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The Hydrogeologic effects of fly ash utilization in concrete at Coal Creek Station, Underwood, North Dakota

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THE HYDROGEOLOGIC EFFECTS OF FLY ASH UTILIZATION IN CONCRETE AT COAL CREEK STATION, UNDERWOOD, NORTH DAKOTA

by

Terry R. Johnson

Bachelor of Science, Bemidji State University, 1987

A Thesis
Submitted to the Graduate Faculty
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for the degree of
Master of Science

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1990

This thesis submitted by Terry R. Johnson in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota has been read by the Faculty Advisory Committee under whom the work has been done, and is hereby approved.

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P. Gerla (Chairman)

J. R. Reid
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F. Beaver

This Thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

Permission

Title The Hydrogeologic Effects of Fly Ash Utilization in Concrete at Coal Creek Station, Underwood, North Dakota

Department Geology

Degree Master of Science

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Signature Terry R Johnson

Date July 16, 1990

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

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My father, Ken, and mother, Arlene, deserve a special thank you. Without their constant encouragement and support

I may have chosen a different path through life. A part of this degree belongs to them.

ABSTRACT

Coal Creek Station is a two-unit 1100 megawatt electrical power plant located in southern McLean County, North Dakota. Annually, 5 million tons (4.5 million metric tons) of lignite are burned at the plant producing 550,000 tons (500,000 metric tons) of fly ash. Approximately 80,000 tons (72,624 metric tons) of ash are sold as a cement replacement, while the remainder is disposed of in lined evaporation ponds. The present study investigates the environmental consequences of ash utilization as an alternative to disposal. The Electric Power Research Institute (EPRI) provided funding for this investigation which involves the installation of 5,288 cu yds (4,043 m^3) of concrete in roadways at CCS. The concrete contains a 70% replacement of Portland cement with fly ash. The purpose of this study was to determine whether or not use of fly ash in concrete releases any environmentally deleterious substances to soil or ground water.

Stratigraphy at the site consists of a variable unit of fill material underlain by Paleocene bedrock of the Sentinel Butte Formation. The fill unit was created by construction projects during the past 10 years. Fill materials are more permeable than bedrock, consequently the occurrence of fill influences recharge rates and ground water flow patterns.

A comprehensive water monitoring network encompassing surface water, unsaturated zone water, and saturated zone

water was designed for the site. Surface water quality was documented using a runoff collector and precipitation collector. Soil moisture and ground water occurrence and quality were monitored using pressure-vacuum lysimeters and monitoring wells.

Two geologically distinct sites were instrumented, one representing a recharge zone (monitoring nest 2) and the other a zone of little recharge (monitoring nest 1). Each monitoring nest contains 3 pressure vacuum lysimeters at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m) and 1 monitoring well. Both monitoring nests were downgradient of fly ash concrete installations. Background water quality data were provided by preconstruction samples and two monitoring wells upgradient from the site.

To date, data suggest that there has been no degradation in water quality attributable to leaching from the concrete. Data obtained from monitoring nest 2 indicate that in recharge zones the composition of water in the saturated zone is largely determined within the unsaturated zone. The creation of localized recharge zones may mobilize certain constituents of the unsaturated zone causing a degradation of water quality in the saturated zone. In settings characterized by low recharge, much of the mineralization available to the system remains in the unsaturated zone and the composition of the unsaturated and saturated zone remains chemically distinct.

INTRODUCTION

General

The demand for electricity combined with increasingly stringent government regulation has caused coal-fired power plants to generate an ever increasing amount of fly ash and flue-gas desulfurization wastes. In the past, pit disposal or mine containment were the only means of waste management. These disposal practices have been shown in some cases to pose a serious threat to the environment. More recently, byproduct utilization has been considered as an alternative to disposal. The present study was designed to monitor the impact of concrete containing a high percentage of fly ash (70%) on soil and ground water quality at Coal Creek Station near Underwood, North Dakota. If proven to be an environmentally and technically sound practice, the use of appropriate quality fly ash in concrete will reduce the need for disposal and associated environmental hazards and liabilities.

