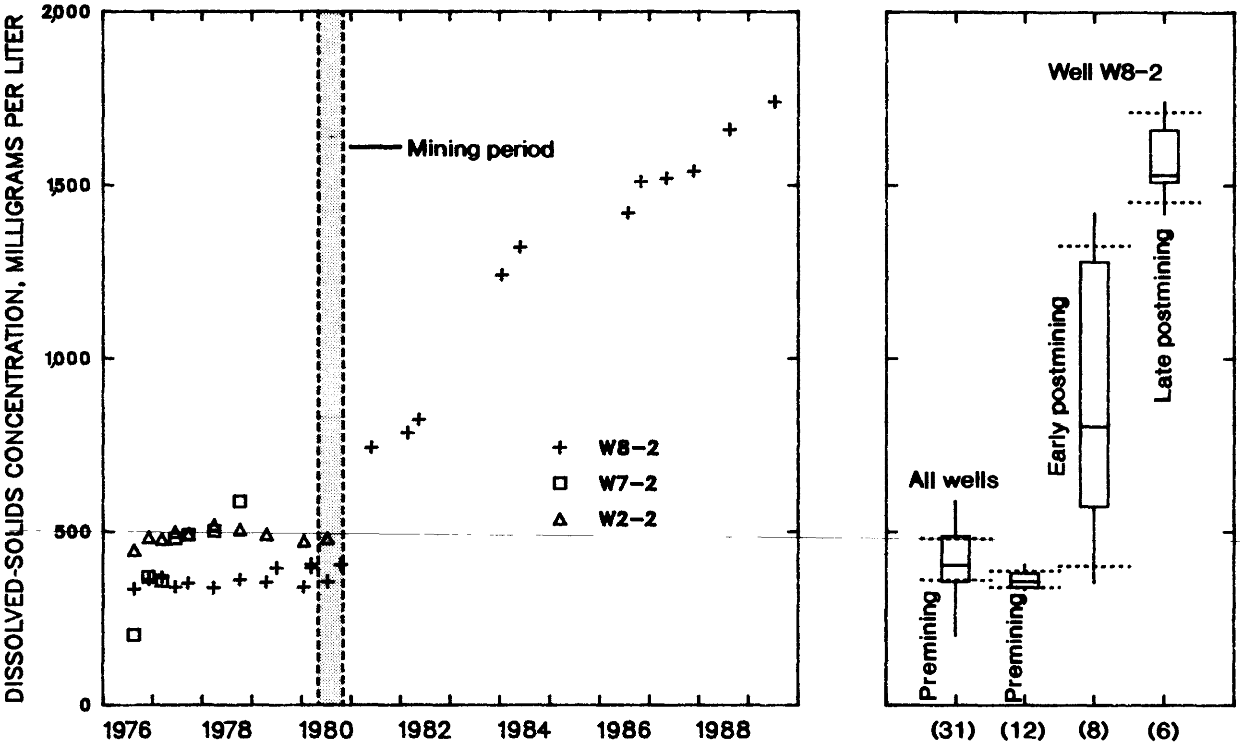


Figure 39.--Comparison of dissolved-solids concentrations of the waters from the middle aquifer in watershed J11.

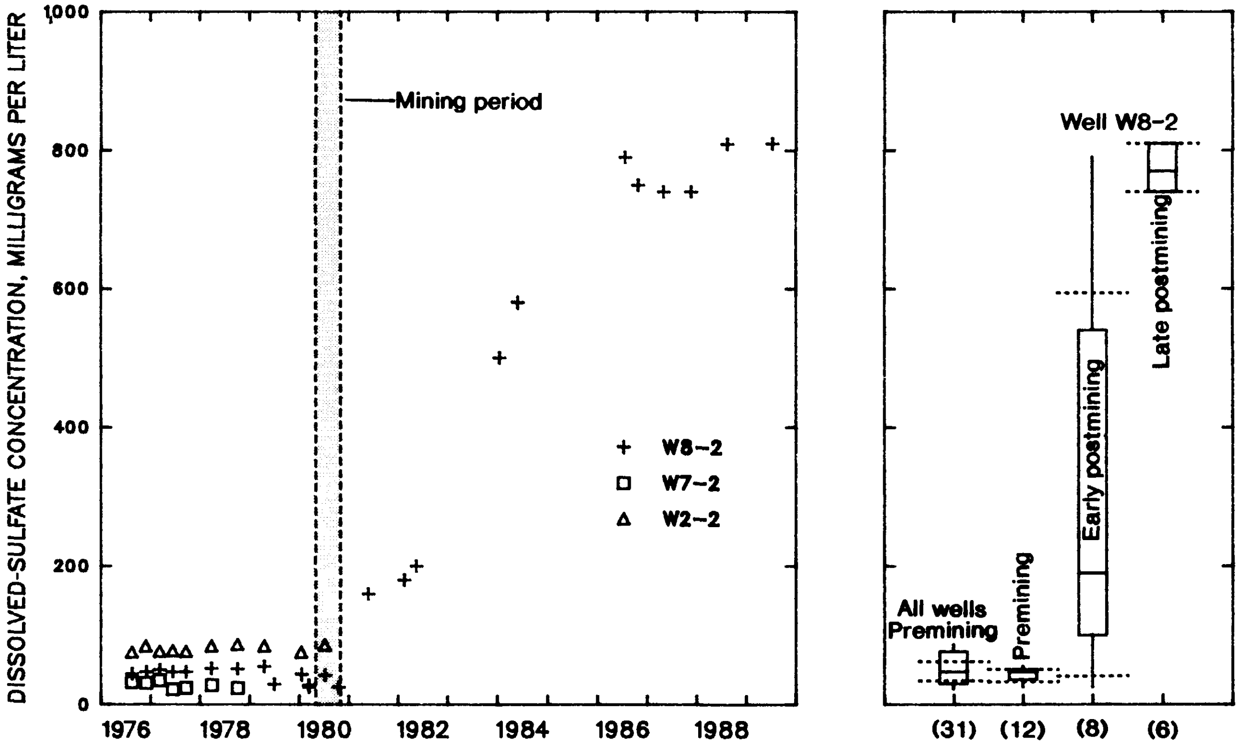


Figure 40.--Comparison of dissolved-sulfate concentrations of the waters from the middle aquifer in watershed J11.

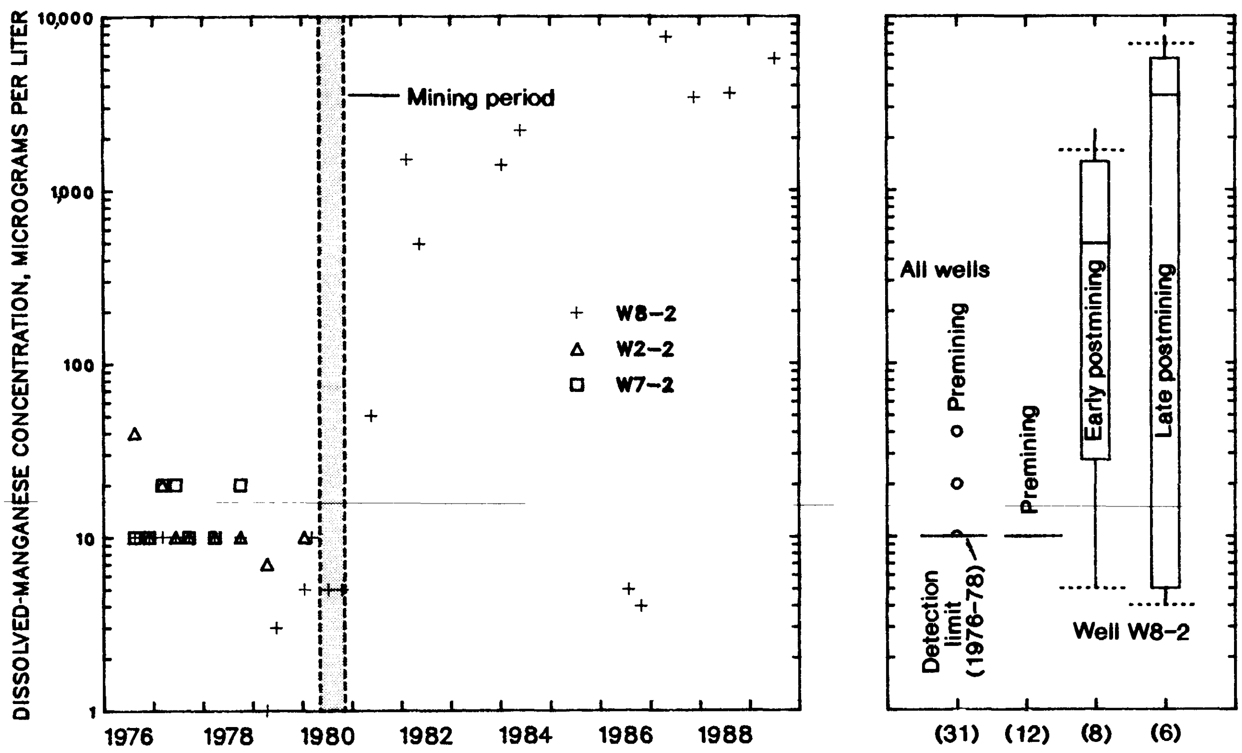


Figure 41.--Comparison of dissolved-manganese concentrations of the waters from the middle aquifer in watershed J11.

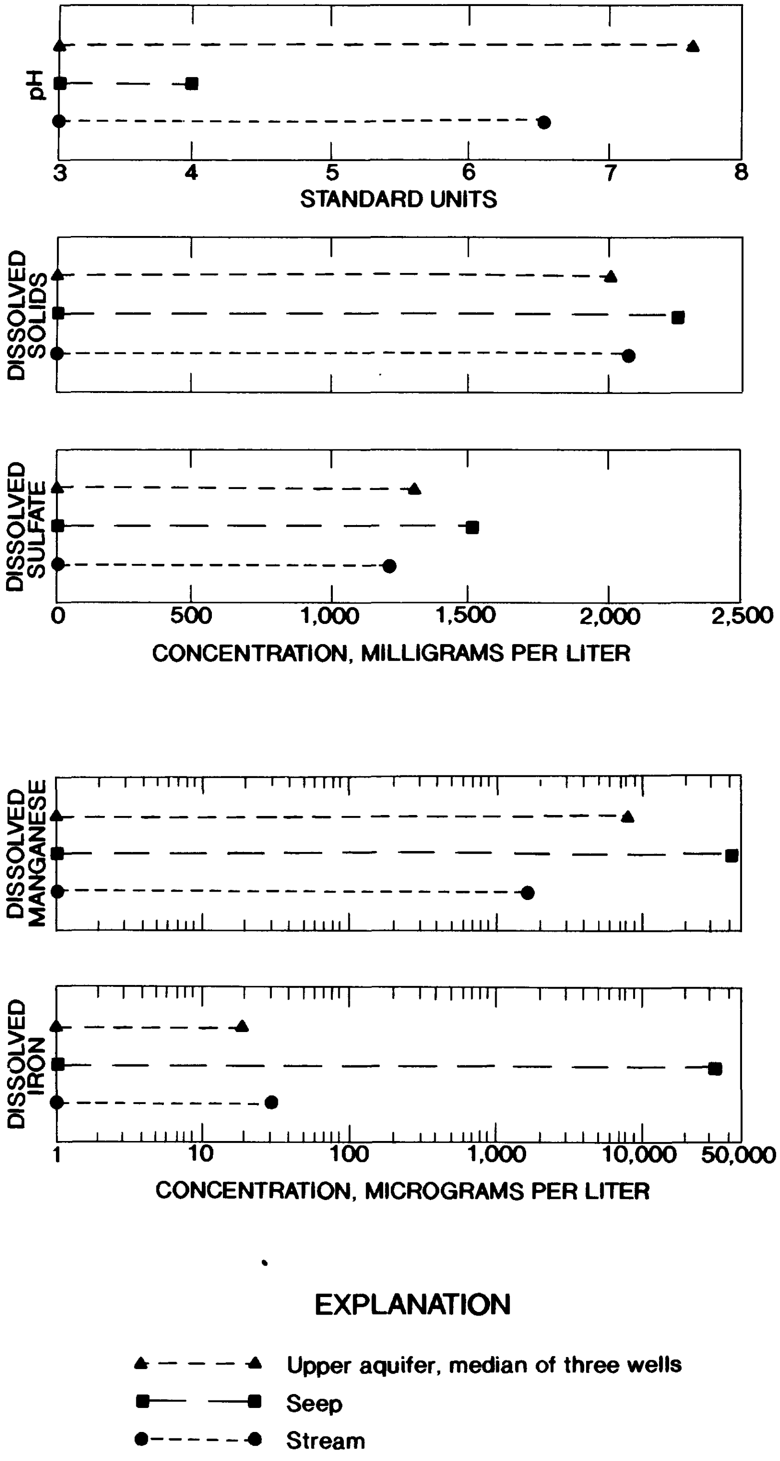


Figure 42.--Selected water quality characteristics in upper aquifer, seep, and stream, watershed J11, July 1989.

