TENNESSEE VALLEY AUTHORITY
ENGINEERING LABORATORY

NFERC REGIONAL GROUNDWATER INVESTIGATION

Report No. WR28-1-520-191

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April 1993

ACKNOWLEDGMENTS

Many friends and colleagues have contributed to this report in many ways. Mark Boggs, Marta Edwards, and Kathy Lindquist of TVA's groundwater staff reviewed this report in draft form and we are grateful for their valuable comments. In addition, Bob Chandler, Danny Moore, and Dorothy Ramey of the Geological Survey of Alabama provided assistance and consultation with several areas of this study. Fieldwork could not have been conducted without the assistance of TVA Field Operations West, particularly Helen Rucker, James Adams, and Johnny McFall. We are grateful to John Dunning and Mel Wagner for the help with well installation and borehole flowmeter work.

TVA's Maps and Surveys group out of Norris, Tennessee, provided GIS mapping services and we are grateful for their assistance. We are indebted to Marilyn Sears and Shelly Coltharp for their support in preparing numerous plots and figures present in this report, and for their patience with seemingly endless revisions. Catherine Patty typed this report and Cynthia Webb edited the final version. They made many excellent suggestions and corrected our errors.

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EXECUTIVE SUMMARY

Temporal and/or spatial variations in areal recharge, hydraulic gradients, soil hydraulic properties, and bedrock fractured/weathered zones are important factors affecting groundwater flow beneath the NFERC reservation. At NFERC, the use of bulk hydraulic parameters and averaged hydraulic gradients have limited applicability, especially with respect to estimating groundwater transport. Because the usefulness of groundwater transport predictions is related to the validity of the assumptions and simplifications required to make those predictions, they should be based on a careful examination of site characterization data, including: aquifer hydraulic properties, hydraulic gradients, and a conceptual aquifer model that includes boundary conditions.

The majority, if not all, of the groundwater beneath the NFERC reservation discharges to the Tennessee River, Tuscumbia Spring, and/or smaller springs in the area. Groundwater flow in the overburden is very different from that in the bedrock, being primarily vertical in the overburden and horizontal in the karstic bedrock. Groundwater from the overburden generally discharges to a lower drainage boundary that is controlled primarily by a very permeable horizontal flow zone in the bedrock epikarst. Whereas, the overburden is characterized by a continuous hydraulic conductivity field, the bedrock is best characterized by an interconnected discrete fracture network.

Borehole flowmeter, pumping, and slug tests in the Tuscumbia Limestone indicate order-of-magnitude differences in the bulk transmissivity among bedrock boreholes and among the different vertical intervals within a borehole. These test results and those from dye tracing studies and lineament surveys indicate an extensive interconnected network of transmissive fractures and solution features in the epikarst zone and upper bedrock. Results of dye trace tests at NFERC and in the Muscle Shoals area show that rapid solute migration accompanied by high dilution occurs in the bedrock. Dye velocities of up to 1,100 ft/day were observed from tracing at NFERC, and velocities as great as miles/day have been estimated for areas south of NFERC. The flowmeter results consistently show a relatively high permeable zone, the epikarst zone, near the contact of the overburden and bedrock. The transmissivity of this zone varies perhaps 4 orders-of-magnitude with some regions exhibiting transmissivity values greater than 500 ft^2/day. The horizontal hydraulic gradients within the bedrock and epikarst zones at NFERC vary from about 0.1 to 2 percent and water level measurements in all bedrock wells indicate that these gradients are generally consistent across the site.

The most extensive and transmissive fracture zones likely have a northwest/northeast orientation as indicated in the lineament study. This rectilinear orientation suggests that the bedrock possesses a structurally controlled joint system. It is probable that different sets of fractures serve as conduits under different hydrologic conditions; for example, a deep set of fractures may conduct groundwater under low water table conditions and a shallower, somewhat differently oriented set may control groundwater movement during higher water table conditions.

Unlike the Tuscumbia Limestone, the overburden does not exhibit laterally extensive highly permeable flow zones. The overburden consists of a continuous, low permeability, clayey

soil matrix with occasional stringers of sandy clay. Borehole flowmeter data at a 1-ft scale provide horizontal conductivities as high as 0.3 ft/day (0.0001 cm/s) for the sandy clay layers. However, neither soil logs nor cone-penetrometer tests from locations spaced several tens of feet apart indicate that these sandy clay units have significant lateral continuity. Permeameter and borehole flowmeter tests suggest that the hydraulic conductivity of the clayey soil matrix is generally less than 10^{-6} cm/s. These tests also suggest that the horizontal permeability is up to 10 times greater than the vertical permeability at a scale of one foot.

Within most of the overburden, groundwater flow is downward. Local areas of upward flow occur near some streams, topographic lows, and areas that receive direct recharge to the bedrock flow system. Within the relatively small region of SWMU 108, nested piezometer data indicate vertical hydraulic gradients from 103 percent downward to 10 percent upward. This range occurs because of seasonal changes and a complex flow system that results in groundwater flow toward Pond Creek in the overburden but away from Pond Creek in the bedrock during most of the year. Data from detailed monitoring of the wells and piezometers across the NFERC reservations produced similar temporal variability as that observed at SWMU 108. Downward and upward vertical gradients were observed to approach 95 and 18 percent, respectively. This assists in explaining the relationship between overburden and bedrock at the site. Generally, the large vertical hydraulic gradients at the site may be attributed to poor vertical hydraulic interconnectivity between the overburden and bedrock. Poor hydraulic interconnectivity between stratified hydraulic units is caused by sediments with low effective vertical hydraulic conductivity. As shown in Appendix C, intermediate to deep overburden sediments at the site consist of clayey soils that possess vertical hydraulic conductivities of less than 10^{-7} cm/s.

In general, the overburden sediments at NFERC consist of heterogeneous low to moderately permeable clayey soils with a porosity near 0.35. The average net recharge from precipitation is expected to range from 10 to 15 in./yr and the average downward groundwater velocity is about 36 in./yr. Therefore, if uniform flow is assumed to occur through the overburden, a conservative tracer might be expected to pass through a 30-ft saturated overburden in about 10 years. However, because of the heterogeneity in the overburden, uniform movement of solutes is unlikely.

An important effect of heterogeneity is the potentially earlier arrival of a solute front and greater dispersion than that of a uniform flow field. The modeling results indicate that heterogeneity in the saturated overburden can cause variations within the solute plume of at least 30 percent from the mean velocity of the infiltrating precipitation. These variations will likely cause up to a 100 percent difference in the migration rates observed from breakthrough curves from staged piezometers across a relatively large area greater than 10,000 ft^2. Breakthrough curves along a theoretical plume centerline indicate that a conservative solute will take from 10 to 18 years to migrate through the heterogeneous overburden to the epikarst zone.

The variability in the velocity field for the heterogeneous modeling cases suggest that large variations in the water quality data will occur among the wells and that no single well could provide a representative data set. The problems with successfully monitoring and predicting the movement of a theoretical contaminant plume will be affected by the size of the

plume. The larger the plume the more reasonable becomes a statistical approach to the breakthrough curves. For a large plume it appears reasonable that plume front will not move uniformly downward, but will finger preferentially toward the epikarst zone. For decreasingly smaller plumes, the time of solute breakthrough becomes more unpredictable and it is more likely that a dispersivity of 0.01 ft applies.

An important feature of the conceptual aquifer model for NFERC is that groundwater from the overburden seeps relatively slowly into the bedrock. A hypothetical contaminant release across one acre would contaminate approximately 125 ft^3 of recharge water per day. Ignoring dispersive processes, the spill concentrations will be diluted by a factor of 45,000 at Tuscumbia Spring based on an average spring discharge of 42 Mg/d. In addition to dilution by mixing, additional dilution is expected from dispersion caused by temporal variations in the hydraulic gradients and spatial variations in the hydraulic properties.

Water quality monitoring of NFERC wells shows no obvious trends that indicate on-site contaminant sources with the possible exception of nitrate from the vicinity of SWMU 108. Young and Julian (1991) identified nitrate as the groundwater contaminant of most concern near SWMU 108 with respect to both health risks and implication to understanding the vertical migration of solutes through the overburden. Nitrate profiles from staged wells show higher nitrate concentrations at the shallowest and deepest wells and low concentrations at the intermediate wells. The staged wells are in the vicinity of a downward vertical hydraulic gradient. Because the nitrate profile at these staged wells could not be explained, using classical solute transport models, and a low-permeability overburden exists at the site the improper construction of several older wells was suspected.

Inspection of several of the earliest well constructs, which included well W12, revealed a design flaw that created a relatively large sand-filled annulus around the well that could serve as a conduit for rapid vertical migration of groundwater from the upper overburden to the bedrock. Wells W9, W11, and W12 were abandoned in September 1992. More recent nitrate profiles from staged wells show a reduction in nitrate concentrations from previous levels, especially below the upper sampling intervals. The data suggests that the suspected problems at wells W9, W11 and W12 were real and contributed to the high nitrate concentrations in the wells screened in the upper bedrock. A closure plan was devised for SWMU 108 (Julian and Young, 1992) that outlines selected monitoring and analysis for nitrate at NFERC over the next several years.

Chemical analyses of groundwater from regional wells at the NFERC site show that nitrate levels in the groundwater are mostly below the MCL of 10 mg/L. The values (nitrate as N) range from less than 0.1 to 18.1 mg/L, with most measurements occurring between 1 and 5.7 mg/L. However, two wells, D1 and F2, showed slightly elevated nitrate levels (18.1 and 16.7 mg/L, respectively). The elevated nitrate concentration in the two wells is not likely to be related to SWMU 108. This conclusion is based on the facts that (1) no elevated nitrate levels were found in the wells between SWMU 108 and wells D1 and F2, and (2) well F2 is an overburden well up-gradient of SWMU 108. Therefore, the slightly elevated nitrate levels in well D1 and F2 are probably the result of local sources, such as surface agriculture activities.

Water quality data from storm-water drainage wells in the Muscle Shoals area show that most of the values for nitrate are below the MCL. Additionally, the nitrate concentrations observed in the regional wells at NFERC are of the same magnitude as the background values from the storm drainage wells. Nitrate levels measured for Tuscumbia Spring since 1929 indicate less than 3 mg/L of nitrate (as N) in spring waters. These results suggest that nitrate contamination from the SWMU 108 area poses little health risk to the Tuscumbia Spring groundwater supply. The regional well data also implies that nitrate contamination from SWMU 108 is limited by dispersion and dilution.

Anomalous high values of Mn and Al were observed in groundwater samples from several regional wells. However, the groundwater samples were not filtered prior to analysis so that some fine soil particles are prevalent in the samples. Aluminum and iron are the prevalent elements associated with fine soils. Mn, a metal typically associated with Fe, has a similar correlation with the turbidity. Therefore, it is probable that the Mn values are also associated with sediments contained in the samples.

Chloride concentrations are elevated in wells located on the southeastern corner in the NFERC reservation. Groundwater investigations at the OxyChem facility just east of NFERC the plant confirmed the presence of plumes of mercury, cadmium, and chloride with elevated chloride concentrations that probably extend off-site. Considering that groundwater flow directions in this vicinity are west-southwest, the relatively high Cl concentrations observed in the NFERC wells are probably the result of chloride contamination from the OxyChem site. Overall, the metal concentrations in groundwater samples are low and no contamination of metals from the NFERC site to groundwater is evident in the wells sampled.

Chloroform was detected in well A1 at a concentration of 73 μg/L. No other samples have concentrations above the detection limit for this compound. Bis(2ethylhexyl)phthlate was detected in two regional wells (B1 and F1). However the concentrations are barely above the analytic detection limit. Several organic compounds, including, carbon tetrachloride, tetrachloroethylene, and bis(2ethlhexyl)phthlate, were found at or above detection limits in groundwater samples from several wells near SWMU 108. Carbon tetrachloride is found in well W9 at a concentration of 25 μg/L, and tetrachloroethylene in well W9, W12, and PZ11C at concentrations of 575, 11, and 38 μg/L, respectively. The concentrations are above the MCLs (5 μg/L). Presence of the two compounds has also been detected in earlier groundwater analyses during 1987-1990 (Young and Julian, 1991) from the same wells. Compared with all other concentrations throughout the last few years, it is apparent that their concentrations have been consistent with a slight decrease in the concentration of carbon tetrachloride in well W9.

Chemical analyses for Pond Creek have indicated no organic compounds in its surface waters; however, numerous organics were found in sediment samples from several locations which included a location upstream of SWMU 108. The organics included polynuclear aromatic compounds, volatile halogenated hydrocarbons, and petroleum compounds. The presence of these organic constituents implies that groundwater, surface water discharges and/or spills into Pond Creek have contaminated the stream's sediments. Based upon assumptions of the ratio of the groundwater flux in Pond Creek to its discharge, the percentage of organic matter in the sediments of Pond Creek, and the potential migration of contaminated groundwater from

upgradient industry, the most likely source of organic contamination at SWMU 108 wells is from off-site via the bedrock groundwater flow system. This is supported by the findings from the sampling of regional well pairs. Bedrock wells A1 and F1 exhibited evidence of organics contamination while their overburden counterparts did not.

The contamination source(s) for organic compounds detected at NFERC have not been absolutely identified. Groundwater investigations at the Ford facility have revealed 35 volatile organic compounds in the vicinity of a contaminate plume from their site. The prevalent organic compounds identified at the site include tetrachloroethane, trichloroethene, 1,2-dichloroethene, chloroform, and benzene. Wells installed by Ford on the OxyChem property have also shown the presence of chloroform, 1,2-dichloroethene, tetrachloroethane, bromodichloromethane, and dibromochloromethane in groundwater. Considering that groundwater flow directions include west-southwest components from the vicinity of the Ford facility, the organics detected in NFERC wells may be a result of contamination from this site.

NFERC REGIONAL GROUNDWATER INVESTIGATION

1.0 INTRODUCTION

1.1 Overview

Potential contamination of groundwater from the National Fertilizer Environmental Research Center (NFERC) is a concern of the Tennessee Valley Authority (TVA) and state and federal regulatory agencies. The Resource Conservation and Recovery Act (RCRA)/Hazardous and Solid Waste Amendments (HSWA) permit for NFERC also requires TVA to evaluate regional and site-specific geohydrologic characteristics affecting groundwater flow beneath the facility. That evaluation is provided in this report.

The NFERC has been in existence for approximately 40 years. Initial work at the NFERC site involved phosphate developments work. More recent research efforts at NFERC have diversified to include environmental research in several areas. Wastes generally handled at NFERC are related to fertilizer and fertilizer processes. However, NFERC has historically handled wastes from off-site TVA facilities. NFERC presently operates a hazardous waste container storage facility under an Alabama "Hazardous Waste Management and Minimization Act" permit. The hazardous wastes handled at the facility are primarily from small laboratories, benchscale units or pilot plants involved in fertilizer research.

A preliminary screening was performed on the solid waste management units (SWMUs) identified in the RCRA Facility Assessment Report dated September 1988. In July 1989, EPA issued a final permit for NFERC under RCRA, as amended by the HSWA of 1984. This permit requires the investigation of potential releases of hazardous constituents from specific SWMUs at the site. Table I, Appendix A of the permit summarizes those 50 SWMUs that required further investigation. In accordance with the permit, SWMU investigations were implemented. Individual SWMU investigations that did not require groundwater sampling have been conducted by NFERC staff. The Engineering Laboratory has assisted with groundwater sampling and analyses for SWMUs 86, 100, and 104, and an extensive groundwater investigation has been conducted for SWMU 108 (Young and Julian, 1991).

1.2 Scope of Work

In addition to on-site studies, several antecedent groundwater investigations have been conducted in the vicinity of NFERC in recent years. A review of these regional studies and site assessments is presented in Chapter 2. Chapter 3 describes the hydrologic features of the NFERC area and their relation to groundwater recharge and movement. Additionally, an understanding of the geology of NFERC (Chapter 4) is critical for developing a conceptual model of the NFERC subsurface and evaluating transport properties of the groundwater system. The lineament study in Chapter 5 assists in describing some potentially dominating flow features of the NFERC region. To further characterize the geohydrology of NFERC and to determine

potential impacts to the regional groundwater flow system, new wells were installed at the site (Chapter 6). In addition to groundwater quality sampling and analyses at these wells, in-situ and lab tests were conducted to estimate the hydraulic properties of the bedrock and weathered bedrock, and to enhance our understanding of overburden physio-chemical characteristics. At the request of the Alabama Department of Environmental Management (ADEM), a qualitative dye trace (Chapter 8) was included as part of the regional groundwater investigation. This information was coupled with other findings from this study to develop a conceptual model of the NFERC (and regional) aquifer which serves to describe transport in the groundwater system (Chapter 9). In order to estimate potential contamination impacts to regional groundwater, an overburden model was constructed from characterization data (Chapter 10). Regional and site-specific groundwater quality is described in Chapter 11. All Appendices information is contained in a separate volume.

1.3 Site Location and Setting

The NFERC facility is located on a 2,600-acre TVA reservation in the northeastern portion of Colbert County, Alabama, between the Tennessee River and the northern city limits of Muscle Shoals, Alabama (Figure 1-1). NFERC is comprised of approximately 625 acres housing numerous buildings, laboratories, greenhouses and nurseries, pilot plants, and demonstration-scale production units. The cities of Sheffield and Tuscumbia, Alabama, are located south and southwest of NFERC, respectively. Florence, Alabama, resides approximately two miles north of NFERC on the north bank of the Tennessee River. Wilson Dam is located approximately one mile northeast of NFERC.

NFERC resides in karst terrane and much of the surrounding area is flood prone due to poor urban planning. The Tuscumbia-Fort Payne aquifer system underlies NFERC. It is the most important water-bearing unit in the NFERC vicinity from a regional perspective since it is a source of water for both wells and springs in the area. Tuscumbia (Big) Spring issues from the Tuscumbia-Fort Payne aquifer system about 3.75 miles southwest of the NFERC reservation boundary. The spring serves as a drinking water supply for the town of Tuscumbia and its existence at this location provides some impetus for this regional investigation since parts of NFERC may be located within recharge boundaries of the spring.

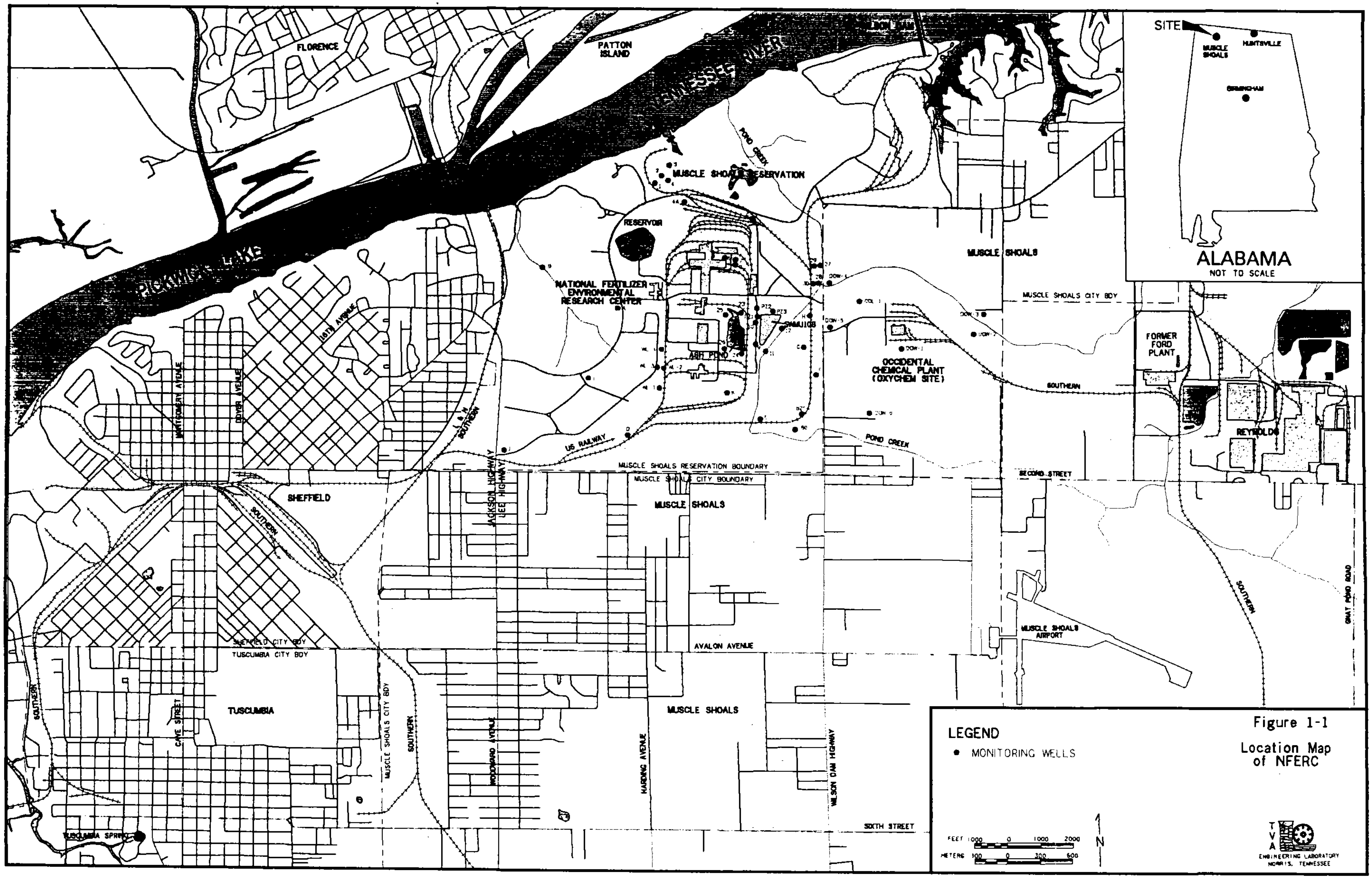


Figure 1-1

Location Map of NFERC

2.0 PREVIOUS STUDIES

2.1 Overview

Previous groundwater investigations at NFERC have been targeted at determining potential impacts to groundwater by leachate from SWMU 108 (Alavian, 1988; and Young and Julian, 1991). In addition to on-site studies, several recent groundwater investigations have been conducted in the vicinity of NFERC. The Alabama Geological Survey (AGS) in a cooperative effort with the ADEM has been involved in evaluating the impacts of storm-water drainage wells to groundwater in the Muscle Shoals area since 1985 (Chandler, 1986; Chandler et al., 1990; and Chandler and Moore, 1991). OxyChem Corporation has conducted groundwater investigations to determine potential impacts to groundwater from contamination sources at their plant site since 1987 (G&E Engineering, Inc., 1991). At the former Ford plant site, Golder Associates (1990) performed groundwater assessments and implemented remediation activities.

Most of these studies were implemented because of known or potential groundwater contamination concerns. The work has been spurred by the fact that the study sites might exist in recharge areas to Tuscumbia Spring. Descriptions of the previous studies are provided in the following sections.

2.2 Previous Studies at NFERC

Previous groundwater investigations at NFERC have consisted of two individual investigations at SWMU 108 (Alavian, 1988; and Young and Julian, 1991). SWMU 108 resides on the eastern edge of the NFERC reservation and is a solid waste disposal mound approximately nine acres in areal extent. In 1981, the Department of the Army (DOA) listed the SWMU as a potential CERCLA site (Fry, 1981). SWMU 108 was included in the final RCRA/HSWA permit issued in June 1989.

2.2.1 1988 SWMU 108 Study

Alavian (1988) used a numerical groundwater flow model (INTERSAT) and a numerical contaminant transport model (INTERTRANS) to estimate groundwater movement beneath SWMU 108. The flow model constructed by Alavian (1988) was calibrated with water level data from the ash pond, Pond Creek, 4 wells and 18 piezometers surrounding the site. In the interest of safety, no drilling activities were performed inside the SWMU. A groundwater mound within SWMU 108 was assumed to exist about 5 ft above the estimated undisturbed ground surface.

Alavian's transport model predicted overburden lateral contaminant movement of approximately 0.8 ft/yr in a westerly direction, and vertical movement of approximately 0.5 ft/yr. A range of uncertainty for lateral contaminant movement is estimated to be 0.008 to 80 ft/yr. Likewise, for vertical movement the range of uncertainty is estimated to be 0.005 to

50 ft/yr. The results were very dependent on assumed values of hydraulic conductivity, the estimate of water surface elevations within the SWMU mound, and the assumption of continuous and contiguous clay layers beneath SWMU 108.

2.2.2 1991 SWMU 108 Study

The assessment of Young and Julian (1991) involved a comprehensive geohydrological site characterization. Site activities included defining the soil stratigraphy near SWMU 108, determining the hydraulic conductivities (highs and lows) of soil units near SWMU 108, defining local and regional groundwater movement, and evaluating water and groundwater quality data from the vicinity of SWMU 108. The subsurface investigation consisted of additional monitoring well installations, borehole flowmeter testing at new wells, cone penetrometer tests, pumping tests, soils testing, extensive water level measurements, and water quality sampling and analysis.

Existing impacts from SWMU 108 were evaluated using all newly acquired information and historical geohydrological information. Both inorganic and organic groundwater contamination was detected in the well samples near SWMU 108. However, correlations of certain chemical concentrations (e.g., iron, aluminum) with field observed turbidity have been observed. This makes accurate quantitative assessment of certain chemical constituents impossible. No organic chemicals or elevated concentrations of inorganic constituents were detected in the surface waters of Pond Creek, at or downstream of SWMU 108. Pond Creek sediments immediately upstream of SWMU 108 have measurable concentrations of organic compounds. The presence of these organic constituents implies that groundwater, surface water discharges, and/or spills into Pond Creek have contaminated the stream's sediments.

Based on available geohydrological data for the vicinity of SWMU 108, an examination was performed of three groundwater sources that were potentially responsible for an increase of organic concentrations in the sediments. These sources are: (1) local groundwater in the overburden from the SWMU 108 area; (2) local groundwater in the overburden from the opposite (east) side of Pond Creek; and (3) regional groundwater from the east side of Pond Creek. Based upon assumptions of the ratio of the groundwater flux in Pond Creek to its discharge, the percentage of organic matter in the sediments of Pond Creek, and the potential migration of contaminated groundwater from upgradient industry, the most likely groundwater source of organic contamination is regional groundwater. However, it is also important to consider industrial organic contamination from upstream discharges and spills into Pond Creek as being the primary source for the organic sediments. Overall, it appears that SWMU 108 has contributed little, if any, to an increase of organic contaminants in Pond Creek sediments.

The data from this study also indicated that nitrogen contamination exists for an area on the north end of SWMU 108. Because nitrate and nitrite are not contained in clay minerals and are not readily adsorbed onto clay particles, the concentrations of nitrate-nitrite nitrogen in the groundwater samples should not be affected by turbidity. A rapid increase in the nitrogen concentration was observed over a relatively short time period and this has been attributed to nitrogen transport through the borehole annulus of well W12. Well W12 was constructed with

a 0.6 ft^2 annulus that is backfilled with pea-gravel and masonry sand. Therefore, it was considered as an avenue for relatively rapid transport of contaminants from the overburden to the deeper bedrock flow regime in the presence of significant downward hydraulic gradients. It was estimated that since its installation in 1985, nearly 23,000 gallons of groundwater from the upper overburden has flowed into the bedrock via well W12. Wells W9 and W11 were similar in construction to well W12 and these wells have since been abandoned.

2.3 Off-Site Studies

Several major industrial facilities are located east of NFERC, upstream along Pond Creek. They include the OxyChem chlor-alkali plant, the former Ford castings plant, and the Reynolds Aluminum production plant. No information related to groundwater studies at Reynolds Aluminum were available for review; however, the reports from the OxyChem and Ford site assessments were examined. Likewise, the AGS studies were reviewed in preparation of this report since they provide considerable information related to regional groundwater quality and movement.

2.3.1 1986 AGS Study

Flood-alleviation in the Muscle Shoals area has included the use of storm-water drainage (Class V) wells that essentially route storm run-off from the ground surface directly to open cavity systems in the bedrock aquifer system. TVA and the AGS (Allen, 1970) were the first to express concern that the wells could be hydraulically interconnected to Tuscumbia Spring. The majority of the storm-water drainage wells are located south of NFERC in urban areas. Chandler (1986) conducted a regional study of the Muscle Shoals area to assess the impacts of these wells to groundwater and Tuscumbia Spring. The study incorporated regional water table mapping, lineament surveys, water quality data from wells and Tuscumbia Spring, and flow measurements at Tuscumbia Spring. The report indicated that there is a significant possibility that some of the water from the drainage wells will ultimately reach Tuscumbia Spring.

2.3.2 1990 AGS Study

Key work elements included in this study (Chandler et al., 1990) were extensions of previous lineament work; determination of rock-fracture, cave, and joint trends; preparation of regional potentiometric surface maps; and extensive fluorescent dye tracing. The emphasis of this study was on dye tracing and results of the AGS tracing studies are provided in Chapter 8 of this report.

2.3.3 1991 AGS Report

This report (Chandler and Moore, 1991) was prepared to summarize hydrogeologic information and water quality data from previous AGS studies (Chandler, 1986; and Chandler

et al., 1990) for estimating the potential environmental impact of storm-water drainage wells in the Muscle Shoals area. Little additional information is included beyond the 1986 and 1990 reports.

2.3.4 OxyChem Studies

The OxyChem Plant, directly east of the NFERC, is a chlor-alkali production plant. G&E Engineering Inc. was retained by OxyChem to conduct a groundwater assessment at the plant from 1987 to 1988. Based on groundwater analyses from a system of 57 observation wells, mercury, cadmium, and chloride were detected in the groundwater at concentrations exceeding drinking water standards. The plumes of these constituents in the groundwater were within OxyChem property with the possible exception of the chloride plume; elevated chloride concentrations were detected in the groundwater within close proximity to the east property boundary. A copy of the initial site report was prepared by G&E Engineering, Inc., in 1989 and submitted to ADEM. However, it was impossible to obtain a copy of the report for review within the time allocated for this project.

A supplemental investigation at the plant was conducted during 1990-1991 at the request of ADEM to further determine the hydrogeologic relationship between the soil profile and fractured limestone aquifer underneath the site, and groundwater quality and plume constituent fate within the limestone. Additional bedrock monitoring wells were installed at the OxyChem plant site and a dye trace test was undertaken. The dye trace study revealed a direct hydraulic connection between the Tuscumbia Limestone underlying the site and Tuscumbia Spring (Chapter 8).

Groundwater quality data from the site have been reviewed and are discussed in Chapter 11.

2.3.5 Former Ford Plant

The former Ford Motor Company Die-Casting Plant is located approximately 10,000 ft east of NFERC. The recent subsurface investigation (Golder Associates, Inc., 1990) involved extensive water quality analysis and geohydrological characterization. The geohydrological information and groundwater quality data are discussed in Chapters 8 and 11, respectively. Groundwater modeling results from the site study are described in Chapter 9.

3.0 HYDROLOGIC SETTING

3.1 Climate

The NFERC has a mild humid climate. Temperature records for the Muscle Shoals National Oceanic and Atmospheric Administration (NOAA) station are available for a 95-year period from 1890 to 1985, and precipitation records are available for a 101-year period from 1884 to 1985. The average annual temperature is 65.8°F, and the average annual precipitation at Muscle Shoals is 51.95 inches. Most precipitation is in the form of rain, but snow generally occurs about twice each year. The highest average monthly precipitation, about 6.2 inches, occurs in March, and the lowest, 2.8 inches, in September. The highest average monthly temperature, 79.9°F, occurs in July, and the lowest, 39.8°F, in January. Freezing temperatures generally do not last more than two days of the year (Chandler, 1986).

In 1991, the precipitation recorded at the NFERC rain gauge showed that 25.66 inches of rain occurred above the annual average of 51.95 inches (Figure 3-1). This was due to an anomalously wet spring and winter. Rainfall during the first half of 1992 was more aligned with average rainfall estimates with the exception of excess precipitation (8.59 in.) in June.

3.2 Recharge

Precipitation is the source of all natural recharge to the groundwater system in the NFERC area. Groundwater recharge in the Muscle Shoals area can occur very slowly through soil infiltration (autogenic), or very rapidly by direct entry (allogenic) through storm-drainage wells or natural openings such as sinkholes.

At the NFERC site, autogenic recharge is the primary source of groundwater renewal; however, a potential exists for some amount of allogenic recharge from areas east of the site. In addition to precipitation, on-site recharge might include leaky water and sewage lines, segments of streams such as Pond Creek, and impoundments such as the Ash Pond and water supply reservoir. However, accurate mapping of these different sources is not possible. Table 3-1 lists several estimates for the average recharge from precipitation to the aquifers in northern Alabama. In addition to the studies in Table 3-1, Golder Associates (1990) estimates a recharge rate of 13 in./yr for the Spring Creek drainage basin.

Much of the Muscle Shoals area possesses topographical lows and is flood-prone. Flooding and accumulation of water after heavy rainfall are associated with the topographic lows and low soil permeability. In many instances, the topographically low areas have a NW-SE and NE-SW orientation with no outlets and are associated with weathering of fractured limestone and solution development (Chapter 4). Methods to reduce flooding of low areas include contoured ditches, runoff control ponds, and storm-water drainage wells (Chapter 2). Twenty or more storm-water drainage wells have been constructed and used for flood alleviation in the area during the last 35 years (Chandler et al., 1990).

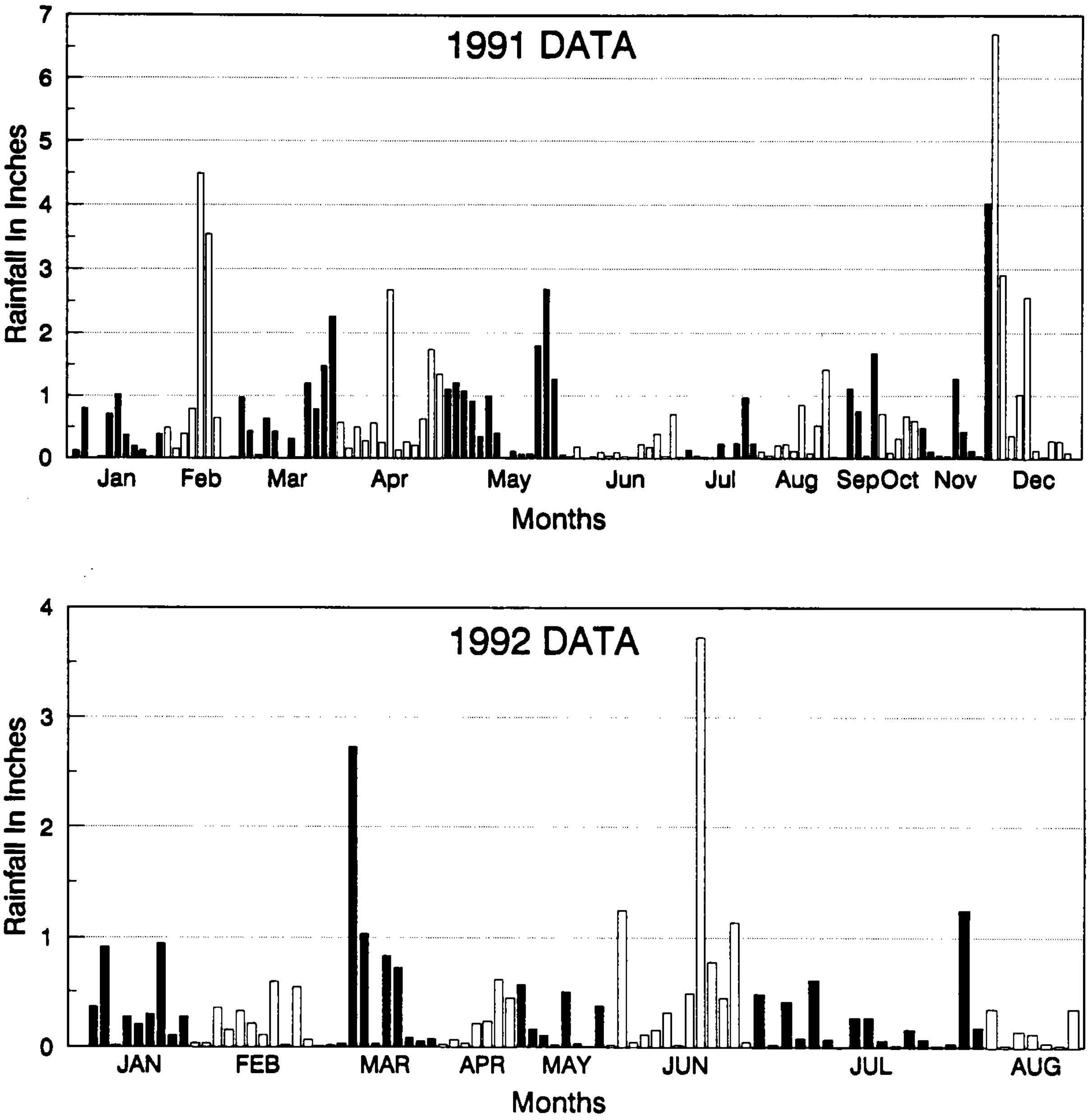


Figure 3-1. Annual Precipitation at NFERC

TABLE 3-1

Estimated Groundwater Recharge

Investigator(s)	Estimated Recharge (in./yr)
Bossong and Harris (1987)	>12
Curtis (1953)	>11.4
Golder Associates (1990)	13

3.3 Streams

The Muscle Shoals area is part of the Tennessee-Elk River hydrologic subregion (0603) (Wentz et al., 1986). Included in these areas are two important reservoirs, Pickwick Lake and Wilson Lake, on the Tennessee River. Two unregulated streams of importance to this study, Pond Creek and Spring Creek, flow northward to Pickwick Lake/Tennessee River. Their 7-day median annual low flows (7-day Q_2) where they enter the lakes are less than 2 and 13 Mg/d, respectively. The 7-day Q_2 of the Tennessee River is more than 1,000 Mg/d. The estimated average flow at State Highway 43 (O'Neil Bridge) is 32,800 Mg/d (Chandler, 1990).

Pond Creek flows in a northerly direction, traversing approximately five stream miles across the east side of the NFERC reservation, and empties into the Tennessee River at Tennessee River Mile (TRM) 258.4. This stream serves as a receiving stream for effluents from NFERC, Muscle Shoals Wastewater Treatment Plant, and local industry that include OxyChem and Reynolds Aluminum. Flow and time-of-travel measurements of Pond Creek and NFERC and OxyChem outfalls were conducted in October 1985 in conjunction with NPDES permitting (Rivers, 1986).

Heavy rainfall was experienced during flow measurements; hence, the values above do not provide any data that assists in estimating groundwater contribution to Pond Creek. Dye tracer travel times after flow increases in Pond Creek, due to the heavy rain, indicates stream velocities of about 1.5 ft/s.

Three small unnamed streams drain areas on the north side of the NFERC reservation. The eastern-most stream is located opposite of the Wilson Power Service Center. Rhodamine WT measurements at the mouth of this stream (Rockpile Cascade) indicates that it probably receives wastewater from the Wilson Service Center (Chapter 8). The remaining two streams drain the northwest area of the NFERC reservation, the largest of which is a recipient stream for wastewater discharge form the IFDC. No streamflow measurements were available for any of these streams.

3.4 Springs

Subsurface drainage of NFERC and the Muscle Shoals area occurs through the Tuscumbia-Fort Payne aquifer system (Chapters 4 and 7), with larger springs being associated with the Tuscumbia Limestone. The major springs in the NFERC area are located along the Tennessee River and Spring Creek. The largest of these are Tuscumbia Spring and TVA Spring.

3.4.1 Tuscumbia Spring

Tuscumbia Spring has an estimated 7-day Q_2 of 9 Mg/d and an average flow of 42 Mg/d. Its calculated variability is 200 percent (Chandler and Moore, 1987). The seasonal variation of discharge is high, as is characteristic of most limestone springs.

Tuscumbia Spring is located about 3.75 miles southwest of the NFERC reservation boundary and about 4.06 miles from the nearest SWMU (SWMU 172) as shown in Figure 1-1. Tuscumbia Spring is actually a combination of three (and perhaps several smaller) springs that discharge into a five-acre pool. The Tuscumbia Water Treatment Plant (WTP) withdraws water from Tuscumbia Spring near Spring Creek mile 3.2. Tuscumbia WTP is permitted by ADEM as a surface water filtration plant. The intake to the plant is a 24-inch diameter pipe located approximately 6 to 8 ft from the resurgence of the largest flowing spring. The intake line is, however, open within the pool that collects water from all springs. Hence, any spring discharging into the pool can potentially effect intake water quality.

Using a value of 11.4 in./yr from Curtis (1953), and an estimated flow of 42 Mg/d, Chandler and Moore (1991) estimate that the recharge area to Tuscumbia Spring is 84 mi^2. However, the direct entry of water into the cavity system at Tuscumbia Spring would have the effect of reducing this estimated recharge area. White (1974) categorizes Tuscumbia Spring as an intermediate-response spring. Intermediate-response springs have response times on the order of several months. That is, it takes several months for Tuscumbia Spring to return to some known base level discharge following a precipitation event in its recharge area. In the case of Tuscumbia Spring, White (1974) estimates the response time of Tuscumbia Spring to be around 65 days. This is a subjective value, however, since it does not consider intensity, spacing, and duration of storm events. The discharge ratio, defined as the ratio of maximum discharge to base flow discharge, is also a parameter of interest in discussing spring discharge since it is a measure of the "flashiness" of the aquifer. For intermediate-response systems such as Tuscumbia Spring, there is an inverse correlation between the discharge ratio and the response time. White (1974) provides a discharge ratio for Tuscumbia Spring of 7.

Additional information related to Tuscumbia Spring (e.g., dye tracing, hydraulics, and water quality) is provided in some of the following chapters of this report.

3.4.2 TVA Spring

TVA Spring is located about 500 ft downstream of Wilson Dam (Figure 1-1). The spring consists of three discrete spring resurgences that have been regarded in the past as a single collective spring. The uppermost is a waterfall spring that issues from the Tuscumbia Limestone (weathered zone) and cascades to the bottom of the river bluff. Two smaller caves springs also discharge west of this location and enter a common pool with waters from the waterfall spring. Discharge from the pool is to the Tennessee River at this location.

TVA Spring has been described as a possible second-magnitude spring by Chandler and others (1990). Estimated discharge for the spring is expected to vary from about 11 to 20 cfs (Chandler and Moore, 1987). The measured specific conductance and temperature values of spring water are low at this location which is indicative of a surface water source(s). In addition, dye trace data for the spring (Chandler et al., 1990) indicate a hydraulic connection with the upstream reservoir (Wilson Dam). Further evidence of this is provided in plots of spring discharge versus lake level from 1987 to 1992. Figure 3-2 shows a typical plot of correlation between Wilson Dam headwater and spring discharge. It is important to note that precipitation has no discernable effect on spring discharge (Figure 3-2). Therefore, this spring appears to represent water lost from Wilson Lake, at least in part, through leakage.

3.4.3 Other Springs

Other springs in the area are characterized by low discharges and/or low variabilities in flow and are not considered significant. Several of these are described in Chapter 8. Additionally, submerged springs probably exist north of NFERC along the Tennessee River. However, they were not located as part of this study.

3.5 Surface and Groundwater Supplies in Vicinity of NFERC

3.5.1 Surface Water Supplies

Several surface water intakes are located in the vicinity of NFERC on the Tennessee River. Those used for community drinking water supplies include the Sheffield WTP intake (downstream) at Tennessee River Mile (TRM) 254.3L, and the Muscle Shoals WTP intake (upstream) at TRM 259.6L. Non-community surface water supplies include the TVA-OACD WTP intake at TRM 259.5L (upstream at Fleet Hollow Embayment), LaRoche Industries, Inc. WTP intake at TRM 238.7L (Meinert, 1987), and an intake at TRM 258.4L for OxyChem.

