SUMMARY AND INTERPRETATION OF DYE-TRACER TESTS TO INVESTIGATE THE HYDRAULIC CONNECTION OF FRACTURES AT A RIDGE-AND-VALLEY-WALL SITE, NEAR FISHTRAP LAKE, PIKE COUNTY, KENTUCKY

By Charles J. Taylor

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[Plate is in pocket]

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
acre	4,047	square meter
	0.4047	hectare
	0.004047	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi.)	0.1894	meter per kilometer
gallon (gal)	3.785	liter
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
mile per day (mi/d)	1.609	kilometer per day
pound (lb)	0.4536	kilogram
square mile (mi^2)	2.590	square kilometer

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

Dye concentrations used in this report are given in metric units, micrograms per liter (µg/L). Micrograms per liter is a unit expressing the concentration of a chemical in solution as weight (micrograms) of solute per unit volume (liters) of water.

Summary and Interpretation of Dye-Tracer Tests to Investigate the Hydraulic Connection of Fractures at a Ridge-and-Valley-Wall Site, Near Fishtrap Lake, Pike County, Kentucky

By Charles J. Taylor

Abstract

Dye-tracer tests were done during 1985-92 to investigate the hydraulic connection between fractures in Pennsylvanian coal-bearing strata at a ridge-and-valley-wall site near Fishtrap Lake, Pike County, Ky. Fluorescent dye was injected into a core hole penetrating near-surface and mining-induced fractures near the crest of the ridge. The rate and direction of migration of dye in the subsurface were determined by measuring the relative concentration of dye in water samples collected from piezometers completed in conductive fracture zones and fractured coal beds at various stratigraphic horizons within the ridge. Dye-concentration data and water-level measurements for each piezometer were plotted as curves on dye-recovery hydrographs. The dye-recovery hydrographs were used to evaluate trends in the fluctuation of dye concentrations and hydraulic heads in order to identify geologic and hydrologic factors affecting the subsurface transport of dye.

The principal factors affecting the transport of dye in the subsurface hydrologic system were determined to be (1) the distribution, interconnection, and hydraulic properties of fractures; (2) hydraulic-head conditions in the near-fracture zone at the time of dye injection; and (3) subsequent short- and long-term fluctuations in recharge to the hydrologic system. In most of the dye-tracer tests, dye-recovery hydrographs are characterized by complex, multipeaked dye-concentration curves that are indicative of a splitting of dye flow as ground water moved through fractures. Intermittent dye pulses (distinct upward spikes in dye concentration) mark the arrivals of dye-labeled water to piezometers by way of discrete fracture-controlled flow paths that vary in length, complexity, and hydraulic conductivity. Dye injections made during relatively high- or increasing-head conditions resulted in rapid transport of dye (within several days or weeks) from near-surface fractures to piezometers. Injections made during relatively low- or decreasing-head conditions resulted in dye being trapped in hydraulically dead zones in water-depleted fractures. Residual dye was remobilized from storage and transported (over periods ranging from several months to about 2 years) by increased recharge to the hydrologic system. Subsequent fluctuations in hydraulic gradients, resulting from increases or decreases in recharge to the hydrologic system, acted to speed or slow the transport of dye along the fracture-controlled flow paths.

The dye-tracer tests also demonstrated that mining-related disturbances significantly altered the natural fracture-controlled flow paths of the hydrologic system over time. An abandoned underground mine and subsidence-related surface cracks extend to within 250 ft of the principal dye-injection core hole. Results from two of the dye-tracer tests at the site indicate that the annular seal in

the core hole was breached by subsurface propagation of the mining-induced fractures. This propagation of fractures resulted in hydraulic short-circuiting between the dye-injection zone in the core hole and two lower piezometer zones, and a partial disruption of the hydraulic connection between the injection core hole and downgradient piezometers on the ridge crest and valley wall. In addition, injected dye was detected in piezometers monitoring a flooded part of the abandoned underground mine. Dye was apparently transported into the mine through a hydraulic connection between the injection core hole and subsidence-related fractures.

INTRODUCTION

In summer 1985, the U.S. Geological Survey, in cooperation with the Kentucky Geological Survey and the U.S. Office of Surface Mining Reclamation and Enforcement, investigated ground-water flow in Pennsylvanian coal-bearing strata at a ridge-and-valley-wall site near Fishtrap Lake, Pike County, Ky. The investigation was designed to accomplish the following two main objectives: (1) to evaluate the importance of fractures to the circulation of ground water in a topographic and geologic setting typical of the Appalachian Plateaus Physiographic Province, and (2) to provide evidence to refute a previously held concept that the stratification of sedimentary rocks of relatively low primary porosity and permeability provides hydrogeologic isolation between ridgetops and valley-bottom aquifers in the Appalachian coal fields. Eight core holes were drilled to various depths along the ridge and valley wall to begin the investigation, and a series of down-hole pressure-injection tests were done to identify hydraulically conductive intervals in each core hole. The results of the pressure-injection tests indicated that the most hydraulically conductive intervals in each core hole were associated with fracture zones and coal beds (Davis, 1987). Multiple piezometers were installed in most core holes to monitor changes, over time, in hydraulic head in fracture zones and coal beds at various depths. A dye-tracer test was then done to determine the hydraulic interconnection between the various piezometer zones.

The dye-tracer test was done by injecting rhodamine WT (a red fluorescent dye) into a 61-ft-deep core hole drilled near the crest of the ridge. This core hole penetrates numerous near-surface and (as determined later) mining-induced fractures. The rate and direction of flow of dye to piezometers downgradient from the injection site was determined by collecting water samples and analyzing for the presence of dye. Within 14 days, rhodamine WT was detected in water samples collected from all the piezometers. This result demonstrated not only the hydraulic interconnection of the fracture zones and coal beds within the ridge, but also the rapidity with which dye (in ground water) could migrate through fractures from the ridgetop to the valley floor (estimated at an average velocity of about 36 ft/d by Davis (1987)).

In an effort to confirm and refine the results of the initial dye-tracer test, five additional dye-tracer tests were done at the site during 1987-92. Preliminary evaluations of the data from these subsequent dye-tracer tests indicated that the apparent rate and pattern of dye migration to piezometer zones varied from one test to another and differed significantly from the first tracer test. This variation indicates that the subsurface transport of dyes injected into the ridge was affected by hydrologic properties not present or recognized during the initial dye-tracer test. Because these factors may be of significance to other studies of ground-water hydrology associated with coal-bearing strata in the Appalachian Plateaus Physiographic Province, the collective results of the dye-tracer tests at the site were examined in more detail.

Purpose and Scope

This report presents a summary and interpretation of dye-tracer tests done at the Fishtrap Lake study site during 1985-92, and it identifies and examines the geologic and hydrologic factors that affected the transport of fluorescent dye tracers through fracture zones at the study site. These factors are also expected to control the movement of ground-water contaminants through the type of hydrologic system associated with steep-sided ridge-and-valley topographic settings in the Appalachian Plateaus Physiographic Province. This information should be useful to the refinement of conceptual models of ground-water flow and will aid the development of ground-water monitoring programs needed to assess the effects of coal-mining and other land-use activities on the Appalachian region's ground-water resources.

Description of Study Site

The study site is delineated by the locations of core holes drilled along the crest and west valley wall of a ridge on the north shore of Fishtrap Lake, a U.S. Army Corps of Engineers impoundment on the Levisa Fork of the Big Sandy River in central Pike County, Ky. (fig. 1). The north-south-trending ridge is the topographic drainage divide between the Left Fork of Grapevine Creek to the east and an unnamed intermittent stream to the west. The site is on the Lick Creek topographic quadrangle (1:24,000) in the Kanawha Section of the Appalachian Plateaus Physiographic Province (Fenneman, 1938). This area is characterized by considerable topographic relief between narrow ridgetops and steep-sided valleys. The rugged topography is mostly the result of extensive stream dissection and downcutting of sedimentary rocks that are variably resistant to erosion. Near Fishtrap Lake, land-surface elevations range from more than 1,800 ft on ridgetops to about 700 ft along the valley floors. Land-surface elevations at the core holes at the site range from about 1,360 to 890 ft. The ridge rises to an elevation of more than 1,700 ft above (north of) the uppermost core hole. Underground mining has occurred beneath much of the ridge, and parts of an abandoned underground mine extend to within several hundred feet of the core holes at the site (fig. 1).

Geologic Setting

The eight core holes drilled at the site extend to various depths in strata of the Breathitt Formation of Lower and Middle Pennsylvanian age (McKay and Alvord, 1969). The Breathitt Formation consists mostly of interbedded and intergradational shale, siltstone, sandstone, and coal deposited in a former fluvial-marine environment similar to that of the modern-day Mississippi River delta complex. The stratigraphy of the Breathitt Formation is characterized by complex intertonguing, lensing, and pinching-out of beds. Stratigraphic correlations are difficult at local and intermediate scales, owing to rapid lateral and vertical changes in sedimentary facies within the formation. Determinations of stratigraphic position within the Breathitt Formation must generally be made on the basis of distinctive fossiliferous strata and coal zones.

Lithologic descriptions of rock cores retrieved during core-hole drilling (Davis, 1986) were used to prepare two geologic sections of the study site (pl. 1). Much of the strata at the site consist of interbedded shale (mudstone) and siltstone. Several lenticular and tabular bodies of sandstone also are present. Bedding contacts between sandstone and shale or siltstone units are generally sharply defined, but contacts between shale and siltstone are mostly gradational. The regional dip of strata is to the northeast at about 100 ft/mi; however, the angle and direction of dip of some strata may be locally altered by syndepositional anticlinal and synclinal structures and by paleochannels and other former erosional surfaces (Hunt and others, 1937).

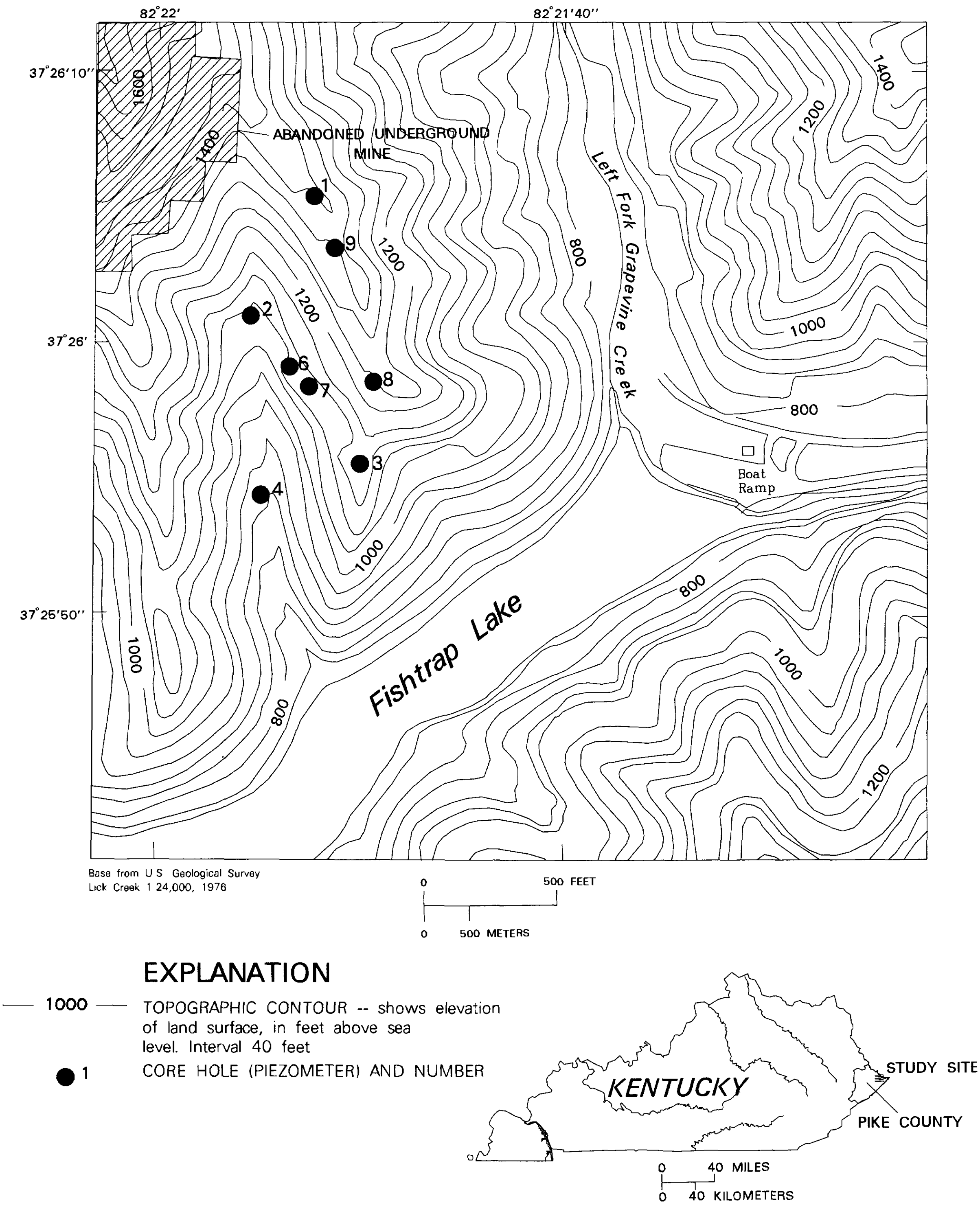

Figure 1. Location of study site, coreholes (piezometers), and part of an abandoned underground mine near Fishtrap Lake, Pike County, Kentucky.

Three coal zones are present at various altitudes within the stratigraphic section (pl. 1). Three thin coal beds (each averaging less than 2 ft in thickness) in the lower part of the section are mapped as members of the Eagle coal zone (McKay and Alvord, 1969). These coal beds crop out near the valley floor at altitudes of about 880, 912, and 940 ft and are separated vertically by intertonguing and interbedded shale, siltstone, and sandstone. A second coal zone is represented by the Clintwood coal bed, situated near the middle of the stratigraphic section at an altitude of about 1,024 ft. It is a laterally continuous coal bed averaging about 6 ft in thickness. The third coal zone is represented by the Lower Elkhorn coal bed, which is at an altitude of about 1,235 ft and averages 6 ft in thickness. The Lower Elkhorn coal bed has been extensively deep mined in the area of the Lick Creek topographic quadrangle including much of the area beneath the ridge at the study site.

Numerous fracture zones were penetrated by the core holes drilled at the site (Davis, 1987). Some fractures are related to regional tectonism, although no mapped faults or major anticlinal or synclinal structures are at the site or in the area included on the Lick Creek geologic quadrangle map. Subvertical joints and horizontal bedding-plane fractures are abundant in brittle rocks such as sandstones and coals and in some of the more competent shales and siltstones. Dense fracturing at right angles to the plane of bedding (cleat fractures) is common to each of the five coal beds at the site (Davis, 1987). Extensive fracturing characterizes the upper 70 to 100 ft of most all bedrock units, regardless of lithology. This shallow fracture system, which is related to tensional stresses resulting from stress relief, erosion, and mass wasting along the ridge crest and valley wall, is typical of the steep-sided terrain in most parts of the Appalachian Plateaus Physiographic Province (Ferguson and Hamel, 1981). At depth and inward towards the core of the ridge, these fractures are much less numerous and well developed because of compressional stresses related to the weight of overlying bedrock.

Hydrogeologic Framework

The hydrogeology of ridge and valley settings in the coal fields of the Appalachian Plateaus Physiographic Province has been conceptualized in detailed studies by Wyrick and Borchers (1981a, b), Kipp and others (1983), Minn (1993), and others. Ground water occurs in primary (intergranular) openings and in secondary (fracture) openings in regolith and bedrock. Secondary openings formed by joints and bedding-plane fractures are much more important to the transmittal of water in the clastic rocks that typify coal-bearing strata in the Appalachian Plateaus (Schubert, 1980). Because of the steep terrain, most recharge occurs on the ridgetops as precipitation infiltrates thin regolith and nearly vertical bedrock fractures. The recharge is mostly distributed and transported by an extensive interconnected network of subvertical and horizontal near-surface fractures (Kipp and others, 1983). Water moves through this near-surface fracture zone under hydraulic gradients influenced by topographic relief.

At depth, the movement of ground water through the stratigraphic section depends largely on the distribution and interconnection of more deeply penetrating fractures and the positions of conductive bedrock strata, which are typically coal beds (Schubert, 1980; Minn, 1993). Large variations in the hydraulic conductivities of the different types of rocks in the stratigraphic section result from differences in lithology, primary porosity and permeability, fracturing, and internal structure or stratification. The layering of strata with differing hydraulic conductivities results in a complex hydrologic system having functionally isolated hydrologic units where well fractured rocks (especially brittle coal beds) conduct most of the flow, saturated zones are generally restricted to the most highly conductive strata, and the water table or potentiometric gradient is vertically discontinuous (fig. 2). Where ground water reaches strata of relatively low hydraulic conductivity, downward flow is impeded and flow is largely directed laterally along the top of the less permeable unit. This lateral flow commonly results in the formation of perched water that discharges to hillside seeps and springs. Nearly vertical joints provide pathways by which ground water infiltrates through confining units and other bedrock units. The hydraulic stratification caused by the alternating sequence of conductive and less conductive bedrock units, topographic influence on flow gradients, and vertical pathways

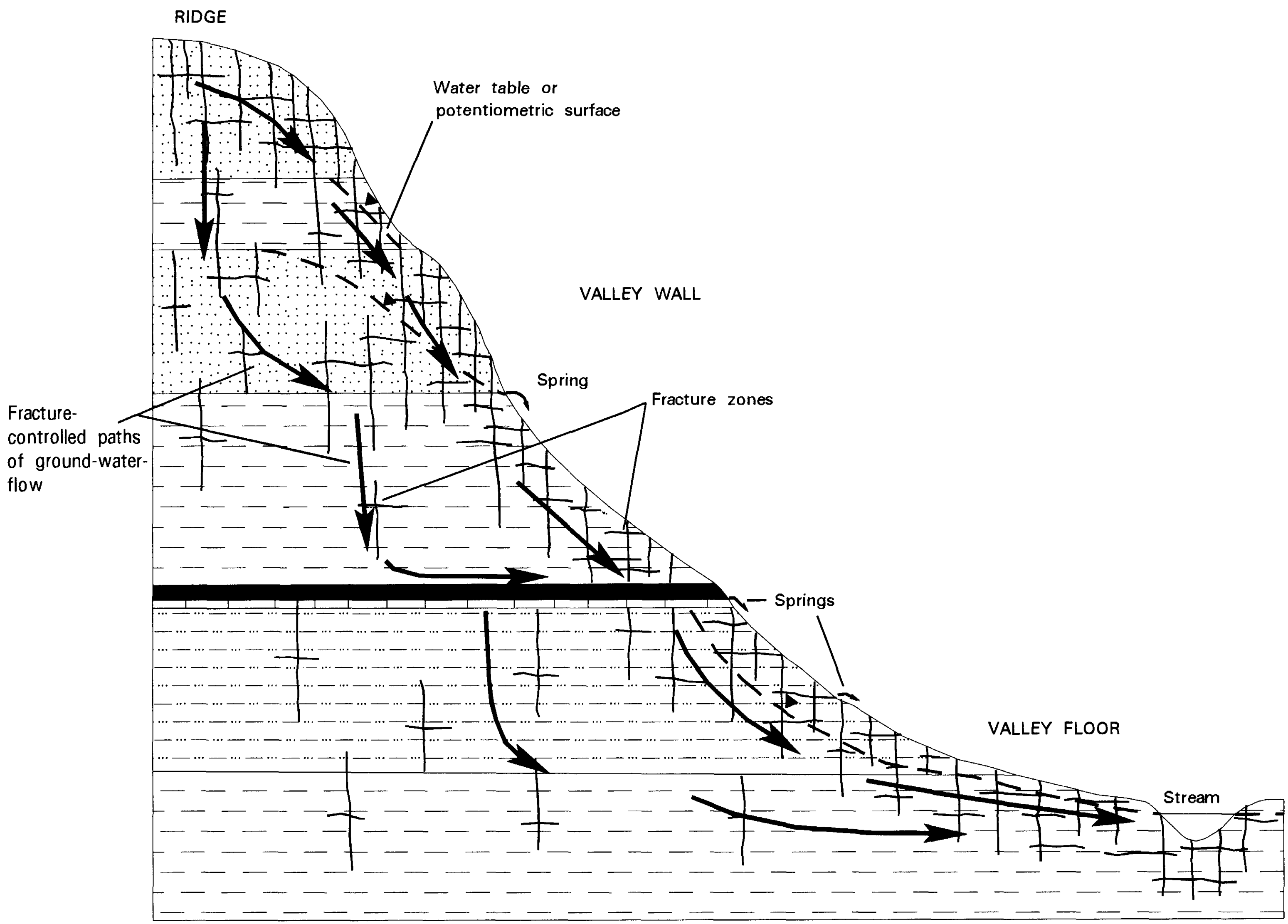

Figure 2. Conceptualized subsurface hydrology of coal-bearing strata at at a typical ridge-and-valley-wall site in the Appalachian Plateaus Physiographic Province, eastern Kentucky.

provided by interconnected joints gives rise to an overall cascading pattern of subsurface flow (fig. 2) in which ground water flows downward through the ridge and outward toward the valley wall (Wyrick and Borchers, 1981a, b; Kipp and others, 1983).

A recent refinement of this general conceptual model of local and regional ground-water flow is described by Minn (1993). Minn's analysis is based on hydrologic data collected at several ridge and valley sites in the eastern Kentucky coal field including water-level and pressure-injection test data from the piezometers at the Fishtrap Lake site. Minn (1993) defines three hydrogeologic zones within a typical steep-sided ridge-and-valley wall in the Appalachian Plateaus: (1) the shallow-fracture zone (SFZ), (2) the elevation-head zone (EHZ), and (3) the pressure-head zone (PHZ). Each hydrogeologic zone is distinguished by variations in flow characteristics and measured hydraulic properties (water quality also is considered in Minn's model but is not discussed here).

As defined by Minn (1993), the SFZ is equivalent to the near-surface fracture zone described in this report and the stress-relief fracture zone described by Wyrick and Borchers (1981a, b) and Kipp and others (1983). Most of the recharge to the hydrologic system results from the infiltration of meteoric waters into the SFZ. Subsurface water moves through the SFZ by gravity drainage. Hydraulic conductivities of fractures in the SFZ are relatively high compared to those of unfractured rock and other fracture zones at greater depths. Little storage is available in the SFZ; therefore, saturated conditions are usually seasonal and transient. The SFZ functions as both a ground-water recharge zone and a discharge zone, and it contributes water to other parts of the near-surface fracture network at lower altitudes along the ridge slope and to conductive zones in the deeper EHZ.

In the EHZ, ground water usually flows under atmospheric (unconfined) conditions. Water levels measured in piezometers in the EHZ are typically controlled by the stratigraphic positions of the most conductive strata, usually fractured coal beds. Large differences in hydraulic conductivity exist between coals and non-coal strata, however, so that hydraulic gradients in rocks between coal beds are steep and horizontal hydraulic gradients are within the coal beds themselves. The alternating horizontal and vertical flow of water through fractures and coal beds in the EHZ forms the basis for much of the cascading flow noted in the conceptual models of Wyrick and Borchers (1981a, b) and Kipp and others (1983). The EHZ provides recharge to the deeper PHZ, and to parts of the SFZ beneath the valley wall.

The PHZ is defined by the occurrence of artesian flow in that part of the stratigraphic section close to the altitude of the local valley floor. Fractures are much less numerous and less well developed in the PHZ than in the SFZ or the EHZ. Confining conditions are a consequence of diminished fracturing and the stratification of conductive units (coals) and less-conductive units within the cores of ridges and lower valley walls. Coal-bed aquifers in this part of the stratigraphic section are typically confined by shaley strata with very poor primary and secondary porosity and permeability. Ground-water flow in the coal-bed aquifers is predominantly lateral, moving toward discharge zones in the lower valley wall and under the valley floor.

Piezometer Network

The piezometers at the site were installed in the most conductive zones identified in each of the core holes (pl. 1). Conductive zones were identified by pressure-injection tests of 5-ft core-hole intervals isolated with inflatable packers (Davis, 1987). As many as three piezometers were installed at different stratigraphic horizons in a single core hole. Piezometers were completed as either open core holes or with porous-cup monitoring zones. The porous cups were installed at the end of 1/2-in. inside-diameter polyvinyl chloride (PVC) tubing, encased in a permeable sand pack extending the full length of the piezometer monitoring zone. Core-hole intervals between individual piezometer monitoring zones were sealed with a cement and bentonite grout mixture.

The piezometer numbering system used by Davis (1987) is retained in this report. Each piezometer is designated by a core-hole number (1-4, 6-9) and a suffix indicating the type of piezometer construction and relative position of the monitoring zone within the core hole. An "OH" indicates installation of an open core-hole piezometer, "PS" indicates a "shallow" porous-cup piezometer, and "PD" indicates a "deep" porous-cup piezometer. A "P" suffix is used where a single porous-cup piezometer was installed in the core hole. Core hole 5 was abandoned because of drilling difficulties and is thus not discussed in this report.

Hydrogeologic Properties of Piezometers

After construction of the piezometer network was completed, decreasing-head slug tests were done to evaluate the hydraulic efficiency of the piezometers (Davis, 1987). The piezometers were slugged with up to several hundred gallons of water and water levels were measured as they returned to static conditions. Water levels measured in all piezometers declined rapidly back to near original static conditions within 20 to 30 minutes, indicating that the monitoring zones of the piezometers were sufficiently transmissible to respond adequately to hydraulic stresses (Davis, 1987).

Minn's summary (1993) of the hydrogeologic characteristics of the piezometers at the study site (table 1) is useful to the interpretation of the dye-tracer test results. The hydraulic behavior of piezometers 2OH, 3OH, 4OH, 6OH, and 8P typifies subsurface flow in the SFZ (shallow-fracture zone). The maximum and minimum water levels in these piezometers (table 1) are controlled by the altitudes of fractures that, depending on head conditions, recharge the piezometer monitoring zone or partially drain it (Minn, 1993). Water-level fluctuations in these piezometers occur in fairly direct response to influx of meteoric recharge or lack of it. During periods of little or no precipitation water levels in these piezometers may decline rapidly, and some SFZ piezometers such as 4OH and 6OH go dry.

According to Minn (1993), piezometers 3PS, 6PS, and 6PD are in the EHZ. The water levels in these are controlled by the stratigraphic position of the Clintwood coal bed. Piezometer 7P also monitors this coal bed and is near core hole 6; therefore, its hydraulic response also typifies ground-water flow in the EHZ. Water levels in these four piezometers do not respond directly to precipitation nor do they exhibit much short-term fluctuation (Minn, 1993). Piezometers 3PS and 6PS, however, go dry during periods of decreased recharge, probably because of drainage through highly conductive fractures near the bottom of the monitoring intervals (pl. 1). Piezometer 7P is completed approximately 20 to 35 ft below a zone of highly conductive fractures; this piezometer stores water because the rate of inflow from these fractures is faster than the rate of outflow through less fractured and less conductive strata in the lower part of the monitoring zone (Minn, 1993). Piezometers 2P, 4P, and 3PD are each completed between altitudes of 855 and 875 ft in coal beds of the Eagle coal zone. Water levels monitored by each of these piezometers are under artesian (confined) pressures, and are indicative of the hydraulic regime of the PHZ.

Minn (1993) did not evaluate hydraulic data from piezometers 1OH, 1PS, 1PD, and 9P because of possible effects of mining activity at the site. These piezometers are proximal to the underground mine and to subsidence-related surface cracks. Piezometer 1OH was completed as an open core hole and intersects numerous fracture zones, some of which are mining induced (Jesse Craft, U.S. Office of Surface Mining Reclamation and Enforcement, oral commun., 1993). Simultaneous water-level fluctuations in the three piezometer zones in core hole 1 indicate a short-circuited hydraulic connection within the core hole, perhaps as a consequence of subsurface propagation of mining-induced fractures and breaching of the annular seal between piezometer zones.

Table 1. Characteristics of piezometers at study site near Fishtrap Lake, Pike County, Kentucky, 1985-92

[Modified from Minn (1993). All elevations and altitudes are in feet above sea level. Piezometer number consists of core-hole number and one of the following abbreviations: OH, open hole; PS, shallow porous cup; PD, deep porous cup; P, porous cup. Monitored-interval codes: SFZ, shallow fracture zone; EHZ, elevation head zone; PHZ, pressure head zone; c, coal bed]

Piezometer number	Total depth (feet)	Land-surface elevation (feet)	Altitude of top of monitored interval	Altitude of bottom of monitored interval	Minimum water-level altitude	Maximum water-level altitude	Monitored-interval hydrogeologic zone
1OH	61.0	1,358.5	1,353.5	1,297.5	1,301.2	1,307.9	SFZ
1PS	209.5	1,358.5	1,168.0	1,142.5	Dry	1,167.1	EHZ
1PD	333.5	1,358.5	1,028.5	1,019.5	1,138.7	1,178.5	PHZ (c)
2OH	25.0	1,059.5	1,048.5	1,031.5	1,047.0	1,052.2	SFZ
2P	183.0	1,059.5	880.5	875.5	884.1	885.5	PHZ (c)
3OH	42.0	1,136.9	1,133.9	1,094.9	Dry	1,102.4	SFZ
3PS	125.0	1,136.9	1,032.9	1,009.0	1,015.4	1,016.3	EHZ (c)
3PD	257.0	1,136.9	883.6	877.7	884.9	893.0	PHZ (c)
4OH	18.0	889.1	886.1	871.1	Dry	878.2	SFZ
4P	32.7	889.1	860.2	855.6	862.0	864.1	PHZ (c)
6OH	44.0	1,093.5	1,090.5	1,049.5	Dry	1,080.9	SFZ
6PS	55.0	1,093.5	1,045.5	1,037.5	1,038.2	1,039.1	EHZ (c)
6PD	91.0	1,093.5	1,031.5	1,001.5	1,008.5	1,009.7	EHZ
7P	110.0	1,105.5	1,085.5	995.5	1,011.2	1,016.0	EHZ (c)
8P	50.5	1,233.5	1,224.5	1,183.0	1,194.9	1,205.8	SFZ
9P	50.5	1,317.5	1,308.5	1,267.0	1,272.3	1,285.9	SFZ

Mining-Related Disturbances

An abandoned underground coal mine occupies an area of about 515 acres beneath the ridge. The mine is in the Lower Elkhorn coal bed, at an altitude of about 1,235 ft, and extends to within approximately 250 ft of core hole 1 (fig. 3). Investigators were unaware of the existence of the mine before 1989. The mine was excavated by the room-and-pillar mining method in the updip direction of the coal, toward the core of the ridge. Most of the mine was later reworked by retreat mining. At that time, pillars of coal that were previously left in place to support the roof of the mine were systematically removed, beginning at the rear of the mine (nearest the study site) and working toward the mine entrance. The roof rock of the mine was allowed to collapse behind the retreating mining operation. As a consequence, large surface cracks, some of which are approximately 1,000 to 1,500 ft in length, have formed on the ridge above parts of the mine where overburden strata have collapsed or subsided (fig. 3).

Most of the surface cracks extend to depths of at least 20 to 30 ft below the surface, although the traces of these fractures may penetrate all the way to the approximate altitude of the mined coal bed. One surface crack trends north to south for approximately 500 ft and extends on the surface to within about 250 ft of core hole 1. Parts of the mine are flooded as a result of entry of surface runoff through the cracks. Water is impounded in the downdip part of the mine, and the buildup of hydraulic head has resulted in the breakout of several seeps along the outer mine wall on the northeast and northwest side of the ridge (fig. 3). Piezometers (fig. 3) were installed on the northeastern flank of the ridge by the former mine operator to monitor buildup of head in the flooded mine. Mine water is periodically discharged through several valved, large-diameter pipes to prevent a hydraulically induced collapse of the mine wall.

No data are available to assess whether water in the flooded parts of the mine contributes recharge to piezometer monitoring zones at the study site. However, results obtained during the later three dye-tracer tests at the site indicate that subsidence cracks may have locally altered ground-water flow directions in the core of the ridge, which resulted in the diversion of dye injected in core hole 1 into the abandoned mine. Subsurface propagation of mining-induced fractures is also suspected to have affected the hydraulic integrity of the two lowest piezometer zones in core hole 1. These issues are discussed in the "Dye-Tracer Tests 5 and 6" section of this report.

Acknowledgments

The writer thanks Jesse Craft, U.S. Office of Surface Mining Reclamation and Enforcement, for his assistance in providing background information about the investigation and mining-related disturbances at the study site, and James Dinger, Kentucky Geological Survey, for providing information about piezometer construction and geology at the study site. Precipitation data presented in this report were provided by the U.S. Army Corps of Engineers, Huntington District Office, W. Va.

DYE-TRACER TEST METHODS

Properties of fluorescent dyes and general ground-water tracing techniques are described by Smart and Laidlaw (1977), Jones (1984a, b), and Mull and others (1988). All dye-tracer tests at the study site were done with either a red dye, rhodamine WT, Color Index (C.I.) Acid Red 338 (Society of Dyers and Colorists, 1971), or a green dye, fluorescein (sodium fluorescein), C.I. Acid Yellow 76. Four of the six dye-tracer tests were done with rhodamine WT. Rhodamine WT is a highly conservative tracer, in that minimal losses of dye occur as a result of interaction with the subsurface aqueous environment. Two of the six dye-tracer tests at the site were done with fluorescein. Fluorescein is considered to be a less conservative tracer than rhodamine WT because it is moderately adsorbed to clay, and its fluorescence may be reduced in acidic waters. Aldous and

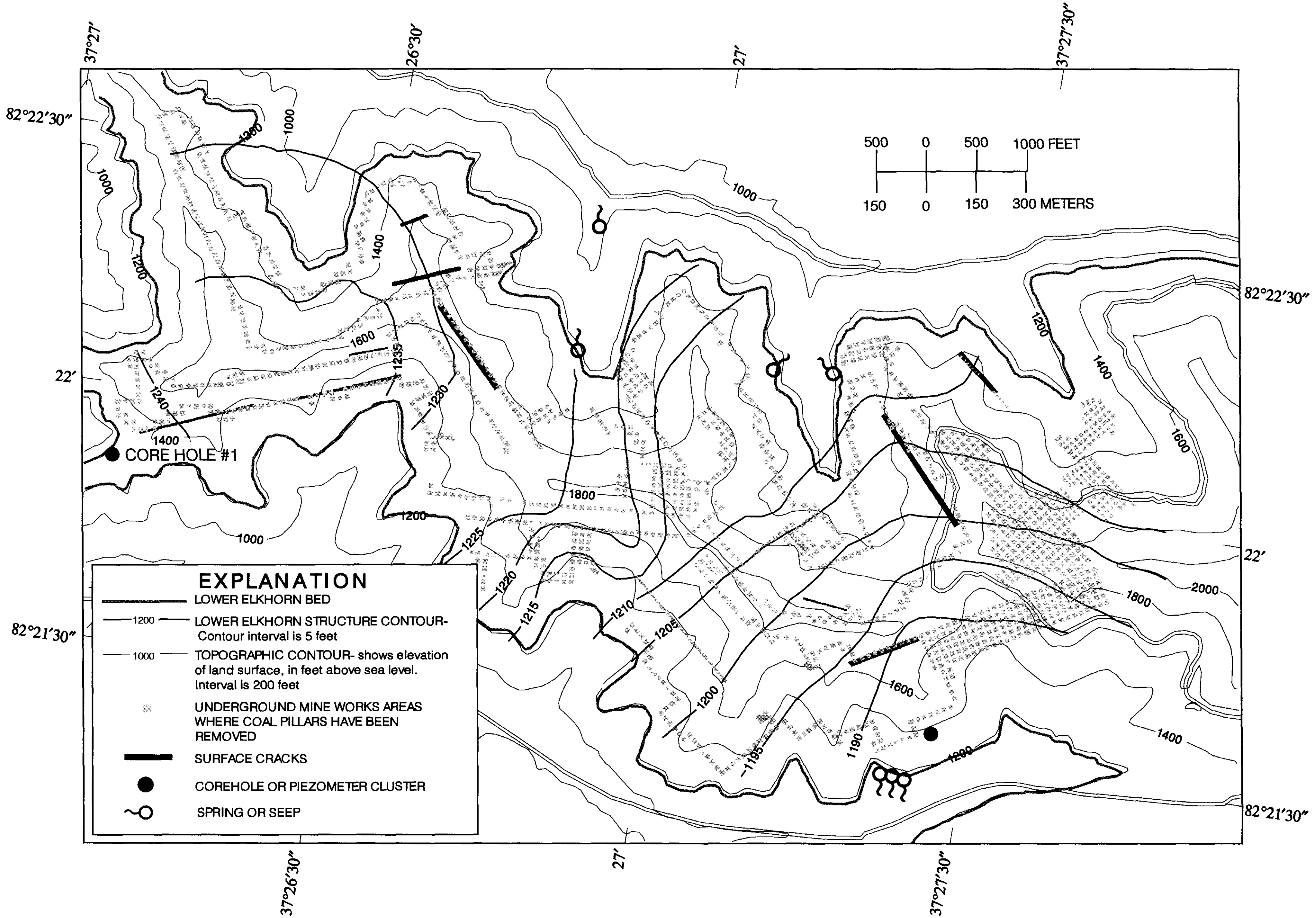

Figure 3. Location of abandoned underground coal mine near study site and locations of surface cracks, dye-injection core hole 1, and mine-monitoring piezometers installed by the former mine operator, Pike County, Kentucky. (Modified from unpublished map provided by Jesse Craft, U.S. Office of Surface Mining Reclamation and Enforcement, 1994)

Smart (1988) reported on laboratory studies that indicated that the fluorescent intensity of fluorescein is retarded by approximately 40 percent in waters having a pH of 4.5 or less. Their study also indicated that the dye may be strongly adsorbed by some mineral precipitates, including ferric hydroxide, which is commonly generated as a result of acidic mine drainage. Quenching of fluorescein by acidic mine waters may have affected the concentration of dye measured in samples taken from the mine-monitoring piezometers during dye-tracer test 6.