The Electric Power Research Institute (EPRI) funded this project. Under EPRI's Waste Management Program six similar projects are currently being funded to demonstrate high-volume ash utilization in backfill, roadways, and embankments. The goal of these efforts is to assemble information pertaining to the environmental acceptability and technical feasibility of ash utilization. The underlying assumption is that development of technical guidelines concurrent with greater awareness of ash utilization will lead to an increase in marketability, thereby allowing utilities to manage their ash through sale rather than disposal.

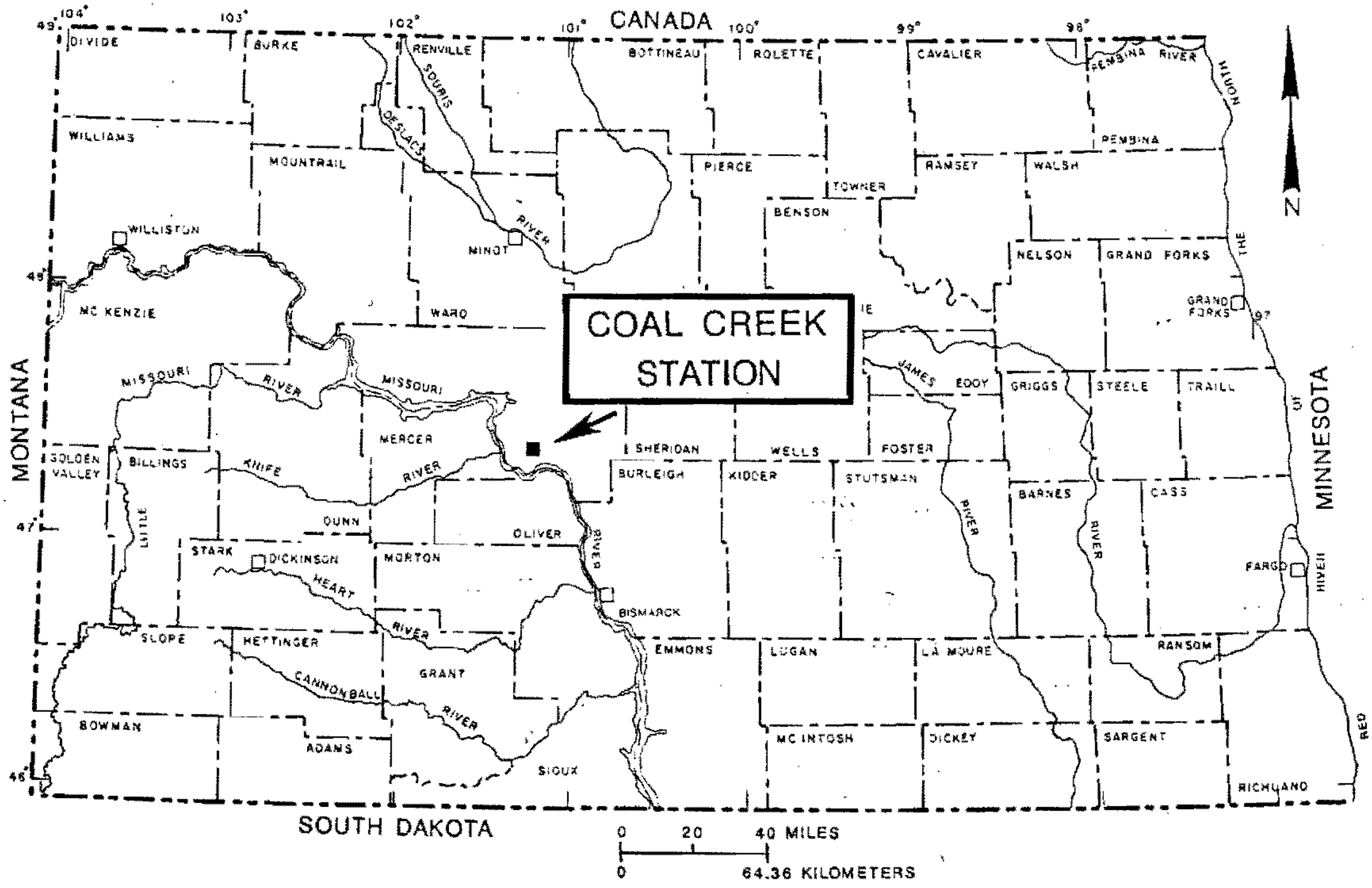
Location

Coal Creek Station (CCS) consists of a two-unit 1100-megawatt mine-mouth facility in southern McLean County, approximately 5 miles (8 km) northeast of the Missouri River (Figure 1). The study area encompasses approximately 0.2 square miles (0.3 km^2) at CCS, 5 miles (8 km) southwest of Underwood and 8 miles (13 km) northeast of Washburn, North Dakota. Lake Sakakawea lies 11 miles (18 km) to the north of the site.

Plant Operations

Lignite is supplied to CCS from the nearby Falkirk Mine through a conveyor system. Annually, over 5 million tons (4.5 million metric tons) of coal are burned at CCS, resulting in 550,000 tons (500,000 metric tons) of fly ash. The ash is collected dry on electrostatic precipitators. Currently 14% of the fly ash is marketed for utilization, the remainder is deposited in lined evaporation ponds. Since the start of production approximately 6 million tons (5.4 million metric tons) of fly ash have been deposited in ponds at CCS at a total cost of 15 million dollars. A significant portion of

