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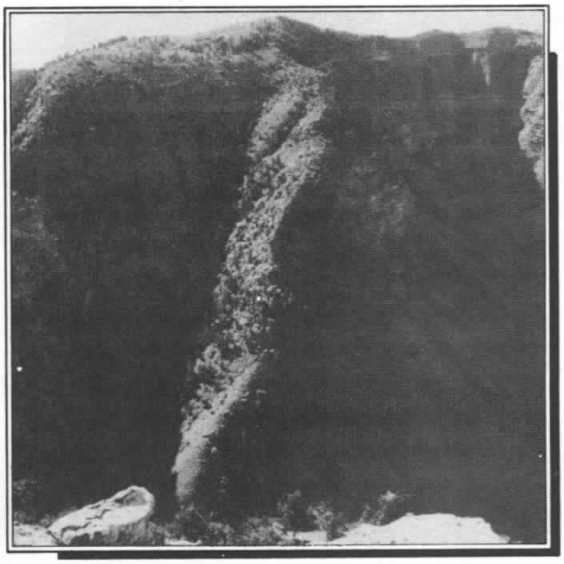
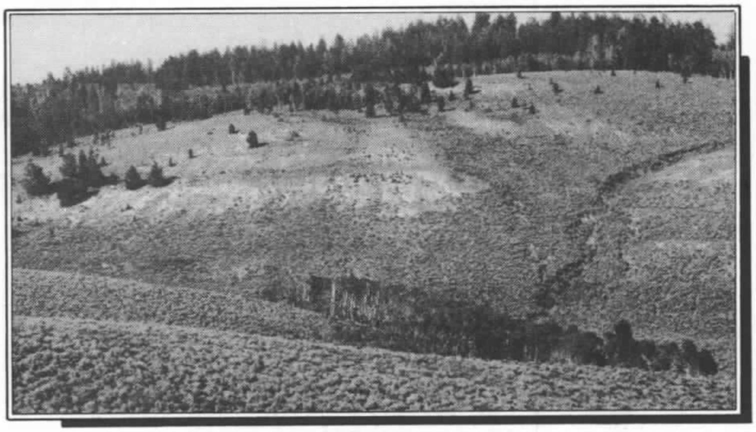
INFORMATION CIRCULAR/1994

Response of Springs to Longwall Coal Mining at the Deer Creek and Cottonwood Mines, Wasatch Plateau, UT

By Liane L. M. Kadnuck





United States Department of the Interior

Bureau of Mines

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Cover: Clockwise from top left: topography of East Mouintain Summit; typical topography of Wasatch Plateau; surveying instrument in winter snowpack, soure of recharge for local springs; spring I and the stock watering pond it creates.

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UNITED STATES DEPARTMENT OF THE INTERIOR
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BUREAU OF MINES

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	m	meter
km	kilometer	pct	percent
L/s	liter per second		

RESPONSE OF SPRINGS TO LONGWALL COAL MINING AT THE DEER CREEK AND COTTONWOOD MINES, WASATCH PLATEAU, UT

By Liane L. M. Kadnuck[1]

ABSTRACT

This report summarizes the results of a hydrologic research study conducted by the U.S. Bureau of Mines (USBM) in cooperation with Energy West Mining Co. at the Deer Creek and Cottonwood Mines, near Orangeville, UT. The USBM evaluated hydrologic and overburden failure data to assess the response of local ground water to underground coal mining in single- and multiple-seam conditions. Fourteen springs located over the two mines were investigated in the study along with overburden failure response caused by longwall panel extraction. Spring discharge was compared to climatic variation and time of undermining to quantify response to undermining. Spring discharge had been reduced owing to below-normal precipitation during the period evaluated. The response of springs to mining in the vicinity was influenced in part by the thick overburden present at the study site, the presence of hydrophilic clays and mudstones in the overburden stratigraphy, and elevation of the springs above the mine level, which buffered the effects of undermining.

[1]Environmental engineer, Denver Research Center, U.S. Bureau of Mines, Denver, CO.

INTRODUCTION

To quantify the response of overburden stratigraphy to high-extraction coal mining, the U.S. Bureau of Mines (USBM) initiated a research program to evaluate the effects of mining and associated subsidence in varying geologic conditions. The primary objective of this program is to understand the mechanics of subsidence and overburden failure response resulting from underground mining in Western U.S. coalfields. Previous USBM studies have focused on surface effects of underground coal mining *(1-5)*.[2] Recognizing that subsidence produces alterations in overburden characteristics which in turn produce associated changes in the hydrologic system, the program was expanded to include characterization of the response of hydrologic systems contained in the overburden. This study addresses the effects of overburden failure on hydrologic resources in proximity to a mined area.

This report describes the response of ground water contained in the overburden to underground mining in the Wasatch Plateau Coalfield. The study involved evaluating the response of local ground water resources overlying the Deer Creek and Cottonwood coal mines in Emery County, UT. The goals of this study were to (1) quantify fluctuations in spring discharge associated with undermining, (2) assess longevity of discharge fluctuations, and (3) correlate the stratigraphic locations and elevations of springs in the overburden stratigraphic column with zones of overburden failure.

ACKNOWLEDGMENTS

PacifiCorp's Fuel Resources Division provided valuable assistance in performing this research. Specifically, Chuck Semborski of the Energy West Mining Co. and Rodger Fry of InterWest Mining contributed much of the data and information contained in this report. Without their assistance, this study could not have been undertaken.

DEER CREEK AND COTTONWOOD MINES STUDY SITE

The Deer Creek and Cottonwood Mines are located in the Wasatch Plateau Coalfield in south-central Utah (figure 1). Two major coal seams are mined in the area by Energy West Mining Co., a subsidiary of PacifiCorp.; the Deer Creek Mine operates in the Blind Canyon Seam, and the Cottonwood Mine produces coal from the Hiawatha Seam approximately 26 m below. The Deer Creek Mine overlies and partly overlaps the Cottonwood Mine; hence the study area contains areas of both single- and multiple-seam mining. The mines are located on East Mountain (elevation 2,942 m). The local topography is typified by rugged mountains dissected by stream-incised canyons. The overburden thickness averages 518 m but ranges from 260 to over 700 m, depending on local topography.

Both mines currently extract coal using longwall retreat methods, and each contains areas of past room-and-pillar extraction. The coal is hard, dense, and ranked B to C bituminous. The Deer Creek Mine operates at an average extraction height of 3.3 m, and the Cottonwood Mine has an average extraction height of 2.6 m.

[2]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

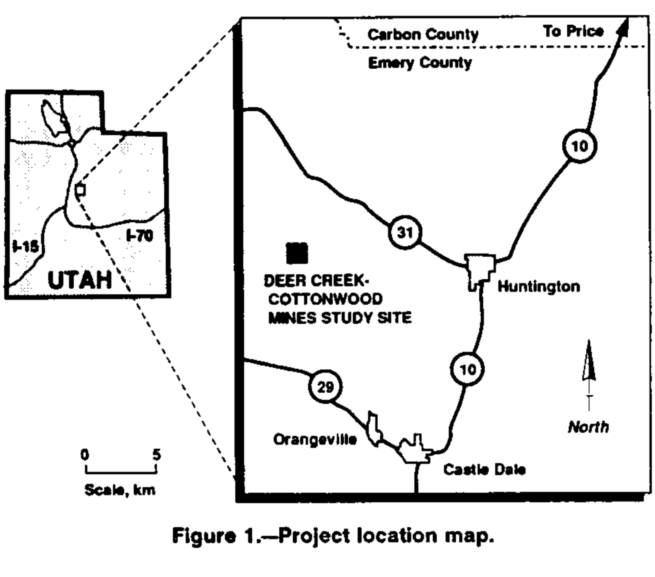

Figure 1.—Project location map.

GEOLOGY

Regional Geology

The mines are located on the Wasatch Plateau, a broad, north-south-trending, flat-topped mesa. The eastern edge of the plateau lies on the western flank of the San Rafael Swell and is typified by gently westward-dipping strata. The western edge of the plateau is complexly faulted and represents the transition between the Colorado plateau region and the Great Basin. Geologic units outcropping in the area range in age from Cretaceous to Tertiary, with some thin, unconsolidated Quaternary deposits present in stream valleys.

Local Geology

Exposed strata in the mine area are of sedimentary origin. The economic coal deposits are found in the lower part of the stratigraphic section. Generalized lithologies and thicknesses of each geologic unit are summarized in figure 2 *(6)*.

The youngest geologic unit in the area, the Flagstaff Limestone, is a freshwater limestone that caps portions of the top of East Mountain. The Flagstaff is underlain by the North Horn Formation, a variegated shale and mudstone sequence derived from fluvial and lacustrine origins. The Price River Formation forms a steep, receding slope under the North Horn and consists of a conglomeratic fluvial sandstone with shale layers. The North Horn and Price River Formations each contain claystones and mudstones that are rich in hydrophilic clays. The fluvial Castlegate Sandstone forms a cliff between the Price River and Blackhawk Formations. The Blackhawk Formation is a marginal marine sequence of lenticular sandstone beds and carbonaceous shales with economic coal deposits. The Blackhawk is typified as having fluvial channels scoured into the top of the coal deposits. Underlying the Blackhawk is the Star Point Sandstone, a thinly bedded marine sandstone with shale interbeds at the base where it intertongues with the older Masuk Shale Member of the Mancos Formation.