# SUMMARY AND CONCLUSIONS

Two small watersheds in eastern Ohio that were surface mined for coal and reclaimed were studied during 1986-89. Water-level and water-quality data were compared with similar data collected during previous investigations during 1976-83 to determine the long-term effects of surface mining on the hydrologic system. Before mining, the watersheds were characterized by sequences of flat-lying sedimentary rocks containing two major coal seams and underclays. An aquifer was present above each of the underclays. Surface mining removed the upper aquifer, stripped the coal seam, and replaced the spoil. This created a new upper aquifer with hydraulic and chemical characteristics that differed from those of the removed aquifer. Mining did not disturb the middle aquifer. A third, deeper aquifer in each watershed was not studied.

The upper aquifer in watershed M09 (in Muskingum County) reached hydraulic equilibrium approximately 2 1/2 years after mining. Water levels in the middle aquifer rose approximately 6 ft during mining. Equilibrium was reached at that new level before mining ended. A downward vertical gradient of 0.3 to 0.6 between the upper and middle aquifers illustrates that mixing of water from the upper aquifer with water from the middle aquifer could occur, depending on the seepage rate through the clay layer.

Recharge to the upper aquifer affected wells in watershed J11 (in Jefferson County) from 5 to 15 months after mining. The aquifer reached hydraulic equilibrium from 2 to 5 years after mining. Water levels in the middle aquifer increased at least 5 ft during mining and stabilized at that new level. In watershed J11, a downward vertical gradient of 1.2 exists between the upper and middle aquifers.

The hydraulic characteristics of the upper aquifer changed significantly after mining. Recharge rates to the aquifer decreased because of destruction of the soil structure and compaction of the soil. However, storativity and hydraulic conductivity increased in the replaced spoil material. A decrease in recharge rate combined with increased storativity and hydraulic conductivity have affected the water levels in wells in both watersheds, as shown by flattening of the hydrographs for those wells.

Responses of aquifers to recharge are shown by changes in hydrographs in wells before and after mining. Premining data for watershed MO9 was sparse, so a comparison of water levels before and after mining was difficult. However, the middle aquifer appeared to be more responsive to recharge after mining than the other aquifers, perhaps because of the partial removal of the clay confining layer and the development of fractures in the clay during mining. The response of the upper-aquifer water levels after mining in watershed J11 depended on distance from the spoil. Water-level fluctuations in wells completed within the spoils were more subdued than those in corresponding premining wells. The response of middle-aquifer water levels to recharge was not definitive, although a slightly subdued response was indicated.

The median pH in the upper aquifers of both watersheds decreased after mining and continued to decrease through the end of the study. Dissolved-solids concentrations were increasing at the end of the study. After mining, median dissolved-solids concentrations increased to at least three times the premining concentrations. Median sulfate concentrations increased by nearly an order of magnitude in watershed J11 and more than an order of magnitude in watershed MO9. The median concentrations of dissolved iron and manganese were more variable than concentrations of the above-mentioned constituents; however, median pH and concentrations of dissolved iron and manganese did increase following mining.

The median pH in the middle aquifers of both watersheds also decreased after mining and through the end of the study. Concentration trends of other constituents differed between watersheds, however. In watershed MO9, median dissolved-solid and iron concentrations changed very little after mining. Yet, median dissolved-sulfate and manganese concentrations increased to more than five times the premining median concentrations. In watershed J11, median dissolved-solid concentrations increased to more than four times the premining median concentration. Median concentrations of dissolved sulfate and manganese increased by more than one order of magnitude.

The surface water in both watersheds before mining was classified as calcium bicarbonate type. After mining, the sulfate contributed by the seeps replaced bicarbonate as the dominant anion. In both basins, the pH of the seep waters was buffered by carbonate riprap in the stream. Dissolved iron precipitated out of solution. The neutralization of pH had little effect on concentrations of dissolved solids, sulfate, and manganese.

In summary, significant increases in dissolved constituents occurred as a result of surface mining—in some areas, by more than an order of magnitude. However, changes in concentrations of some constituents appeared to have stabilized. For example, dissolved-manganese concentrations in the upper aquifer of watershed MO9 and dissolved-sulfate concentrations in the middle aquifers of both watersheds appeared to be fairly stable at the end of the study. But the continued decrease in pH indicates that the ground water had not yet reached geochemical equilibrium in either watershed more than 8 years after mining.

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Table 1. Selected records of water quality data at watershed M09.

[µS/cm indicates microseimens per centimeter at 25 degrees C. mg/L indicates dissolved milligrams per liter. µg/L indicates dissolved micrograms per liter. < indicates value below detection limit following symbol. Dashes indicate value not calculated.]

| Station Number and Local Well Number | Date | Conductance (µS/cm) | pH | Calcium (mg/L) | Magnesium (mg/L) | Sodium (mg/L) | Potassium (mg/L) | Alkalinity (mg/L as $CaCO_3$ | Acidity (mg/L as $CaCO_3$) | Sulfate (mg/L) | Chloride (mg/L) | Sum of Constituents (mg/L) | Aluminum (µg/L) | Iron (µg/L) | Manganese (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 394859081462800 | 07-29-76 | 560 | 7.7 | 71 | 42 | 4.0 | 1.5 | 349 | -- | 31 | 2.8 | 361 | -- | <10 | <10 |
| Well W1-1 | 11-19-76 | 540 | 7.7 | 62 | 48 | 5.3 | 1.8 | 341 | -- | 30 | 3.7 | 367 | -- | <10 | <10 |
| 394855081462700 | 07-28-76 | 430 | 7.8 | 58 | 17 | 5.3 | .7 | 200 | -- | 37 | 4.0 | 242 | -- | <10 | 30 |
| Well W3-1 | 11-17-76 | 460 | 7.6 | 62 | 19 | 5.2 | .6 | 221 | -- | 35 | 1.6 | 266 | -- | <10 | <10 |
| 394855081461600 | 07-29-76 | 890 | 7.8 | 81 | 59 | 15 | 2.3 | 373 | -- | 120 | 3.7 | 507 | -- | 60 | 30 |
| Well W6-1 | 11-18-76 | 800 | 7.4 | 80 | 48 | 22 | 2.7 | 371 | -- | 120 | 5.6 | 501 | -- | 60 | 20 |
| 394852081462000 | 07-27-76 | 645 | 7.6 | 73 | 33 | 28 | 1.8 | 341 | -- | 44 | 2.8 | 388 | -- | 30 | 70 |
| Well W8-1 | 11-18-76 | 840 | 7.5 | 73 | 33 | 24 | 1.9 | 328 | -- | 49 | 4.2 | 401 | -- | <10 | 80 |
| 394852081462002 | 03-03-81 | 1,100 | 7.1 | 180 | 35 | 7.3 | 3.8 | 365 | -- | 290 | 1.7 | 753 | -- | 4,000 | 820 |
| Well P8-1 | 07-24-86 | 1,520 | 6.7 | 280 | 53 | 6.2 | 2.2 | 395 | -- | 560 | 2.6 | 1,150 | <10 | 9,300 | 1,300 |
| | 11-04-86 | 1,830 | 6.7 | 370 | 64 | 8.3 | 2.2 | 510 | -- | 840 | 2.7 | 1,590 | <10 | 7 | 1,200 |
| | 05-28-87 | 1,300 | 6.8 | 330 | 55 | 6.5 | 2.2 | 404 | -- | 700 | 2.0 | 1,340 | 10 | 5 | 930 |
| | 11-18-87 | 1,450 | 6.9 | 230 | 58 | 8.2 | 3.1 | 558 | -- | 350 | 2.5 | 1,010 | <10 | 20,000 | 990 |
| | 08-08-88 | 1,500 | 6.9 | 260 | 53 | 6.5 | 2.3 | 420 | -- | 500 | 2.0 | 1,090 | 20 | 9,700 | 970 |
| | 07-12-89 | 2,400 | 6.5 | 490 | 77 | 8.4 | 2.0 | 467 | 53 | 1,100 | 1.2 | 2,060 | <10 | 30 | 2,700 |
| 394858081462801 | 10-14-80 | 5,050 | 6.9 | 450 | 740 | 150 | 12 | 619 | -- | 3,300 | 23 | 5,080 | 10 | 3,400 | 2,300 |
| Well P12-1 | 03-03-81 | 5,150 | 6.9 | 490 | 560 | 150 | 12 | 677 | -- | 3,000 | 33 | 4,680 | -- | 700 | 2,000 |
| | 04-27-83 | 4,200 | 6.7 | 560 | 500 | 85 | 11 | -- | -- | 2,800 | 9.3 | 4,310 | 200 | 1,400 | 980 |
| | 07-23-86 | 4,530 | 6.6 | 520 | 560 | 57 | 9.6 | 610 | -- | 2,900 | 5.5 | 4,420 | 20 | 1,700 | 2,100 |
| | 11-04-86 | 4,340 | 6.9 | 550 | 590 | 56 | 9.7 | 554 | -- | 3,000 | 4.6 | 4,540 | 20 | 600 | 1,500 |
| | 05-27-87 | 4,100 | 6.7 | 530 | 470 | 47 | 9.2 | 581 | -- | 2,900 | 11 | 4,320 | 10 | 1,400 | 1,900 |
| | 08-08-88 | 4,050 | 6.6 | 580 | 490 | 44 | 9.4 | 535 | -- | 2,800 | 2.2 | 4,250 | 20 | 940 | 1,700 |
| | 07-12-89 | 5,080 | 6.4 | 560 | 650 | 41 | 8.9 | 578 | 28 | 3,500 | .6 | 5,410 | <10 | 690 | 1,100 |
| 394851081462803 | 10-15-80 | 1,640 | 6.4 | 230 | 53 | 15 | 1.5 | 1070 | -- | 170 | 6.6 | 1,160 | 10 | 9,300 | 19,000 |
| Well P14-1 | 03-03-81 | 1,700 | 6.6 | 200 | 50 | 12 | 1.8 | 951 | -- | 210 | 5.3 | 1,080 | -- | 6,300 | 7,600 |
| | 07-23-86 | 1,520 | 6.7 | 240 | 61 | 18 | 1.1 | 969 | -- | 13 | 11 | 963 | <10 | 35,000 | 3,300 |
| | 10-29-86 | 1,510 | 6.7 | 230 | 58 | 13 | 1.1 | 992 | -- | 9.3 | 5.7 | 947 | 10 | 32,000 | 3,100 |
| | 05-27-87 | 1,100 | 6.8 | 250 | 58 | 13 | 1.0 | 1120 | -- | 8.5 | 11 | 1,050 | <10 | 41,000 | 3,300 |
| | 11-18-87 | 1,430 | 6.7 | 230 | 56 | 14 | 1.1 | 872 | -- | 54 | 5.1 | 915 | <10 | 29,000 | 3,000 |
| | 08-09-88 | 1,180 | 6.5 | 200 | 54 | 15 | 1.0 | 700 | -- | 100 | 4.0 | 800 | 20 | 3,900 | 2,500 |
| | 07-13-89 | 1,380 | 6.4 | 210 | 54 | 14 | .9 | 826 | -- | 45 | 3.8 | 806 | 20 | 22,000 | 2,400 |
| 394859081462801 | 07-29-76 | 710 | 7.8 | 51 | 27 | 83 | 1.9 | 379 | -- | 48 | 1.7 | 440 | -- | 30 | 60 |
| Well W2-2 | 11-19-76 | 700 | 7.8 | 76 | 39 | 25 | 1.5 | 367 | -- | 53 | 2.4 | 431 | -- | 160 | 40 |