3.5.2 Groundwater Supplies

Tuscumbia Spring is the only spring in the area known to serve as a drinking water supply in the NFERC vicinity.

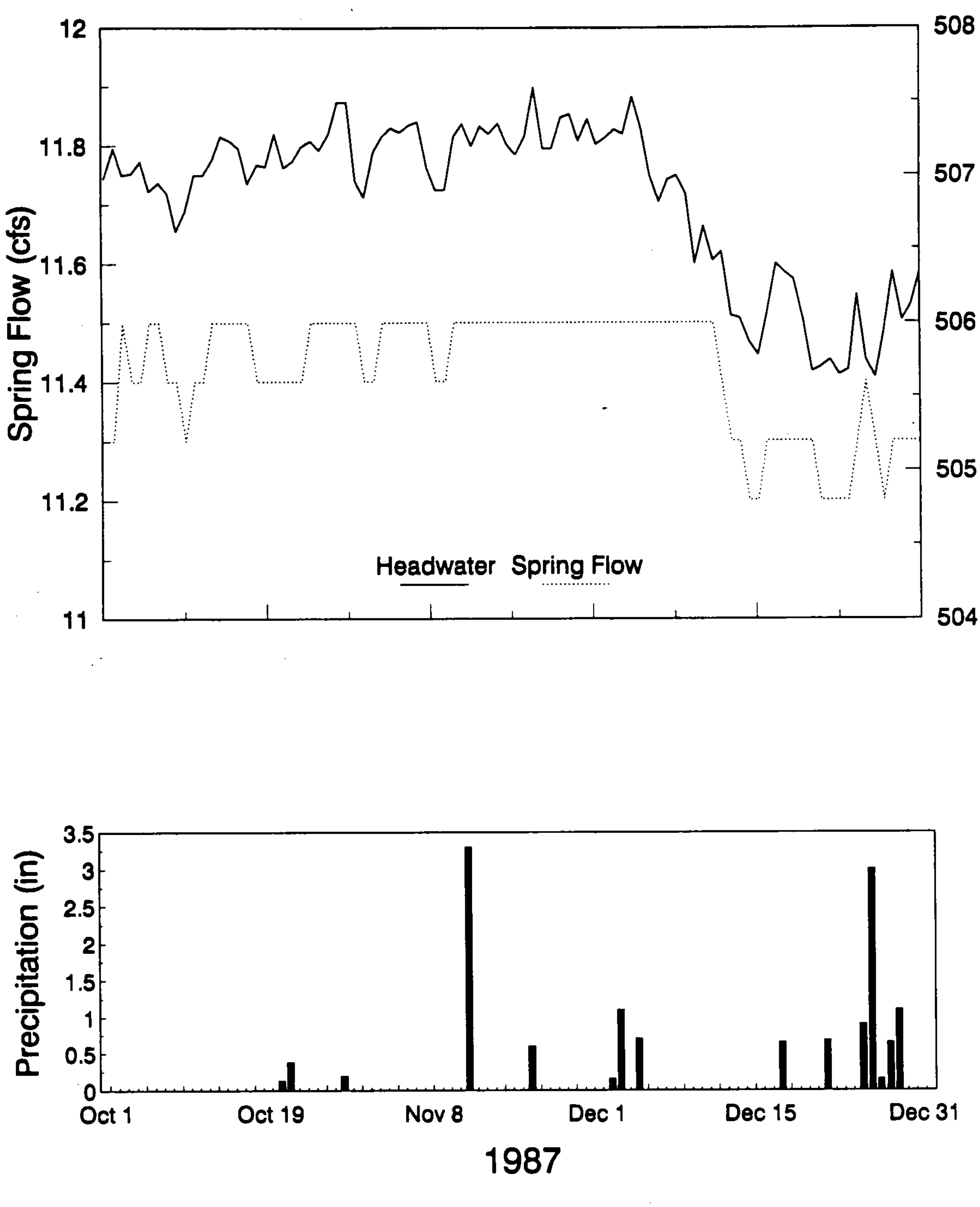


Figure 3-2. Correlation Between Wilson Dam Headwater and Spring Discharge

In performing a water well survey (Davis, 1992), NFERC contacted the Regional Health Department, ADEM, local utilities, and regional authorities. Sixteen private water wells are listed in available information and only one well (Ricky Carter residence), may be used for drinking water according to the report. This well is located about 3 miles southwest of the facility. Golder Associates (1990) indicates well locations in the area of the former Ford Plant. In the preliminary assessment report for NFERC (Meinert, 1987), NFERC reported the nearest drinking water well at the Lloyd Vincient residence, about 10,000 ft east of NFERC. It is possible that other residential and commercial groundwater supply wells might exist in the vicinity of NFERC; however, their locations are unknown.

4.0 GEOLOGY OF NFERC

4.1 Tectonic Setting

NFERC is located in the Interior Low Plateau, a karst plateau lying on the southern flank of the Nashville Dome in northern Alabama. The Nashville Dome is a broad structural arch centered in central Tennessee and extends from Alabama to Kentucky. The Nashville Dome emerged probably during late Silurian period (Jewell, 1967) and continued into Cenozoic time (Stringfield et al., 1974). Erosion over a long period of time has stripped off Pennsylvanian and younger Mississippian clastic rocks to expose Mississippian limestone formations throughout much of Tennessee, Alabama, and Kentucky. NFERC lies on the Mississippian limestone rocks which have a regional south-southwest dip of 25 to 30 ft per mile.

4.2 Stratigraphy

The general stratigraphy in the area, from both surface mapping and well logging, is Paleozoic sedimentary rocks ranging from Ordovician to Mississippian (Harris et al., 1963). Figure 4-1 shows the generalized stratigraphy in the region. The underlying crystalline basement rocks are probably Precambrian metavolcanics (Raymond et al., 1988). The Paleozoic rocks, in ascending order, are undifferentiated Ordovician rocks, dark gray, finely to coarsely crystalline, argillaceous to pure limestones; Silurian silty limestone; Devonian Chattanooga Shale; and Mississippian rocks of Fort Payne Chert, Tuscumbia Limestone, Ste. Genevieve Limestone, Bethel Sandstone, Gasper Formation, Hartselle Sandstone, and Bangor Limestone. Only the lower Mississippian rocks are exposed on the surface in the NFERC and adjacent areas. The outcropping rocks consist of Tuscumbia Limestone and Fort Payne Chert. Most of the bedrocks have been weathered to a residuum of clay, sand, and gravel of Quaternary regolith near the surface. Alluvial, colluvial, and terrace deposits are also developed in some places.

The most relevant stratigraphic units underlying the site, the Chattanooga Shale, Fort Payne Chert, and Tuscumbia Limestone, are discussed below.

4.2.1 Chattanooga Shale

The Chattanooga Shale is comprised mainly of black fissile shale and minor amounts of fine-grained sandstone. The shale is bituminous and partly pyritic. The Chattanooga Shale is an extensive regional marker and unconformably overlies the undifferentiated Ordovician and Silurian rocks. It does not crop out in the region, but well drilling suggests that the Chattanooga shale underlies the entire region with a thickness from 5 to 37 ft. It ranges from 250 to 450 ft below the surface in the NFERC area. The Chattanooga Shale is unconformably overlain by either the Mississippian Maury Formation, a thin layer (less than 5 ft) of green, glauconitic, pyritiferous shale containing phosphate nodules (probably absent in NFERC area), or the Mississippian Fort Payne Chert where the Maury Formation is absent.

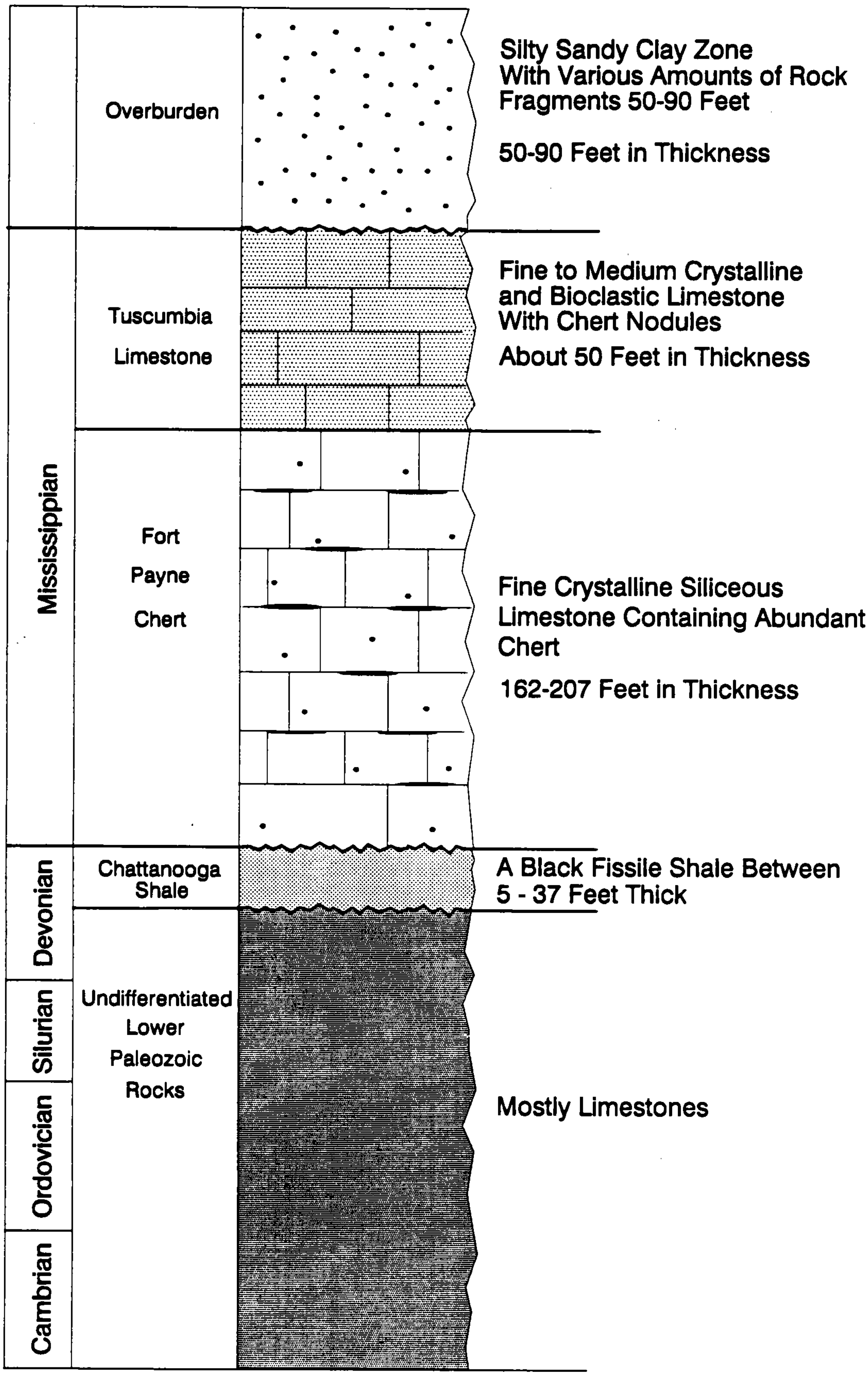


Figure 4-1. Generalized Stratigraphic Section in NFERC Area

4.2.2 Fort Payne Chert

The Fort Payne Chert underlies all the area and crops out along the southern bluffs of the Tennessee River in the NFERC. It is a distinctive lithologic marker at the base of the Mississippian system of northern Alabama (Thomas, 1972). The Fort Payne Chert is comprised of light-gray to blue-gray, finely crystalline, siliceous limestone containing large quantities of gray-brown to smoky chert, which occurs as disseminated nodules and lenses, or distinguished thick beds throughout the limestone (Thomas, 1967, 1972; Harris et al., 1963; Raymond, 1992). Fort Payne Chert is relatively poorly sorted and frequently dolomitized (Smith, 1967). Detrital quartz is present in the lower part of the Fort Payne Chert and diminishes toward the top of the formation (Smith, 1967). However, overall no significant supply of clastic sediment is indicated. The thickness of the Fort Payne Chert in the subsurface ranges from 162 to 210 ft. The well log of Colbert-1, a USGS monitoring well 1,000 ft east of the NFERC, shows a thickness of 210 ft. The widespread, relatively uniform Fort Payne Chert reflects a tectonically stable marine shelf (Thomas, 1972). The Fort Payne Chert is conformably overlain by the Tuscumbia Limestone; the contact is commonly gradational. However, in the weathered outcrops, the nodular, thin beds of the Fort Payne Chert contrast with massive limestone beds of Tuscumbia Limestone along the southern bluff of the Tennessee River.

4.2.3 Tuscumbia Limestone

The Tuscumbia Limestone is a light-gray, fine to medium crystalline and bioclastic limestone which is characterized by abundant light-colored chert (Thomas, 1967). Chert nodules are concentrated in relatively thin stratigraphic units which alternate with non-cherty to slightly cherty units throughout the full thickness of the formation. However, the cherty units are too laterally discontinuous to serve as stratigraphic markers. Massive beds of bioclastic limestone are generally crossbedded and some of them are oolitic (Thomas, 1972). The Tuscumbia Limestone is very fossiliferous limestone and represents a carbonate shelf environment (Thomas, 1972).

The Tuscumbia Limestone underlies all the region and is the uppermost bedrock unit in the NFERC area. Exposures are common along the Tennessee River and along the valleys of the larger tributaries (Harris et al., 1963). The thickness of the Tuscumbia Limestone is probably up to 200 ft (Thomas, 1972; Harris et al., 1963). However, the formation generally has been weathered in the area and its thickness remains as little as 50 ft in places, as indicated from well logs and measurements of outcrops along the bluffs of the Tennessee River. In most of the area, the Tuscumbia Limestone is covered by a clayey overburden.

4.3 Local/Site Geology

The rocks exposed in the NFERC area are Mississippian Fort Payne and Tuscumbia formations, and Quaternary fluvial sediments along a creek (Raymond, 1992). Figure 4-2 is a geologic map of the NFERC. The Tuscumbia Limestones and Fort Payne Chert are exposed only along the south bank of the Tennessee River. The Mississippian rocks are deeply

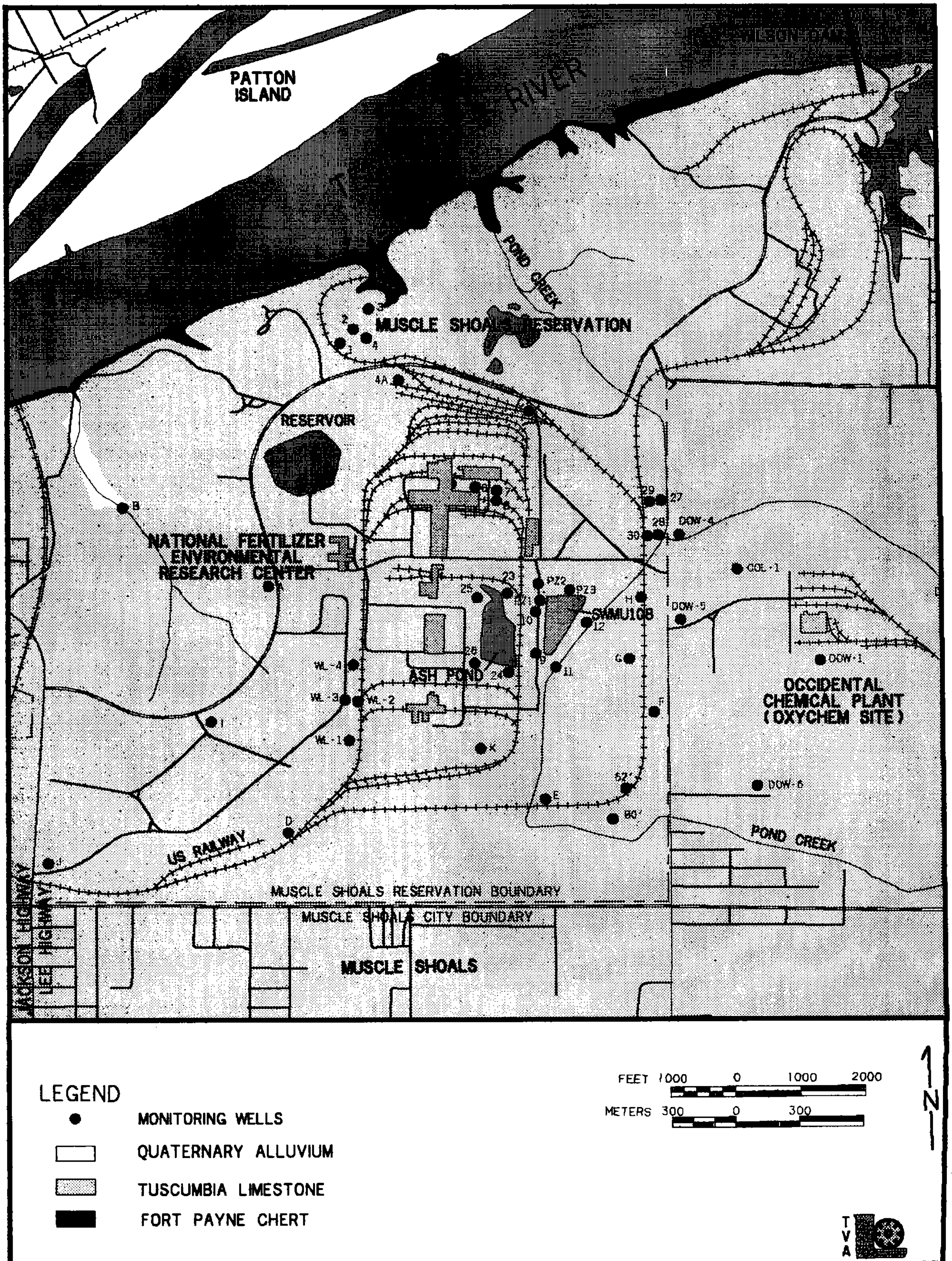


Figure 4-2 Geologic Map of the NFERC Area

weathered to form a layer of weathered residuum (overburden) consisting of clays and rock fragments with some local zones of possible alluvial deposits. Elevation of the top of the Tuscumbia Limestone, inferred from bedrock well logging, is mostly between 450 to 470 ft above MSL (Figure 4-3). The thickness of the overburden at the NFERC ranges from 50 to 100 ft (Figure 4-4). Figures 4-5 and 4-6 present two cross sections in the NFERC based on well log data. The overburden and bedrock zones have very different geologic/hydrogeologic characteristics. Between the overburden and bedrock, a weathered zone exists which is characterized by the presence of abundant rock fragments.

4.3.1 Overburden

4.3.1.1 Overburden Stratigraphy. Vertical profiles of the overburden stratigraphy were obtained from well logs and cone penetrometer tests. The classification is based on the composition of the overburden in terms of proportions of clay, silt, sand, and rock.

In general, the upper overburden is composed of a silty-sandy clay zone with a thickness ranging from 10 to 50 ft. In places it contains small amounts of cherty limestone fragments. A relatively thin layer (< 10 ft) of debris and gravel are observed in some well logs on the top of the silty clay zone. The bottom half of the overburden consists of a mixture of silty clay and various amounts (> 30 percent) of rock fragments. The rock fragments are mostly weather-resistant chert and cherty limestone which are similar to the underlying bedrock lithology.

4.3.1.2 Mineralogy and Geochemistry of the Overburden Residuum. The overburden residuum is mostly white-yellow brown to dark brown soil consisting of heavily altered, extremely oxidized argillaceous clays with various amounts of cherty rock fragments. The soils are mostly ferruginous and in places admix with white kaolinitic clay. Manganese oxides/hydroxides are disseminated in the clay matrix.

The bulk soil analyses of selective samples reveal that the soils consist of 35-60 percent chert fragments, 35-60 percent clays, and less than 7 percent other accessory minerals. Microscopic modal analyses indicate a similar result (Table 4-1). Microscopic studies also show that chert fragments and quartz are commonly coated by clay minerals and most of the clay minerals are intensively strained by hydrous iron oxides. Some opaque minerals and traces of feldspar are also observed in the soils.

The clay minerals were identified by X-ray diffraction (XRD) analysis and are listed in Table 4-1. The clays are dominated by kaolinite and illite, with minor amounts of interstratified clay minerals, including kaolinite-smectite, smectite-illite, and chlorite-smectite.

Geochemical analyses of the soils were performed to determine the moisture, pH, cation exchange capacity, exchangeable cations, and soluble cations and ions. Table 4-2 lists the results. The moisture of the soils is mostly between 20 and 45 percent. The pH of the soils ranges from 3.80 to 7.19 with most being between 3.9 and 5.7.

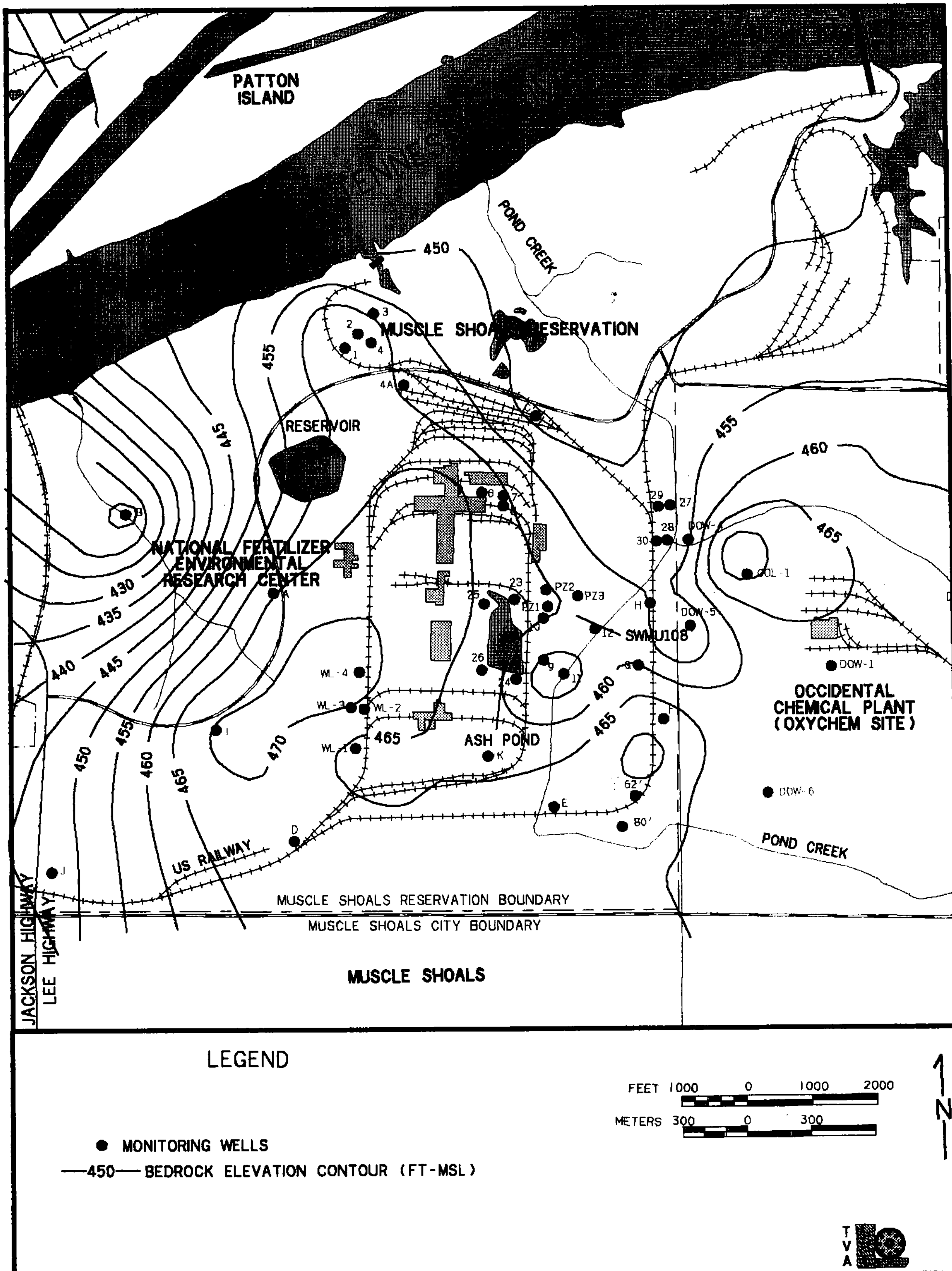


Figure 4-3 Top of Tuscumbia Limestone Inferred from Bedrock Wells in the Area

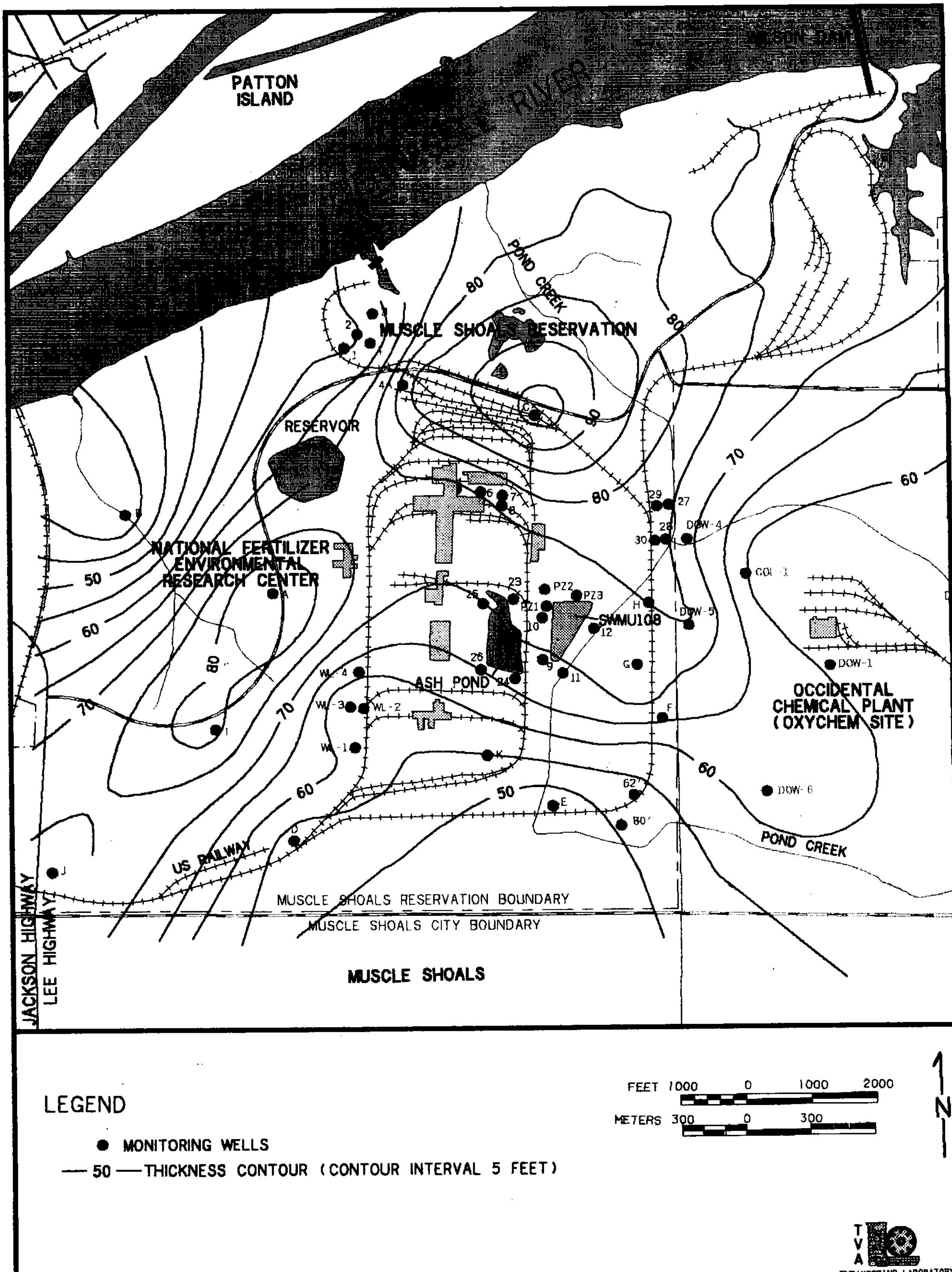


Figure 4-4 Overburden Thickness at NFERC (FT)

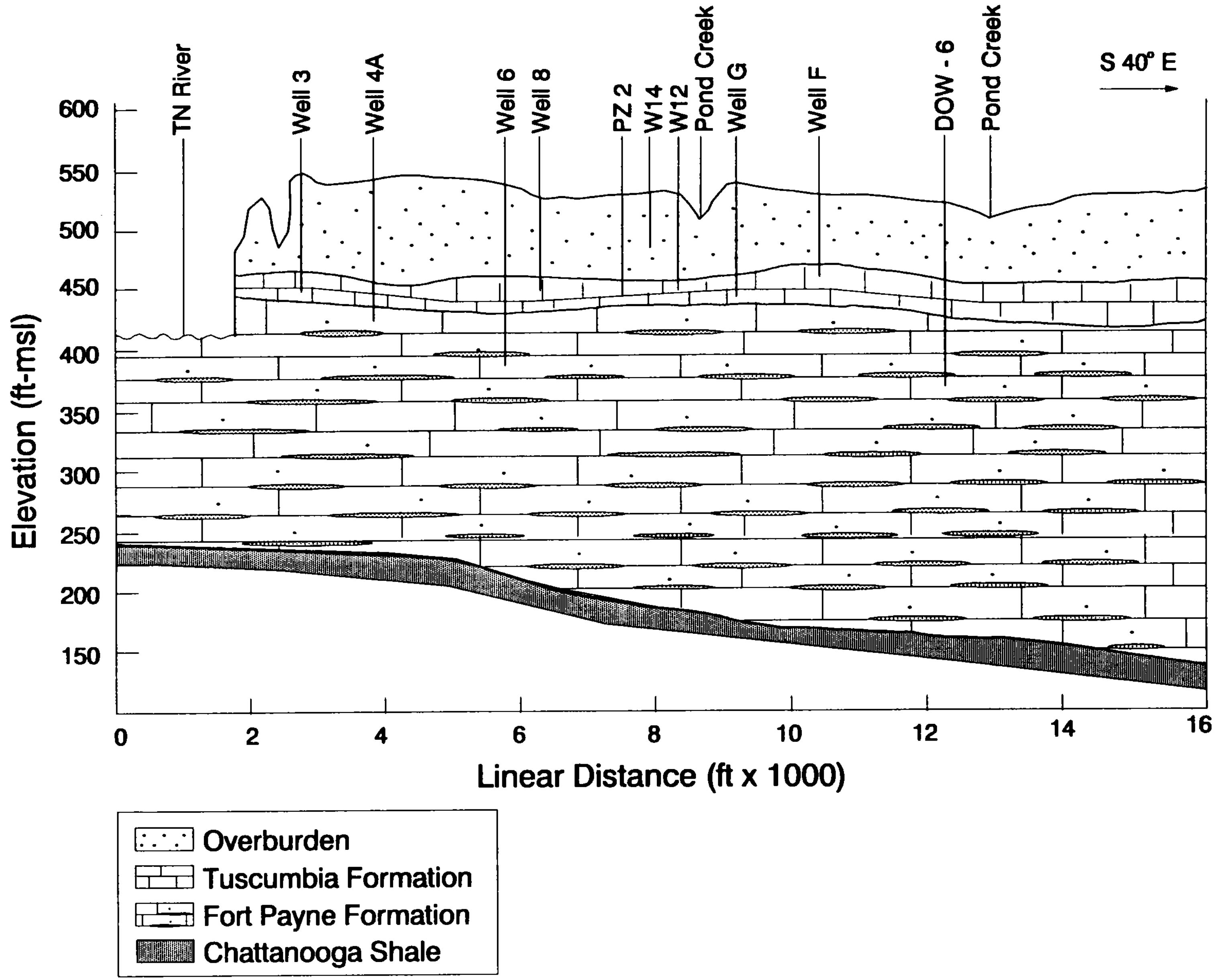


Figure 4-5. Geologic Cross Section at NFERC, in NW-SE Direction

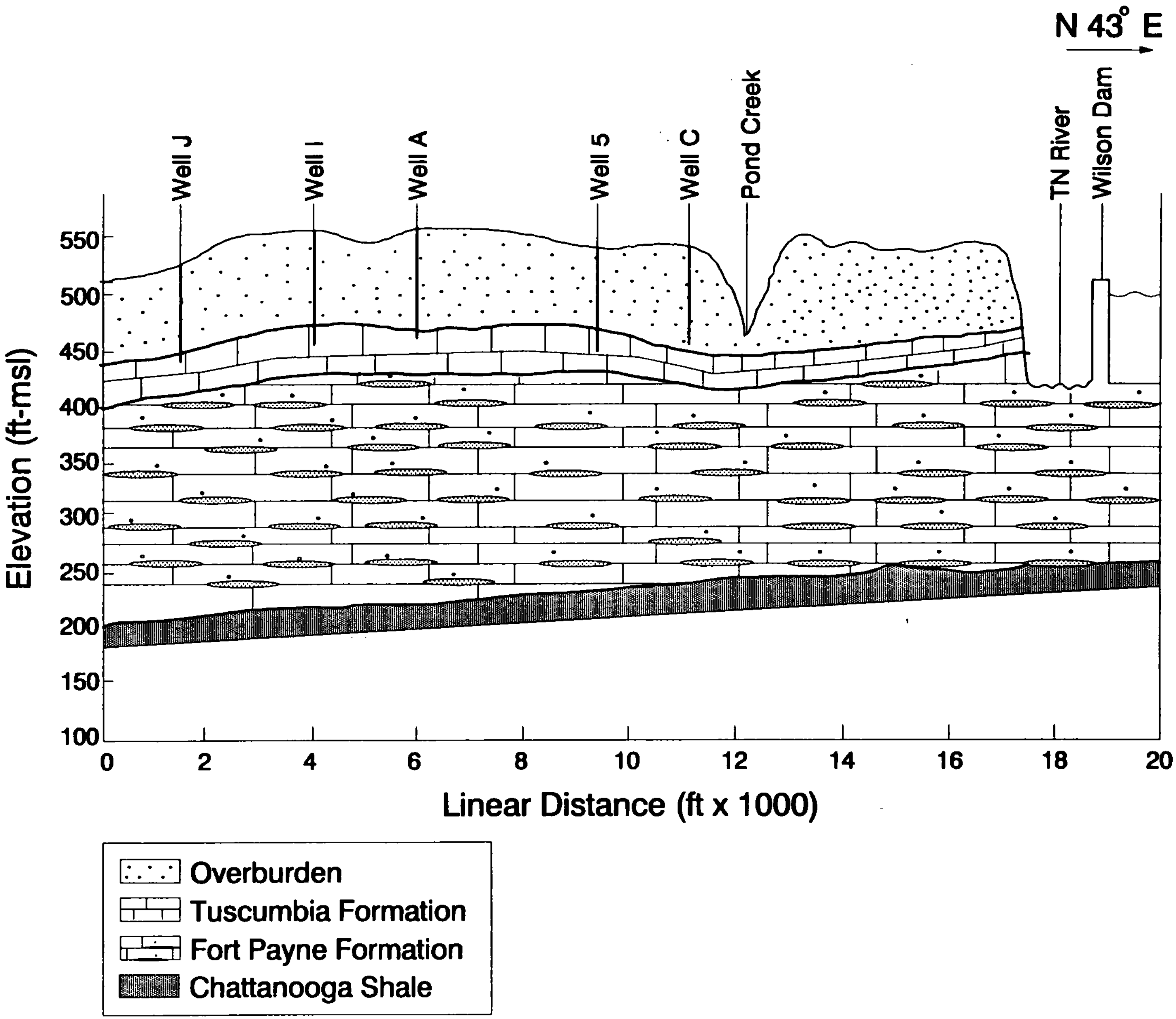


Figure 4-6. Geologic Cross Section at NFERC, in SW-NE Direction

TABLE 4-1

Mineralogic Analyses of NFERC Soils

	A1,46-48	C1,30-32	D1,30-32	G,55-57
Bulk Soil Analysis (vol. %)				
Chert Fragments	55	35	39	59
Clays	38	60	56	35
Misc. Minerals	7	5	5	6
Microscopic Modal Analysis (Vol. %)				
Chert/Quartz	61	38	40	62
Clay Minerals	38	60	60	36
Opaque Minerals	1	2	<1	2
XRD Clay Mineralogy Analysis (%)				
Kaolinite	>20	>20	>20	>20
Diooctahedral Illite	5-20	>20	5-20	>20
Kaolinite-Smectite	5-20	5-20	5-20	<5
Smectite-Illite	5-20	ND	5-20	<5
Chlorite-Smectite	<5	<5	ND	<5
ND - not detected				

Cation exchange capacity (CEC) is a measure of degree of ion exchange ability of soils, typically of clay minerals. Higher CEC values represent greater abilities of the clays (soils) exchanging ions with fluids. CEC varies as functions of pH and nature of the ions occupation of exchange site (in clay structure). In general, interstratified mixed clays and swelling clays, such as smectites and vermiculites, have higher CEC values (>100 meq/100g), whereas kaolinite and chlorite have lower CEC values (kaolinite/chlorite <10 meq/100g). Illite commonly has intermediate CEC values (10-40 meq/100g). The measured CEC values for the NFERC soils are mostly less than 15 meq/100g), suggesting that the constituents of the clays are mostly kaolinite and illite. A few samples have intermediate CEC (~40 meq/100g), indicating the presence of some swelling clays. The results are supported by the XRD clay mineral analyses (Table 4-1). Overall, CEC of the soils in the NFERC is low to moderate.

Measurement of exchangeable cations shows that Ca and Mg have higher values (mostly >1 meq/100g) and Na and K have lower values (<1, mostly <0.3 meq/100g). The soluble components of the soils are listed in Table 4-2.

Quantity of both naturally occurring and anthropogenic organic carbon influences contaminant fate and transport, microbial ecology, and effective treatment methodology. Therefore, quantifying the total organic carbon (TOC) content of soils is essential for understanding subsurface chemistry during environmental site characterization. TOC of the NFERC soils ranges from 0.03 to 0.25 percent, with one sample up to 0.51 percent. Overall, TOC decreases with depth (Figure 4-7). Below 60 ft from the surface, the contents of TOC in the soil (overburden material) are less than 0.1 percent. Three zones can be approximately

TABLE 4-2

Geochemical Analyses of NFERC Soils

				Exchangeable Cations				Soluble Components (mg/L)						
Sample #	Soil pH	Moisture (%)	CEC (meq/100g)	Na	K	Mg	Ca	Na	K	Mg	Ca	HCO_3	SO_4	Cl
A1,19-21	3.81	40.6	13.30	.783	.173	.923	.768	8.63	1.3	1.31	4.52	<2	<1	6
A1,69-71	4.40	17.5	3.76	.589	.126	.385	.661	4.22	1.2	0.36	1.72	6	<1	3
A2,37-39	3.80	38.9	41.50	.634	.215	1.20	1.55	6.40	1.0	0.48	2.83	10	<1	3
B,14-16	7.19	19.0	5.50	.640	.224	.561	7.51	6.07	2.0	3.70	50.6	70	35	4
B,26-28	5.68	34.3	42.20	.539	.481	3.48	11.8	6.75	2.8	9.92	50.6	130	45	4
C1,35-37	4.06	37.9	12.10	.575	.245	.382	1.51	4.84	1.3	0.32	2.92	<2	<1	3
C1,50-52	3.97	37.8	14.0	.563	.227	.312	.549	4.22	1.2	0.25	1.73	13	4	2
C2,27-29	3.92	37.3	13.60	.036	.238	.456	.616	6.59	1.0	0.34	2.49	6	6	4
D1,20-22	4.33	44.0	11.40	.026	.193	1.34	2.60	4.47	0.6	0.35	1.93	6	3	4
D1,40-42	4.90	30.9	15.00	.023	.289	2.59	5.26	5.16	0.7	0.41	2.98	20	4	5
D2,17-19	4.45	31.1	10.60	.042	.247	2.69	4.64	4.65	0.8	0.47	2.27	6	3	3
E,14-16	4.07	29.3	13.20	.049	.160	1.80	2.52	6.76	0.8	1.04	3.42	6	3	5
E,34-36	3.93	0.3	7.94	≤.005	.121	.469	.888	4.14	0.9	1.15	5.23	<2	2	2
F1,29-31	4.86	33.3	12.50	.026	.231	1.68	3.84	4.92	1.5	1.23	4.88	6	2	2
F1,54-56	6.83	44.3	20.90	.145	.581	2.13	17.6	6.09	1.4	1.97	10.5	<2	4	7
F2,17-19	4.40	36.4	15.90	.082	.277	2.07	3.97	6.95	2.4	5.66	16.4	20	2	1
G,30-32	4.84	23.4	13.60	.058	.289	2.16	4.29	3.58	1.0	0.48	2.27	<2	3	1
G,50-52	4.88	19.5	9.24	.089	.252	1.48	4.02	3.46	0.9	0.33	1.82	20	3	1
H,19-21	4.08	30.0	13.50	.056	.091	.411	1.27	4.11	0.3	0.23	1.71	<2	3	3
H,46-48	5.48	38.6	16.80	.102	.252	3.46	.641	5.01	0.8	0.53	2.70	10	3	2

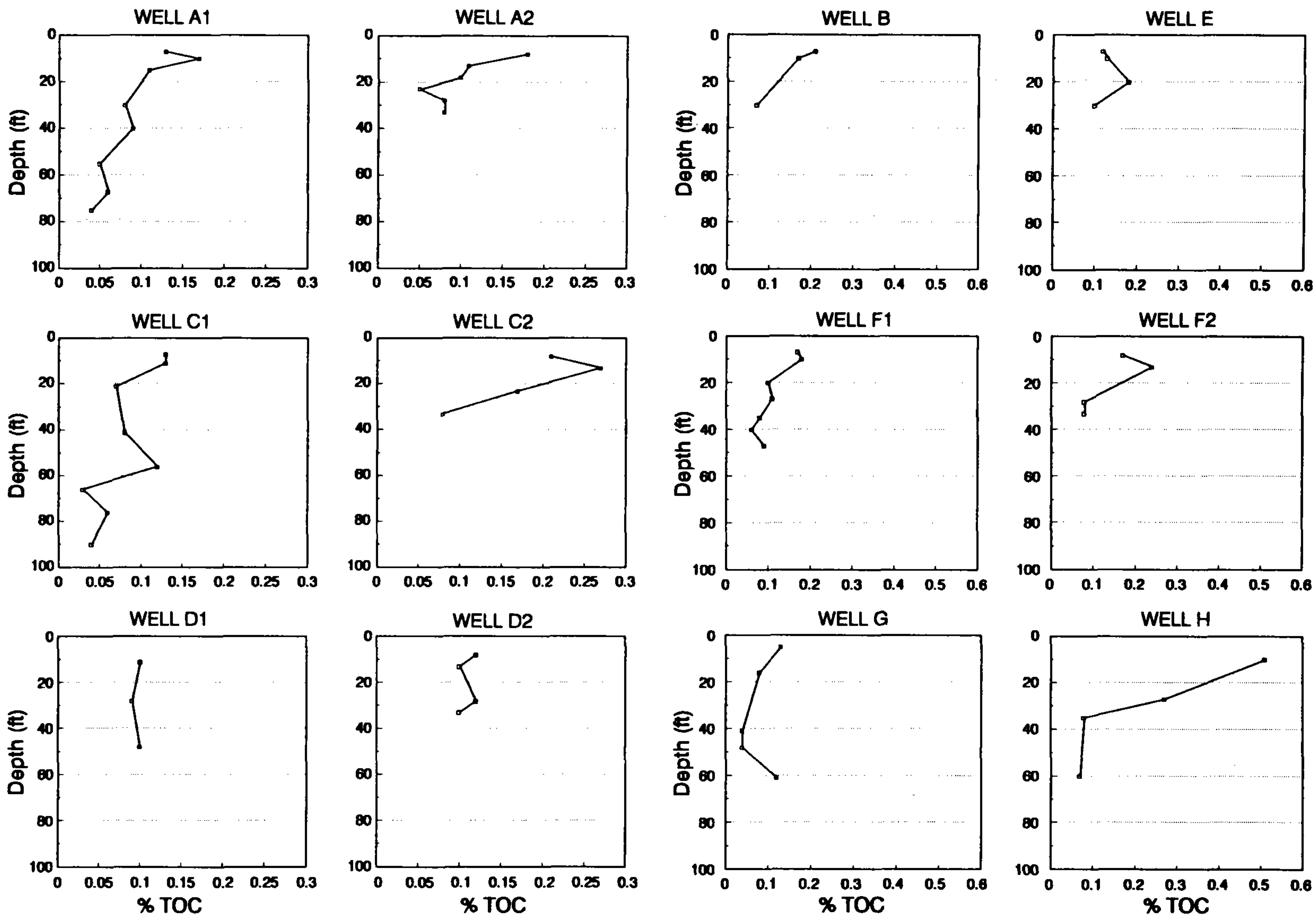


Figure 4-7. Variation of Total Carbon Concentration With Depth at NFERC Regional Wells

classified: the top zone (0.05-0.51 percent TOC); middle zone (0.04-0.12 percent TOC); and bottom zone (<0.06 percent TOC).