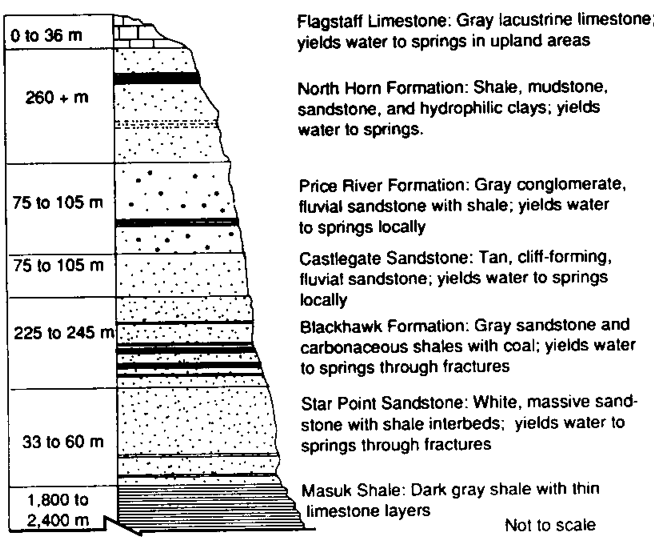

Figure 2.—Generalized overburden stratigraphy (modified from Danielson and others (7)).

The regional dip of the strata is broken by the northeast-trending axis of the Straight Canyon syncline, located on the western end of East Mountain. Faulting is common on the Wasatch Plateau, and three faults, the Deer Creek, Pleasant Valley, and Roan's Canyon, crosscut the permit area *(6)*. Jointing is also prevalent in the area, and joint sets trending northeast-southwest and northwest-southeast crosscut the study area. Figure 3 shows the locations and trends of the major structural features.

HYDROLOGIC SYSTEM

Ground Water Hydrology

Ground water occurs in all exposed geologic units discussed in the previous section in continuous or discontinuous water-bearing zones. The formations yield ground water from perched zones[3] to springs[4] where the hydraulic conductivity of the water-bearing zone is higher than that of the surrounding rock, and where the formations are fractured or faulted. The lateral continuity of these perched water tables is not known, though there is some evidence for limited lateral extent based on springs located at the same elevation *(6)*. The lateral extent of water-bearing zones is limited based on the discontinuous nature of the local topography. A continuous water-bearing unit was found to be present in the Star Point sandstone through drillers' logs and regional ground water studies.

Ground water in the area is recharged largely from precipitation, most of it from snowmelt, which percolates into the subsurface through fractures or matrix flow *(9)*. The flat top of East Mountain allows water to infiltrate to the subsurface through fractures exposed at the surface. Some recharge also infiltrates to the subsurface on the mountain flanks. Older units are recharged mainly from water that migrates through fractures. Impermeable lenses of shale and mudstone in the North Horn and Price River Formations retard downward migration of water, although some water is transmitted to the lower geologic units through continuous fractures. Geotechnical tests performed on the North Horn Formation indicated hydrophilic or swelling materials were present in the clays and mudstones that swelled 40 pct in the first hour of testing *(10)*. As a result, a large number of springs issue from the North Horn and Price River Formations. The Star Point Sandstone and the Blackhawk Formation are recharged from overlying units, mainly through faults and fractures *(6)*.

[3]By definition, perched water is "unconfined ground water separated from an underlying main body of ground water by an unsaturated zone" *(7)*.

[4]By definition, springs are a place where ground water flows naturally from a rock or the soil onto the land surface or into a body of water, and the occurrence depends upon the nature and relationship of rocks, especially permeable and impermeable strata *(8)*.

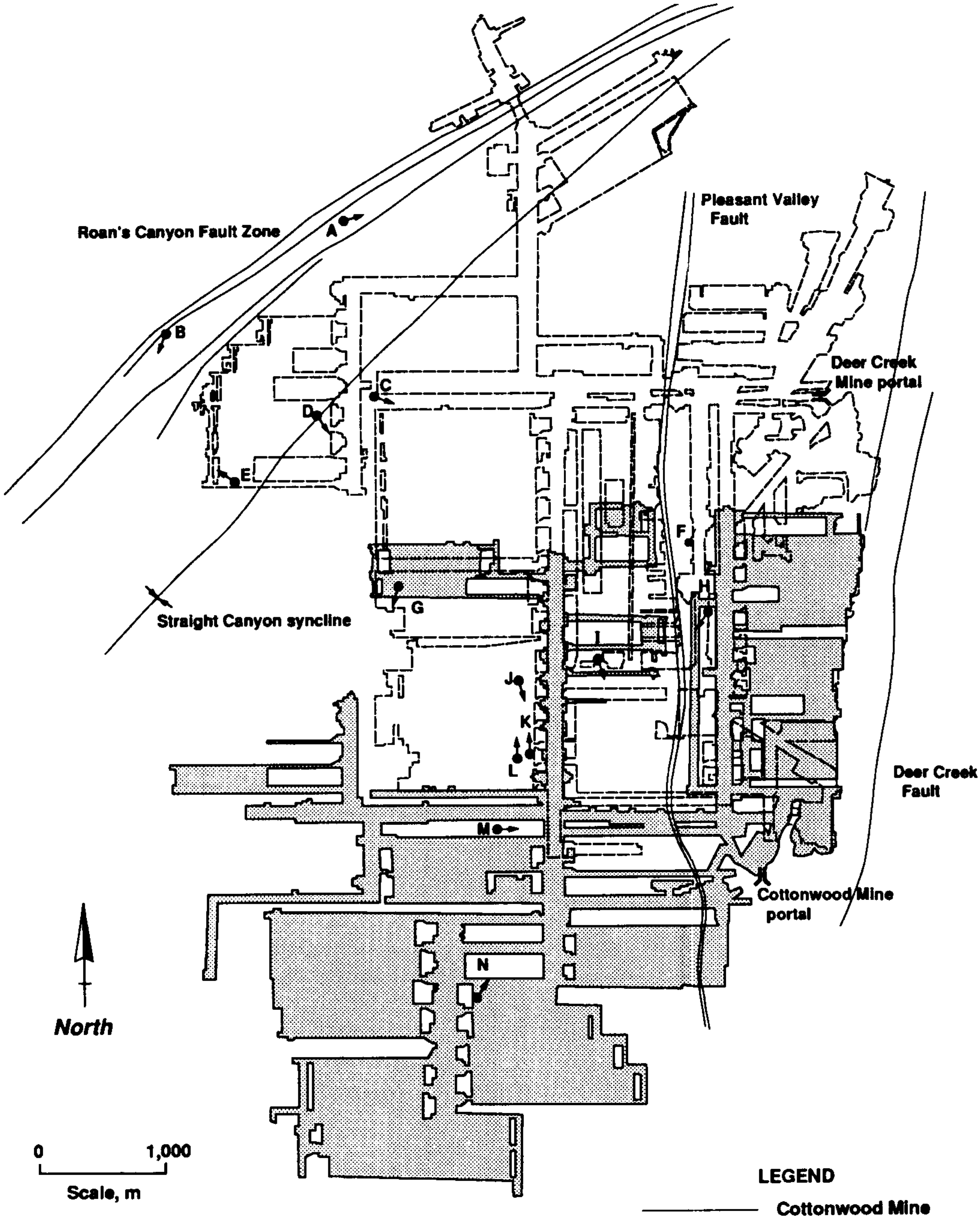

Figure 3.—Mine map showing spring locations.

Water movement is controlled by dip of bedding, primary hydraulic conductivity, and fractures. Regional ground water flow in the immediate area is affected by the Joes Valley and Pleasant Valley fault zones, which are thought to be major conduits of interbasin flow. Water-bearing fractures encountered in the mines further indicate that ground water is transported along faults and fractures *(10)*.

Surface Water Hydrology

As shown on figure 4, East Mountain forms a drainage divide between Huntington Creek to the north and Cottonwood Creek on the south. The north fork of Cottonwood Creek drains the area between Trail and East Mountains, while Huntington Creek drains the area between East Mountain and Gentry Mountain to the north. There are numerous tributaries to these creeks, most of which are ephemeral, flowing only during precipitation events, or intermittent, flowing during wet seasons of the year.

Most of the overland drainage is derived from snowmelt, and most baseflow in the streams originates as ground water discharged from perched aquifers issuing water to springs *(6, 11)*. Large fracture systems associated with the fault zones in the area are thought to control the surface drainage and may intercept creek flow and divert it into other basins. A lineament analysis *(12)* coupled with a drainage trace analysis indicated that the major trunk streams follow a regional northwest-southeast trend and that tributary drainages follow either a north-south, east-west, or northeast-southwest trend. The linearity of the drainage traces suggests that the surface drainage is following fracture or joint systems.