Table 1. Selected records of water quality data at watershed M09--Continued.

| Station Number and Local Well Number | Date | Con-duct-ance (µS/cm) | pH | Cal-cium (mg/L) | Mag-nesium (mg/L) | Sod-ium (mg/L) | Potas-ium (mg/L) | Alka-linity (mg/L as $CaCO_3$ | Acid-ity (mg/L as $CaCO_3$) | Sul-fate (mg/L) | Chlo-ride (mg/L) | Sum of Consti-tuents (mg/L) | Alum-inum (µg/L) | Iron (µg/L) | Mang-anese (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 394845081462600 | 07-28-76 | 890 | 8.4 | 5.4 | 1.7 | 220 | 1.3 | 464 | -- | 32 | 8.4 | 561 | -- | 140 | <10 |
| Well W5-2 | 11-18-76 | 900 | 8.1 | 5.7 | 1.4 | 230 | 1.4 | 466 | -- | 36 | 8.3 | 572 | -- | 20 | <10 |
| 394852081462001 | 07-27-76 | 2,800 | 8.2 | 9.0 | 3.2 | 580 | 3.4 | 476 | -- | 9.0 | 600 | 1,490 | -- | 20 | <10 |
| Well W9-2 | 11-18-76 | 3,000 | 7.9 | 15 | 5.3 | 670 | 3.3 | 499 | -- | 12 | 680 | 1,690 | -- | 30 | <10 |
| 394852081462003 | 10-24-78 | 810 | 7.5 | 86 | 32 | 80 | 2.7 | 381 | -- | 120 | 6.2 | 572 | 30 | 600 | 70 |
| Well P9-2 | 01-10-79 | 855 | 7.3 | 60 | 23 | 120 | 2.4 | 376 | -- | 110 | 5.1 | 562 | 150 | 750 | 120 |
|  | 04-19-79 | 820 | 7.6 | 54 | 21 | 83 | 2.2 | 361 | -- | 92 | 3.9 | 486 | -- | 360 | 90 |
|  | 07-18-79 | 946 | 7.0 | 88 | 25 | 99 | 2.2 | 353 | -- | 170 | 8.9 | 628 | 600 | 3,200 | 400 |
|  | 10-22-79 | 765 | 7.0 | 56 | 21 | 68 | 2.2 | 310 | -- | 79 | 2.9 | 430 | 30 | 340 | 100 |
|  | 04-23-80 | 760 | 6.9 | 54 | 22 | 68 | 2.2 | 330 | -- | 82 | 3.4 | 443 | 960 | 890 | 120 |
|  | 10-27-80 | 813 | 7.0 | 50 | 20 | 97 | 2.5 | 348 | -- | 110 | 4.7 | 507 | -- | 20 | 40 |
|  | 07-24-86 | 800 | 7.4 | 62 | 25 | 88 | 2.3 | 463 | -- | 130 | 2.8 | 588 | <10 | 16 | 74 |
|  | 11-04-86 | 919 | 7.4 | 55 | 22 | 140 | 2.2 | 347 | -- | 160 | 5.3 | 593 | 30 | 9 | 75 |
|  | 05-28-87 | 905 | 7.5 | 55 | 21 | 120 | 2.4 | 363 | -- | 130 | 2.6 | 549 | <10 | 23 | 96 |
|  | 11-18-87 | 1,000 | 6.9 | 54 | 21 | 140 | 2.4 | 364 | -- | 170 | 6.0 | 612 | <10 | 10 | 80 |
|  | 08-09-88 | 840 | 7.4 | 55 | 24 | 100 | 2.2 | 330 | -- | 150 | 3.4 | 533 | 20 | 15 | 71 |
|  | 07-13-89 | 810 | 7.4 | 44 | 19 | 120 | 2.0 | 305 | -- | 160 | 1.9 | 519 | <10 | 21 | 52 |
| 394853081462800 | 07-28-76 | 645 | 8.9 | 13 | 4.8 | 130 | 1.5 | 336 | -- | 21 | 12 | 406 | -- | 20 | 20 |
| Well W11-2 | 11-17-76 | 620 | 7.3 | 35 | 12 | 100 | 1.9 | 354 | -- | 18 | 1.9 | 395 | -- | 470 | 100 |

Table 2. Selected records of water quality data at watershed J11.

[µS/cm indicates microseimens per centimeter at 25 degrees C. mg/L indicates dissolved milligrams per liter. µg/L indicates dissolved micrograms per liter. < indicates value below detection limit following symbol. Dashes indicate value not calculated.]

| Station Number and Local Well Number | Date | Conductance (µS/cm) | pH | Calcium (mg/L) | Magnesium (mg/L) | Sodium (mg/L) | Potassium (mg/L) | Alkalinity (mg/L as $CaCO_3$ | Acidity (mg/L as $CaCO_3$) | Sulfate (mg/L) | Chloride (mg/L) | Sum of Constituents (mg/L) | Aluminum (µg/L) | Iron (µg/L) | Manganese (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 401011080521600<br>Well W1-1 | 08-17-76 | 830 | 7.6 | 110 | 31 | 5.8 | 1.7 | 316 | -- | 28 | 12 | 378 | -- | <10 | 20 |
| | 12-02-76 | 720 | 7.3 | 110 | 31 | 5.7 | 1.8 | 339 | -- | 28 | 11 | 401 | -- | 40 | <10 |
| | 03-09-77 | 725 | 7.3 | 110 | 30 | 6.3 | 1.7 | 329 | -- | 29 | 12 | 398 | -- | 30 | <10 |
| | 06-14-77 | 730 | 7.3 | 110 | 29 | 5.6 | 1.6 | 339 | -- | 24 | 11 | 395 | -- | <10 | <10 |
| | 09-20-77 | 740 | 7.3 | 120 | 31 | 6.0 | 1.7 | 346 | -- | 28 | 10 | 415 | -- | <10 | <10 |
| | 03-29-78 | 750 | 7.3 | 99 | 27 | 12 | 1.7 | 332 | -- | 40 | 11 | 444 | -- | 60 | 1,400 |
| | 10-04-78 | 760 | 7.2 | 120 | 31 | 6.7 | 1.6 | 344 | -- | 32 | 12 | 470 | 20 | <10 | <10 |
| | 04-17-79 | 810 | 7.5 | 110 | 27 | 5.4 | 1.3 | 340 | -- | 38 | 13 | 458 | 20 | 50 | 3 |
| | 01-16-80 | 730 | 6.5 | 120 | 28 | 5.7 | 1.3 | 320 | -- | 38 | 11 | 451 | 0 | 10 | 3 |
| | 07-08-80 | 770 | 7.0 | 110 | 27 | 5.4 | 1.4 | 340 | -- | 33 | 9.5 | 446 | 20 | 20 | 20 |
| 401011080521602<br>Well P1-1 | 05-27-81 | 1,310 | 6.9 | 180 | 57 | 32 | - | 349 | -- | -- | 80 | -- | -- | -- | 670 |
| | 02-17-82 | 1,210 | 6.8 | 160 | 49 | 30 | 3.4 | 394 | -- | 230 | 73 | 800 | -- | 11 | 810 |
| | 05-19-82 | 1,500 | 7.0 | 210 | 61 | 31 | 3.6 | 328 | -- | 460 | 92 | 1,070 | -- | 200 | 330 |
| | 08-03-82 | 1,400 | 7.0 | 210 | 57 | 28 | 3.4 | 353 | -- | 430 | 87 | 1,040 | -- | 67 | 410 |
| | 01-17-84 | 1,500 | 6.8 | 230 | 63 | 30 | 3.4 | 308 | -- | 530 | 70 | 1,130 | 40 | 59 | 850 |
| | 05-31-84 | 1,760 | 6.8 | 260 | 74 | 29 | 3.5 | 298 | -- | 700 | 68 | 1,330 | <100 | 46 | 2,000 |
| | 07-30-86 | 1,950 | 6.8 | 330 | 85 | 32 | 3.9 | 291 | -- | 850 | 69 | 1,540 | 20 | 35 | 4 |
| | 10-28-86 | 2,120 | 6.8 | 350 | 94 | 30 | 3.6 | 305 | -- | 980 | 58 | 1,700 | <10 | 20 | 6,200 |
| | 05-05-87 | 1,700 | 6.8 | 310 | 80 | 32 | 3.7 | 260 | -- | 800 | 68 | 1,450 | <10 | 29 | 4,200 |
| | 11-23-87 | 2,200 | 6.7 | 360 | 96 | 32 | 3.9 | 330 | -- | 1,000 | 55 | 1,750 | <10 | 90 | 6,600 |
| | 08-16-88 | 2,000 | 6.8 | 330 | 89 | 32 | 3.5 | 300 | -- | 890 | 67 | 1,600 | 10 | 200 | 5,500 |
| | 07-11-89 | 2,520 | 6.4 | 420 | 120 | 30 | 3.6 | 242 | 95 | 1,300 | 58 | 2,220 | <10 | 30 | 10,000 |
| 401010080521800<br>Well W3-1 | 08-17-76 | 520 | 6.6 | 57 | 16 | 13 | 1.9 | 41 | -- | 190 | 11 | 314 | -- | 40 | 120 |
| | 12-02-76 | 405 | 6.7 | 48 | 13 | 9.1 | 1.5 | 67 | -- | 110 | 14 | 251 | -- | 120 | 60 |
| | 03-09-77 | 415 | 5.9 | 49 | 14 | 8.0 | 1.8 | 23 | -- | 140 | 14 | 260 | -- | 170 | 250 |
| | 03-29-78 | 535 | 6.7 | 49 | 15 | 7.9 | 3.2 | 126 | -- | 120 | 14 | 329 | -- | 17,000 | 330 |
| | 04-17-79 | 465 | 6.8 | 42 | 12 | 8.2 | 3.0 | 143 | -- | 63 | 11 | 258 | 20 | 5,000 | 240 |
| | 01-16-80 | 360 | 5.8 | 39 | 10 | 6.6 | 2.1 | 56 | -- | 100 | 9.0 | 222 | 100 | 4,200 | 180 |
| 401010080521801<br>Well P3-1 | 05-04-87 | 2,180 | 6.8 | 330 | 110 | 23 | 4.4 | 377 | -- | 930 | 49 | 1,670 | 20 | 80 | 450 |
| | 07-10-89 | 2,470 | 6.5 | 410 | 130 | 25 | 4.0 | 320 | 160 | 1,200 | 53 | 2,080 | 20 | 140 | 570 |
| 401002080521800<br>Well W4-1 | 08-17-76 | 550 | 7.4 | 80 | 16 | 11 | 1.5 | 171 | -- | 83 | 21 | 315 | -- | <10 | 40 |
| | 12-01-76 | 530 | 7.1 | 77 | 17 | 10 | 1.5 | 180 | -- | 89 | 18 | 334 | -- | 60 | <10 |
| | 03-08-77 | 525 | 6.8 | 81 | 16 | 12 | 1.6 | 157 | -- | 78 | 33 | 331 | -- | <10 | <10 |
| | 09-20-77 | 560 | 7.0 | 80 | 16 | 10 | 1.7 | 176 | -- | 84 | 17 | 329 | -- | 80 | 70 |
| | 03-28-78 | 525 | 7.0 | 68 | 13 | 11 | 1.4 | 118 | -- | 68 | 43 | 308 | -- | 90 | <10 |
| | 10-04-78 | 600 | 7.2 | 88 | 17 | 11 | 2.4 | 181 | -- | 100 | 26 | 369 | 10 | 740 | <10 |
| | 04-17-79 | 622 | 7.6 | 84 | 15 | 11 | 1.3 | 148 | -- | 65 | 48 | 338 | 20 | <10 | 3 |
| | 01-15-80 | 675 | 6.6 | 85 | 15 | 12 | 1.3 | 170 | -- | 67 | 38 | 348 | 10 | 20 | 4 |
| | 07-09-80 | 550 | 6.7 | 90 | 16 | 9.4 | 1.6 | 220 | -- | 79 | 15 | 357 | 10 | 70 | 30 |
| | 10-17-80 | 644 | 6.7 | 84 | 16 | 13 | 1.5 | 156 | -- | 98 | 41 | 362 | 20 | 730 | 70 |