4.3.2 Bedrock

Petrographic studies of bedrock samples from NFERC wells indicate that the rocks include dolomitic cherty grainstone, dolomitic calcareous chert, biomicrite, and biosparite (Figure 4-8). All the rocks are light to medium gray, dense limestones composed primarily of calcite, with minor dolomite and traces of quartz in some samples. No microfractures were observed in the thin sections. The biosparite contains approximately 90 percent fossil fragments of echinoderm, bryozoan, and brachiopod and 10 percent spar cement. The biograinstone is composed of primarily grain-to-grain contacted crinoid fragments and 1-2 percent thin dark stringers of stylolites. The dolomitic chert limestone is mostly made up of light-gray, fine-grained quartz cherty mottles in a medium-gray, predominant calcite matrix. The calcareous chert consists of a mixture of fine-grained quartz and calcite and thin, irregular sub-parallel stringers of medium-gray calcite and dolomite. Dolomite typically occurs as rhombic grains and is up to 20 percent in the dolomitic limestone.

4.4 Structure

Northwestern Alabama is located in the southern-southwestern flank of the Nashville Dome, so regionally the rocks are quite flat with dip slightly to the south-southwest. However, fold has modified the dip locally at NFERC. The most prominent structure in the area is a northeast trending basin in the south of the NFERC (Figure 4-9) mapped from well logs by using the Chattanooga Shale as a marker (Harris et al., 1963). Within this elongate basin, the Chattanooga Shale reaches a low of 79 ft-MSL; whereas, on the northern edge of the basin the elevation is about 180 ft-MSL. Because of the effect of this basin, bedrocks at NFERC dip to the southeast at about 30 ft per mile (Raymond, 1992).

Fractures are breaks in rocks with or without displacement, due to the response of the rocks to stress. Fractures include faults, joints, and cracks. They are the most important aspects of hydrogeologic study because they often act as conduits for groundwater flow in less permeable rocks, such as carbonate rocks. No major faults were reported in the area, perhaps due to the poor exposure of bedrocks in the area.

Joints are well developed in the bedrocks of the area, as observed along the southern bluff of the Tennessee River. As shown in Figure 4-10, measurement of fractures and joints in these outcrops show two dominant joint directions: N 50-70°W and a lesser significant N 25-60°E (Chandler, 1986; Raymond, 1992). These directions are similar to the orientations of axe of synclines in the area, which are N 50°W and N 40°E. The dominant joints at NFERC appear to be oriented parallel and orthogonal to the strike of the strata. These features are generally referred to as strike/dip joints.

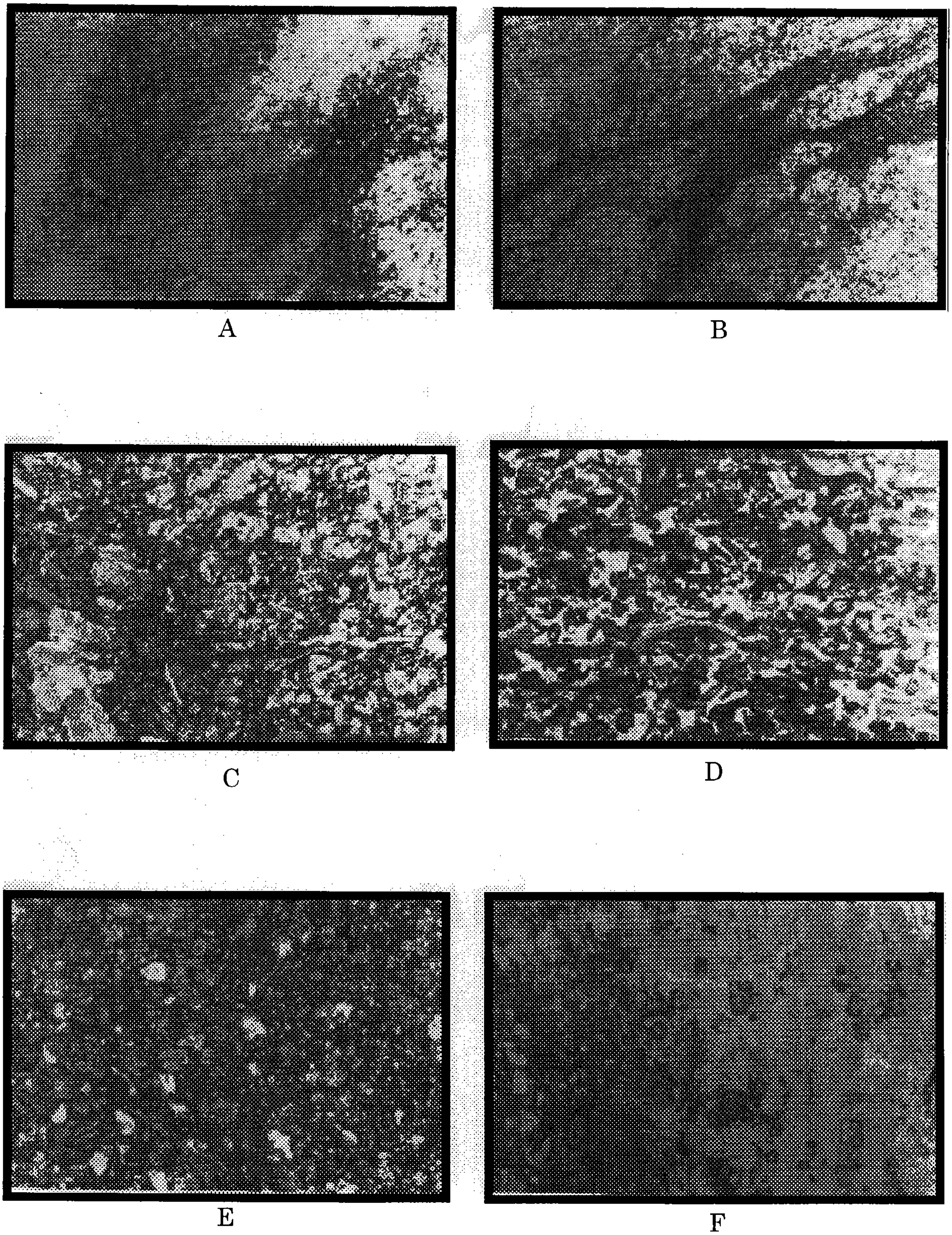
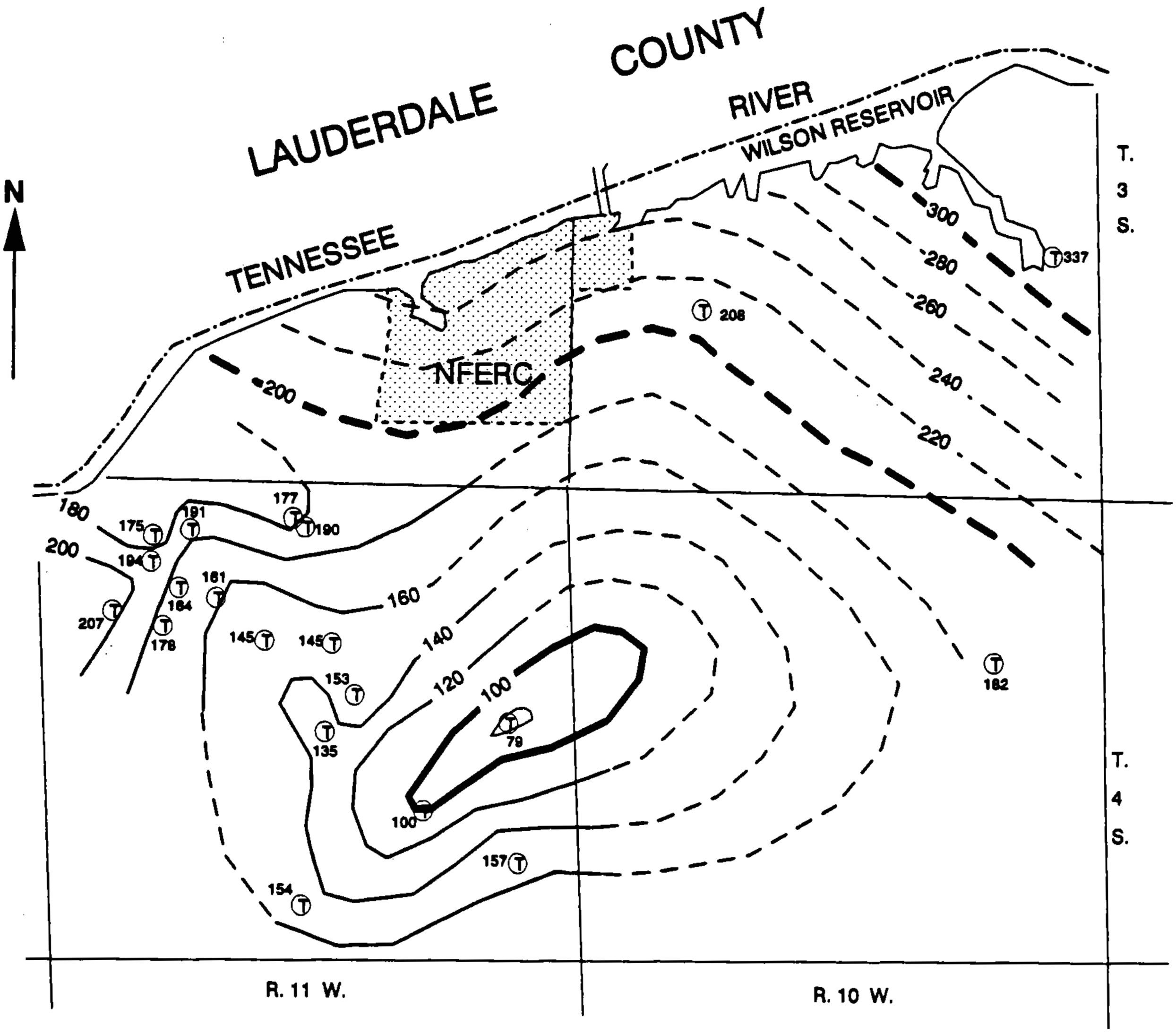


Figure 4.8 . Microphotographs of core samples. All photos are 1 cm across except E and F which are 2 cm across. A: dolomitic chert limestone; B: calcareous chert; C: biograinstone; D: biosparite; E: dolomitic chert limestone; F: dolomitic chert limestone.



EXPLANATION

145

Altitude of top of Chattanooga Shale
from U.S. Geological Survey test-well data

140

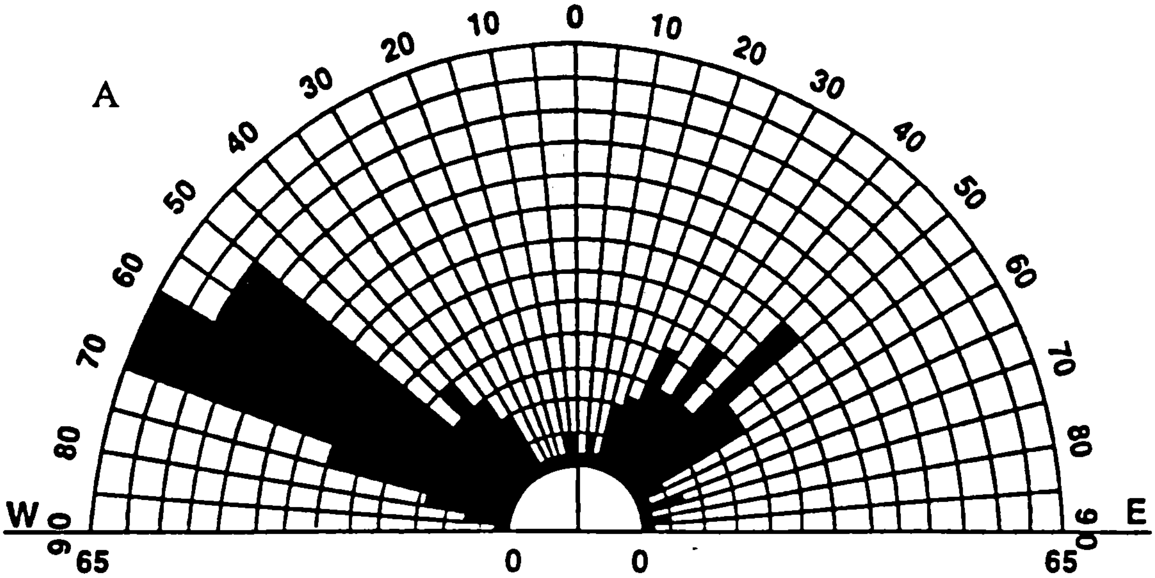
Structure contour
Drawn on top of Chattanooga Shale
Dashed where approximate
Contour interval 20 feet

Scale

0 1 2 3 4 5 6 Miles

Figure 4-9. Top of the Chattanooga Shale (after Harris et al., 1963; and Moser and Hyde, 1974)

A



B

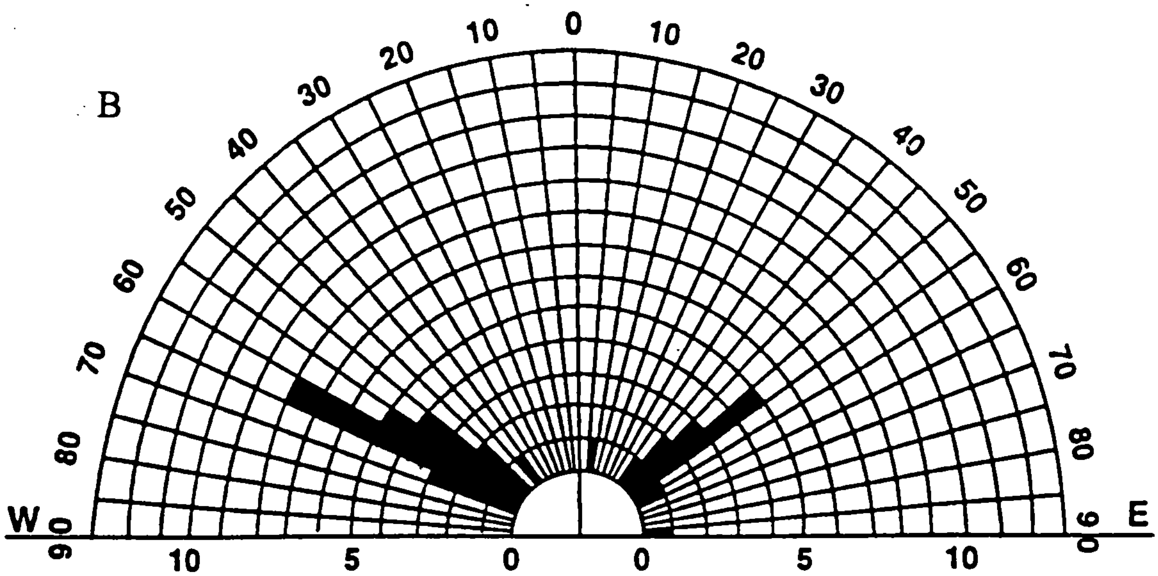


Figure 4-10. Orientation of Fractures and Joints Measured Along South Bank of Tennessee River

Strike joints are those that strike parallel to the orientation of the bedding of the sedimentary rock. Likewise, dip joints are those that strike parallel to the direction in which the bedding is oriented. Characteristically, a large number of joints are parallel.

The size of joints in three dimensions is rarely known. For example, in an area of low relief, even with 100 percent exposure, the vertical dimensions of joints are unknown. The size of the joints are also difficult or impossible to analyze statistically. However, preferred orientations and attitudes of joints can provide some insight regarding the regional movement of groundwater. The lineament study described in Chapter 5 provides such information.

4.5 Karst Features

Of those carbonate formations continuous beneath NFERC and regionally extensive, the Tuscumbia Limestone and Fort Payne Chert are of importance in this study. The Fort Payne Chert comprises a major portion of the Tuscumbia-Fort Payne aquifer system underlying the NFERC region (Moore, 1976). It is highly permeable in places because of numerous fractures that have been enlarged by solution activity. These openings generally occur at depths of less than 100 ft (Fry, 1981) and serve as conduits for rapid movement of groundwater. The Chattanooga Shale forms an aquiclude at the base of this unit and restricts downward movement of groundwater. Similar to the Fort Payne, the Tuscumbia Limestone has groundwater that moves primarily within a network of highly permeable and sometimes cavernous fractures. Because weathering of the carbonate bedrocks diminishes with depth, the upper portion of the Tuscumbia-Fort Payne aquifer has a higher bulk permeability than deeper intervals. This is especially true at the Tuscumbia Limestone/overburden interface where a relatively thin epikarst zone exists.

4.5.1 Subsurface Karst Features

4.5.1.1 Bedrock Zone. Bedding planes, joints, and fractures are of the utmost importance in characterizing karst terranes because they compose the underground solution conduit/fracture network. The principal openings in the Tuscumbia-Fort Payne aquifer are secondary, and result from solution activity along bedding planes, joints, and fractures. Chapter 5 shows a correlation between rectilinear joint patterns and other karst phenomena in the area, such as sinkholes and cave passages. It appears that these same directional trends apply to joints and fractures in the Tuscumbia Limestone and Fort Payne formations. Joints and fractures are most pronounced in the upper portion of bedrock and generally close with depth as the weathering front subsides.

At greater depths (within the Fort Payne formation), solution activity is expected to occur along fractures and bedding or parting planes. The bedding or parting planes in sedimentary rocks are produced by changes in sedimentation or by an interruption of it. The areal extent of bedding planes in the area varies considerably based upon lithologic logs from coreholes in the vicinity of NFERC. Therefore, any prediction of groundwater movement within the deeper bedrock flow regime is much more difficult than in the shallow bedrock.

4.5.1.2 Epikarst Zone. No sharp interface exists between residuum and the Tuscumbia Limestone across the NFERC site. Differential weathering has produced a zone of material above bedrock that consists of cherty limestone gravel in a matrix of silty clay. The weathering front in this epikarst zone is irregular which results in an uneven bedrock surface, especially where purer limestone zones are encountered. This highly corroded zone possesses void spaces where residual material has been piped through the deeper bedrock drainage network. It is estimated that the epikarst zone generally varies from about 3 to 5 ft in thickness across the site (Chapter 7).

Groundwater movement through the overburden is relatively diffuse at NFERC and percolating water generally accomplishes the majority of its solutional work in the epikarst zone and upper bedrock. Corrosion within the epikarst is greatest where flow paths converge above the more efficient percolation routes. Fissures that are considerably widened by corrosion beneath the overburden close rapidly with depth. As a result, infiltration into the epikarst zone is much easier than drainage from it (Williams, 1983). This bottleneck effect results in perched conditions after heavy rains with an epikarst base that is essentially a leaky boundary (Ford and Williams, 1989).

Recent observations show that the epikarst zone has significant water storage capacity and sufficient interconnection to diffuse dye quite widely (Chapter 8). Drainage from/through the zone is not uniform, but down and through preferred paths which act as foci for subcutaneous streamlines. Lateral movement is expected to follow rectilinear routes with orientations correlated with regional joint trends (Chapters 5 and 7). Because of initial spatial variability in fissure frequency arising from tectonic and lithologic influences, vertical leakage paths develop down connected pipes at the base of the aquifer. These paths are enlarged by solution with the result that a depression develops in the epikarst water table similar to a cone of depression around a pumped well. Flow paths then adjust in the epikarstic aquifer to converge on the dominant leakage route(s). The extra flow encourages more solution and with it an enhancement in permeability. The zone of influence of the leakage route(s) widens according to the cone of depression in the epikarstic water table. The dimension of the radius depends on the hydraulic conductivity of the epikarst and the rate of water loss down the leakage path at its base.

These processes can explain the focusing of corrosion in the epikarst zone. As the surface lowers, the more intensely corroded zones begin to obtain topographic expression as solution dolines (surface depressions), their dimensions being controlled by the radius of the epikarst drawdown cone.

4.5.2 Surface Karst Features

Surface karst phenomena associated with weathering of calcareous rocks are common in the vicinity of NFERC and have a pronounced effect on both the groundwater and surface water hydrology of the area. Topographic features in the Muscle Shoals area typical of karst terrane include sinkholes, sinking streams, caves and springs.

4.5.2.1 Sinkholes and Sinking Streams. Sinkholes are considered by many karst geomorphologists to be the 'diagnostic' karst landform since they provide information related to natural processes that focus corrosion. No sinkholes exist on the NFERC reservation; however, sinkholes and sinking streams do occur in the surrounding area. The majority of these features are located along bedrock joints (NE-SW and NW-SE). Sinkholes in the vicinity of NFERC commonly appear as linear topographic depressions and sinking streams are rare. Relatively young sinkholes are usually circular in shape that will become elongated along bedrock joint orientations with increasing time (i.e., linear depressions). These sinkholes can also be mantled by clayey soils that function as infiltration inhibitors resulting in ponding of runoff during extreme events. The soils can even create semi-permanent ponds (doline ponds) that reduce storm surcharges of flow underground.

A combination of two different geomorphologic mechanisms produce sinkholes in the Muscle Shoals area, subsidence and collapse. Subsidence is a gradual process involving sagging or settling of the surface without obvious breaking of the soil cover. At a small scale, it can create subsidence sinkholes where the cavity is at the rock-soil interface (epikarst zone). However, some amount of collapse usually accompanies sinkhole development in the NFERC area, whereby soil is pirated through the deeper bedrock flow system. These sinkholes have interconnected solution conduits at greater depth in the bedrock or are open at the ground surface.

4.5.2.2 Caves. Smith (1980) used local cave channel trends and sinkhole orientations to deduce that a northwest-southeast trend exists for karst phenomena in the vicinity of NFERC. Linear features or trends developed by the alignment of induced or natural sinkholes and depressions are especially important because they indicate the locations of fractures, joints, and perhaps purer carbonate strata that have been subjected to some amount of solution activity. Bedrock openings in the vicinities of these geologic structures would generally be expected to be more numerous and perhaps larger than in other areas.

Three small caves in the river bluff north of NFERC (Young and Julian, 1991) are developed in the upper bedrock. The orientations of these caves, as well as numerous others in the area, support the regional NW-SE and NE-SW trend in cave genesis. However, these directional trends disappear somewhat with depth for caves developed in deeper sections of the bedrock.

The caves indigenous to the Muscle Shoals area can best be described as single- to multi-level, reticulate maze caves. These caves are frequently encountered either as separate entities or as anomalous parts of common caves. They are reticulate mazes of comparatively small passages that follow joints confined to one or a few rock beds. The cave systems generally possess passages that are indicative of phreatic (pressure flow) development. Parallel passages (i.e., in one joint set) are of similar dimensions. Characteristically, their morphology is that created by slowly flowing waters.

In essence, such mazes develop where strata possessing a high fissure frequency are confined (Ford and Williams, 1989). A "sandwich" situation exists where the jointed carbonate beds are semi-confined or confined between the thick clayey overburden and the Chattanooga Shale aquiclude. The mazes are typically of a two-dimensional variety, i.e., they are guided by one local joint system, thereby forming a single level of passages. Three-dimensional mazes may be created where phreatic waters penetrate upwards into overlying joint systems. Usually such joint systems are separated by thin aquitard beds or locally breached clays. The upper passages of multi-level caves are generally subordinate to the basal levels; they are smaller and may comprise only discontinuous fragments of the maze superimposed upon the larger base. Where, however, major outflow to springs passes through them, they will be enlarged.

4.5.2.3 Springs. The resurgence of groundwater to the surface occurs at several springs distributed according to the structure of the Tuscumbia-Fort Payne aquifer. The major springs in the Muscle Shoals area are located along the Tennessee River and Spring Creek. Chapters 3 and 8 describe major springs related to the groundwater flow system in the vicinity of NFERC.

4.6 Topographic Changes

A comparative analysis between pre-disturbed (1916 and 1918) and present (1990) topographic maps was made to evaluate landform (elevation) changes at the NFERC Reservation that might influence recharge patterns and groundwater movement. Figure 4-11 shows topographic changes that have occurred at NFERC since 1918. Digitized 1918 and 1990 topographic maps were available with contour intervals of 2 ft which provided high resolution images for Figure 4-11. A 1916 topographic map (U.S. Army Corps of Engineers, 1916) was available for visual comparisons and includes topographic information compiled from 1912 and 1914 survey data.

The majority of the NFERC plant area in Figure 4-11 shows less than 5 ft of variation between pre-disturbed and existing site conditions. Most of these small topographic changes are related to cut-and-fill construction associated with structures, roads, railroad tracks, and reservoirs. Two areas indicate much higher elevations than from the 1918 maps. The areas include the phosphate slag disposal areas just north of the main plant site and SWMU 108. The elevation increases at these two locations are between 10 and 80 ft, and 10 and 50 ft, respectively. Most importantly, the 1916 and 1918 maps show no surface karst features such as sinkholes or depressions that might have been subsequently filled during construction activities or waste disposal at the site.

Comparison between the 1990 and the 1916 topographic maps indicates that the flowing course of Pond Creek was altered after 1916. On the 1916 topographic map, Pond Creek flowed to the southwest from the area immediately south of NFERC into the city of Tuscumbia. Sometime thereafter, the stream was channelized from the southeast corner of NFERC so that it flowed along the west of SWMU 108 and NFERC intercepting natural drainage to the

Figure 4-11 Changes in Topography After 1918

Tennessee River. The 1990 topographic map shows remnants of Pond Creek that flows overland and eventually sinks into a cave system at the corner of Woodward and Avalon Avenues. Rerouting of the stream was probably conducted in response to increased development in the area (increased runoff) and higher stream flows to an already flood-prone area of Tuscumbia.

5.0 LINEAMENT STUDY

5.1 Introduction

The use of remote sensing imagery such as aerial photographs, satellite images, and airborne radar images to locate zones of groundwater movement and concentration has become relatively common in the last few years. In areas underlain by carbonate or nonpermeable rocks, where water movement is controlled by solution channels or fractures, lineaments visible on remotely sensed images may indicate the position of underlying fractures not discernible in the field.

Lineaments, as defined by O'Leary, Friedman, and Pohn (1976), are mappable simple or composite linear features of a surface whose parts are aligned in a rectilinear or slightly curvilinear relationship which differs distinctly from the patterns of adjacent forms and presumably reflects a subsurface phenomenon. Lineaments may be formed by the alignment of straight ridges, valleys, or stream segments; alignment of ridge offsets, terminations or gaps; linear soil tonal anomalies; or combinations of any or all of these. Although lineaments are defined by naturally occurring phenomena, in some cases land-use patterns can accentuate lineaments; for example, cultivation may stop sharply at a lineament representing the line where a fault juxtaposes arable and non-arable soils or slopes.

At the NFERC site, lineament analysis was used as an aid to understand the pattern of groundwater movement in the bedrock flow regime. Any karst features that may have existed at the site prior to development have probably been obscured by extensive reworking of the land surface over the long period of time the facility has been in existence, and the clues that these features may have provided have been lost. However, a sequence of aerial photographs taken periodically from 1949 to 1986 by the Soil Conservation Service, NASA, and the U.S. Geological Survey provide important information about past configurations of the site and any karst features that may have existed at the time the photographs were taken.

5.2 Previous Studies

Several previous studies provided important background information for this investigation. One of the first controlled studies documenting the relationship between lineaments and water-bearing fractures was done by Lattman and Parizek (1964) to locate water well sites in folded and faulted Lower Paleozoic carbonate rocks. The authors first delineated lineaments (called "fracture traces" in their study) on black and white aerial photographs, then located wells on long lineaments or lineament intersections. Caliper logs for these wells determined that cavity development was extensive in the wells located on the lineaments, and pump tests proved greater water yields from these wells than from wells not located on lineament traces or intersections in the same areas.

In north Alabama, several studies of the relationship of satellite-image lineaments to hydrogeologic factors were done as part of a state-wide investigation of the uses of satellite data

(Henry, 1974). High-yield wells and springs in Madison County, Alabama, were found to correlate with the Anniston lineament complex, a regional linear anomaly that extends from the Alabama Piedmont through Madison County and into Tennessee (Moravec and Moore, 1974). The Anniston lineament complex is characterized by changes in structural style and in depositional patterns, high fracture intensity, anomalous yields of water wells and springs, and deeper weathering of surface rocks, among other evidences of structural disruption (Drahovzal, 1974). Since that study, several other northwest-trending lineament complexes have been identified in Alabama that exhibit the same characteristics (Coleman et al., 1988). Elsewhere in Alabama, large-scale northeast trending lineaments have been associated with anomalous water-well and spring yields, high mineral concentrations in water, increased incidence of solution features in carbonate rocks, and large numbers of open fractures and faults (Richter, 1990).

A recent hydrogeologic and water quality evaluation section of the Muscle Shoals area was made by the Geological Survey of Alabama to determine the potential environmental impacts of storm water drainage wells (Chandler and Moore, 1991). Lineament analyses made for this study using Landsat images and aerial photographs delineated an orthogonal pattern of major and minor lineaments trending NE-SW/NW-SE, similar to the lineament patterns documented in previous studies in Alabama. Dye-trace and groundwater movement studies suggested that several of the lineaments were surface indications of fracture systems that may control the movement of groundwater in the area. Additionally, Golder Associates (1990) describe a similar relationship in the area southwest of the former Ford plant. At this location, a linear trough in the Chattanooga Shale is correlated with major lineament trends and a depression in the potentiometric surface. The orientation of the features is NE-SW in the general direction of Tuscumbia Spring.

5.3 Methodology

Lineament analyses are most effective if several different types of imagery, taken at different times and under different climatological conditions, and of different scale, are used. For this study, preliminary regional lineament analysis was done on Landsat 3 band 6 and 7 1:250,000-scale paper prints dated December 14, 1980, 1:250,000-scale prints of sidelooking airborne radar imagery flown during April and May 1985, and NASA U-2 aerial color infrared film transparencies made February 1973. The Landsat and aerial color infrared images were more useful than the radar images, because the fracture zones that underlie the area have little or no vertical topographic expression necessary for good radar definition. For detailed analysis of the NFERC site, USDA Agricultural Conservation and Stabilization Service (ASCS) 1:20,000-scale black and white aerial photographs taken January 1949 and U.S. Geological Survey NHAP 1:24,000-scale aerial black and white and color-infrared enlargements taken January 1981 and June 1987, were used. Lineaments were interpreted on transparent overlays and transferred manually to site maps. Because regional lineaments were derived from small-scale images and were located on 1:250,000-scale maps with a cartographic tolerance of approximately 1/16 mile, and because some large lineaments may represent zones instead of individual fractures, broad bands are used to denote these lineaments on the site maps.

After the lineaments were drawn on the image overlays, several were checked in the field. The projected locations of several lineaments coincided with short straight stream segments, linear depressions in two fields, and small, wet depressions in areas of the reservation that, from comparison of the 1949 and 1986 photographs with the present land use, appeared to have had the least amount of land-surface alteration.

5.4 Lineament Interpretation

5.4.1 Regional Analysis

Regional lineament analyses using small-scale imagery are important in site studies to establish not only the structural framework that may control the lineament pattern, but also to project the traces of lineaments that may cross or affect the site but are obscured on the site itself by land-use patterns or recent sediment accumulations. Satellite images provide coverage of large areas at a constant sun angle, which allows very large-scale structures that are visible only as individual components on low-altitude imagery to be seen in their entirety.

Landsat 3 band 6 and 7 images covering most of north Alabama were used to interpret lineaments in the Muscle Shoals area. Band 6 and 7 images reflect near-infrared and infrared light; areas that are white or light gray on the image reflect the highest amount of the near-infrared and infrared wavelengths, and dark areas reflect the least amount. Because water reflects no infrared light, water bodies appear black on these images, and water-saturated soils appear darker gray than surrounding dry soil. Topographic features are also more visible because land-use patterns and vegetation are somewhat obscured as compared to their appearance in black and white and color-infrared images. These factors combine to emphasize water-related features such as zones of water-filled fractures, soil over large incipient sinkholes, and solution conduits in otherwise featureless residuum. For example, faults can be delineated on the basis of structural offsets and other geomorphic criteria, and a fault open to water movement can often be indicated by a dark tonal anomaly along it on band 6 and 7 images.

Figure 5-1 is part of a Landsat 3 band 6 image of the area surrounding the TVA NFERC site. Lineament analysis was concentrated on the central section of the image surrounding the site; at the edges of the figure, only those lineaments that appeared to extend into the Muscle Shoals area were depicted. Although several lineaments striking roughly N80°W are present on the lower part of the image, these lineaments do not appear to be related to the general pattern of lineaments present in the Muscle Shoals area, and may be artifacts produced along scan direction.

At least two orthogonal (roughly perpendicular) pairsets of lineaments are present in the region (Figure 5-2). One pairset has a strong northeast component, ranging between N62°-78°E, with an equally well-developed N25°-35°W set. One of the northeast trending lineaments of this pairset appears to cross the extreme southeastern corner of the NFERC site, and a northwest-trending lineament crosses the northwest corner just south of Wilson Dam. The second pairset has well-developed and numerous lineaments trending between N38°-50°E, roughly parallel to Valley and Ridge structures, with a less numerous but well-developed set

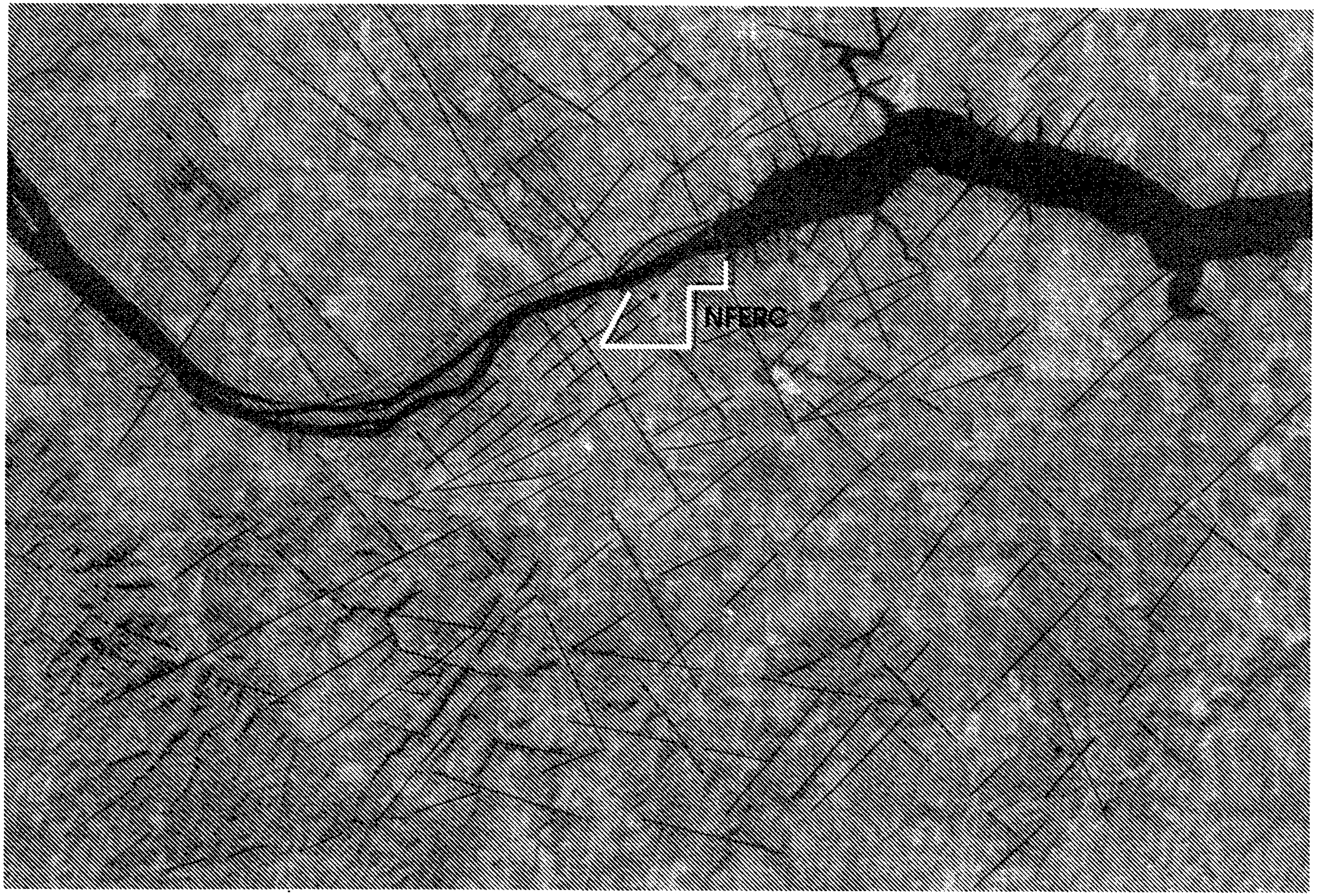


Figure 5.1: Lineaments in the region of the National Fertilizer Environmental Research Center site, Muscle Shoals, Alabama, from Landsat 3 band 6 image, dated January 14, 1980. Nominal scale 1:250,000.

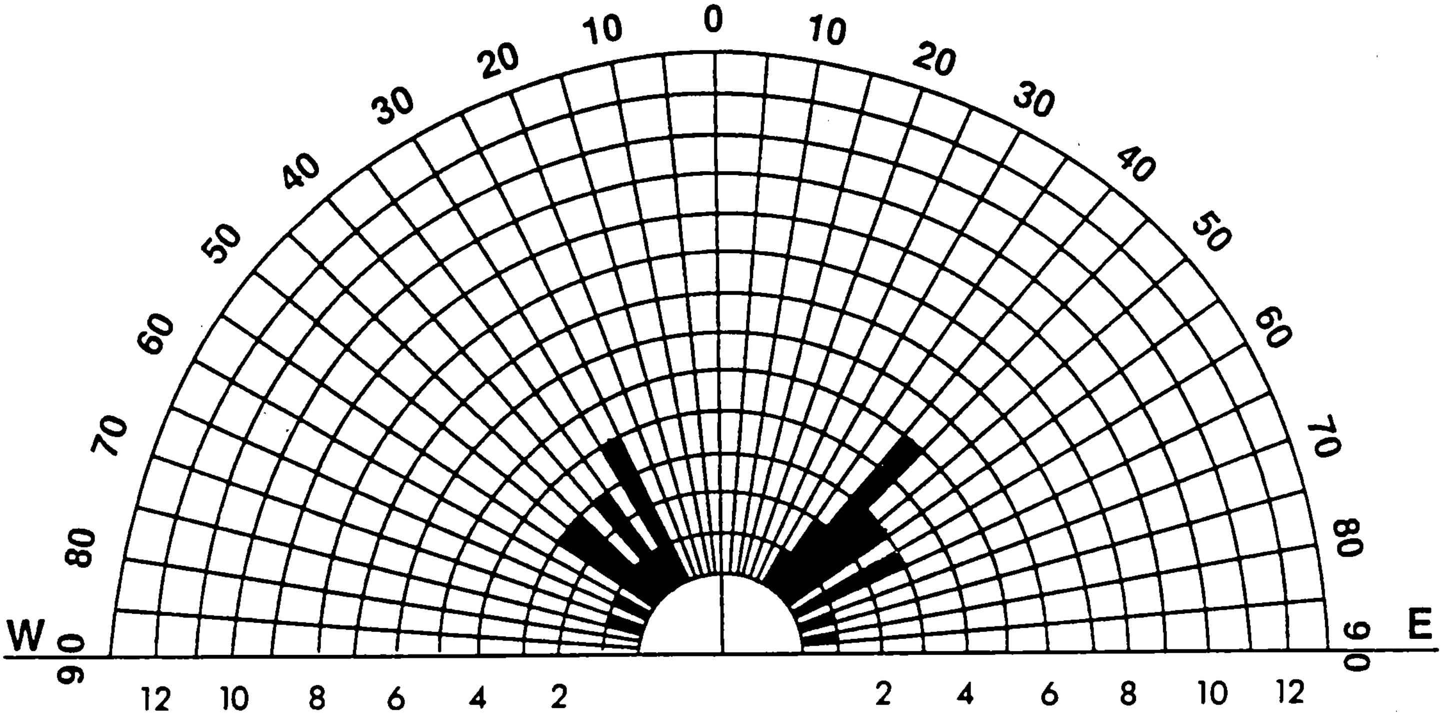


Figure 5-2. Orientation of Lineaments From Landsat 3 Band 6 Image

trending N50°-60°W. Two of the northeast-trending lineaments of this pairset extend onto the NFERC site, and one of the northwest-trending lineaments appears on either side of the boundary but not on the site itself. All of the lineaments in the vicinity of NFERC, are characterized by the dark, linear soil tonal anomalies that frequently indicate water-saturated areas or zones of groundwater movement. The position of Landsat lineaments coincided with several lineaments visible on the 1:125,000-scale NASA aerial color infrared transparencies, which were used to check both lineament position and the presence of man-made structures such as roads and fence lines that could produce false lineaments.

The orientation of the N38°-50°E/N50°-60°W lineament pairset, the most strongly expressed on and near the site, coincides with the axes of two elongate lows in the subsurface as mapped on the top of the Chattanooga Shale (Figure 4-9). These lows may represent the effects of basement faults or fractures in the underlying rocks.