Figure 1. Location of study area.


COAL CREEK STATION
CANADA
MONTANA
SOUTH DAKOTA
MINNESOTA
N
104°
103°
102°
101°
100°
99°
98°
97°
49°
48°
47°
46°
DIVIDE
BURKE
RENVILLE
BOTTINEAU
ROLETTE
CAVALIER
PEMBINA
WILLIAMS
MOUNTRAIL
PIERCE
TOWNER
RAMSEY
WALSH
BENSON
NELSON
GRAND FORKS
MC KENZIE
WARD
EDDY
GRIGGS
STEELE
TRAILL
MERCER
SHERIDAN
WELLS
FOSTER
GOLDEN VALLEY
BILLINGS
BURLEIGH
KIDDER
STUTSMAN
BARNES
CASS
DUNN
OLIVER
STARK
MORTON
SLOPE
HETTINGER
GRANT
EMMONS
LOGAN
LA MOURE
RANSOM
BOWMAN
ADAMS
SIOUX
MC INTOSH
DICKEY
SARGENT
RICHLAND
WILLISTON
MINOT
DICKINSON
BISMARCK
GRAND FORKS
FARGO
SOURIS
DESLACS
RIVER
MISSOURI
RIVER
KNIFE
RIVER
LITTLE
HEART
RIVER
CANNONBALL
RIVER
JAMES
RIVER
PEMBINA RIVER
RED RIVER OF THE NORTH
0 20 40 MILES
0 64.36 KILOMETERS

these costs have resulted from the need to repair and replace leaking pond liners. All of these disposal costs result in higher energy costs to the consumer. Fly ash produced at CCS is of an excellent quality for cement replacement because of its high lime content. The ash has a wholesale market value of $2.71 per ton ($2.46 per metric ton), whereas disposal costs average $2.50 per ton ($2.27 per metric ton). If all the ash produced annually at CCS where marketed, the result would be a positive annual cash flow of 1.5 million dollars. At present, fly ash disposal causes a negative annual cash flow of 1 million dollars. Other positive effects of increasing utilization include a reduction in the environmental liability for the utility and a general improvement in the facility aesthetics.