Table 2. Selected records of water quality data at watershed J11--Continued.

| Station Number and Local Well Number | Date | Conductance (µS/cm) | pH | Calcium (mg/L) | Magnesium (mg/L) | Sodium (mg/L) | Potassium (mg/L) | Alkalinity (mg/L as $CaCO_3$ | Acidity (mg/L as $CaCO_3$) | Sulfate (mg/L) | Chloride (mg/L) | Sum of Constituents (mg/L) | Aluminum (µg/L) | Iron (µg/L) | Manganese (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 401004080521900<br>Well W6-1 | 08-17-76 | 480 | 7.7 | 69 | 9.3 | 7.7 | 1.6 | 69 | -- | 130 | 26 | 286 | -- | 30 | 690 |
| | 12-02-76 | 555 | 7.2 | 81 | 12 | 8.7 | 2.1 | 101 | -- | 100 | 55 | 337 | -- | 40 | 190 |
| | 03-09-77 | 595 | 6.9 | 90 | 16 | 8.5 | 2.2 | 84 | -- | 190 | 21 | 398 | -- | 30 | 720 |
| | 06-14-77 | 435 | 7.2 | 59 | 11 | 6.6 | 1.6 | 69 | -- | 120 | 9.5 | 267 | -- | <10 | 30 |
| | 09-20-77 | 450 | 7.3 | 65 | 9.3 | 7.8 | 1.6 | 105 | -- | 85 | 15 | 266 | -- | <10 | <10 |
| | 03-28-78 | 520 | 6.8 | 73 | 15 | 6.7 | 1.6 | 56 | -- | 170 | 9.8 | 330 | -- | <10 | 70 |
| | 10-04-78 | 475 | 7.5 | 68 | 11 | 9.4 | 1.6 | 98 | -- | 120 | 18 | 303 | 30 | <10 | 30 |
| | 04-17-79 | 320 | 6.8 | 40 | 12 | 6.0 | 1.2 | 16 | -- | 120 | 7.5 | 223 | 30 | 20 | 40 |
| | 01-16-80 | 335 | 6.9 | 54 | 9.1 | 6.0 | 1.0 | 46 | -- | 100 | 10 | 231 | 0 | 30 | 170 |
| | 07-09-80 | 357 | 6.7 | 47 | 9.5 | 6.2 | 1.2 | 54 | -- | 99 | 9.9 | 226 | 10 | 60 | 30 |
| | 10-17-80 | 650 | 6.7 | 89 | 14 | 9.1 | 1.8 | 84 | -- | 200 | 19 | 405 | 10 | 410 | 500 |
| 401009080521500<br>Well P10-1 | 05-18-82 | 1,050 | 6.8 | 140 | 34 | 16 | 2.9 | 262 | -- | 260 | 42 | 669 | -- | 26 | 400 |
| | 08-03-82 | 1,150 | 6.9 | 180 | 43 | 20 | 2.5 | 336 | -- | 300 | 53 | 813 | -- | 32 | 380 |
| | 01-17-84 | 1,100 | 6.7 | 170 | 45 | 20 | 2.7 | 270 | -- | 330 | 46 | 788 | 10 | 99 | 600 |
| | 05-31-84 | 1,170 | 7.0 | 160 | 46 | 18 | 2.7 | 274 | -- | 360 | 42 | 806 | <100 | 48 | 590 |
| | 07-29-86 | 1,310 | 6.6 | 230 | 58 | 20 | 2.9 | 254 | -- | 480 | 38 | 982 | 20 | 32 | 870 |
| | 10-28-86 | 1,460 | 6.7 | 240 | 63 | 21 | 2.7 | 255 | -- | 540 | 44 | 1,060 | <10 | 14 | 920 |
| | 05-05-87 | 1,300 | 6.7 | 210 | 53 | 18 | 2.7 | 243 | -- | 480 | 33 | 943 | 30 | 10 | 740 |
| | 11-24-87 | 1,300 | 6.6 | 220 | 55 | 18 | 2.8 | 285 | -- | 500 | 31 | 999 | <10 | 39 | 930 |
| | 08-15-88 | 1,400 | 6.7 | 230 | 64 | 21 | 2.7 | 280 | -- | 600 | 35 | 1,120 | <10 | 20 | 1,100 |
| | 07-10-89 | 1,620 | 6.5 | 250 | 68 | 21 | 2.9 | 235 | -- | 690 | 34 | 1,270 | <10 | 18 | 1,600 |
| 401011080521601<br>Well W2-2 | 08-16-76 | 760 | 8.2 | 73 | 25 | 62 | 2.5 | 317 | -- | 76 | 21 | 450 | -- | <10 | 40 |
| | 12-02-76 | 760 | 7.2 | 93 | 32 | 29 | 2.4 | 335 | -- | 85 | 25 | 484 | -- | 40 | <10 |
| | 03-09-77 | 750 | 7.2 | 99 | 33 | 27 | 2.4 | 328 | -- | 77 | 25 | 478 | -- | <10 | 20 |
| | 06-14-77 | 817 | 7.2 | 78 | 28 | 65 | 2.5 | 346 | -- | 78 | 23 | 498 | -- | <10 | <10 |
| | 09-20-77 | 805 | 7.1 | 100 | 33 | 33 | 2.4 | 343 | -- | 77 | 24 | 493 | -- | <10 | <10 |
| | 03-29-78 | 825 | 7.2 | 68 | 25 | 85 | 2.7 | 350 | -- | 85 | 25 | 519 | -- | <10 | <10 |
| | 10-04-78 | 890 | 7.1 | 98 | 34 | 33 | 2.4 | 344 | -- | 87 | 25 | 506 | 10 | 20 | <10 |
| | 04-17-79 | 840 | 7.2 | 93 | 31 | 28 | 2.3 | 346 | -- | 85 | 26 | 491 | 20 | <10 | 7 |
| | 01-16-80 | 750 | 6.8 | 89 | 31 | 34 | 2.2 | 330 | -- | 76 | 24 | 473 | 10 | 50 | 10 |
| | 07-08-80 | 830 | 6.8 | 89 | 28 | 37 | 2.4 | 330 | -- | 86 | 23 | 480 | 30 | 10 | 8 |
| 401004080521901<br>Well W7-2 | 08-17-76 | 600 | 8.0 | 39 | 15 | 74 | 2.0 | 279 | -- | 32 | 8.8 | 339 | -- | 60 | <10 |
| | 12-01-76 | 595 | 7.6 | 36 | 14 | 84 | 1.8 | 295 | -- | 31 | 9.9 | 369 | -- | 80 | <10 |
| | 03-09-77 | 575 | 7.5 | 47 | 18 | 60 | 2.2 | 281 | -- | 35 | 11 | 358 | -- | 30 | 20 |
| | 06-14-77 | 790 | 7.8 | 15 | 5.8 | 170 | 1.4 | 386 | -- | 22 | 22 | 480 | -- | 60 | 20 |
| | 09-20-77 | 810 | 7.8 | 16 | 6.0 | 170 | 1.5 | 385 | -- | 24 | 29 | 491 | -- | <10 | <10 |
| | 03-29-78 | 810 | 7.9 | 17 | 6.2 | 170 | 1.5 | 385 | -- | 28 | 33 | 501 | -- | 160 | <10 |
| | 10-04-78 | 910 | 8.0 | 13 | 5.5 | 230 | 1.2 | 417 | -- | 24 | 49 | 587 | 30 | 290 | 20 |

Table 2. Selected records of water quality data at watershed J11--Continued.