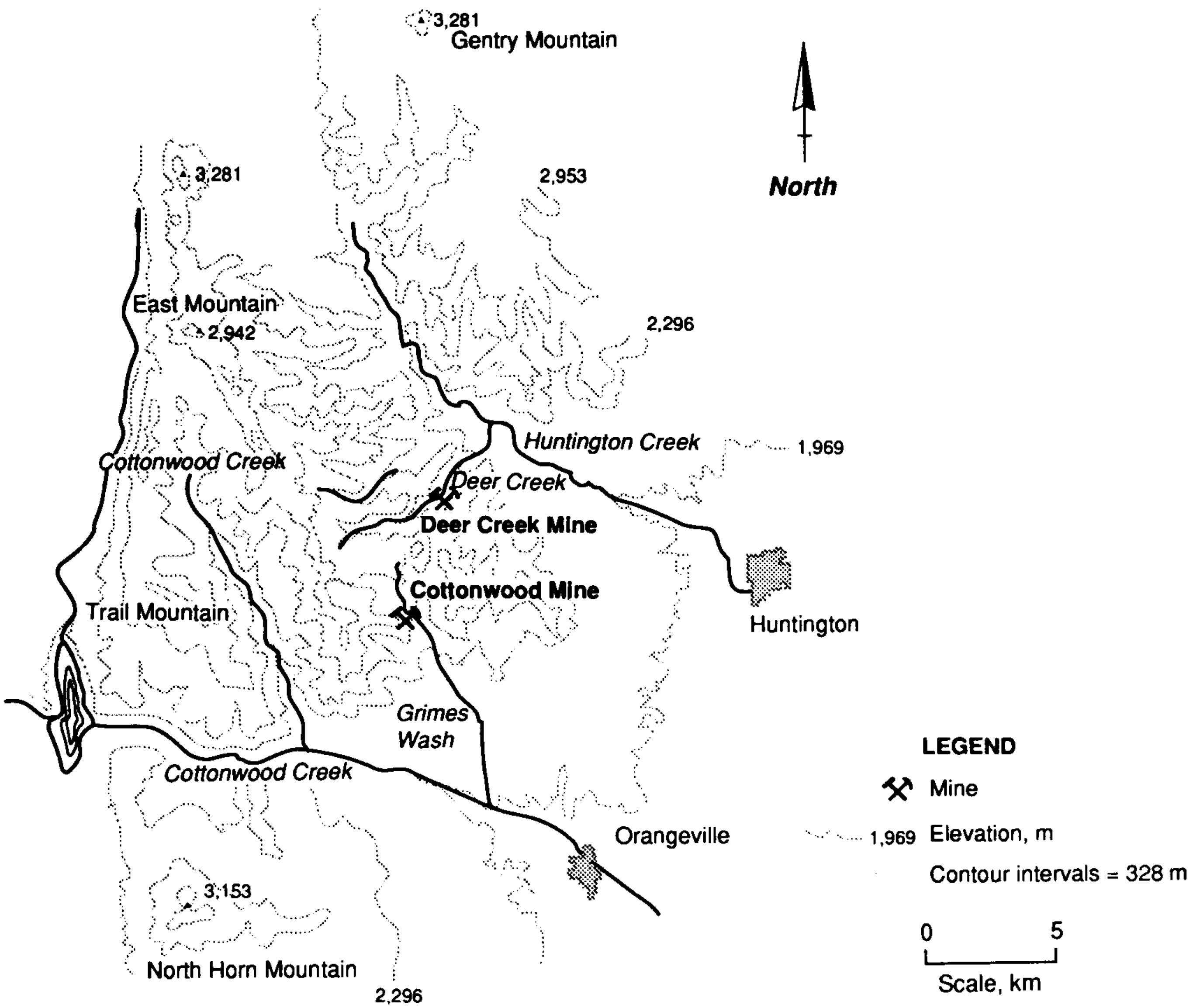

Figure 4.—Topography of East Mountain showing surface drainage.

HYDROLOGIC DATA COLLECTION

The mining company is required by law to monitor quantity of water resources within the permit area. Monitoring includes spring and stream discharge, piezometric levels in the mine floor, and mine discharge from both the Deer Creek and Cottonwood Mines. This study focused on ground water resources located above the mine level, namely springs, that could potentially be affected by mining. Springs issuing from East Mountain within the Deer Creek and Cottonwood Mines permit area were chosen by PacifiCorp and the Utah Division of Oil, Gas and Mining to be monitored for discharge and water quality. Thirty springs within the permit area are monitored, some on a semiannual basis and some on a monthly basis. Discharge monitoring was started in 1979, and additional springs have been added each year since that time; thus records vary for all the springs monitored. Discharge is measured by weirs, flumes, or manually. The 14 springs selected for use in this study were those with the longest available monitoring records. The springs monitored on a monthly basis are measured from July through October, since they are inaccessible during winter months. Discharge is reported from annual runoff through baseflow in the fall.

The monitoring is performed to allow comparison and assessment of the effects that mining has on the springs. The springs were characterized by mine personnel for issuing mechanism (for example, a fracture or a perched zone), issuing formation, and elevation measurements taken. This information is provided in table 1.

Water enters the mines through faults, fractures, and drill holes, and where localized saturated zones (fluvial sandstone channels) are intercepted by mine workings. Water discharged from the mines is measured at the discharge point on a daily basis and reported as a monthly total. Mine water from the Cottonwood Mine is discharged into Grimes Wash, and water from the Deer Creek Mine is discharged into Huntington Creek (figure 4).

Table 1.—Spring characteristics

Spring	Geologic unit	Issuing mechanism	Elevation, m	Location	Date undermined
A	North Horn	Fracture	2,850	Not in mined area	Not applicable.
B	Flagstaff	..do.	2,969	..do.	Do.
C	North Horn	..do.	2,831	Deer Creek barrier pillar	Do.
D	Flagstaff	Formation contact	2,921	Deer Creek panel	Oct. 1991.
E	North Horn	Perched zone	2,868	..do.	Feb. 1992.
F	Price River	..do.	2,743	Deer Creek barrier pillar	Not applicable.
G	North Horn	Fracture	2,831	Deer Creek panel	Apr. 1988.
H	..do.	Formation contact	2,754	Deer Creek mains, Cottonwood pillar	May 1976.
I	..do.	Perched zone	2,822	Deer Creek submains, Cottonwood panel	Aug. 1993.
J	..do.	..do.	2,831	Deer Creek panel	Aug. 1986.
K	Price River	Fracture	2,737	..do.	Dec. 1982.
L	..do.	Perched zone	2,743	..do.	Aug. 1982.
M	North Horn	..do.	2,850	Cottonwood barrier pillar	Not applicable.
N	..do.	Fracture	2,845	Cottonwood panel	Aug. 1989.

ANALYSIS OF SPRING RESPONSE TO MINING

This study concentrates on characterizing the impacts mining has on perched water-bearing zones in the overburden. In the study area, water-bearing zones above the mine level issue water to springs, representing an important part of water supply in the region for stream baseflow, agricultural, irrigation, and wildlife habitat purposes. Fourteen springs located on East Mountain were targeted for study based on availability of monitoring records and proximity to the mines and were designated with a letter identifier of A to N. Analysis of spring response followed a method used by Coe and Stowe *(13)*, which is one of the few published studies that have examined responses of springs to undermining. This methodology required use of information sets including precipitation, spring discharge, and time of undermining.

This method involved comparing spring discharge hydrographs to precipitation for the period of monitoring. Monthly and total annual precipitation data for water years[5] 1981 to 1993 were utilized and are shown on figure A-1 in the appendix. Precipitation data are collected at a weather station on East Mountain on a daily basis. The availability of seasonal, monthly discharge data dictated using seasonal recession curves to assess mining impacts by determining if the springs departed from normal response. Patterns or trends in the spring discharge recession curves were sought to assess if the springs showed similar responses each year to precipitation, runoff, and baseflow conditions. Curves were compared to one another to discern if springs in the area responded differently based on issuing mechanism (fracture versus perched zone). There did not appear to be large differences in response as a result of issuing mechanism. Several years of data prior to mining were incorporated to establish baseline conditions. Spring discharges, shown as seasonal recession curves, are given on figure A-2.

Initial comparison of spring discharge to precipitation indicated that discharge did not immediately follow precipitation. Therefore, a statistical analysis that cross-correlated precipitation data with spring discharge was performed for two of the springs. This analysis showed that the springs in the study area respond to precipitation events within 6 months to 1 year *(14)*. Discharge data for springs I and M were correlated with precipitation; this indicated that there is an approximate 6-month to 1-year lag time between precipitation events and discharge. The lag information was used to better assess variations due to climatic events without confusing them with response that may have been a result of mining. Results of the statistical analysis are given graphically on figure A-3. The graphs show the calculated lag time by offsetting the spring flow hydrograph by 1 year on the precipitation curve; for example, spring flow for 1982 is placed over precipitation for 1981. Local variation of lag time is expected based on differences in elevation, recharge source, and issuing mechanism for each of the springs studied. The statistical correlation gives an indication of the approximate lag time for the area. Figure A-4 gives the statistical results showing match position and correlation coefficient to demonstrate the validity of the correlation of the two data sets.

Spring discharge variation of both preundermining and postundermining was evaluated to identify if the spring discharge changed as the spring was undermined, or as mining progressed close by. Each spring location was compared with a map of mine workings and located with regard to placement over a mine structure such as a panel or a barrier pillar, as shown on figure 3. This information is also listed on table 1. Springs D, E, G, I, J, K, L, and N are located over longwall panels. Springs C, F, H, and M are located over other mine structures such as barrier pillars or mains. Springs A and B are located in an area that has not been undermined and were thus used as controls to identify discharge fluctuations due to climatic events. Spring discharge was carefully compared with precipitation, location of the spring over the extracted area, and time of undermining to assess response.

[5] The water year runs from October 1 to September 30.

RESULTS AND DISCUSSION

Possible responses of springs to coal extraction include enhanced recharge to the spring from dilation of preexisting fractures, reduction of spring discharge due to drainage into subsidence-induced fractures or dilation of existing fractures, or flow loss along planes of bedding separation *(9)*. Springs located over panels are expected to show a greater response to undermining than those located over mains or barrier pillars since most subsidence, and hence overburden deformation, occurs over the longwall panels. In a study in Appalachia where the overburden ranged from 120 to 245 m, rapid and dramatic decreases in spring discharge were observed as the longwall face passed underneath *(13)*. Trevits and Matetic observed a similar response in water wells located over longwall panels with 70 to 210 m of overburden present *(15)*. With the longwall mining method, subsidence occurs quickly after the coal is extracted as the immediate mine roof caves in behind the active face. Reports from mine personnel indicate that the majority of subsidence occurs at the site over single panels within 1 month after undermining.[6] Previous USBM studies reported that maximum subsidence occurred at these mines within a year where a group of panels had been extracted *(1, 3)*. Given these observations, hydrologic response is expected to occur within a similar timeframe as overburden response. As soon as the overburden fractures and moves in response to coal extraction and roof caving, the hydrologic system is also altered. The expected response of springs would be dramatic changes in discharge after undermining occurred.

Springs A and B were located outside the area disturbed by mining and provided information on the normal seasonal response of springs in the area to precipitation or recharge. From 1986 to 1992, precipitation in the area was 70 to 85 pct of normal. The recession curves for these springs show a general downward trend from 1986, in response to the decreased precipitation during that period. Precipitation increased in 1993 and is shown in the increase in spring discharge on the hydrographs (figure A-2). The shapes of the recession curves show smooth and repeatable patterns for the period of record.