Fluorometric analysis of ground-water samples from the piezometers was done to determine the presence of dyes and to monitor their movement at the site. The small diameter of the porous-cup piezometer tubes and the fact that most of the piezometers are slowly recharged (Davis, 1987) made purging of the piezometers before sampling impractical. The water samples were withdrawn from the piezometers by use of a plastic pipette (with a fused tip) attached to the probe of an electric water-level measuring tape. Water samples withdrawn by the pipette were poured into 40-mL glass vials for storage and transport. After each use, the pipette and the water-level tape were triple rinsed with distilled water and thoroughly dried to prevent cross-contamination of subsequent water samples. Water levels were measured in the piezometers before each water sample was withdrawn. Sample vials were stored in a light-tight cardboard box to prevent possible photochemical degradation of dye during transport to the laboratory.

Water samples were collected from each piezometer no more than 1 week before a planned dye injection in order to evaluate background fluorescence. After a dye injection, water samples were usually collected at weekly to monthly intervals throughout a 1-year dye-monitoring period designated for the tracer test. Water samples were usually collected semiweekly during the first 4 weeks after a dye injection. Water samples could not be collected from certain piezometers during some of the dye-tracer tests because of an insufficient amount of recharge.

Ground-water samples were analyzed by use of two Turner Designs[1] Model 10 filter fluorometers. One fluorometer was calibrated for the analysis of rhodamine WT, and the other was calibrated for the analysis of fluorescein. Dye-solution standards were prepared and used to calibrate fluorometers to detect rhodamine WT at a concentration of 0.01 µg/L, and fluorescein at a concentration of 0.1 µg/L. The identification and quantification of dye in the water samples was determined by relating the fluorescent intensity of the sample measured by the fluorometer to that of the dye standards used in calibration. Taking possible analytical errors into account, the practical detection limits of the dyes in collected water samples are estimated to be about 0.03 µg/L for rhodamine WT and 0.3 µg/L for fluorescein. Water was pipetted from the 40-mL sample vial into a glass cuvette and then placed in the appropriate fluorometer for analysis. During this procedure, care was taken to prevent any suspended solids (clays, or other mineral or colloidal matter) contained in the sample vial from being transferred to the cuvette. After the cuvette was inserted into the fluorometer, the relative concentration of dye (or dyes) indicated by the fluorescent intensity was recorded. After analysis of each water sample, the cuvette and pipettes were carefully drained, rinsed several times with tap water and distilled water, and dried. The calibration of each of fluorometer was checked periodically for drift caused by fluctuations in the operating temperature of the instrument; a sample of a dye-solution standard and a distilled water blank were used to assure that proper calibration was maintained.

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

SUMMARY AND INTERPRETATION OF DYE-TRACER TESTS

In all, six dye injections were made at the study site during 1985-91. The results of the initial dye-tracer test made in October 1985 (dye-tracer test 1) described by Davis (1987) are reexamined in this report for comparative purposes. Five subsequent dye injections were made at the site in December 1987 (dye-tracer test 2), June 1988 (dye-tracer test 3), March 1989 (dye-tracer test 4), and May 1991 (dye-tracer tests 5 and 6). The details and results of each of these tracer tests are described in the following sections of this report. A discussion of the approach used to analyze the collective results of the six dye-tracer tests is presented next.

Method of Analysis of Data

A time-series approach was considered to be the most appropriate way to evaluate the collective results of dye-tracer tests for this investigation. A computer spread-sheet program was used to compile all dye-concentration and water-level measurements collected during the six tracer tests into a single data base. The data were plotted on graphs to illustrate changes in water levels and dye concentrations measured in each piezometer during the monitoring period of individual dye-tracer tests. The graphs are termed dye-recovery hydrographs in this report and are presented in the "Supplemental Data" section at the back of this report (figs. 14-54). The dye-recovery hydrographs are organized into three sets: (1) dye-recovery hydrographs for dye-tracer test 1 (figs. 14-26); (2) dye-recovery hydrographs for dye-tracer tests 2, 3, and 4, (figs. 27-38); and (3) dye-recovery hydrographs for dye-tracer tests 5 and 6 (figs. 39-54). Peak fluctuations in dye concentrations and water levels (hydraulic head) in piezometers during each dye-tracer test are represented by upward spikes on the dye-concentration and water-level curves for each dye-recovery hydrograph. Discrete dye pulses are identified on the dye-concentration curves where the peak concentrations of individual upward dye spikes rise to levels at least 2 to 3 times above background. Dye pulses could be identified where the presence of residual dye from a previous dye injection had resulted in the elevation of background-dye concentrations by evaluating the trend in the lowest dye concentrations and establishing a baseline on which the dye concentration spikes that define dye pulses are superimposed. Each dye pulse is interpreted to represent arrival and passage of a discrete quantity of dye-laden water to the monitoring zone of one of the piezometers. Characteristics trends in the arrival of successive dye pulses have been demonstrated to represent certain geologic and hydrologic controls on the migration of a dye tracer through a hydrologic system (Smart, 1988). Hydrologic controls are identified by comparing the trends or patterns of dye pulses relative to fluctuations in hydraulic heads, illustrated by spikes on plotted water-level curves on the dye-recovery hydrographs. To compare the relation between trends in meteoric recharge (precipitation) at the site and fluctuations in water-level and dye-concentration curves, rainfall histograms are plotted beneath each dye-recovery hydrograph in the "Supplemental Data" section of this report. The rainfall histograms were prepared from reported daily precipitation totals obtained from a rain gage operated by the U.S. Army Corps of Engineers at Fishtrap Lake Dam, approximately 1 mi west of the study site.

Limitations of the Data

Discrete sampling techniques commonly fail to accurately represent the frequency and magnitude of changes in a transient hydrologic system, especially if the rate of change is much faster than the frequency of sample collection. The choice of the sampling interval used to collect time-dependent data can introduce biases that are especially troublesome in the interpretation of time-series plots. An example of the effects of this type of sampling bias is illustrated by three hypothetical dye-concentration curves representing plotted dye-concentration data collected at different sampling frequencies (fig. 4). The three dye-concentration curves reflect apparent trends in the concentration of dye in water samples collected continuously and at weekly and semiweekly intervals. The actual fluctuations in dye concentration (represented by continuous sampling in

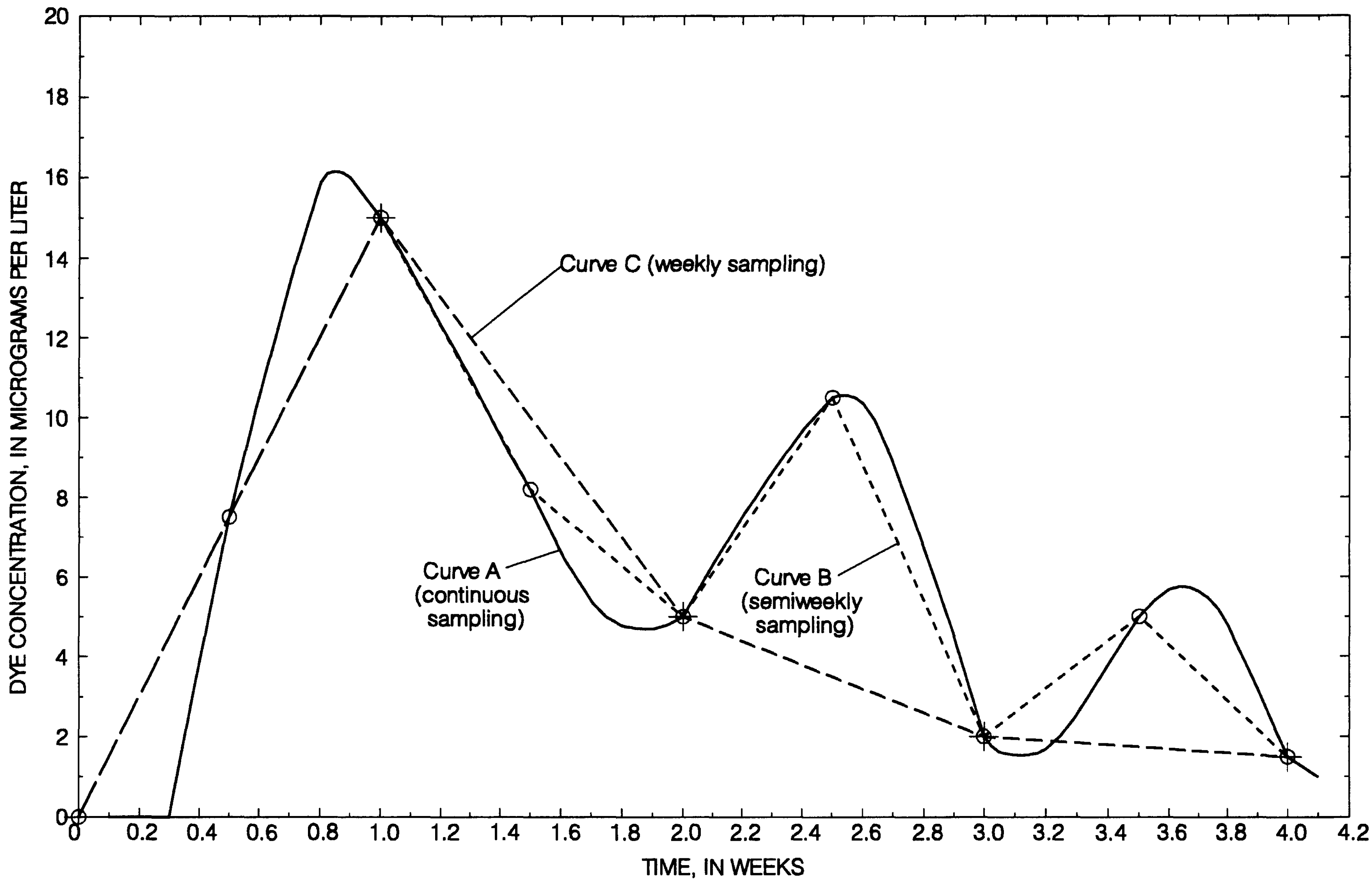

Figure 4. Hypothetical dye-concentration curves illustrating the effects of sampling-interval bias.

figure 4) are poorly represented by data collected on a weekly sampling interval (fig. 4). The more frequent (semi-weekly) sampling interval (fig. 4) more accurately reflects the fluctuations in dye concentration that occurred. Interpretations about peak dye concentrations and arrival of dye pulses to a piezometer are obviously affected by the choice of the sampling interval used to collect the data.

The use of relatively lengthy sampling intervals (weekly to semimonthly) by the investigators who did the dye-tracer tests imparted a sampling-interval bias to the data that likely underestimates the actual magnitude and frequency of fluctuations in dye concentrations and hydraulic head in piezometers. The effects of this sampling-interval bias preclude the use of statistical or other quantitative methods to analyze and compare the dye-tracer test data. Graphical interpretation of plotted data can be effectively used to analyze the apparent trends in dye concentrations and hydraulic heads in piezometers because the sampling-interval bias imparted to the data affects curves plotted on the dye-recovery hydrographs equally for each piezometer monitored during each dye-tracer test. Relative comparisons of trends in dye concentration and hydraulic heads depicted on dye-hydrographs for each piezometer can be made in order to evaluate processes affecting each tracer test.

Dye-Tracer Test 1

Dye-tracer test 1 began on October 24, 1985, with an injection of 1 L of rhodamine WT in core hole 1. Peak dye concentrations were detected in water samples collected on November 7, 1985, from all downgradient piezometers, indicating a maximum traveltime of about 14 days for the migration of dye from the injection core hole on the ridge crest to the valley floor. Dye concentrations were markedly higher in water samples collected from piezometers completed in the Clintwood and Eagle coal zones. Davis (1987) concluded that injected dye moved rapidly under the influence of steep hydraulic gradients through fractures to these coal beds. It seemed that the dye had been flushed rapidly from the near-surface fracture zone after a storm dropped more than 4 in. of rain at the site in 3 days (Davis, 1987). Considering the unusual magnitude and timing of the storm (relative to the injection) and the frequency and short duration of sampling, Davis suggested that additional dye-tracer tests be done to refine and confirm the results of the tracer test under other hydrologic conditions.

Dye-recovery hydrographs prepared from the data reported for dye-tracer test 1 (Davis, 1987) are in the "Supplemental Data" section of this report (figs. 14-26). The water-level and dye-concentration curves for rhodamine WT plotted on the dye-recovery hydrographs for this tracer test are, in general, poorly defined because of the small number of samples (six water samples and three to six water-level measurements per piezometer) and the short duration (4 months) of the dye-monitoring period. Even with these limitations, the dye-recovery hydrographs confirm the general assessment by Davis (1987): dye concentrations peaked early in most piezometers because of a sharp rise in hydraulic heads in the hydrologic system at the beginning of the tracer test, and dye concentrations were highest in deeper piezometers that monitored coal-bed zones.

The dye-recovery hydrographs also indicate that piezometers completed in the SFZ, EHZ, and PHZ (table 1) responded to the dye injection in different ways. Dye concentrations peaked and declined rapidly in SFZ piezometers such as 2OH, 4OH, 8P, and 9P (fig. 16, 21, 25, and 26, respectively). With the exception of 2OH, these piezometers are aligned down the slope of the ridge crest (pl. 1). Rapid movement of dye to these piezometers indicates that the pathway in the near-surface fracture zone (SFZ) is highly conductive beneath the crest of the ridge. Fluctuations in dye concentrations measured in these piezometers are generally coincident with short-term (daily to weekly) fluctuations in water levels. Dye concentrations generally increase and water levels generally rise in these piezometers within a few days of precipitation. The rapid decline in dye concentrations from peak concentrations recorded on November 14, 1985, indicates a relative lack of storage of dye in the SFZ under the hydrologic conditions during the tracer test.

Dye concentrations in piezometers completed in the EHZ and the PHZ also peaked rapidly after dye injection. However, dye concentrations in these piezometers declined at much more gradual rates than those in SFZ piezometers during the same period, and they sometimes stabilized at elevated concentrations. This trend indicates an increased amount of storage and a more gradual discharge of dye-laden water from piezometers monitoring the EHZ and PHZ zones. Dye concentrations measured in the EHZ piezometers and some PHZ piezometers generally correlated with changes in water level, but the elevation of dye concentrations and the occurrence of dye pulses usually lagged several days to a month behind an increase in hydraulic head.

In PHZ piezometers 1PD, 2P, and 4P (fig. 15, 17, and 22), water levels rose and dye concentrations increased until they were considerably elevated (10 or more times background concentration). Dye concentrations in piezometer 6PD (fig. 23) increased gradually during the first 2 months after the injection, then declined slightly during the next 2 months before increasing again toward the end of the monitoring period. The elevated concentrations of dye correlate with long-term (weekly to monthly) changes in hydraulic head. Because of the sampling interval, no short-term (daily to weekly) changes in hydraulic head were detected; therefore, the measured peaks in dye concentration cannot be related directly to individual recharge events.

A somewhat anomalous response to the dye injection was noted for piezometers in core hole 3, on the southern part of the ridge crest (pl. 1). Minute concentrations of dye were detected in piezometer 3OH (fig. 19) more than 2 months after the dye injection. This open-core-hole piezometer is completed at the contact between a massive, fractured sandstone below the Clintwood coal and a shale. A rapid peak and decline in dye concentrations was measured in piezometer 3PD (fig. 20) during the dye-monitoring period, which was more typical of SFZ piezometers than of other PHZ piezometers. Piezometer 3PD monitors the lowest coal bed in the Eagle coal zone and is the furthest point down the crest of the ridge (pl. 1). The relatively weak responses of these two piezometers to the injection of dye is probably related to dilution or depletion of the dye as it migrated to the SFZ and the PHZ at this distant monitoring location.

Dye-Tracer Tests 2, 3, and 4

Dye-tracer test 2 began on December 3, 1987. One liter of rhodamine WT was injected into core hole 1, and 200 gal of water trucked to the site from Fishtrap Lake was used to flush the dye. Water samples and water-level measurements were collected from December 2, 1987, through June 29, 1989. A preliminary evaluation of the results of the tracer test indicated that dye concentrations in most piezometers did not respond to the injection of dye, although concentrations of rhodamine WT in some piezometers rose intermittently above detection limits throughout early 1988. The investigators who made this tracer test therefore concluded that most of the dye had become trapped in water-depleted fractures because hydrologic conditions were relatively dry at the time of the injection. Another dye injection was attempted on June 30, 1988 (dye-tracer test 3), in which 1 L of rhodamine WT was followed by approximately 3,000 gal of water to saturate the fracture network and flush the dye. Water samples were collected from, and water-level measurements were made at piezometers from June 29, 1988, through March 20, 1989. As in dye-tracer test 2, dye concentrations in most piezometers seemed to respond little to the injection; dye concentrations intermittently fluctuated slightly above detection limits through February 1989. The apparently weak response to the dye injection was puzzling and prompted a decision on the part of the investigators to wait until hydrologic conditions were more favorable to attempt another dye injection. Nevertheless, dye concentrations and water levels in piezometers continued to be monitored.

The next dye injection (dye-tracer test 4) was made on March 3, 1989. The dye was injected after several days of rainfall and under the assumption that the hydrologic system had been recharged, even though some shallow piezometers (3OH, 4OH, and 6PS) remained dry. One pound of sodium fluorescein dye solution was injected in core hole 1 using 340 gal of water to flush the dye. Fluorescein was used for the dye tracer test because significantly elevated concentrations of rhodamine WT were being detected in many of the piezometers in the weeks preceding the injection. Water samples and water-level measurements were collected from March 23, 1989, through August 9, 1989.

The dye-recovery hydrographs prepared for the piezometers monitored during dye-tracer tests 2, 3, and 4 are shown in figures 27-38 in the "Supplemental Data" section. The monitoring periods of these three consecutive tracer tests are combined into one period extending from December 2, 1987, through August 9, 1989, on the dye-recovery hydrographs. Separate dye-concentration curves are plotted for rhodamine WT and fluorescein on each dye-recovery hydrograph. Dye-recovery hydrographs were not prepared for piezometers 3PS, 4OH, and 6PS because of the lack of water-level and dye-concentration data.

Dye-concentration curves plotted on some dye-recovery hydrographs indicate that residual quantities of rhodamine WT injected in dye-tracer test 1 were present in SFZ piezometers 2OH, 8P, and 9P (fig. 29, 37, and 38, respectively) and in PHZ piezometers 2P, 3PD, 4P, and 6PD (fig. 30, 32, 33, and 35, respectively) before the injection of rhodamine WT to begin tracer test 2. Dye-concentration curves are skewed to the left in the PHZ piezometers (toward the beginning of the monitoring period) because the highest concentrations of rhodamine WT were detected before or around the time of the second dye injection (December 3, 1987). The slopes of the dye-concentration curves decline sharply from December 1987 through March 1988, and in profile, they resemble typical decay curves. Thus, the steep decline in the dye-concentration curves for the PHZ piezometers represents flushing of the rhodamine WT injected in dye-tracer test 1 from the lower part of the hydrologic system, indicating a residence time in the hydrologic system of more than 2 years for the residual dye.

The injection of rhodamine WT dye into core hole 1 on December 3, 1987 and again on June 29, 1988 does not seem to have significantly affected dye concentrations until several months later and after hydraulic heads increased in the SFZ and EHZ piezometers in early January 1989. Only infrequent pulses of rhodamine WT were detected in SFZ piezometers 3OH, 8P, and 9P (fig. 31, 37, and 38) and in PHZ piezometers 2P, 4P, and 6PD (fig. 30, 33, and 35) between May 1988 and December 1988. Distinctive dye pulses on the dye-recovery hydrographs during this period include (1) a dye pulse detected in piezometer 2P in May 1988, with an apparent peak dye concentration of 1.8 µg/L; (2) a dye pulse detected in piezometer 3OH in December 1988, with an apparent peak concentration measured at 3.1 µg/L; (3) two dye pulses detected in piezometer 4P in June 1988 (just before the June injection date) and August 1988, with apparent peak dye concentrations of 1.1 and 0.7 µg/L, respectively; (4) a dye pulse detected in piezometer 6PD in July 1988, with an apparent peak dye concentration of 0.6 µg/L (again, just before the June injection date). These dye pulses arrived 5 to 8 months after the injection of rhodamine WT in dye-tracer test 2.

The delayed movement and later punctuated transport of rhodamine WT to piezometers after the injection of dye in tracer tests 2 and 3 contrast sharply with the rapid transport of this same dye to piezometers after the injection in 1985 (dye-tracer test 1). A comparison of the two sets of dye-recovery hydrographs for these tracer tests indicates that the principal difference is that the injection of dye for tracer test 1 was made during a period of time when hydraulic heads in the piezometers were high or increasing. In contrast, the injections of dye in tracer tests 2 and 3 were made when hydraulic heads were relatively low or declining. Thus, the capacity for migration and the rate of transport of dyes injected at the site seems to depend on hydraulic heads in the system at the time of injection.

Further evidence for the concept of head-dependent transport of dye is provided by the results of dye-tracer test 4. The fluorescein solution for this tracer test was injected when hydraulic heads in SFZ piezometers were relatively high or increasing. Within several days of the injection, the dye was detected in all piezometers at concentrations as much as 6 times greater than background. The rapid transport of fluorescein in this tracer test is similar to that of the rhodamine WT injected in dye-tracer test 1. During the monitoring period, dye pulses detected in SFZ piezometers responded directly to short-term fluctuations in hydraulic heads, which usually followed rainfall. Multiple dye pulses with apparent peak concentrations ranging from 0.6 to 1.2 µg/L were detected frequently in SFZ piezometers 2OH, 3OH, 6OH, 8P, and 9P (fig. 29, 31, 34, 37, and 38) for several months after the injection. Dye concentrations in these piezometers rose to their highest levels 2 to 3 months after the dye injection in May or June 1989.

Fluorescein dye pulses also reached EHZ and PHZ piezometer zones within 1 week of the dye injection. Dye concentrations fluctuated intermittently at concentrations about 2 to 3 times above background concentrations from April through August 1989 in piezometers 1PD, 2P, and 4P (fig. 28, 30, and 33). Fluctuations in fluorescein concentration in piezometers 6PD (fig. 35) and piezometer 7P (fig. 36) were the most pronounced of any EHZ or PHZ piezometers. Multiple fluorescein dye pulses with apparent peak concentrations of 0.58, 0.7, and 0.85 µg/L were detected in piezometer 6PD at the beginning of the months of April, May, and July 1989. Six successive dye pulses were detected in piezometer 7P from March through July, with apparent peak concentrations ranging from about 0.6 to 0.9 µg/L. The monitoring zone for each of these two piezometers includes the Clintwood coal bed and a densely fractured sandstone beneath. The baseline trend of measured fluorescein concentrations in some SFZ and most PHZ piezometers exhibits a generally increasing slope, indicating that dye concentrations were increasing with the arrival of each successive pulse of fluorescein-labeled water.

Data obtained during dye-tracer test 4 also indicate that the hydraulic integrity of the core-hole seal between piezometers 1PS and 1PD had been compromised. Fluctuations in hydraulic heads and fluorescein dye concentrations after the dye injection on March 23, 1989, indicate that the two piezometer zones were in direct hydraulic communication and that water from the upper piezometer zone was recharging the lower zone. After 340 gal of water was injected into core hole 1 to flush the dye, water levels measured in piezometers 1PS and 1PD rose sharply to their highest recorded levels and they fell rapidly to approximate pre-injection levels by July (fig. 5). Water injected into core hole 1 to flush the fluorescein dye may have migrated directly downward to the two lower piezometers by way of newly opened fractures intercepting the core hole. No evidence of such a direct hydraulic communication between the upper and lower piezometer zones was recorded during previous dye-tracer tests. This apparent short-circuiting of flow between the injection zone and the two piezometer zones seems to have occurred between 1989 and 1991. Given the proximity of the subsidence-related surface cracks to core hole 1, it is possible that subsurface propagation of these fractures breached the annular seal and (or) altered fracture flow paths around core hole 1.

Dye-Tracer Tests 5 and 6

After the completion of dye-tracer test 4, the proximity of injection core hole 1 to the abandoned underground mine and subsidence cracks became a concern. Water-level and dye-concentration responses measured in piezometers 1PS and 1PD during dye-tracer test 4 indicated that the annular seal in the core hole had been breached and that the injection zone and two lower piezometer zones were in direct hydraulic communication. The most probable cause for the loss of hydraulic integrity of the annular seal was thought to be the subsurface propagation of mining-induced fractures near core hole 1 (fig. 3). In an attempt to determine whether subsidence-related fracturing had affected flow paths between injection core hole 1 and other piezometers at the site, or whether such fracturing resulted in diversion of dye to the abandoned underground mine, two concurrent dye-tracer tests were done. On May 21, 1991, 3 L of rhodamine WT solution was injected in core hole 1 (dye-tracer test 5) using approximately 500 gal of water to flush the dye. The next day, 3 lb of fluorescein dye solution was injected into piezometer 9P (dye-tracer test 6) using approximately 300 gal of water. Piezometer 9P is approximately 250 ft downslope from core hole 1 and is completed in the near-surface fracture zone (pl. 1). There is no direct indication that piezometer 9P has been affected by mining-related subsidence. Grab water samples were collected from the downgradient ridge and valley piezometers (fig. 1), seven piezometers at the northeast flank of the ridge in the abandoned, flooded underground mine

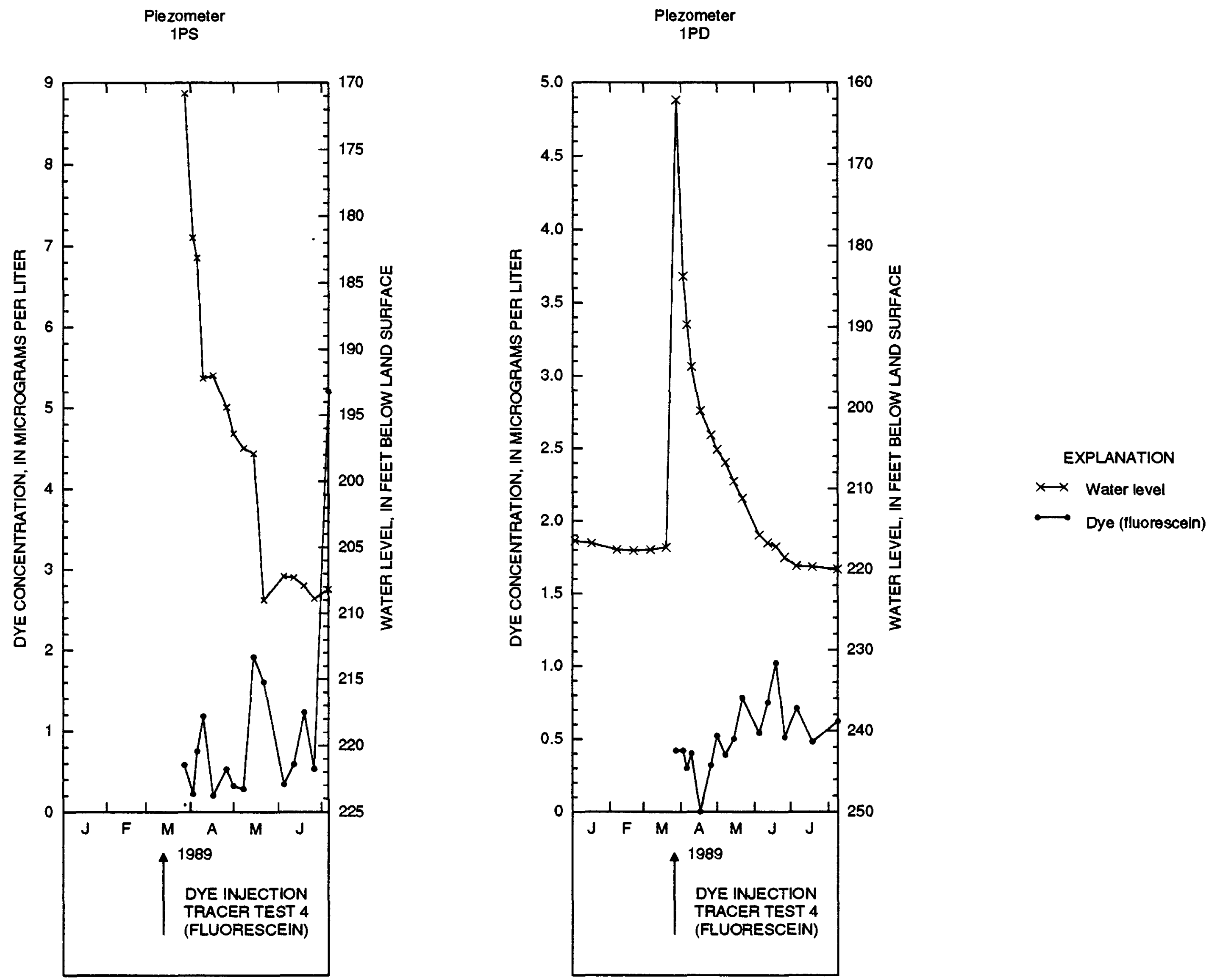

Figure 5. Responses of water levels and dye concentrations in piezometers 1PS and 1PD at the beginning of dye-tracer test 4, at study site near Fishtrap Lake, Pike County, Kentucky.

(fig. 3), several hillside seeps along the northern flank of the ridge (fig. 3), and from the Left Fork of Grapevine Creek (fig. 1). It was anticipated that the rhodamine WT injected in core hole 1 would be detected in the water samples from the mine and in the deepest (PHZ) piezometers at the study site. The fluorescein injected in piezometer 9P was expected to migrate to the SFZ, EHZ, and PHZ piezometers along the ridge crest and valley wall, as in the previous tracer tests. Water samples and water-level measurements were collected from May 21, 1991, through April 7, 1992. Water samples were not collected and water-level measurements were not made during this period for piezometers 1PS, 3PS, 4OH, and 6PS because of insufficient recharge.

The injection of rhodamine WT in core hole 1 does not appear to have affected dye concentrations in most of the piezometers, with the exception of PHZ piezometer 1PD and SFZ piezometer 8P. Low concentrations of residual rhodamine WT (0.03 μg/L or less) were detected in most piezometers at the time of the injection. Dye concentrations did not increase significantly in any piezometers after the injection, with two exceptions. One dye pulse with an apparent peak concentration of 0.6 μg/L was detected in piezometer 1PD (fig. 39) on June 3. The dye pulse is coincident with a sharp increase in hydraulic head, which represents the rapid arrival of injection water to the piezometer. A similar response, which occurred as a result of the hydraulic short-circuiting between the upper dye-injection zone (core hole 1) and the lower piezometer zone (1PD), was observed previously during dye-tracer test 4. In contrast to the earlier tracer test, however, no hydraulic response was detected in piezometer 1PS (which was dry during most of the monitoring period); the injection water apparently bypassed or drained rapidly through this piezometer zone. This indicates that the breach in the annular seal had worsened in the 1-year period between tracer tests 4 and 5. In addition to the dye pulse in piezometer 1PD, two dye pulses were detected in piezometer 8P (fig. 47) in May and June; apparent peak concentrations were 0.09 and 0.05 μg/L, respectively. These may have been random fluctuations in the concentration of residual dye, or, they may have resulted from leakage of dye from the Little Elkhorn coal bed, which is topographically and stratigraphically higher than piezometer 8P. After June 1991, the concentration of rhodamine WT in most all piezometers decreased rapidly to near detection limits (approximately 0.03 μg/L).

The lack of transport of rhodamine WT to most piezometers in dye-tracer test 5 is significant. The dye injection was made during May to September 1991 during a period of prolonged decrease in hydraulic heads in the SFZ and EHZ piezometers. Dyes injected under such hydrologic conditions in tracer tests 2 and 3 became temporarily trapped by storage in water-depleted fractures but were later remobilized as the system was recharged. This remobilization does not seem to have taken place in tracer test 5, even after hydraulic heads began to increase on or about October 1991. The implication is that the hydraulic connection between core hole 1 and the downgradient piezometers had become disrupted as a result of subsidence-related fracturing that occurred sometime between 1989 and 1991. If so, the injected dye may have migrated out of the core-hole injection zone and continued along unmonitored fracture flow paths. Given the limited distribution of piezometers along the ridge and west valley wall, migration of dye north toward the core of the ridge (in the direction of geologic dip) or east toward the valley wall on Left Fork of Grapevine Creek may have occurred; however, rhodamine WT was not detected in any water samples collected from the seeps on the northern flank of the ridge, or in the Left Fork of Grapevine Creek. Rhodamine WT was detected at low concentrations (0.02 to 0.5 μg/L) in water samples collected from several of the mine piezometers; however, it is not clear whether these detections were related to the presence of residual dye from previous injections or dye injected in tracer test 5.

In contrast to the behavior of rhodamine WT, fluorescein was immediately detected at relatively high concentrations in all piezometers, including some piezometers in the abandoned underground mine. Most of the highest concentrations were detected in PHZ piezometers in May and June 1991, just days or weeks after the May 22 injection. Fluorescein concentrations ranged from 2.0 to 7.0 μg/L in PHZ piezometers. Significant dye pulses indicated on dye-recovery hydrographs include (1) a dye pulse with an apparent peak of 7.0 μg/L in piezometer 3PD (fig. 43) in May, (2) a dye pulse with an apparent peak of 4.9 μg/L in piezometer 2P (fig. 41) in May, and (3) a dye pulse with an apparent peak of 3.5 µg/L in piezometer 6PD in June (fig. 45). Piezometers 2P and 3PD monitor the lowest coal bed aquifer in the Eagle coal bed near the valley floor (pl. 1), and piezometer 6PD monitors the Clintwood coal bed. Dye pulses shown on dye-recovery hydrographs for SFZ piezometers include (1) a dye pulse with an apparent peak concentration of over 0.8 µg/L and 0.4 µg/L in piezometer 8P (fig. 47) and (2) a dye pulse with an apparent peak concentration of 1.7 µg/L in piezometer 3OH (fig. 42). Dye concentrations measured in most other SFZ and EHZ piezometers were generally less than 1.5 µg/L.

The fluorescein dye-concentration curves plotted on most of the dye-recovery hydrographs for dye-tracer test 6 are greatly skewed to the left because the highest dye concentrations were detected in May and June 1991, at the beginning of the dye-monitoring period. After this time, dye concentrations decreased rapidly. The profiles of the dye-concentration curves resemble those of typical decay curves. The steeply declining slopes of the curves, which indicate that dye was being flushed from the piezometer monitoring zones, are similar to those plotted for the piezometers in which residual concentrations of rhodamine WT were detected in the early part of the dye-monitoring period for dye-tracer test 2. Therefore, the fluorescein detected in the piezometers in May and June 1991 was probably not the dye that was injected during dye-tracer test 6 in piezometer 9P but rather was residual fluorescein injected during dye-tracer test 4. Because the fluorescein used in dye-tracer test 4 was injected in June 1989, and the apparent flushing of dye from piezometers in the lower aquifer zones occurred from May through July 1991, a residence time of slightly more than 2 years is indicated. This result agrees with the data collected in dye-tracer test 2.

Residual fluorescein dye was also detected at high concentrations in some mine-water samples (figs. 48-54). Dye-concentration curves on dye-recovery hydrographs for mine-monitoring piezometers exhibit spiked profiles similar to those plotted for fluorescein in SFZ piezometers in this tracer test and in dye-tracer test 4. The spiked pattern of dye pulses from May to July 1991 indicates that the transport of dye into and through the mine was controlled by multiple branching flow through various interconnected fractures, channels, and possibly voids between rocks in the collapsed part of the mine. Dye-concentration curves for mine piezometers JW-1, JW-4, and JW-5 (fig. 48, 51, and 52) are greatly skewed to the left because the high dye concentrations were detected in May and June 1991, at the beginning of the dye-monitoring period. After July 1991, dye concentrations declined rapidly, despite intermittent upward fluctuations, indicating that the dye was being flushed from the mine at the same time that dye was being flushed at the PHZ piezometers at the study site.

Although the outcomes of dye-tracer tests 5 and 6 were not as anticipated, the two primary objectives of these tests were completed by August 1991 because (1) dye had been detected in water samples from the flooded, abandoned underground mine; and (2) additional evidence had been obtained to confirm breaching of the annular seal and hydraulic short-circuiting of flow between piezometer zones in core hole 1. Each of these results indicated that the flow of dye had been affected as a result of the presence of subsidence-related fracturing. Therefore, project investigators decided to use bimonthly or longer sampling intervals to finish out the designated 1-year dye-monitoring period. Unfortunately, this decision to change the sampling interval introduces additional bias in the data that makes it difficult to evaluate dye-concentration and water-level curves after August 1991 and to compare that data with data collected before August 1991 and during the previous dye-tracer tests. Before August 1991, the concentration of fluorescein sharply declines in most piezometers. After August 1991, dye concentrations seem to fluctuate in response to long-term changes (monthly to seasonal) in hydraulic heads in piezometers, regardless of hydrogeologic position (SFZ, EHZ, or PHZ). This relation was not evident on dye-recovery hydrographs for any of the previous dye-tracer tests and is probably an artifact of the graphical data presentation related to sampling bias. Moreover, the elevated and gradually fluctuating concentrations of fluorescein are probably affected by the diffusion of fluorescein out of the sandpack in piezometer 9P. In previous dye-tracer tests, dyes were injected into the open-hole interval of core hole 1, so the release of dye from the injection zone was controlled by head-dependent drainage through discrete fracture openings. In the case of tracer test 6, however, the release of dye was controlled by the diffusion of dye from storage in the granular medium used for the piezometer sandpack. Therefore, fluorescein was released continuously into the hydrologic system over time, as reflected in the gradually fluctuating dye concentrations measured in all piezometer zones. For this reason, dye-tracer test 6 was not successful in achieving its purpose as a control by which flow of dye from core hole 1 (tracer test 5) could be evaluated.

Factors Affecting Subsurface Transport of Dye

The results of the dye-tracer tests at the Fishtrap Lake study site indicate that the transport of dye in the hydrologic system associated with the fractured coal-bearing strata beneath the ridge crest and valley wall is controlled by a combination of several geologic and hydrologic factors. Analysis of dye-recovery hydrographs indicates that these factors are (1) fracture characteristics—distribution, interconnection, and hydraulic properties; (2) hydraulic head conditions in the near-fracture zone at the time of dye injection; and (3) subsequent short- and long-term fluctuations in ground-water recharge.