| Station Number and Local Well Number | Date | Conductance (μS/cm) | pH | Calcium (mg/L) | Magnesium (mg/L) | Sodium (mg/L) | Potassium (mg/L) | Alkalinity (mg/L as $CaCO_3$ | Acidity (mg/L as $CaCO_3$) | Sulfate (mg/L) | Chloride (mg/L) | Sum of Constituents (mg/L) | Aluminum (μg/L) | Iron (μg/L) | Manganese (μg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 401007080522400<br>Well W8-2 | 08-17-76 | 600 | 7.9 | 57 | 23 | 39 | 2.0 | 262 | -- | 44 | 10 | 333 | -- | <10 | <10 |
| | 12-02-76 | 570 | 7.6 | 46 | 20 | 58 | 2.2 | 274 | -- | 47 | 12 | 361 | -- | 30 | <10 |
| | 03-09-77 | 590 | 7.5 | 34 | 15 | 85 | 2.2 | 264 | -- | 50 | 11 | 367 | -- | <10 | <10 |
| | 06-14-77 | 580 | 7.4 | 61 | 23 | 33 | 1.9 | 254 | -- | 47 | 10 | 340 | -- | <10 | <10 |
| | 09-20-77 | 605 | 7.3 | 61 | 24 | 33 | 2.0 | 264 | -- | 47 | 14 | 351 | -- | <10 | <10 |
| | 03-28-78 | 590 | 7.6 | 55 | 22 | 32 | 2.1 | 254 | -- | 52 | 9.3 | 337 | -- | 40 | <10 |
| | 10-04-78 | 580 | 7.5 | 68 | 26 | 27 | 1.7 | 267 | -- | 51 | 12 | 360 | 30 | <10 | <10 |
| | 04-17-79 | 625 | 7.6 | 74 | 25 | 11 | 1.7 | 272 | -- | 55 | 9.3 | 353 | 30 | <10 | 1 |
| | 06-28-79 | 680 | 7.6 | 32 | 13 | 99 | 1.8 | 328 | -- | 29 | 12 | 395 | -- | <10 | 3 |
| | 01-16-80 | 580 | 6.9 | 71 | 26 | 16 | 1.6 | 270 | -- | 43 | 10 | 340 | 0 | 0 | 5 |
| | 03-12-80 | 680 | 7.5 | 34 | 13 | 110 | 1.5 | 330 | -- | 25 | 12 | 405 | 20 | 10 | 10 |
| | 07-09-80 | 475 | 7.1 | 68 | 23 | 26 | 1.6 | 290 | -- | 42 | 11 | 355 | 10 | 10 | 5 |
| | 10-17-80 | 702 | 7.8 | 29 | 11 | 110 | 1.8 | 339 | -- | 25 | 12 | 404 | 20 | 20 | 5 |
| | 05-28-81 | 1,090 | 7.1 | 160 | 52 | 14 | 2.2 | 540 | -- | 160 | 15 | 743 | -- | <10 | 50 |
| | 02-18-82 | 1,230 | 6.9 | 170 | 56 | 11 | 2.2 | 558 | -- | 180 | 12 | 785 | -- | 11 | 1,500 |
| | 05-18-82 | 1,250 | 7.1 | 180 | 56 | 14 | 2.2 | 591 | -- | 200 | 2.4 | 823 | -- | 16 | 490 |
| | 01-16-84 | 1,750 | 7.0 | 250 | 79 | 37 | 2.7 | 560 | -- | 500 | 18 | 1,240 | 10 | 4 | 1,400 |
| | 05-30-84 | 1,780 | 6.8 | 250 | 83 | 33 | 2.8 | 553 | -- | 580 | 19 | 1,320 | 100 | 33 | 1,200 |
| | 07-29-86 | 1,980 | 6.6 | 340 | 93 | 17 | 3.0 | 237 | -- | 790 | 32 | 1,420 | 30 | 34 | 5 |
| | 10-28-86 | 1,920 | 6.8 | 330 | 94 | 17 | 2.5 | 470 | -- | 750 | 31 | 1,510 | <10 | 9 | 4 |
| | 05-05-87 | 2,000 | 6.6 | 330 | 91 | 15 | 2.7 | 493 | -- | 740 | 33 | 1,520 | <10 | 150 | 7,600 |
| | 11-24-87 | 2,100 | 6.8 | 340 | 91 | 17 | 3.1 | 522 | -- | 740 | 30 | 1,540 | <10 | 20 | 3,400 |
| | 08-15-88 | 2,000 | 6.6 | 410 | 88 | 20 | 2.4 | 490 | -- | 810 | 31 | 1,660 | <10 | 30 | 3,600 |
| | 07-11-89 | 2,100 | 6.5 | 370 | 97 | 17 | 2.9 | 478 | 90 | 810 | 30 | 1,740 | <10 | 40 | 5,700 |

Table 3. Surface water quality data for watersheds J11 and M09.

[μS/cm indicates microseimens per centimeter at 25 degrees C. mg/L indicates dissolved milligrams per liter. μg/L indicates dissolved micrograms per liter. < indicates value below detection limit following symbol. Dashes indicate value not calculated.]

| Station Number and Local Site Name | Date | Con-duct-ance (μS/cm) | pH | Cal-cium (mg/L) | Mag-nesium (mg/L) | Sod-ium (mg/L) | Potas-ium (mg/L) | Alka-linity (mg/L as $CaCO_3$ | Acid-ity (mg/L as $CaCO_3$) | Sul-fate (mg/L) | Chlo-ride (mg/L) | Sum of Consti-tuents (mg/L) | Alum-inum (μg/L) | Iron (μg/L) | Mang-anese (μg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 394839081463000 | 07-23-86 | 2,000 | 8.1 | 350 | 140 | 20 | 2.4 | 206 | -- | 1,200 | 2.2 | 1,840 | <10 | 30 | 1,900 |
| M09 STREAM | 10-29-86 | 2,200 | 7.8 | 350 | 150 | 15 | 2.1 | 225 | -- | 1,300 | 3.0 | 1,960 | 10 | <10 | 1,800 |
| | 05-28-87 | 1,850 | 7.8 | 370 | 140 | 14 | 1.6 | 243 | -- | 1,200 | 11 | 1,880 | 10 | 20 | 580 |
| | 11-18-87 | 2,380 | 7.5 | 350 | 140 | 14 | 3.2 | 238 | -- | 1,400 | 12 | 2,060 | <10 | 40 | 320 |
| | 08-09-88 | 2,150 | 7.7 | 420 | 180 | 15 | 2.0 | 245 | -- | 1,500 | 2.5 | 2,270 | 20 | 30 | 2,400 |
| | 07-13-89 | 2,720 | 7.8 | 470 | 190 | 10 | 1.7 | 257 | -- | 1,700 | 1.0 | 2,650 | <10 | 50 | 480 |
| 394846081463100 | 07-24-86 | 3,000 | 7.7 | 560 | 230 | 20 | 1.9 | 368 | -- | 1,800 | 2.7 | 2,840 | <10 | 50 | 2,700 |
| M09 SEEP | 10-29-86 | -- | 7.6 | 630 | 270 | 19 | 3.1 | 374 | -- | 2,000 | 3.5 | 3,150 | <10 | 20 | 2,100 |
| | 11-17-87 | 3,250 | 7.5 | 530 | 210 | 16 | 3.4 | 437 | -- | 2,000 | 4.3 | 3,030 | <10 | 120 | 1,900 |
| | 08-09-88 | 2,900 | 7.5 | 490 | 240 | 15 | 1.8 | 360 | -- | 1,900 | 1.7 | 2,860 | 20 | 30 | 460 |
| | 07-13-89 | 3,360 | 6.6 | 640 | 250 | 14 | 2.7 | 459 | -- | 2,200 | 1.1 | 3,420 | 20 | 1000 | 5,500 |
| 401008080522900 | 05-04-87 | 1,400 | 8.2 | 210 | 68 | 13 | 3.4 | 137 | -- | 680 | 23 | 1,080 | 30 | 11 | 6 |
| J11 STREAM | 07-11-89 | 2,270 | 7.6 | 360 | 130 | 24 | 3.7 | 156 | -- | 1300 | 43 | 2,010 | 10 | 20 | 8,100 |
| 401007080522000 | 05-31-84 | 2,390 | 4.8 | 240 | 130 | 17 | 7.3 | 0 | -- | 1500 | 34 | 2,090 | 7,200 | 3,000 | 63,000 |
| J11 SEEP | 05-04-87 | 2,200 | 3.8 | -- | -- | -- | -- | 0 | -- | -- | -- | -- | -- | -- | -- |
| | 07-11-89 | 2,400 | 4.0 | 330 | 140 | 21 | 5.5 | 0 | 160 | 1500 | 37 | 2,260 | 1,400 | 2,000 | 41,000 |

# Supplemental Data

## Explanation for the following time-series plots

### M09 UPPER AQUIFER

△ Well P8-1/W8-1

+ Well P12-1

□ Well P14-1

### M09 MIDDLE AQUIFER

× Well P9-2/W9-2

### J11 UPPER AQUIFER

△ Well P1-1/W1-1

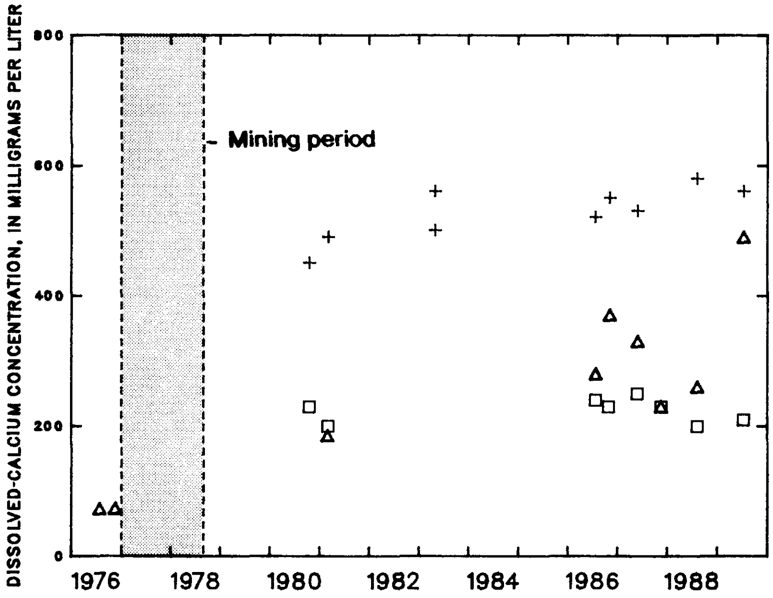
+ Well P3-1/W3-1

□ Well P10/1

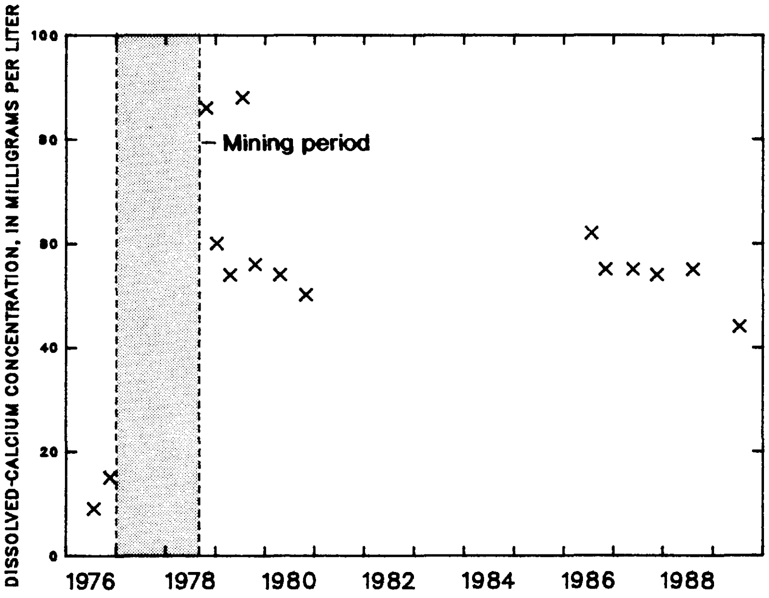
### J11 MIDDLE AQUIFER

+ Well W8-2

M09 UPPER AQUIFER



M09 MIDDLE AQUIFER



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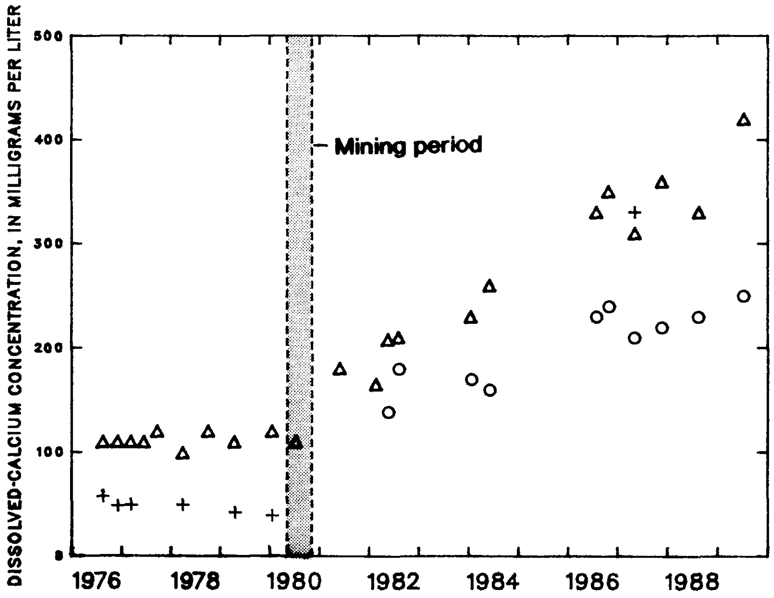