Spring I is used as a water source for a stock watering pond. It was undermined by submains in the Deer Creek Mine in 1985, and by a longwall panel in the Cottonwood Mine in August 1993. It was noted that the recession curves departed from a normal shape coincident with mining activity underneath spring I. However, adjustments of valves and blockage in the pipe installed at the spring also occurred during this time, and available data do not allow for distinguishing the effects of the two activities. Weekly discharge measurements were available after the longwall panel passed underneath. Although surface tension cracks appeared in the vicinity, the spring discharge remained constant at 0.6 L/s. According to aerial surveys, the surface subsidence in the vicinity of spring I ranged from 0.6 to 1.2 m.

Spring E was undermined by a Deer Creek panel in February 1992. This spring exhibited inconsistent recession curves in the 5 years prior to undermining and then had a flat recession curve in the year after undermining. The surface subsidence at spring E was estimated to be 1.6 to 1.8 m. The spring has a very low discharge, making detection of discharge alteration more difficult. It is felt that the discharge alteration for this spring is a result of reduced recharge available from the decrease in precipitation.

Spring N was undermined by a Cottonwood panel in August 1989. The recession curves for the spring have a less consistent shape than those for springs A and B, although the shapes of the spring N curves are repeated over several years. The spring exhibits the same response both before and after undermining and also shows a general downward trend from 1986 due to decreased precipitation. The surface subsidence in the vicinity of spring N was 0.6 to 1.2 m. Given the repeatable nature of the recession curves, spring N does not appear to have been affected by mining.

The remaining springs located over panels and springs located over pillars or mains did not exhibit discernible effects from undermining.

Springs H, K, L, and M exhibited flat recession curves at some point during the period of monitoring. In these cases, the springs were reduced to low or no flow. These springs experienced no-flow conditions for several years corresponding to the drought years. Flow returned in springs K, L, and M in 1993; spring H had not recharged

[6]Personal communication with C. A. Semborski, Energy West Mining Co., Sept. 1993.

to normal flow by 1993. The flat curves are likely due to depleted recharge from precipitation to the spring source or to depleted storage. Springs D and N each had 1 year where the recession curves were flat, but returned to normally shaped curves the following year. In these cases, the flat recession curves did not correspond to times of undermining. The control springs, A and B, did not show flat recession curves during the period of study, which is likely a result of fracture recharge conditions and locations at high elevations.

The undermined springs do not show the dramatic decreases in flow that have been observed in other studies. The lack of dramatic effects and the limited response observed may be attributed to several factors. One factor is that the springs that have been undermined are situated above the panels at ratios of panel width to overburden thickness (between the spring and the mine level) greater than 1.0. In a study by Tieman and Rauch (*16*), partial to total dewatering was observed in springs that were located above the panels at panel width to overburden ratios of 0.75 to 1.0. Table 2 summarizes the range of panel width to overburden ratios for springs undermined by panels evaluated in this study. Since the ratios are greater than 1.0 for the springs in this study, dewatering would not be anticipated, based on the observations made by Tieman and Rauch. This does not preclude minor discharge variations occurring as a result of strata movement or stress redistribution. Table 2 also lists the estimated surface subsidence in the vicinity of the springs located over panels.

Table 2.—Ratios of panel width to overburden thickness for springs over panels

Spring	Ratio of panel width to overburden thickness	Surface subsidence, m
D	1.1	0.6 - 1.2
E	1.3	1.2 - 1.8
G	1.1	0.6 - 1.2
I	1.2	0.6 - 1.2
J	1.3	0.6 - 1.2
K	1.2	< 0.6
L	1.1	0.6 - 1.2
N	1.1	0.6 - 1.2

The limited response observed for the springs was thought to be influenced by site-specific conditions that buffered the effects of mining. These include the thick overburden present and the presence of formations in the overburden that contain hydrophilic clays and mudstones. Results from other studies have concluded that the presence of hydrophilic clays lessens the extent of strata dewatering *(13, 17)*. Additionally, the presence of a massive sandstone layer (the Castlegate Sandstone) can cause bridging in the overburden, thereby limiting subsidence and associated hydrologic response *(1)*.

Another factor contributing to the limited spring response was the elevations of the springs above anticipated heights of fracturing and caving in the overburden, as estimated using formulas developed by Peng *(18)*. The relationship of fracture height equal to 30 times mining thickness was used. This relationship was developed based on mining conditions common to Eastern U.S. coalfields and does not account for differences in Western U.S. conditions such as the presence of massive sandstones in the overburden or thicker overburden. However, no similar value has been developed for the West, so the published relationship is commonly applied. Use of the relationship indicated that overburden fracturing might occur up to an elevation of 2,400 m from the Deer Creek Mine and up to approximately 2,330 m from the Cottonwood Mine. Spring K was the lowermost spring studied and was located at 2,737 m, 337 m above the computed height of fracturing. For the case that both coal seams had been extracted, gob formation and fracturing associated with mining the second lower seam would be incorporated into the fracturing produced by mining the first upper seam.[7] A conceptual subsurface overburden failure schematic is shown on figure 5.

Although all the springs studied were located at elevations higher than the computed elevations of fracturing in the overburden, the springs were located in a zone of the overburden where, according to Peng, continuous bending of the strata occurs. Preexisting fractures can dilate in response to the bending, causing flow variation. The bending and redistribution of stresses in the overburden can also cause flow variations.

[7]Personal communication with C. Haycocks, Department of Mining Engineering, Virginia Polytechnic Institute, Aug. 1993.

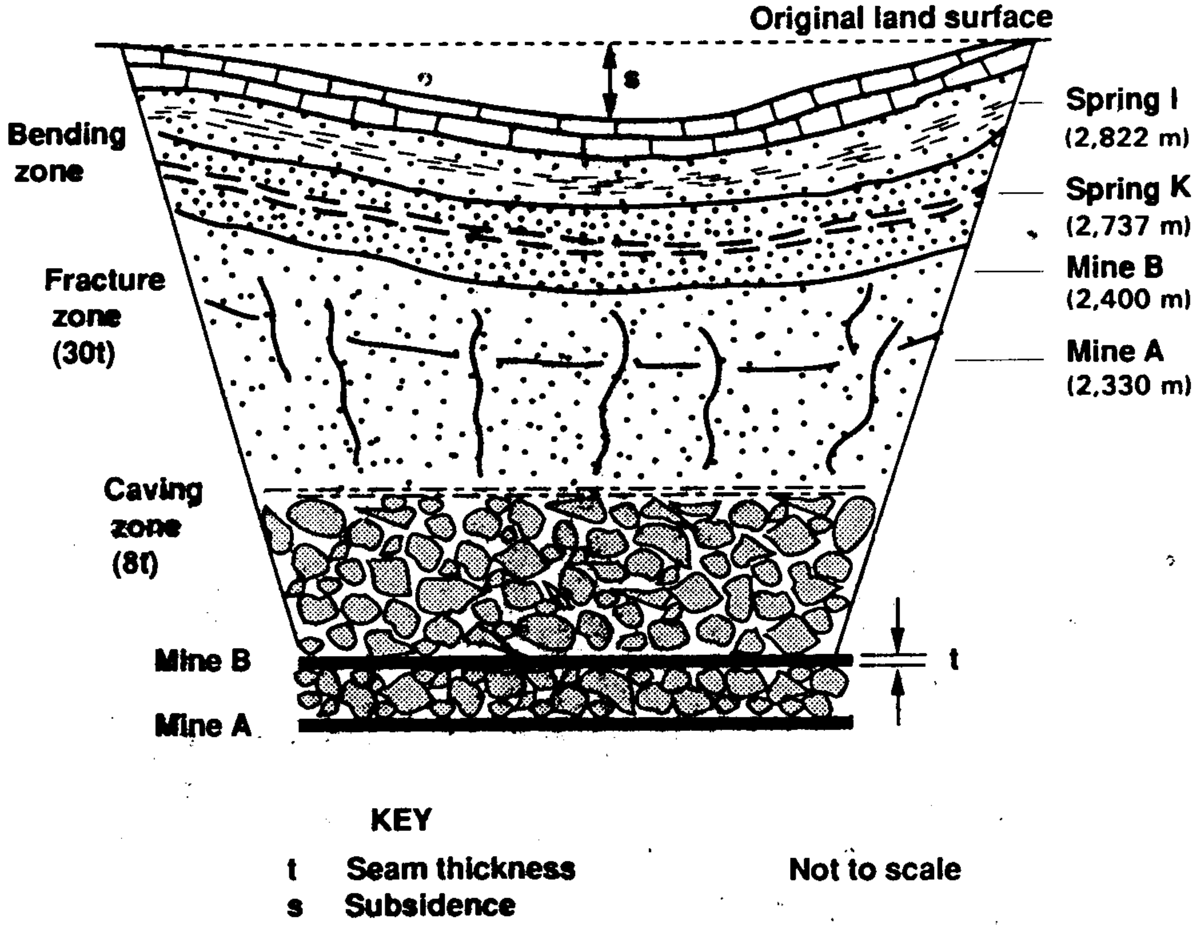

Figure 5.—Conceptual overburden failure schematic.

SUMMARY

The USBM used data available from the Deer Creek and Cottonwood Mines to perform a study of underground coal mining effects on local overburden hydrology. Data used in the study included seasonal and annual spring discharge, precipitation, surface subsidence, and overburden failure mechanics information. These data sets were used to quantify the response of 14 springs to underground mining.

Eight springs occurred over longwall panels. One of the eight, spring I, exhibited a departure from a normal recession curve coincident with the time of mining activity underneath it. Adjustments to valves and blockage of a pipe installed at the spring also occurred in the same time period and contributed to the variations in curve shape. The spring exhibited a constant discharge rate in the weeks after being undermined by a longwall panel, indicating that little variation occurred as a result of mining. The eight springs over panels all occurred at locations where the ratio of panel width to overburden thickness was greater than 1.0, thus limiting dewatering effects, as was observed in previous studies in Eastern U.S. coalfields. Surface subsidence did not appear to play a major role in the response of springs at this site.