5.4.2 Site-Area Analysis

Lineaments in the site area were plotted on large-scale aerial photographs. As previously described, several types of aerial photographs taken at different times were used, of which the most effective were the aerial color infrared (CIR) NHAP photos, enlarged to a scale of 1:24,000. Both leaf-off (winter 1981) and leaf-on (summer 1987) coverage was available. As a general rule, leaf-on imagery is not as useful for geologic and hydrologic evaluation because the leaf coverage obscures details of ground features. However, drought conditions were widespread in parts of Alabama during the summer of 1987 and hydrologic features that normally would not be visible on summer photography were revealed. Figure 5-3 shows part of the June 1987 NHAP CIT photograph of the site area, with lineament interpretation. Healthy vegetation appears almost solid red, like the vegetation on the NFERC site at upper right. At lower right, fields with crops that would normally be thriving and reflecting almost solid red were either stressed by lack of water or had not been planted. These fields appear light in color, with darker patches that probably indicate soils that are slightly more saturated at depth over sinks or conduits to the water table. Irrigated fields, such as those in the lower right corner, show light patches in a reverse pattern, which may indicate sinks and conduits where water applied to the surface can drain more quickly to the water table. In several of the fields, linear northwest-trending tonal anomalies and alignments of the dark patches can be clearly seen. These conditions also produce linear tonal anomalies in forested or shrub-covered areas, because those trees or plants growing over water-filled fractures or zones of water movement are healthier and reflect solar infrared more strongly than surrounding plants growing in water-deficient soils.

Lineaments are abundant in the vicinity of the NFERC site on the January 1981 CIR photograph (Figure 5-4). Leaf-off (winter) imagery commonly displays more lineaments because the ground surface is bare of masking vegetation. Winter groundwater levels are usually higher, producing different types of hydrologic signatures on photographs. Stream channels are more visible, and saturated soils over incipient sinks are more visible in fallow and bare fields. Groundwater levels may have been lower than normal when this photograph was taken, because several linear soil tonal anomalies in fields appear to reflect the underlying fracture pattern. A

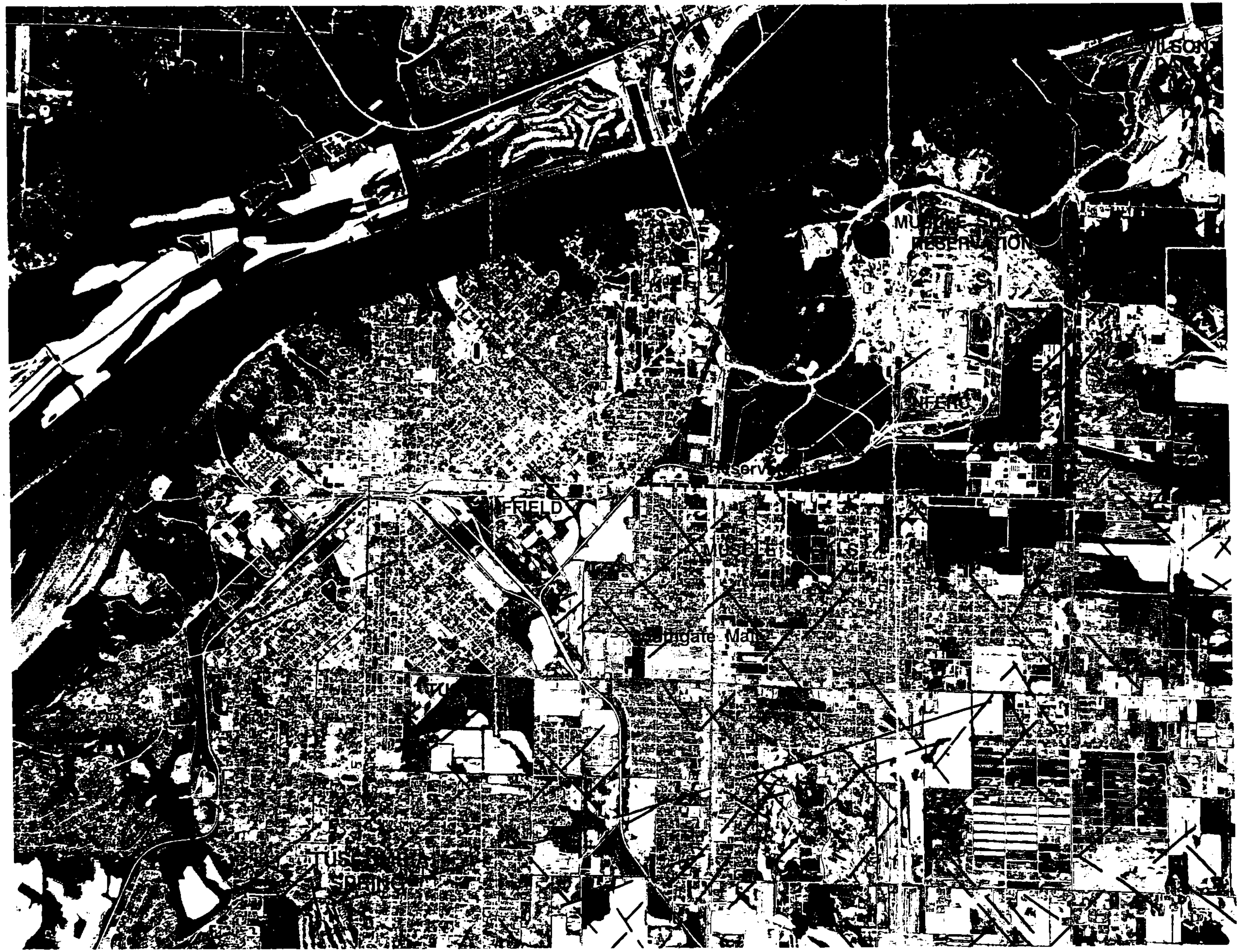


Figure 5-3.

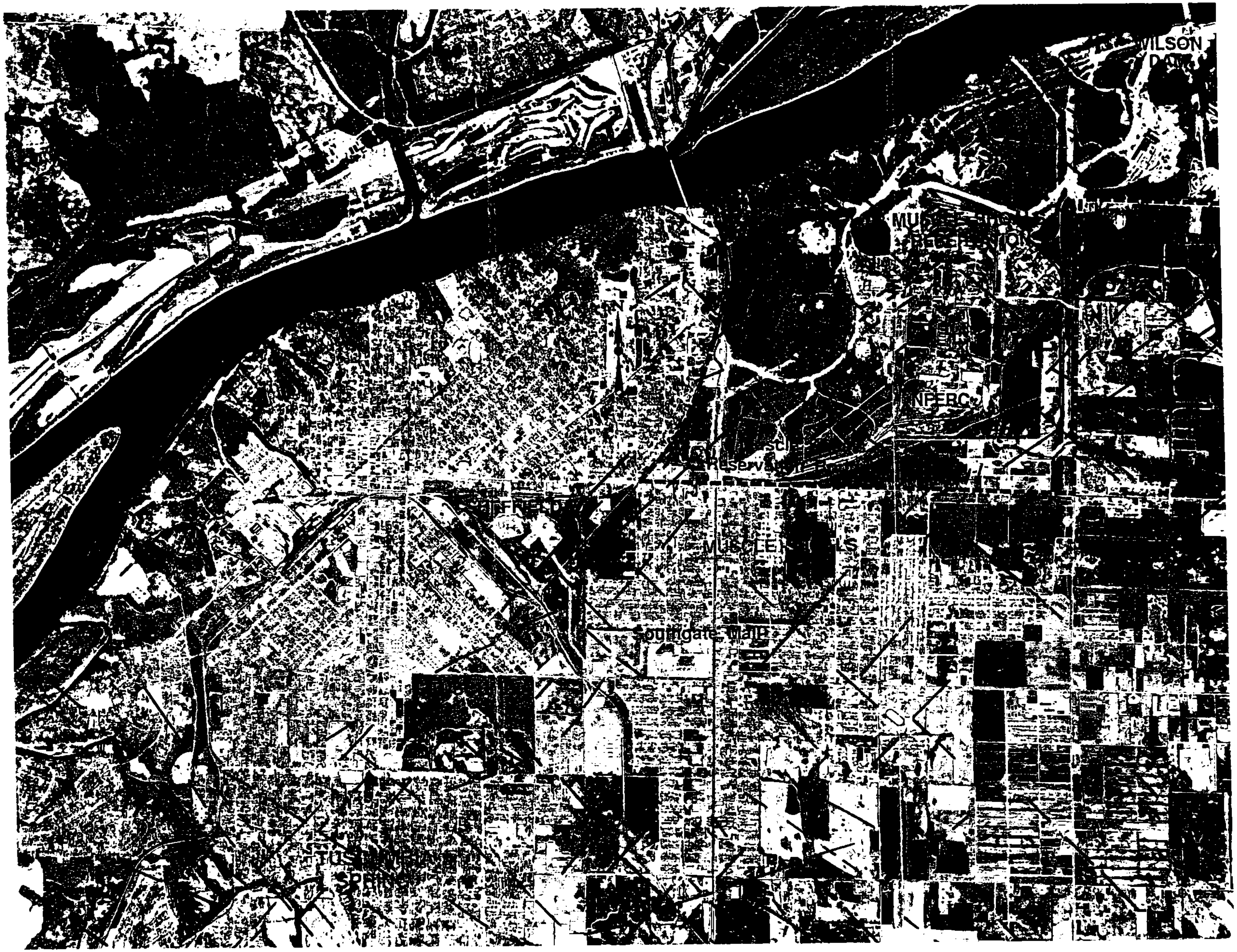


Figure 5-4.

hydrograph of observation well USGS Col-1 shows a groundwater level considerably below normal for this period (Gillett and Moore, 1992). Lineaments from this photograph have very similar orientations to regional lineaments from Landsat images (Figure 5-5). These orientations are also well correlated with those from previous lineament surveys (Chandler and Moore, 1991) and field measured joint orientations (Figure 4-10).

Black and white NHAP photographs taken simultaneously with each CIR photograph were also analyzed for lineaments. Because these photographs record different wavelengths of light and are taken at a slightly smaller original scale, different features may be emphasized. Lineaments delineated on these photographs, however, closely matched those from the CIR photographs taken on the same date. A few very short lineaments were present on these photographs and not on the CIR photographs, but they conformed to the same orientations as the CIR lineaments.

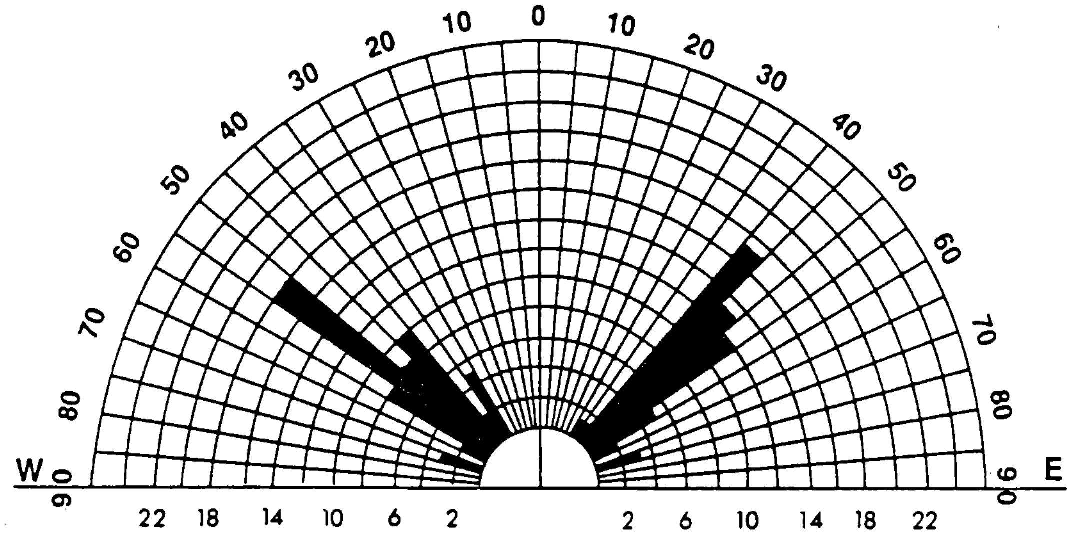
The orientations of many of the lineaments on all of the low-altitude photos corresponded with the orientations of fracture and joint sets mapped in the field (Figure 4-10). This indicates that these fractures and joints appear as surface tonal anomalies and are probably conduits for groundwater flow.

Black and white photographs taken by ASCS in January 1949 (scale 1:20,000) were used to check for the presence of old roads, ditches, embankments, and any other linear man-made construction that, even though no longer present on the ground, may have affected soil patterns or ground contours and caused apparent lineaments. These photographs were also used to check for the presence of subsidence structures or hydrologic signatures in areas where the land surface may have been subsequently altered.

As in other carbonate terranes in Alabama, many of the lineaments in the Muscle Shoals area appear to be caused by surficial karst features such as aligned or elongated sinkholes, and by linear soil and vegetation tonal anomalies corresponding to subsurface joint systems. This indicates that the underlying fracture pattern is controlling groundwater movement in the bedrock flow regime.

5.5 Conclusions

Several factors combine to suggest that bedrock groundwater movement through the NFERC site and Muscle Shoals area is controlled by sets of regional fractures, many of which are visible as lineaments on remotely sensed imagery. First, the appearance of these lineaments on all of the imagery analyzed for this study is consistent with that of lineaments in other areas of northern Alabama where they have been checked in the field and found to correspond to surface expressions of linear structural, depositional, or solutional features that might control groundwater movement. The lineament patterns and orientations are similar to those of lineaments from a similar carbonate terrane in Madison County, Alabama, where they are associated with high-yield wells and springs (Moravec and Moore, 1974).



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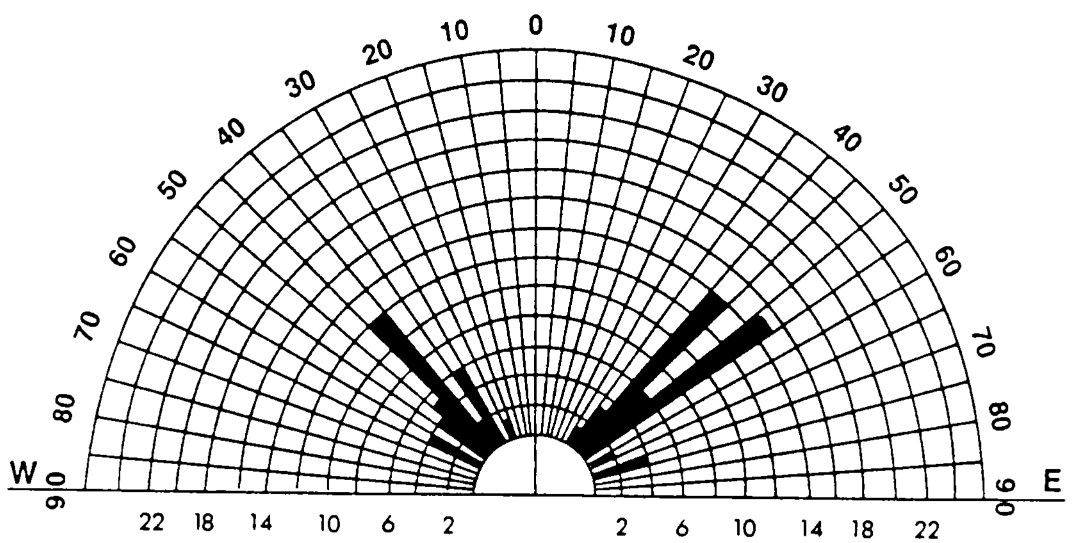

1987

Figure 5-5. Orientation of Lineaments From NHAP Aerial Color Infrared Photos, 1981 and 1987

Second, a rectilinear system of water-filled fractures is plainly visible on the two large-scale color-infrared aerial photographs, as linear saturated zones in surrounding dry soil in plowed fields and as elongated wet depressions or lines of sinkholes (Figures 5-3 and 5-4).

Third, the numerous northwest-trending elongated depressions, swampy areas, and sinks that characterize the Muscle Shoals area decrease markedly southeast of a line extending northeastward from Tuscumbia Spring to just south of Wilson Dam, although there is no change in lithology. This can indicate a change in the hydrologic conditions that produced these features, most notably a change in the direction of flow. A long, northeast-trending lineament occurs very close to this line.

The factors mentioned above point to the presence of fracture systems underlying the Muscle Shoals area that conduct groundwater in a rectilinear pattern oriented northwest/northeast. A major fracture zone may occur along a line from just west of Wilson Dam to Tuscumbia Spring. It is probable that different sets of fractures serve as conduits under different hydrologic conditions; for example, a deep set of fractures may conduct groundwater under low water table conditions and a shallower, somewhat differently oriented set may control groundwater movement during higher water table conditions.

6.0 MONITORING WELL NETWORK

6.1 Introduction

During the course of groundwater studies at NFERC since 1980, about 78 monitoring wells have been installed. Some off-site wells also are used for this study; they include six bedrock wells and a USGS well (Col-1) located at the OxyChem Plant site east of the NFERC. Figure 6-1 shows the locations of these monitoring wells and Appendix A provides construction diagrams, figures, and pertinent data for most of the wells.

The monitoring wells can be grouped into four areas based upon their designed use:

1. regional wells - wells distributed around the NFERC and those installed for this investigation;
2. SWMU 108 wells - wells concentrated near the SWMU 108 site;
3. other on-site wells - wells installed for specific investigations at SWMUs 86, 100, 104, and the constructed wetlands project;
4. off-site wells - OxyChem and USGS wells.

These wells are described in the following sections.

6.2 Regional Wells

Regional wells include the wells drilled during coal-to-ammonia and phosphorus entombment projects (wells 1 to 8), wells at the Nursery site, and wells installed for this study. Figure 6-1 shows the locations of these wells. These wells have different constructs because they were installed in various stages (Appendix A).

6.2.1 Wells A-K

Nineteen wells were specifically installed for the regional groundwater investigation at NFERC (Figure 6-1). The wells were carefully located to provide additional site characterization information, groundwater quality data, and as detection/injection wells for the dye trace study. The wells were installed in May 1991 and April 1992. Thirteen wells, wells A through H, were completed in May 1991. These wells include eight bedrock wells and five counterpart overburden wells. Another six wells, wells E2, J1, J2, I1, I2, and K, were installed in April 1992. These wells include two bedrock wells and four overburden wells. Law Engineering, Inc., was contracted to install the wells.

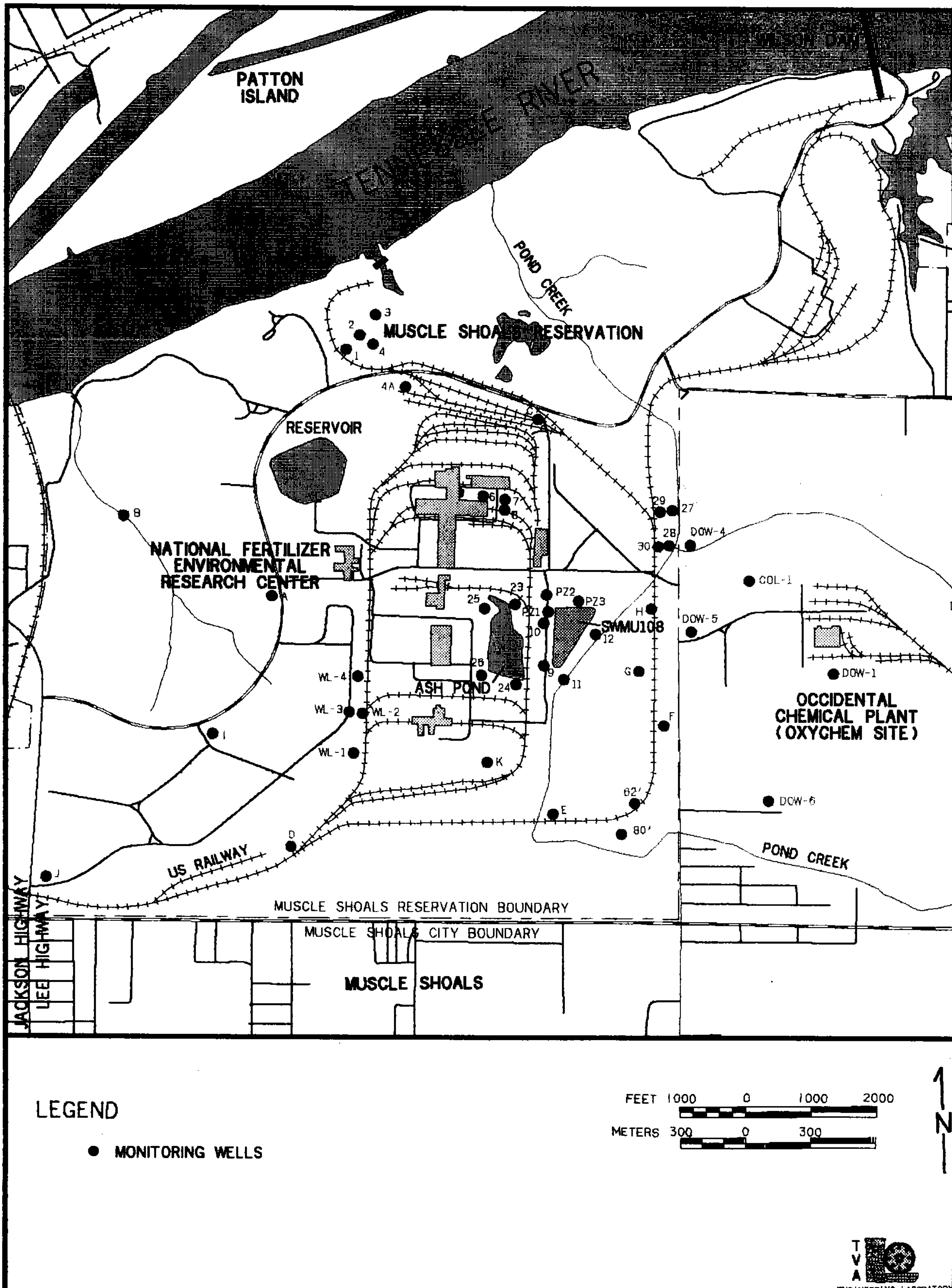

Figure 6-1 Monitoring Well Location Map

During drilling, split-spoon soil samples were obtained at 5-ft intervals, and undisturbed (Shelby tube) samples were obtained at a depth of 5 ft and at succeeding intervals of approximately 20 ft thereafter in selected borings. The split-spoon samples were used for grain size distribution analyses in accordance with ASTM Method D-422, and undisturbed samples for permeability tests in accordance with the Army Corps of Engineers' Engineering and Design Laboratory Soils Testing Manual, EM-110-1906, Appendix VII.

The construction of the wells is illustrated in Appendix A. Bedrock wells were installed using auger drilling techniques to the top of bedrock and HQ corebarrel drilling through bedrock. Four-inch, schedule-40 PVC casing and screen was then installed. All bedrock wells were screened in 5-ft intervals at the top of rock (i.e., weathered bedrock zone) and were subsequently completed as coreholes. The 4-inch bedrock well screens, were surrounded with 1/16- to 1/8-inch pebble sand. Bentonite was then used to seal the sand-pack and the remainder of the auger hole was filled with bentonite-grout to ground surface. To protect against silting, an inner 2-inch, schedule-40 PVC casing and screen (with centralizers) was installed inside most of the 4-inch wells. Two-inch, schedule-40 PVC casing and screen was used to construct overburden wells. Auger methods were used to install the wells and they were completed like the outer screen of the bedrock wells. Lockable covers were installed for all wells.

6.2.2 Wells 1-8 and Well 4A

Wells 1, 2, 3, 4, 5, 6, 7, 8 and 4A were installed in conjunction with NFERC's ammonia-from-coal and phosphorus entombment projects in the 1980s. Wells 1, 2, 3, and 4 are located in the coal slag storage pond area, and wells 5, 6, 7, and 8 are located at the phosphorus entombment. Well 4A is located between the two areas (Figure 6-1).

Wells 1 through 8 were drilled and installed by Miller Drilling Company in July 1980. A 12.5-inch diameter hole was installed in the overburden and a 6-inch diameter corehole was drilled in bedrock. Six-inch diameter PVC casing was installed for the wells and the annulus between the well wall and casing was filled with pea gravel, sand, and cement grout from the bottom to the top of the wells, respectively. Heavy duty surface casings were installed serving as an envelope for the upper four to five feet of plastic casing. The surface casings are equipped with protruding handlebars, and are enclosed at the top with a locked metal covering.

Well 4A was added later to supplement the projects in order to provide an up-gradient monitoring point from the coal slag storage pond. Graves Well Drilling Company installed the well in October 1984. Using a 9-7/8-inch bit driven by a Gardner Denver 15W air rotary drill, the hole was drilled using air and mist with Orvus-K drill soap. The well was cleaned with air and 6-inch schedule-80 PVC casing and screen were installed. The screen was made by drilling 1/4-inch diameter holes on 3-inch centers in the four quadrants of a 20-ft section of 6-inch PVC casing. PVC glue was used to connect sections of the casing and the screen. The annular space was filled with pea gravel, sand, and grout, respectively. The well was capped with an 8-inch steel case and cover.

6.2.3 NFERC Nursery Wells

Two water-supply wells are located at the NFERC Nursery (i.e., the farm), an area used for small-scale biological studies and testing. A 62-ft well was drilled in 1976 to provide process water for the Muscle Shoals Biological Recycling Project. In October 1980, an 80-ft well was installed for providing additional water supply for other projects in the area. The location of the wells are shown on Figure 6-1. Details of these wells, including well installation and construction, are unknown.

6.3 SWMU 108 Wells

Appendix A lists the monitoring wells near SWMU 108 and includes a site map showing their locations. All of the wells are constructed of PVC casing and screen. The wells have been installed in three stages. Differences in the well construction among the three stages has occurred because of an improved understanding of the site geohydrology and/or the need to collect different types of information.

Wells W9, W10, W11, and W12 were installed near SWMU 108 in 1985 to provide groundwater water quality information. Well clusters PZ-1, PZ-2, PZ-3, PZ-9, PZ-10, PZ-11, and PZ-12 were installed in 1987 to provide hydraulic head information. Wells W13, W14, W15, W16, W17, and W18 were installed in 1990 to provide detailed information on the zones of high and low groundwater flow in the soil overburden. Appendix A shows the specifications for each well and illustrates the screened interval for each well.

6.3.1 Monitoring Wells W9, W10, W11, and W12

Graves Well Drilling Company installed monitoring wells W9, W10, W11, and W12 from September 11-18, 1985 (Appendix A). Drilling was accomplished using 8-inch, tri-cone or roller-cone bits. Cuttings were removed using compressed air with addition of water, or a mixture of water and a small amount of detergent (Orvus-K), to lift the cuttings to the ground surface.

The well casing was prepared from flush-jointed PVC pipe with an inside diameter (ID) of 6 inches. The well screen was made from a 20-ft length of the well casing, with 0.25-inch diameter holes drilled at 3-inch intervals on four sides of the pipe. After the well screen was set to the desired depth, a "filter-pack" consisting of pea-gravel was poured around the screen. The filter pack extends two feet above the top of the well screen. The remainder of the annulus was filled with a light-colored masonry sand to a depth of about 13 ft below ground surface. Cement grout was then used to fill the annulus to within 3 ft of the ground surface.

Wells W9, W11, and W12 were abandoned in October 1991 after Young and Julian (1991) identified their potential for providing a potential avenue for contaminant (e.g., nitrate) transport from upper to lower zones in the aquifer. Abandonment procedures consisted of

overdrilling the wells using a 10-inch hollow-stem auger and pressure grouting the auger hole to ground surface.

6.3.2 Monitoring Well Clusters PZ-1, PZ-2, PZ-3, PZ-9, PZ-11, and PZ-12

Singleton Materials Engineering Laboratories installed well clusters PZ-1 to PZ-3 from January to February 1987, and well clusters PZ-9, PZ-11, and PZ-12 from June 9-25, 1987 (Appendix A). Drilling was accomplished using a truck-mounted, Mobile B-61 rig equipped with 6-inch ID hollow-stem augers.

The well casing was prepared from threaded, flush-jointed PVC pipe with an outside diameter (OD) of 2 inches. The well screen was made from 5-ft sections of threaded, flush-jointed PVC pipe with 0.01-inch slots. After the well screen was set to the desired depth, a "filter-pack" consisting of sand and gravel was poured around the screen to its approximate top. Immediately above the screen, a bentonite seal was placed. The well annulus between the bentonite layer and the ground surface was then grouted using a bentonite-grout mixture.

Monitoring wells PZ11D and PZ12D were installed in October 1991 as replacements for abandoned wells W11 and W12. The replacement wells were installed using methods similar to those described for other PZ11 and PZ12 wells.

6.3.3 Monitoring Wells 13-18

Singleton Materials Engineering Laboratories installed wells W13 to W18 (Appendix A) in May 1990. The drilling was accomplished using a Mobile B-61 drill rig equipped with 3.25-inch ID, hollow-stem augers.

The well configurations consist primarily of 2-inch OD PVC pipe with 0.01-inch slotted screen that extends from near the borehole's bottom to within about 4.5 ft from the ground surface. After the well was installed, the hollow-stem augers were extracted, allowing the aquifer material to collapse around the well. A 20/40 filter sand was placed around the well to within about 0.5 ft from the ground surface. A 1.5-ft bentonite cap was then placed and allowed to hydrate for approximately 60 minutes before placing a final grout seal at the ground surface.

Well 16 has been destroyed and wells W13, W14, W15, W17, and W18 have been abandoned using a bentonite-grout mixture.

6.4 Other On-Site Wells

6.4.1 SWMU 86 and 104 Wells

Several new wells were installed recently near SWMUs 86 and 104 (Appendix A). These wells are used for the specific investigations of the two SWMUs. Two overburden and

four bedrock wells were installed near SWMU 86 (two Phosphate Development Works (PDW) lagoons). Two overburden wells and four bedrock wells were also installed at the SWMU 104 site (ash settling pond). The wells were not used in this study, so detailed descriptions are not provided.

6.4.2 SWMU 100

Four shallow overburden wells (wells 19, 20, 21, 22) were installed at the SWMU 100 site (Appendix A). These wells have depth between 25 and 28 ft. Again, these wells were not included in the present study.

6.4.3 Wetland Wells

Four wells were installed in July 1990 in conjunction with the constructed wetlands area, an ecological/biological project site (Figure 6-1). These wells were using hollow-stem auger methods to bedrock, ranging from 53 to 60 ft.

6.5 Off-Site Wells

6.5.1 OxyChem Wells

Six wells (DOW-1, 2, 3, 4, 5, and 6) from the OxyChem are used in this study. They are bedrock wells with depth between 117 and 150 ft (Figure 6-1). Detailed descriptions of the wells can been found in the reports by G&E Engineering (1989, 1991).

Well DOW-4, 5, and 6 were drilled in October through December 1990 by Miller Drilling Company of Lawrenceburg, Tennessee, utilizing rotary air drill bits powered by a truck-mounted drill rig. Six-inch diameter, steel casing was permanently installed in the borehole from land surface to the top of the bedrock during drilling to prevent the collapse of the borehole. Two-inch diameter, schedule-40 PVC casing and well screen were installed. The well screens, which ranged in length from 10 to 17 ft, were sealed from the borehole by two formation packer seals. Five to nine feet of sand was then placed directly over the packer seals and the annular space was grouted with a cement-bentonite to land surface. Lockable steel well shroud was constructed for the wells. The well diagrams are illustrated in Appendix A.

Well DOW-1, 2, and 3 were drilled and installed in 1988. The well construction is similar to that of well DOW-4, 5, and 6 with two-inch PVC casing extending through the bedrock zone.

6.5.2 USGS Well

Well Col-1, a USGS observation well located on the site of the OxyChem Plant, is about 1,000 ft east of NFERC (Figure 6-1). It was drilled in 1951 by the U.S. Army Corps of Engineers. This is the deepest well in the area, at 405 ft. It is the only well in the NFERC area drilled through the Chattanooga Shale that provides important lithologic information. The well has an 8-inch diameter with casing to unknown depth; it is open hole below the casing (Moore, 1981).

7.0 HYDRAULIC PROPERTIES OF BEDROCK AND EPIKARST ZONE

7.1 Overview

The bedrock groundwater flow system at NFERC is largely controlled by joints, fractures, karst solution features, and lithologic contacts. Resolution of the groundwater flow patterns in this system is scale-dependent. At the local scale (1 to 100 ft), randomness is important: one cannot predict whether a borehole will enter a karst cavity or miss it by a few feet (Ford and Williams, 1989). At the regional scale (>10,000 ft), an organized drainage structure is important: the structure includes a hierarchy of tributary fractures and solution channels that drain to primary conduits.

To help define the hydraulic properties of the bedrock, borehole flowmeter tests, single-well pumping tests, and slug tests were performed in bedrock wells. To obtain a better understanding of hydraulic head gradients and boundary conditions, monitoring of groundwater levels was performed at selected overburden and bedrock wells. The procedures and results of these activities are the focus of this chapter.

7.2 Slug Tests

A slug test is conducted by producing an instantaneous change in the water level in a well and measuring the changes in the water level over time. Analysis of the slug tests provide hydraulic conductivity values that are generally considered as order of magnitude estimates (Cooper et al., 1967). A large source of error for slug tests are skin effects (Faust and Mercer, 1984). Positive skin effects represent a reduction in the aquifer permeability near a well and are most common in granular materials that include clay deposits. During drilling, clayey material near to smear and partly seal a borehole wall. Negative skin effects represent an increase in the aquifer permeability near a well and are most common in bedrock. Fracturing of the bedrock during drilling can produce negative skin effects.

If fractures caused by drilling do not extend far beyond the borehole, negative skin effects can be shown to have a minor influence on the water table response in a well (Dudgeon and Huyakorn, 1976). Fracturing near a borehole is largely determined by the drilling method and the bedrock properties. Fracturing is most extreme when pressurized air (typically >100 psi) is used to create the borehole. At NFERC, bedrock boreholes were drilled by rotating a core barrel to help minimize the fracturing and to obtain core samples for examination.

Slug tests were performed in all regional bedrock wells by injecting 2 to 8 gallons of water. Water level changes were monitored for approximately 1 hour. The Bouwer-Rice (Bouwer and Rice, 1976) method was used to provide the results in Table 7-1. In Table 7-1, the larger saturated thickness is the entire open length interval of the well. The 4-ft saturated thickness was selected to represent the epikarst zone based on the assumption that the majority of the groundwater flow is through a relatively thin horizon. This assumption is support by the borehole flowmeter results in Chapter 7.3.

TABLE 7-1

Results of Slug Tests at Bedrock Wells

Well	Saturated Thickness (ft)	Hydraulic Conductivity (ft/s)	Transmissivity (ft^2/day)
A1	22	3.8×10^{-7}	0.72
A1	4	3.0×10^{-6}	1.04
B1	22	1.8×10^{-7}	0.34
B1	4	1.2×10^{-6}	0.42
C1	22	6.2×10^{-6}	11.80
C1	4	4.2×10^{-5}	14.52
D1	23	5.2×10^{-6}	10.33
D1	4	4.8×10^{-5}	16.59
E1	23	3.5×10^{-7}	0.70
E1	4	2.2×10^{-6}	0.76
F1	23	2.8×10^{-5}	55.64
F1	4	1.6×10^{-4}	55.30
G	23	3.5×10^{-5}	69.55
G	4	2.2×10^{-4}	76.03
H	23	2.2×10^{-6}	4.37
H	4	1.5×10^{-5}	5.18

7.3 Borehole Flowmeter and Single Well Tests

7.3.1 Testing Methods

An electromagnetic borehole flowmeter test includes measuring drawdown and incremental vertical flow measurements in a well during a constant-rate pumping test. Vertical flow measurements are conducted with the electromagnetic (EM) flowmeter. EM flowmeter tests have been successfully performed at the NFERC site (Young and Julian, 1991) and in different geohydrologic settings that include fractured carbonates (Moore and Young, 1992) and fractured sandstones and gypsum (Young et al., 1992a).

Details of the flowmeter application is described by Young et al. (1992b). A flowmeter test includes four steps: (1) measure ambient (natural) vertical flow in the well at selected depths; (2) pump the well at a constant rate until the water table stabilizes; (3) measure vertical flow in the well at selected depths; and (4) calculate flow and/or hydraulic conductivity profiles by systematic analysis of the drawdown and flow data.

Borehole flowmeter tests were performed in bedrock wells A1, C1, D1, E1, and G in December 1991. Tests could not be performed at wells F1 and H because background currents from overhead power lines interfered with the EM flowmeter's measurements. Well B1 could not be tested because of an impasse (casing joint) in the well.

For each test, potable water was injected into the wells at rates between 0.2 and 4.1 gal/min. Figure 7.1 shows the well injection rates and drawdown responses for each well. After the injection ceased, the well recoveries were recorded (see Figure 7.2). Analysis of the injection data is not straightforward because of the non-idealities associated with each well response. Assumptions required for the data analysis include an homogeneous and infinitely confined aquifer. The step-like responses at wells C1, D1, and E1 resemble recharge (e.g., constant head) boundary conditions. Such a recharge boundary could be simulated by a nearby region of highly weathered and/or fractured bedrock. From the five wells, only injection data from wells G and A1 are suitable for some type of analysis. Even the data sets from these two wells suggest inhomogeneity in bedrock hydraulic properties. As a result, the calculated transmissivity values should be considered as order-of-magnitude estimates.

For pump test data in which radial inhomogeneities are significant, the Cooper-Jacob straight-line (CJSL) equation (see Equation 7-1) has been shown to be useful for calculating transmissivity from analyses of the pumping test theory (Butler, 1990; Butler, 1988; and Butler, 1986) and analyses of data from a heterogeneous aquifer (Young and Herweijer, 1993; Young, 1993). For the injection test data, the CJSL equation was applied to the latter portion of the test to estimate transmissivity values. The four-order magnitude difference in the transmissivity values for wells G and A1 is consistent with the spatial variability attributed to the bedrock's hydraulic properties. It is expected that the area of highly fractured and/or weathered bedrock serving as a recharge boundary for wells C1, D1, and E1 has a transmissivity greater than the 500 ft^2/day estimated at well G.

$$T = \frac{2.3Q}{4\pi \frac{ds}{d(\log t)}} \tag{7-1}$$

where: T = Transmissivity (ft^2/day)

Q = Total Discharge Rate (ft^3/day)

$\frac{ds}{d(\log t)}$ = Derivative of drawdown with respect to the logarithm of time

7.3.2 Transmissivity Results

At wells A1 and G, the transmissivity values calculated for the recovery data are consistent with the values for the injection data. Well C1 recovery is too rapid to permit data analysis. From the recovery at well D1, a transmissivity of 105 ft^2/day is calculated for a period beyond 250 seconds. Transmissivity values for the recovery data from well E1 is for time

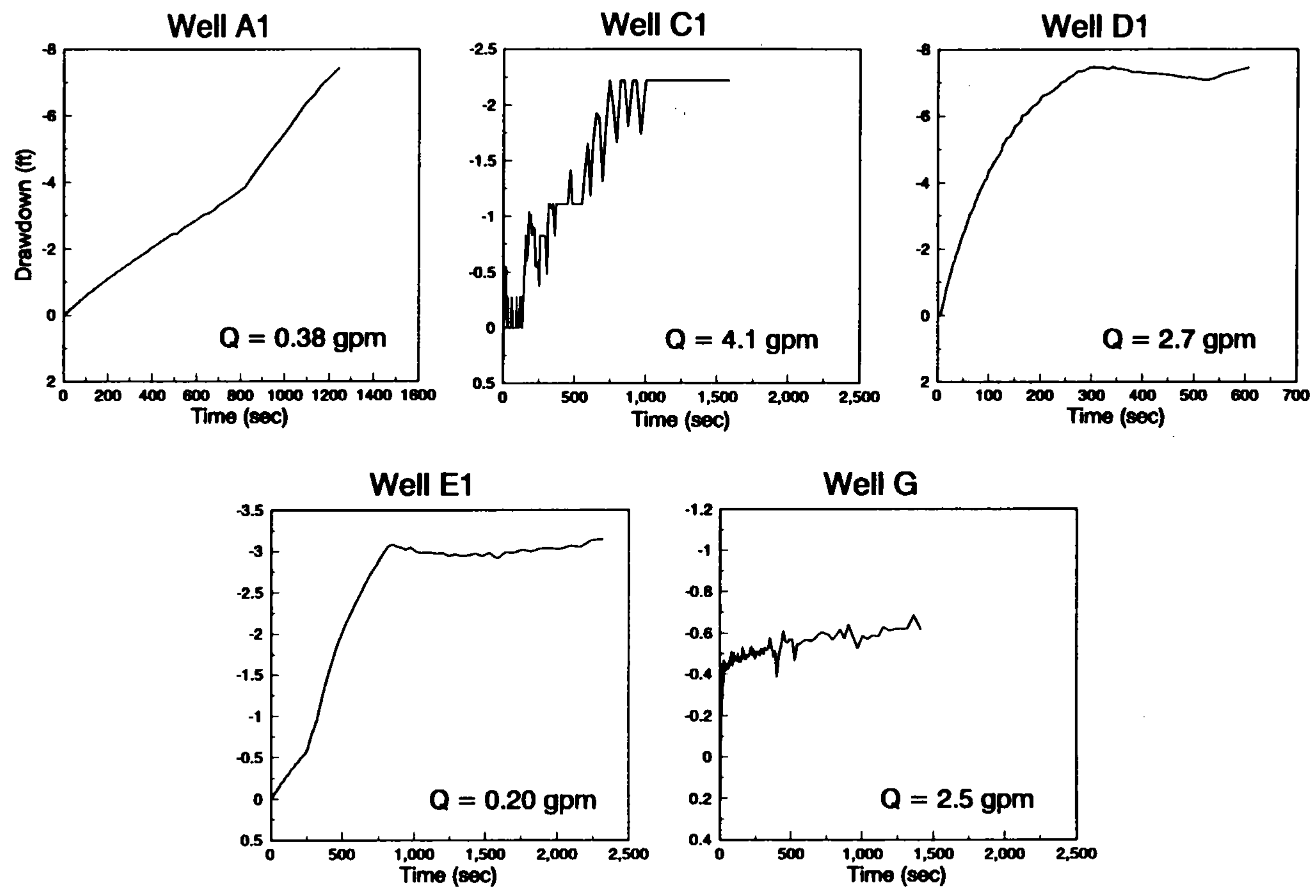

Figure 7-1. Semi-Log Drawdown Curves for Bedrock Well Tests

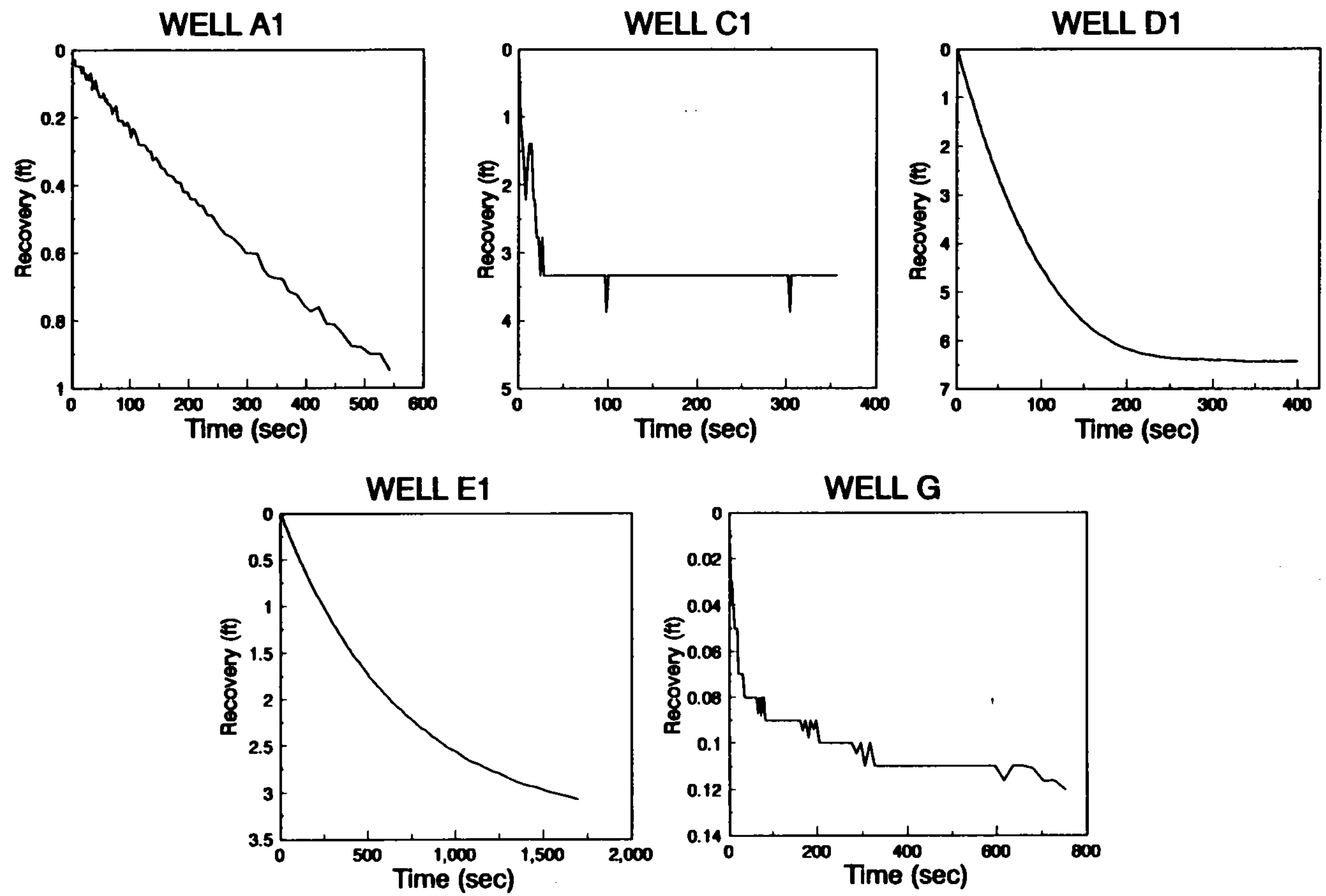

Figure 7-2. Recovery Curves for Bedrock Well Tests

beyond 1000 seconds. The differences among the transmissivity values at each well are partly explained by the errors associated with each test and differences among the tests. Because of the small amount of water involved, slug test results primarily reflect bedrock properties within a few feet of the borehole. The injection test results are most sensitive to the bedrock properties within the ring-of-influence (Butler,1988) at any given time. For this application, the CJSL transmissivity values from the injection tests are reflective of a high transmissivity zone hydraulically connected to the wellbore, rather than a bulk transmissivity for the entire wellbore. The results shown in Table 7-2 indicate that large spatial variability exists in the bedrock transmissivity with some regions having transmissivity values greater than 500 ft^2/day.