Fracture Characteristics

As the geologic sections of the site illustrate (pl. 1), fractures are most numerous within 50 to 75 ft of the land surface and in core holes located nearest the valley wall (core holes 3, 6, and 7). At depth in the ridge, approximately 75 to 100 ft below the surface, fractures diminish in number and are abundant only in more brittle strata, such as coal beds. This pattern of fracture distribution is consistent with that reported in other ridge-and-valley settings in the Appalachian coal fields and is attributable to extensional fracturing related to stress relief (Ferguson and Hamel, 1981; Wyrick and Borchers, 1981a, b; Kipp and others, 1983).

Multiple dye pulses characterize dye-concentration curves on the dye-recovery hydrographs for every piezometer for dye-tracer tests 2 through 6 (fig. 6), regardless of the hydrogeologic zone (SFZ, EHZ, or PHZ) monitored. The lack of multiple dye pulses on dye-concentration curves for piezometers monitored in dye-tracer test 1 can be attributed to sampling biases related to the small number of total samples and the short dye-monitoring period (3 months). In conduit-flow karst aquifers, this type of pulsed dye transport is commonly interpreted as a type of advective dispersion, resulting from channelized flow of dye along braided or branching multiple conduits that differ in length and (or) hydraulic conductivity (Smart, 1988). A similar type of flow regime seems to be an appropriate conceptualization for the hydrologic system in the fractured strata at the Fishtrap Lake site, except that the "conduits" are interconnected, conductive fractures.

Injections into core hole 1 resulted in a splitting of the dye slug by ground-water flow into numerous hydraulically-connected fractures. The arrivals of dye-labeled water to piezometers from these discrete, fracture-controlled flow paths are marked by the successive occurrences of dye pulses on the dye-concentration curves of the dye-recovery hydrographs. The time it takes a dye pulse to travel to a piezometer monitoring zone is directly affected by the length and complexity of the individual fracture flow path. Increasing or decreasing hydraulic gradients, resulting from fluctuations in recharge to the hydrologic system, act to speed or slow the transport of dye along the fracture-controlled flow paths.

The combined effects of length of fracture-controlled flow paths and increasing or decreasing recharge on the transport and behavior of dye tracers in the hydrologic system is best illustrated by data collected during dye-tracer tests 2, 3, and 4 (figs. 27-38). Two characteristic patterns in dye pulses are evident in dye-recovery hydrographs for piezometers monitored during these three tracer tests. The two patterns can be best described as serrated and spiked. Dye-concentration curves for fluorescein detected in water samples from piezometers 2OH, 6OH, 6PD, and 7P (fig. 29, 34, 35, and 36, respectively) and for rhodamine WT and fluorescein detected in water samples from piezometers 3OH, 8P, and 9P (fig. 31, 37, and 38, respectively) are generally

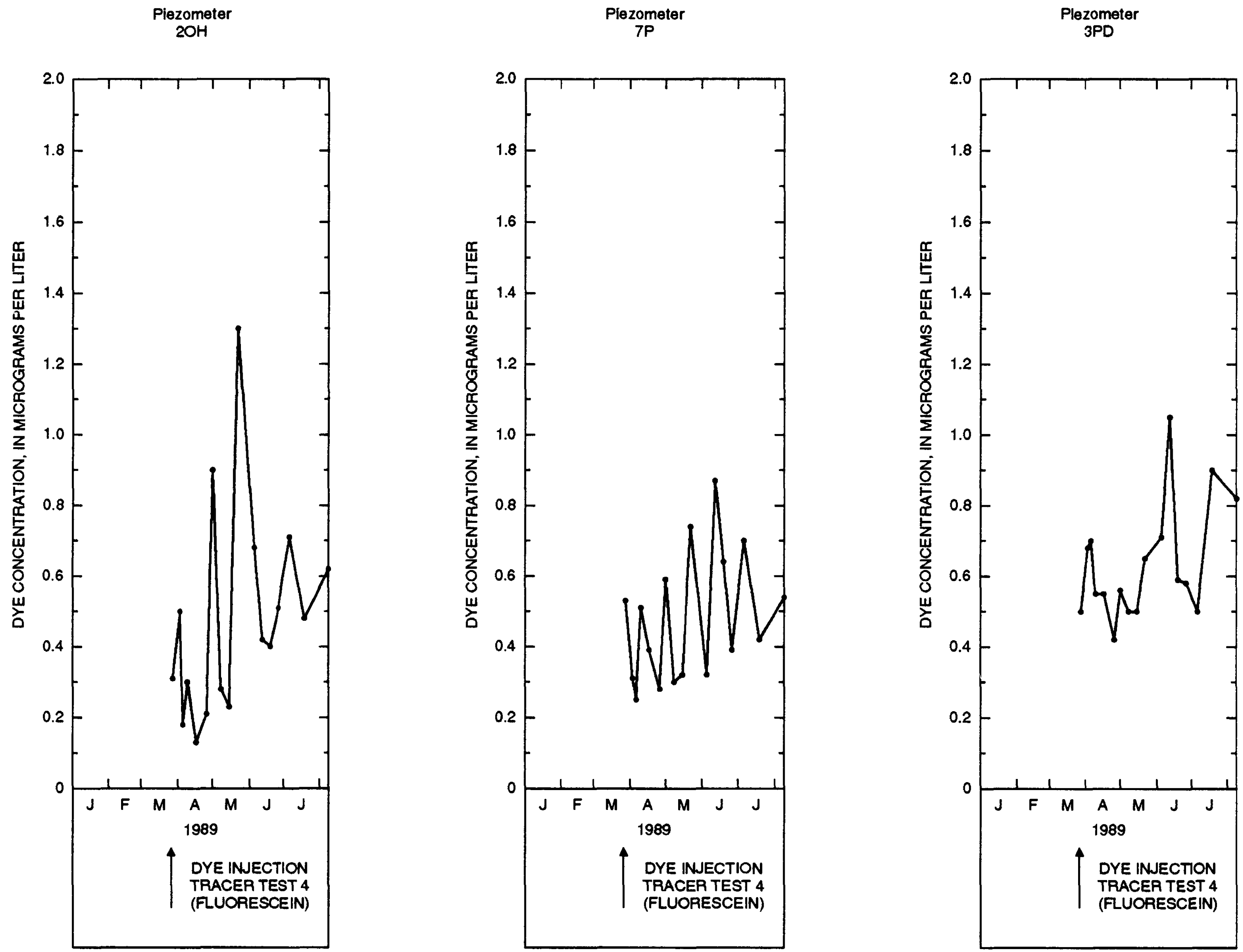

Figure 6. Examples of multiple dye pulses on dye-concentration curves for shallow-fracture-zone piezometer 2OH, elevation-head-zone piezometer 7P, and pressure-head-zone piezometer 3PD, at study site near Fishtrap Lake, Pike County, Kentucky.

characterized by spiked patterns. The dye-concentration curves for fluorescein and rhodamine WT detected in water samples from piezometers 2P, 3PD, and 4P (fig. 30, 32, and 33, respectively) are generally characterized by serrated patterns.

Spiked dye-concentration curves have well-defined dye pulses that abruptly increase to apparent peak concentrations and then sharply decline back to background concentrations. The spiked pattern is mainly limited to SFZ and EHZ piezometers (fig. 6, piezometers 2OH and 7P, respectively). The frequent and large fluctuations in dye concentration in these piezometers reflect the high hydraulic conductivities and low storativity associated with the near-surface fracture zone. In contrast, the serrated dye-concentration curves are indicative of piezometers in which changes in dye concentration are somewhat more gradual and dye pulses are muted. Such conditions reflect a lower hydraulic conductivity, increased storativity, and more dispersion of dye. The serrated pattern is mostly limited to PHZ piezometers (fig. 7), particularly those piezometers that monitor the coal beds in the Eagle coal zone near the valley floor in the deepest part of the hydrologic system (pl. 1).

Shallow piezometer 2OH exhibits characteristics associated with both types of dye-concentration curve patterns (fig. 29): the dye-concentration curve for rhodamine WT seems to be of the serrated type, and the dye-concentration curve for fluorescein is typical of the spiked type. The monitoring zone for this piezometer includes the Clintwood coal bed and parts of an overlying sandstone (pl. 1). The occurrence of each of the two curve types might reflect variance in the hydraulic properties of the monitored zone as a consequence of local head conditions—whether dye flow was conveyed primarily (1) through the coal under low-head conditions (which is probably what happened in tracer tests 2 and 3, giving rise to the serrated rhodamine WT curve) or (2) through fractures in the overlying sandstone under high-head conditions (which is probably what happened in tracer test 4, giving rise to the spiked fluorescein curve).

Preferential directions of flow along branching fractures are not indicated from the results of the dye-tracer tests, although they undoubtedly exist. Ground water can be expected to flow in the directions of steepest topographic slopes through fractures that are oriented in directions that provide the most hydraulically efficient pathway. The presence of a major ground-water-flow path in the near-surface fracture zone beneath the ridge crest (that parallels the slope of the ridge crest toward the valley occupied by Fishtrap Lake) is indicated by the responses of piezometers 9P, 8P, and 3OH during tracer tests 1 and 4. The flow path is likely to represent a north-south-trending fracture set. The trend of this postulated fracture set parallels the strike of many stream valleys in the area adjacent to the site, including that of Left Fork Grapevine Creek (fig. 1). Fractures trending north-south would be expected to serve as preferential ground-water flow paths because they are oriented in the direction of the steepest hydraulic gradient. Similarly, fractures oriented east-west would serve as preferential paths for ground water flowing from the ridge crest toward the valley wall. The rapid responses of piezometers 2OH, 6OH, and 7P (which are along the wall of the tributary valley west of the ridge) to injections in core hole 1 support this conclusion.

Hydraulic-Head Conditions

The hydraulic-head conditions in the near-surface fracture zone at the time of dye injection are a principal factor affecting the transport of dyes at the Fishtrap Lake study site. Rapid transport of dye (within several days or weeks) from near-surface fractures at the injection point to downgradient piezometers occurred only where dye was injected during high or increasing hydraulic-head conditions. This relation is illustrated by the dye responses recorded in piezometers following the injection of rhodamine WT in dye-tracer test 1 and the injection of fluorescein in dye-tracer test 4. As indicated by water-level curves on dye-recovery hydrographs, each of these dye injections was done at a time when the near-surface fracture zone was charged with water. The injected dye was able to migrate rapidly from fractures in core hole 1 and was transported under high hydraulic gradients to downgradient piezometers. In most SFZ and EHZ piezometers, individual dye pulses

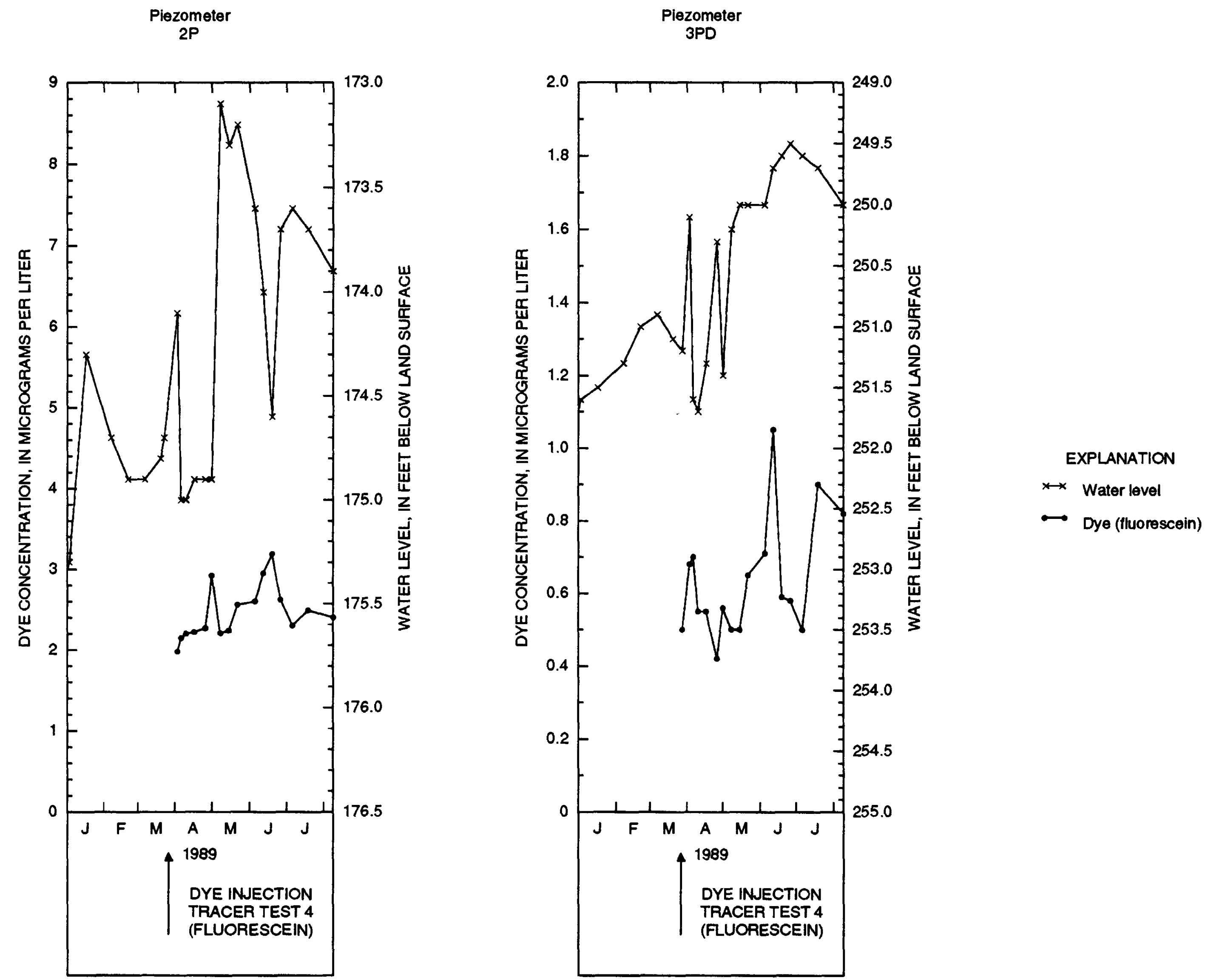

Figure 7. Examples of serrated pattern of dye-concentration curve for pressure-head-zone piezometers 2P and 3PD, at study site near Fishtrap Lake, Pike County, Kentucky.

can be correlated directly to short-term upward fluctuations in recharge. The rate of flow of dye-labeled water through fracture-controlled flow routes of differing lengths introduces a time lag between most of the occurrences of dye pulses and upward fluctuations in hydraulic head that signify recharge to the piezometer zones. The time lag tends to increase with increasing lateral or vertical distance of the piezometer zone from the injection point. This response is illustrated by dye-concentration curves for piezometers 9P, 2OH, and 7P (fig. 8). Piezometers 9P and 2OH are completed in the SFZ, whereas piezometer 7P is completed in the EHZ. Piezometer 9P is on the ridge crest, approximately 250 ft directly downgradient from the injection point. Piezometers 2OH and 7P are along the valley wall at distances of approximately 500 ft and 740 ft, respectively, from the injection point. Although the range of dye concentrations detected in the three piezometers is similar, only dye pulses in piezometer 9P are in phase with upward fluctuations in hydraulic heads. Dye pulses in piezometer 2OH lag slightly behind upward fluctuations in hydraulic head, whereas dye pulses in piezometer 7P lag considerably behind upward fluctuations in hydraulic head.

The negative effects of low or decreasing hydraulic heads on the transport of dye through the hydrologic system are illustrated by data from dye-tracer tests 2 and 3. In each of these dye-tracer tests, rhodamine WT was injected when low hydraulic heads measured in SFZ piezometers indicated depletion of water in the near-surface fracture zone. Movement of dye in the hydrologic system under these conditions was considerably inhibited because the decrease in hydraulic heads resulted in dye migrating from the injection zone through fewer fracture outlets. Dye-labeled injection water leaving the core hole may have been trapped by capillary pressures in intergranular pore spaces, small-aperture fractures in bedrock, and sediment within the fractures.

The diminished recharge to the SFZ, EHZ, and PHZ under low and decreasing hydraulic-head conditions also resulted in long-term (months to years) storage of dye in water-depleted fractures zones. Dyes trapped by this hydraulic dead-zone storage were remobilized when recharge to the fractures resulted in a rise in hydraulic heads. Re-initiated transport of dye to piezometer monitoring zones is indicated where the dye pulses on the dye-recovery hydrographs for SFZ, EHZ, and PHZ piezometers lag several months behind the injections of the dye. This is evident on dye-recovery hydrographs for piezometers 2OH, 2P, 3OH, 3PD, 6PD, 7P, 8P, and 9P, monitored from January 1988 to August 1989, during dye-tracer tests 2, 3, and 4. On the dye-recovery hydrographs for these piezometers, dye pulses of rhodamine WT are diminished in frequency and magnitude (concentration) until after a significant rise in water levels in September 1988 (for example, piezometer 2OH; fig. 9). The correlation between occurrences of individual dye pulses and short-term fluctuations in hydraulic heads become less obvious with increasing lateral and horizontal distance from the injection point because the time of travel for dye increases directly with the length in fracture-controlled flow paths. Individual dye pulses correlate directly with upward fluctuations in recharge (hydraulic heads) in most SFZ piezometers (piezometer 2OH) because of the relatively short distance the dye travels from the injection point. In EHZ and PHZ piezometers (piezometers 7P and 2P, respectively), however, a greater time lag is introduced between the occurrences of individual dye pulses and the upward fluctuations in recharge because dye-labeled water must travel longer, more tortuous routes through interconnected fractures. In EHZ piezometer 7P (fig. 10) and PHZ piezometer 2P (fig. 11) correlations between individual dye pulses and upward fluctuations in recharge can easily be made, but the dye pulses seem to lag 2 to 3 months behind the recharge. In PHZ piezometer 3PD (fig. 12), the upward fluctuations in recharge are entirely out of phase with the occurrences of dye pulses, and it is not possible to correlate the two.

Ground-Water Recharge

In the Appalachian Plateaus Physiographic Province, recharge to the hydrologic system beneath ridges and valley walls occurs principally by the infiltration of precipitation into near-surface fracture zones on ridge crests (Kipp and others, 1983; Minn, 1993). The amount of infiltration directly affects the amount of water available as recharge to the subsurface hydrologic system. Infiltration of meteoric water at the study site is strongly affected by topographic and geologic factors. Antecedent moisture and the degree of saturation in soil

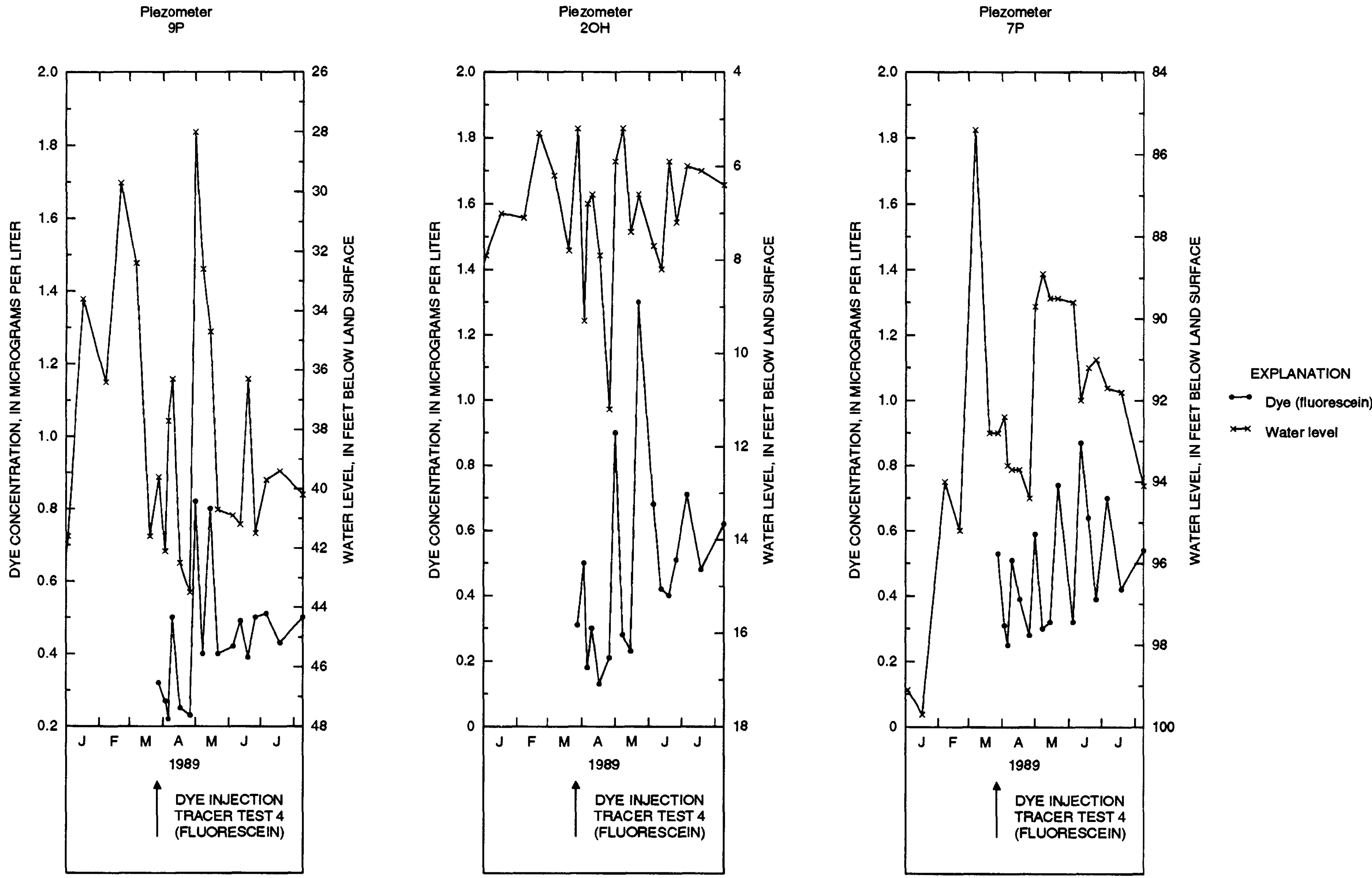

Figure 8. Relation of water-level fluctuations to dye pulses in shallow-fracture-zone piezometers 9P and 2OH, and in elevation-head-zone piezometer 7P, at study site near Fishtrap Lake, Pike County, Kentucky.

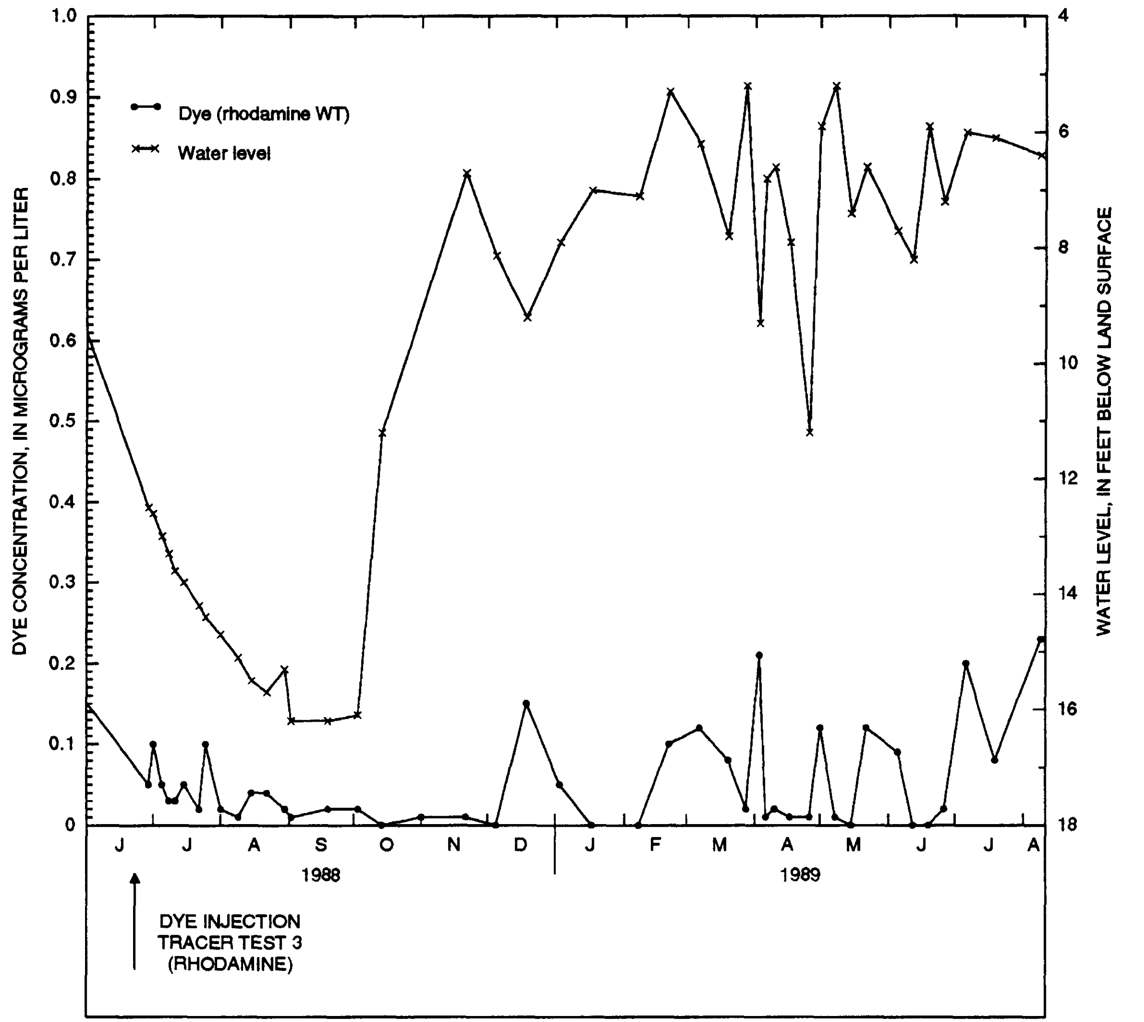

Figure 9. Time-series plot showing dye pulses, water-level fluctuations, and time of dye injection in shallow-fracture-zone piezometer 2OH, dye-tracer test 3, at study site near Fishtrap Lake, Pike County, Kentucky.

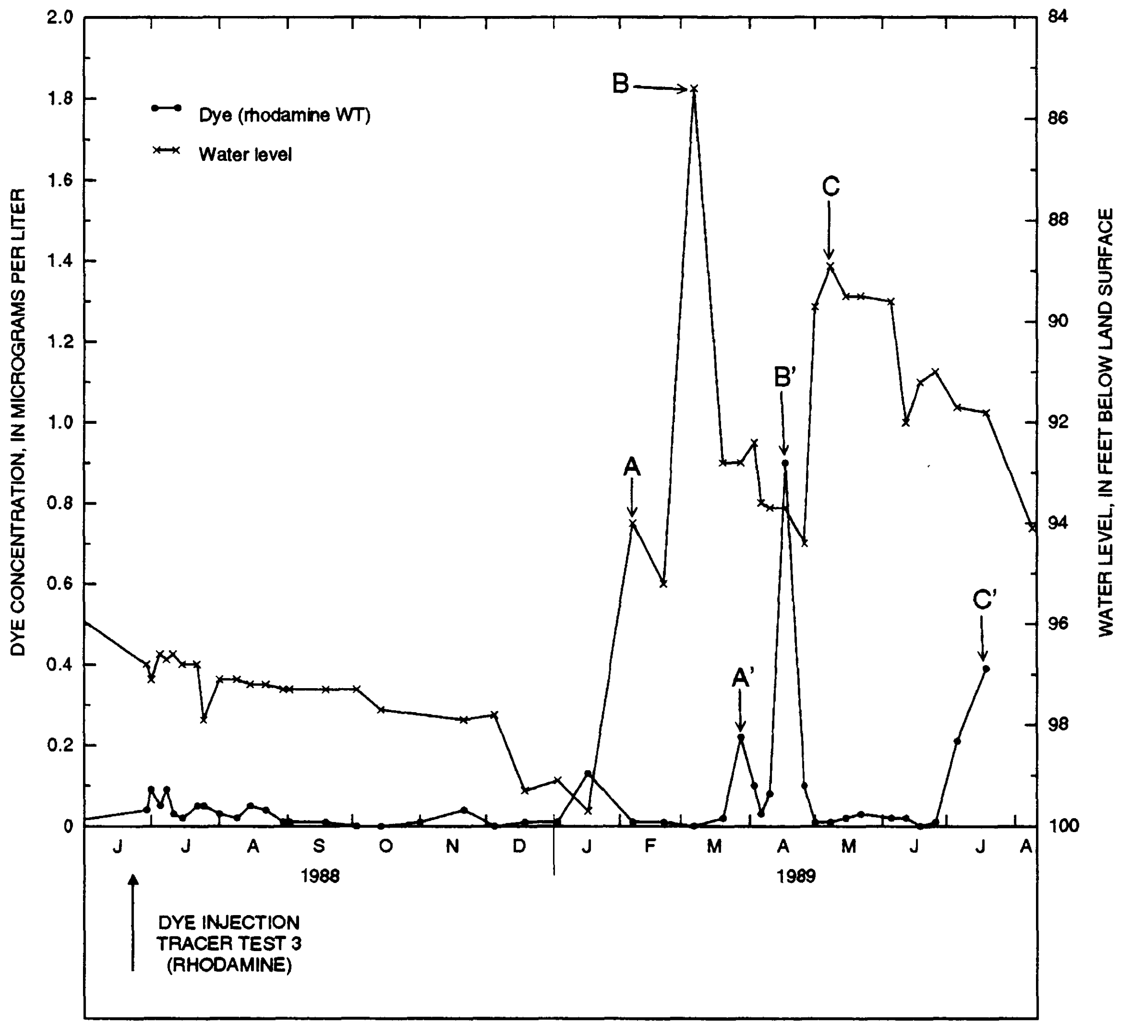

Figure 10. Time-series plot showing dye pulses, water-level fluctuations, and time of dye injection in elevation-head-zone piezometer 7P, dye-tracer test 3, at study site near Fishtrap Lake, Pike County, Kentucky. (Letters (A,A') represent a correlation between peaks on dye-concentration and water-level curves.)

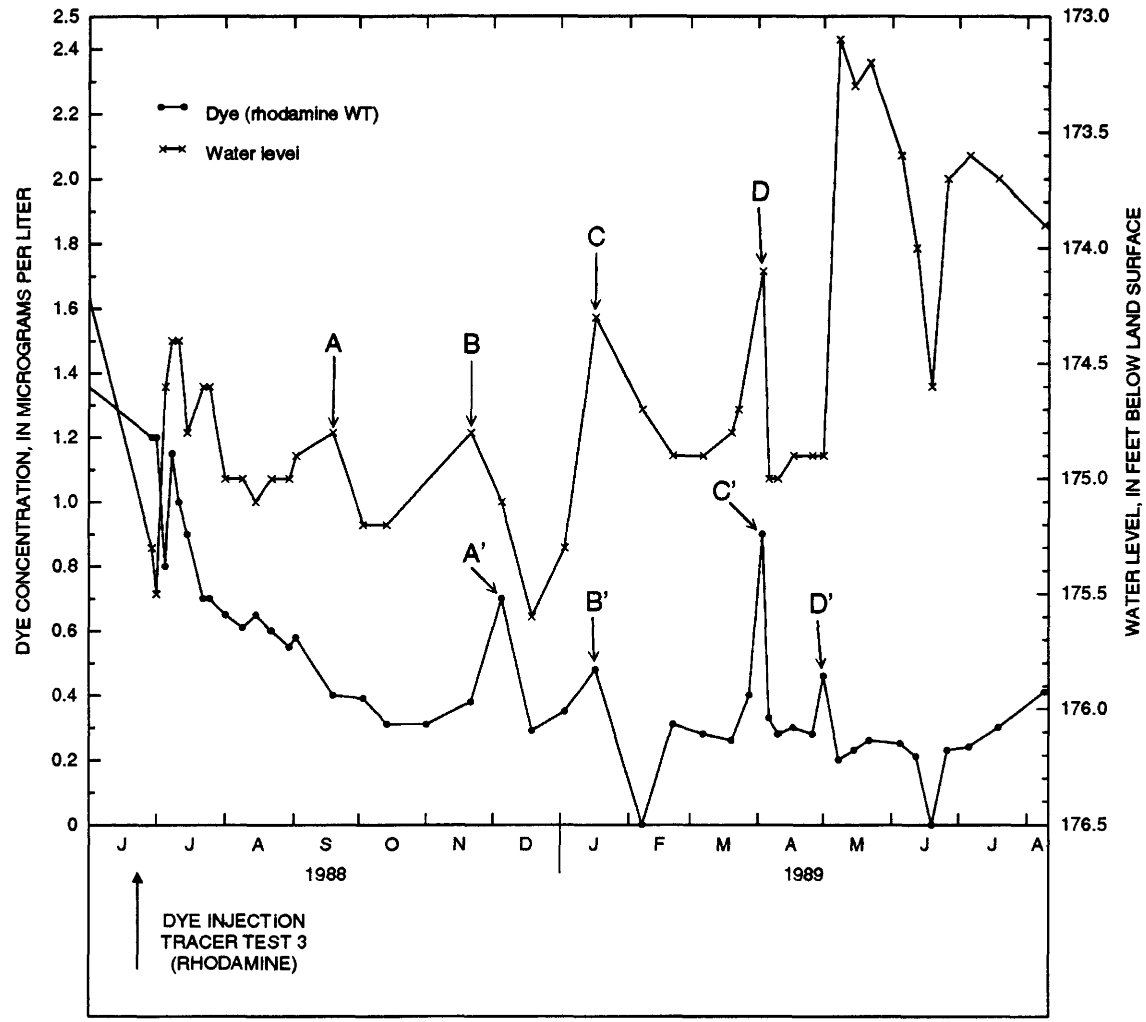

Figure 11. Time-series plot showing dye pulses, water-level fluctuations, and time of dye injection in pressure-head-zone piezometer 2P, dye-tracer test 3, at study site near Fishtrap Lake, Pike County, Kentucky. (Letters (A,A') represent a correlation between peaks on dye-concentration and water-level curves.)

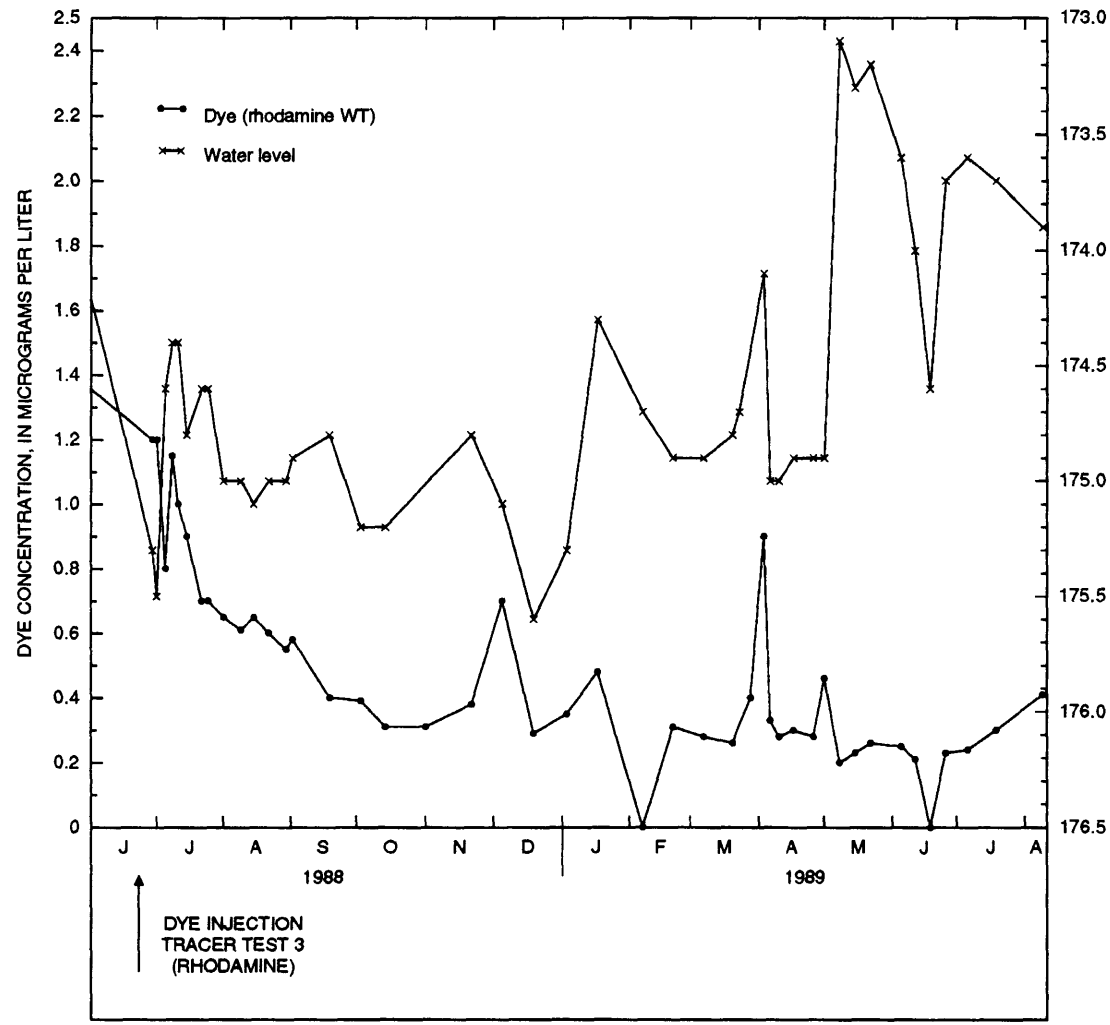

Figure 12. Time-series plot showing dye pulses, water-level fluctuations, and time of dye injection in pressure-head-zone piezometer 3PD, dye-tracer test 3, at study site near Fishtrap Lake, Pike County, Kentucky. (Note general lack of correlation between individual peaks in dye-concentration and water level curves.)

and regolith are important in governing the amount of water that infiltrates the regolith and the near-surface fracture zone. Another factor that has a major affect on the amount of recharge available to the subsurface flow system is the steepness of the topography, in that the steepness controls the fraction of precipitation lost by surface runoff. Steep slopes along the ridge and valley wall at the site shed water quickly, increasing runoff, and considerably reducing the amount of water percolating into the regolith and becoming available as recharge.