Four springs experienced no discharge conditions during the period of study that were attributed to effects of regional decreased precipitation. Springs located over mine structures such as pillars or mains did not exhibit discernible effects from mining. For this study, the long-term availability of water resources was important and therefore dictated examining the seasonal response of springs in relation to mining.

The expected response of springs to undermining would be dramatic alterations in flow, as previously documented in other studies. The lack of observed responses was attributed to geologically driven site-specific conditions that buffered the effects of mining. These conditions included the thickness of overburden between the mine level and the springs, which ranged from 440 to over 600 m. Studies performed in the Appalachian coalfields noted dramatic decreases in spring discharge and water levels in wells where thinner (70 to 245 m) overburden was present *(13, 15, 17)*. Additionally, the presence of hydrophilic clays and mudstones in the overburden, which act as aquitards retarding the migration of water, likely lessened the vertical extent of strata dewatering, as has been observed in other studies *(17)*. The location of the springs above the estimated elevations of fracturing and caving in the overburden due to subsidence also contributed to the limited effects.

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APPENDIX.—HYDROLOGIC DATA GRAPHS

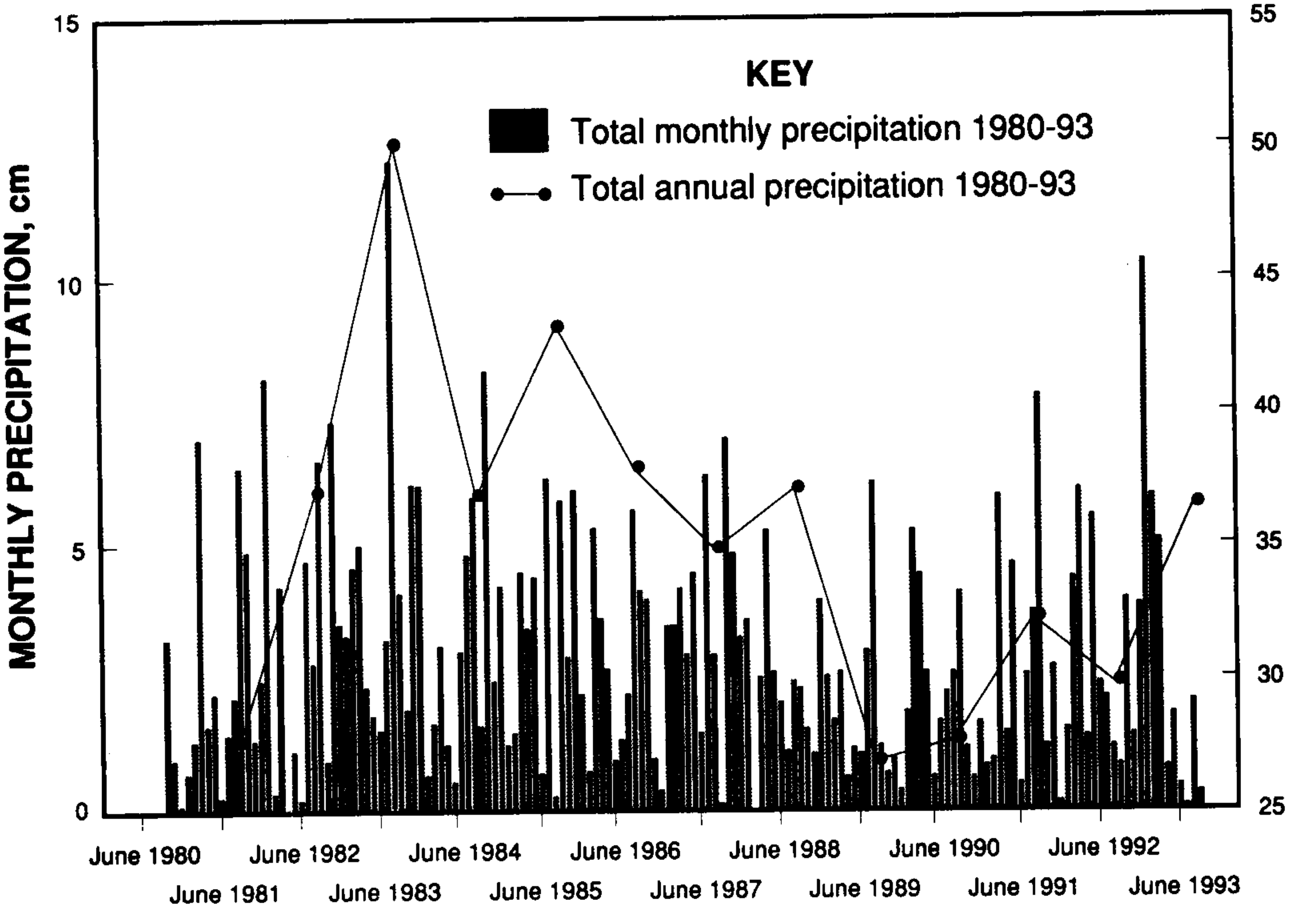


Figure A-1.—East Mountain precipitation for water years 1981-93.

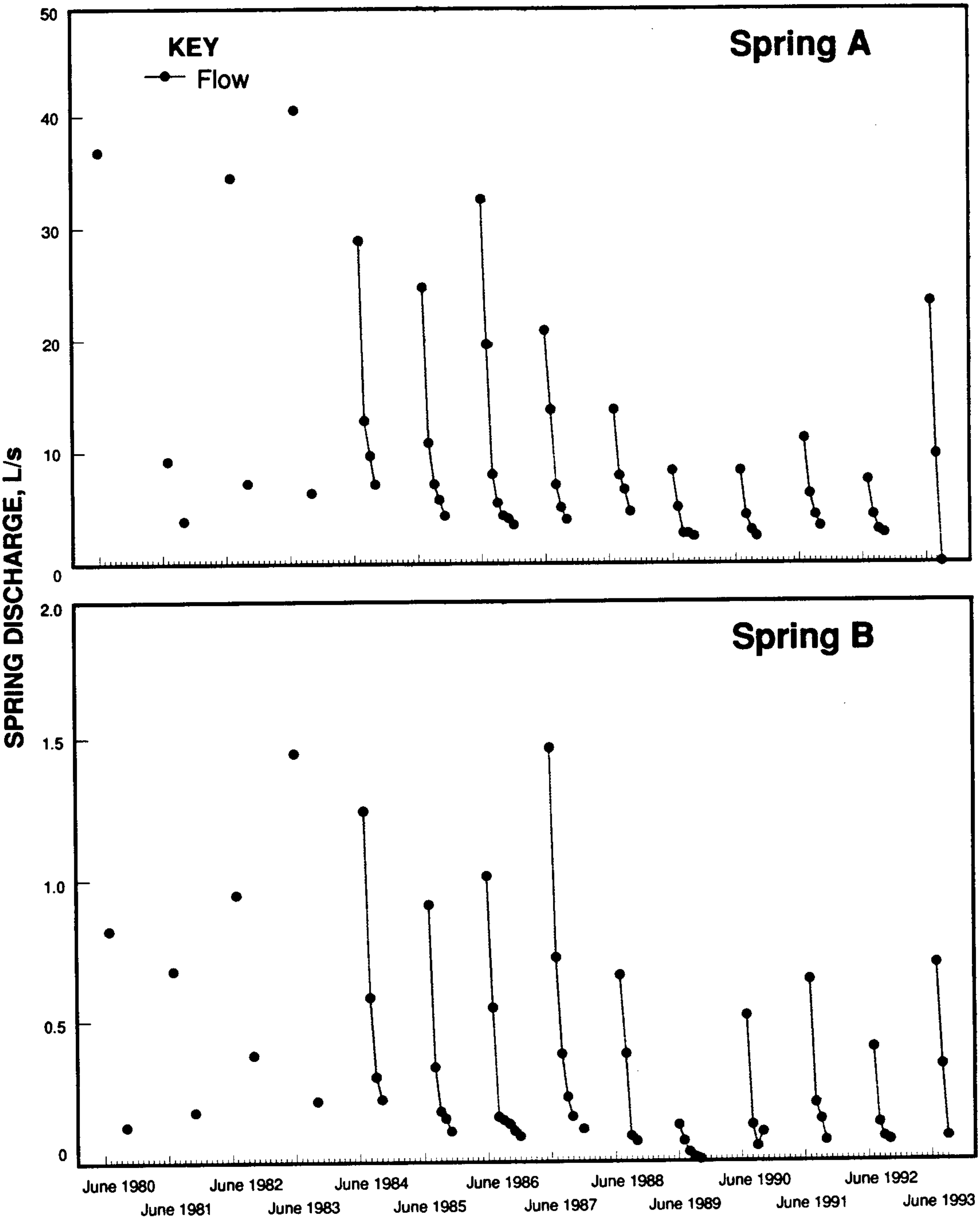


Figure A-2.—Spring discharge hydrographs for water years 1981-93.