TABLE 7-2

Transmissivity Results

		Transmissivity (ft^2/day)		
Well	Flow (gal/min)	Injection Tests	Recovery Tests	Slug* Tests
A1	0.38	0.6	1.7	1.0
C1	4.10	NP	NP	14.5
D1	2.70	NP	105.0	16.6
E1	0.20	NP	1.5	0.8
G	2.50	489.4	550.0	76.0
*4-ft thickness				

7.3.3 Borehole Flowmeter Testing Results

Figures 7-3 and 7-4 present the flow profiles measured with an electromagnetic borehole flowmeter. The ambient flow profiles show natural vertical flow prior to pumping. The cumulative flow is measured during the injection test. The net differential flow represents the incremental differences between the ambient and cumulative flow profiles. The cumulative and net differential flow profiles have been normalized to the total injection rate.

Ambient vertical flow occurs in response to aquifer boundary conditions and spatial variability in the aquifer's hydraulic properties. Ambient flows exist because of vertical hydraulic gradients that cause water to enter the wellbore through fractures (and/or fracture zones) and exit at others. The ambient flows measured at all wells were very small (less than 0.02 gal/min). In general, the ambient flow profiles for all the logged wells indicate upward gradients from some small mid-core fractures to the epikarst zone. Downward flow was also observed for wells A1, D1 and E1 from small fracture increments about 10 ft below the epikarst zone to fractures near the bottoms of the wells. In well G, downward ambient flow was

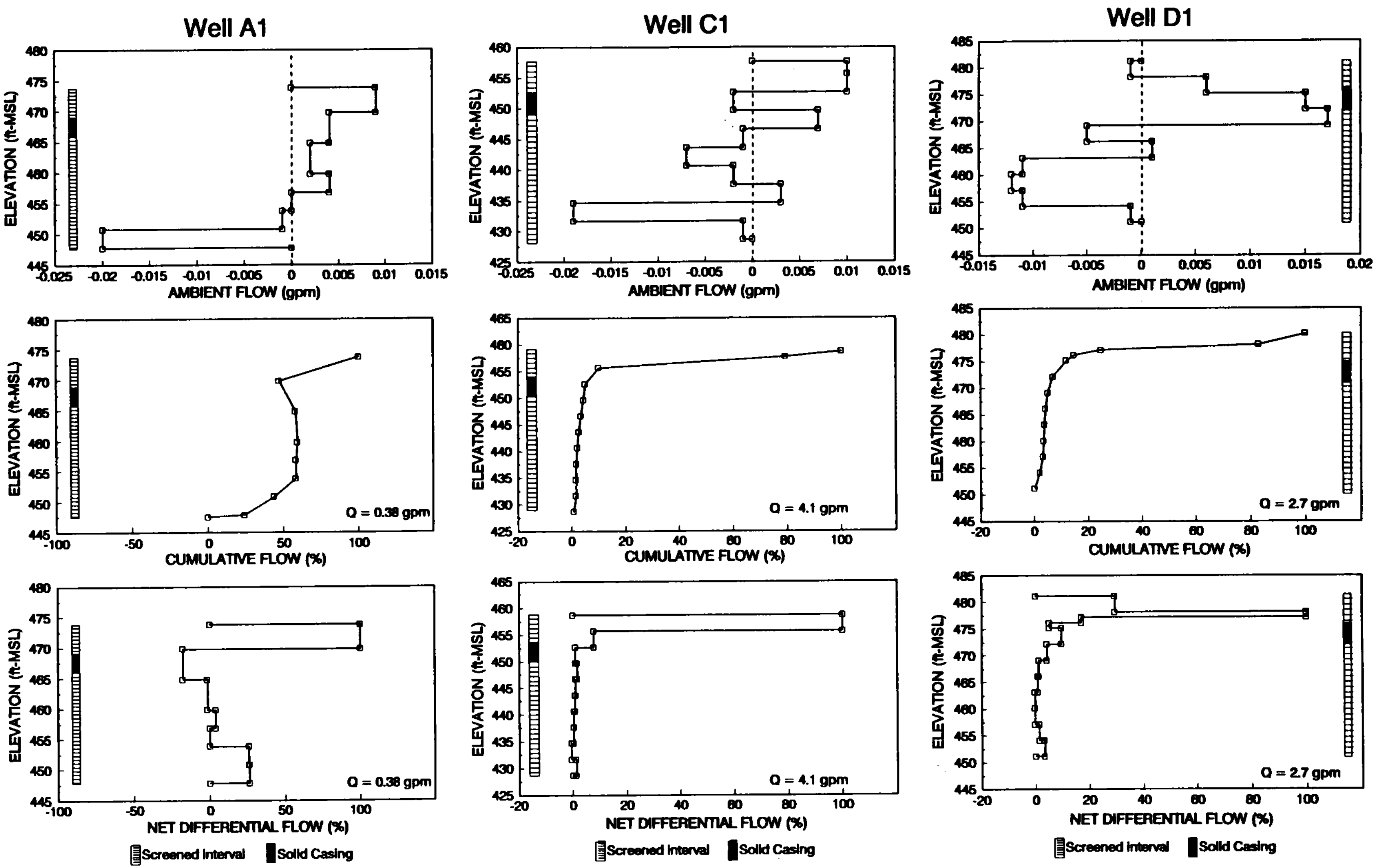

Figure 7-3. Flowmeter Profiles for Bedrock Wells A1, C1, and D1

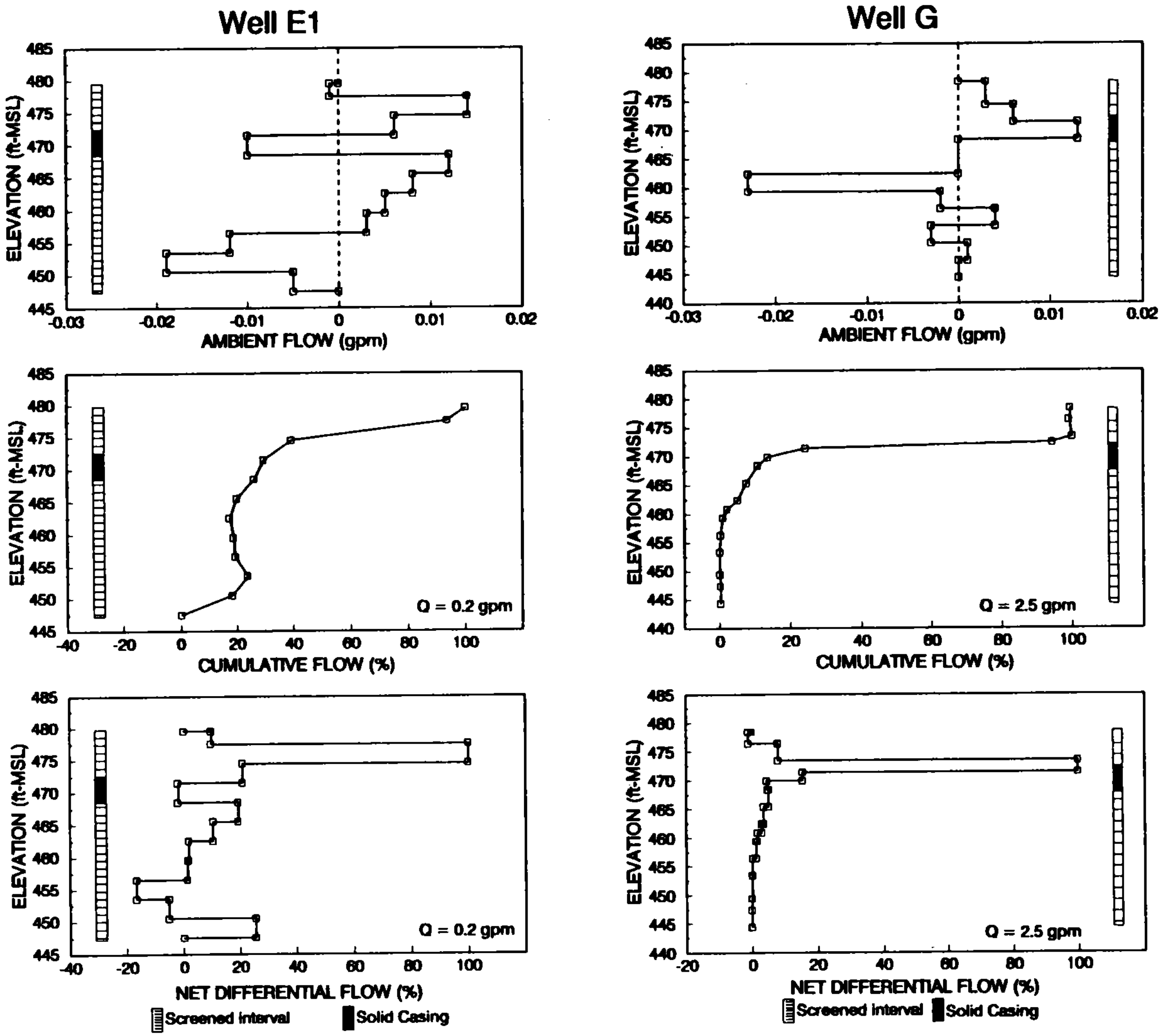

Figure 7-4. Flowmeter Profiles for Bedrock Wells E1 and G

measured near mid-core with virtually no ambient flow below this level. In well C1, smaller erratic upward and downward ambient flows were observed below the epikarst zone and these measurements are attributed to the absence of transmissive fractures with depth.

In viewing the net differential flow profiles in Figures 7-3 and 7-4, some correlation is observed between apparent fractures or fracture zones and ambient flow measurements. An obvious feature common to all the induced flowmeter profiles is the relatively high flow zone near the top of the screened intervals of all wells. It should be noted that the 2- to 3-ft section of solid casing located 5 ft from the top of the screened interval represents the location of auger refusal--which is our best estimate of the bottom of the epikarst zone. In wells C1, D1, and G, groundwater flow appears to occur almost exclusively within a 3- to 5-ft thick epikarst zone and only very small perturbations in the flowmeter profiles are observed at greater depths in the coreholes. The net differential profile for well D1 does indicate the possible existence of hydraulically active fractures at the bottom of the wellbore and this would assist in explaining the downward ambient gradients at this level. Likewise, well G shows the possible existence of fractures at mid-core (460-468 ft-MSL) which also correlates with downward ambient flows at this increment. At wells A1 and E1, transmissive fracture zones are observed at deeper intervals (about 447 to 453 ft-MSL). At these two locations, the deeper transmissive fractures (or fracture zones) appear to exhibit about one-half of the flow observed in the epikarst zone.

These measurements provide direct evidence related to aquifer zonation and thickness. The relatively high flow epikarst zone should be recognized as a regional phenomena considering that the regional wells are spaced hundreds to thousands of feet apart. However, other important considerations are that the "active" karst aquifer thickness varies spatially and temporally. It is reasonable to assume that active circulation is less close to resurgence points (e.g., Tuscumbia Spring) than further into the aquifer (e.g., beneath NFERC). An examination of groundwater levels assists in describing the behavior of the active karst aquifer and its relationship with the overburden.

7.4 Groundwater Levels

7.4.1 Potentiometric Maps

Weekly to biweekly water level measurements were made for selected overburden wells, all bedrock wells at NFERC, and the DOW wells at the OxyChem site. Figure 7-5 shows potentiometric maps produced from water level measurements at all NFERC wells and OxyChem (DOW) wells for four dates from November 1991 to July 1992. It is important to note that these potentiometric plots reflect averaged water level values for piezometer nests and well pairs and are, therefore, considered as only generalized plots.

Figure 7-5 generally indicates that groundwater movement is to the northwest from the majority of the site during November 1991. The potentiometric surface is much flatter on the east side of the site during the time higher groundwater levels are observed just SE of SWMU 108. The December 13, 1991, potentiometric map (Figure 7-5) reflects the potentiometric surface following 12.77 inches of rainfall that occurred during December 1 and

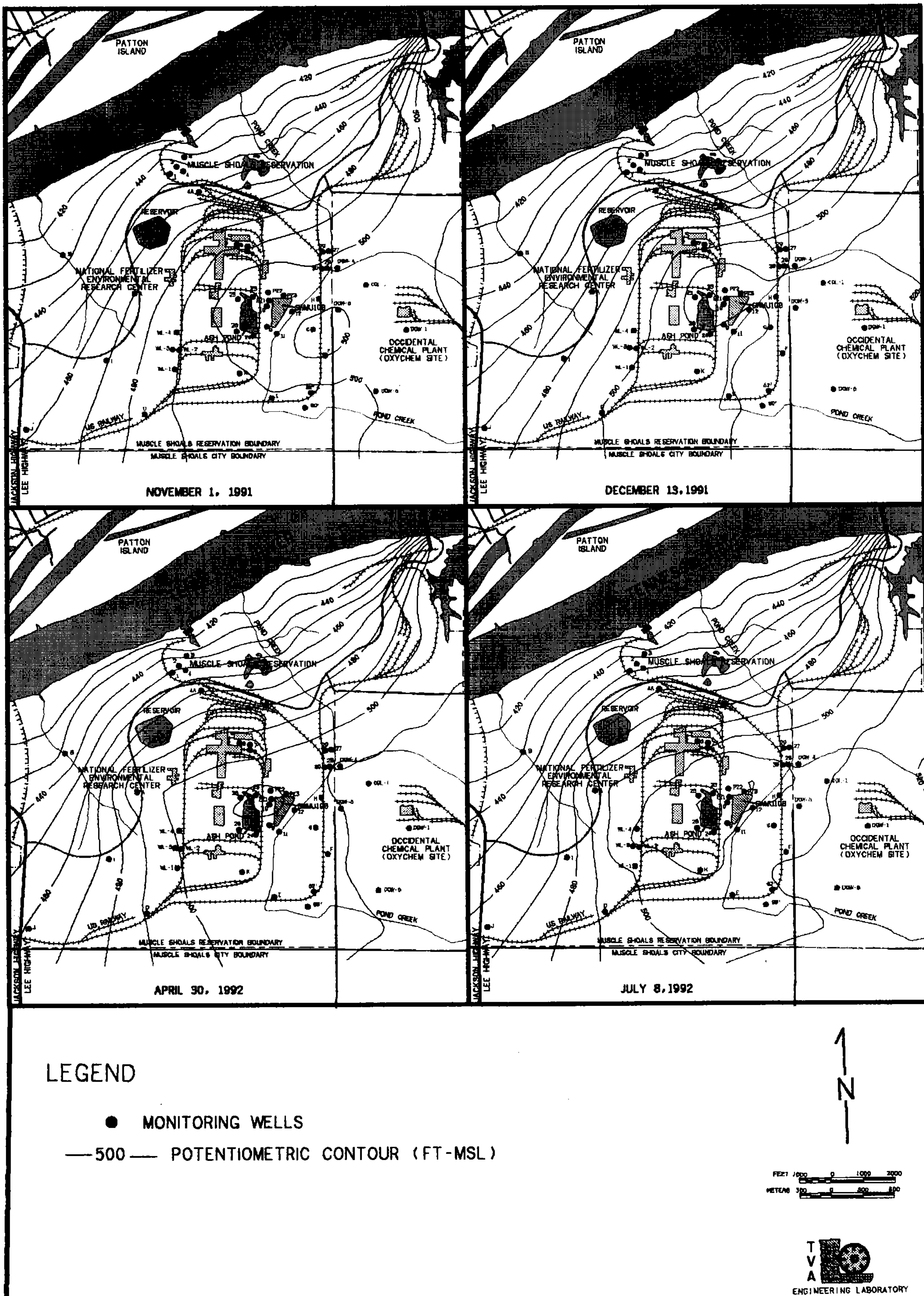

Figure 7-5 Potentiometric Maps from Water Level Measurements at all NFERC Wells

2, 1991. Groundwater levels were highest during this time relative to the period of measurement. This plot also indicates groundwater movement to the W-NW over the site and obvious mounding effects in the SWMU 108/Ash Pond area. The April 30 and July 8, 1992 plots display potentiometric contours during lower groundwater stages that retain shapes similar to the 1991 plots. However, the mounding effects are much more pronounced for these two times and are generally centered on the Ash Pond.

During the last several years, the Ash Pond's elevation has remained relatively constant near 520 ft-MSL (Young and Julian, 1991). Its impact on the direction of groundwater flow changes with time because of seasonal fluctuations in groundwater levels. During low groundwater table conditions that result from low rainfall and moderate to high evapotranspiration, the Ash Pond is a source of recharge for the overburden in its vicinity. During high groundwater table conditions, that result from moderate to high precipitation and low evapotranspiration, it appears that the effects of recharge from the Ash Pond are diminished.

For comparison purposes, potentiometric plots were produced for dates as shown in Figure 7-5 using only bedrock wells and are shown in Figure 7-6. Although these plots generally indicate similar trends in groundwater movement W-NW across the NFERC, and are consistent with Figure 7-5, an obvious difference is observed between the two sets of maps. The effects of groundwater recharge in the vicinity of the Ash Pond and SWMU 108 are less pronounced, as shown in the bedrock potentiometric plots.

7.4.2 Vertical Hydraulic Gradients

Young and Julian (1991) have shown that large vertical gradients exist at overburden and upper bedrock (epikarst zone) wells in the vicinity of SWMU 108, and that Pond Creek appears to be an important influence on the three-dimensional pressure field. Near SWMU 108, the vertical gradients are greatest and least at wells farthest from and nearest to Pond Creek, respectively. For instance, at well cluster PZ-12 near Pond Creek, the vertical gradient can approach 20 percent downward. Whereas, at well cluster PZ-2 farther from Pond Creek, the vertical gradient can approach 100 percent downward. Well cluster PZ-11 is closest to Pond Creek and exhibits small (< 10 percent) upward and downward vertical gradients.

At the banks of Pond Creek, a seepage face exists that maintains the potentiometric head in the overburden near the elevation of the water surface of the stream. Hence, Pond Creek is a discharge location to the groundwater in the upper overburden and a recharge source for groundwater to the lower residuum and bedrock.

Figure 7-7 shows water levels measured at regional well pairs for selected dates. Wells designated with a number "1" are bedrock wells and those with a number "2" are overburden wells. Table 7-3 provides the average vertical hydraulic gradients calculated from the data. Well pair E exhibits very small upward and downward gradients as shown in Table 7-3 because of the wells' proximity to Pond Creek. These vertical gradients agree favorably with those of SWMU 108 wells located near Pond Creek. Figure 7-7 shows that vertical gradients are consistent in magnitude with the exception of well pair J. As shown in

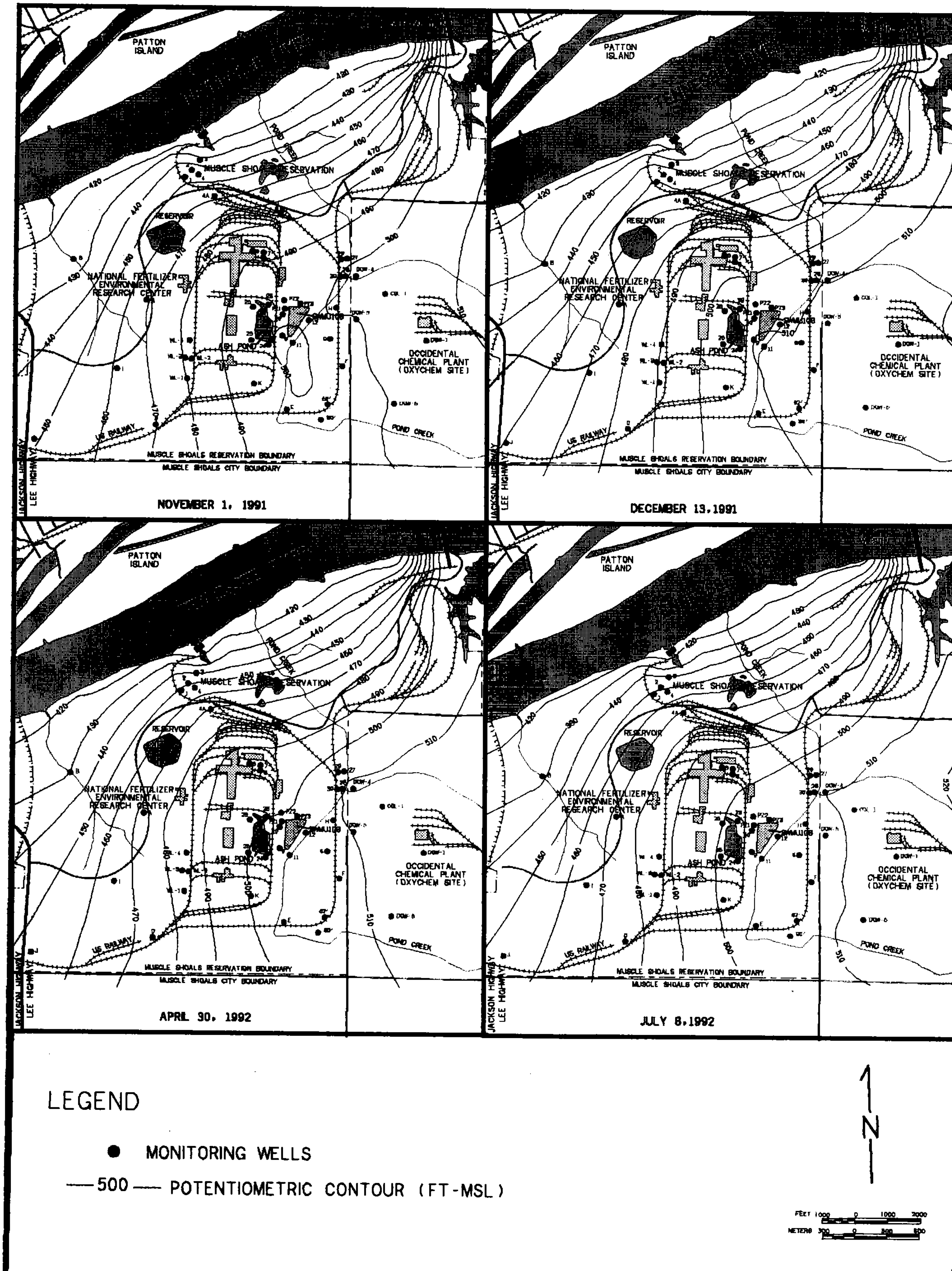

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Figure 7-6 Potentiometric Maps from Water Level Measurements at Bedrock Wells

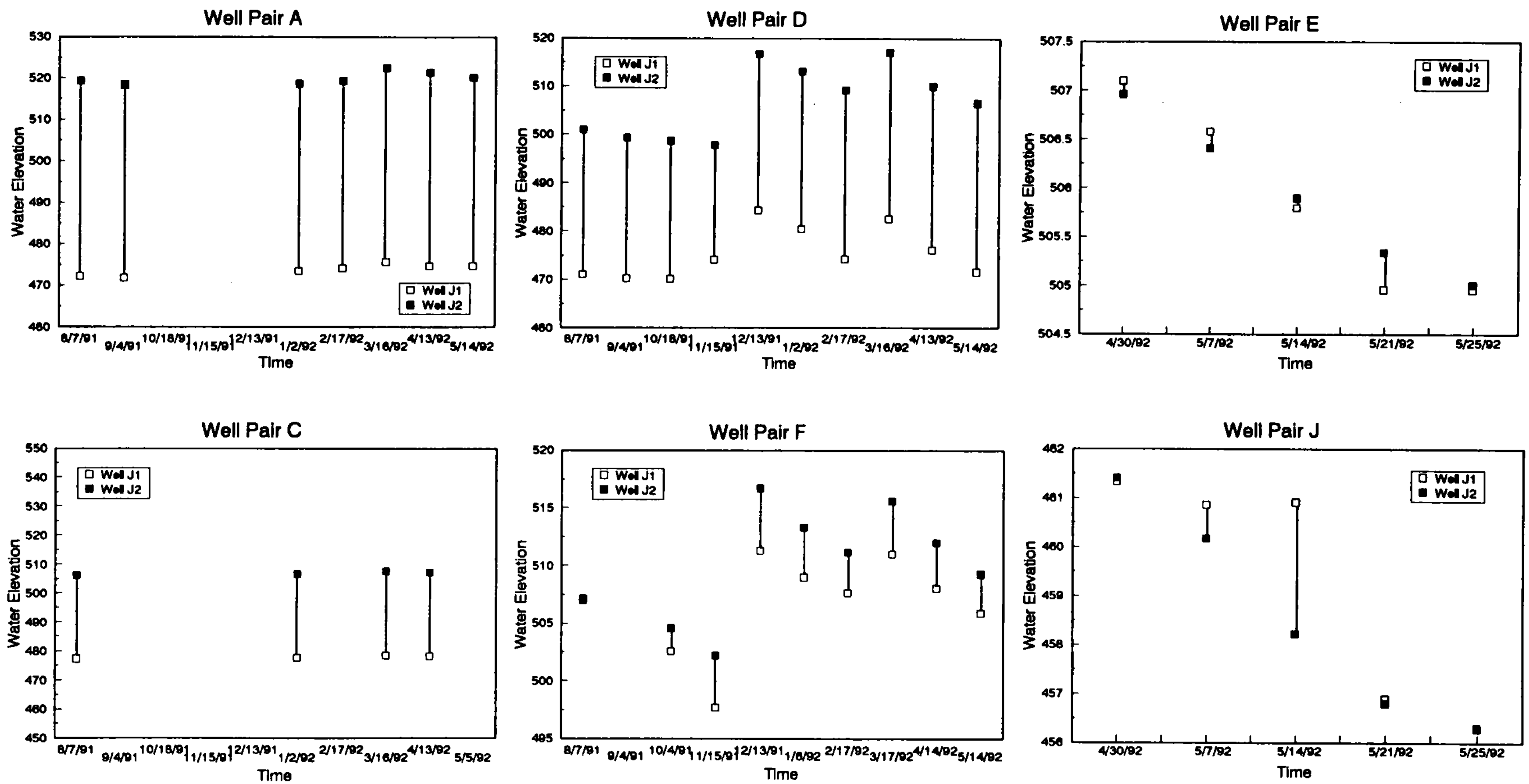


Figure 7-7. Hydrographs for Selected Wells

Table 7-3, both downward and upward vertical gradients have been observed at this location. The anomalous upward vertical gradients (as large as 18 percent) were observed at this location in mid-May 1992 following a 2- to 3-week period of rainfall. Well pair J is located about 2,500 ft northwest of a series of sinkholes and a sinking stream (old Pond Creek; Chapter 4.6) that receive a significant amount of surface runoff. Relatively rapid recharge to the bedrock aquifer through these features is probably the cause of the upward vertical hydraulic gradients encountered at well pair J.

TABLE 7-3

Average Vertical Hydraulic Gradients at Regional Well Pairs

	Vertical Gradient	
Well Pair	Direction	Magnitude (%)
A	Downward	63
C	Downward	35
D	Downward	95
E	Upward Downward	1 2
F	Downward	11
J	Upward Downward	18 1

The highest vertical gradients were observed at regional well pairs A and D as shown in Table 7-3. The water table resides at the epikarst zone for bedrock wells at these two locations. By comparison, groundwater levels for bedrock wells C1 and F1 are generally much higher (about 25 ft) in the overburden and the vertical gradients are smaller (Table 7-3). This assists in explaining the relationship between overburden and bedrock at the site.

Generally, the large vertical hydraulic gradients at the site may be attributed to poor vertical hydraulic interconnectivity between the overburden and bedrock. Poor hydraulic interconnectivity between stratified hydraulic units is caused by sediments with low effective vertical hydraulic conductivity. As shown in Appendix C, intermediate to deep overburden sediments at the site consist of clayey soils that possess vertical hydraulic conductivities of less than 10^{-7} cm/s.

7.4.3 Horizontal Hydraulic Gradients

The horizontal hydraulic gradients within the bedrock and epikarst zones at NFERC vary from about 0.1 to 2 percent. Water level measurements in all bedrock wells indicate that horizontal hydraulic gradients are generally consistent. As shown in Figure 7-6, smaller

horizontal gradients are observed across the southeast portion of the site. Increasingly larger horizontal hydraulic gradients might be expected across the site from southeast to northwest approaching the Tennessee River and is a result of greater bedrock relief, as shown in Figure 4-3.

8.0 DYE TRACE STUDY

8.1 Introduction

At the request of the Alabama Department of Environmental Management (ADEM), a semi-quantitative groundwater dye trace study was included in this regional groundwater investigation. The distinguishing characteristic of semi-quantitative tracing is instrumental analysis of elutants and detectors to confirm dye recovery. Point-to-point dye tracing was employed to identify groundwater trajectories and to assist in providing some structural interpretation of the upper Tuscumbia Limestone bedrock underlying the NFERC. Dye detection sites included on-site and off-site wells, springs, and surface streams. Since the clayey overburden is relatively thick (60-90 ft), and karst features (e.g., sinkholes and sinking streams) are absent across the NFERC reservation, introduction of dye via natural surface features was impossible. Therefore, wells extending into the epikarst zone and shallow bedrock aquifer were used for injection of the selected tracers. The results obtained from this study should, therefore, apply only to this groundwater flow regime.

The AGS and Ozark Underground Laboratory provided contracting services for the dye trace study. Bob Chandler of the AGS provided guidance and consulting for the study, and the Ozark Underground Laboratory was used for scanning spectrofluorometer analysis of passive dye detectors.

8.2 Previous Dye Traces

Dye tracing in the vicinity of NFERC has been conducted in the past by the Ozark Underground Laboratory, AGS, G&E Engineering, and Golder Associates. These reports were reviewed prior to planning and implementing the NFERC dye trace. Additionally, the investigators from these organizations were interviewed to obtain supplementary information that might be considered useful for the NFERC dye trace. A brief description of each previous dye trace is provided as follows.

8.2.1 Key Cave Aquifer System Dye Trace

This dye trace study (Aley, 1990) was conducted to delineate the recharge area for the Key Cave aquifer system located in a region known as "Bend of the River" in Lauderdale County. The study area is located on the opposite side of the Tennessee River and about six river miles downstream from NFERC. Although the Key Cave aquifer is hydraulically separated from the NFERC site, it does bear some similarities in terms of lithologic controls to groundwater movement. The Key Cave area is located in karst topography developed in the Tuscumbia Limestone. Based upon tracing results and maps obtained for caves in the study area, Aley (1990) reports that groundwater flow routes are linear and preferentially developed along bedrock joint systems. Approximately 57 percent of the mapped passages possess orientations between N21°-50°E, and an additional 28 percent have orientations between

N40°-49°W (Aley, 1990). These orientations are well correlated with those obtained from a vector analysis of lineaments across the NFERC (Chapter 5). Tracer travel times for the Key Cave aquifer system varied from about 100 ft/day to as much as 7,300 ft/day.

8.2.2 Dye Trace for Storm Water Drainage Wells - Muscle Shoals Area

The most extensive dye tracing work in the Muscle Shoals vicinity has been conducted by the AGS. Chandler et al. (1990) and Chandler and Moore (1991) present the results from semi-quantitative fluorescent dye tracing of 14 storm drainage wells in the Muscle Shoals area. This study was conducted by the AGS to determine if hydrologic connections existed between tested storm water drainage wells and important springs in the area (e.g., Tuscumbia Spring). The results of the AGS dye trace are shown in Figure 8-1 with blue arrows representing positive tracer detection. The regional-scale potentiometric contours shown on the figure were obtained from Chandler et al. (1990). The storm drainage wells used for injection of dye in this study are located about 6,000 to 8,000 ft south of the NFERC (Figure 8-1).

With the exception of TVA Spring just downstream of Wilson Dam, dye monitoring locations included springs and caves streams located west-southwest of the NFERC. No positive dye recovery was measured at TVA Spring. However, the tracer test provided positive dye recovery for Tuscumbia Spring west-southwest of the injection wells, and several smaller springs and monitoring stations north-northwest of the injection wells. The data indicate an integrated and cross-connected network of water-bearing solution openings in the upper Fort Payne-Tuscumbia aquifer. The directions of groundwater flow are northwestward and southwestward in most instances. In the deeper bedrock flow regime, the directions may be more variable (Chandler et al., 1990). The AGS dye trace indicated groundwater velocities within the Tuscumbia Limestone that might approach one to two miles per day.

As part of the AGS study, time-of-travel traces were conducted from selected storm drainage wells. Quantitative traces such as these are continuously monitored to measure dye concentrations over time for a known quantity of dye. Injection and detection of tracer dye was conducted along two (of three) presumed corridors, or cavity systems, that provide recharge to Tuscumbia Spring. The two cavity systems trend SE and NE from the spring. Analysis of the breakthrough curves for these traces indicates that distinct upper and lower levels of groundwater flow exist in the Tuscumbia Limestone for this area. Although both levels are obviously interconnected, the upper level corresponds to the epikarst zone and contributes a relatively greater amount of recharge to Tuscumbia Spring than the system deeper within the Tuscumbia Limestone. This data agrees well with the information obtained from borehole flowmeter measurements at NFERC monitoring wells. However, although distinct time differentials were observed on the break-through curves, flow could not be accurately quantified based upon measured dye concentrations (Chandler, 1993).

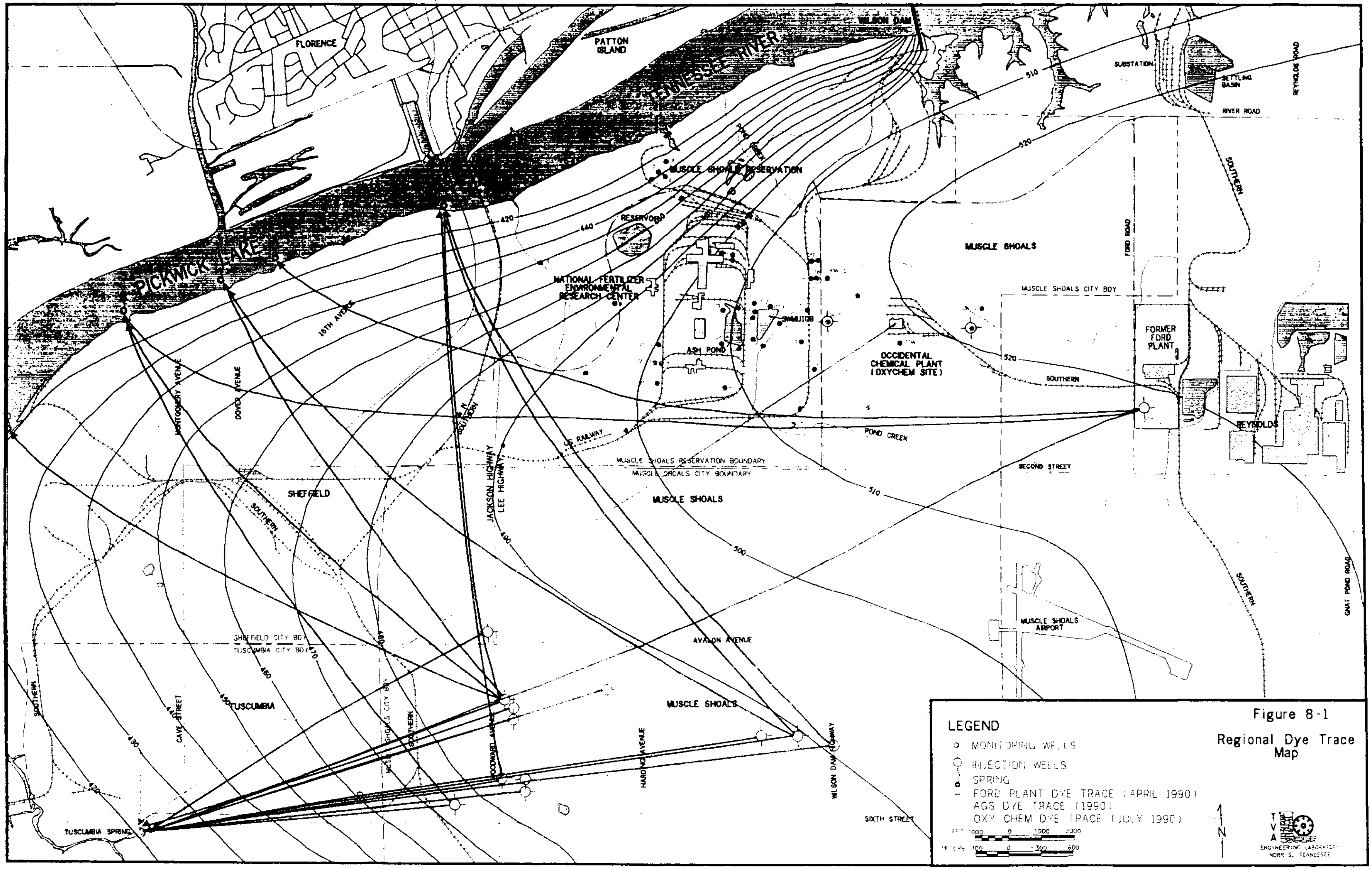


Figure 8-1
Regional Dye Trace Map

8.2.3 Ford Plant Dye Trace

Golder Associates Inc. (1990), conducted a dye trace for the former Ford plant (about 10,000 ft east of NFERC) as part of an aquifer characterization and remediation study. The dye trace was designed to determine if there is detectable rapid groundwater movement from the former Ford castings plant to springs in the area. The results of the Ford plant dye trace are shown in Figure 8-1 with green arrows representing positive tracer detection. The monitoring well used for injection of dye in this study is located on the former Ford plant site.

Dye monitoring locations included springs and cave streams west-southwest of the NFERC, and TVA Spring just downstream of Wilson Dam. No positive dye recovery was detected at the TVA Spring. However, the tracer test provided positive dye recovery at Tuscumbia Spring west-southwest of the injection wells, and two smaller springs and monitoring stations north-northwest of the injection wells. Straight-line velocities of approximately one-half mile per day have been estimated from this dye trace (Golder Associates, Inc., 1990).

8.2.4 OxyChem Dye Trace

A dye trace study was performed by G&E Engineering Inc. (1991) to investigate the groundwater flow direction and velocity in the upper portion of the Tuscumbia Limestone in the vicinity of the OxyChem Muscle Shoals facility. OxyChem is located immediately east of NFERC. The results of the OxyChem dye trace are shown in Figure 8-1 with a red arrow representing positive tracer detection from a generalized plant mid-point. Wells DOW-2 and DOW-5 were used as injection wells for this dye trace (Figure 8-1). Dye monitoring locations included Tuscumbia Spring and several smaller springs in its vicinity, TVA spring just downstream of Wilson Dam, and eight monitoring wells located on the NFERC reservation. The eight TVA wells used for dye detection monitoring are 5, 6, 7, 8, W9, W11, W12, and the 80-ft deep well in the old nursery (farm) area. The TVA wells are located approximately 1,600 to 3,000 ft downgradient from the nearest injection well (DOW-5).

No positive dye detection was reported by G&E Engineering (1991) for TVA Spring. Laboratory test results indicated that dye passed through Tuscumbia Spring and Little Tuscumbia Spring between 2 and 17 days after injection. This travel time and direction is on the same order of magnitude as the Ford plant dye trace which revealed dye at Little Tuscumbia Spring 3 to 17 days after injection. The straight-line travel times, therefore, range from about 0.25 to 2.75 miles per day from OxyChem to Tuscumbia Spring. Dye appears to have been weakly detected in TVA wells 5, W9, W11, W12, and the 80-ft deep well between 14 to 31 days after injection. This would produce straight-line travel times of about 100 to 200 ft/day in the direction of NFERC from OxyChem.

8.3 Dye Trace Methodology

In a nutshell, the NFERC dye trace consisted of the injection of three specific dyes (i.e., fluorescein, rhodamine WT, and Blankaphor BBH) into two shallow bedrock monitoring wells (F1 and G) at NFERC. Monitoring was then conducted for the injected tracers at local springs, streams, and selected monitoring wells using passive sampling devices. The injection of three different dyes at two individual locations offered an advantage in tracing evaluation since the dyes possess different characteristics and monitoring could be conducted simultaneously. The dye trace began February 18, 1992, following a scan for background fluorescence, and was terminated June 6, 1992. Detailed descriptions of the methods and materials used in the dye trace are described in the following paragraphs.

8.3.1 Tracer Dyes

Based upon a review of the literature for dye tracing in karst terranes and previous traces in the vicinity of NFERC, three fluorescent tracers were selected for use in this study. The tracers were sodium fluorescein, Rhodamine WT, and Blankaphor BBH. All three dyes are commonly used in groundwater tracing studies and create no adverse impacts on health or the environment (Smart, 1984). These tracers possess different properties; each behaves somewhat differently in the subsurface; and there are advantages and disadvantages for the use of each.