Other sources of recharge to the hydrologic system that have not been studied at the site, but which are probably important, include the parts of the near-surface fracture zone at higher elevations on the ridge (upgradient from the study site) and the amount of infiltration and runoff entering subsidence cracks on the ridge. The subsidence cracks provide easy routes of entry to precipitation and surface runoff and increase the vertical and lateral extent of circulation locally within the stratigraphic section. The fractures are linear zones of concentrated recharge. Surface runoff drained to the subsurface by way of subsidence-related cracks (fig. 3) probably contributes greatly to the volume of water flooding the abandoned underground mine beneath the ridge.

Davis (1987) assumed that the rapid transport of rhodamine WT injected in the near-surface fracture zone at the site in dye-tracer test 1 was largely affected by infiltration of precipitation following a storm event in early November 1985. Subsequent dye injections at the site were made after rains under the assumption that dye would be flushed through the aquifer system in a similar manner. Comparison between trends in the measured water-level fluctuations in piezometers and trends in the frequency and amount of rainfall during each of the dye-tracer tests indicates that this assumption was generally not valid. The injections of rhodamine WT in dye-tracer test 1 and fluorescein in dye-tracer test 4 were done when water levels were rising in all piezometers; however, these injections were directly preceded by periods of relatively diminished rainfall. Fluctuations in hydraulic heads, indicated by the upward and downward trends of water-level curves on the dye-recovery hydrographs, are difficult to correlate with trends in the frequency and amount of rainfall indicated on the rainfall histograms. Water levels in some piezometers in the SFZ seem to respond quickly to rainfall, but others do not. Frequent or prolonged periods of rainfall appear to correlate better with positive changes in water levels than do isolated storms with heavy rainfall. Some of the near-surface fracture zone may not have an intrinsic capability to transmit water. The results of several pressure-injection tests reported by Davis (1987) indicated that the effective permeability of some fracture zones in core holes 2, 3, 6, and 7 was fairly low. The diminished fracture permeability may be a consequence of subsurface weathering and breakdown of fractured bedrock and (or) clogging of fractures by washed-in sediment or residuum, a lack of hydraulic interconnection between fractures, or a combination of these. Otherwise, with increasing depth there is an increasing lag in time between rainfall and increasing hydraulic heads because the recharge follows fracture flow paths of increasing length and generally decreasing conductivity. This fact demonstrates the importance of monitoring trends in water level fluctuations at different hydrostratigraphic levels when planning and implementing dye-tracing studies of subsurface hydrologic systems where ground-water flow is controlled principally by fractures.

Conceptual Model for Transport of Injected Dyes

A conceptual model that describes the transport of injected dyes in the fractured and stratified hydrologic system at the study site and explains the patterns of dye-concentration curves on dye-recovery hydrographs is presented in this section of the report. The model describes the ideal results expected from hypothetical dye-tracer tests made under conditions of high and low hydraulic head. These results are illustrated by use of the generalized geologic section and four hypothetical dye-recovery hydrographs shown in figure 13.

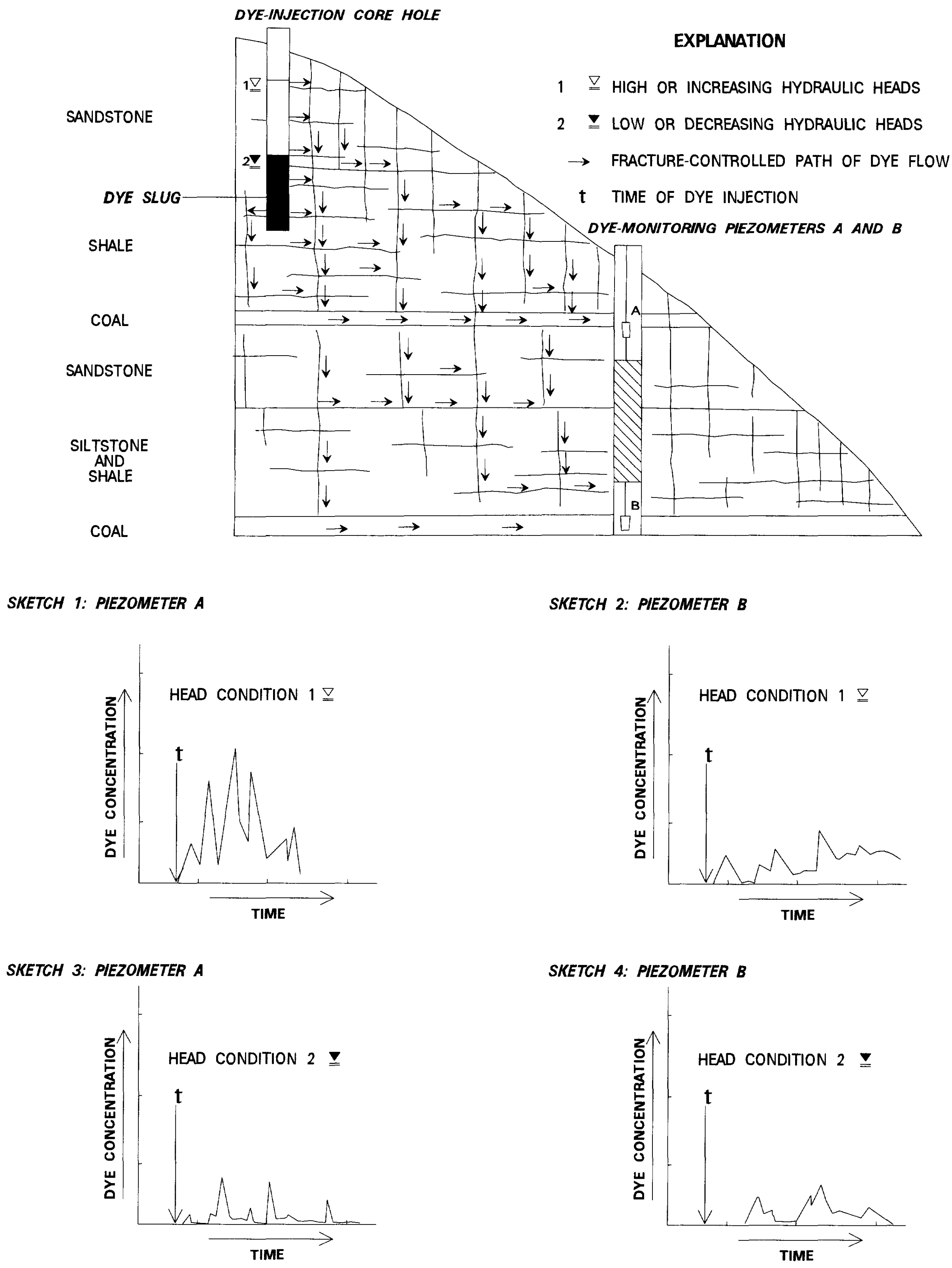

Figure 13. Conceptualized transport of injected dye to shallow and deep piezometer zones during conditions of high and low hydraulic head at study site near Fishtrap Lake, Pike County, Kentucky.

The primary factors affecting the rate of transport of dye in the subsurface and the properties of the dye-recovery hydrographs were determined to be (1) the total length and hydraulic conductivities of fracture-controlled dye flow paths, (2) hydraulic-head conditions in the near-surface fracture zone at the time of the dye injection, and (3) short-term and (or) long-term fluctuations in recharge to SFZ, EHZ, and PHZ piezometers. When hydraulic heads in the near-surface fracture zone are high or increasing, more fractures penetrated by the dye-injection core hole are charged with water and are available as flow routes than when hydraulic heads are low (fig. 13, hydraulic head condition 1). The relatively high hydraulic conductivity and low storativity associated with the near-surface fracture zone enable rapid transport of dye-labeled water to downgradient areas of the SFZ, EHZ, and PHZ hydrogeologic zones. Dye-labeled water moves to an SFZ piezometer under high hydraulic gradients along numerous fracture-controlled flow paths that differ in length and hydraulic conductivity (fig. 13, piezometer A). Arrival of frequent, successive dye pulses forms a spiked pattern on the dye-concentration curve of a dye-recovery hydrograph for the piezometer (fig. 13, sketch 1).

With increasing depth and (or) distance from the valley wall, the number of fractures decreases and the conductivity of most fractures is diminished because of lithostatic pressures exerted by overlying strata (Kipp and others, 1983). At depth, dye-labeled ground water is conducted mostly by densely fractured bedrock, such as sandstones and coal beds. The lower hydraulic conductivity and higher storage (relative to open fractures in the near-surface fracture zone) of these hydrostratigraphic units act to moderate peak fluctuations in dye concentration. Because of the longer distance and increased traveltime of dye-labeled water, the arrival of dye pulses to a deeper piezometer (fig. 13, piezometer B) lags much behind that of the shallow piezometer (fig. 13, piezometer A). Dye concentrations may increase gradually over time with the arrival of each new pulse of dye-labeled ground water. The peaks of individual dye pulses, when plotted on a dye-concentration curve of the dye-recovery hydrograph, appear less attenuated and form a serrated pattern (fig. 13, sketch 2).

When ground-water levels in the near-surface fracture zone are low (fig. 13, hydraulic-head condition 2), fewer fractures penetrated by the dye-injection core hole are charged with water and are available as dye flow routes. Dye-labeled water leaving the injection zone moves slowly under the influence of low hydraulic heads. The dye-labeled water may become pooled in water-depleted fractures. This hydraulic dead zone storage acts to retard the transport of dye until sufficient recharge arrives to re-initiate flow. The intermittent, punctuated transport of dye under these hydraulic conditions gives rise to variations in the pattern of arrival of dye pulses on the dye-recovery hydrographs of shallow and deep piezometers (fig. 13, sketches 3 and 4) from those described above. Arrival of dye to shallow piezometers monitoring the near-surface fracture zone appears as infrequent, individual pulses that peak and quickly fall to background concentrations (fig. 13, sketch 3). Dye pulses may continue to arrive in the piezometer for many months with each additional influx of recharge from the near-surface zone. The arrival of dye to deep piezometers (fig. 13, piezometer B) lags well behind the time of dye injection, and prolonged gaps occur between dye pulses, as indicated on the time-concentration curves on the dye-recovery hydrographs (fig. 13, sketch 4).

CONCLUSIONS

The results of the dye-tracer tests made at the Fishtrap Lake study site demonstrate the importance of the hydraulic connection of fractures in conducting ground-water flow through coal-bearing strata in ridge-and-valley-wall settings typical of the Appalachian Plateaus Physiographic Province. The dye tracer tests validate the role of fractures as preferential routes by which ground water migrates from the ridge crest to the valley wall and valley floor, as proposed in the conceptual models described by Wyrick and Borchers (1981a, b), Kipp and others (1983), and Minn (1993).

The transport of dyes injected into the fractured strata beneath the ridge crest and valley wall was determined to be controlled by a combination of several geologic and hydrologic factors. The analysis of dye-recovery hydrographs in this investigation indicates that these factors include (1) the distribution, interconnection, and hydraulic properties of fractures; (2) hydraulic-head conditions in the near-fracture zone at the time of dye injection; and (3) subsequent short- and long-term fluctuations in recharge to the hydrologic system that affect storage and hydraulic gradients. If the dyes injected during the tracer tests are considered as surrogates for potential ground-water contaminants produced or released by land-use activities such as mining on the ridge crests and upper valley walls, then the same geologic and hydrologic factors can be expected to affect the transport and behavior of the contaminants in the subsurface hydrologic system. The transport of potential ground-water contaminants may therefore be rapid, or slow, depending on the hydraulic-head conditions at the time of the introduction of the contaminant and the fluctuations in hydraulic heads afterwards. Residual contaminants could be retained in the hydrologic system for periods of months to years, trapped by hydraulic dead zone storage in fracture zones, and could be remobilized and transported intermittently following periods of recharge.

The dye-tracer tests also demonstrate that the effects of mining-related disturbances can significantly alter the natural fracture-controlled flow paths and disturb the subsurface hydrologic system. The apparent breach of the annular seal and resulting hydraulic short-circuiting between the dye-injection zone and the two lower piezometer zones in core hole 1 (detected first during dye-tracer test 4) are believed to have occurred because of subsurface propagation of mining-induced subsidence fractures. Data collected during dye-tracer tests 5 and 6 confirmed the breach in the annular seal of core hole 1 and indicated that the disruption of the hydraulic connection between the injection core hole and downgradient piezometers at the study site worsened during the 1-year period between tracer tests 4 and 5. In addition, dye was detected in the flooded, abandoned underground mine beneath the core of the ridge, apparently as a result of flow along pathways provided by subsidence-related fractures and the collapsed mine adits. In this case, the direction of dye (and ground-water) flow was contrary to that predicted by the conceptual models of previous investigators. The presence of mining-related disturbances must therefore be carefully evaluated and must be considered to have hydrologic effects that are superimposed on the natural fracture-controlled ground-water-flow regime.

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SUPPLEMENTAL DATA

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DYE-RECOVERY HYDROGRAPHS FOR DYE-TRACER TEST 1, AT STUDY SITE NEAR FISHTRAP LAKE, PIKE COUNTY, KENTUCKY

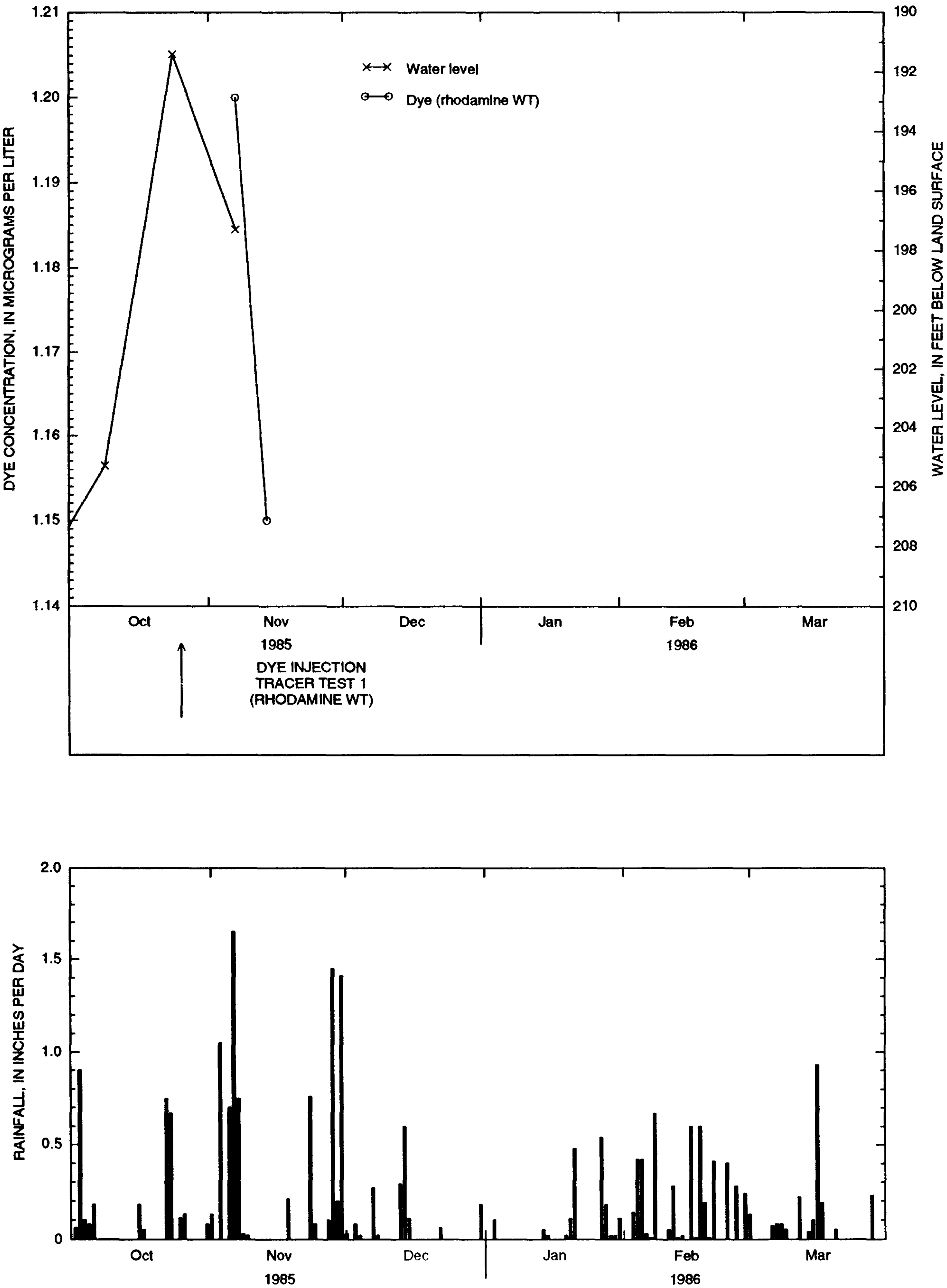
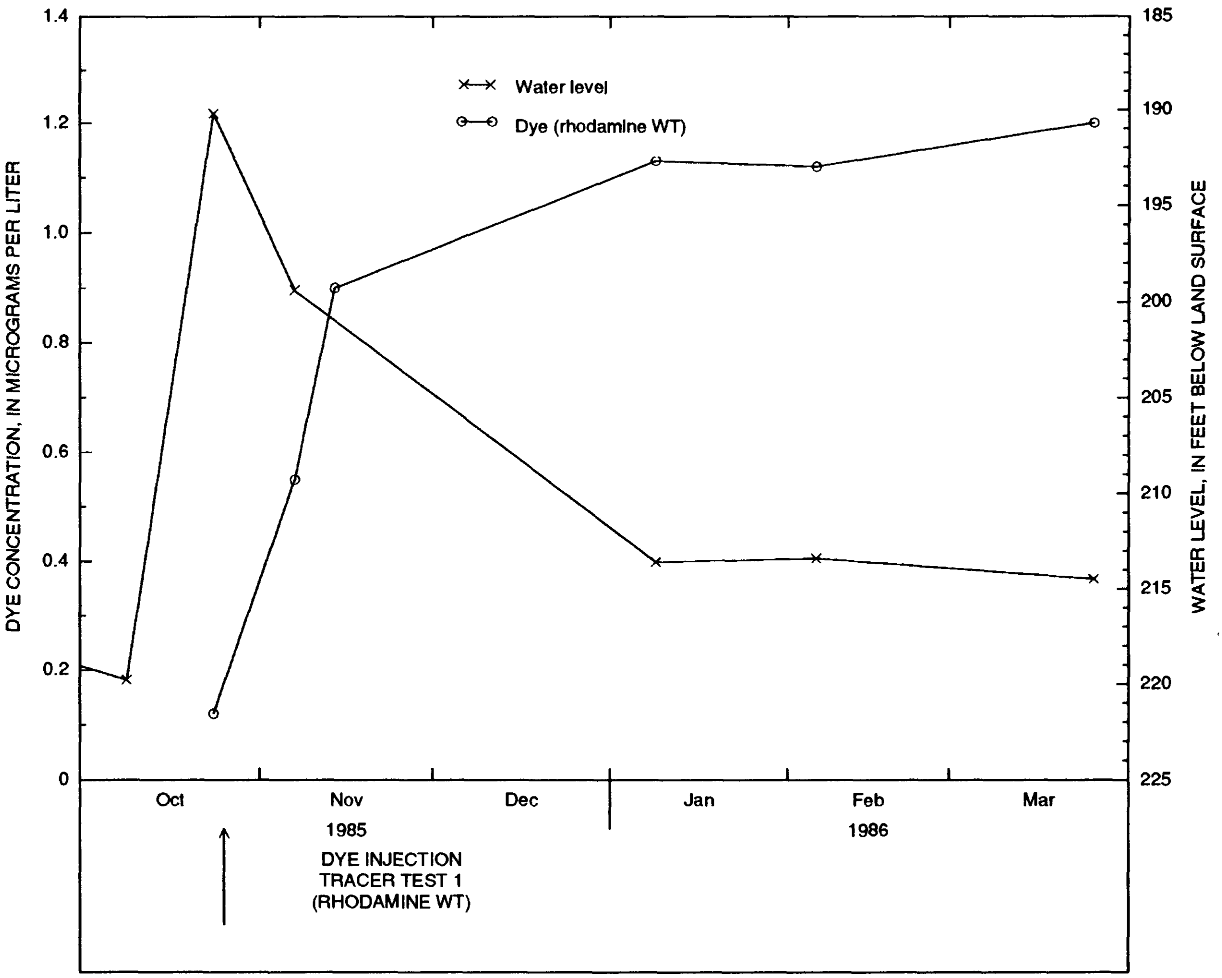


Figure 14. Dye-recovery hydrograph for piezometer 1PS (elevation-head zone) and rainfall histogram for dye-tracer test 1.



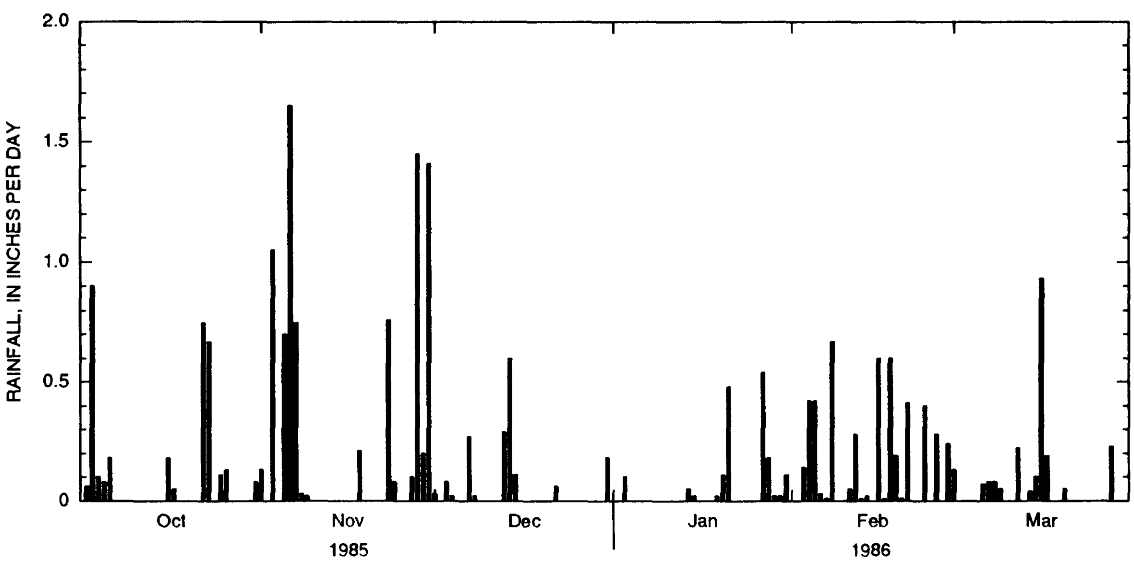


Figure 15. Dye-recovery hydrograph for piezometer 1PD (pressure-head zone) and rainfall histogram for dye-tracer test 1.

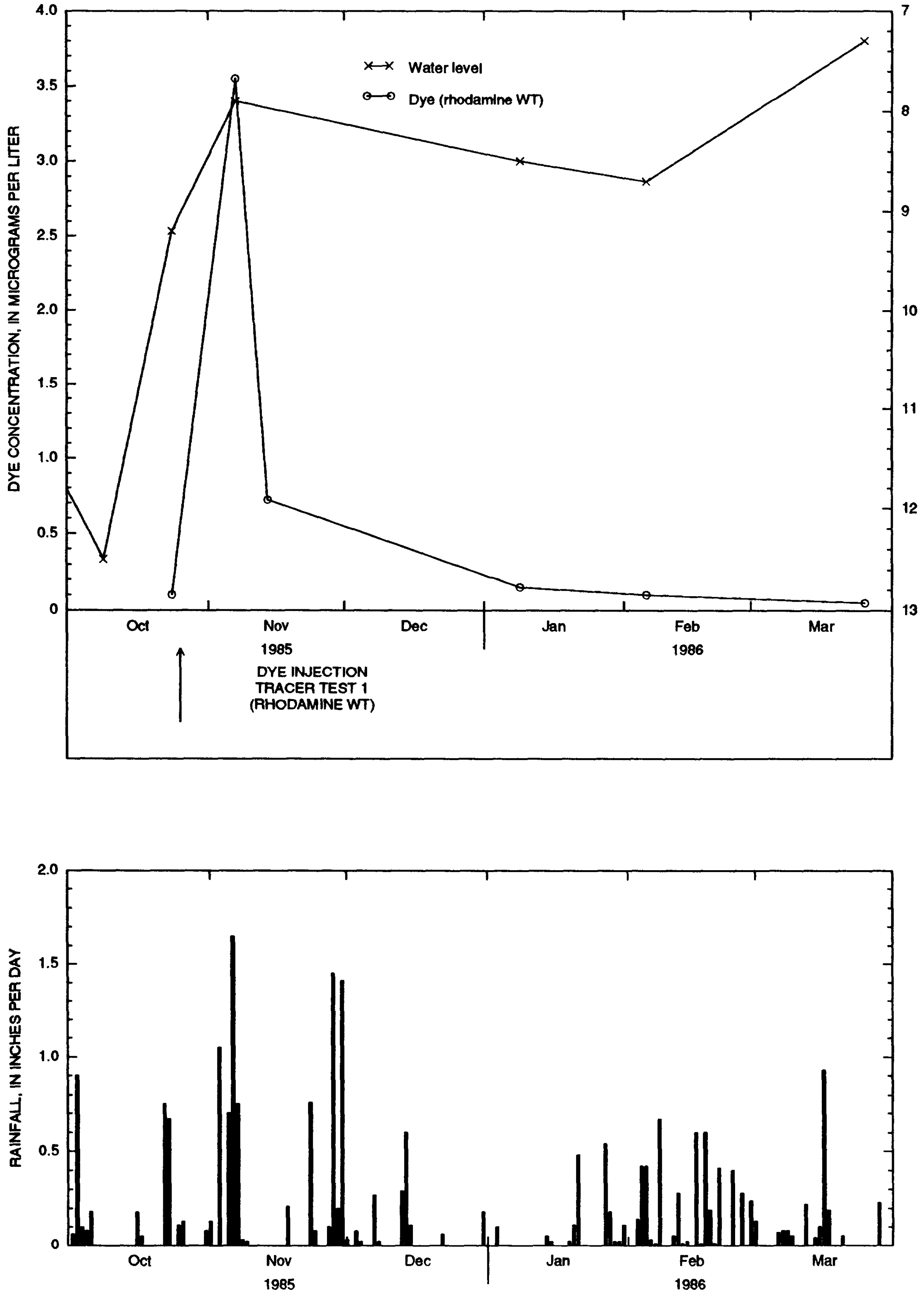


Figure 16. Dye-recovery hydrograph for piezometer 2OH (shallow-fracture zone) and rainfall histogram for dye-tracer test 1.

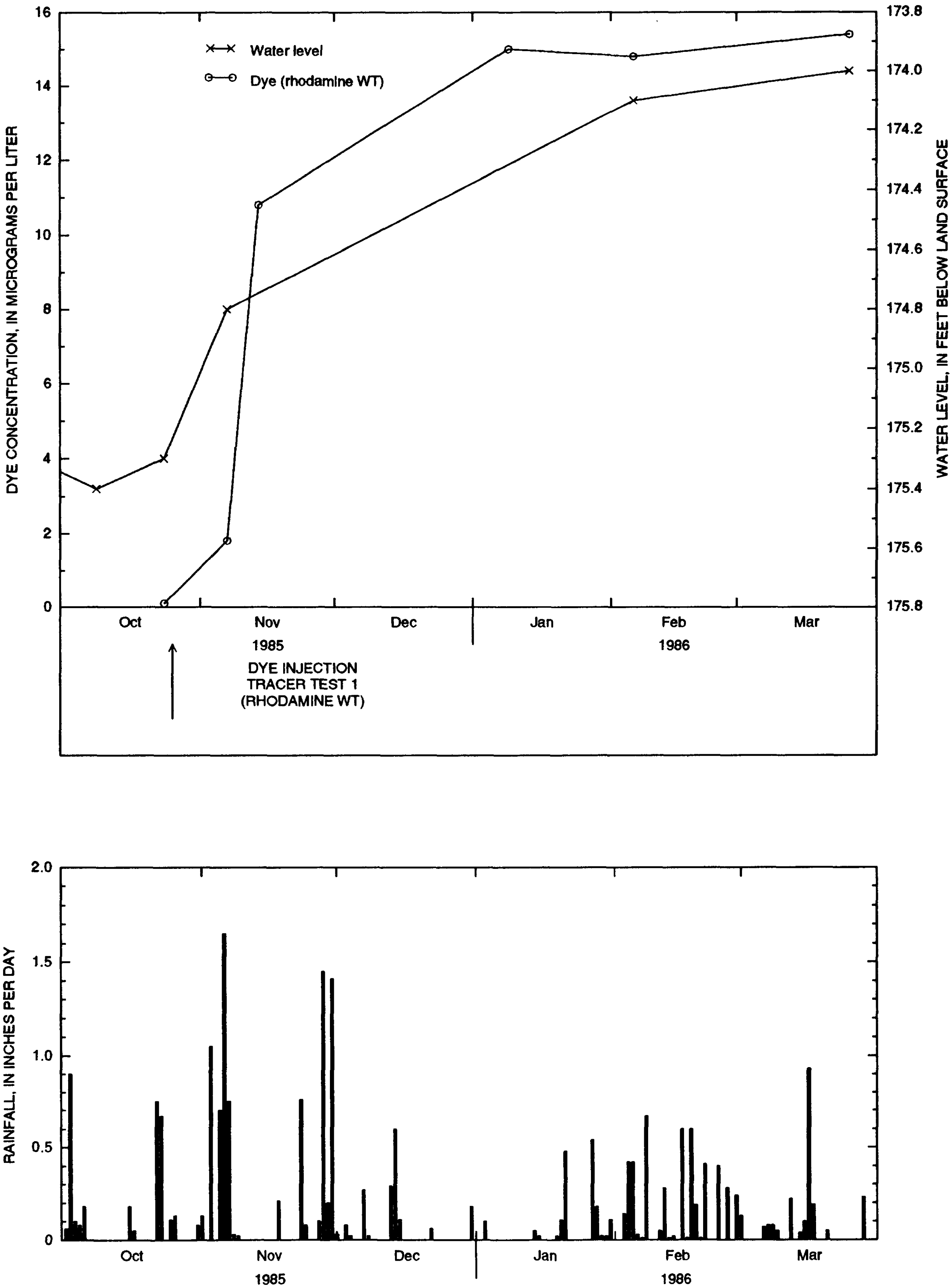


Figure 17. Dye-recovery hydrograph for piezometer 2P (pressure-head zone) and rainfall histogram for dye-tracer test 1.

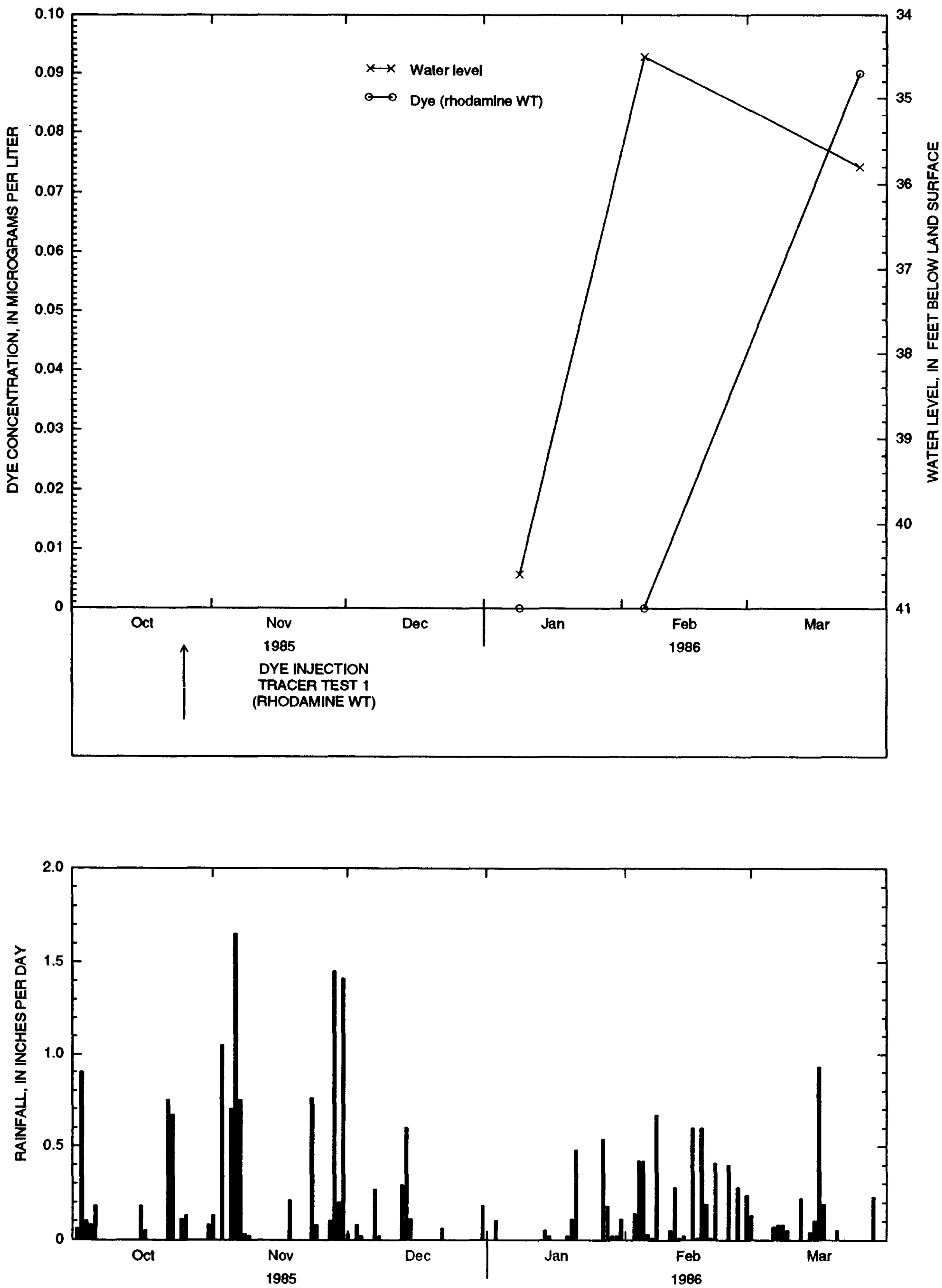


Figure 18. Dye-recovery hydrograph for piezometer 3OH (shallow-fracture zone) and rainfall histogram for dye-tracer test 1.

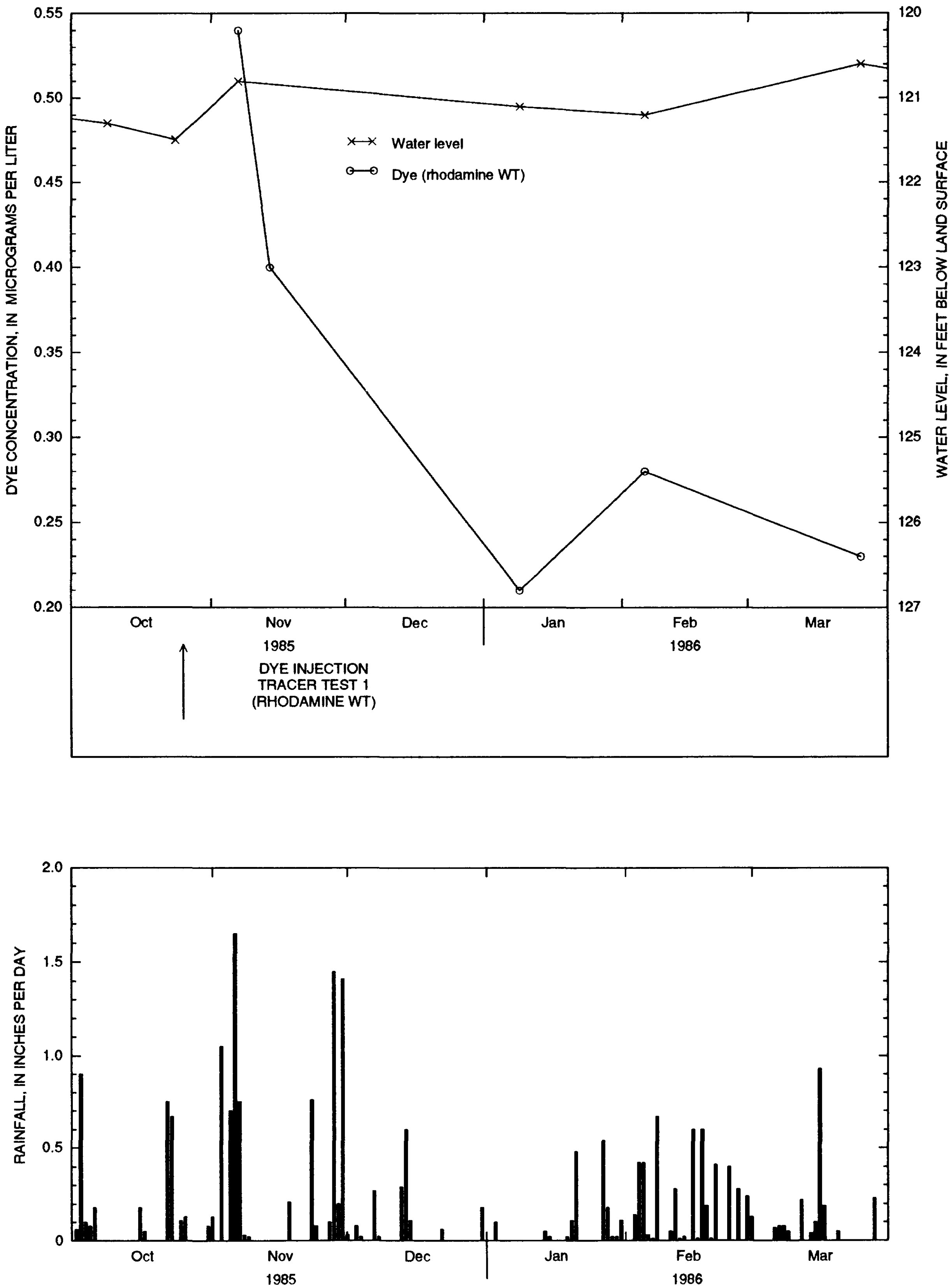


Figure 19. Dye-recovery hydrograph for piezometer 3PS (elevation-head zone) and rainfall histogram for dye-tracer test 1.