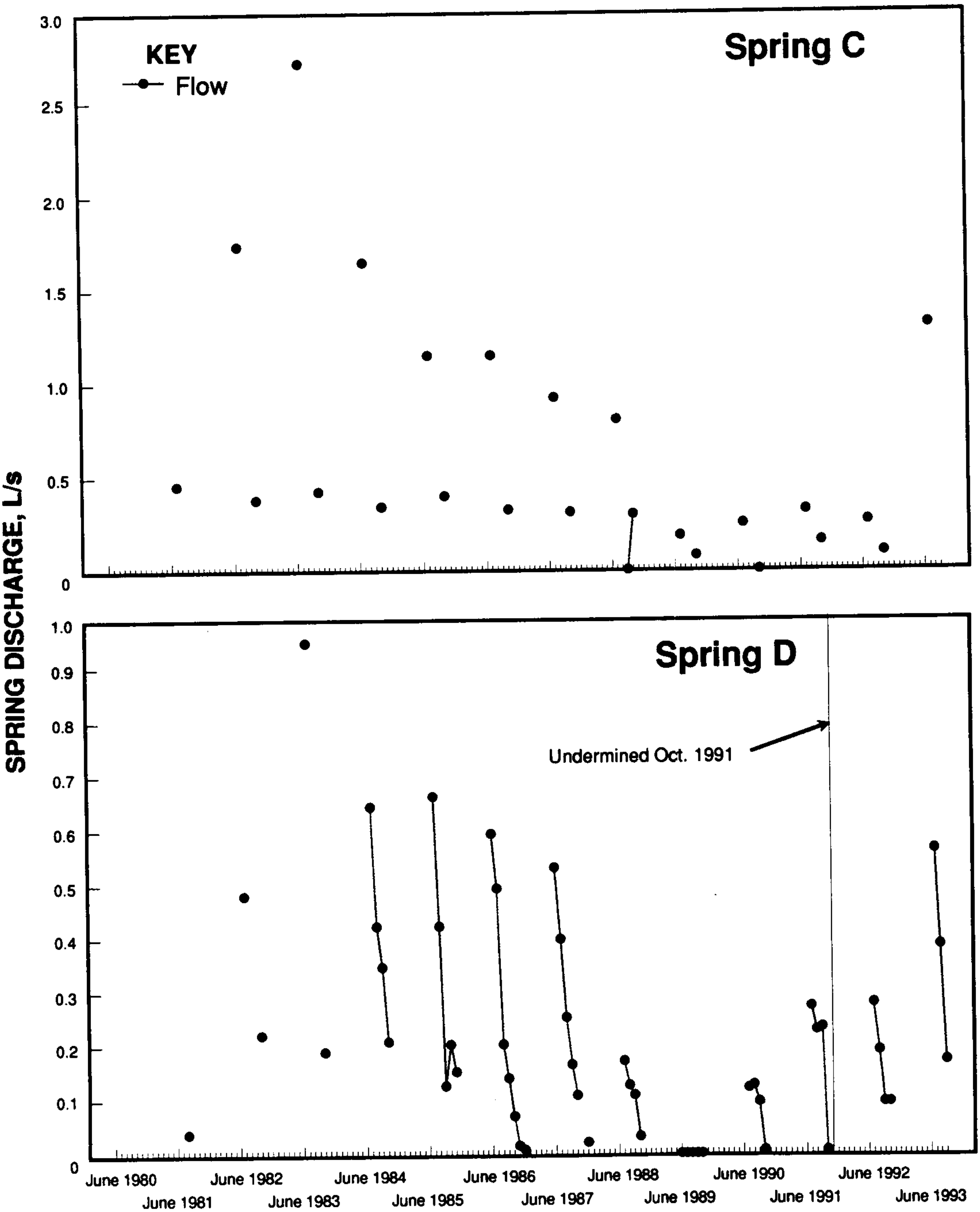
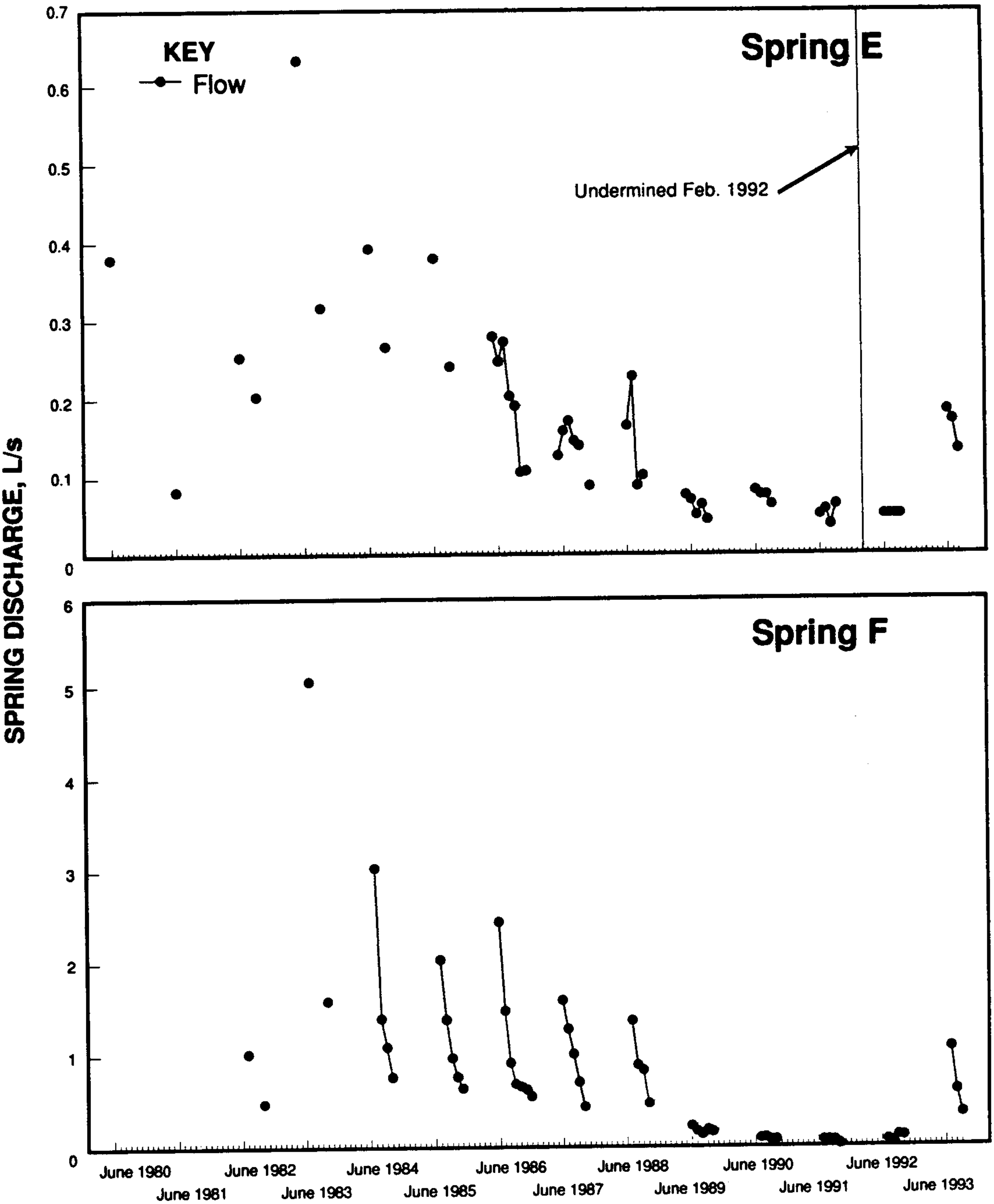


Figure A-2.—Continued.



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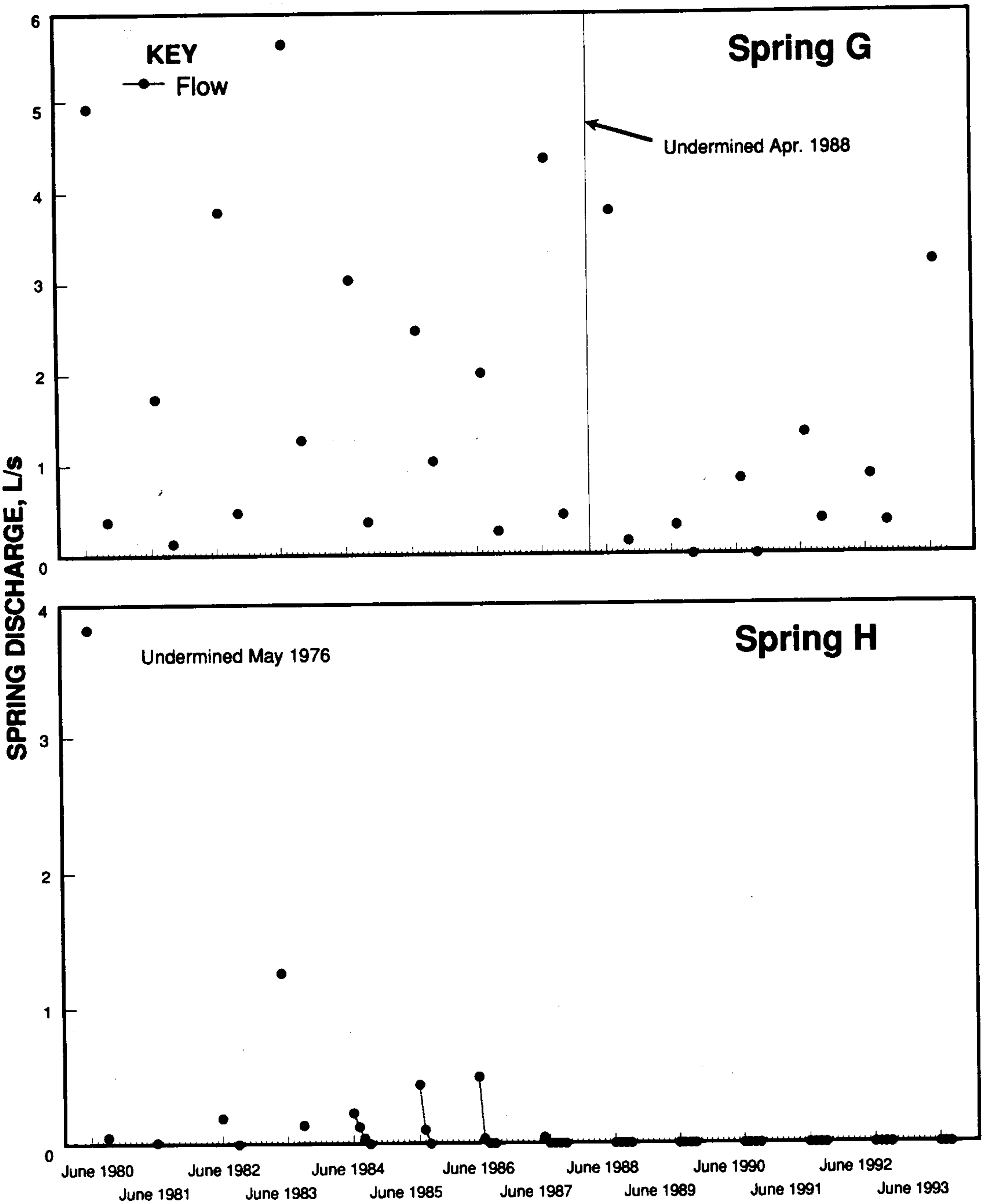