Fluorescein (CI Acid Yellow 73) has been widely used for groundwater tracing in karst terrane since the late 1800s (Aley and Fletcher, 1976) and is presently the most commonly used in karst areas of the United States. Fluorescein is a nontoxic reddish-brown powder that turns vivid green in water. It exhibits moderate sorption on clay, is photochemically unstable, loses fluorescence in water with pH less than 5.5, and adsorbs readily onto activated coconut charcoal (Mull et al., 1988). Although photochemically unstable, this was not perceived to be a problem for the NFERC dye trace since dye detectors were suspended in monitoring wells, installed below depths of nominal light penetration at springs, and were installed in sunlight protected areas of caves and surface streams. Likewise, previous sampling results at NFERC wells and local springs indicate that pH levels are acceptable for the use of fluorescein. The level of background fluorescence is important in analyses involving fluorescein since it is often used as a coloring agent in home products such as shampoos, bathroom cleaners, and antifreeze. Additionally, some amount of attenuation was anticipated for fluorescein since many of the solution conduits in the epikarst zone and upper Tuscumbia can be partially or completely infilled with clayey sediments. Fluorescein is less subject to adsorption on sediments and rock materials than is Rhodamine WT.

Rhodamine WT (CI Acid Red 388) is a nontoxic dye that possesses sorption characteristics similar to those of fluorescein and is generally used for quantitative traces requiring fluorometer measurement of dye concentration. Unlike fluorescein, Rhodamine WT is photochemically stable and can be used in low pH waters. This dye also readily adsorbs to detectors such as activated coconut charcoal. With regard to the attributes of Rhodamine WT, there were no obvious subsurface features at NFERC that would preclude its use in this study.

Again, however, some amount of adsorption to clayey sediments was expected for Rhodamine WT in the upper Tuscumbia.

Blankaphor BBH is a nontoxic optical brightener commonly used in qualitative karst dye tracing since detectors can be visually examined under ultraviolet light. Blankaphor BBH has a low affinity for adsorption onto clays (to a much lesser extent than fluorescein or rhodamine WT) and is readily adsorbed on passive detectors such as undyed surgical cotton. This optical brightener is, however, widely used in laundry detergents and soaps for enhancing fabric colors and is thus a common constituent of domestic wastewater. Therefore, background measurements were critical to its success as a tracer.

8.3.2 Tracer Injection

Success of a dye trace study depends primarily upon proper selection of the injection location. As mentioned above, the thick clayey overburden and an absence of karst features (e.g., sinkholes and sinking streams) at the NFERC reservation prevented introduction of dye via natural surface features. Therefore, wells extending into the epikarst zone and shallow bedrock aquifer were used for injection of the selected tracers. Chapter 6 describes the installation of wells used for this regional groundwater investigation. Dye trace monitoring was a major consideration in well location and design. Monitoring well locations were field selected based upon preliminary lineament mapping of the NFERC (Chapter 5). The well locations were restricted to accessible areas and were also distributed across the site to provide adequate areal coverage for groundwater quality monitoring.

Two injection wells were required for the three tracer dyes in this tracer study. In the selection of injection wells, two criteria were of primary importance. These included wells that are hydraulically upgradient at the site and effectively integrated into the bedrock aquifer system. Manual and continuous water level measurements for selected on-site and off-site wells were used to construct local potentiometric maps, and regional maps were obtained from Chandler (1986). Based upon these potentiometric maps, the upgradient wells deemed suitable for injection were restricted to the east side of NFERC. Borehole flowmeter tests, slug tests, and single-well pumping tests were used to evaluate wells with respect to their integration into the karst aquifer system (Chapter 7). The data indicated that wells F1 and G (Figure 6-1) were most appropriate for injection of tracer dyes. As shown in Chapter 7 high K zones for these wells correspond to the epikarst zone which is probably the upper level of bedrock groundwater flow described by Chandler (1991, 1993).

Background sampling for the three tracer dyes was conducted and the results were evaluated prior to tracer injection. Dye injection was performed on February 17 and 18, 1992. Bob Chandler of the AGS assisted in the dye injection.

Fluorescein and rhodamine WT were used for injection at well F1 (Figure 6-1) on February 17, 1992. Groundwater levels were continuously monitored in well F1 to verify that natural gradients were not excessively influenced by any injection activities. Monitoring was accomplished using a pressure transducer connected to a data logger and laptop computer for

real-time displays of groundwater levels. The well was pre-slugged with approximately 100 gallons of potable water using a fire truck supplied by NFERC public safety. The pre-slug injection rate was approximately 2.5 gal/min and water levels increased by 0.3 ft in the well. Approximately five pounds of dry fluorescein was then mixed with potable water in 5-gallon containers and poured into the well. A small quantity (about 50 gallons) of water was injected into the well to chase the fluorescein dye into the aquifer and approximately five pounds of liquid rhodamine WT was then poured into the well. The water remaining in the fire truck (about 500 gallons) was then injected into well F1 at a rate of approximately 15 gal/min.

The following day (February 18, 1992), Blankaphor BBH was injected into well G (Figure 6-1). Approximately 5 pounds (dry weight) of Blankaphor BBH was used for tracing and the techniques for injection were similar to those described for well F1. However, well G allowed water injection at a higher rate (5.7 gal/min) without increasing water levels by more than 0.3 ft.

8.3.3 Tracer Detection Sites

Monitoring for tracer dyes was conducted at on-site and off-site monitoring wells, springs, and surface streams from January 7 to June 5, 1992. Initially, 15 wells were used as sampling stations, wells I1, J1 and PZ1C were added to the sampling list for fluorescein and rhodamine WT near the end of study and no brightener scans were conducted for these stations. The locations of the local detector stations are shown on Figure 8-2. Spring and stream detector locations outside of the NFERC Reservation boundaries are shown on Figure 8-1. Descriptions of spring and stream sampling stations are provided in Table 8-1.

8.3.4 Sampling for the Presence of Tracers

Sampling for the presence of Blankaphor BBH began on January 17, 1992, and ended April 10, 1992. Sampling for the presence of fluorescein and rhodamine WT dyes began on January 17, 1992 and ended June 5, 1992. Sampler collection was generally at weekly intervals. However, after March 27, 1992, several samplers were reduced to a biweekly sampling frequency and analysis was run on only selected samplers (Appendix B).

Passive detection for fluorescein and rhodamine WT dyes relied on the use of fiberglass screen samplers filled with activated coconut charcoal. Each of the samplers was filled with 0.15 ounces of Fisher Scientific 6- to 14-mesh activated carbon. Passive detection for Blankaphor BBH was accomplished using unbrightened cotton pads placed in aluminum screen samplers. Passive samplers continuously adsorb some portion of the tracer dyes which pass through them; they are thus cumulative samplers. The concentration of dye in a sampler is, therefore, greater than the concentration in the waters being monitored.

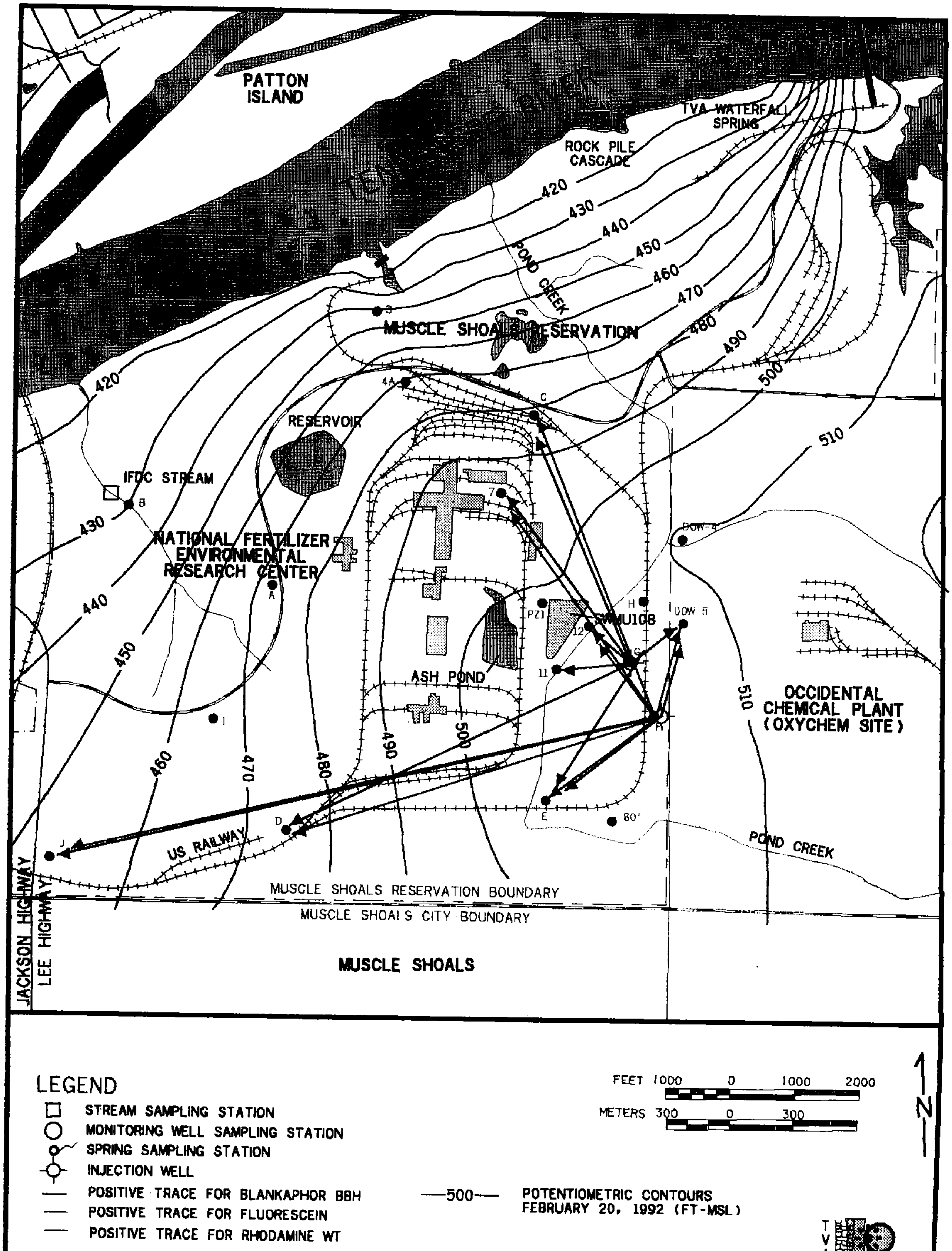


Figure 8-2 NFERC Dye Trace Map

TABLE 8-1

NFERC Dye Tracer Detection Locations

Station	Description
Tuscumbia Spring, Middle	Middle resurgence of Tuscumbia Spring
Tuscumbia Spring, South	South resurgence of Tuscumbia Spring
Tuscumbia Spring, North	North resurgence of Tuscumbia Spring
Tuscumbia Spring, Stream	Downstream of Tuscumbia Spring (Back-up) before confluence with Spring Creek
Jr. High School Cascade	Small cave spring along Tennessee River; 6,000 ft downstream of O'Neil Bridge
Annapolis Avenue Cascade	Small cave spring along Tennessee River; 7,000 ft downstream of O'Neil Bridge
TVA Waterfall Spring	Large spring along Tennessee River; 500 ft downstream of Wilson Dam
TVA Cave Spring #2	Cave spring along Tennessee River; 700 ft downstream of Wilson Dam
Rockpile Cascade	A small stream near the mouth of a tributary valley; 3,700 ft downstream of Wilson Dam
IFDC Stream	A small stream about 1,500 ft upstream of O'Neil Bridge (detection monitoring was near well B)

Samplers were suspended in wells, and placed in the flowing waters of springs and surface streams. At springs and surface streams, care was taken to assure that the samplers were protected from sunlight. The samplers were installed at these locations using concrete weights (gumdrops) fitted with double-loop hanger devices for retaining the samplers. At monitoring wells, the samplers were suspended in the well with nylon parachute cord at depths corresponding to the highest K zone obtained from borehole flowmeter analysis (Chapter 7). The monitoring well samplers were weighted with stainless steel bolts.

When samplers were collected, new samplers would be placed. Collected samplers were placed in labeled sterile plastic bags (Whirl-Paks) upon retrieval and immediately placed in igloo coolers for overnight shipment. Cotton pads were mailed to the Engineering Lab for visual analysis and charcoal samplers were couriered to the Ozark Underground Laboratory for instrumental analysis.

The cotton pad samplers were scanned at the TVA Engineering Laboratory using a long-wave 366 nm ultraviolet light. Wet samplers were initially scanned upon arrival. The

samplers were then allowed to air dry at room temperature and analysis was repeated. An even blue-white fluorescence of one or both sides of the scanned cotton pad was considered a positive test for optical brightener. Brightener has a tendency of accumulating on the side of the cotton pad toward the flow of water. For verification purposes, selected cotton pads were subjected to analysis for optical brightener on a Shimadzu RF-5000U spectrofluorophotometer.

Analyses of charcoal samplers for fluorescein and rhodamine WT were conducted by the Ozark Underground Laboratory. Charcoal samplers arriving at the Lab were washed using strong jets of water to remove sediment and organic matter. They were then eluted for one hour in 15 ml of a 5 percent aqua ammonia and 95 percent isopropyl alcohol solution. A sample of the resulting elutant was then subjected to analysis in a scanning spectrofluorophotometer. A plot of the synchronous scan for each sample is produced by the instrument; the plot shows emission fluorescence only. Fluorescence peaks were then computer selected to the nearest 0.1 nm. A more detailed description of the procedures used for analysis of rhodamine WT and fluorescein dyes in water and charcoal samplers is provided in Appendix B. Appendix B provides the detailed criteria for determination of positive dye recoveries in charcoal sampler elutants. These criteria are, in general:

- There must be at least one fluorescence peak on the dye recovery curve in the range of fluorescence for the dye being analyzed;

- The dye concentration associated with the fluorescence peak must be at least three times greater than the detection limit. For the RF-540 instrument, the detection limit for fluorescein and rhodamine WT are 0.015 and 0.235 μg/L, respectively. These values equate to dye concentrations of 0.045 and 0.705 μg/L, respectively, for positive detection fluorescein and rhodamine WT. For the RF-5000U instrument the detection limit for fluorescein and rhodamine WT are 0.01 and 0.15 μg/L, respectively. These values equate to dye concentrations of 0.03 and 0.45 μg/L, respectively, for positive detection of fluorescein and rhodamine WT.

- The dye concentration must be at least 10 times greater than any other concentration reflective of background at any given sampling station;

- The shape of the fluorescence peak must be typical of the tracer dye. In addition, there must be no other factors which suggest that the fluorescence peak may not be dye from the groundwater tracing work under investigation.

There is often some fluorescence background in the range of fluorescein dye present at some of the stations used in groundwater tracing studies. In comparison, there is generally little or no detectable fluorescence background in the general range of rhodamine WT dye. Several dye trace studies have recently been conducted in the Muscle Shoals, Sheffield, and Florence area. Hence, this enhances the probability that there is relic tracer dye within the karst aquifer system. Results from the AGS dye trace (Chandler et al., 1990) indicated that Pond Creek and possibly TVA Spring presented background readings too high to be used as sampling

stations due to industrial pollution. Therefore all sampling stations used during the course of this study were monitored for background fluorescence prior to dye injection.

8.4 Dye Trace Results

8.4.1 Background Sampling

Background monitoring was conducted for two weekly sampling events from January 17 to January 31, 1992. Pond Creek was determined to present excessively high background measurements and was not used as a detection station. High background levels are attributed to upstream discharge from a wastewater treatment plant and local industry. TVA Waterfall Spring and Cave Spring #2 (Figure 8-2) did not show background for fluorescein and rhodamine WT and were used as detector stations for these two dyes. However, positive detection of optical brightener was observed for these two springs during background sampling. Likewise, scans for optical brighteners at all Tuscumbia Spring and the Jr. High School Cascade indicated background fluorescence for optical brighteners. An anomalous yellow-orange fluorescence was observed in background samples of wells 3 and 7 (Figure 8-2); however, this coloration is not representative of the blue-white fluorescence normally associated with Blankaphor BBH.

Fluorescein background was observed at Tuscumbia Spring, Jr. High School Cascade, wells A1, H, 3, DOW-4, and DOW-5, and possibly the IFDC stream. No true background check was possible for wells I1 and J1 since they were installed after dye injection. Rhodamine WT background was observed at no sampling stations except for Rockpile Cascade. Subsequent sampling at this location indicates the presence of Rhodamine WT for all sampling events except the last.

8.4.2 Optical Brightener Results

Table 8-2 provides the results for ultraviolet light scans of cotton pad samplers where positive indications of brightener were observed. As indicated in the table, optical brightener first began to be detected at well DOW-5 and possibly (very subtle) at well H from the February 28, 1992 sampler retrieval (10 days after injection). A hint of brightener was also visible on the well E1 sampler from this same retrieval date. The March 6, 1992 sampling retrieval indicated that brightener was beginning to show at well D1 (17 days following injection). Brightener was also present at the IFDC stream station. This stream receives wastewater discharge from the IFDC facility adjacent to NFERC. This brightener detection is, therefore, attributed to the wastewater discharge. The March 13, 1992 sampling date showed the strongest visibility of brightener at well D1 and a possibility of brightener beginning to show at well 7. Brightener was vividly apparent at the IFDC stream sampling station at this sampling date.

The March 20, 1992 sampling date (31 days after injection) produced the first evidence of brightener at wells PZ11D, PZ12D, A1, C1 and B2 although the fluorescence of the

TABLE 8-2

Results for Blankaphor BBH
Positive Indications of Brightener from Injection at Well G

Retrieval Date	Detector Location	Results*	Remarks
2/18/92			Injection of Brightener
2/21/92			No Brightener Detected
2/28/92	Well H Well DOW-5 Well E1	WP WP WP	Very Weak-False Positive Very Weak Very Weak
3/6/92	Well H Well DOW-5 Well E1 Well D1 IFDC Stream	WP WP WP WP MP	Very Weak-False Positive Still Very Weak More Brightener Visible Very Weak Wastewater Influence
3/13/92	Well DOW-5 Well E1 Well D1 Well 7 IFDC Stream	WP WP MP WP SP	Very Weak No change Strongest Fluorescence Very Weak Wastewater Influence
3/20/92	Well E1 Well D1 Well 7 Well PZ12D Well PZ11D Well B2 Well A1 Well C1	MP MP WP WP WP WP WP WP	Stronger Fluorescence No Change No Change Very Weak Very Weak Very Weak-IFDC Influence Very Weak-IFDC Influence Very Weak
3/27/92	Well E1 Well D1 Well 7 Well PZ12D Well PZ11D Well B2 Well A1 Well C1	SP MP MP WP WP WP WP WP	Strongest Fluorescence Fluorescence Fading Stronger Fluorescence Very Weak Very Weak Very Weak Very Weak-IFDC Influence Very Weak-IFDC Influence
4/3/92	Well E1 Well D1 Well 7	MP MP MP	Brightener Fading No Change No Change
4/10/92	Well E1 Well D1 Well 7	MP WP MP	No Change Brightener Barely Visible Strongest Fluorescence

*Result Categories:

WP = Weakly Positive
MP = Moderately Positive
SP = Strongly Positive

brightener was low. Fluorescence of samplers from wells B2 and A1 indicated fluorescence that was just detectable. Based upon the presence of brightener in the IFDC stream (March 6 and March 13, 1992) and the fact that wells B2 and A1 are downgradient from the IFDC, this facility and its wastewater system is presumed to be a source of brightener for the two wells. The March 27, 1992 sampling date (38 days after injection) showed the greatest fluorescence of brightener at well E1 with fluorescence beginning to diminish at well D1. Approximately 38 days after injection, scanning produced no evidence of brightener for any wells except well E1, D1, and 7.

No optical brightener was apparent for springs or streams (except for the IFDC stream) that were sampled during this study other than that due to background.

Since ultraviolet scanning of cotton pad samplers is a subjective analysis, eight of the most uncertain samplers were subjected to laboratory analysis for optical brighteners using a scanning spectrofluorophotometer. If optical brighteners are present on the samplers, they produce a distinct excitation fluorescence peak at wavelengths between approximately 412 and 419 nm. Two separate scans were made for each cotton sampler (one on either side). Table 8-3 summarizes data from the analysis. The analysis is qualitative since the brighteners do not adsorb uniformly across the sampler. Therefore, relative differences in concentration are reflected by fluorescence units in Table 8-3.

As shown in Table 8-3, results were weakly or moderately positive for all wells except well H. This data generally confirms ultraviolet scanning results for all wells except well H. The instrumental analysis is considered much more reliable than those of ultraviolet scanning. Therefore, brightener detected at well H is considered to be a false positive.

Table 8-4 presents estimated time ranges for arrival of brightener from the well G injection site. These results should be viewed only on a qualitative basis. This data interpretation does not account for mass-balance, dispersion, temporal changes, or subjectivity of analysis since we are considering only snapshots in time. Table 8-4 provides apparent groundwater velocities that range from 30 to 750 ft/day for straight-line distances between the injection and monitoring wells.

8.4.3 Fluorescein and Rhodamine WT Results

Appendix B presents complete analysis results for charcoal samplers. Tables are also provided in Appendix B are provided indicating sampling results on a station-by-station basis for dye recovery curves. Some of the fluorescent peaks observed on the breakthrough curves are not the results of dyes injected during this study, but are instead dyes introduced in conjunction with tracing in the area from other studies, or are from background fluorescence. All concentrations are calculated as though the fluorescence peaks were actually fluorescein or rhodamine WT. Photocopies of all analysis graphs are organized in the same manner and in the same order in Appendix B.

TABLE 8-3

Optical Brightener Sampling Results. Each sampler was in place for approximately one week; the dates of sampler recoveries are indicated.

Lab Number and Station Name	Scan 1 Peak nm	Scan 2 Peak nm	Scan 1 Conc.	Scan 2 Conc.	Mean Conc.	Result*
7024 Well H Collected 3/6/92	ND	ND	ND	ND	ND	ND
7025 DOW 5 Collected 3/6/92	414.0	414.0	15	16	15.5	WP
7026 PZ 11D Collected 3/27/92	ND	414.0	ND	17	8.5	WP
7027 PZ 12D Collected 3/27/92	414.0	ND	17	ND	8.5	WP
7028 Well A1 Collected 3/27/92	413.2	412.0	20	20	20.0	WP
7029 Well B2 Collected 3/27/92	414.0	414.0	14	48	31.0	MP
7030 Well C1 Collected 3/27/92	417.6	ND	18	ND	9.0	WP
7031 Well 7 Collected 4/10/92	413.6	ND	365	ND	182.5	MP

*Result Categories:
ND = None Detected above background noise
WP = Weakly Positive; no scan conc. >29 units
MP = Moderately Positive; maximum scan conc. 30 to 499 units
SP = Strongly Positive; maximum scan conc. 500 units or more

TABLE 8-4

Estimated Time Ranges for Arrival of Optical Brightener

Monitoring Well	Distance From Well G (ft)	Time of Arrival (days)	Apparent Velocity (ft/day)
DOW-5	1023	3 to 10	100 to 340
E1	2257	3 to 10	220 to 750
D1	5648	10 to 17	330 to 570
7	3465	17 to 24	140 to 200
PZ12D	904	24 to 31	30 to 40
PZ11D	996	24 to 31	30 to 40
C1	4230	24 to 31	140 to 180

Table 8-5 provides the results from instrumental scans of charcoal samplers where positive indications of fluorescein of rhodamine WT were observed. Criteria used to distinguish between positive and negative results are described in Chapter 8.3.4 and Appendix B.

As shown in Table 8-5 and Appendix B, no fluorescein or rhodamine WT was detected in any springs or surface streams beyond background levels. The sampling locations that indicated positive results for fluorescein agreed very well with those from the dye traces. Fluorescein was detected in the same wells as brightener except for well C1 (remember that well J1 was later added as a sampling location for fluorescein and rhodamine WT). Rhodamine WT was measured from sampling at wells E1, J1, and DOW-5 only. There was an obvious lag between the detection of fluorescein and rhodamine WT for these two wells.

Table 8-6 presents estimated time ranges for arrival of dyes from the well F1 injection site. Again, these results should be viewed only in a qualitative sense in that the data interpretation does not account for mass-balance, dispersion, temporal changes, or subjectivity of analysis. Table 8-6 provides apparent groundwater velocities that range from 20 to 1,100 ft/day for straight-line distances between the injection and monitoring wells.

TABLE 8-5

Results for Fluorescein and Rhodamine WT
Positive Indications of Dyes From Injection at Well F1

Retrieval Date	Detector Location	Fluorescein Results		Rhodamine WT Results		Results
		Peak (nm)	Conc. (μg/L)	Peak (nm)	Conc. (μg/L)	
2/17/92						Dye Injection
2/21/92	Well 7	515.3	0.108	ND*		
2/28/92	Well E1	520.0	0.065	ND		
3/6/92	Well E1	516.8	SH	ND		
3/20/92	Well G	518.1	0.190	ND		
3/27/92	Well G	517.3	0.099	ND		
4/3/92	Well E1 Well G	518.5 515.3	SH 0.140	ND ND		
4/10/92	Well E1 Well G	518.3 516.2	0.247 0.096	ND ND		
4/17/92	Well E1 Well G Well PZ12D	517.3 520.1 515.9 518.7	0.580 SH 0.156 3,260	ND ND ND ND		
4/24/92	Well E1	517.8	0.410	ND		
5/1/92	Well E1 Well G	512.8 510.4	0.460 0.080	ND ND		
5/8/92	Well E1 Well G Well J1	512.4 510.4 509.6	0.408 0.058 0.018	ND ND ND		
5/15/92	Well 7 Well E1 Well G Well DOW-5 Well J1	510.0 512.8 510.0 515.2 512.8	0.023 0.479 0.064 12,700 0.146	ND ND ND 564.0 ND	 15.9 	
5/22/92	Well E1 Well G Well J1	513.2 512.0 512.8	1.26 0.630 0.588	566.8 ND 565.2	SH 0.279	
5/29/92	Well E1 Well G Well C1 Well D1 Well J1	512.4 514.0 513.6 510.8 512.8	0.379 0.190 0.029 0.082 0.874	ND ND ND ND 564.4	 0.239	
6/5/92	Well J1	514.0	0.593	563.6	0.119	Only Wells I1 and J1 Sampled for This Date

*ND = Not Detected

TABLE 8-6

Estimated Time Ranges for Arrival of Fluorescein and Rhodamine WT From Injection at Well F1

Monitoring Well	Distance From Well F1 (ft)	Time of Arrival (days)	Apparent Velocity (ft/day)
7	4489	0 to 4	1100
E1	1796	4 to 11	160 to 450
G	1050	25 to 31	30 to 40
PZ12D	1902	53 to 60	30 to 40
DOW-5	1678	53 to 60	20 to 40
J1	9205	74 to 81	110 to 130
C1	5279	95 to 102	50 to 60
D1	5640	95 to 102	50 to 60

9.0 GROUNDWATER TRANSPORT

9.1 Overview

Temporal and/or spatial variations in areal recharge, hydraulic gradients, soil hydraulic properties, and bedrock fractured/weathered zones are important factors affecting groundwater flow beneath the NFERC reservation. At NFERC, the use of bulk hydraulic parameters and averaged hydraulic gradients have limited applicability, especially with respect to estimating groundwater transport. Because the usefulness of groundwater transport predictions is related to the validity of the assumptions and simplifications required to make those predictions, they should be based on a careful examination of site characterization data, including: hydraulic properties, hydraulic gradients, and a conceptual aquifer model that includes boundary conditions.

9.2 Hydraulic Properties

Borehole flowmeter, pumping, and slug tests in the Tuscumbia Limestone (this report and Young and Julian, 1991) include order-of-magnitude differences in the bulk transmissivity among the boreholes and among the different vertical intervals within a borehole. Based on these tests and visual observation of cores, groundwater flow in the Tuscumbia Limestone occurs exclusively in fractured and weathered zones. The flowmeter results (Chapter 7) consistently show a relatively high permeable zone near the contact of the overburden and bedrock. These test results and those from dye tracing studies (Chapter 8) and lineament surveys (Chapter 5) indicate an extensive interconnected network of transmissive fractures and solution features in the epikarst zone and upper bedrock. The fracture network exhibits a rectilinear pattern oriented northwest-northeast as described in the lineament study. This orientation suggests that the Tuscumbia Limestone possesses a structurally controlled joint system (i.e., along strike and dip).

Unlike the Tuscumbia Limestone, the overburden does not exhibit laterally extensive highly permeable flow zones. The overburden consists of a continuous, low permeability, clayey soil matrix with occasional stringers of sandy clay. Borehole flowmeter data at a 1-ft scale provide horizontal conductivities as high as 0.3 ft/day (0.0001 cm/s) for the sandy clay layers. However, neither soil logs nor cone penetrometer tests from locations spaced several tens of feet apart indicate that these sandy clay units have significant lateral continuity. Permeameter and borehole flowmeter tests (Young and Julian, 1991) suggest that the hydraulic conductivity of the clayey soil matrix is generally less than 10^{-6} cm/s. These tests also suggest that the horizontal permeability is approximately 10 times greater than the vertical permeability at a scale of 1-ft (Appendix A).

9.3 Hydraulic Gradients

The complexity of the hydraulic gradients at NFERC is exemplified in the SWMU 108 data (Young and Julian, 1991). Within the relatively small region of SWMU 108, nested piezometer data indicate vertical hydraulic gradients from 103 percent downward to 10 percent upward. This range occurs because of seasonal changes and a complex flow system that results in groundwater flow toward Pond Creek in the overburden but away from Pond Creek in the bedrock during most of the year. At SWMU 108, two important features are illustrated. First, no one set of results from a piezometer nest over time nor one snapshot of all the piezometers at a given time reflects the transients of the system. Secondly, the measured hydraulic gradients at each piezometer nest are very dependent on the vertical locations of the well screens.

Data from detailed monitoring of the wells and piezometers across NFERC produced similar temporal variability as that observed at SWMU 108. Based on the detailed studies at SWMU 108, the water level data collected in the overburden at the regional wells should be considered only as point measurements and not representative of the vicinity because of complex three-dimensional flow in the overburden. It is prudent to use the overburden wells only to establish the ranges and trends in the vertical hydraulic gradients across the NFERC reservation since deeper groundwater flow extends over a relatively larger horizontal scale than the shallow system.

Four regional well pairs with vertical separation distances greater than 30 ft (i.e., wells A, C, D, and F) consistently provide a downward vertical gradient from the overburden to the bedrock. The piezometer nests and well pairs near Pond Creek (i.e., PZ11, PZ12, PZ1, PZ2, and E) include upward and downward gradients. The upward gradients are attributed to groundwater in the overburden discharging into Pond Creek.

9.4 Conceptual Model

A conceptual aquifer model describes the important processes and properties controlling the groundwater flow system. It includes integrated site characterization data that affects regional trends (e.g., scale of a watershed). Spatial properties at the local scale (e.g., scale of a point-source contamination problem) are not delineated but the effects of their variability are considered. Conceptual models should be developed and analyzed before constructing mathematical models in order to determine the most useful modeling exercises.

Across the NFERC reservation, groundwater flow in the overburden is very different from that in the bedrock. Groundwater flow is primarily vertical in the overburden and horizontal in the karstic bedrock. Whereas, the overburden is best characterized by a continuous hydraulic conductivity field, the bedrock is best characterized by an interconnected discrete fracture network. Because of the distinct differences in the overburden and bedrock, the two regions are discussed separately.

9.4.1 Overburden

In general, the overburden at NFERC consists of heterogeneous low to moderately permeable clayey soils with a porosity near 0.35. Within most of the overburden, groundwater flow is downward. Local areas of upward flow likely occur near some streams, topographic lows, and where extensive root systems exists. The average net recharge from precipitation is expected to range from 10 to 15 in./yr (Table 3-1). Dividing an average recharge rate of 12.5 in./yr by the porosity, the average downward groundwater velocity is about 36 in./yr. Therefore, if uniform flow is assumed to occur through the overburden, a conservative tracer might be expected to pass through a 30-ft saturated overburden in about 10 years.

However, because of the heterogeneity in the overburden, uniform movement of solutes is unlikely. Two factors that affect dispersion are spatial variability in the hydraulic conductivity field and the existence of microfractures in the clayey overburden. The spatial variability in the hydraulic conductivity values include at least a three-order magnitude range (see Appendix A). Microfractures are created by periods of drying or of uneven tensional stress. Microfractures probably exist in the overburden but their detection is difficult.

The effect of heterogeneity is to increase the number and type of flow paths solutes might follow. An important effect of this phenomena is earlier arrival of a solute front and greater dilution than that of a uniform flow field. The significance of these effects are site-specific and depend on the aquifer hydraulic conductivity field and boundary conditions. The flow through the overburden serves as recharge to bedrock.

9.4.2 Bedrock

The majority, if not all, of the groundwater beneath the NFERC reservation discharges to the Tennessee River and Tuscumbia Spring. However, determination of the structure and main physical properties of an anisotropic and heterogeneous karst aquifer poses several practical problems. Direct observations of the regional bedrock aquifer are limited to caves, boreholes, lineaments, inputs, and outputs. Mapping and characterization of the karst aquifer is not possible at sufficient detail to create a numerical model of flow and transport in the bedrock fractures. In lieu of sufficient information, bedrock flow and transport will be considered part of a "grey box" model. Based primarily on the results of dye tracer tests in the Muscle Shoals area (Chapter 8), rapid solute migration accompanied by high dilutions occurs in the bedrock. Dye velocities of 100 ft/day are commonly reported, and some velocities as great as miles/day have been estimated for areas exhibiting discrete conduit flow. Based on the borehole flowmeter data, the majority of the groundwater flow occurs near the overburden-bedrock contact across a 3- to 5-ft vertical interval. The transmissivity of this epikarst zone varies more than 4 orders-of-magnitude and may often be greater than 500 ft^2/day. The most extensive and transmissive fracture zones likely have a SW/SE orientation as indicated in the lineament study. Across the reservation, a network of tributary fractures probably contribute flow to increasingly larger fractures. Increase in size (or openness) is generally in downgradient directions and is accompanied by increased groundwater flow to resurgence points (e.g., Tuscumbia Spring).

The borehole flowmeter data and information from regional studies (G&E Engineering, Inc., 1991; and Chandler, 1991) suggest that a network of less transmissive fractures exists below the epikarst zone. Groundwater flow through these deeper fractures likely takes significantly longer to reach resurgence points and contacts appreciably more matrix material than flow in the epikarst zone. Solute migration within the deeper fractures would likely experience significant matrix diffusion. From a risk assessment perspective, the flow regime of most concern is that of the epikarst zone and upper bedrock where the highest flowrates are expected.

Besides the uncertainty associated with the fracture network, predictions of groundwater flow in bedrock is complicated by the temporal variability in the hydraulic gradients. Figure 7-6 shows several potentiometric maps based on water levels in the bedrock wells. Seasonal changes with both magnitude and direction of the gradients occur. In fractured bedrock, groundwater flow does not necessarily follow the direction of maximum gradient change. Groundwater flow directions are along pathways of least hydraulic resistance determined by properties of both the fracture network and the hydraulic gradients. If it is assumed that groundwater flowed in the direction of the maximum gradient, then groundwater in the northern portion of the reservation flows towards the Tennessee River, and groundwater in the southern portion flows towards the Tennessee River and Tuscumbia Spring. The potentiometric data suggests that some type of groundwater divide exists across the NFERC reservation. This divide should be used in evaluating the potential for different regions to contribute recharge to Tuscumbia Spring.

An important feature of the conceptual aquifer model is that groundwater from the overburden seeps relatively slowly into the bedrock. A hypothetical contaminant release across one acre would contaminant approximately 125 ft^3 of recharge water per day. Ignoring any dispersive processes, the spill concentrations will be diluted by a factor of 45,000 at Tuscumbia Spring based on an average spring discharge of 42 Mg/d (Chandler et al., 1990). In addition to the estimated dilution by mixing from plug flow, additional dilution is expected from dispersion caused by temporal variations in the hydraulic gradients and spatial variations in the hydraulic properties. These dispersive factors would provide greater dilution for contaminant releases.

9.5 Previous Numerical Models

Based on the conceptual model described above, uncertainties associated with the hydraulic gradients and fractures suggest that regional models have very limited applicability for predicting groundwater transport. Nevertheless, regional models can be useful for investigating the processes and properties important in controlling groundwater flow. With very limited data, Golder Associates (1990) developed a very simplistic numerical model to help define the hydraulic boundary conditions near the former Ford facility. The model results have limited value beyond their intended purpose, but are worthy of review.

The regional model covered approximately 240 miles and was bounded by the Tennessee River on the north, Spring Creek on the west, and McKieren Creek on the northeast. Additional boundaries were extracted from a March 1958 potentiometric map shown in Figure 9-1, which was the only potentiometric map used to calibrate the model. With an

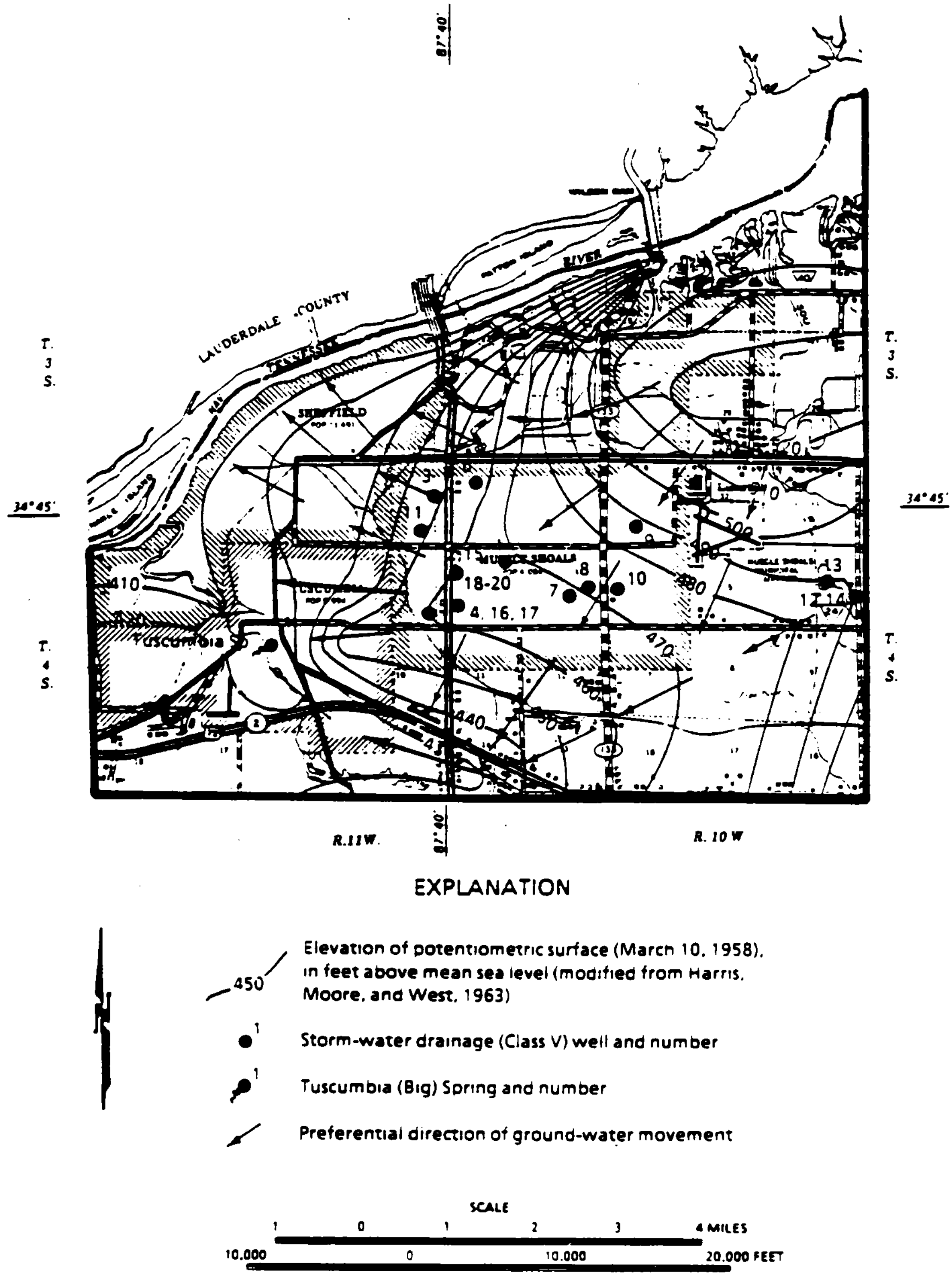


Figure 9-1. Regional Map of Potentiometric Surface (from Chandler, 1986)

average recharge rate of 14 in./yr, the model was "calibrated" by adjusting the regional hydraulic conductivity value to obtain the best match with the contours shown in Figure 9-1. Figure 9-1 reveals a major anomaly in the elevation of the water table southwest of the Ford facility. There is a 10-mile long, southwest trending depression in the potentiometric surface that coincides with a depression of about 100 ft in the Chattanooga Shale (Figure 4-9). Water levels in the depression are about 10 to 15 ft lower than elsewhere. If this is real and not an artifact of the limited data used to produce the contours, the depression reflects a large increase in the transmissive properties of the underlying bedrock. This feature has also been identified as an area of major lineaments from a regional study by CH_2M Hill (1986). The nature of the increased transmissivity has not been fully discerned; it could be a broad zone of increased fracture density, or a single cave-like feature. The conductivity of the zone was increased relative to the regional K until the water levels in the model produced a depression similar to that shown in Figure 9-1. Figure 9-2 shows the water level contours produced with the model for K ratios of 1:1, 5:1, 10:1, and 100:1. A final K ratio of 40:1 was selected as a minimum value which would produce model-generated water levels consistent with observed water levels. The "regional" and "trough" hydraulic conductivity values in the calibrated model are 12 and 480 ft/day, respectively.

In addition to the regional model, Golder Associates (1990) used very limited data to develop a conceptual groundwater model for the former Ford facility. Among the conclusions provided by Golder Associates (1990, page 16) from their modeling results are:

- the lower residuum and top of rock are hydraulically connected, the model shows that pumping in the lower residuum could be used to produce an upward gradient from bedrock to the lower residuum;

- there is a possible off-site hydrogeological feature associated with a bedrock depression, resulting in significantly higher transmissivity in the Muscle Shoals region;

- the former Ford site appears to be close to the groundwater divide between water discharging to Spring Creek and water discharging to the Tennessee River but most of the water from the site discharges to Spring Creek; and,

- most of the leakage through the residuum in the site area (i.e., the Ford site) is downward except to the west and to the south of the site where there are some swampy areas present; in these areas there appears to be an upward component of flow from the limestone into the residuum.