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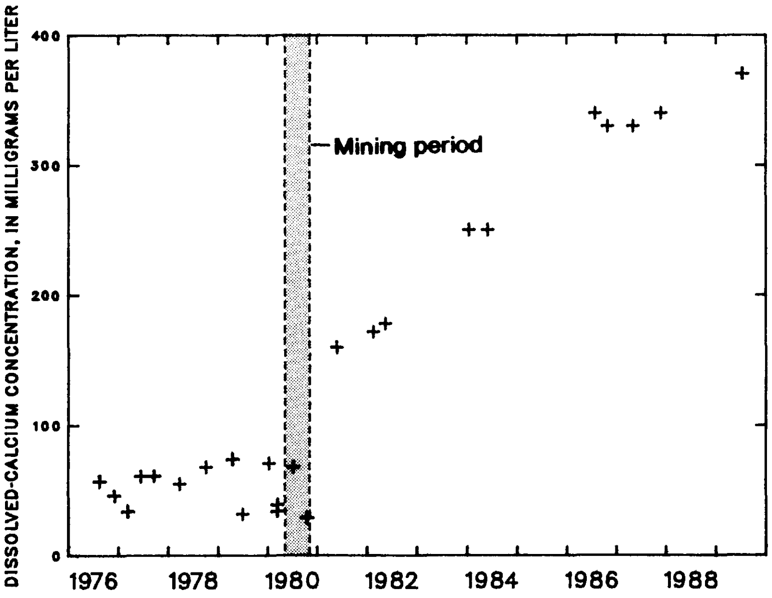

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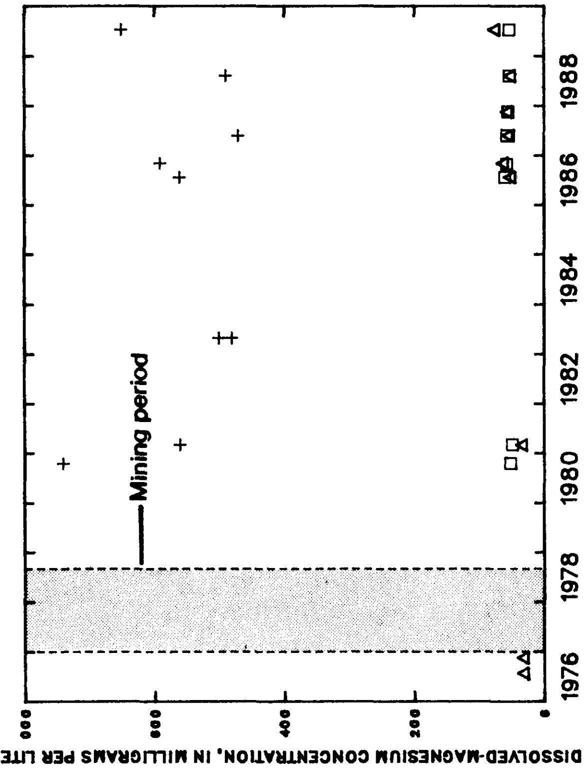

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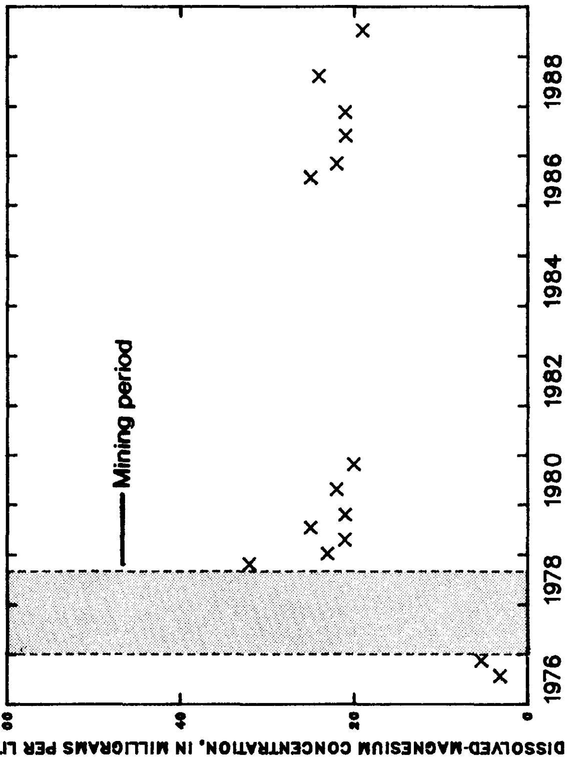

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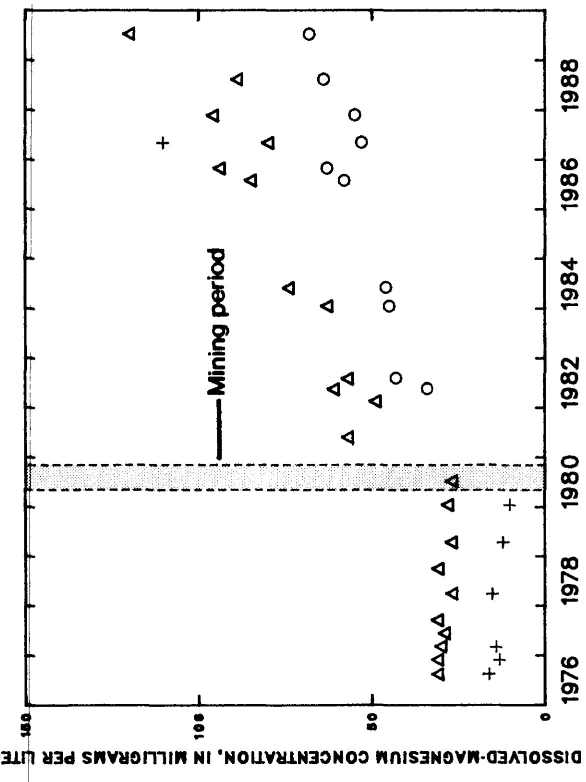

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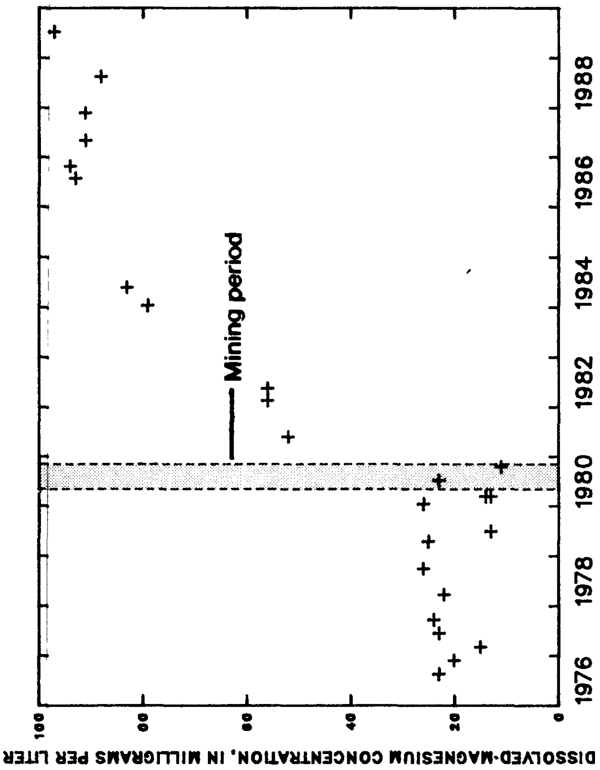