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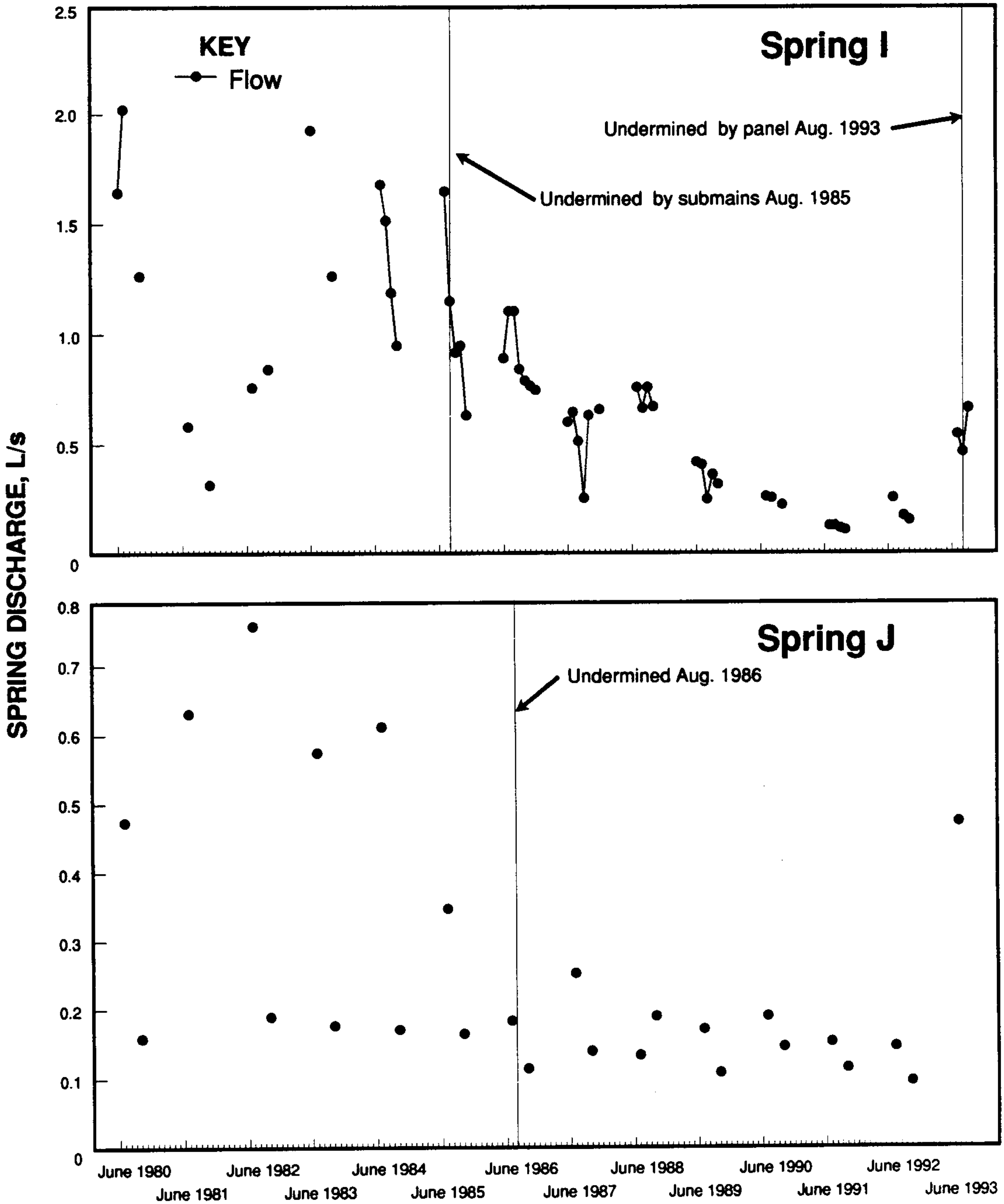

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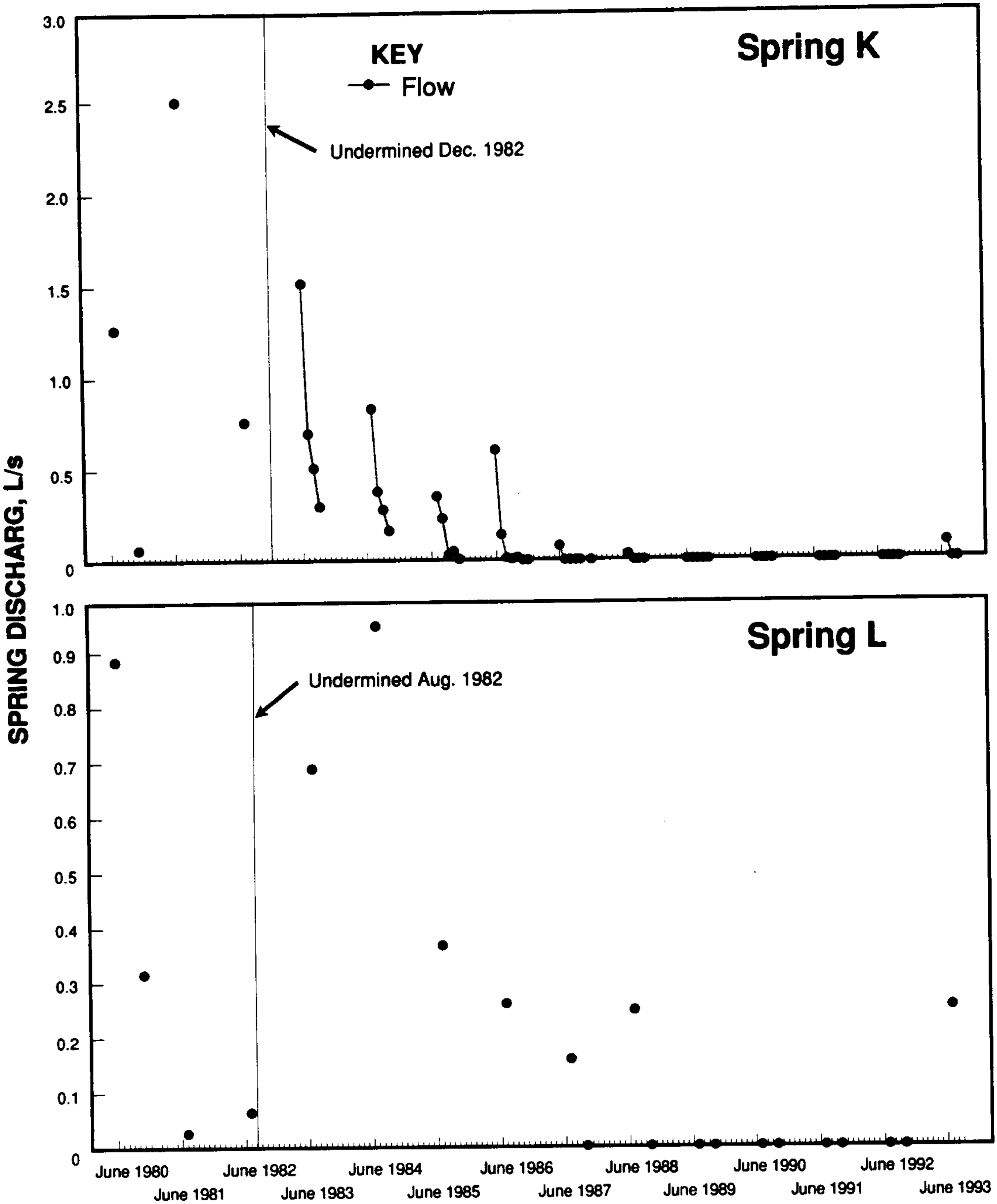