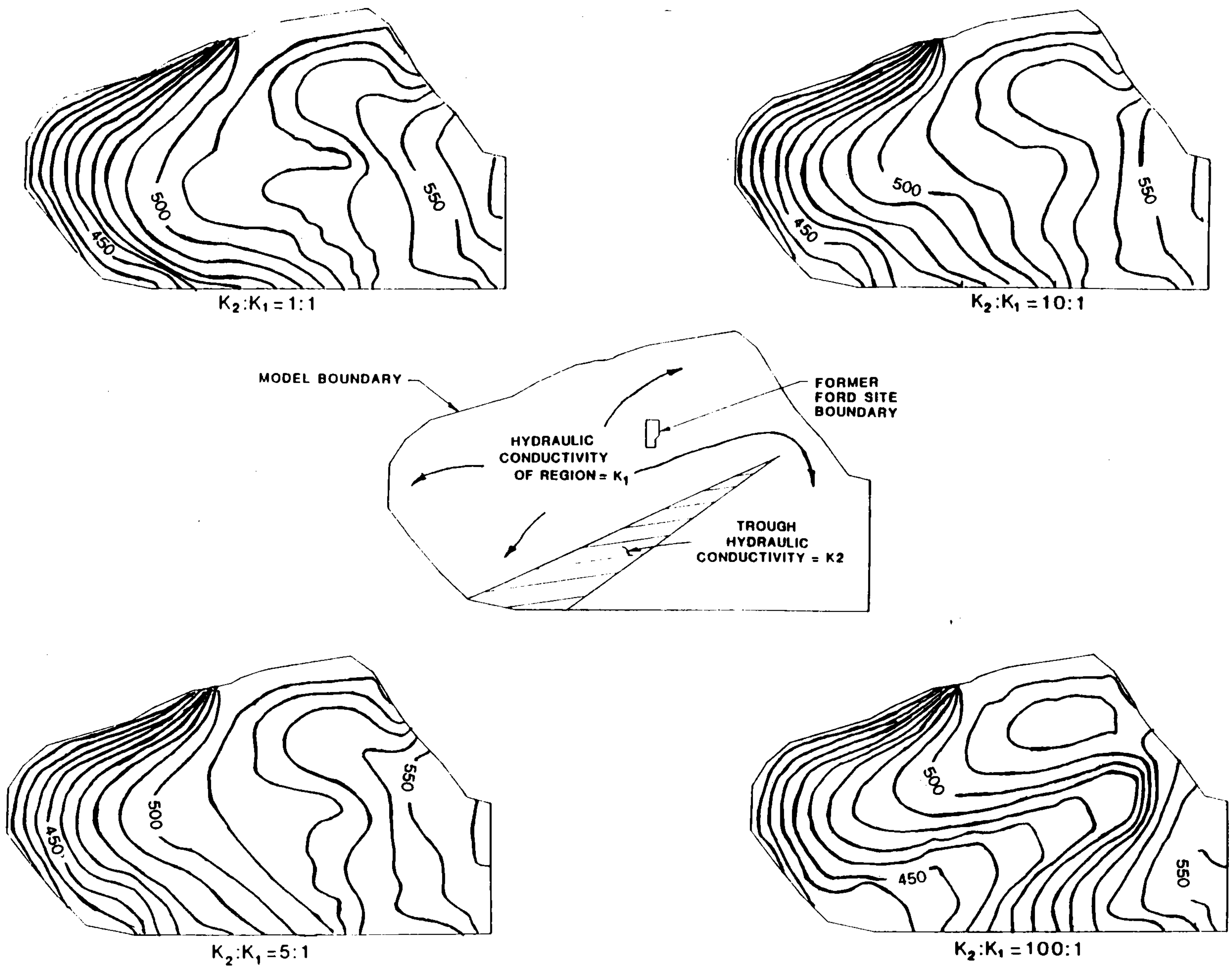


Figure 9-2. Model-Generated Water Levels From "Regional" and "Trough" Hydraulic Conductivity Values (from Golder Associates, 1990)

10.0 GROUNDWATER MODELING

10.1 Overview

The field data presented in previous chapters has helped to describe the important processes and the bulk parameters affecting groundwater flow beneath the NFERC. This information and the conceptual aquifer model in Chapter 9 provide the basis for investigating and evaluating risks associated with chemical spills or contaminant plumes at NFERC. The spatial variability exhibited in field measurements such as hydraulic gradients and hydraulic conductivity suggest that overburden and bedrock properties are not defined in sufficient detail to justify a three-dimensional groundwater transport model for the NFERC site.

With regard to numerically modeling groundwater transport at NFERC, two major problems exist. The first is the uncertainty associated with defining the network of fractures and weathered zones in bedrock. Another problem is the quantification of groundwater recharge, especially from large precipitation events. In this context, a large precipitation event is one that provides significant groundwater recharge because of: (1) percolation into microfractures and macropores that quickly drains beneath the zone of evaporation in the upper overburden; and/or (2) runoff into either karst features or storm drainage wells that are directly connected to the bedrock flow system. The uncertainty associated with these two problems limits the utility of numerical models at the NFERC.

A review of the borehole flowmeter tests, the lineament survey, the well tests, and the dye trace tests provides sufficient information to develop a "grey box" model (see Chapter 9) that predicts relatively rapid and highly diluted solute transport in the bedrock and epikarst zone. This "grey box" model appears to be applicable across most of NFERC and any attempts to refine the "grey box" model via a numerical model cannot be justified. Similarly, the development of a model to include the effects of a large precipitation event on the transport of a chemical spill or plume through the bedrock and epikarst flow system cannot be justified. The effects will be highly site-specific and dependent on the unsaturated hydraulic properties of the upper 10 to 30 ft of the overburden soils, local meteorological conditions (e.g., groundcover, wind velocity), and proximity to drainage ditches and creeks. Because of the sheer complexity of this problem (with respect to both the data and computational resources required), temporal and spatial recharge fluxes are simplified to a uniform annual recharge rate between 10 to 15 in./yr through the unsaturated zone.

Based on the available field data and a partial understanding of the groundwater flow system at NFERC, the numerical modeling of groundwater transport in either the unsaturated overburden or the fractured bedrock would not provide useful information. The primary area in which numerical models can be useful is the saturated overburden. Of interest is the effect of the spatial variability in the hydraulic conductivity on the migration rate of solutes through the saturated overburden.

10.2 Purpose

The conceptual model for the saturated overburden (see Chapter 9) includes an upper recharge boundary of 10 to 15 in./yr and a lower drainage boundary controlled primarily by a very permeable horizontal flow zone in the bedrock epikarst. Results from cone-penetrometer tests, borehole flowmeter tests, laboratory core permeameter tests, and soil logs (Appendix C) provide the information needed to develop a hydraulic structure for the saturated overburden. The integration of boundary conditions and field properties into a numerical model assist in investigating the importance of spatial variability in the hydraulic conductivity field on the transport of a conservative solute. Specifically, these results will help determine the applicability of a uniform recharge rate and whether significant variability exists in the transport rates of solutes through the saturated overburden.

10.3 Numerical Models

10.3.1 Selection of MODFLOW and MT3D

The numerical simulation involves two-dimensional groundwater flow and transport in the saturated overburden with hydraulic conductivity variations of up to three orders of magnitude. In modeling, large changes in aquifer properties can produce inaccurate numerical solutions whose error can easily go undetected. Detection of these problems is enhanced by performing accurate mass balances and sensitivity analyses on the temporal and spatial discretization. In order to perform the required simulation, the groundwater codes MODFLOW (McDonald and Harbaugh, 1984) and MT3D (Zheng, 1990) were selected. Both of these models have been thoroughly validated and provide global mass balance information.

The development and testing of MODFLOW has been ongoing at the United States Geological Survey for approximately a decade. Currently, MODFLOW is the most widely used groundwater flow code in the United States. MODFLOW is a three-dimensional block-centered finite difference model. The development and testing of MT3D has been funded by the United States Environmental Protection Agency. MT3D was designed to couple with the output from MODFLOW. MT3D offers four options to solve the transport equation. Three of these options are based on the Method of Characteristics (MOC) and the fourth option on an upstream, finite difference method.

10.3.2 Preliminary Testing With MODFLOW

The main accuracy criteria in a groundwater flow model is the head closure criteria and water balance. In MODFLOW, the head closure is specified as input for the solver modules (i.e., SIP, SSOR, or PCG1/2). During the solution of the head equations, the maximum head difference in the model between successive iterations is checked. Iteration toward a solution stops when the maximum head difference does not exceed the specified head closure criterium (e.g., a small head difference). At each iteration, MODFLOW reports a water balance that represents the summation of all the outside fluxes and changes in mass storage in the grid cells.

Generally, a mass balance error of 0.1 percent of the total in-flux (or out-flux) is considered acceptable. In practice, the head closure criteria is set at a certain value and the global water balance is checked. Although the local water balance at each node should be verified, this is often ignored by numerical modelers. To provide a rigorous check on MODFLOW's solution, a program was written to calculate the nodal mass-balances. The program is similar to one provided in MODPATH (Pollock, 1988). The check on nodal mass-balances is considered essential for modeling groundwater flow in a heterogeneous aquifer.

For the case of uniform soil hydraulic properties, the strongly implicit procedure (SIP) produced acceptable global mass balances with a head closure of 0.01 ft. The error in the nodal water-balances was less than one percent. Test runs with the SIP procedure of several heterogeneous aquifer properties (discussed in following paragraphs) with the same head closure of 0.01 ft produced acceptable global mass balance errors less than 0.1 percent, but unacceptable global mass balance errors (up to 50 percent). To reduce the nodal mass balance errors, the head closure criteria was reduced to 0.0001 ft. For this small head closure criteria, neither the SIP nor the SSOR solver supplied with the original MODFLOW version (McDonald and Harbaugh, 1984) could provide a convergent solution for the heterogeneous hydraulic conductivity fields. In order to achieve a convergent solution with this head closure criteria, the pre-conditioned conjugate-gradient solver (PGC2) (Hill, 1990) was used.

10.3.3 Preliminary Testing With MT3D

With regard to options available for solving the transport equation, it is important to note that both finite element and finite difference groundwater transport models are susceptible to smearing the solute breakthrough curve. This is due to coarse spatial discretization that occurs when the grid length exceeds twice the dispersivity (e.g., the grid Peclet constraint). In order to minimize the problems associated with smearing of the solute breakthrough curve, groundwater models based on random walk theory and the method of characteristics may have been developed. Both of these methods involve moving particles to simulate advective transport.

For a vertical grid spacing of 3.5 ft, the finite difference option in MT3D performed well with a longitudinal dispersivity of 1.0 ft for homogeneous and heterogeneous aquifer conditions. For a longitudinal dispersivity of 0.01 ft, the finite difference option failed for both conditions. For the heterogeneous case, which is the case of most interest, a longitudinal dispersivity of 0.01 ft is more appropriate than 1.0 ft. Dispersivity values are used as a means to indirectly introduce the spreading effect that aquifer heterogeneity produces on concentration fronts. As an aquifer model incorporates more of the "true" heterogeneous aquifer structure, the dispersivity values should decrease from some macroscale value (Gelhar and Axness, 1983) to more microscale value (Molz et al., 1986). Because of the problems with the finite difference option at low dispersivity values, the MOC option was used.

One of the parameters that MT3D requires for the MOC option is the Courant number. The Courant number can be considered as the maximum number of grid cells a solute particle can travel during one time step. The Courant number should ideally lie between 0.5 and 1. MT3D uses the Courant number and the highest values of velocity to calculate the time

increment with which to advect the particles. The velocity field for the heterogeneous aquifer model includes velocities that vary over two orders of magnitude. This range of velocities produces an exceedingly small time step for many of the grid cells with velocities significantly lower than the highest velocity values in a few grid cells. To prevent a uniformly small time step, the Courant number was specified at 5. In selecting such a high Courant number, some of the aquifer heterogeneity is distorted. When MT3D runs were based on MODFLOW output with the 0.0001 head closure criteria, solute mass balances near three percent were achieved.

10.4 Simulation of Overburden Properties

10.4.1 Model Set-Up

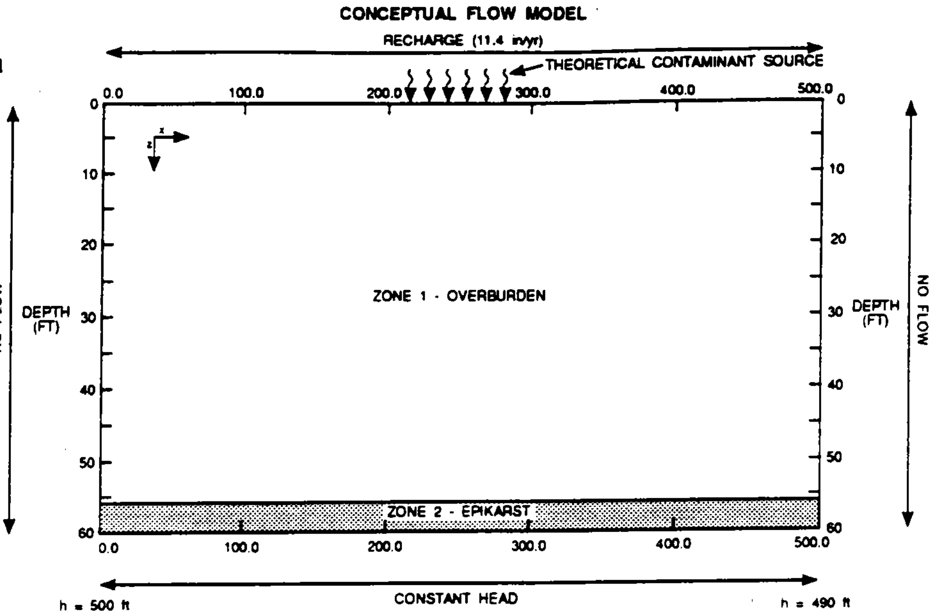
The approach for the numerical simulations was to: (1) select boundary conditions consistent with the conceptual mode; (2) generate a hydraulic conductivity field consistent with the field data presented in this report and that in Young and Julian (1991); (3) use MODFLOW to solve for the steady-state flow field; (4) use MT3D to simulate breakthrough curves at different depths; and (5) perform a sensitivity analysis using different hydraulic conductivity fields.

The model set-up included a 56-ft thick overburden and a 4-ft thick epikarst zone. For the simulations, the thickness of the epikarst zone is somewhat arbitrary because the property of most importance is the transmissivity, which is the product of saturated thickness and horizontal hydraulic conductivity. The boundary conditions included an upper recharge boundary of 11.4 in./yr, no flow boundaries along the sides of the overburden (remember overburden flow is considered primarily vertical), and a constant head boundary with a 2 percent horizontal hydraulic head gradient in the epikarst zone. Figure 10-1a provides a schematic of the model set-up.

Modeling exercises included both heterogeneous and homogenous conditions. The homogenous runs were used to help calibrate MODFLOW's and MT3D's output and to evaluate the runs of heterogeneous conditions. The detailed characterization of the overburden material near SWMU 108 performed by Young and Julian (1991) indicates that the overburden is heterogeneous. Appendix C summarizes much of the information in Young and Julian (1991) and suggests the overburden consists of a somewhat chaotic mixture of various types of discontinuous sandy and/or silty clay lenses embedded in a clayey soil matrix. Across the NFERC reservation, the detailed structure of the overburden is expected to vary considerably. Because of the spatial variability, a probabilistic approach was used to generate several equally plausible hydraulic conductivity fields based on a geostatistical analysis of the data.

Appendix C presents two types of soil log data and two types of hydraulic conductivity data. Soil logs were constructed from visual observations during drilling activities and from cone-penetrometer tests (CPTs), which produced soil characterization numbers (SCNs) at about 1,500 defined locations. Borehole flowmeter and laboratory permeameter tests provided values for horizontal and vertical hydraulic conductivity, respectively. The data collection was designed so that all four types of data could be correlated. The observed correlations allowed the CPT

10 - 1a



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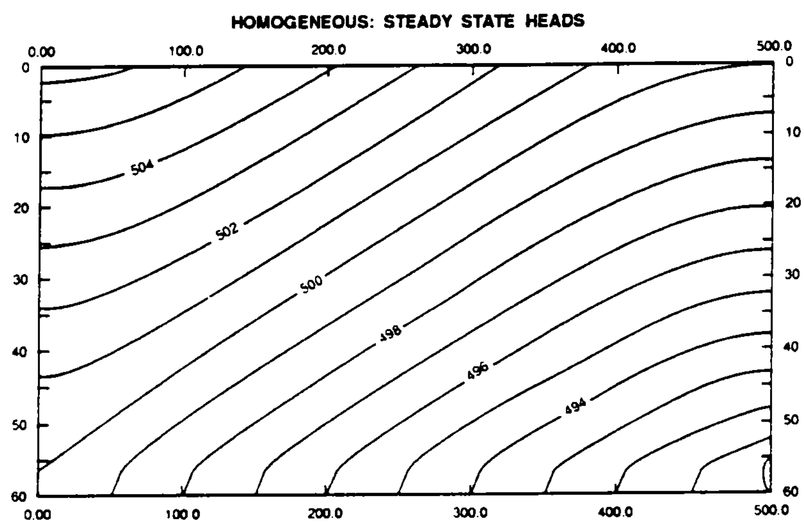

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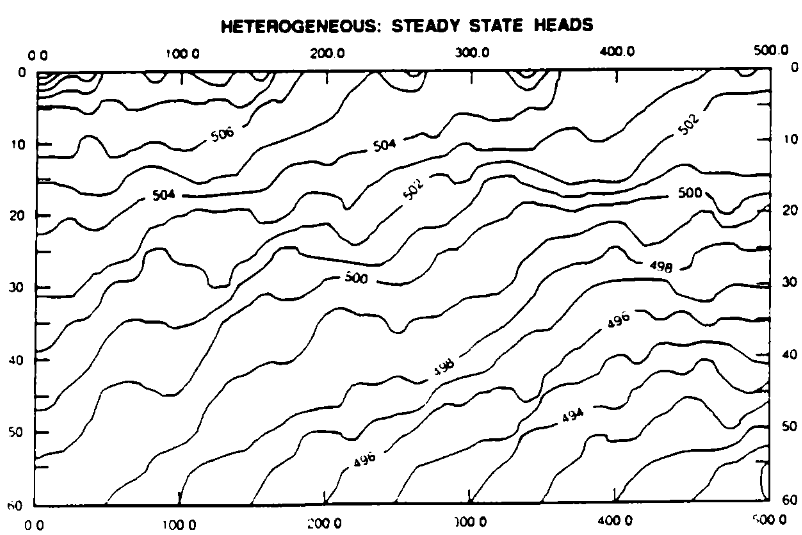

Figure 10-1. (a) Conceptual Flow Model for the NFERC Area; (b) Steady-State Head Produced by MODFLOW for a Homogeneous Medium; (c) Steady-State Head Produced by MODFLOW for a Heterogeneous Medium

measurements to represent a soil type, which was then transformed into a vertical and horizontal hydraulic conductivity value.

In review of the hydraulic conductivity data, Young and Julian (1991) estimated that the vertical hydraulic conductivity values were approximately an order of magnitude too low (Appendix C). As a result, all of the measured vertical hydraulic conductivity values were adjusted by an order of magnitude for the numerical model. Table 10-1 provides the correlation used to obtain 1,500 K_v values from the 1,500 SCN numbers. Figure 10-2a,b provides the resulting histogram and variogram calculated from the K_v values and SCNs.

TABLE 10-1

Correlation Between SCN*, Soil Type, and
Vertical Hydraulic Conductivity

SCN Number*	Soil Type	K_v** (ft/s)
0 to 1	Clays	1.0 E-8
1 to 2	Silty Clay mixtures	1.0 E-7
2 to 3	Sandy Clay mixtures	1.0 E-6
3 to 4	Sands	1.0 E-5

*SCN - soil characterization number (CPT measurements)
**vertical hydraulic conductivity (lab tests)

Correlation lengths provide estimates for distances over which aquifer properties can be considered constant. The vertical correlation represents an average distance over which the hydraulic conductivity values are correlated in the vertical direction. In order to estimate the vertical correlation length of the hydraulic conductivity values, a negative-exponential variogram was fitted to the experimental data in Figure 10-2b. Figure 10-2b shows that the match between the theoretical and experimental variogram is good. The match provides a vertical correlation length of 3.5 ft. There is not sufficient data to calculate a variogram for the horizontal direction. Because depositional processes favor lateral over vertical continuity, the correlation lengths are expected to be greater in the horizontal than vertical directions. Boggs (1990) and Young (1993b) show that for a heterogeneous fluvial aquifer in Columbus, Mississippi, the correlation lengths are 3 to 4 times greater in the horizontal than the vertical directions. For our purposes, a ratio of 3 appears reasonable.

In both MODFLOW and MT3D, the aquifer properties are constant within a grid cell. Hence, it is appropriate to dimension the grid cells in the numerical model according to the correlation lengths. The grid network for the numerical models was set to a constant 3.5 ft and 10 ft in the vertical and horizontal directions, respectively. The overburden zone shown in Figure 10-1a is thus represented by 800 (16 rows x 50 columns) elements, each potentially with

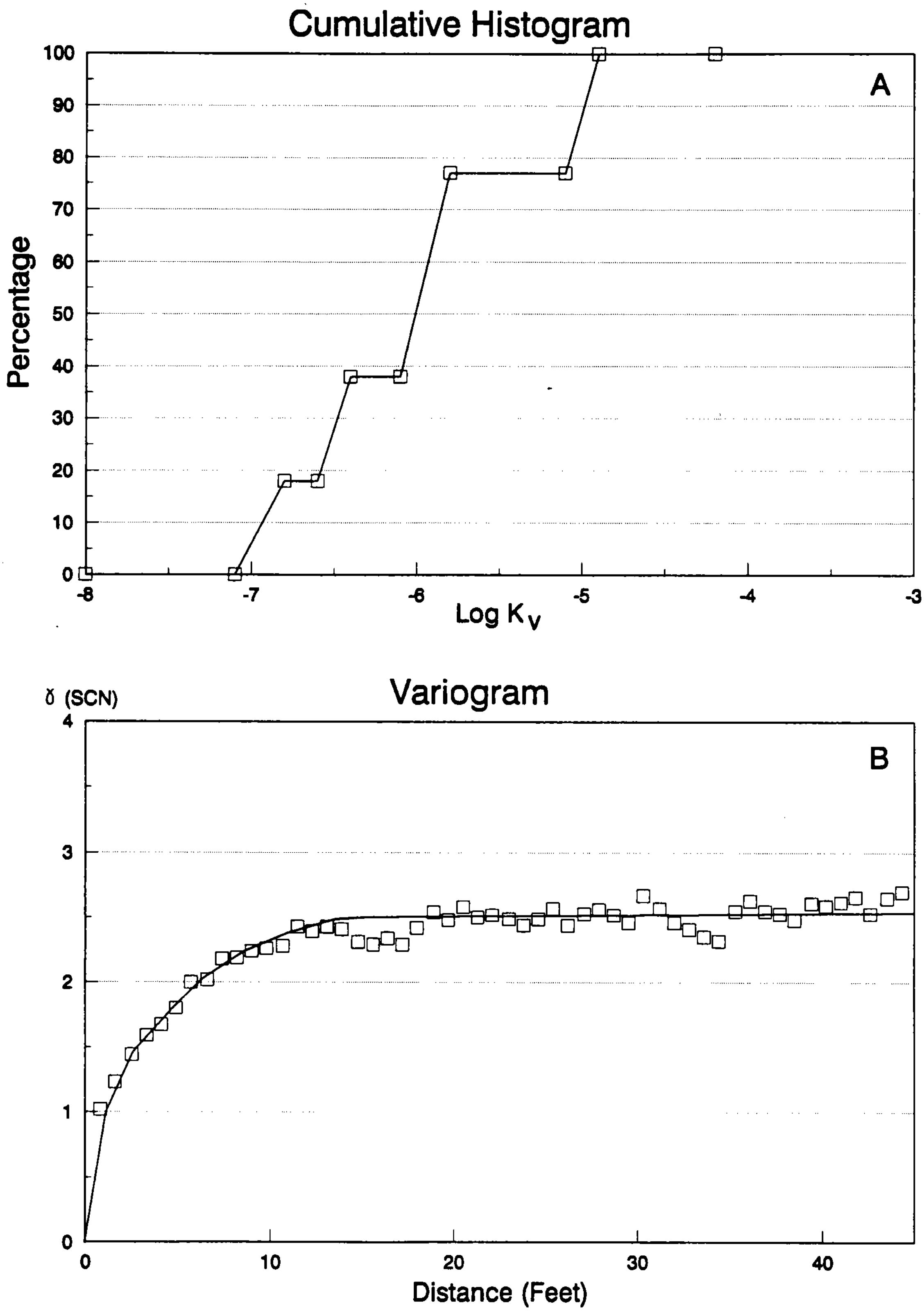

Figure 10-2. (a) Cumulative Histogram Produced From Vertical Hydraulic Conductivity Data; (b) Variogram Produced From Soil Characterization Numbers

a different value for hydraulic conductivity. It should be noted that this grid mesh was overlain with a finer mesh consisting of three times the number of elements before the flow field was solved by MODFLOW. The finer mesh assists in capturing the effects of heterogeneity on the hydraulic head values.

In order to generate overburden heterogeneity, the vertical hydraulic conductivity value for each of the 800 grid cells was randomly assigned from the cumulative histogram shown in Figure 10-2a. Because none of field data suggested a different ratio between the vertical and horizontal hydraulic conductivity for the different soil types, a constant ratio for all soil types was assumed. Based on the available data, the ratio was expected to range between 1 and 10. However, because of the uncertainty in this ratio, its determination was considered as part of the model calibration.

10.4.2 Model Calibration

The calibration of MODFLOW focused on: (1) checking consistency between the selected boundary conditions and aquifer properties; and (2) determining a reasonable ratio of K_h/K_v. In order to establish a ratio for K_h/K_v, MODFLOW runs were performed with a uniform K_v and K_h/K_v ratio. Figure 10-1b shows the predicted hydraulic head contours for $K_v = 2.0 \times 10^{-7}$ ft/s and $K_h/K_v = 5$. The K_v represents a lower estimate of the effective hydraulic conductivity that may be generated from the random hydraulic conductivity field. Because the recharge flux is fixed at 11.4 in./yr, an inverse relationship exists between the value of K_v and the average vertical hydraulic gradient.

The downward vertical hydraulic gradient for the homogeneous case ranges between 11 and 17 percent, which compares favorably with field data. A higher K_v value would produce smaller hydraulic vertical gradients. The K_h/K_v ratio of 5 is in the middle of the estimated ranges of 1 to 10. It was found that larger anisotropy causes the head gradient along the topographic surface to diminish. Figure 10-1b provides a horizontal hydraulic gradient of 0.01 percent in the upper overburden which compares favorably with field data.

The calibration of MT3D focused on: (1) determining the number of particles required to accurately define a theoretical solute plume; and (2) checking the migration rate of the 0.5 concentration front with the recharge rate. The MT3D calibration runs used the output from MODFLOW for the homogeneous case discussed above. The MT3D runs included a continual source located at the surface between x = 200 and 300 ft. The total number of particles used in the simulations were 7,500 and transverse dispersivity was set to 0.333 of the longitudinal dispersivity. Figure 10-3a shows the breakthrough concentration curves at 10 depth intervals for x = 250 ft with the longitudinal dispersivity of 0.01 ft. Analysis of the figure shows the tracer plume's center of mass is moving at a constant rate equal to the recharge rate dividing by the porosity of 0.35. Figure 10-3b shows the breakthrough concentration curves at the same locations for a longitudinal dispersivity of 1.0 ft. The results in Figure 10-3 suggests that MT3D is performing well and that a sufficient number of particles are being used.

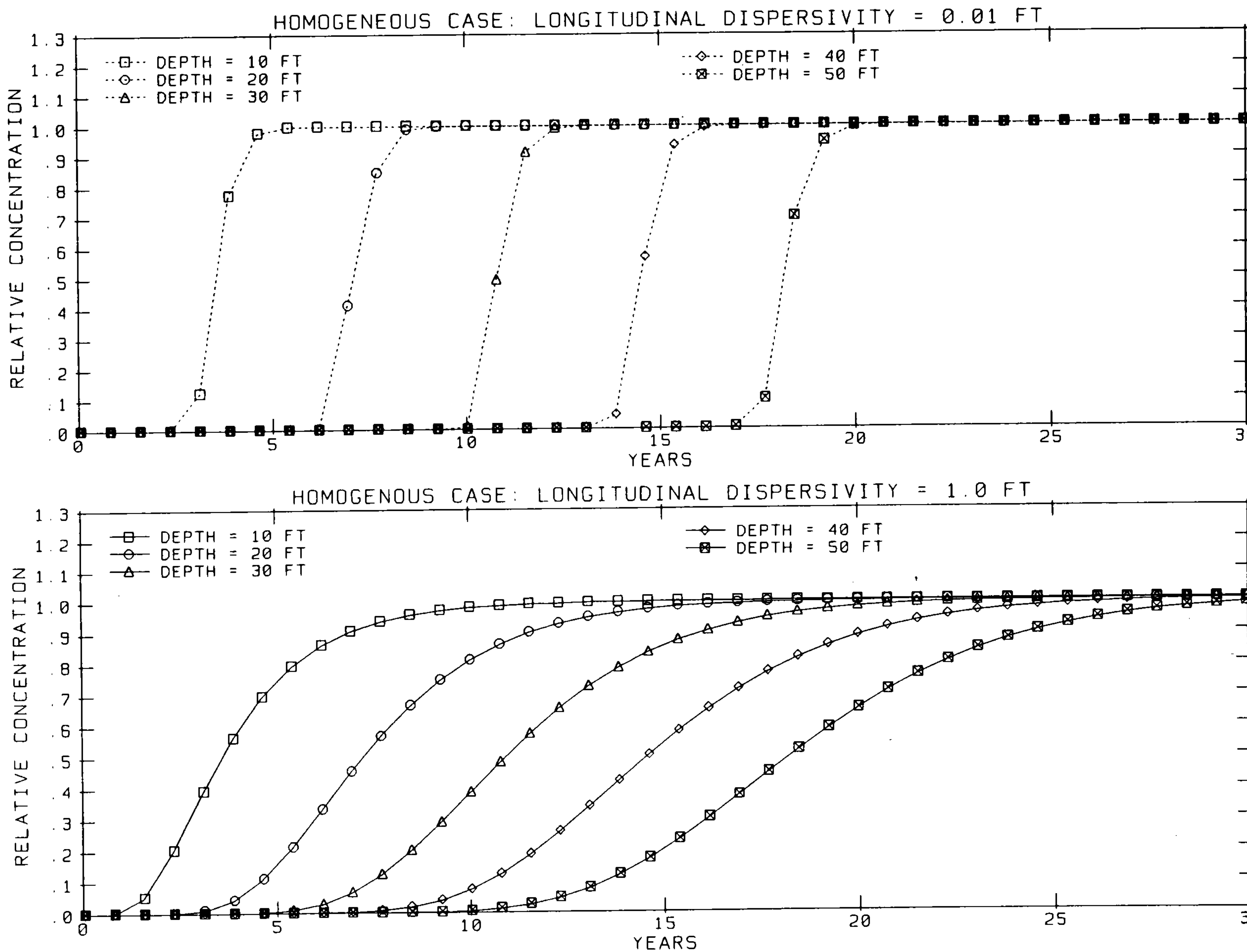

Figure 10-3. (a) Breakthrough Curves in a Homogeneous Medium Generated by MT3D for Longitudinal Dispersivity = 0.01 ft; (b) Breakthrough Curves in a Homogeneous Medium Generated by MT3D for Longitudinal Dispersivity = 1.0 ft

10.4.3 Modeling Results

The objective of numerical modeling is to investigate the variability in the transport rates of solutes through the saturated overburden. The modeling scenarios listed in Table 10-2 were used to achieve the objective. For each run, MODFLOW was used to solve for a steady flow field and MT3D was used to simulate the plume from the 100-ft long continual source illustrated in Figure 10-1a. For convenience, the data analysis focuses primarily on the breakthrough curves at 10-ft intervals along the centerline of the plume (x = 250 ft).

TABLE 10-2

Modeling Scenarios for MODFLOW and MT3D for the
500 x 60 ft Cross-Section of the Overburden

			K_h/K_v	Dispersivity (ft)	
Case	Runs	Porosity	Ratio	Longitudinal	Transverse
Heterogeneous K_v Field	5	0.35	5	0.01	0.0033
Uniform K_v = 2 E-7 ft/s	1	0.35	5	0.01	0.0033
Uniform K_v = 2 E-7 ft/s	1	0.35	5	0.01	0.3300

For each of the heterogeneous K_v fields, MODFLOW had a head closure of 0.0001 ft in order to obtain acceptable mass balance errors for among the individual grid cells. Figures 10-1b,c show the hydraulic head field generated by MODFLOW for the uniform K_v run and one of the heterogeneous runs (i.e., run 1). The figures show that compared to homogeneous conditions, heterogeneity introduces significant deviations at the local scale and affects the average horizontal hydraulic gradient across the top boundary.

Unlike those for the homogeneous runs (Figure 10-3), the breakthrough curves for the heterogeneous runs are not equally displaced on the time axis. The variability occurs because of the non-uniform advection rate in the heterogeneous aquifer. An interesting feature in Figure 10-4b is the somewhat erratic breakthrough curve at a depth of 50 ft. Further analysis of the modeling results suggest that the oscillations resulted from fingering in the tracer plume. A similar oscillation occurs in Figure 10-5 for the breakthrough curve at a depth of 40 ft for run 4. These oscillations should be considered when analyzing temporal trends in water quality data.

Figure 10-5 compares the breakthrough curve at a depth of 40 ft for all the modeling runs. As expected, the modeling runs for a homogeneous overburden with different dispersivities exhibit the same breakthrough time, but have different sigmoidal curves. The heterogeneous modeling results, on the other hand, have similar sigmoidal curves, but different breakthrough times. The span of breakthrough times for the five heterogeneous runs is approximately ±5 years (or about 30 percent) of the 14.6-year breakthrough time for the

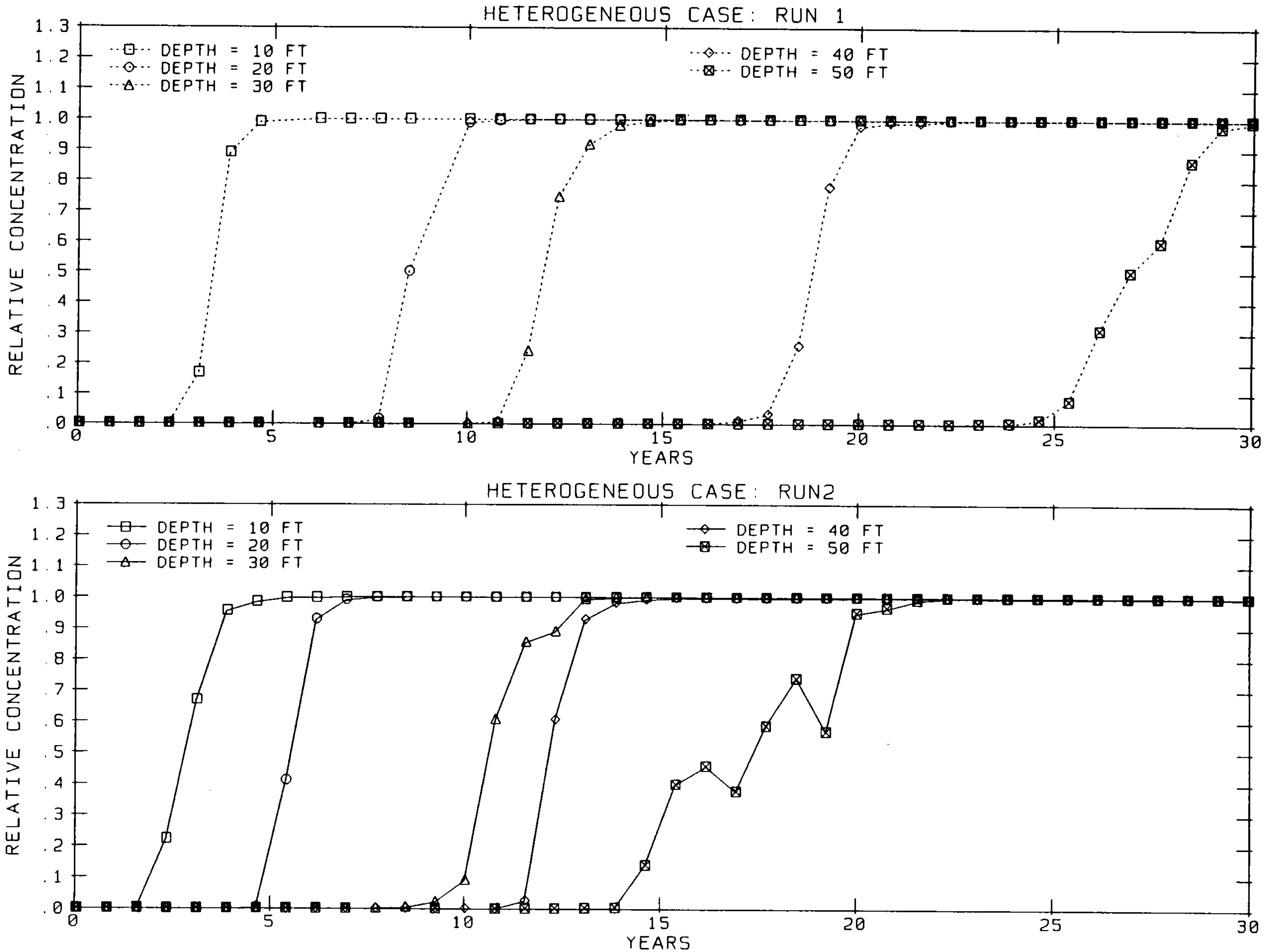

Figure 10-4. (a) Breakthrough Curves in a Heterogeneous Medium Generated by MT3D for Longitudinal Dispersivity = 0.01 ft; (b) Breakthrough Curves in a Heterogeneous Medium Generated by MT3D for Longitudinal Dispersivity = 1.0 ft

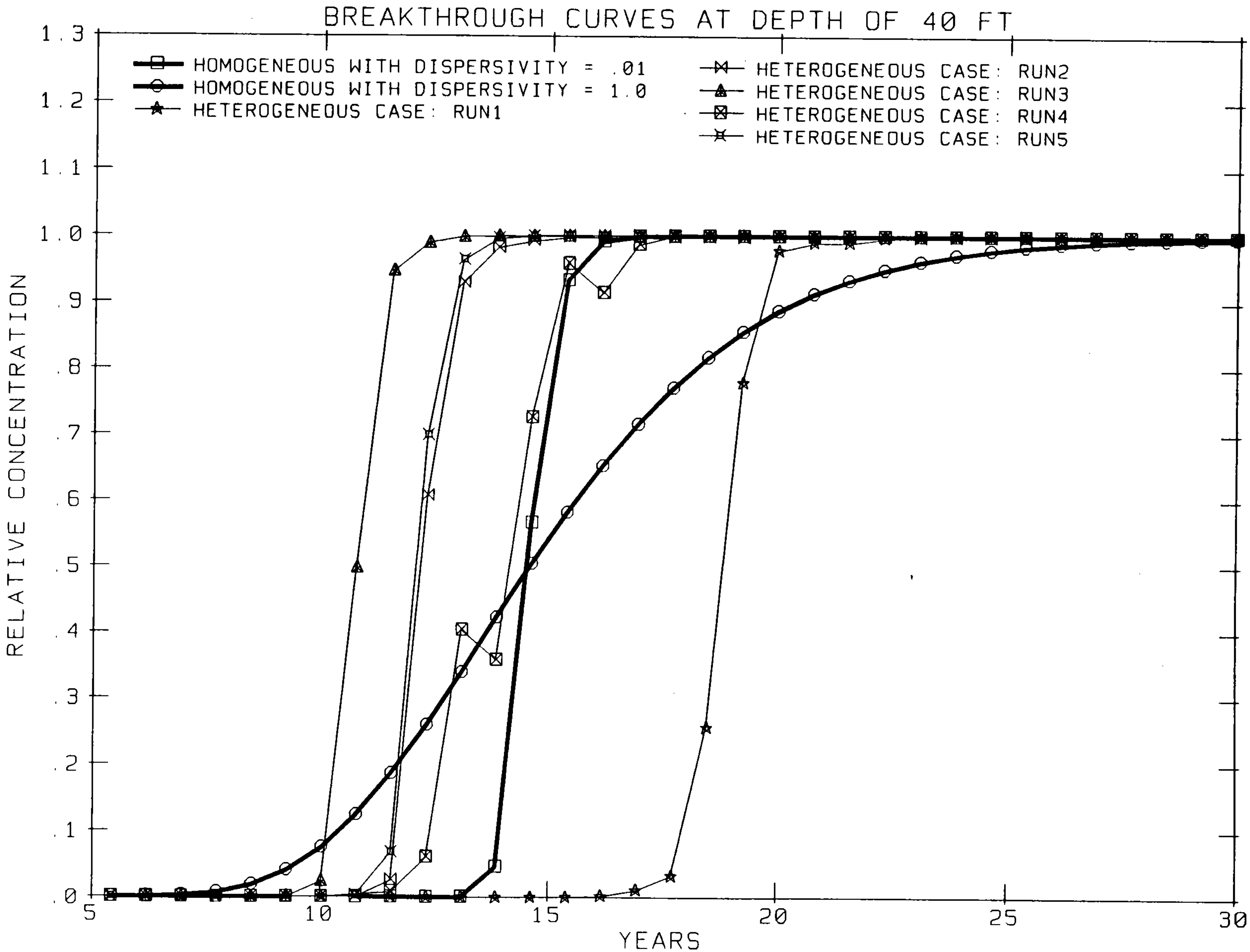

Figure 10-5. Composite Breakthrough Curves Generated by MT3D at Depth of 4.0 ft

homogeneous runs. The breakthrough times among the heterogeneous runs vary from approximately 10 years to 18 years.

If numerous heterogeneous runs had been performed, their average breakthrough time would coincide with the homogeneous runs at 14.6 years at a depth of 40 ft. This occurs because the average flux for each model run is 11.4 in./yr. In the event that numerous runs had been performed and plotted in Figure 10-5, more than 8 years would have existed between the two extreme results.

10.4.4 Implications

The modeling results indicate that heterogeneity in the saturated overburden can cause variations within the solute plume of at least 30 percent from the mean velocity of the infiltrating precipitation. These variations will likely cause up to a 100 percent difference in the migration rates observed from breakthrough curves (considering the slowest and fastest pathways) from staged piezometers across a relatively large area (> 10,000 ft^2). The variability in the velocity field for the heterogeneous cases suggest that large variations in the water quality data will occur among the wells and that no single well can provide a representative data set. The problems with successfully monitoring and predicting the movement of a plume will be affected by the size of the plume. The larger the plume, the more reasonable becomes a statistical approach to the breakthrough curves. For a large plume it appears reasonable that the plume front will not move uniformly downward, but will finger preferentially toward the epikarst zone. The fingering will produce a result over a large area similar to the response predicted by the homogeneous case with longitudinal dispersivity of 1.0 ft. For a smaller plume, the time of solute breakthrough becomes more unpredictable and a dispersivity of 0.01 ft is more likely to apply.

11.0 GROUNDWATER QUALITY

11.1 Introduction

Groundwater quality investigations at NFERC started in the early 1980s and a detailed investigation focusing on a solid waste management unit (SWMU) 108 was conducted from 1989 to 1991 (Young and Julian, 1991). During the last two years, groundwater sampling for suspect contaminants has also been conducted for SWMUs 86, 100 and 104.

Several studies on groundwater quality in the Muscle Shoals area have been carried out by other organizations in the last few years (Chapter 2). These investigations include the Occidental Chemical Corporation site (G&E Engineering, Inc., 1991), the former Ford Plant site (Golder Associates, 1990), and work by the Geologic Survey of Alabama (Chandler, 1986; Chandler and Moore, 1987, 1991; and Chandler et al.,-1990).