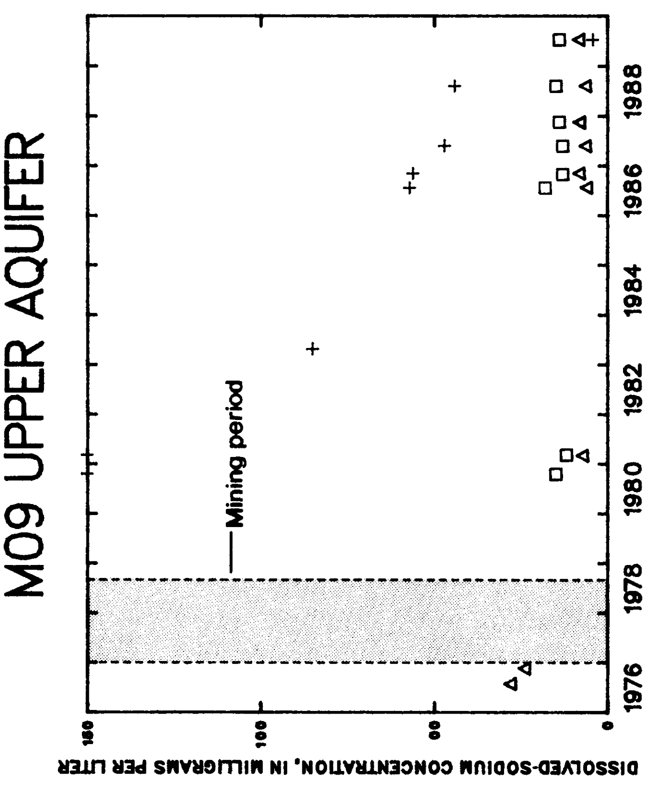
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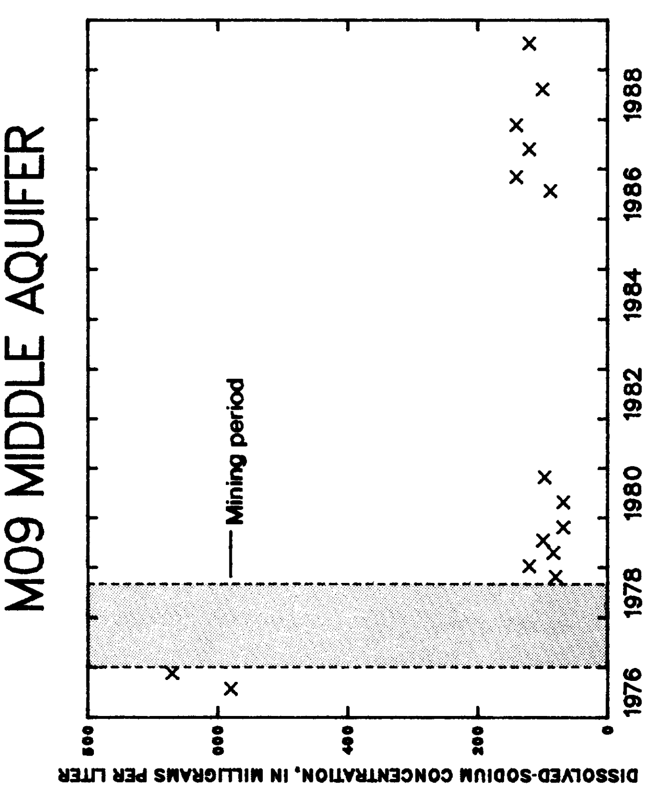
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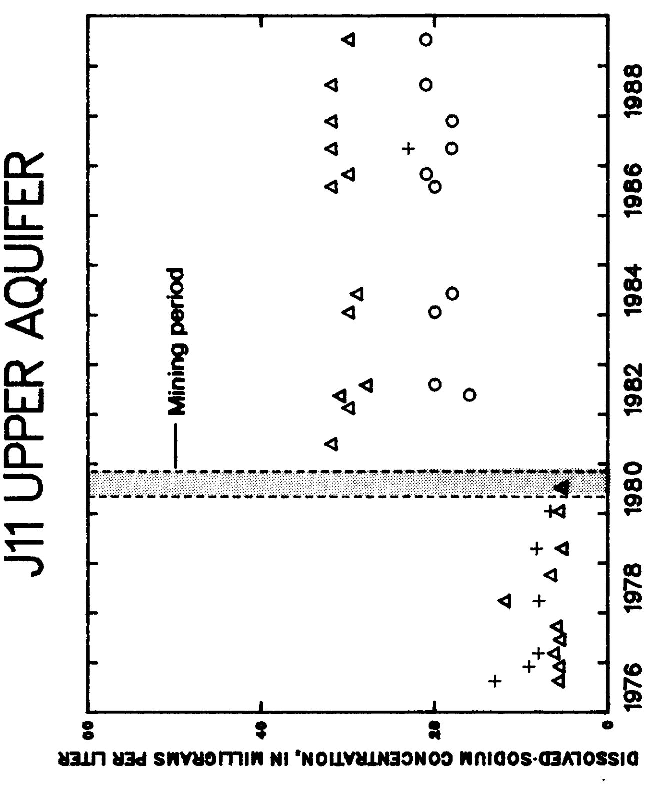
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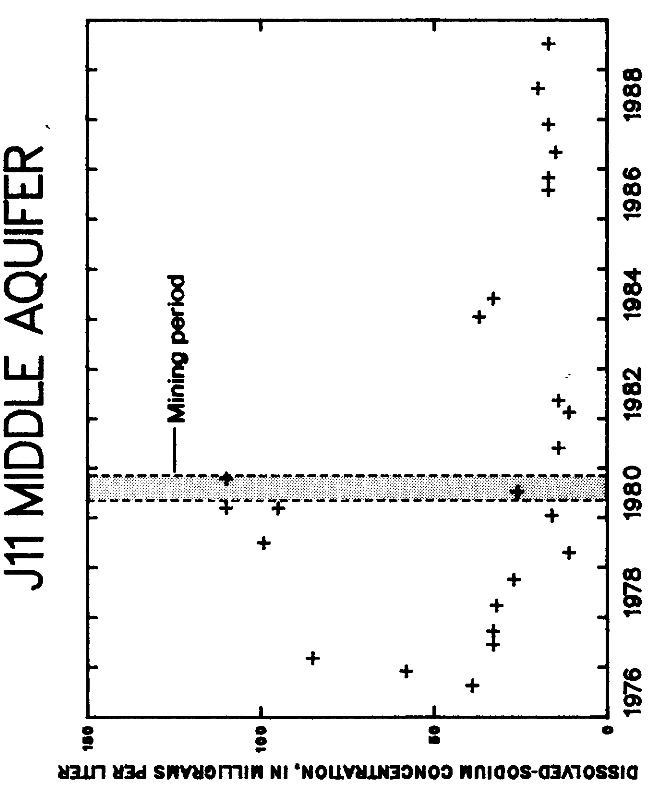
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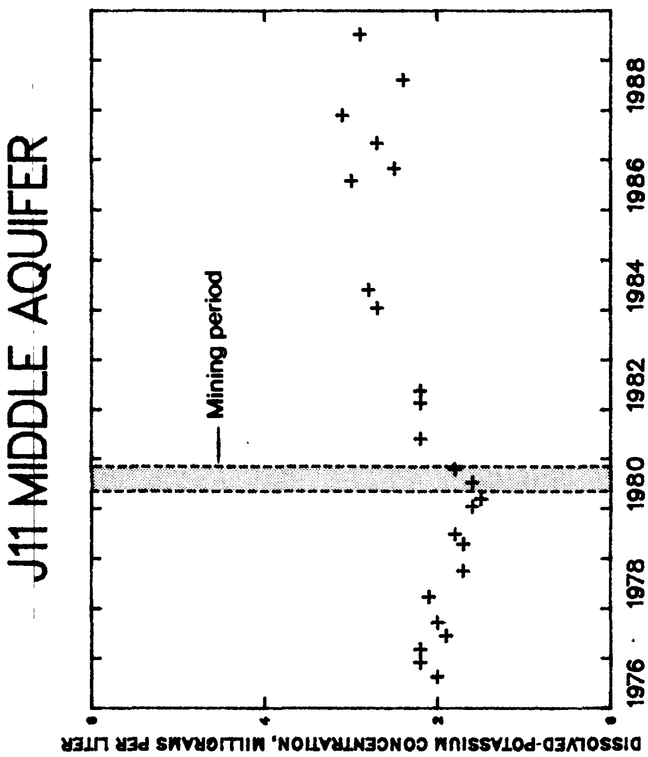
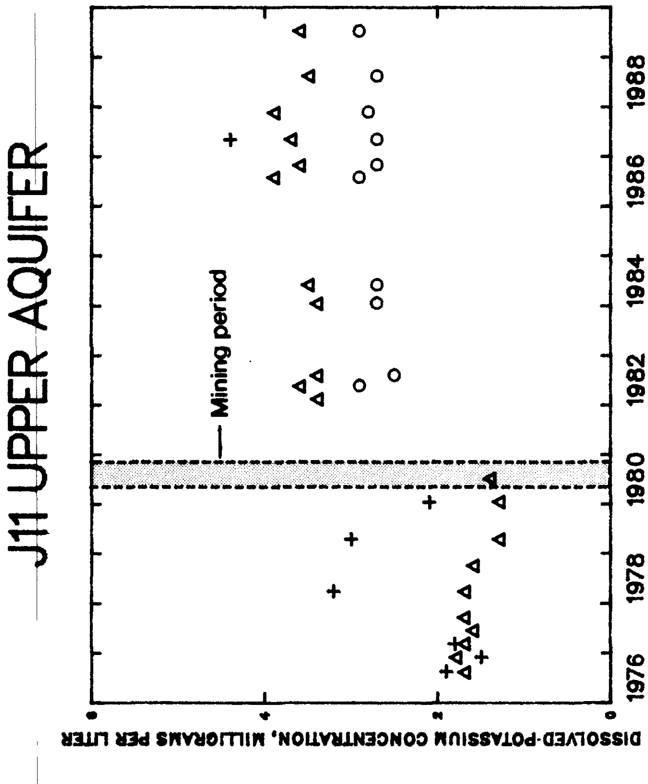
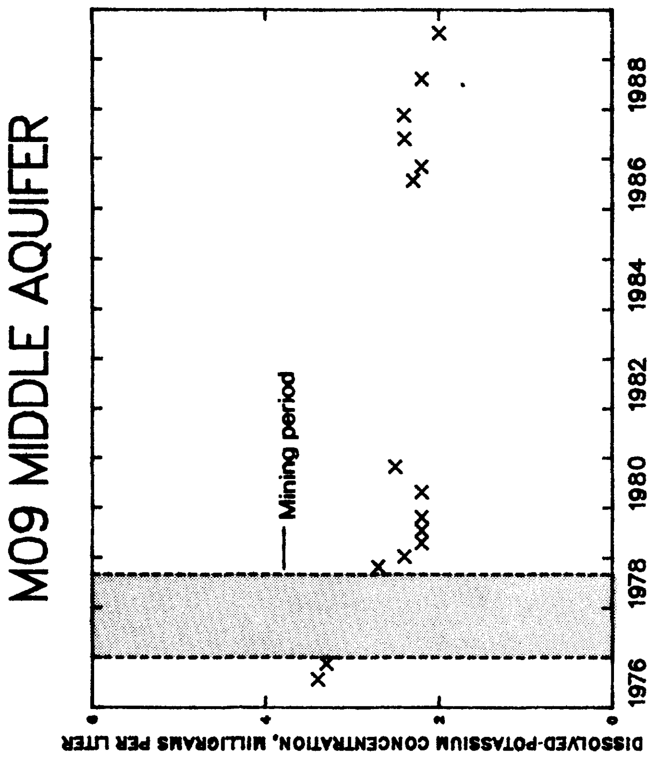
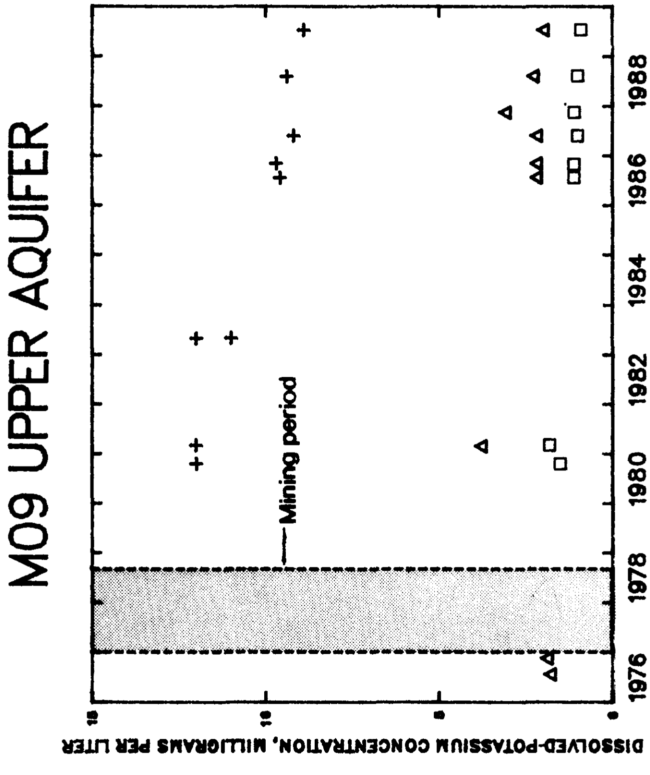
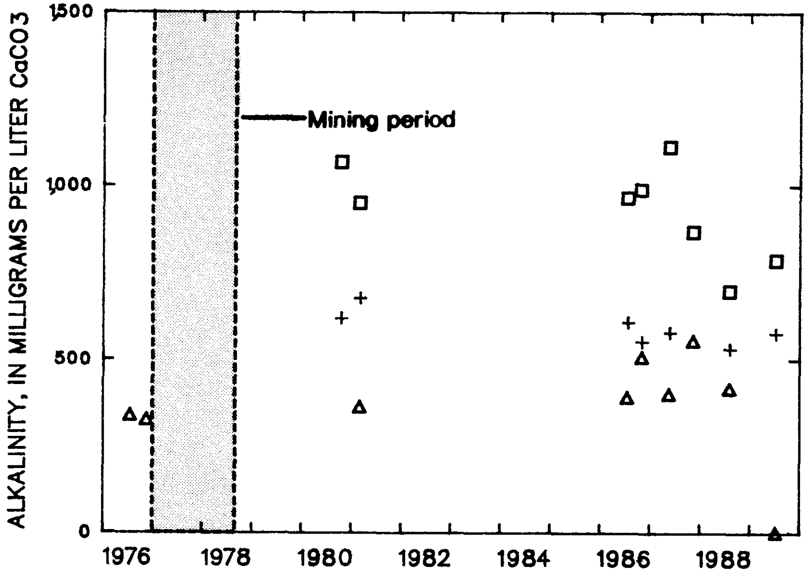

J11 MIDDLE AQUIFER
Mining period
DISSOLVED-POTASSIUM CONCENTRATION, MILLIGRAMS PER LITER
6
4
2
0
1976
1978
1980
1982
1984
1986
1988


J11 UPPER AQUIFER
Mining period
DISSOLVED-POTASSIUM CONCENTRATION, MILLIGRAMS PER LITER
6
4
2
0
1976
1978
1980
1982
1984
1986
1988