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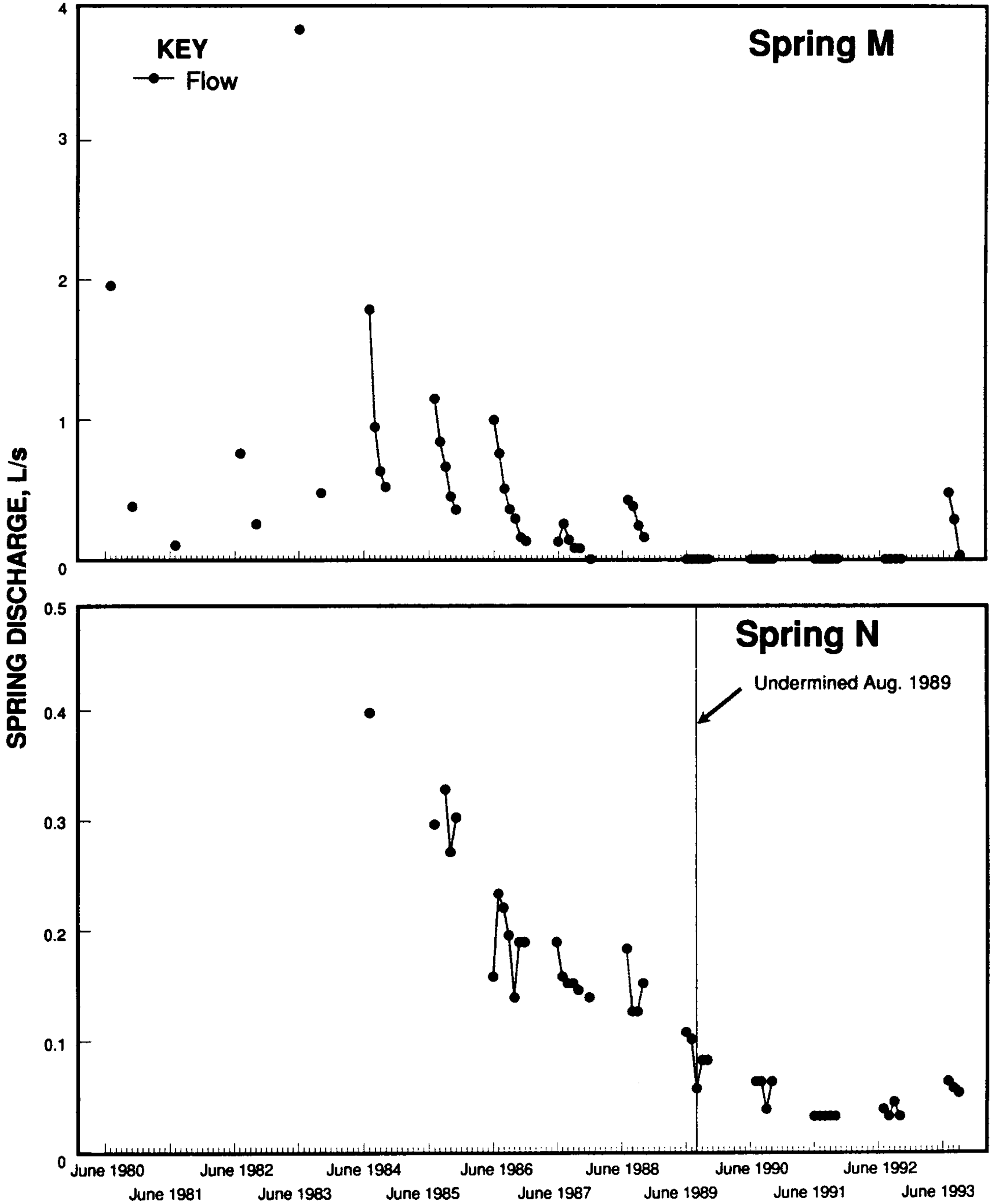

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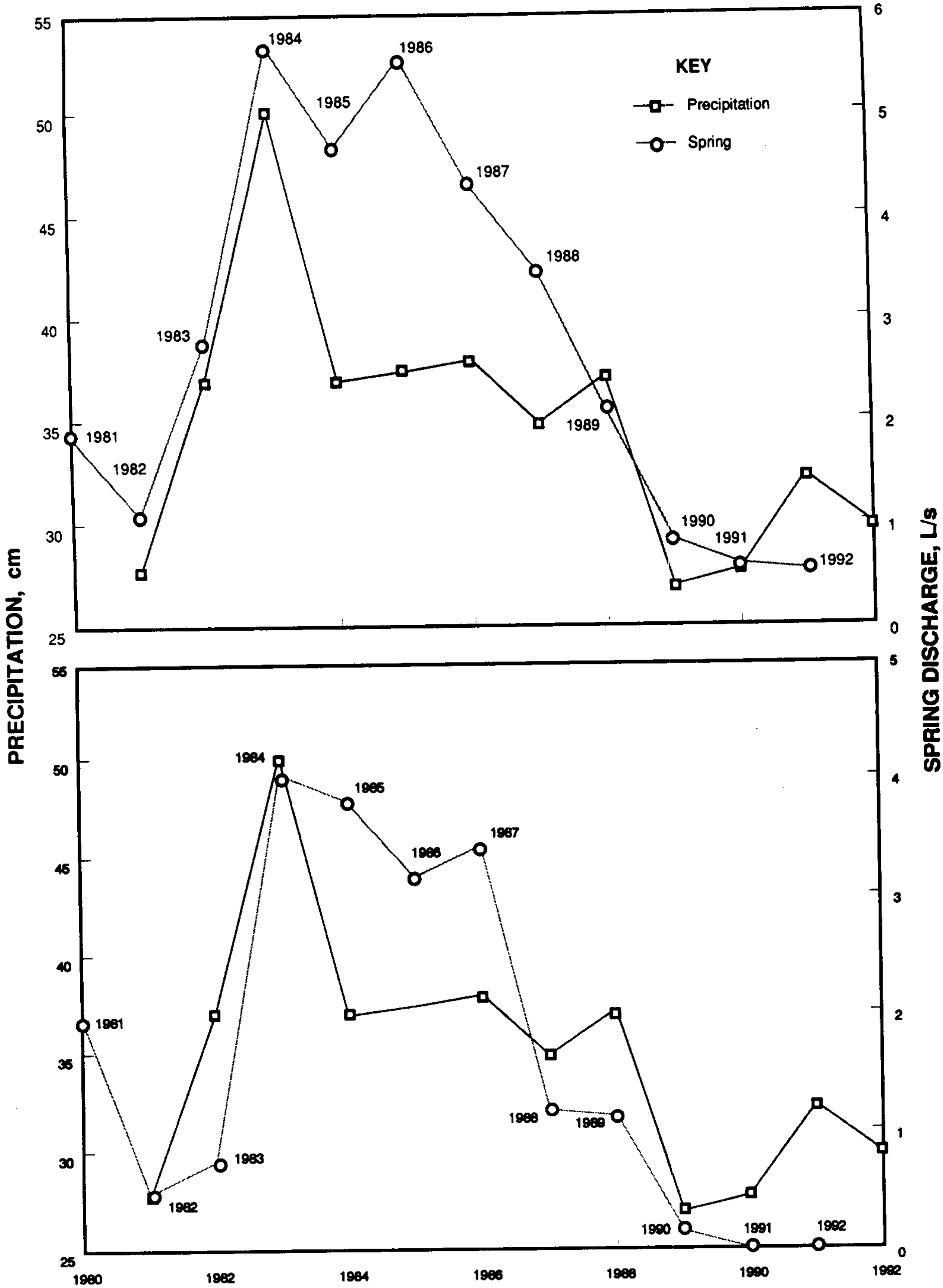

Figure A-3.—Cross-correlated spring and precipitation data. Top, spring I; bottom, spring M.

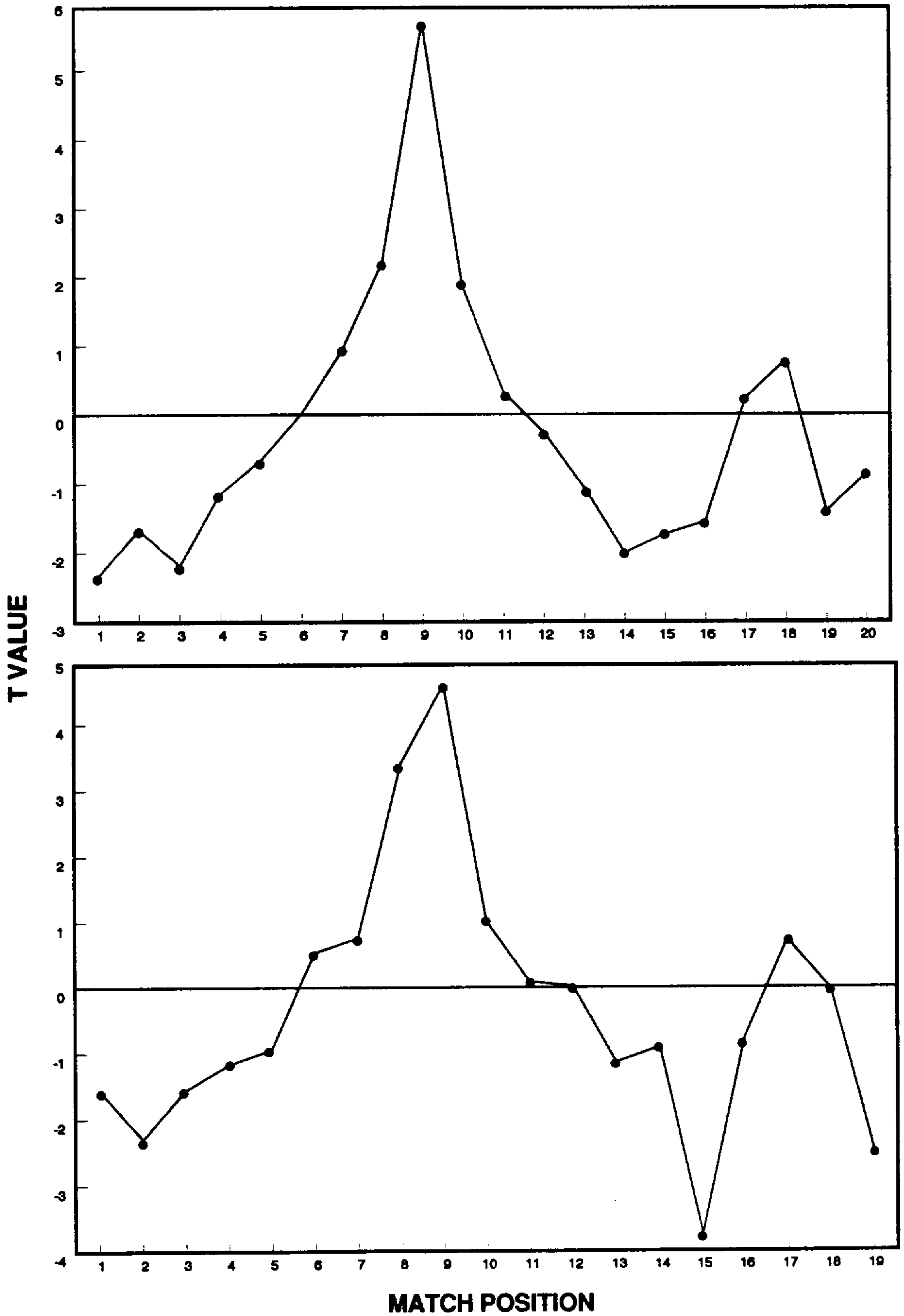

Figure A-4.—Match position versus T value. Top, spring I; bottom, spring M.