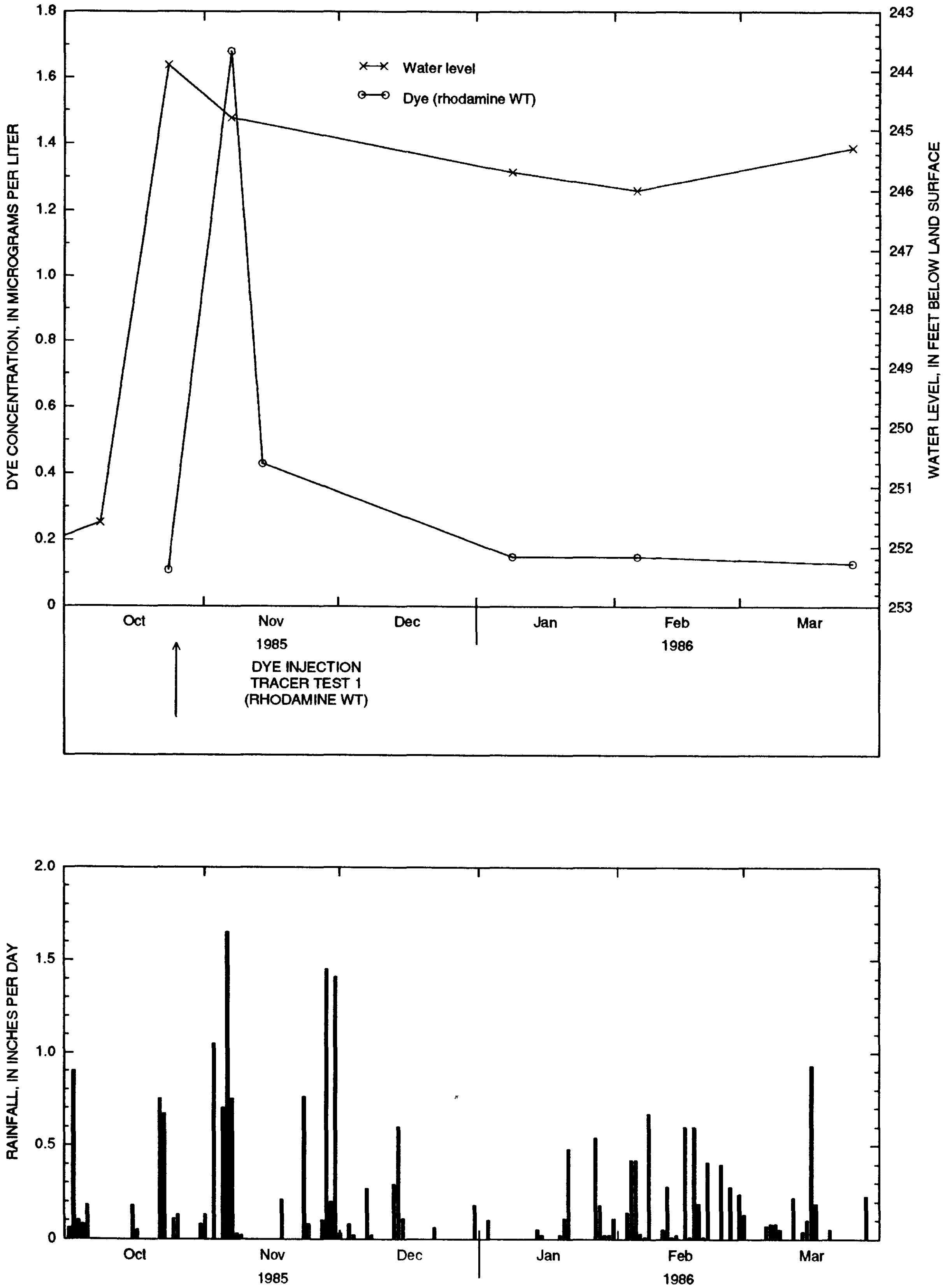


Figure 20. Dye-recovery hydrograph for piezometer 3PD (pressure-head zone) and rainfall histogram for dye-tracer test 1.

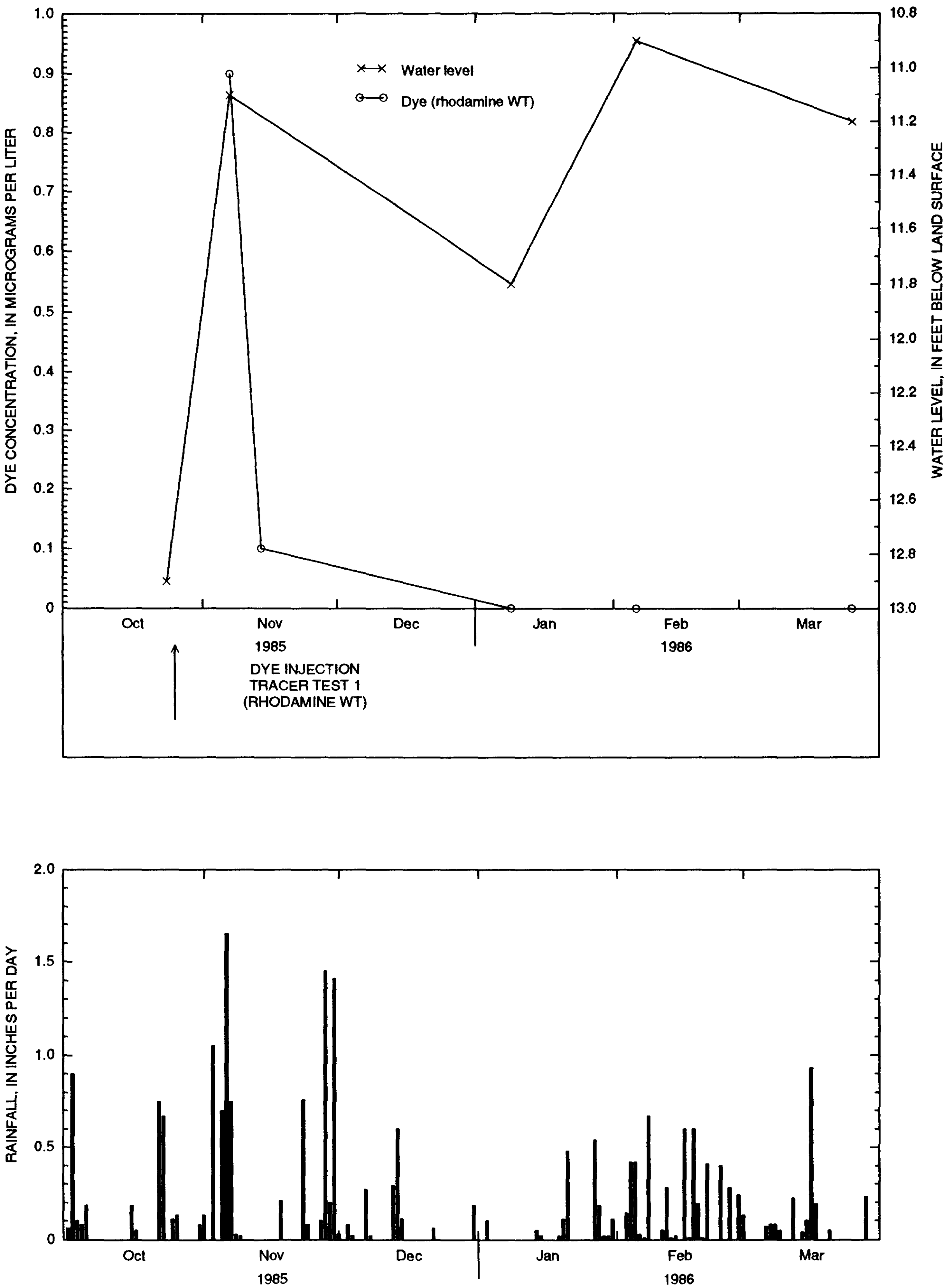


Figure 21. Dye-recovery hydrograph for piezometer 4OH (shallow-fracture zone) and rainfall histogram for dye-tracer test 1.

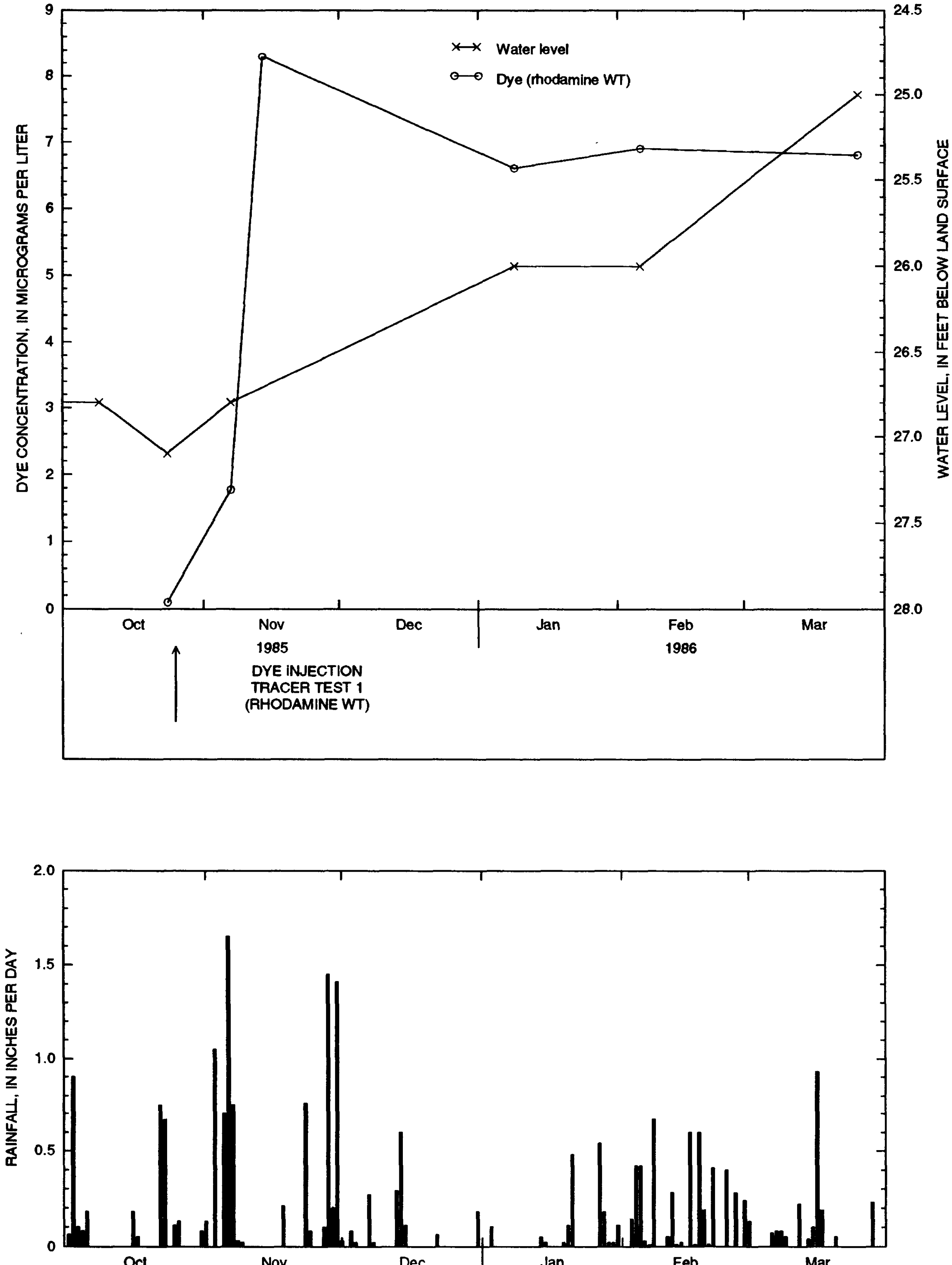
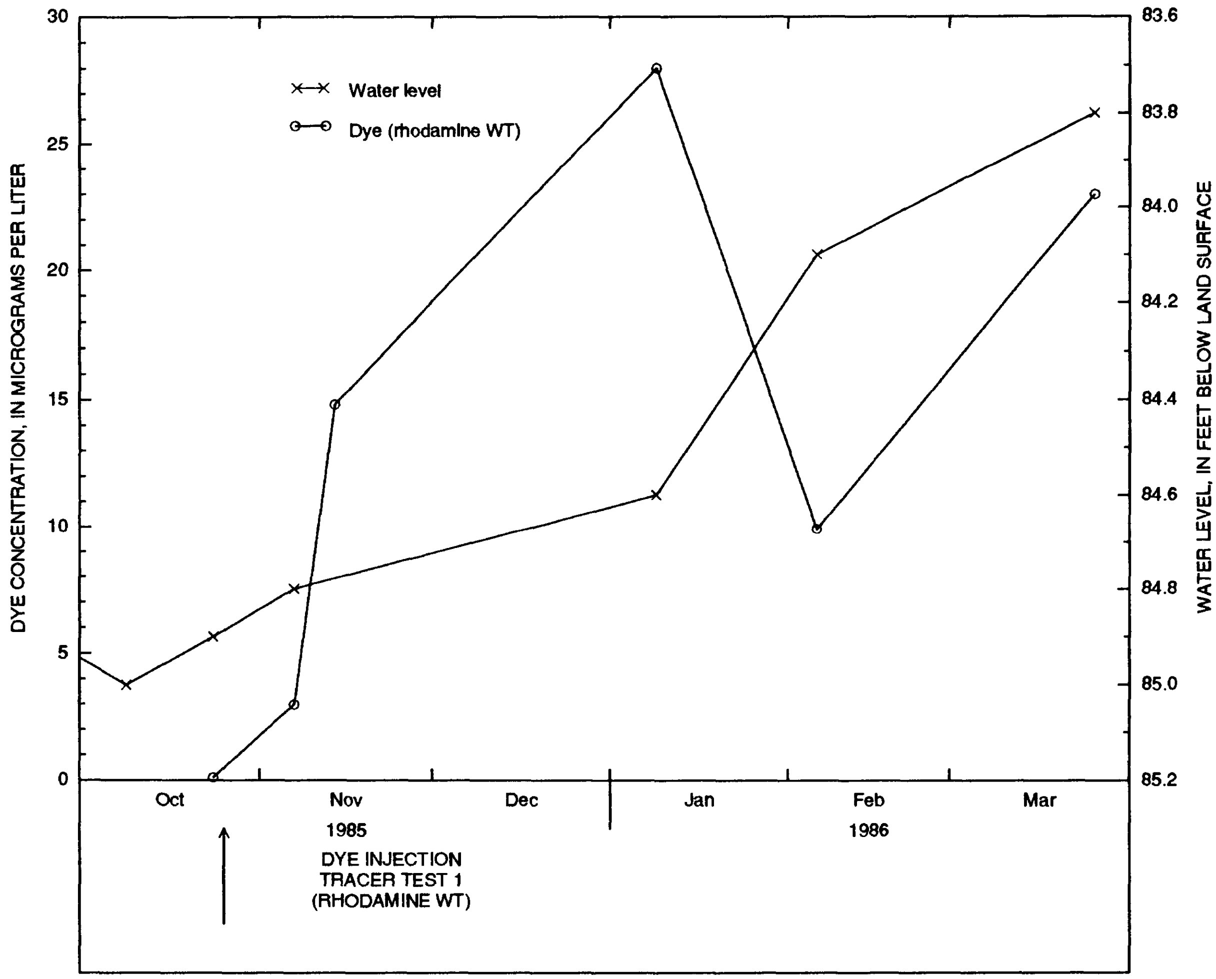


Figure 22. Dye-recovery hydrograph for piezometer 4P (pressure-head zone) and rainfall histogram for dye-tracer test 1.



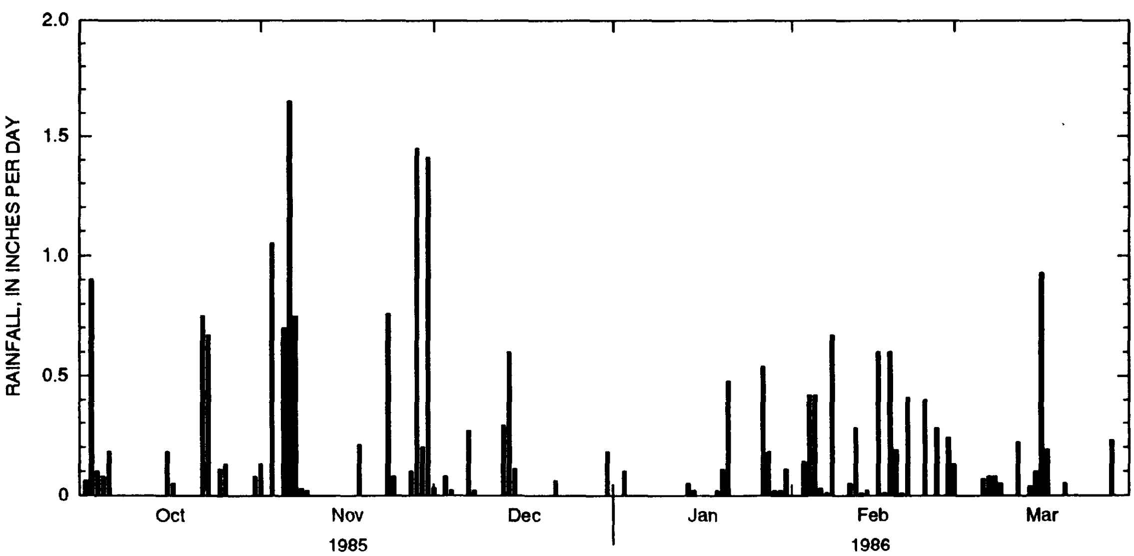


Figure 23. Dye-recovery hydrograph for piezometer 6PD (elevation-head zone) and rainfall histogram for dye-tracer test 1.

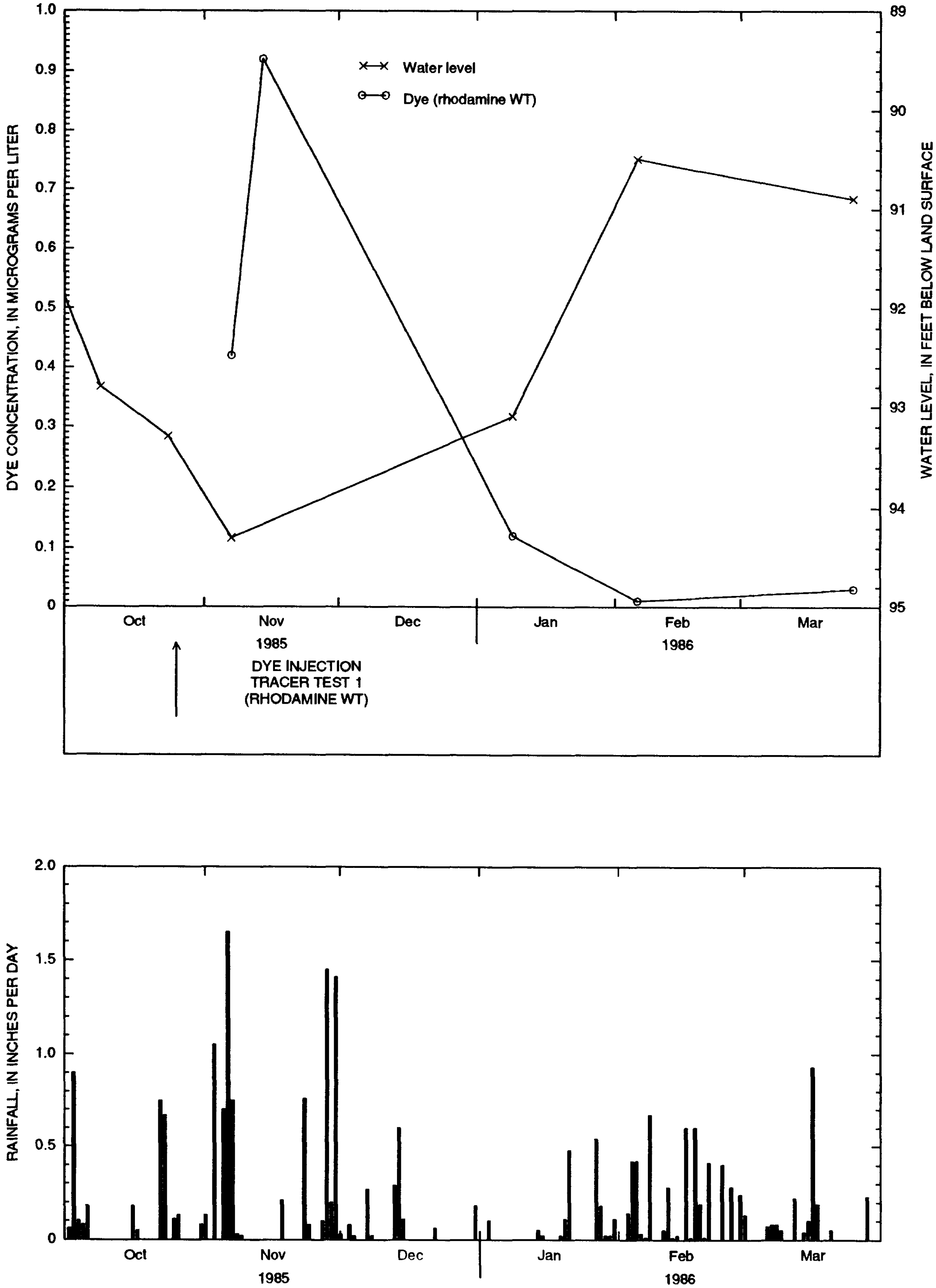


Figure 24. Dye-recovery hydrograph for piezometer 7P (elevation-head zone) and rainfall histogram for dye-tracer test 1.

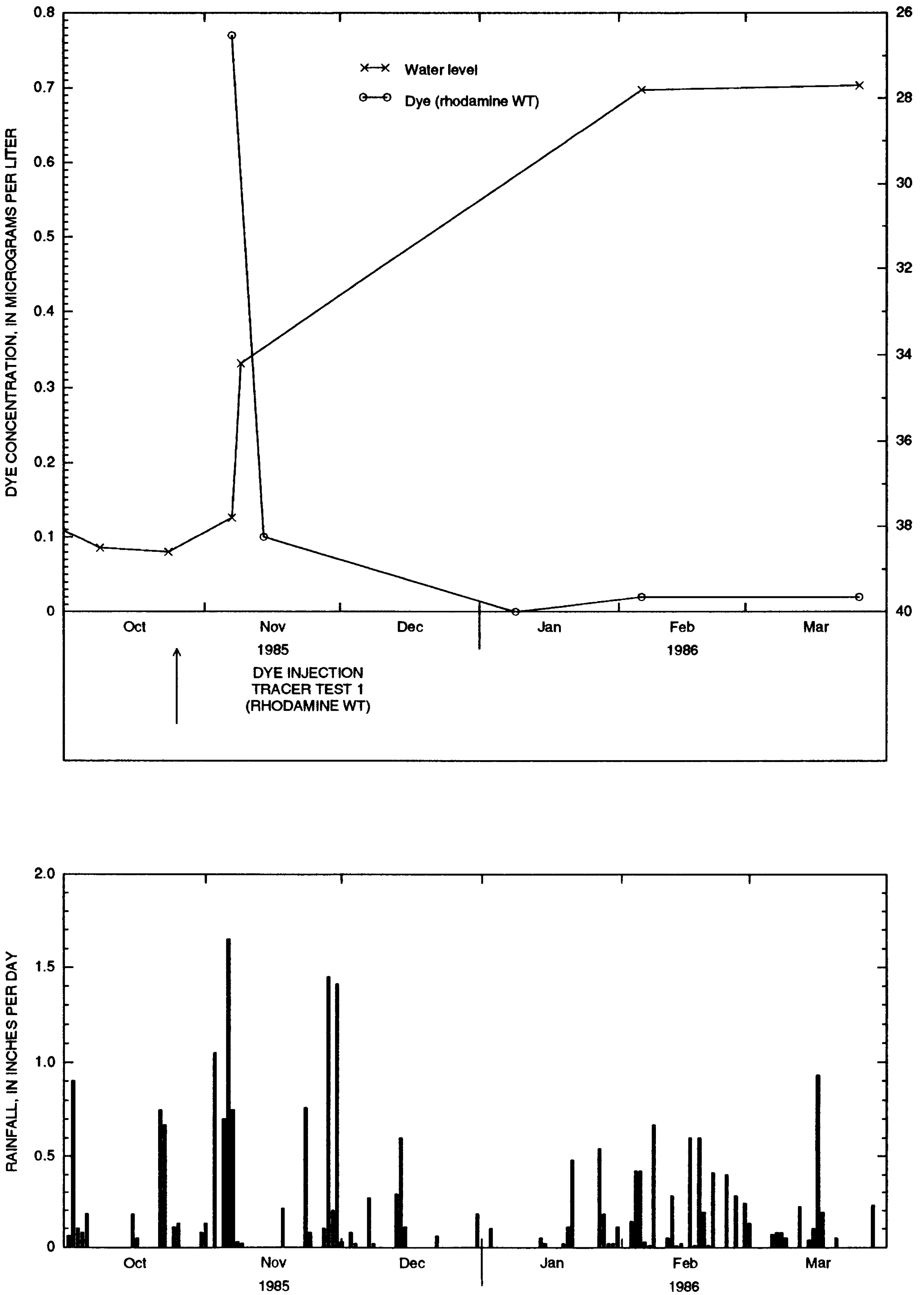
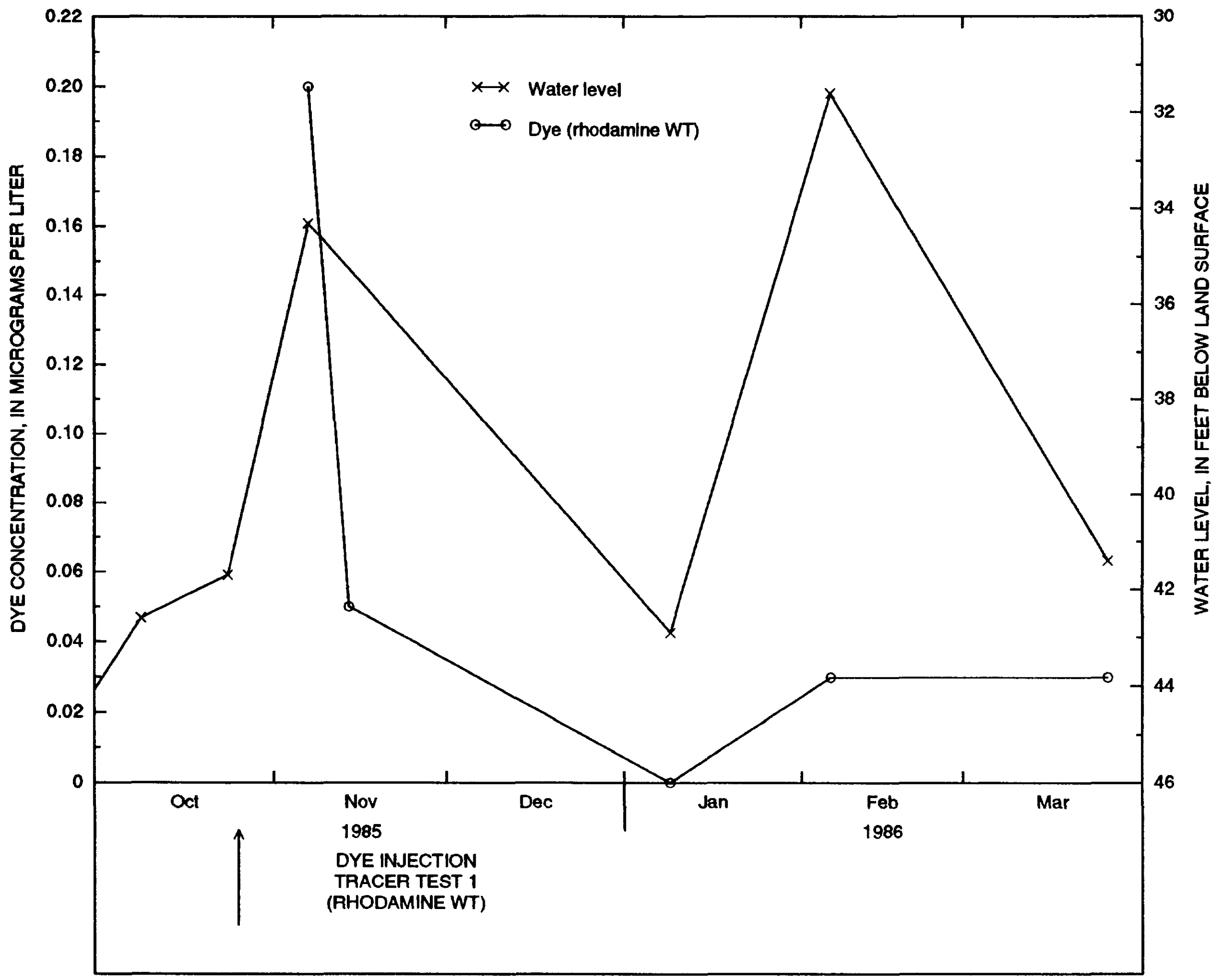


Figure 25. Dye-recovery hydrograph for piezometer 8P (shallow-fracture zone) and rainfall histogram for dye-tracer test 1.



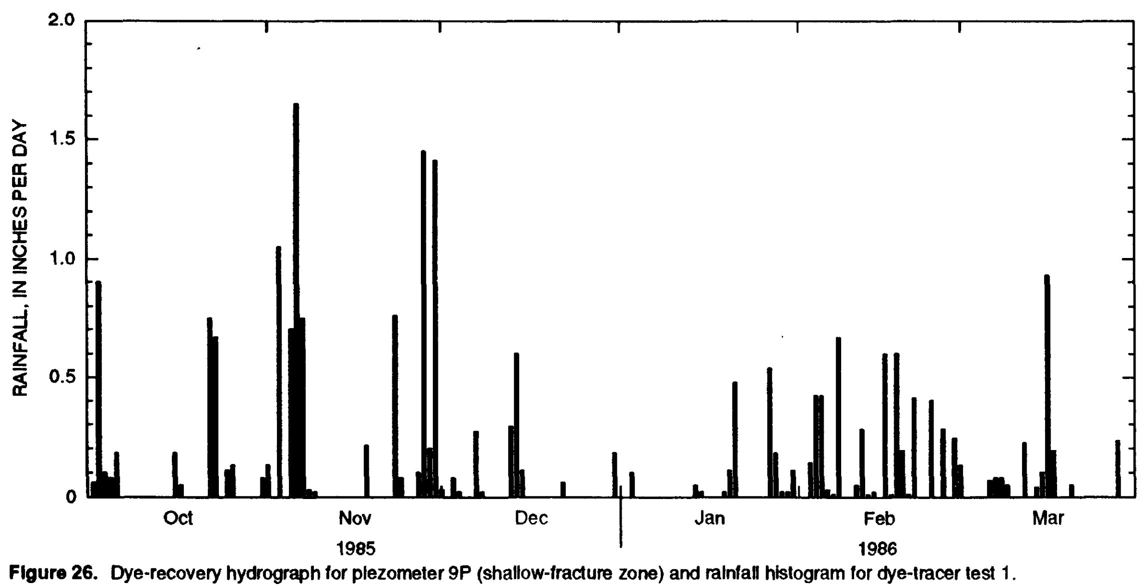
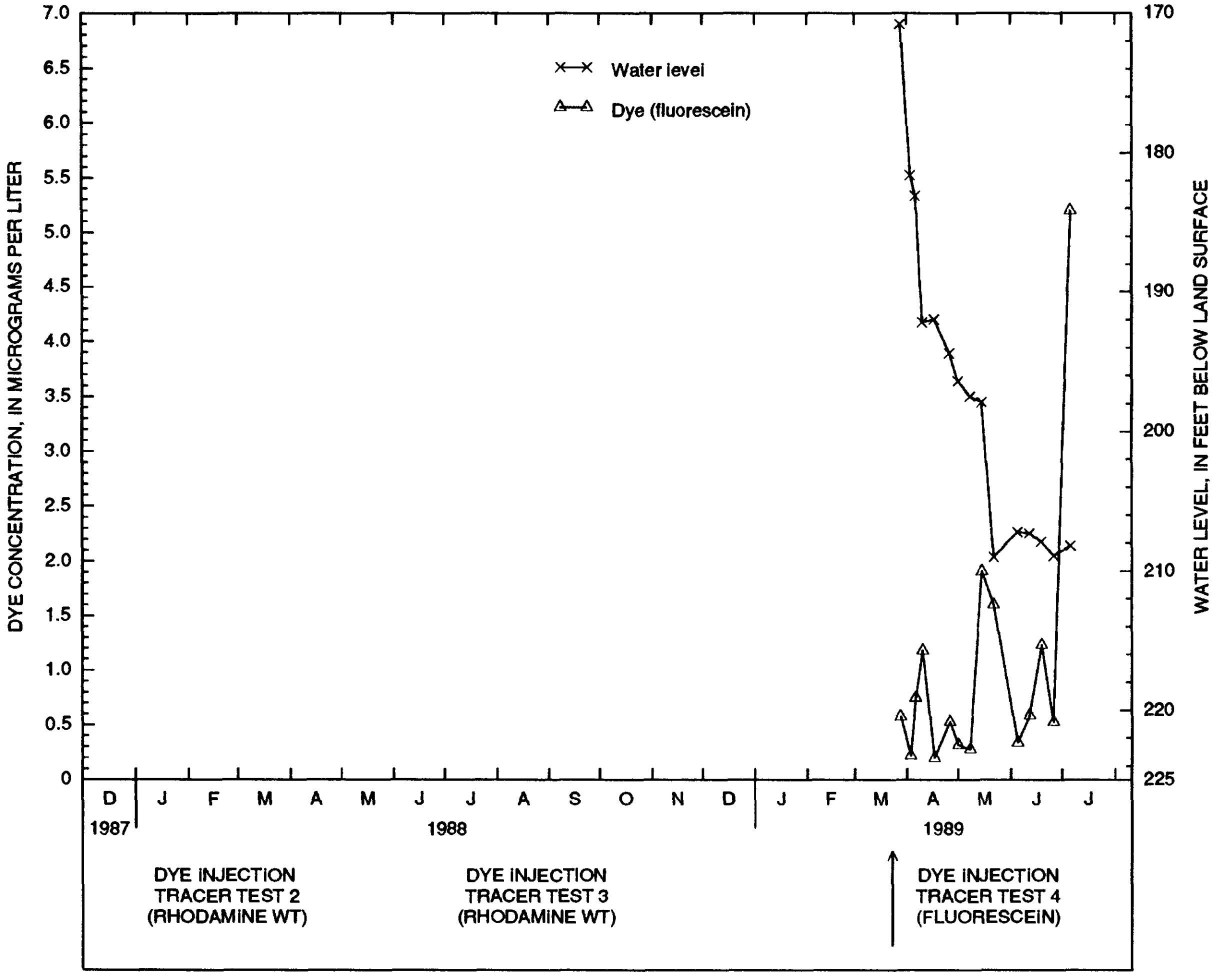


Figure 26. Dye-recovery hydrograph for piezometer 9P (shallow-fracture zone) and rainfall histogram for dye-tracer test 1.