The OxyChem facility, just east of NFERC, is a chlor-alkali production plant. Groundwater investigation at the plant (G&E Engineering, Inc., 1991) confirmed that the presence of plumes of mercury, cadmium, and chloride with elevated chloride concentrations probably extend offsite. The former Ford plant, approximately 1.5 miles east of the NFERC, used on-site evaporation and drying ponds as places for wastewater and slugs during its operation. The prevalent compounds identified at the site are volatile organic compounds (IVOCs) including tetrachloroethane, trichloroethane, 1,2-dichloroethene, and vinyl chloride. Other compounds detected in the groundwater at the site include PCBs (PCB-1242), dense non-aqueous phase liquids, ethyl benzenes, xylenes, cyanide, zinc, and arsenic.

Chandler (1986) and Chandler and Moore (1991) evaluated the storm-water drainage (Class V) wells in the Muscle Shoals area. These studies found that high color and turbidity in samples of groundwater and surface water runoff entering the drainage wells were major water quality problems associated with the drainage wells. The studies further advised that the storm-water discharge wells should not be permitted and their use as runoff-control devices should be discontinued. Fluorescent dye trace tests for these storm-water drainage wells were conducted in the following years (Chandler et al., 1990).

Table 11-1 provides a chronology of sampling events for the NFERC regional groundwater wells. Groundwater from wells A through H was sampled and analyzed in July 1991, and from wells I1, J1, and K in June 1992. During the first sampling event, groundwater was sampled from 10 newly installed wells in accordance with EPA's groundwater monitoring list in Appendix D of 40 CFR. The groundwater analyses include a detailed chemical analysis for organic constituents, a broad-spectrum check for the different groups of hazardous compounds listed in the Interim Final RFI Guidance Manual of U.S. Environmental Protection Agency, an analysis of radionuclides, and field parameter measurements. Several existing wells near SWMU 108 were also sampled for organic compounds during the regional study. The second regional well sampling event includes a complete chemical analysis of well groups (I1, J1, and K) and selective chemical analysis of existing wells based on the results of the earlier

TABLE 11-1

Groundwater Sampling Events of the Regional Wells at NFERC

Sampling Date	Well Sampled	Parameter Sampled	Analyzing Labs*
July 29-30, 1991	A1,B1,C1,D1,D2, E,G,F1,F2,H	Field parameters Inorganics Volatile organics Pesticides/Herbicides PCBs/Base-neutral extractables Radionuclides	TVA FEW TVA GAL TVA ECL TVA WARL
	PZ11C,W9,W11,W 12	Volatile organics Pesticides/Herbicides PCBs/Base-neutral extractables	TVA ECL
June 9-11, 1992	I1,J1,K	Field parameters Inorganics Volatile organics Pesticides/Herbicides PCBs/Base-neutral extractables Radionuclides	TVA FEW TVA GAL ETC TVA WARL
	E1	Inorganics	TVA GAL
	H,G,E1,PZ11, PZ12,4A,W7	Field Parameters	TVA FEW
	PZ11,PZ12 E1,F1,G,H	Nitrate Chloride	TVA GAL TVA GAL

*Note:
TVA Organizations
FEW - Field Engineering West (Muscle Shoals, AL)
GAL - General Analytical Laboratory (Muscle Shoals, AL)
WARL - Western Area Radiological Laboratory (Muscle Shoals, AL)
ECL - Environmental Chemistry Laboratory (Chattanooga, TN)
Other
ETC - Environmental Testing & Consulting, Inc. (Memphis, TN)

analyses. Earlier groundwater investigations, especially in the vicinity of SWMU 108, were summarized in the report by Young and Julian (1991).

11.2 Inorganics

11.2.1 Metal Concentrations

Table 11-2 lists the inorganic concentrations of groundwater samples from regional wells. Most of the metal concentrations in the groundwater samples from the regional wells are below Maximum Contaminant Levels (MCLs) of the EPA Drinking Water Standard (DWS). Aluminum and manganese, however, show elevated concentrations in most of the groundwater samples from the wells. The concentrations of aluminum are mostly between 0.4 to 12 mg/L. The groundwater sample of well D2 has an exceptionally higher concentration of 368 mg/L. These concentrations exceed the 0.05-0.2 mg/L MCL (Table 11-2). The concentrations of manganese are also above the MCL (0.05 mg/L) in most samples.

There are no obvious trends from the data that indicates a contaminant source. Rather, it appears that the Mn and Al are related to sediments in the water samples. The groundwater samples were not filtered prior to analysis so that some fine soil particles are prevalent in the samples. Aluminum and iron are the prevalent elements associated with fine soils. The presence of Al-rich soil particle in the water sample probably resulted in the elevated Al concentration. Correlation between turbidity of the groundwater sample and concentration of several inorganics, including Al, Fe, Cu, Hg, As, Cr, and Ba, was shown by Young and Julian (1991) in the SWMU 108 groundwater assessment. Mn, a metal typically associated with Fe, has a similar correlation with the turbidity. Therefore, it is probable that the Mn values are also associated with sediments contained in the samples.

The groundwater sample from well D2, an overburden well, shows exceptionally higher metal concentrations in Al and As compared to samples from other wells. Gross alpha and beta levels of the groundwater samples are mostly low for this same sampling event; however, the sample from well D2 again exhibited a relatively higher value (Table 11-2). Visual comparison indicated that the groundwater sample from well D2 contained a high amount of sediment. The same groundwater sample was filtered and a second analysis for radioactivity provided gross alpha and beta levels one- to two-orders of magnitude lower than the initial unfiltered sample. This provides positive evidence of the correlation of sediment in the D2 groundwater sample, and anomalously high metal concentrations.

Overall, the metal concentrations in the groundwater samples from the regional wells are low and no contamination of metals from the NFERC to the groundwater is evident in the wells sampled.

TABLE 11-2

Inorganic Concentrations of Regional Well Samples

(all results in mg/L unless otherwise noted)

Well # Sampling date	MCLs	A1 7/91	B1 7/91	C1 7/91	D1 7/91	D2 7/91	E1 7/91	E1(dup) 7/91	F1 7/91	F2 7/91	G 7/91	H 7/91	I1 6/92	J1 6/92	K 6/92
Ag	0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Al	0.5-0.2	0.4	6.7	1	5	368	12	5	12	3.6	4.1	12			
As (ug/l)	50	1.1	48.2	<1	2.5	113	1.3	87	<1	<1	4.5	4	<4	<4	<4
At													<0.2	<0.2	<0.2
B		<0.1	0.1	<0.1	<0.1	0.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
Ba	2	<0.1	<0.1	0.3	0.1	0.4	<0.1	<0.1	<0.1	0.1	<0.1	0.1	<0.1	<0.1	<0.1
Be		<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07
Cd	0.005	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Co													<0.04	<0.04	<0.04
Cr	0.1	<0.3	<0.3	<0.3	<0.3	0.5	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Cu	1	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Hg (ug/l)	2		<0.5	<0.5	<0.5	<0.5	1.4	<0.5	<0.5	<0.5	<0.5	<0.5	1.3	1.3	1.3
K		4	8.6	5.7	18.1	1	1.1	1.2	6.7	1.6	29	2.1			
Mn	0.05	<0.1	0.3	0.5	0.5	2.6	0.2	0.2	0.1	1.1	0.5	12			
Mo		<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
Na		11.3	0.96	32.9	3.9	<0.05	5.8	6.2	53.9	1	24.1	2.2			
Ni		<0.2	<0.2	<0.2	<0.2	0.3	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Pb	0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sb		<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2			
Se (ug/l)	50	2.86	2.87	<2	<2	20.6	<2	2.12	<2	<2	<2	<2	<8	<8	<8
Sr		0.6	0.7	0.1	0.5	0.4	0.2	0.2	0.2	<0.03	0.3	0.2			
Th													<0.4	<0.4	<0.4
Ti													<0.04	<0.04	<0.04

TABLE 11-2

(continued)

Well # Sampling date	MCLs	A1 7/91	B1 7/91	C1 7/91	D1 7/91	D2 7/91	E1 7/91	E1(dup) 7/91	F1 7/91	F2 7/91	G 7/91	H 7/91	I1 6/92	J1 6/92	K 6/92
Tl		<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
V		<0.04	<0.04	<0.04	<0.04	0.7	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Zn	5	<0.1	<0.1	0.2	<0.1	1.4	0.2	0.2	<0.1	<0.1	0.2	0.1	<0.1	0.2	0.1
Cl	250						35.22'		71.49'		75.16'		7.13'		
Cyanide		<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.10	<0.10	<0.10
F	2	0.5	0.5	0.4	0.3	0.4	0.5	0.5	0.5	0.2	0.2	0.3			
Nitrate(as N)	10	0.4	8.6	5.7	18.1	1	1.8	1.7	4.3	16.7	4.1	<0.1			
Nitrite(as N)	1	0.4	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1			
Nitrogen		0.81	0.35	0.03	0.09	1.24	0.26	0.29	0.16	0.03	0.54	0.68			
SO_4		53.7	29.6	1	9.6	1.5	4.1	4.1	7.1	1.3	5.5	19.4			
total sulfides		<0.1	0.1	<0.1	<0.1	0.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.8	2	1
Solid (%)		<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5			
Alkaline		340	210	17	162	18	170	157	171	24	152	137			
Acidity		0	18	62	15	25	8	7	6	19	0	100			
pH		11.8	7.1	5.4	7.1	5.3	7.4	7.4	7.2	5.5	9.3	5.9	10.05	11.26	7.16
Gross alpha (pCi/L)		<1.5	4.4	<1.5	<1.5	54(<1.5)*	6.7	5.7	<1.5	4.7	10.2	5.1	<1.2	<2.2	<3.3
Gross Beta (pCi/L)		4.2	18.7	5.4	14	142(<1.7)*	12.5	9.2	9	22.4	53.1	12.3	2.14	48.7	7.7
Radium 226 (pCi/L)													0.17	0.16	2.2

*results after filtering the sample 'results of 6/92 analysis

11.2.2 Other Inorganics

The concentrations of other inorganics, including cyanide, F, and sulfate, are below the MCLs. These data, along with measured field parameters, are listed in Table 11-2.

11.3 Chloride

Chloride (Cl) concentrations in groundwater can be affected by several sources. In the vicinity of NFERC, these sources include the (1) rock type and composition of both the hosting and flow-path rocks, and (2) contaminant sources from industrial, human and agricultural activities. Chloride components and complexes are typically very soluble in the water, and chloride is commonly present in the rocks as Na, K, and Ca salts. The increases in chloride concentrations (salinity) in groundwater often increases calcite solubility.

Both hosting and flow-path rocks have a major contribution to the groundwater chemical compositions. When the water either resides in or flows through the rocks, water-rock interactions will alter the compositions of the groundwater by dissolution/precipitation processes. This is especially true of carbonate rocks such as the Tuscumbia Limestone and Fort Payne formation. However, the effect of rock composition on chloride concentrations of the groundwater at the Muscle Shoals area is nil because the aquifer is located in rocks of predominantly limestone and cherty limestone that lack evaporate layers and are underlain by an aquiclude (Chattanooga Shale). Additionally, the groundwater is not known to flow through any chloride-containing rock units. Various groundwater analyses of aquifers in the Tuscumbia Limestone show that most of the aquifers have very low chloride concentrations (<7 mg/L; Table 11-3).

Since most chloride compounds are soluble in the water, chloride can be easily introduced into groundwater. Chloride is also a conservative contaminant and moves through the groundwater system with very little attenuation. Compared to other aquifers in the Tuscumbia Limestone (Table 11-4), Tuscumbia Spring exhibits significantly higher chloride concentrations (20-32 mg/L), indicating some possible non-natural inputs. Other springs along the south bank of the Tennessee River and along Spring Creek exhibit chloride concentrations ranging from 10 to 35 mg/L, with one spring (Len's Spring) as high as 1720 mg/L during a measurement on November 1990 (G&E Engineering, Inc., 1991). This indicates an anthropogenic source of groundwater contamination for these springs.

Additional evidence of non-natural input of chloride to groundwater of the Muscle Shoals area is the elevated chloride concentrations measured at Tuscumbia Spring during the last 60 years (Table 11-3; Figure 11-1). The increase of Cl concentrations seems to correlate to industrial development in the area. The Cl levels show a marked increase in the late 1950s from about 1 mg/L to 5 to 10 mg/L.

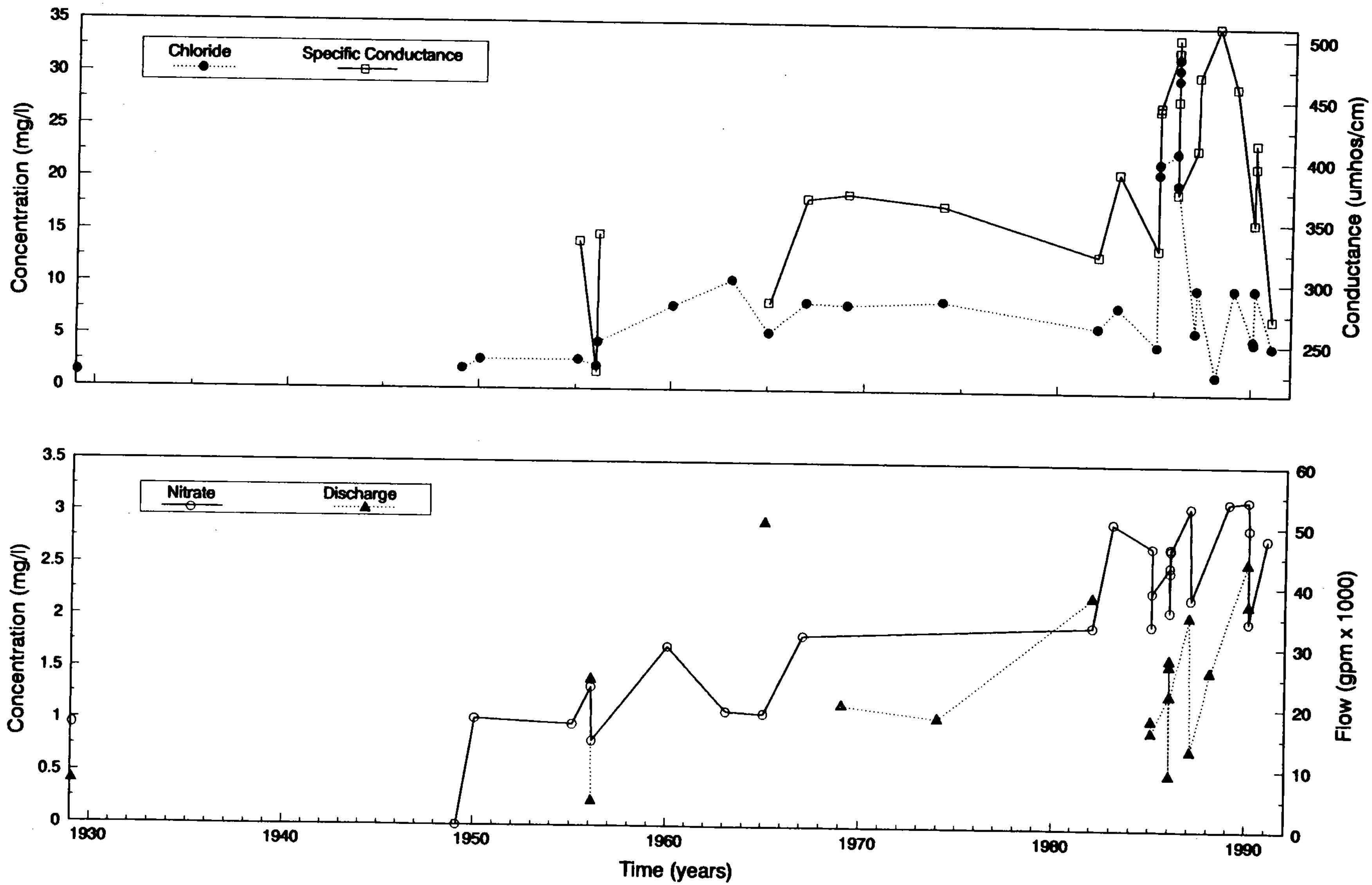

Figure 11-1. Nitrate and Chloride Concentrations at Tuscumbia Spring from 1929 to 1991

TABLE 11-3

Historical Water Quality Data of Tuscumbia Spring

Date	Specific Conductance (umhos/cm)	Chloride (mg/L)	Nitrate (as N) (mg/L)	Discharge (gal/min)
08/03/29	--	1.4	0.95	6750
12/28/94	--	1.9	nd	--
02/24/50	--	2.8	1.02	--
11/30/55	331	2.8	0.97	--
04/10/56	224	2.2	1.33	23625
11/23/56	337	4.5	0.81	4050
03/27/60	--	8.0	1.72	--
11/16/63	--	10.5	1.10	--
05/06/65	282	5.5	1.08	49500
02/07/67	367	8.4	--	--
08/03/67	--	--	1.83	--
10/12/67	371	8.2	--	19800
11/03/69	362	8.6	--	18270
01/08/74	322	6.2	1.94	37800
06/08/82	390	8.2	2.94	--
06/10/83	328	4.5	2.71	--
09/17/85	442	21.0	1.96	18450
10/01/85	445	22.0	2.28	15930
11/12/85+	490	23.0	2.53	22172
02/06/86	500	32.0	2.10	8730
03/19/86	490	31.0	2.71	26500
03/21/86	450	30.0	2.48	28220
05/28/86+	374	20.0	2.69	22441
05/20/87#	410	5.9	3.1	35278
11/16/87#	470	10.0	2.22	12886
05/02/88*	510	1.7	0.13	25767
12/12/88#	461	10.0	3.15	--
06/12/90#	350	5.2	3.17	43653
06/18/90#	415	4.9	2.9	36840
12/10/90#	396	10.0	2.0	--
05/21/91#	271	4.5	2.8	--

nd = not detected -- not available

Data Source: Chandler and Moore, 1991.
*Moore, 1989
#Geologic Survey of America
+Chandler and Moore, 1987

TABLE 11-4

Chloride Concentrations for Selected Well and Springs
Developed in Tuscumbia Limestone

Well/Spring	Chloride Concentrations (mg/L)			
	1986[+]	1987[+]	1988[+]	1990[#]
Muscle Shoals Area				
Tuscumbia Spring	20-32			
Big Tuscumbia				35
Little Tuscumbia				17
Railroad Trestle Spring				27
Len's Spring				1720
Jr. High School Cascade				10
Lower Shoeshine				13
Ice Plant Spring				23
TVA waterfall				12
Other Areas in Alabama				
Ardmore		5.2	3.1	
Rogersville		1.7	6.4	
Stevenson		2.3	2.6	
Trussvile		1.4	1.6	
Huntsville		3.3	3.9	

Note: [+]AGS, 1988, 1989
[#]G&E Engineering, Inc., 1991

Another significant increase can be observed during a period in 1985 and 1986 with chloride levels returning to the approximate 5 to 10 mg/L range thereafter. Although the data is scarce, there does appear to be some reverse (i.e., negative) correlation between chloride levels and spring discharge. That is, chloride levels increase with corresponding reductions in spring flow. This indicates that chloride becomes more concentrated in the groundwater system during drier periods when dilution is lower. As expected, a positive correlation exists between chloride and specific conductance for the period of record. Specific conductance is highly correlated with major ionic species and therefore can be considered a master variable.

Chemical analyses of groundwater from wells F1 and G at NFERC (Figure 6-1) reveal elevated levels of Cl (>70 mg/L) relative to background values (10-30 mg/L) for other wells (Table 11-2), although all of these concentrations are below the MCL of 250 mg/L. Wells F1 and G, and water supply wells in the nursery area of NFERC (62' and 80' wells) that also exhibit elevated levels of Cl (Young and Julian, 1991) are located in the east and southeast part of NFERC, hydraulically downgradient from the OxyChem plant site (Figure 6-1).

G&E Engineering, Inc.'s studies (1991) at the OxyChem site revealed the presence of a chloride contaminant plume that is the result of storage and handling of chloride salts at the facility (Figure 11-2). In the center of the plume, the Cl concentration is about 50,000 mg/L. The chloride plume extends somewhat radially away from surface contaminant sources. As shown in Figure 11-2, the lower plume isopeths indicate that chloride concentrations in groundwater can be as much as 250 mg/L near the south and west edges of the OxyChem site. Considering that groundwater flow directions in this vicinity are west-southwest, and Cl concentrations are elevated in wells located on the southeastern corner in the NFERC reservation, the relatively high Cl concentrations observed in NFERC wells is probably the result of chloride contamination from the OxyChem site.

11.4 Nitrate

Young and Julian (1991) identified nitrate as the groundwater contaminant of most concern near SWMU 108 with respect to both health risks and implication to understanding the vertical migration of solutes through the overburden. At several of the deeper wells sampled near SWMU 108, nitrate concentrations were near 100 mg/L, which is ten times greater than the MCL (Table 11-5). High nitrate concentrations measured at several bedrock wells suggested that nitrate-contaminated recharge has migrated downward relatively quickly and with minimal dilution.

Table 11-5 lists the nitrate-nitrite concentrations observed in groundwater samples from wells near SWMU 108 during the last several years. The nitrate information shows that most wells screened in the upper overburden typically had nitrate concentrations of less than 20 mg/L. Relatively high nitrate concentrations were present at the staged wells designated with a '12'. Figure 11-3 shows the nitrate concentration for these staged wells. The nitrate profile shows high concentrations at the shallowest and deepest wells and low concentrations at the intermediate wells. The staged wells are in a vicinity of a downward vertical hydraulic gradient. Because the nitrate profile at these staged wells could not be explained using classical solute transport models and a low-permeability overburden exists at the site, the improper construction of several older wells was suspected.

Inspection of several of the earliest well constructs, which included well W12, revealed a design flaw that created a relatively large sand-filled annulus around the well that could serve as a conduit for rapid vertical migration of groundwater from the upper overburden to the bedrock. Young and Julian (1991) estimated that from September 1985 to July 1990, about 89,000 liters of groundwater from the upper residuum may have short-circuited ambient groundwater flow patterns and entered the regional groundwater flow regime through the annulus of well 12.

Wells W9, W11, and W12 were abandoned in September 1992 as described in Chapter 6. Figure 11-3 shows the vertical nitrate concentrations profile in the vicinity of the staged '12' piezometers in June 1992. The plot shows a reduction in nitrate concentrations from previous levels, especially below the sampling interval represented by PZ12A. The data suggests that the suspected problems at wells W9, W11 and W12 were real and contributed to

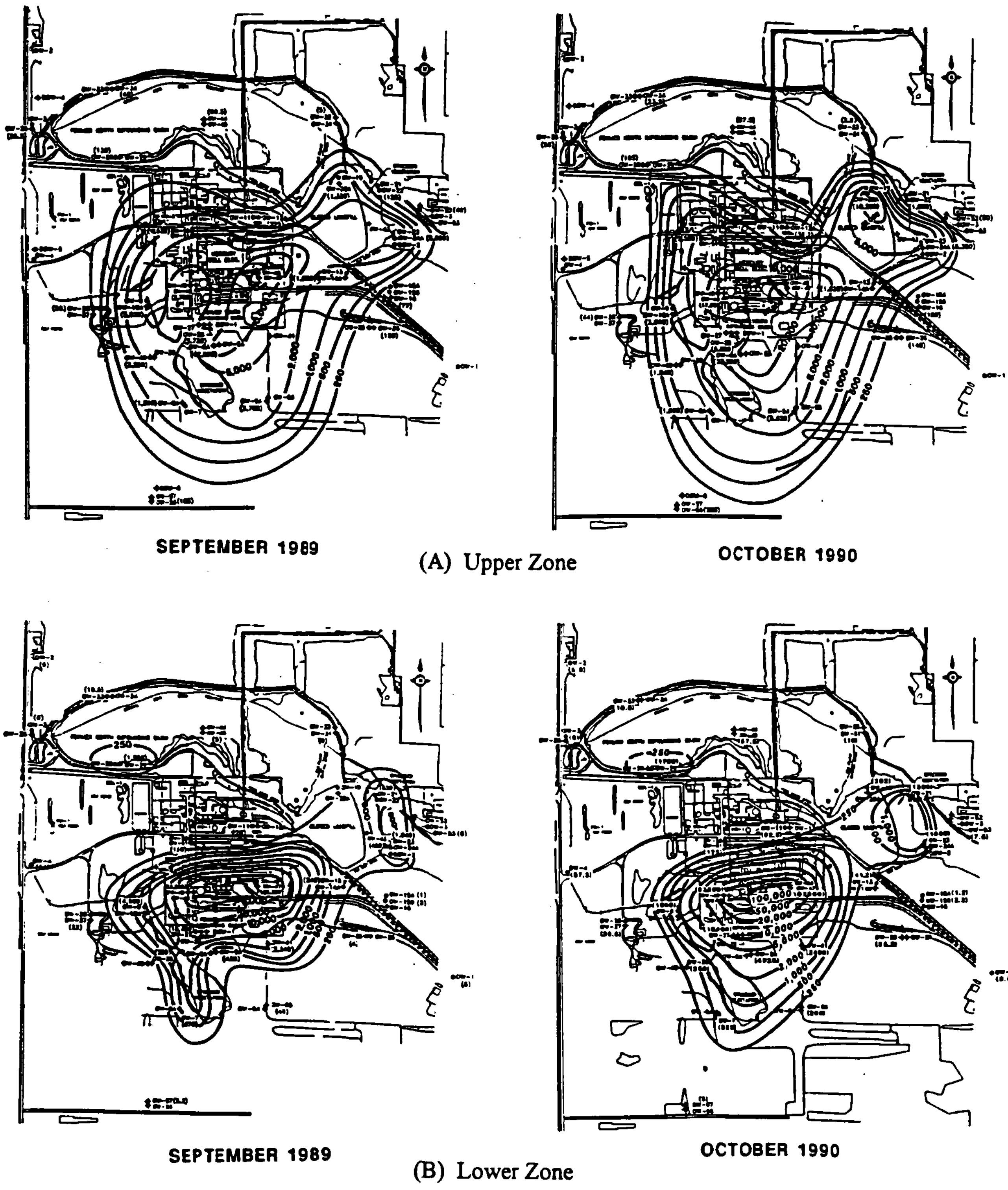

Figure 11-2. Chloride Plumes at the OxyChem Site. The (A) Upper Zone Represents Overburden Concentrations of Chloride (mg/L) and the (B) Lower Zone Provides Chloride Concentrations (mg/L) in the Upper 5 to 10 ft of Tuscumbia Limestone

TABLE 11-5

Nitrate-Nitrite Concentrations (mg/L) at SWMU 108

	July 1991				June 1992	July 1990	June 1989
	Before Purge		After Purge				
Well #	Nitrate	Nitrite	Nitrate	Nitrite	Nitrate	Nitrate	Nitrate
W9	30.20	<0.1	25.10	<0.1		12	
W10	181.00	<0.1	132.00	<0.1			
W11	19.60	<0.1	14.50	<0.1		11	
W12	199.00	<0.1	218.00	<0.1		210	
W13	80.10	<0.1	146.00	<0.1		150	
W15	19.60	<0.1	147.00	<0.1			
W18	2.00	<0.1	1.10	<0.1		0.52	
PZ1A	11.30	<0.1	9.80	<0.1		11	12.8
PZ1B	1.70	<0.1	1.40	<0.1			
PZ1C	5.90	<0.1	96.10	<0.1		100	
PZ2A	2.80	<0.1	2.70	<0.1			
PZ2B	1.80	<0.1	2.20	<0.1		1.1	1.1
PZ2C	1.10	<0.1	0.70	<0.1			
PZ2D	1.70	<0.1	1.80	<0.1		2.2	
PZ9A	8.10	<0.1	6.70	<0.1			
PZ9B	0.90	<0.1	0.50	<0.1		0.49	
PZ9C	54.20	<0.1	76.80	<0.1			
PZ11A	15.50	<0.1	23.00	<0.1	69.20	29	51
PZ11B	2.00	<0.1	<0.1	<0.1	0.13		
PZ11C	2.80	<0.1	1.20	<0.1	0.15		
PZ11D					14.30		
PZ12A	205.00	<0.1	208.00	<0.1	165.30		253
PZ12B	2.90	<0.1	83.20	<0.1	77.78	94	
PZ12C	6.10	<0.1	9.60	<0.1	26.80		
PZ12D					30.77		

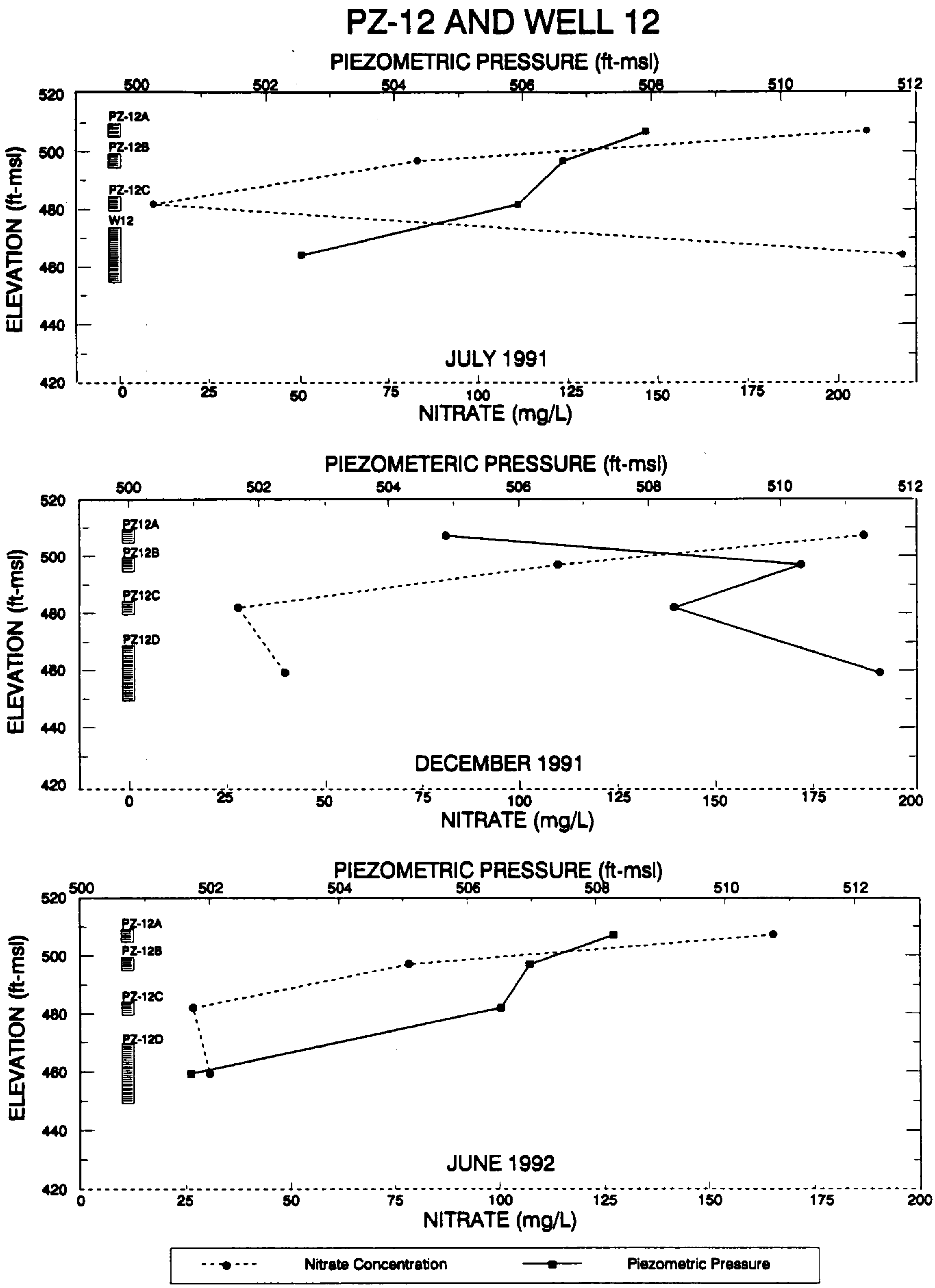

Figure 11-3. Nitrate Concentrations at PZ12 Near SWMU 108

the high nitrate concentrations in the wells screened in the upper bedrock. A closure plan was devised for SWMU 108 (Julian and Young, 1992) that outlines selected monitoring and analysis for nitrate at NFERC over the next several years.

Chemical analyses of groundwater from the regional wells of the NFERC (Table 11-2) show that nitrate levels in the groundwater were mostly below the MCL of 10 mg/L. The values (nitrate as N) range from less than 0.1 to 18.1 mg/L, with most measurements occurring between 1 and 5.7 mg/L. However, two wells, D1 and F2, show slightly elevated nitrate levels (18.1 and 16.7 mg/L, respectively). The elevated nitrate concentration in the two wells is not likely to be related to SWMU 108. This conclusion is based on the facts that (1) no elevated nitrate levels were found in the wells between SWMU 108 and wells D1 and F2, and (2) well F2 is an overburden well up-gradient of SWMU 108. Therefore, the slightly elevated nitrate levels in well D1 and F2 are probably the result of local sources, such as surface agriculture activities.

Chandler and Moore (1991) conducted a water quality evaluation of storm-water drainage wells in the Muscle Shoals area. Groundwater from the drainage wells, water wells, and Tuscumbia Spring were sampled and analyzed in September 1985 and March 1986. The nitrate (as N) concentrations of groundwater samples from the drainage wells were between 0.01 and 1.64 mg/L during 1985-1986. The concentrations of nitrate in samples from the water wells ranged from 0.05 to 3.33 mg/L in the same period. Tuscumbia Spring had nitrate concentrations between 1.96 and 2.71 mg/L. Most of the values are below the MCL for nitrate. The nitrate concentrations observed in the regional wells at NFERC is in the same magnitude as the background values presented by Chandler and Moore (1991).

Nitrate levels have been measured for Tuscumbia Spring since 1929 as part of a water quality monitoring program by the Geological Survey of Alabama (Table 11-3; Figure 11-1). Although Figure 11-1 indicates that there might be a slight increasing trend in nitrate levels at the spring, almost all measurements indicate less than 3 mg/L of nitrate (as N) in spring waters. These nitrate concentrations are below the MCL of 10 mg/L for nitrate. The few coincident data points that are available for nitrate and spring discharge indicate a possible positive correlation between the two. If this is the case, it would indicate that nitrate is not being diluted in the groundwater system during periods of higher flow; rather, additional nitrate is being introduced into the system. This might be the result of surface nitrate sources such as agricultural activities in the area.

These results suggest that nitrate contamination from the SWMU 108 area poses little health risk to the Tuscumbia Spring groundwater supply. The regional well data also implies that the migration of nitrate from SWMU 108 is limited, most likely by dispersion and dilution.

11.5 Organic Compounds

Organic compound analyses were performed on all new regional wells and four existing wells near SWMU 108 that exhibited low levels of organic contamination from previous sampling events (Young and Julian, 1991). Altogether, 19 groundwater samples were analyzed

according to Table 8-9, Volume 1, of the EPA Interim Final RFI Guidance Manual. Results of the analysis are included in Appendix D.

Table 11-6 lists only those organic compounds detected in the groundwater samples. Overall, only the volatile organic compounds were positively identified in a few groundwater samples. These wells include regional wells of A1, B1, and F1, and three SWMU 108 wells. All other organic compounds are below detection limits.

TABLE 11-6

Volatile Organic Compounds Above Detection Limits in NFERC Wells (in μg/L)

Well # Sampling Date		A1 7/91	B1 7/91	F1 7/91	W9 7/91	W9(dup) 7/91	W12 7/91	PZ11C 7/91	I1' 6/92
	MCL(μg/L)								
Carbon disulfide									431*
2-Chloroethylvinyl ether						110			
Bis(2ethylhexyl)phthlate			7	7	5				
Carbon tetrachloride	5				26	24			
Tetrachloroethylene	5				550	600	11	38	
Vinyl chloride	2					110			
Chloroform		73							

Note: Analyzed by TVA's Environmental Chemistry Laboratory (Chattanooga, TN)
'Analyzed by Environmental Testing & Consulting, Inc. (Memphis, TN)
*Also detected in blank sample

11.5.1 Volatile Organic Compounds

Chloroform was detected only in well A1 at a concentration of 73 μg/L. No other samples have concentrations above the detection limit (5 to 10 μg/L) for this compound. Chloroform ($CHCl_3$) is used as solvents, in cleansing agents, and in fire extinguishing agents. It is water soluble and very mobile in groundwater.

Bis(2ethylhexyl)phthlate was detected in two regional wells (B1 and F1). However, the concentrations are barely above the analytic detection limit. Bis(2ethylhexyl)phthlate is also detected in groundwater samples from well W9 at detection limit (5 μg/L) in this study. The groundwater samples from well I1 show the presence of carbon disulfide (Table 11-5). However, the compound was also detected in blank samples so that the carbon disulfide is probably a false positive.

Several organic compounds, including carbon tetrachloride, tetrachloroethylene, and bis(2ethlhexyl)phthlate, were found at or above detection limits in groundwater samples from several wells near SWMU 108. Carbon tetrachloride is found in well W9 at a concentration of 25 μg/L, and tetrachloroethylene in well W9, W12, and PZ11C at concentrations of 575, 11, and 38 μg/L, respectively (Table 11-6). The concentrations are above the MCLs (5 μg/L).

Presence of the two compounds has also been detected in earlier groundwater analyses during 1987-1990 (Young and Julian, 1991) from the same wells. Carbon tetrachloride concentration from well W9 in 1987 was 25 μg/L, that is essentially the same as this study. Tetrachloroethylene concentration in well 9 was 684 μg/L in 1987, and 590 μg/L in 1990. The tetrachloroethylene concentration in well 12 was 12 μg/L. Compared with all other concentrations throughout the last few years, it is apparent that their concentrations have been consistent with a slight decrease in concentration of carbon tetrachloride in well W9.

Compounds 2-chloroethylvinyl ether and vinyl chloride are present in a duplicate groundwater sample from well 9. However, the initial sample from this well shows no presence of the two compounds. Considering that both of the samples have nearly identical concentrations of other compounds (carbon tetrachloride and tetrachloroethylene), 2-chloroethylvinyl and tetrachloroethylene in the duplicate samples appear to be the result of contamination from small pieces of the PVC well casing (samples were not filtered).

11.5.2 Tentatively Identified Organic Compounds

As shown in Appendix D, several base-neutral and acid extractable compounds were tentatively identified in the three most recently installed regional wells (I1, J1, and K). Table 11-7 shows the estimated concentrations in the samples. Fifteen compounds were tentatively identified. All these compounds are not target compounds as listed by EPA. Two of the compounds, dodecanoic acid and cyclotrasiloxane, octamethyl, are present in all samples, including reagent and equipment samples. Therefore these two compounds are the result of contamination during sampling. The other organics are probably false positives or are the result of contamination from the PVC well casing.

11.6 Effect of Pond Creek on Groundwater Quality

As described in Chapter 3, Pond Creek is a receiving stream for wastewater and stormwater runoff from NFERC, the Muscle Shoals Wastewater Treatment Plant, and industries that include OxyChem and Reynolds. Pond Creek is probably both a sink and a recharge source to the groundwater across the NFERC site. Various studies have been performed for Pond Creek. These studies included the collection and analysis of surface water and sediment samples, flow measurements, and dye tracing. In 1985, TVA conducted surface water sampling and flow measurements for Pond Creek. Dye tracing was used to determine stream velocities in the study (Chapter 3). Additionally, temperature, pH, and dissolved oxygen were measured at five 15-minute intervals. Selected water samples were analyzed for biochemical oxygen

demand, ammonia nitrogen (NH_3-N), and kjeldahl nitrogen. The data indicate that most of the nitrogen is in the form of NH_3-N that ranges from 0.00 to 8.7 mg/L.

TABLE 11-7

Tentatively Identified Organic Compounds in Regional Wells

Well No.	I1	J1	K
Sampling Date	June 1992	June 1992	June 1992
Base, Neutral, and Acid Extractables (in μg/L)			
Cyclotetrasiloxane, octamethyl	15*	29*	32*
Dodecanoic Acid	28*	9*	110*
1-Penten-3-ol, 2-methyl	41	146	
Hexanedioic acid, dicyclohexyl ester	14	240	
Silane ethenyldiethylmethyl-1-Octanol		7	4
Octanoic Acid		7	
6H-Ourin-one,2-(dimethylamino)-1,7-dihydro-		7	
Tinuvin P		5	
Eicosane		35	
Heptadecane		105	
Hexatriacontane		33	
Pentriacontane		26	
Dotriacontane		22	
Cyclohexanol, 2-bromo, cis			8

Note: Analyzed by Environmental Testing & Consulting, Inc. (Memphis, TN)
*Also detected in reagent and equipment samples

In 1989, TVA again collected and analyzed samples of surface water and sediments from Pond Creek adjacent and slightly upstream of SWMU 108 during the SWMU 108 investigation (Young and Julian, 1991). Details of the study are described in the report by Young and Julian (1991). Chemical analyses indicated no organic compounds in Pond Creek's surface water; however, numerous organics were found in the sediment sample from several locations which included a location upstream of SWMU 108. The organics included polynuclear aromatic compounds, volatile halogenated hydrocarbons, and petroleum compounds. All these are common products of industrial use and could be contributed from upstream industrial

sources. The water quality in Pond Creek is diversely affected by various industrial pollution sources, surface water runoff, and interchange with groundwater.

11.7 Off-Site Facilities

Several major industrial facilities are located east of NFERC, upstream along Pond Creek. They include the OxyChem chlor-alkali plant, the former Ford castings plant, and the Reynolds Aluminum production plant. Based on regional water table measurements as shown in Figure 9-1, these plants are upgradient of NFERC. Therefore, any contaminations from these sites might affect the groundwater water quality at NFERC via groundwater or surface/groundwater interaction associated with Pond Creek.

Groundwater investigations have been completed at some of the sites as described in Chapter 2. The groundwater quality assessments of these studies are summarized below.

11.7.1 OxyChem Plant

Analyses of groundwater samples from existing wells at the OxyChem site confirmed the observations of initial site studies. The mercury concentrations in groundwater samples ranged from below 2 to 280 μg/L; cadmium concentrations from below 5 to 250 μg/L; and chloride concentrations from 1 to 170,000 mg/L. Laboratory analysis of groundwater samples from the deep wells (DOW wells) revealed consistent concentrations of mercury, cadmium, and chloride. Hg concentrations ranged from <0.2 to 20 μg/L; Cd from <5 to 21 μg/L; and Cl from 102 to 16,400 mg/L.

11.7.2 Former Ford Plant

The most prevalent compounds identified at this site are volatile organic compounds (IVOCs). They include tetrachloethene, trichloroethane, 1,2-dichloroethene, and vinyl chloride. Priority pollutant analysis indicates that the four IVOCs comprise over 95 percent of total volatiles detected at the facility. IVOCs are widely distributed across the Ford site, both horizontally and vertically. IVOCs were also detected in soil samples as high as 543 mg/L and in groundwater as high as 822 mg/L. Off-site IVOC detection that were above their respective MCL show that a possible plume was extended to southwest direction. A dye tracing performed during the investigation also suggested the similar direction of groundwater movement.

Polychlorinated biphenyls (PCBs), mostly as PCB-1242, were also detected in on-site wells although they were not observed in any wells off-site. Dense nonaqueous phase liquids have been observed at the site containing IVOCs, PCBs, and hydrocarbons. Ethyl benzene and xylenes have also been identified at the site and are assumed to be associated with local spills and leaking fuel oil and gas tanks. Other chemical parameters that have been identified on-site but are considered to have originated east of the site (possibly from the Reynolds Aluminum site) include cyanide, arsenic, zinc and possible 4-penten-2-ol.

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