M09 MIDDLE AQUIFER
Mining period
DISSOLVED-POTASSIUM CONCENTRATION, MILLIGRAMS PER LITER
6
4
2
0
1976
1978
1980
1982
1984
1986
1988


M09 UPPER AQUIFER
Mining period
DISSOLVED-POTASSIUM CONCENTRATION, MILLIGRAMS PER LITER
15
10
5
0
1976
1978
1980
1982
1984
1986
1988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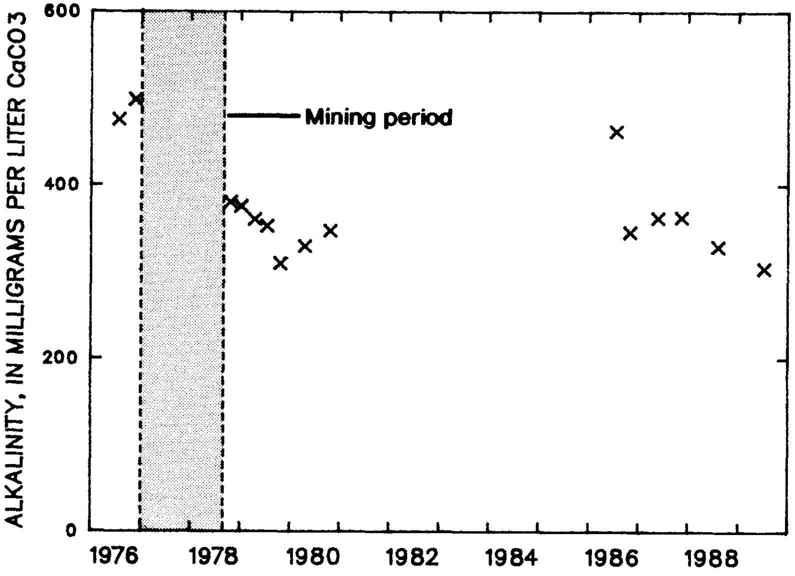
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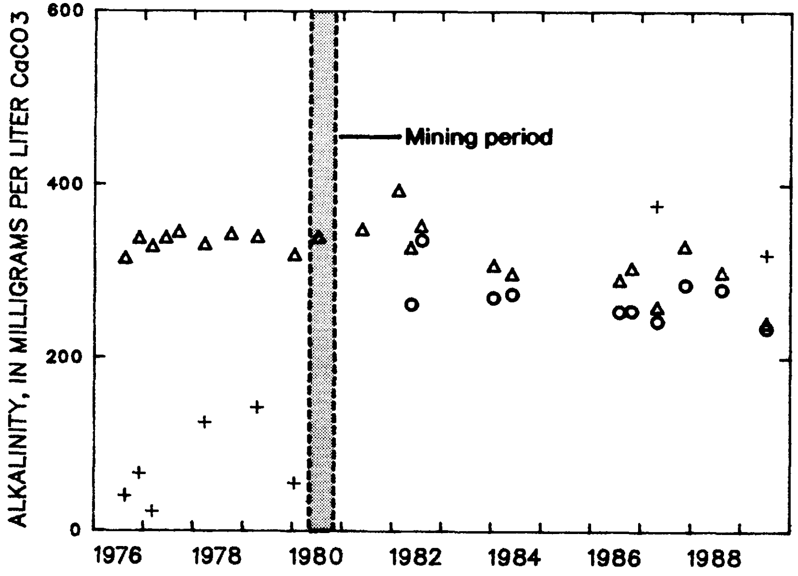
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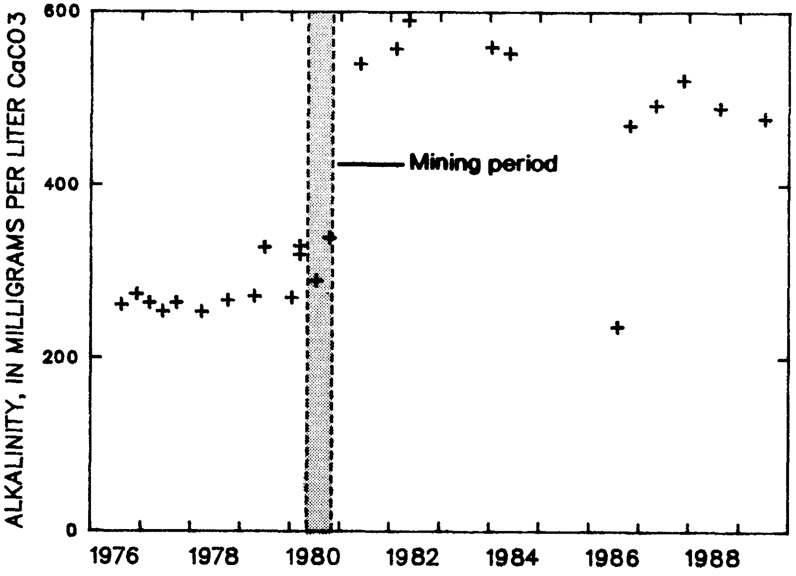
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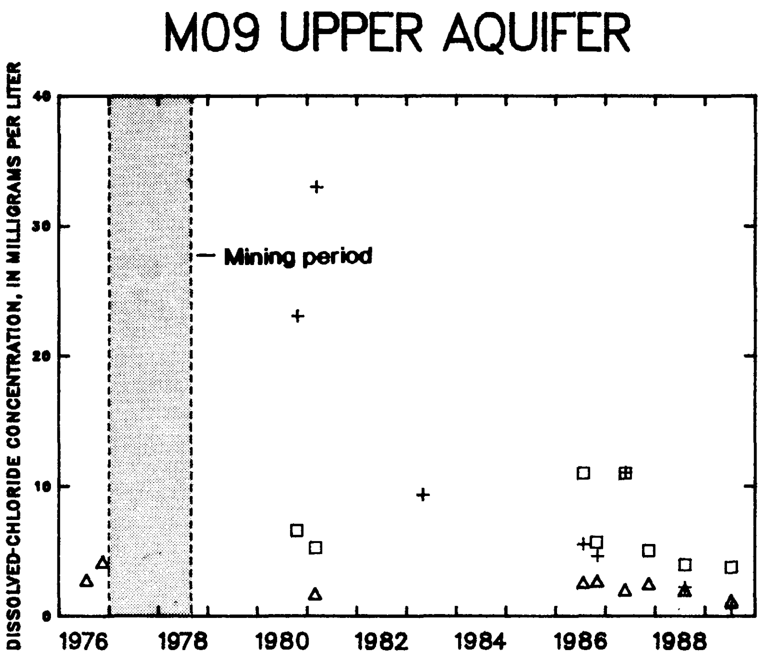
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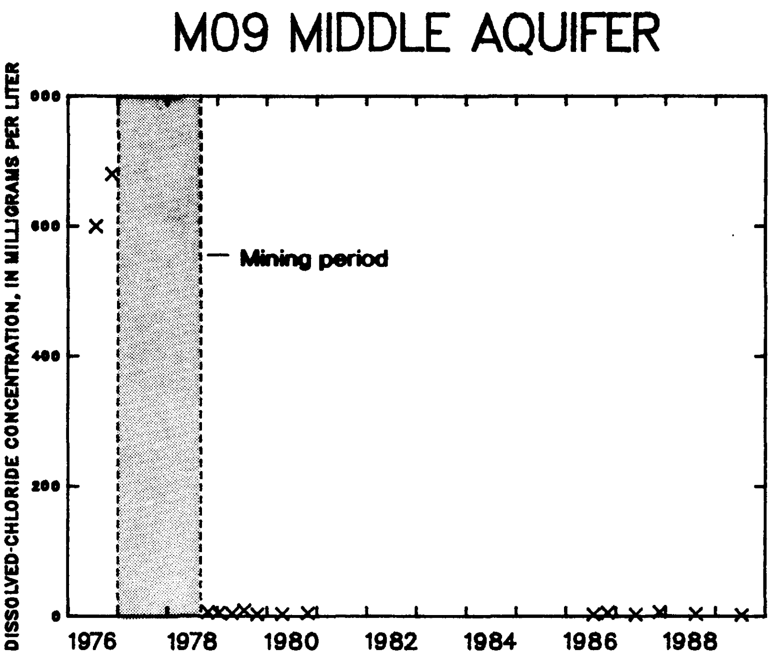
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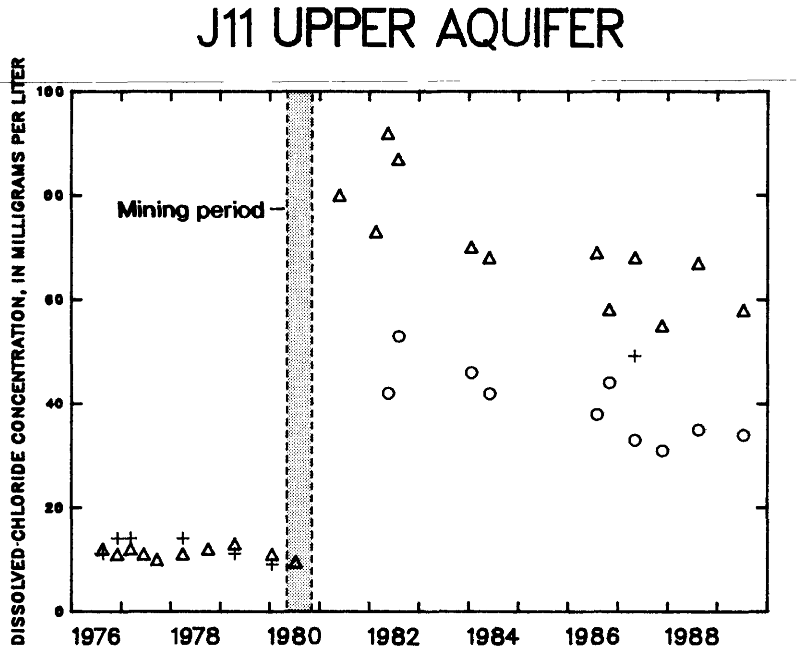
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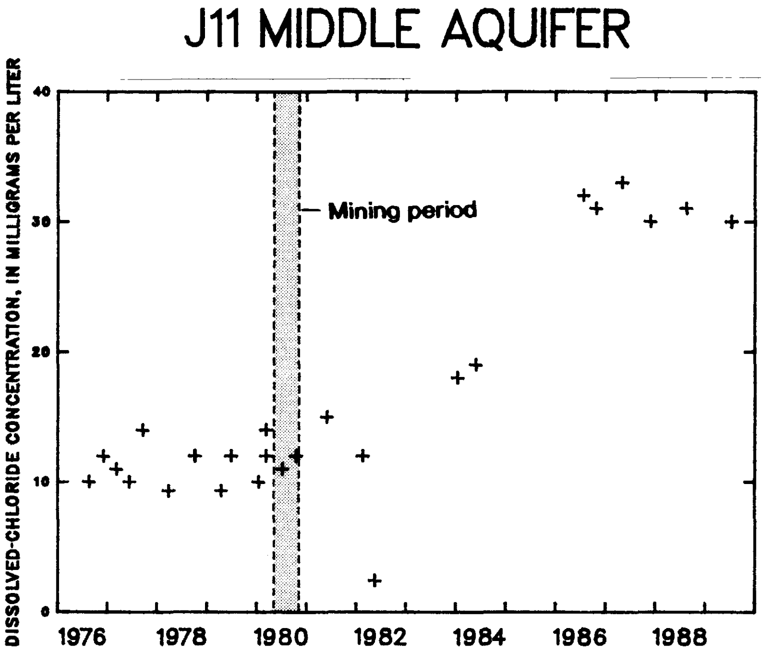
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