DYE-RECOVERY HYDROGRAPHS FOR DYE-TRACER TESTS 2, 3, AND 4, AT STUDY SITE NEAR FISHTRAP LAKE, PIKE COUNTY, KENTUCKY



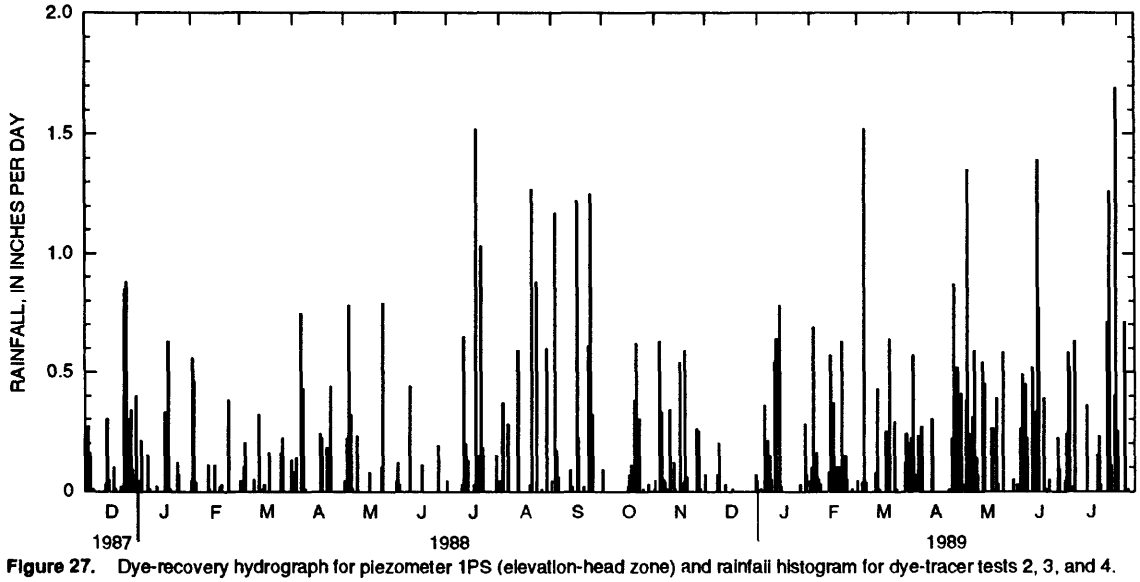


Figure 27. Dye-recovery hydrograph for piezometer 1PS (elevation-head zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

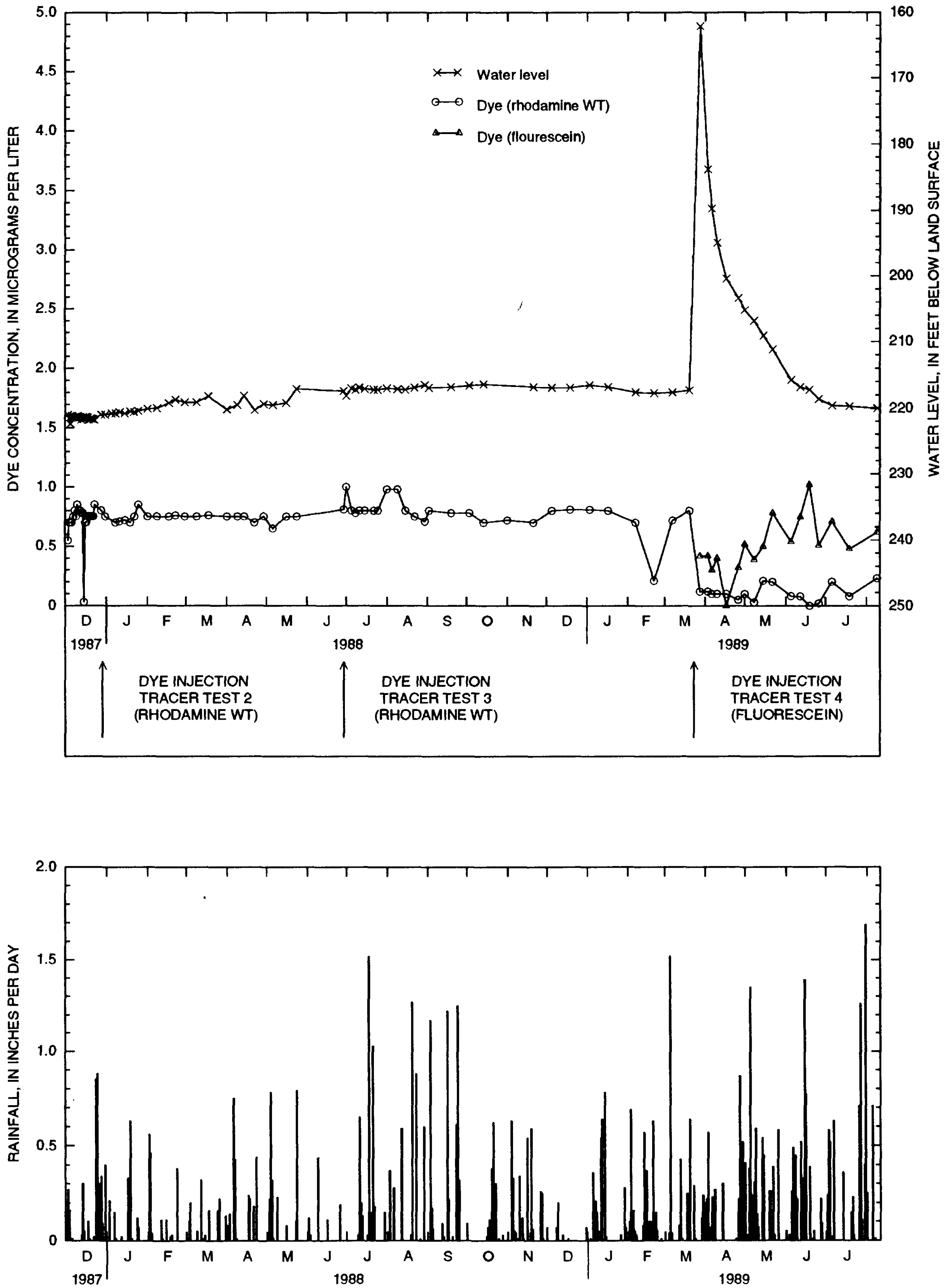


Figure 28. Dye-recovery hydrograph for piezometer 1PD (pressure-head zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

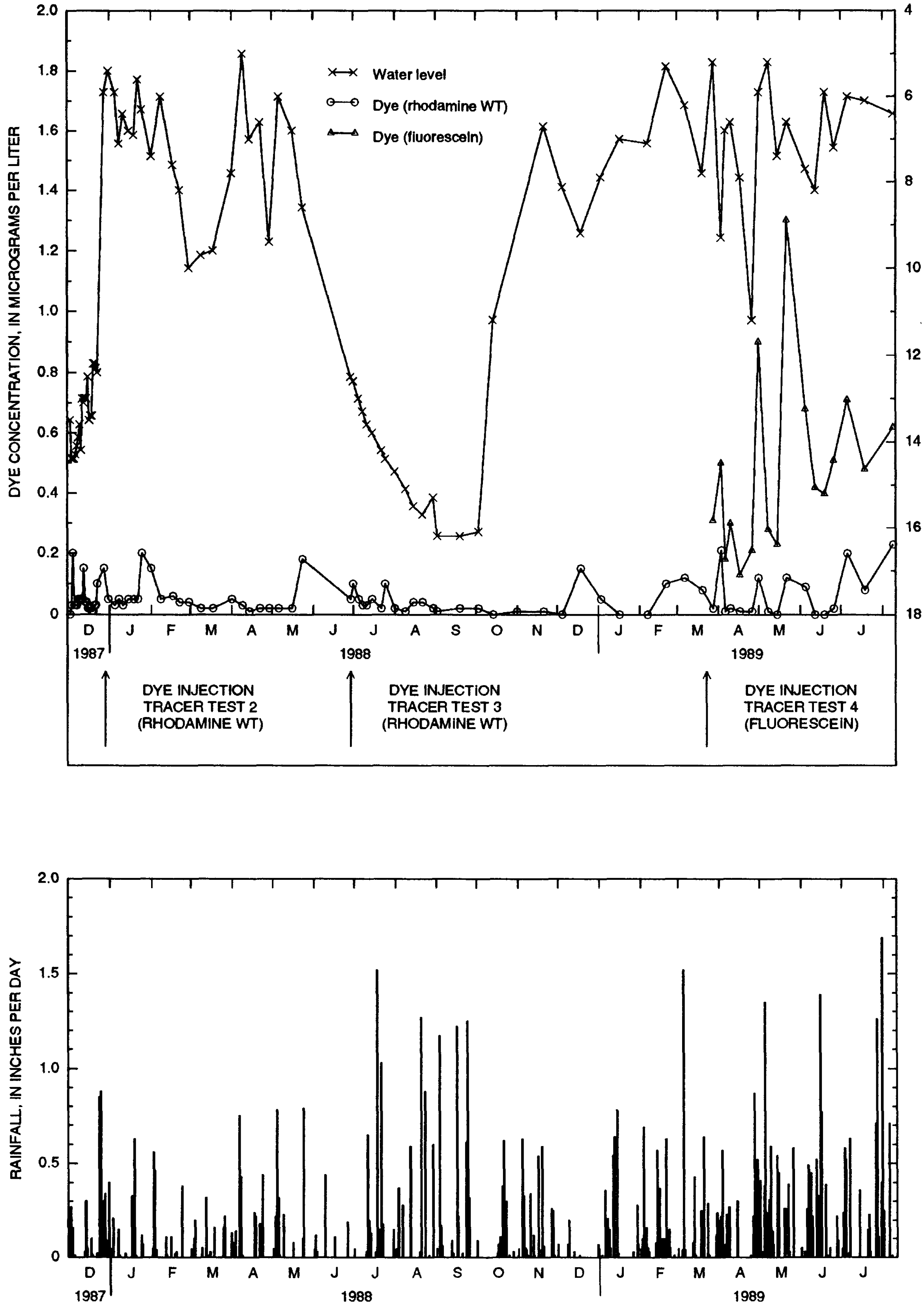


Figure 29. Dye-recovery hydrograph for piezometer 2OH (shallow-fracture zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

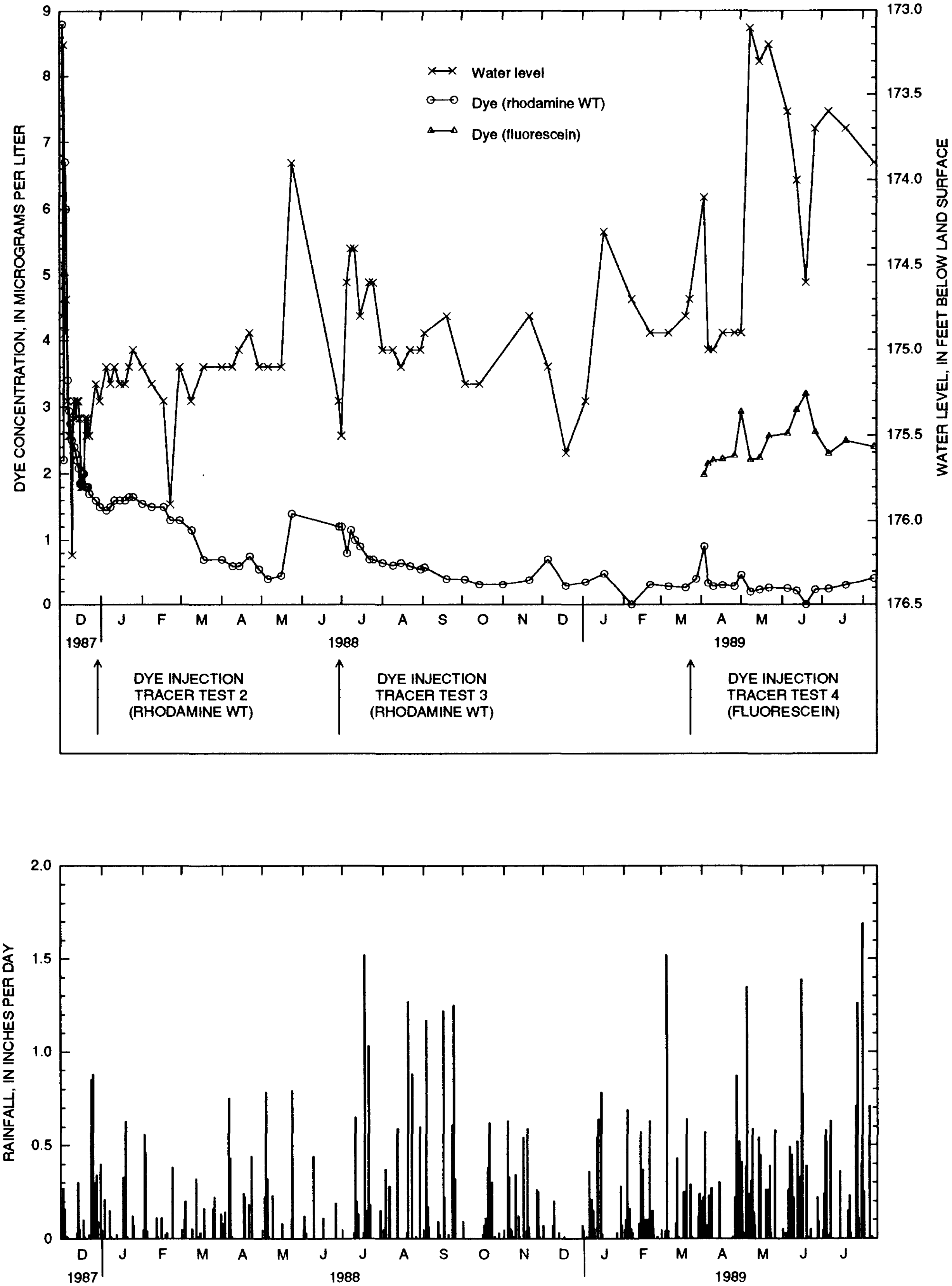


Figure 30. Dye-recovery hydrograph for piezometer 2P (pressure-head zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

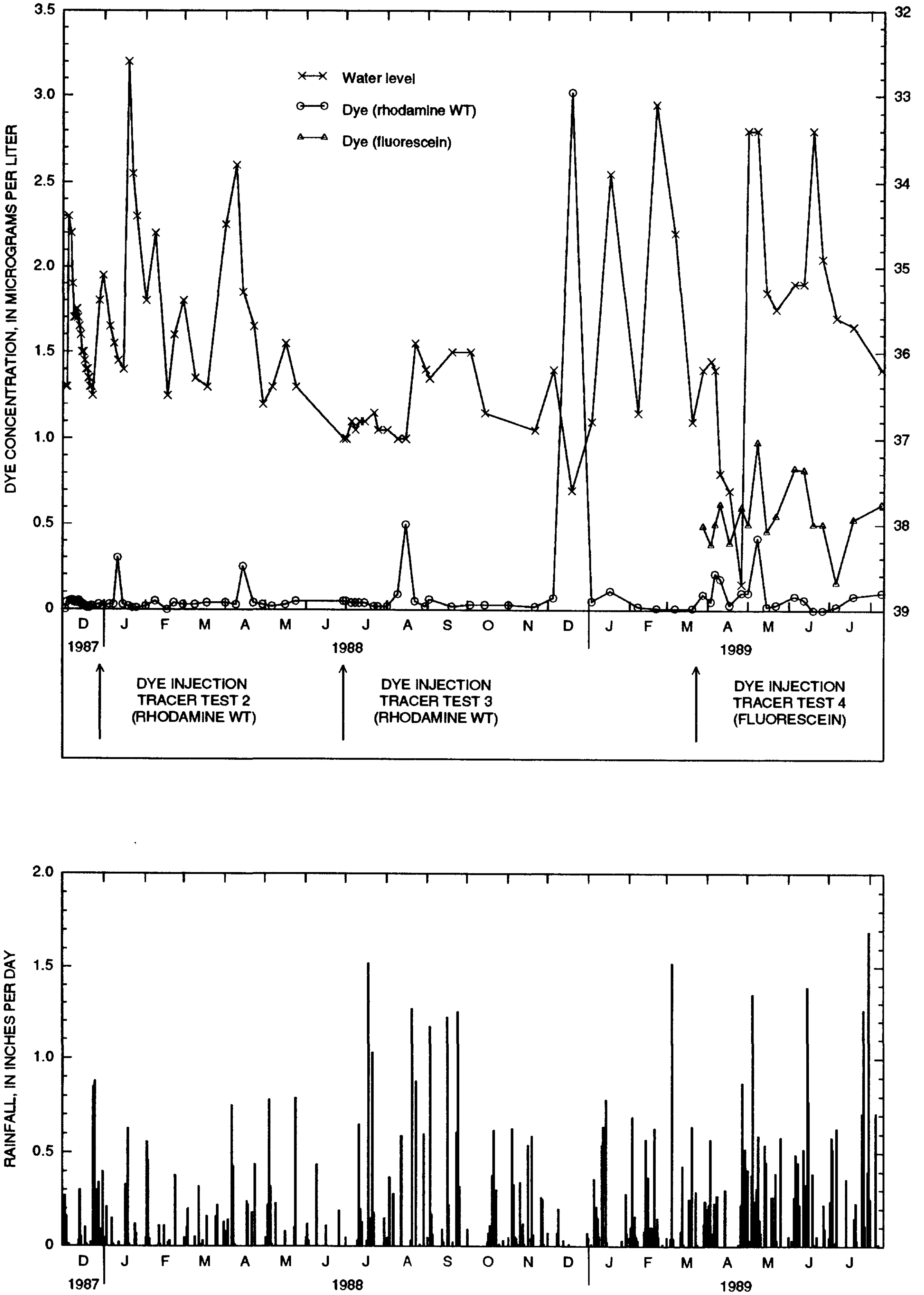
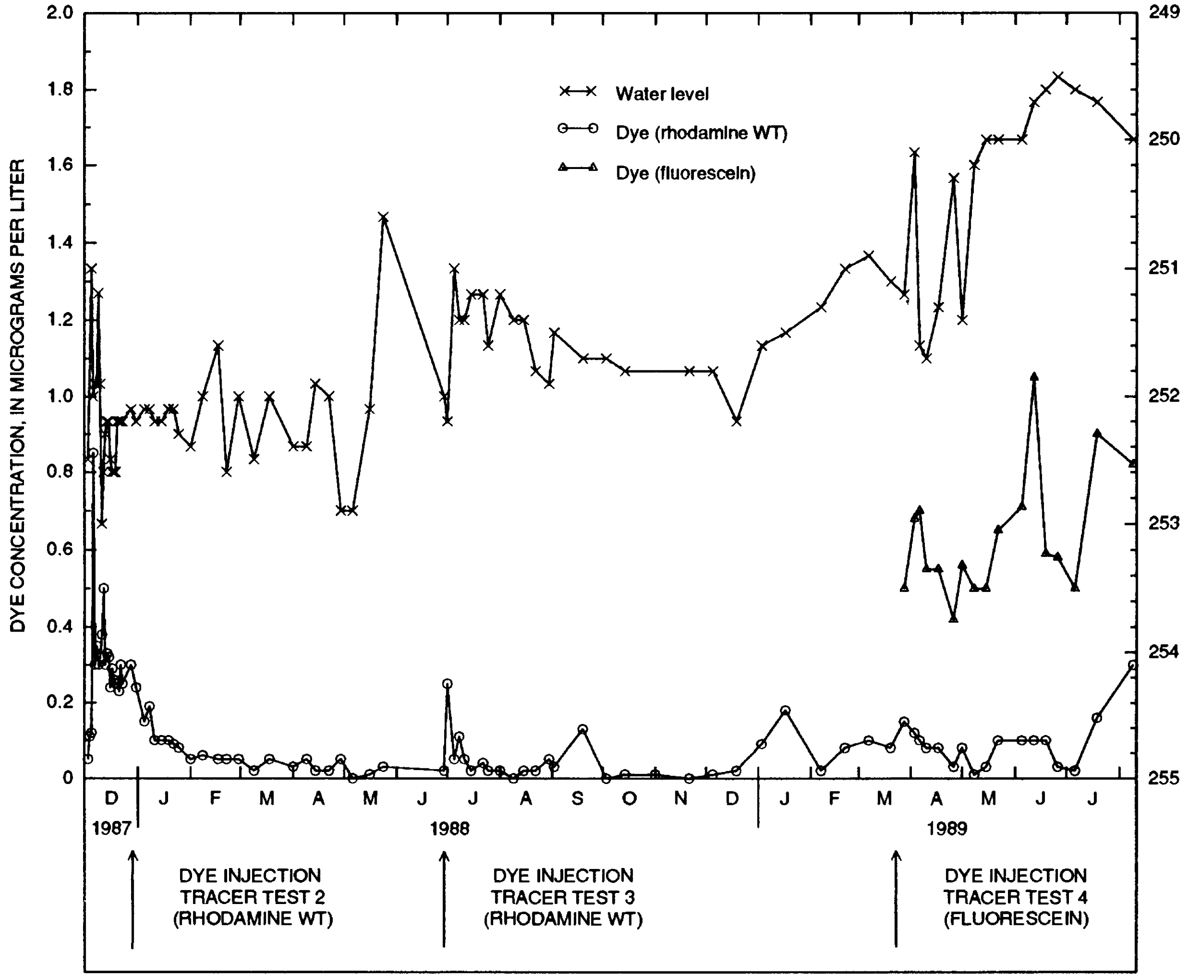


Figure 31. Dye-recovery hydrograph for piezometer 3OH (shallow-fracture zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.



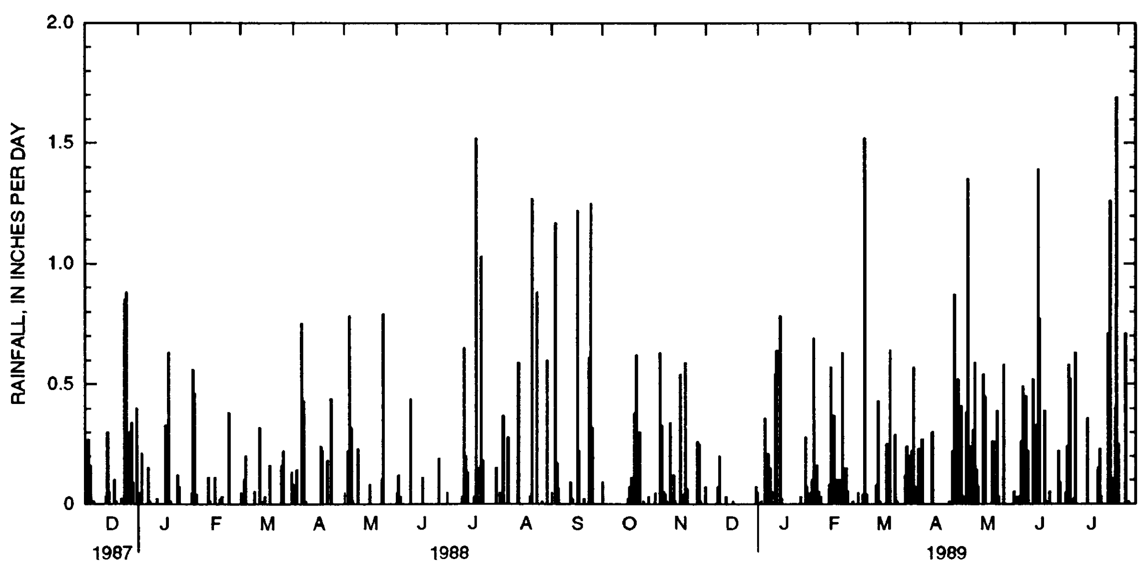


Figure 32. Dye-recovery hydrograph for piezometer 3PD (pressure-head zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

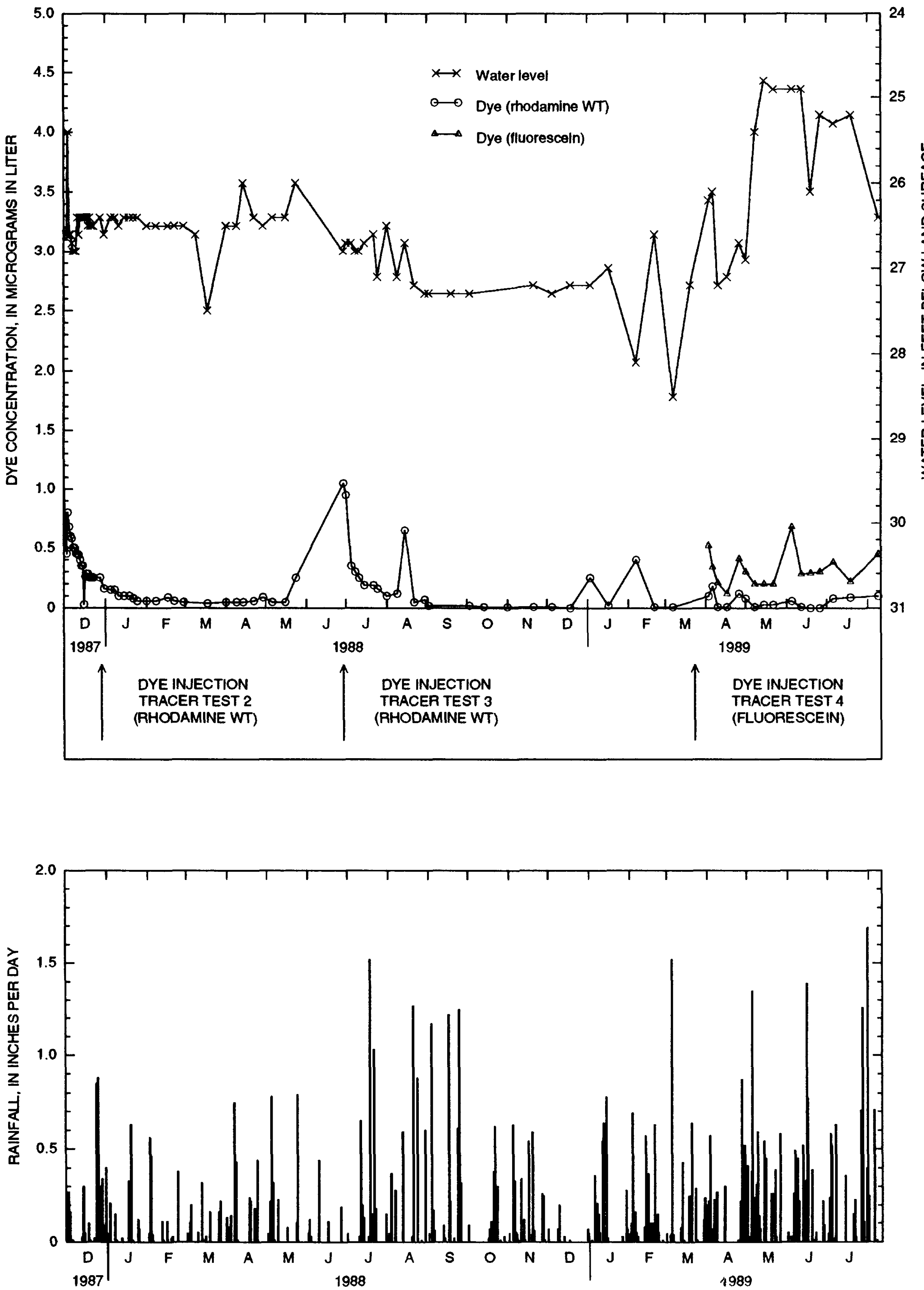


Figure 33. Dye-recovery hydrograph for piezometer 4P (pressure-head zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

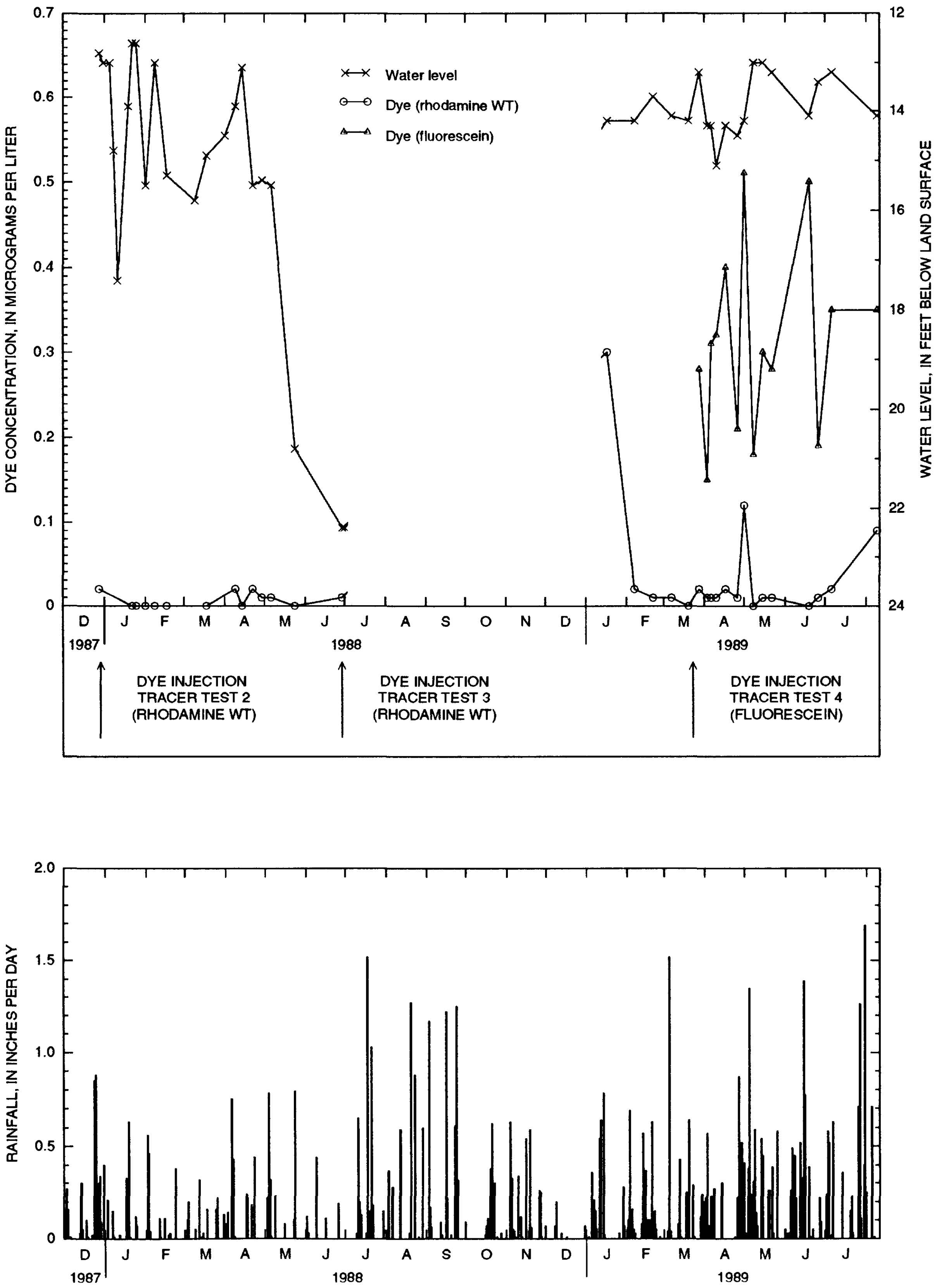


Figure 34. Dye-recovery hydrograph for piezometer 6OH (shallow-fracture zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

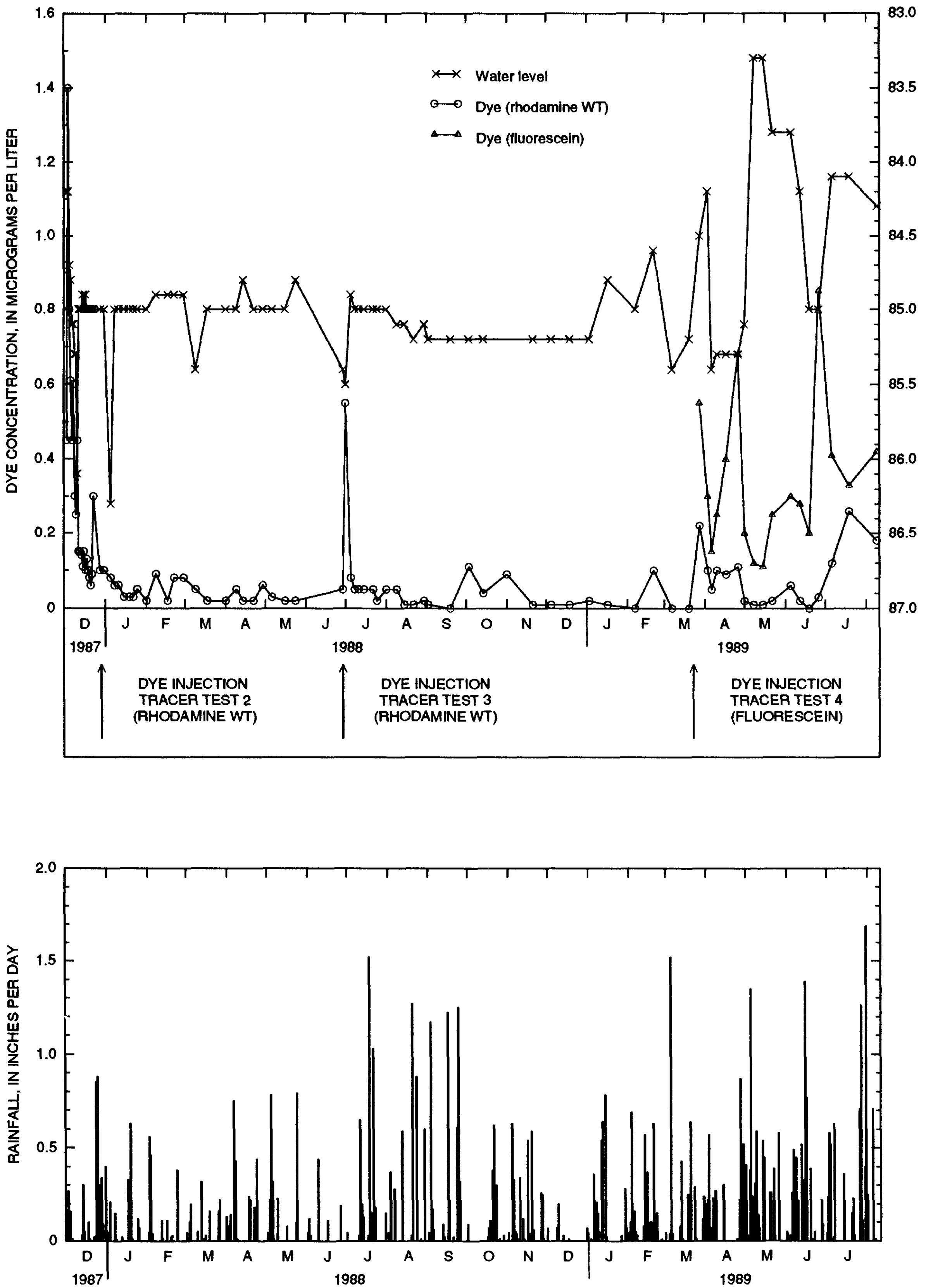


Figure 35. Dye-recovery hydrograph for piezometer 6PD (elevation-head zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

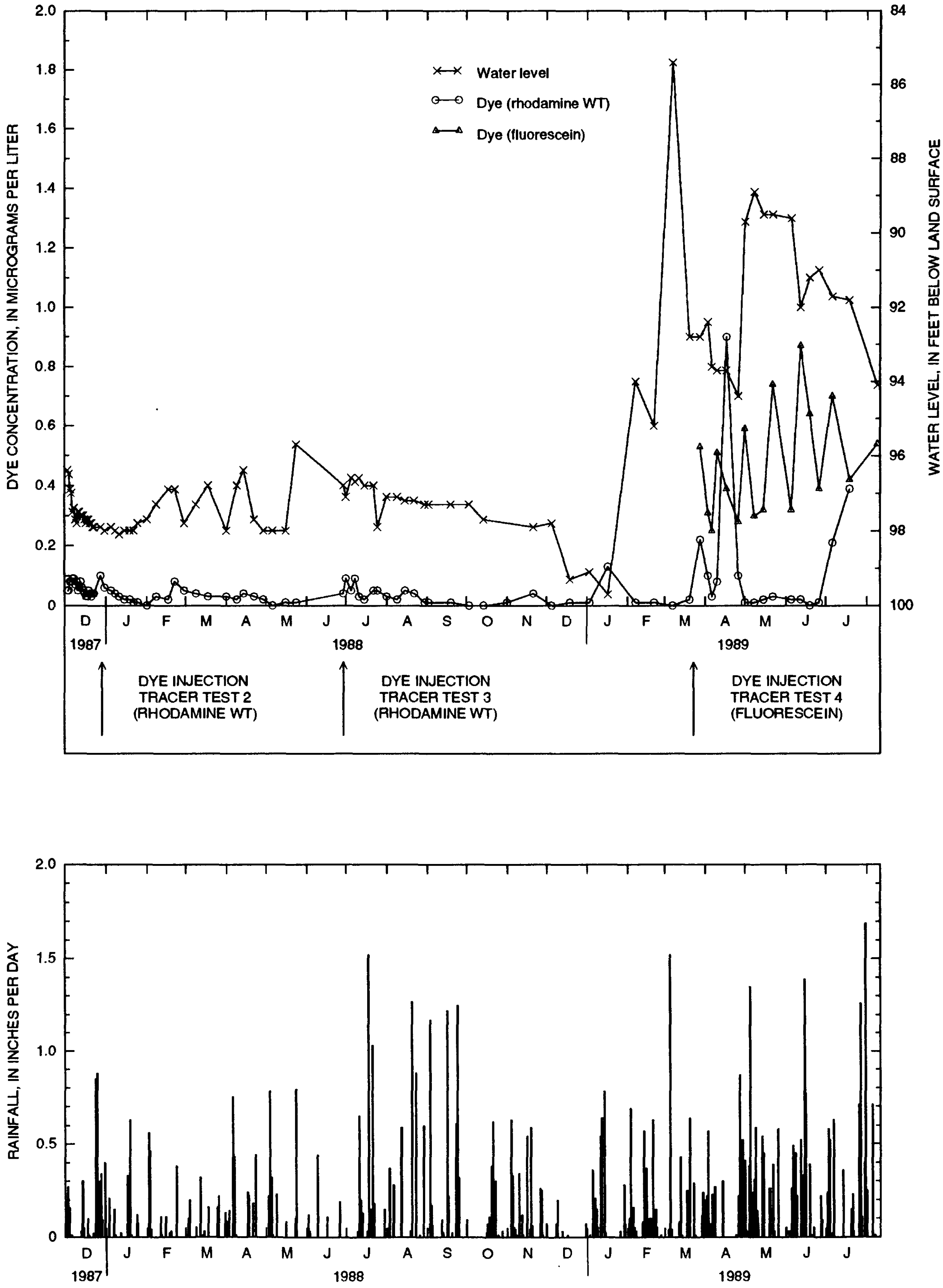


Figure 36. Dye-recovery hydrograph for piezometer 7P (elevation-head zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

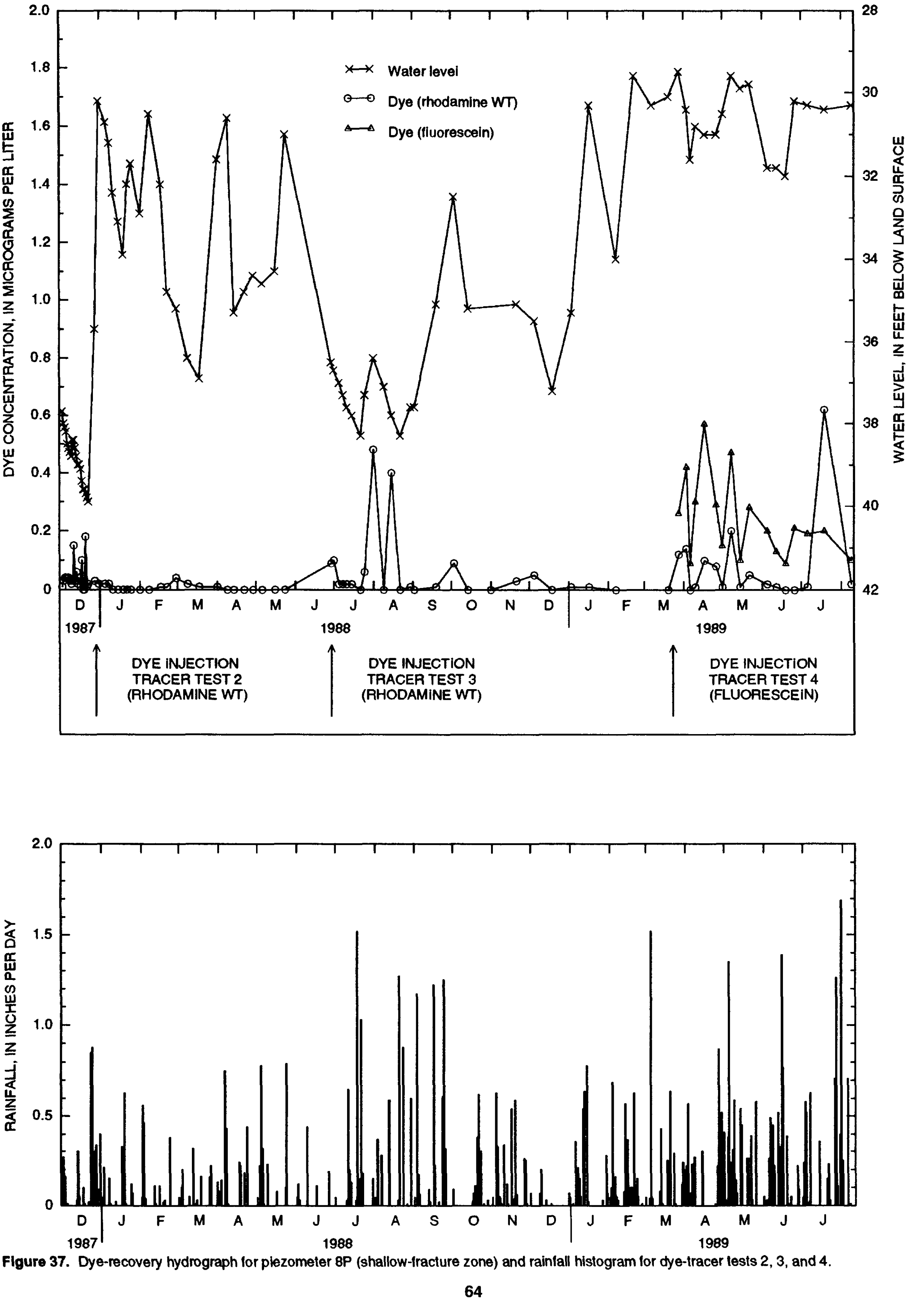


Figure 37. Dye-recovery hydrograph for piezometer 8P (shallow-fracture zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

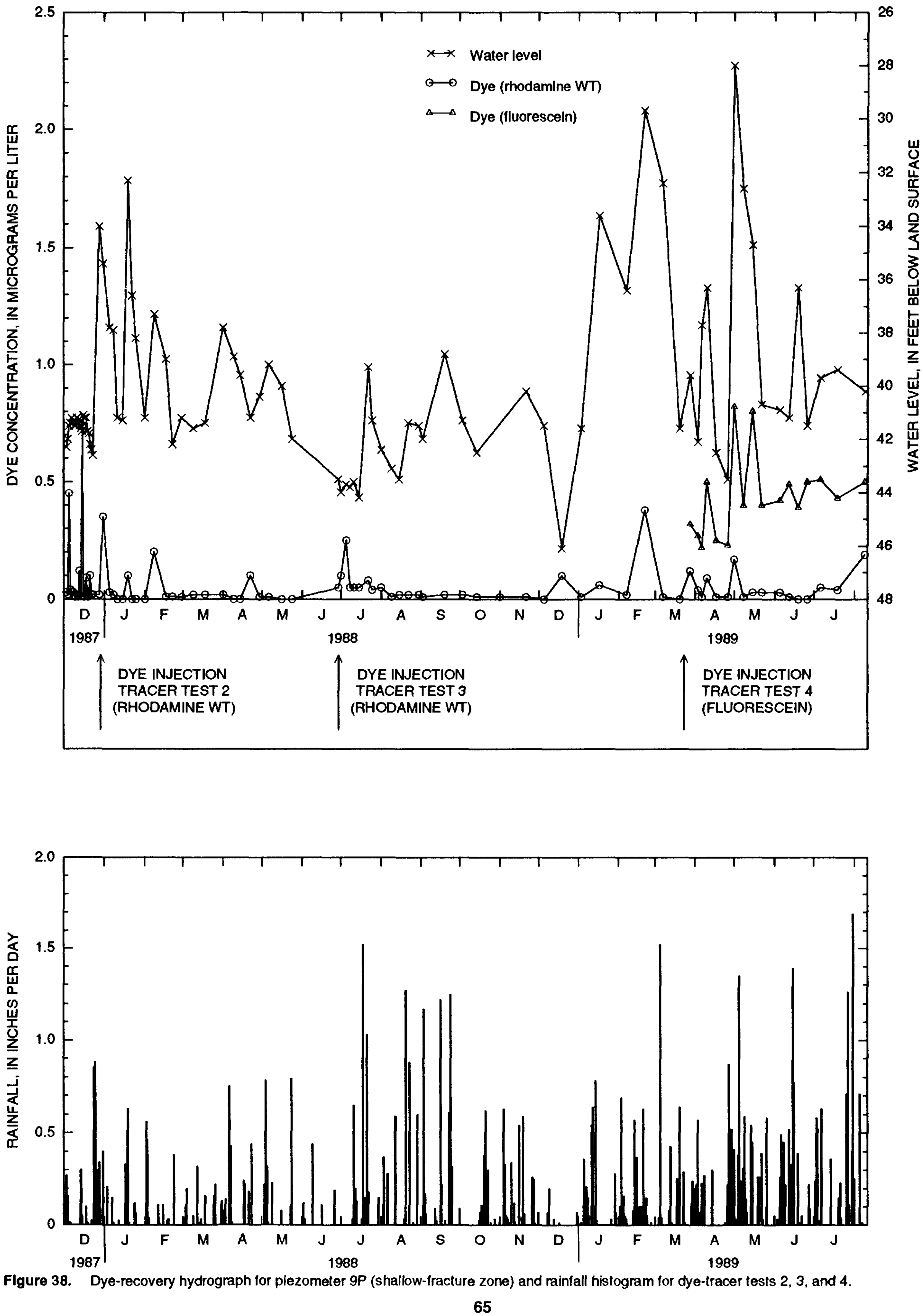


Figure 38. Dye-recovery hydrograph for piezometer 9P (shallow-fracture zone) and rainfall histogram for dye-tracer tests 2, 3, and 4.

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DYE-RECOVERY HYDROGRAPHS
FOR
DYE-TRACER TESTS 5 AND 6,
AT STUDY SITE NEAR
FISHTRAP LAKE,
PIKE COUNTY, KENTUCKY

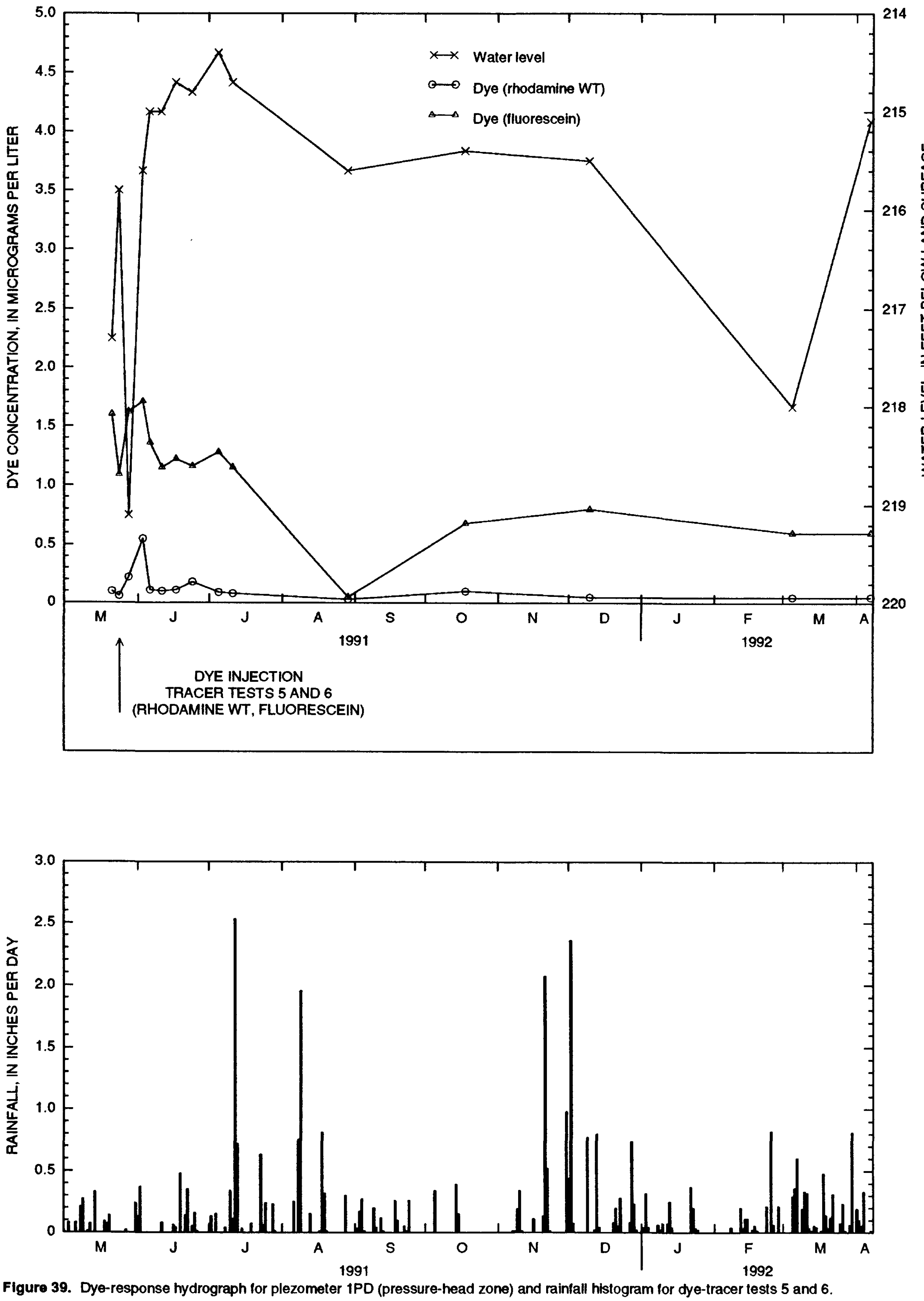


Figure 39. Dye-response hydrograph for piezometer 1PD (pressure-head zone) and rainfall histogram for dye-tracer tests 5 and 6.

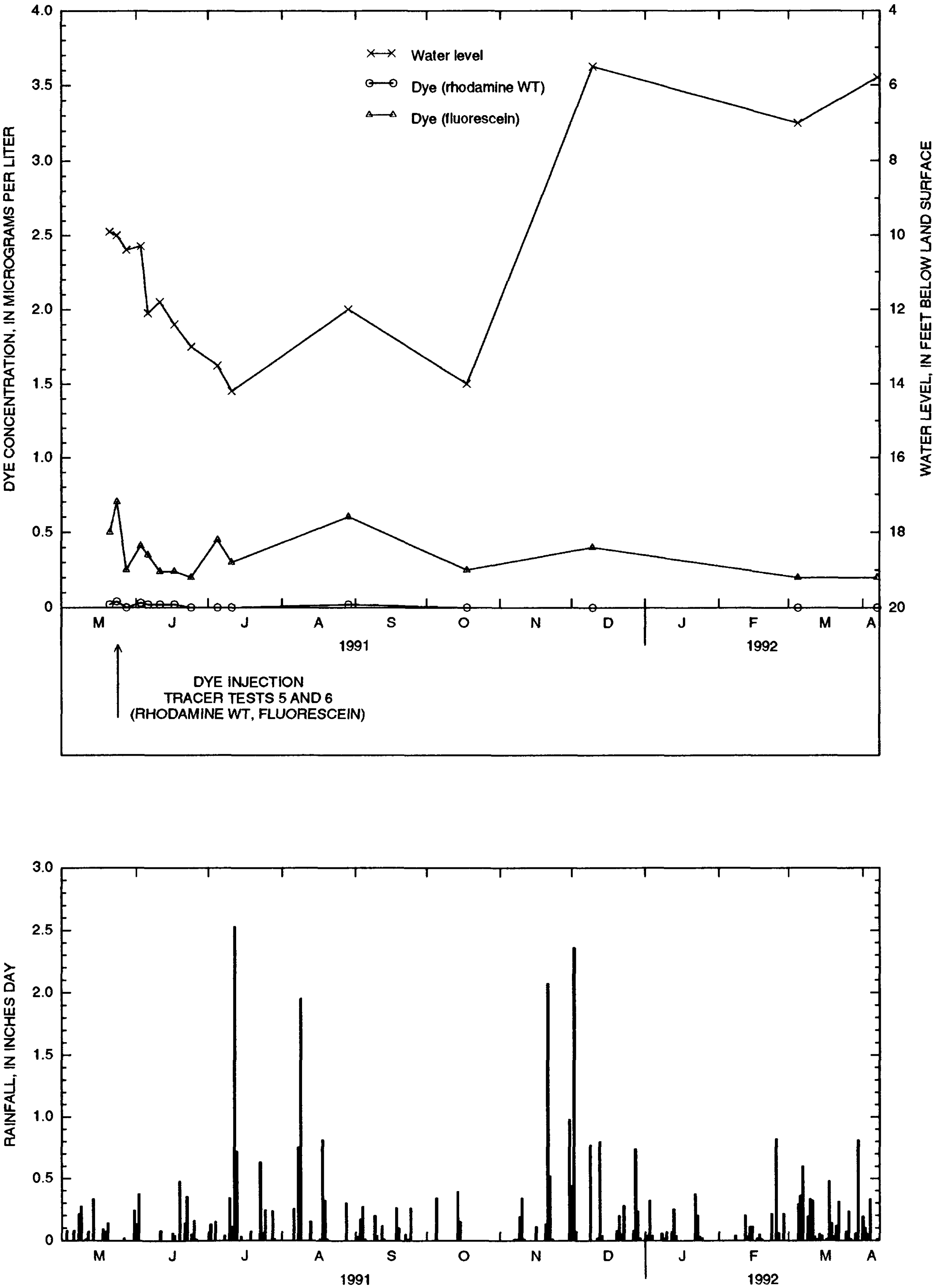


Figure 40. Dye-recovery hydrograph for piezometer 2OH (shallow-fracture zone) and rainfall histogram for dye-tracer tests 5 and 6.

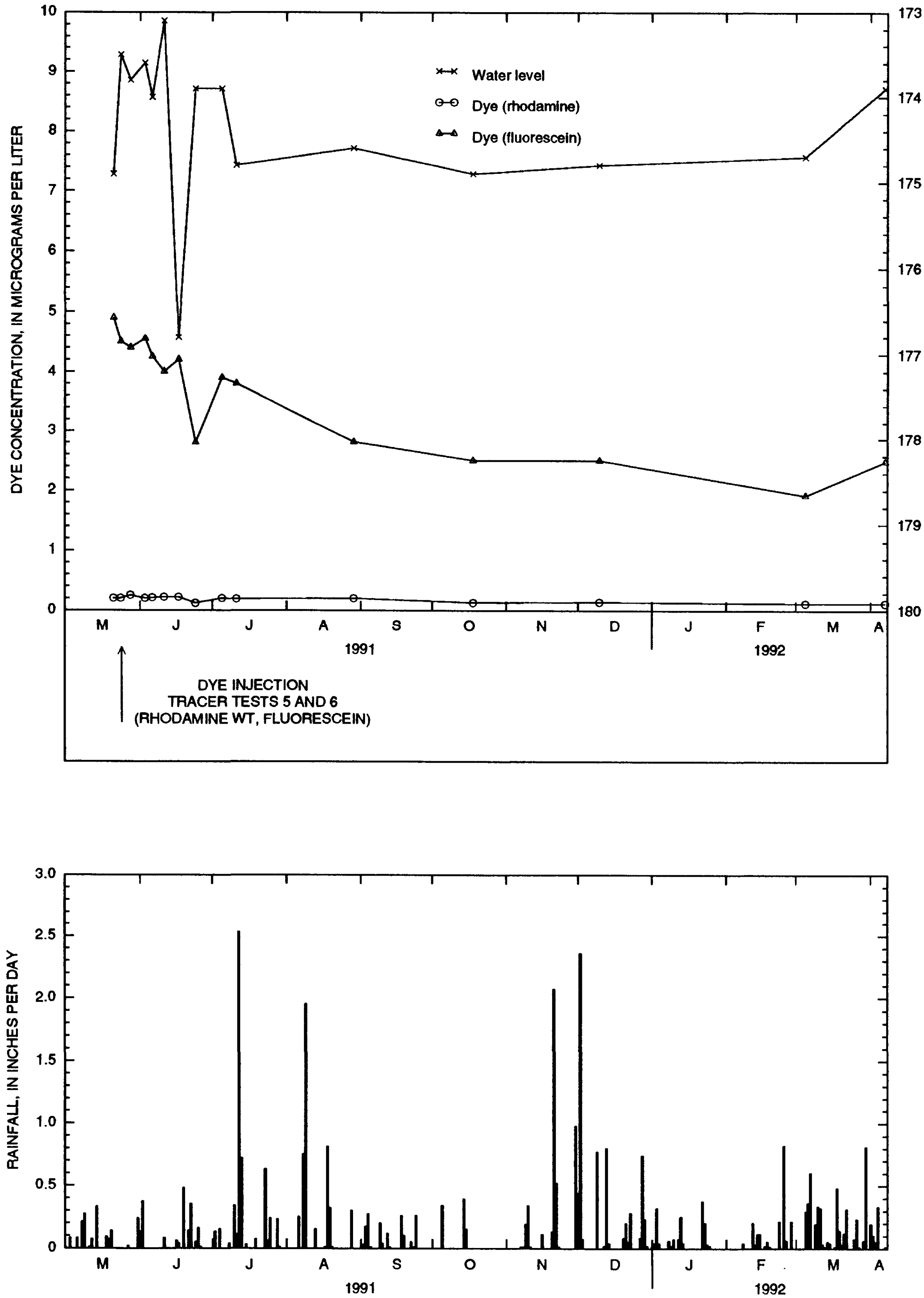


Figure 41. Dye-recovery hydrograph for piezometer 2P (pressure-head zone) and rainfall histogram for dye-tracer tests 5 and 6.

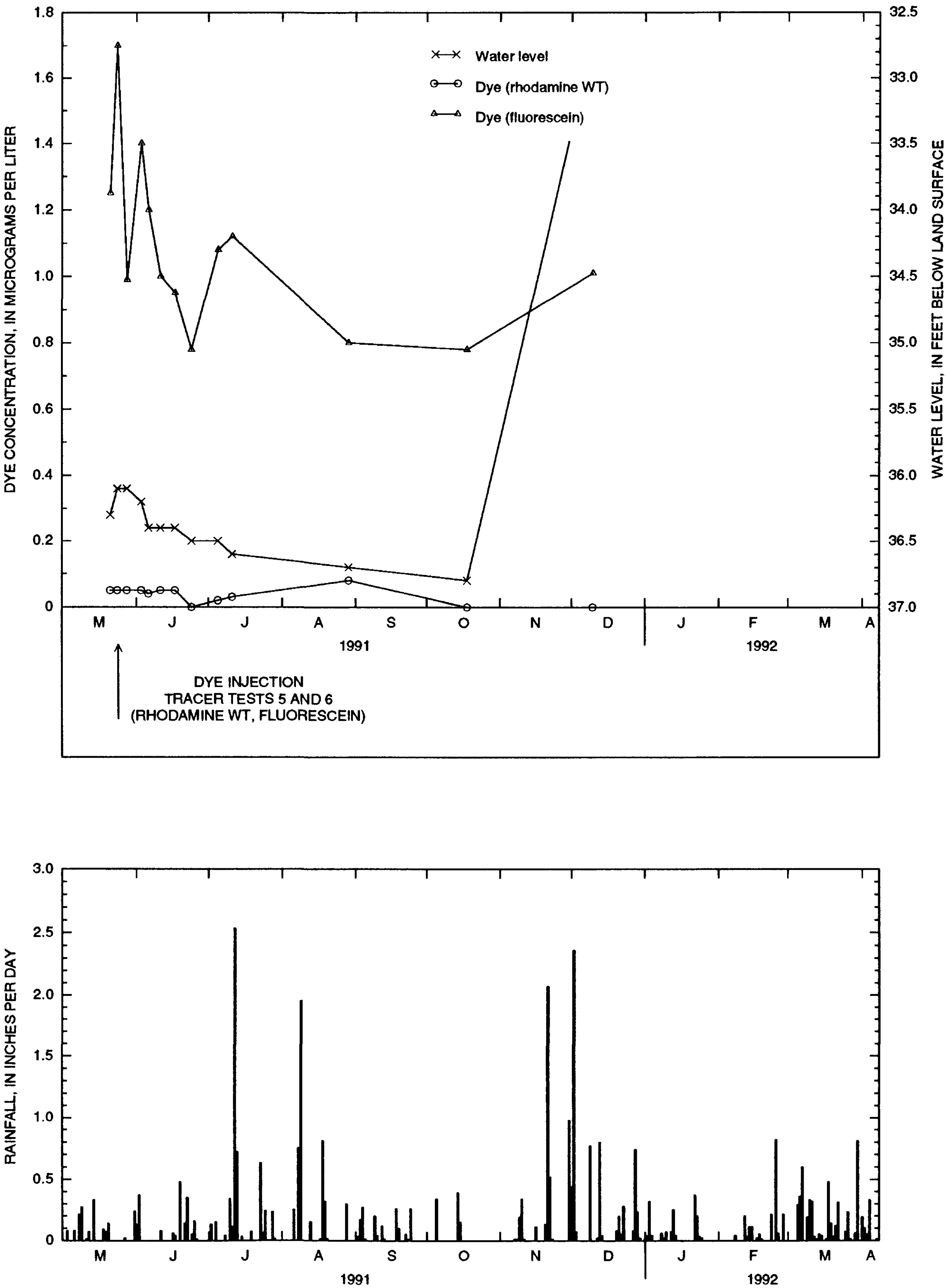
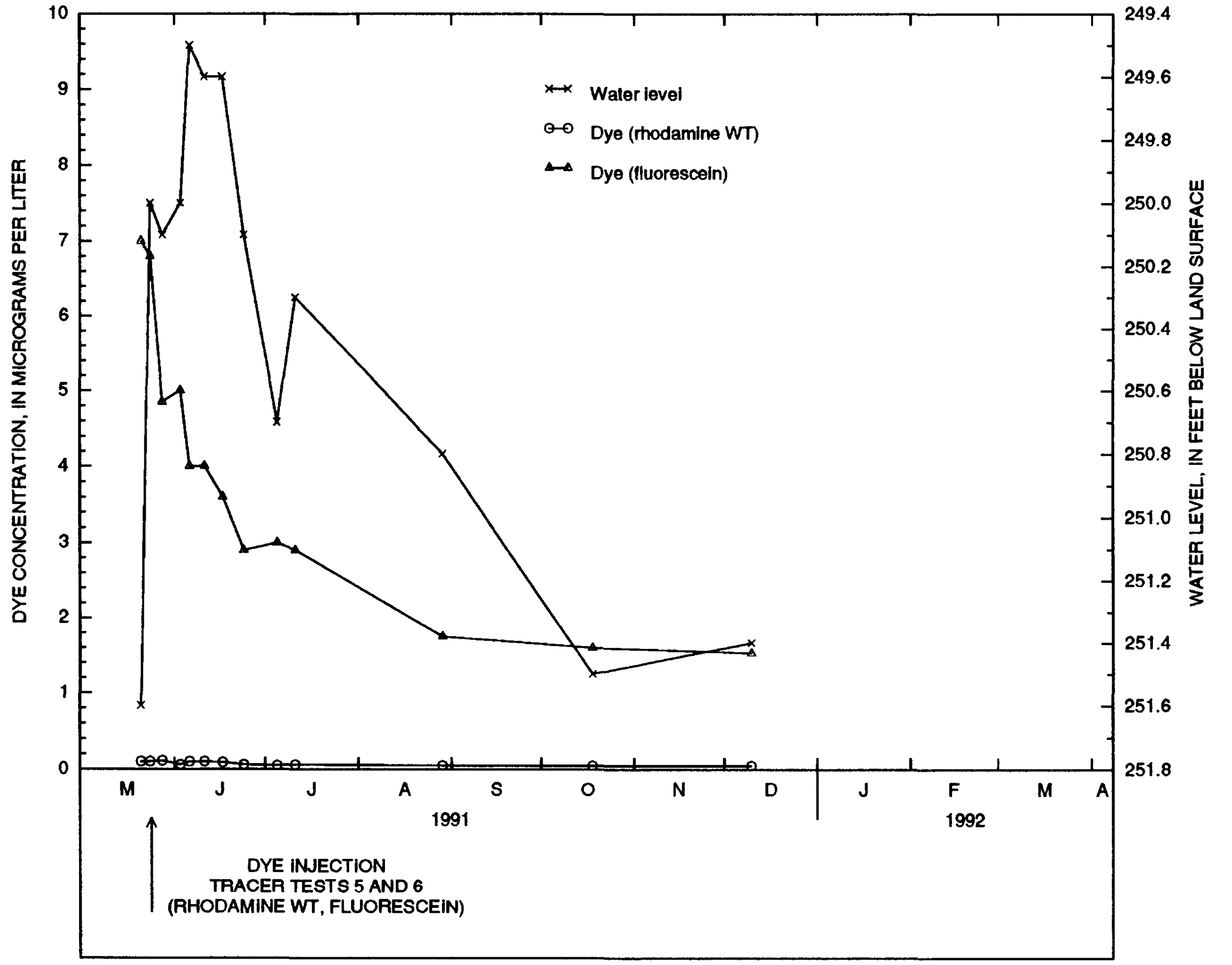


Figure 42. Dye-recovery hydrograph for piezometer 3OH (shallow-fracture zone) and rainfall histogram for dye-tracer tests 5 and 6.



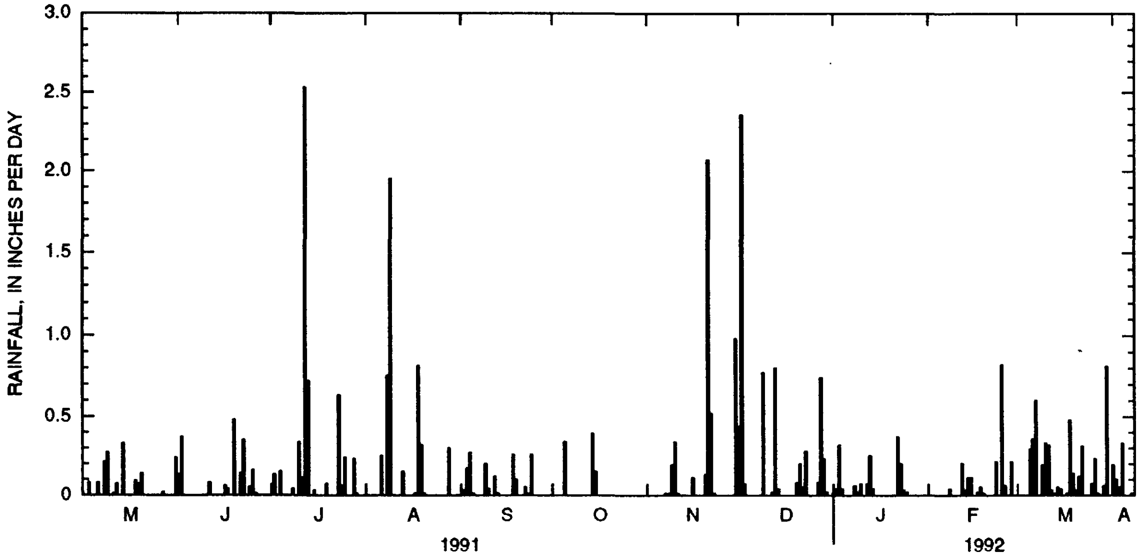
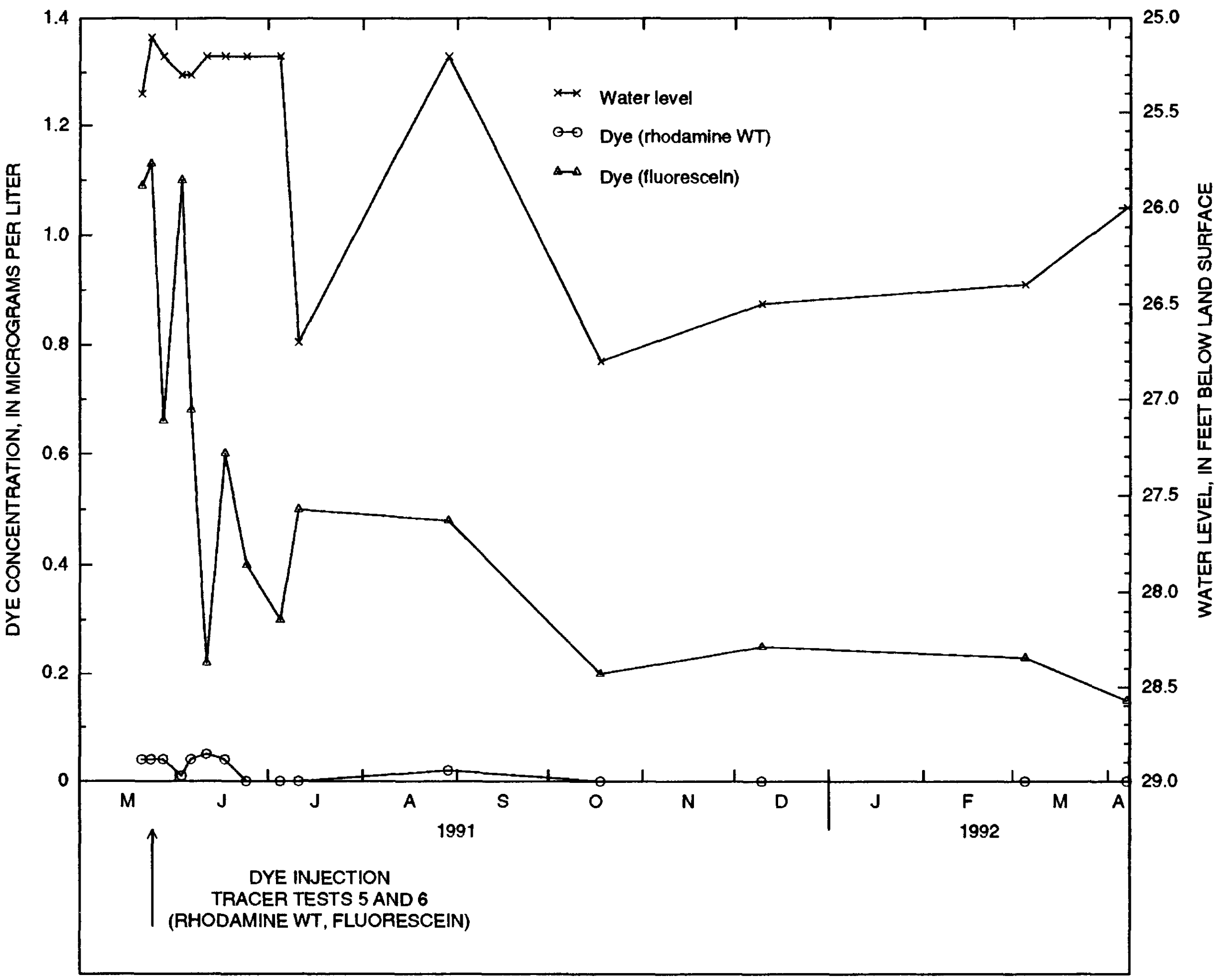


Figure 43. Dye-recovery hydrograph for piezometer 3PD (pressure-head zone) and rainfall histogram for dye-tracer tests 5 and 6.



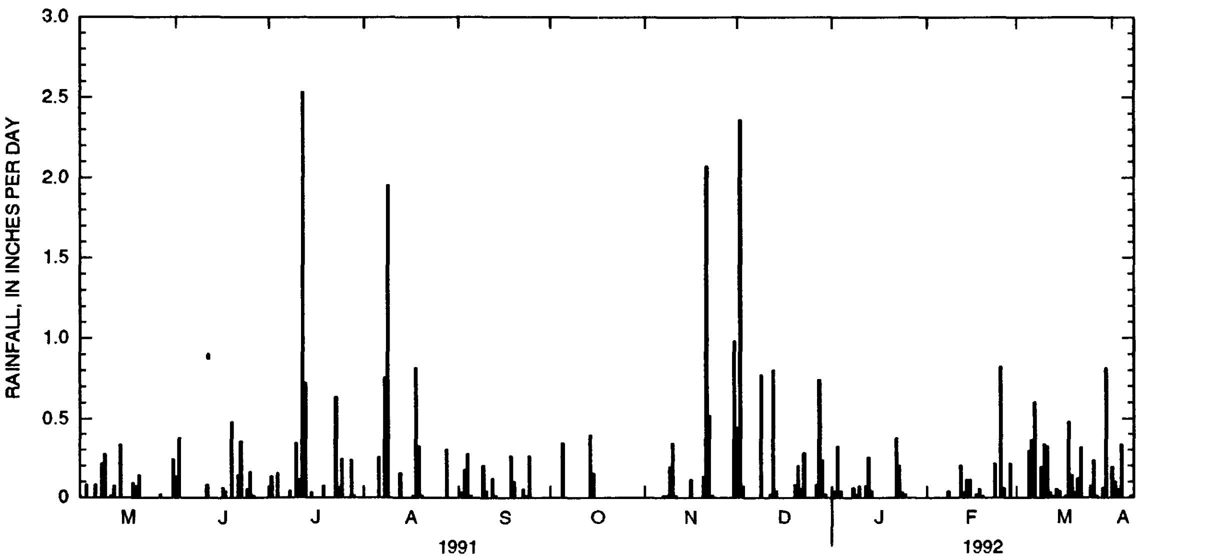


Figure 44. Dye-recovery hydrograph for piezometer 4P (pressure-head zone) and rainfall histogram for dye-tracer tests 5 and 6.

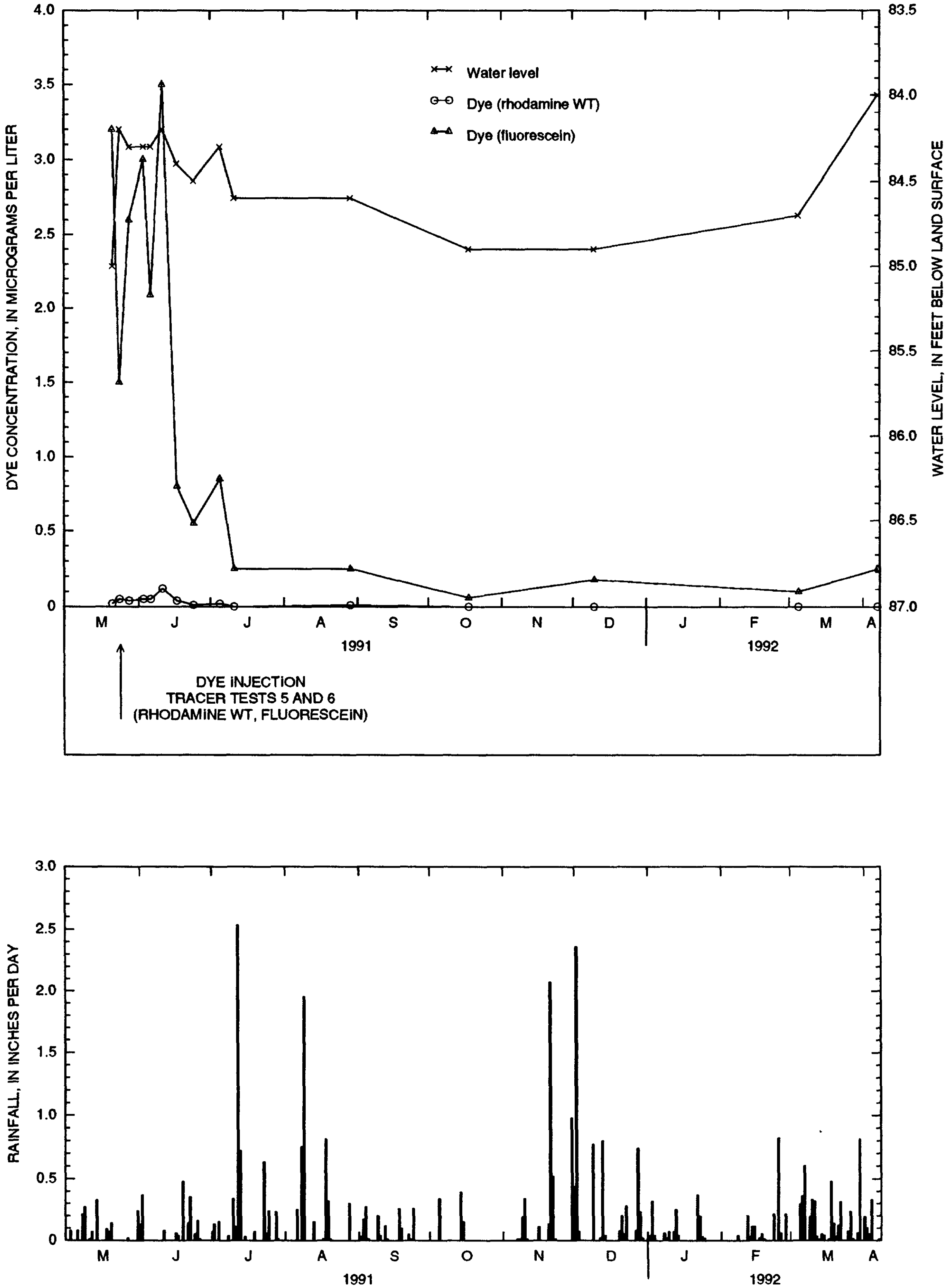


Figure 45. Dye-recovery hydrograph for piezometer 6PD (elevation-head zone) and rainfall histogram for dye-tracer tests 5 and 6.

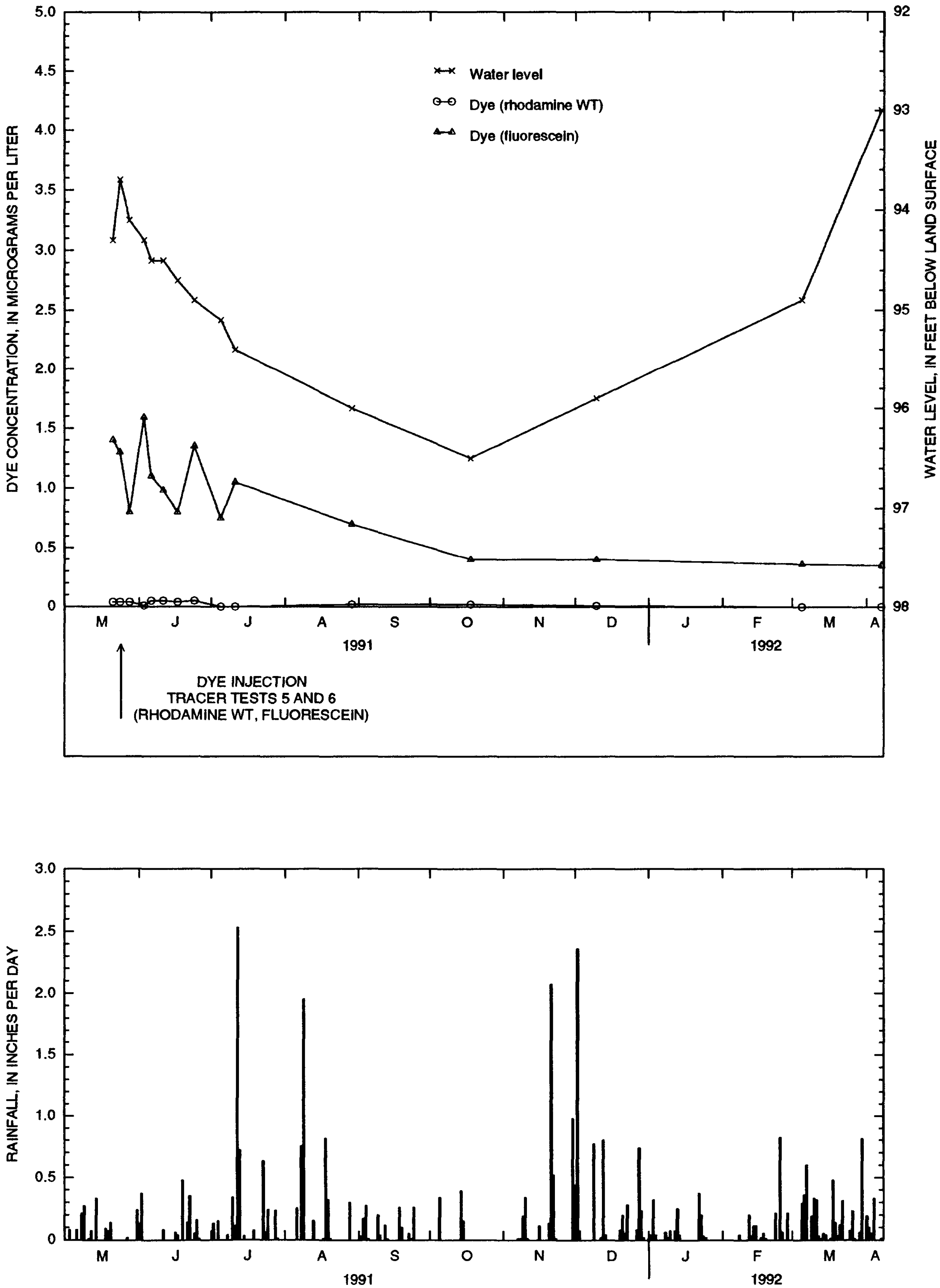


Figure 46. Dye-recovery hydrograph for piezometer 7P (elevation-head zone) and rainfall histogram for dye-tracer tests 5 and 6.

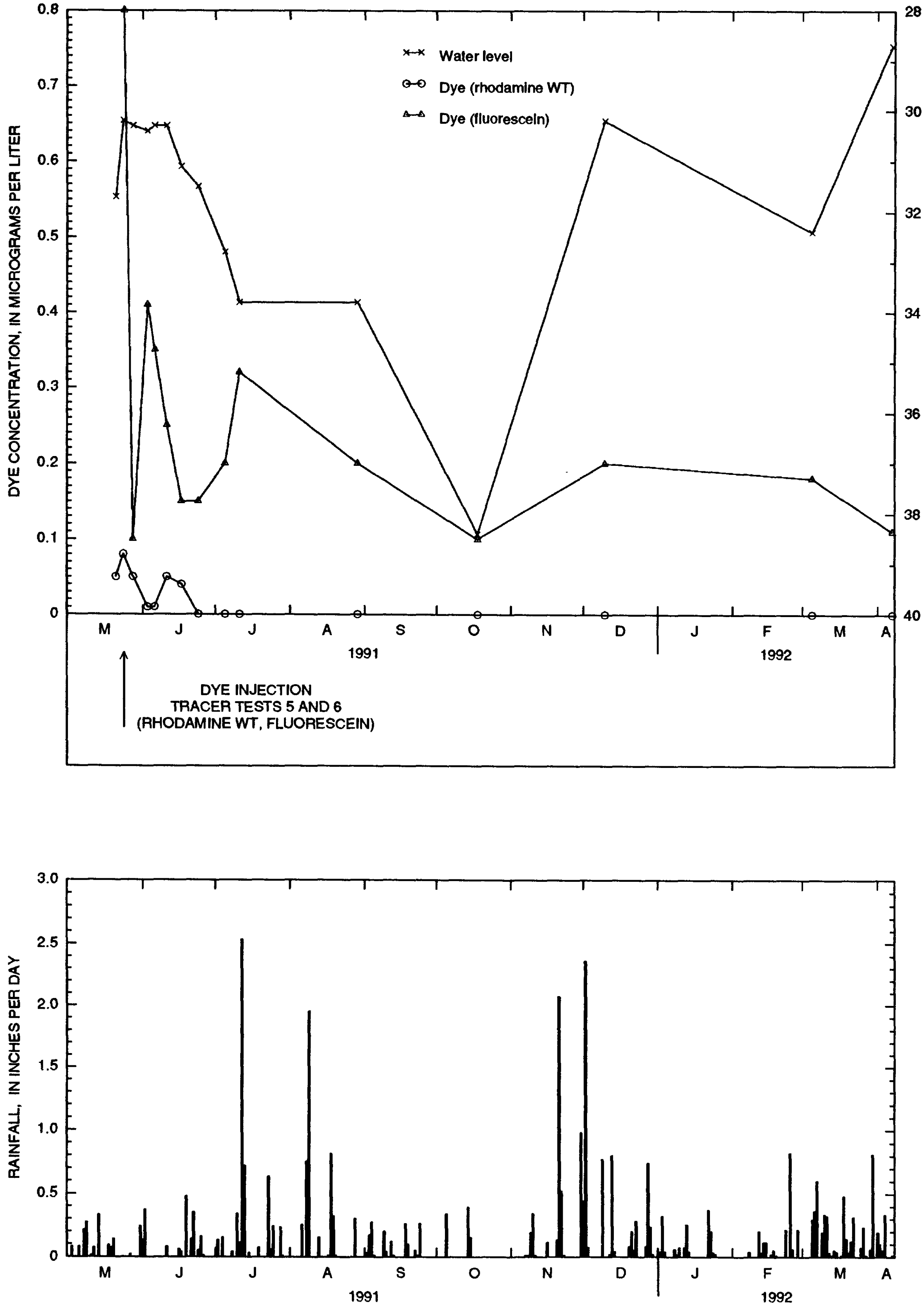


Figure 47. Dye-recovery hydrograph for piezometer 8P (shallow-fracture zone) and rainfall histogram for dye-tracer tests 5 and 6.

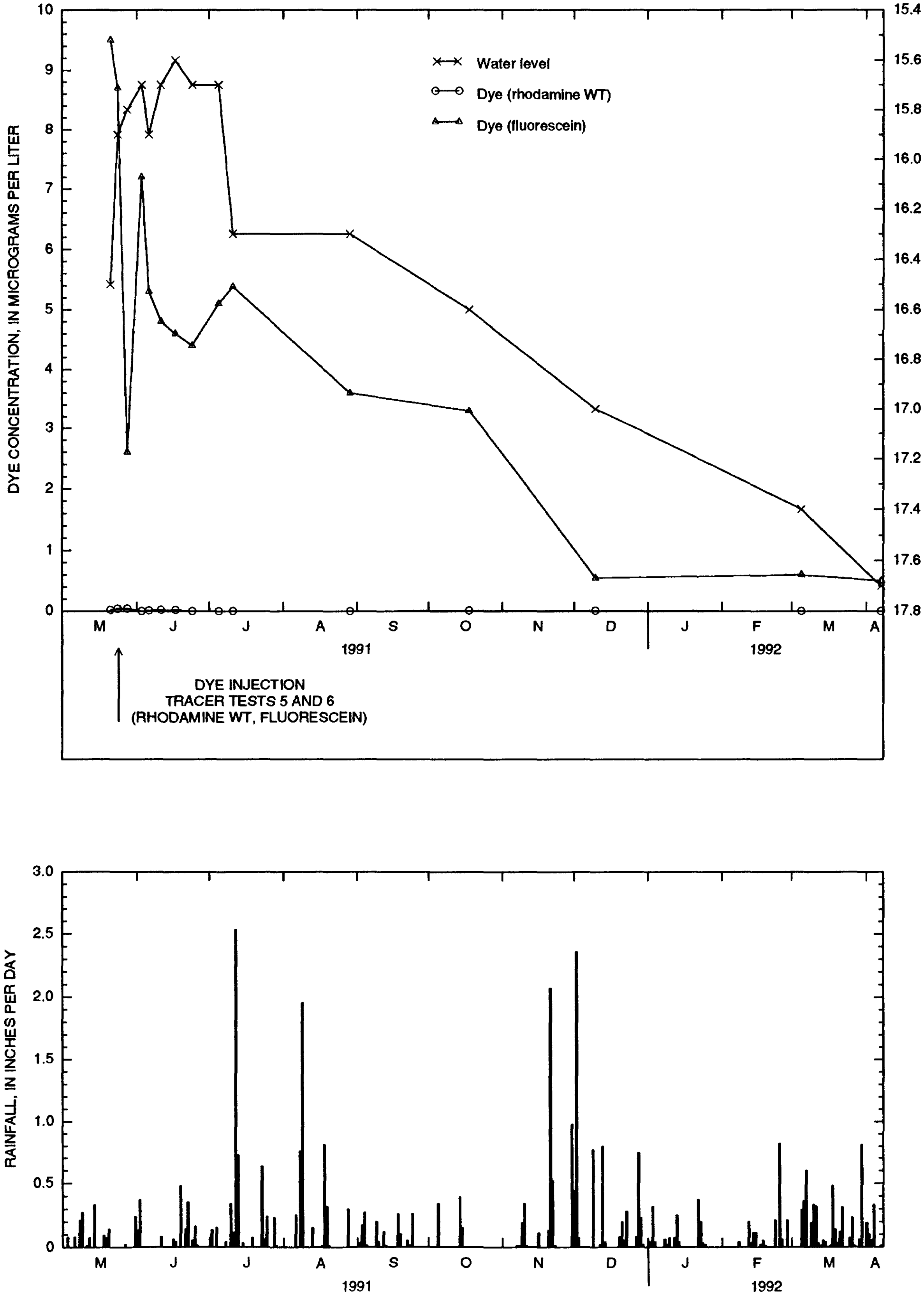


Figure 48. Dye-recovery hydrograph for piezometer JW-1 (flooded, abandoned mine) and rainfall histogram for dye-tracer tests 5 and 6.

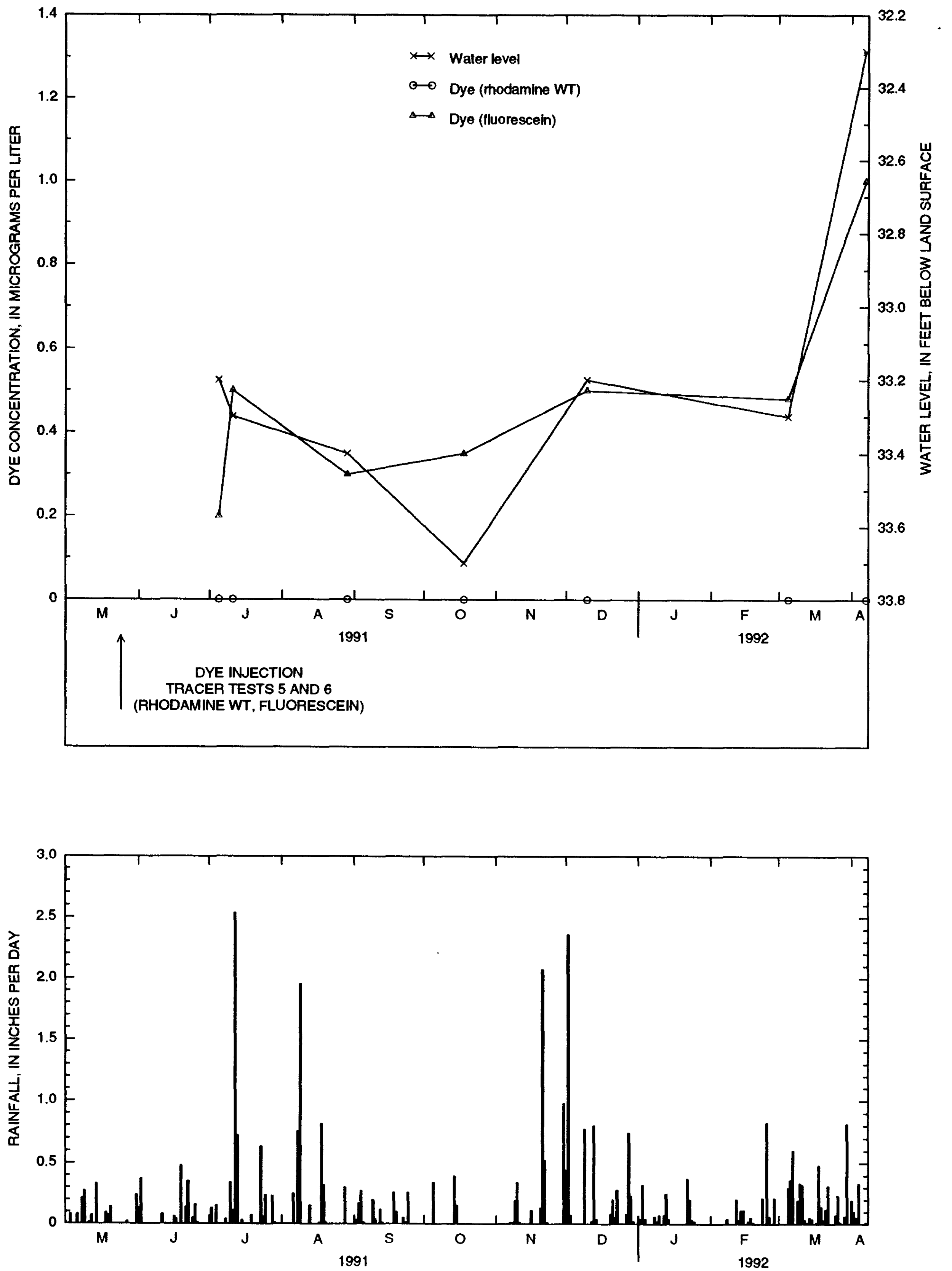


Figure 49. Dye-recovery hydrograph for piezometer JW-2 (flooded, abandoned mine) and rainfall histogram for dye-tracer tests 5 and 6.

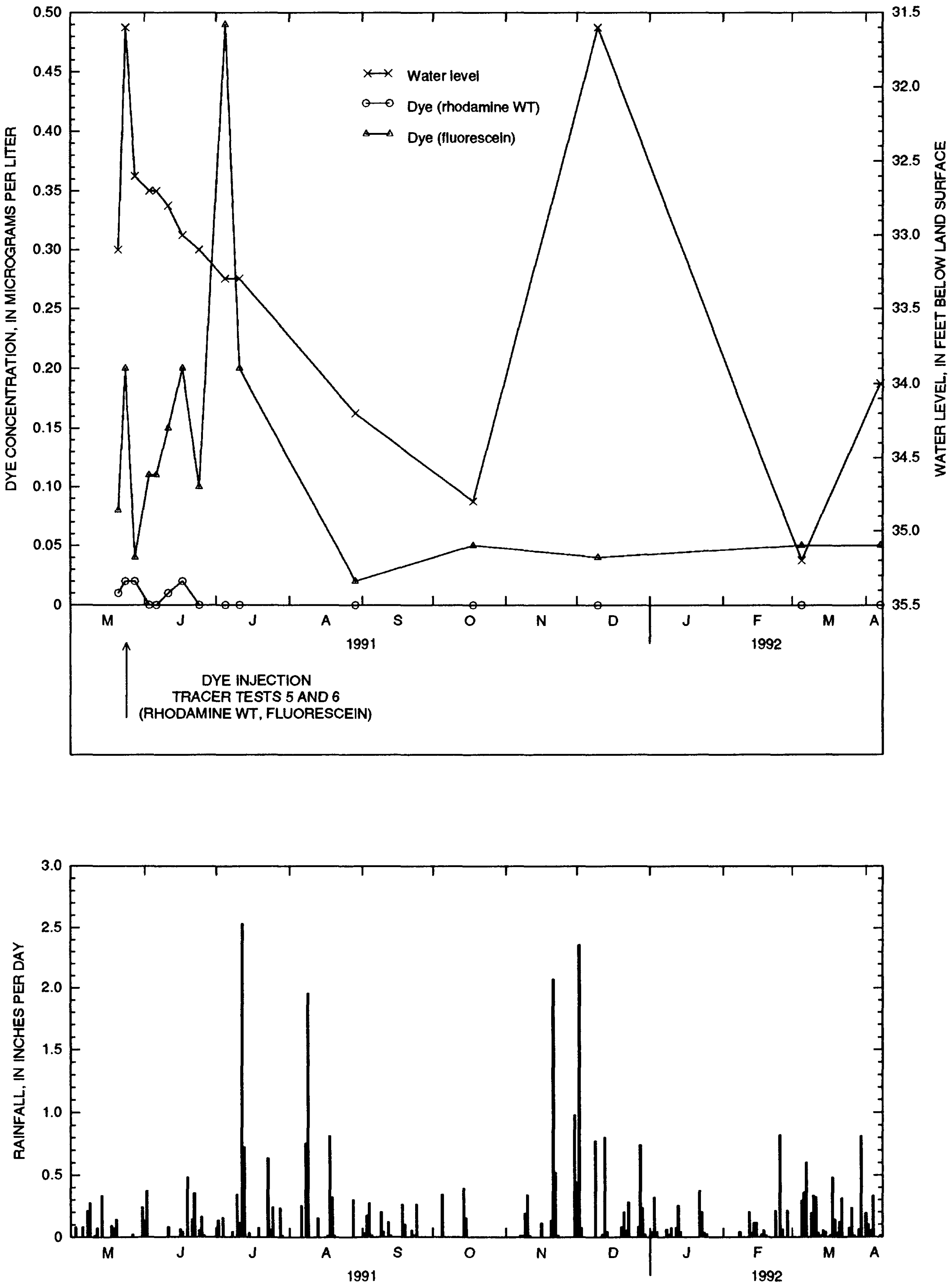


Figure 50. Dye-recovery hydrograph for piezometer JW-3 (flooded, abandoned mine) and rainfall histogram for dye-tracer tests 5 and 6.

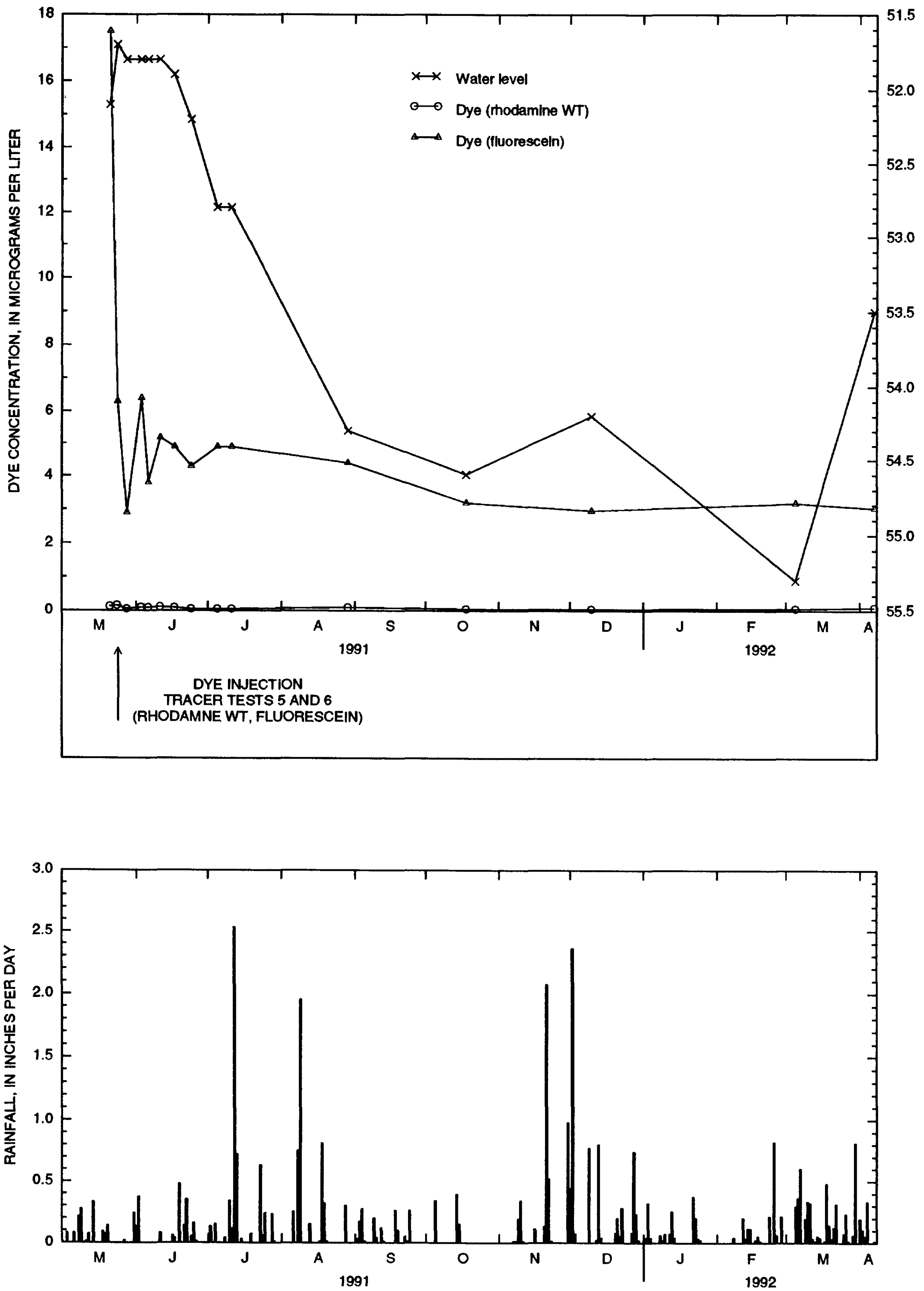


Figure 51. Dye-recovery hydrograph for piezometer JW-4 (flooded, abandoned mine) and rainfall histogram for dye-tracer tests 5 and 6.

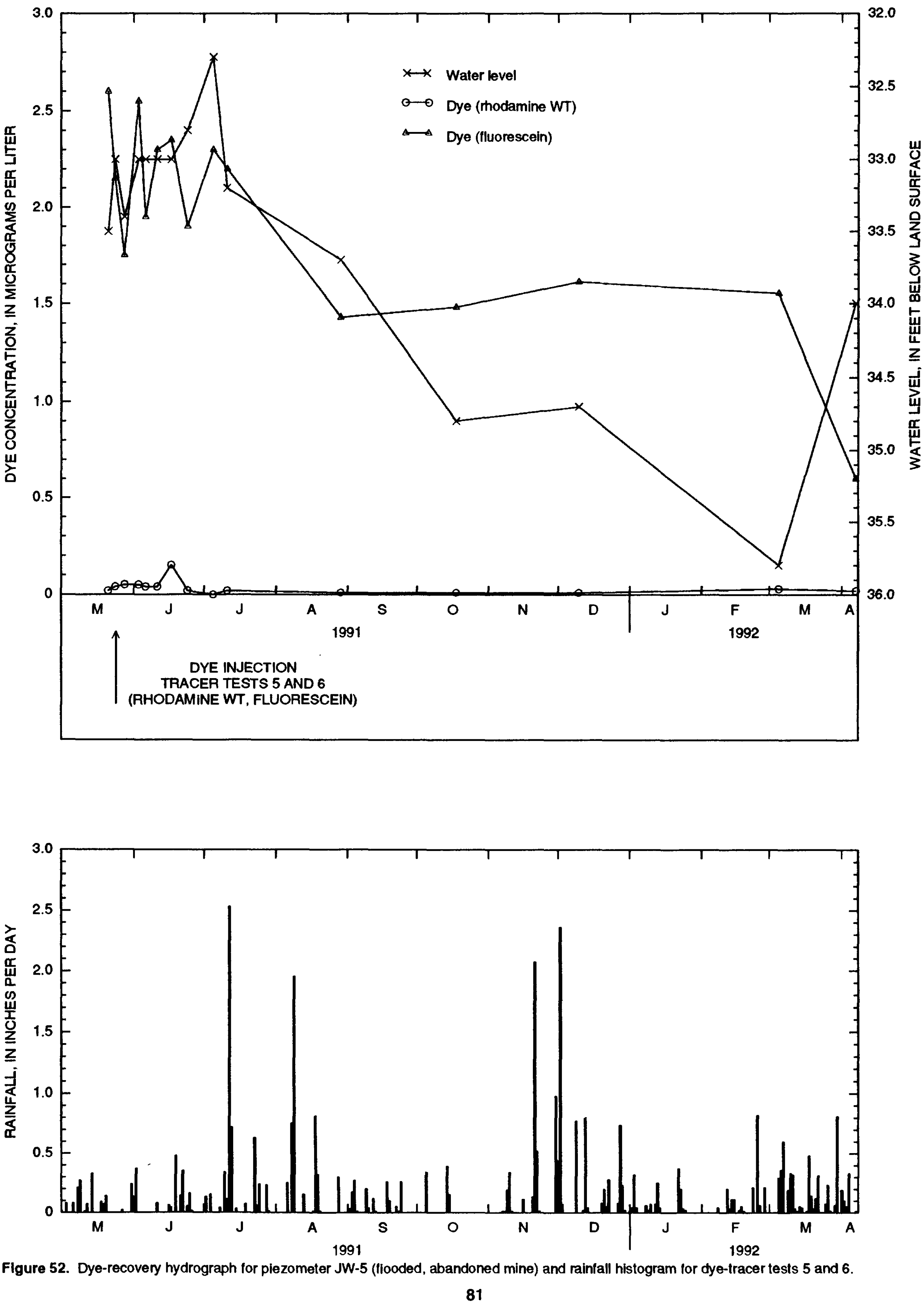


Figure 52. Dye-recovery hydrograph for piezometer JW-5 (flooded, abandoned mine) and rainfall histogram for dye-tracer tests 5 and 6.

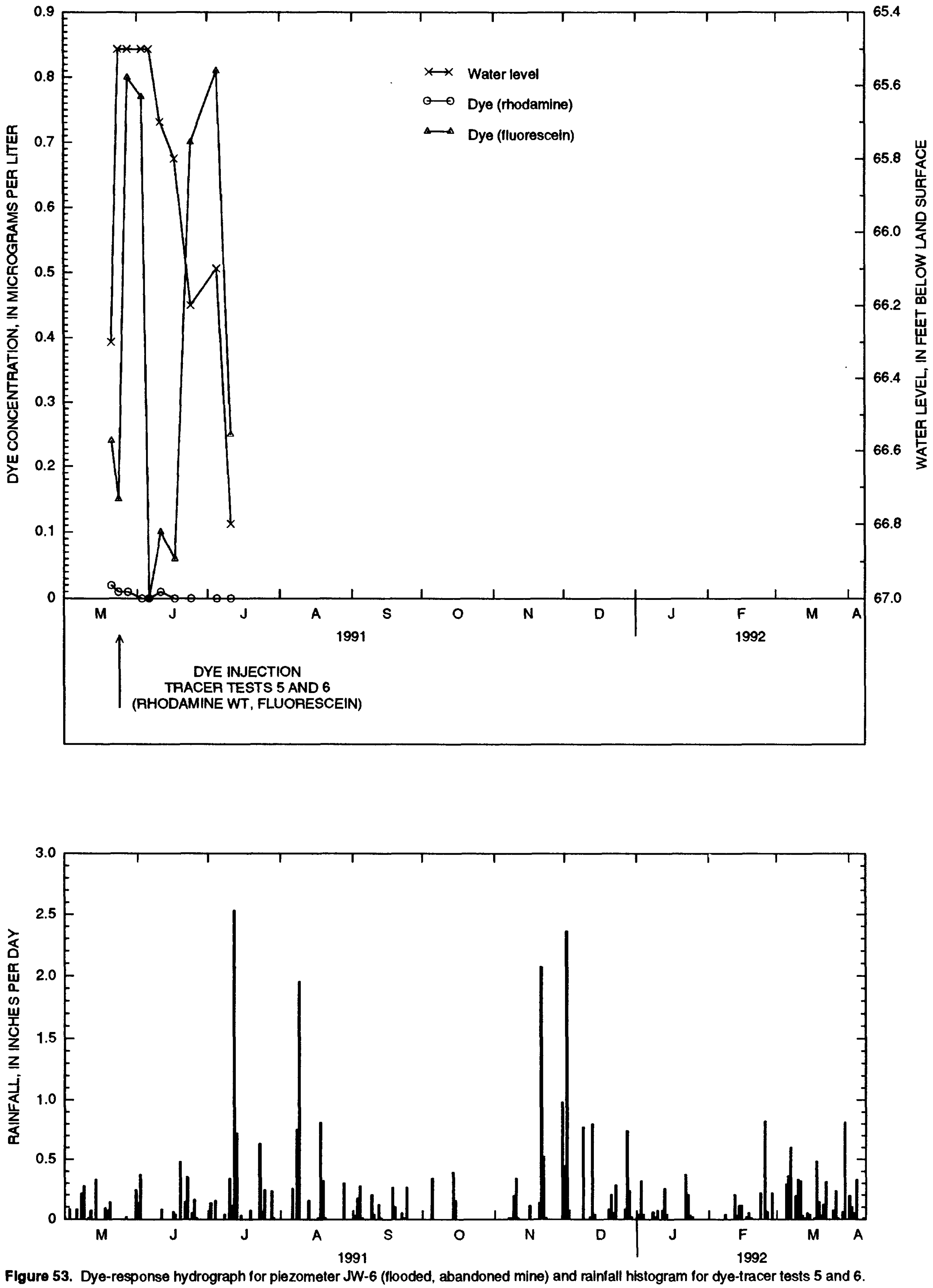
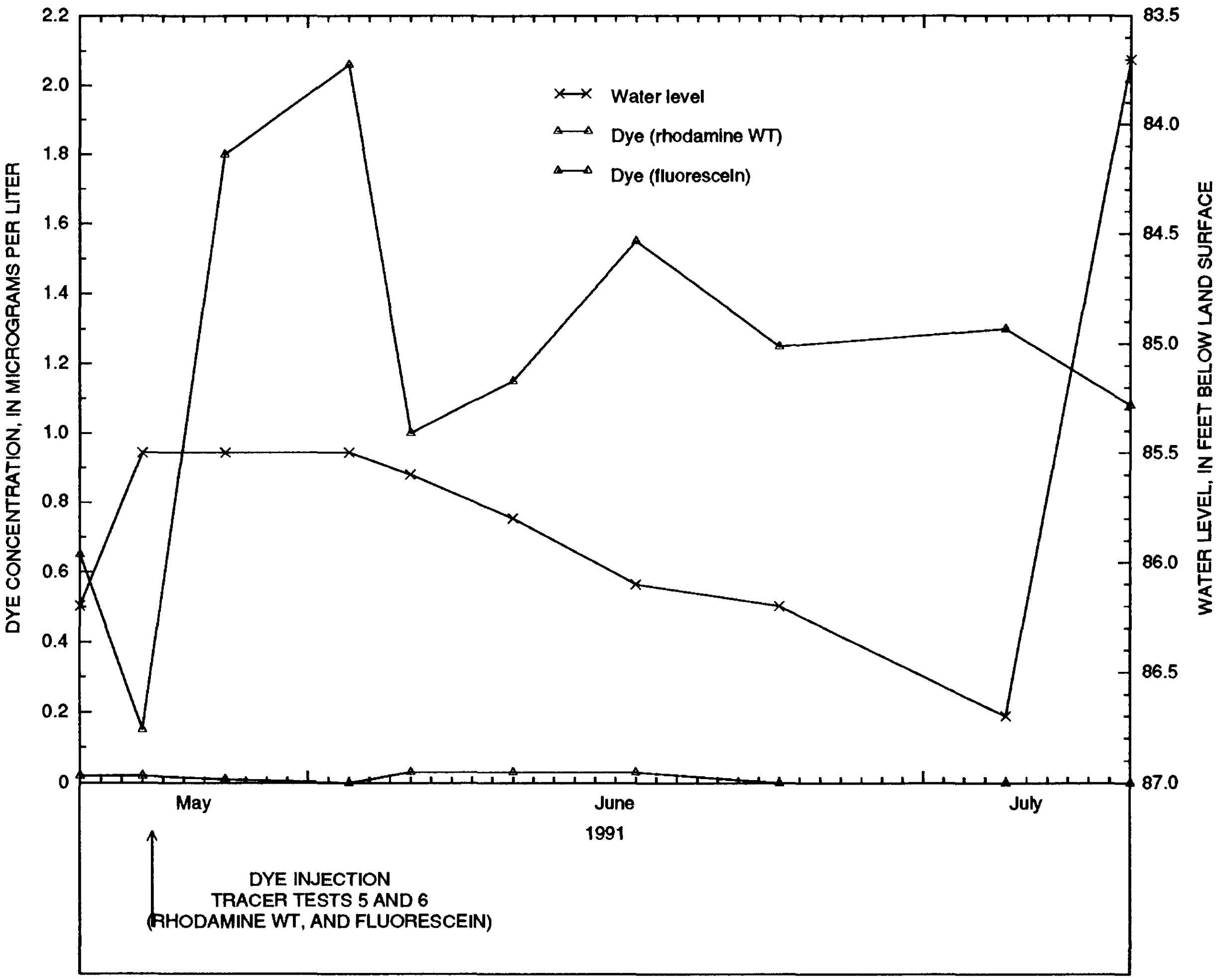


Figure 53. Dye-response hydrograph for piezometer JW-6 (flooded, abandoned mine) and rainfall histogram for dye-tracer tests 5 and 6.



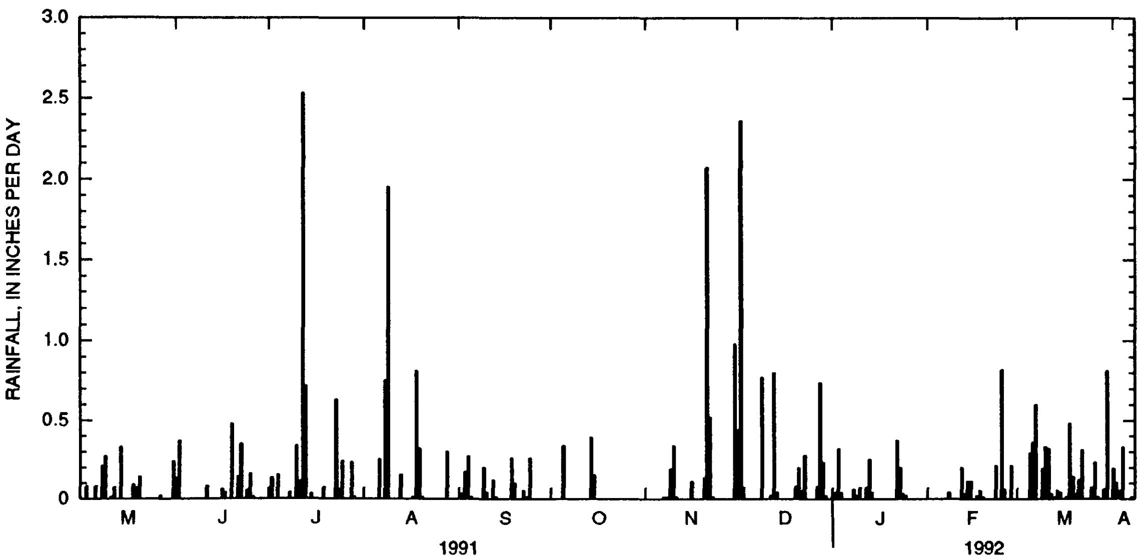


Figure 54. Dye-recovery hydrograph for piezometer JW-7 (flooded, abandoned mine) and rainfall histogram for dye-tracer tests 5 and 6.