Objectives

This project evolved from the need for additional information regarding the environmental effects of fly ash as a cement replacement. Specific objectives are:

1. to determine the occurrence, movement and quality of surface, soil and ground water at the site,
2. to determine the effect of concrete on the normal hydrogeochemical evolution of ground water in both disturbed and undisturbed strata,

3. to determine if 70% replacement of fly ash for Portland cement in roadway concrete releases any environmentally deleterious substances in the form of leachates and/or runoff, and
4. to assess the adequacy of the current monitoring network for future studies.

Related Research

Considerable research regarding fly ash utilization has been sponsored through the Electric Power Research Institute (EPRI). Other groups such as the Department of Energy (DOE) and the Environmental Protection Agency (EPA) have also shown considerable interest. Earlier studies have emphasized study of the environmental effects of fly ash in disposal settings. As the trend continues to shift from disposal to utilization, so must the research effort. Attention must be focused to provide environmental as well as technical guidelines on coal byproduct utilization. This is the goal of the current study and the other EPRI highway demonstration projects in progress in Michigan, Pennsylvania, Delaware, and Kansas.

The applications of fly ash in the Netherlands were investigated by Bolt and Snel (1986) with emphasis on the environmental effects due to leaching. Laboratory tests were done to assess the long-term potential of products containing fly ash to degrade water quality.

Specifically, clay/fly ash bricks were subjected to leaching by simulated rainfall. In addition, the adsorptive capacity of soil was evaluated as an attenuation mechanism. Arsenic was found to leach proportionately more than the other trace elements studied (Cd, Cr, Se, and V). However, Bolt and Snel (1986) concluded that the upper 3 feet (1 m) of soil was effective in adsorbing nearly 100% of the arsenic. The need for field studies to properly evaluate laboratory data was emphasized.

The leachability of lignite fly ash used as road base was investigated in Louisiana (Garcez and Tittlebaum 1987). The purpose of this study was to determine the influence of the soil stabilization process on ash leaching. Samples of a 30% fly ash/soil mixture were leached following the U.S. EPA multiple extraction procedure. Results indicated the soil stabilization process caused little change in the characteristics of the leachate. The lack of a reduction in leaching capacity was attributed to the low cation exchange capacity of the soil.

The impact to ground water quality from fly ash utilization in highway (asphaltic concrete) base-course was studied by Southern Company Services (1989). To simulate accelerated leaching, saw cuts were made through the pavement and placed so as to drain into leachate collection devices. In addition, laboratory leaching tests were performed on paving mixtures containing ash. Water quality monitoring data provided little evidence of leaching. Indicator concentrations tended to decrease through time after initial cleansing and accelerated leaching of test sections, suggesting long-term effects would also be minor. Laboratory data confirmed the low leaching potential of cement-stabilized fly ash sub-base.

Field and laboratory studies have documented the leaching potential of fly ash and various attenuation mechanisms in mine disposal settings in western North Dakota (Beaver, 1986; Hassett and Groenewold, 1986). The primary geochemical processes, such as oxidation, carbonate dissolution, gypsum dissolution, bacterial sulfate reduction, ion exchange, and adsorption, thought operative in the region have been identified and described (Cherry, 1972; Groenewold et al., 1983). This study extends this information to an evaluation of the susceptibility of soil and ground water at the CCS site to degradation by fly ash concrete.

Geological Setting

Climate

The climate at the site is classified as sub-humid continental (Jensen, 1972). Average temperatures range from -13°C in January to 22°C in July, with an average annual temperature of 6°C. Frozen conditions in the subsurface begin in November and may persist until early

May, with an average depth of freezing of 4.5 feet (1.4 m). Compaction in high traffic areas around the project site have caused freezing depths to exceed 5 feet (1.5 m). Frost in the region may reach 7.5 feet (2.3 m) below the surface (Jensen, 1972).

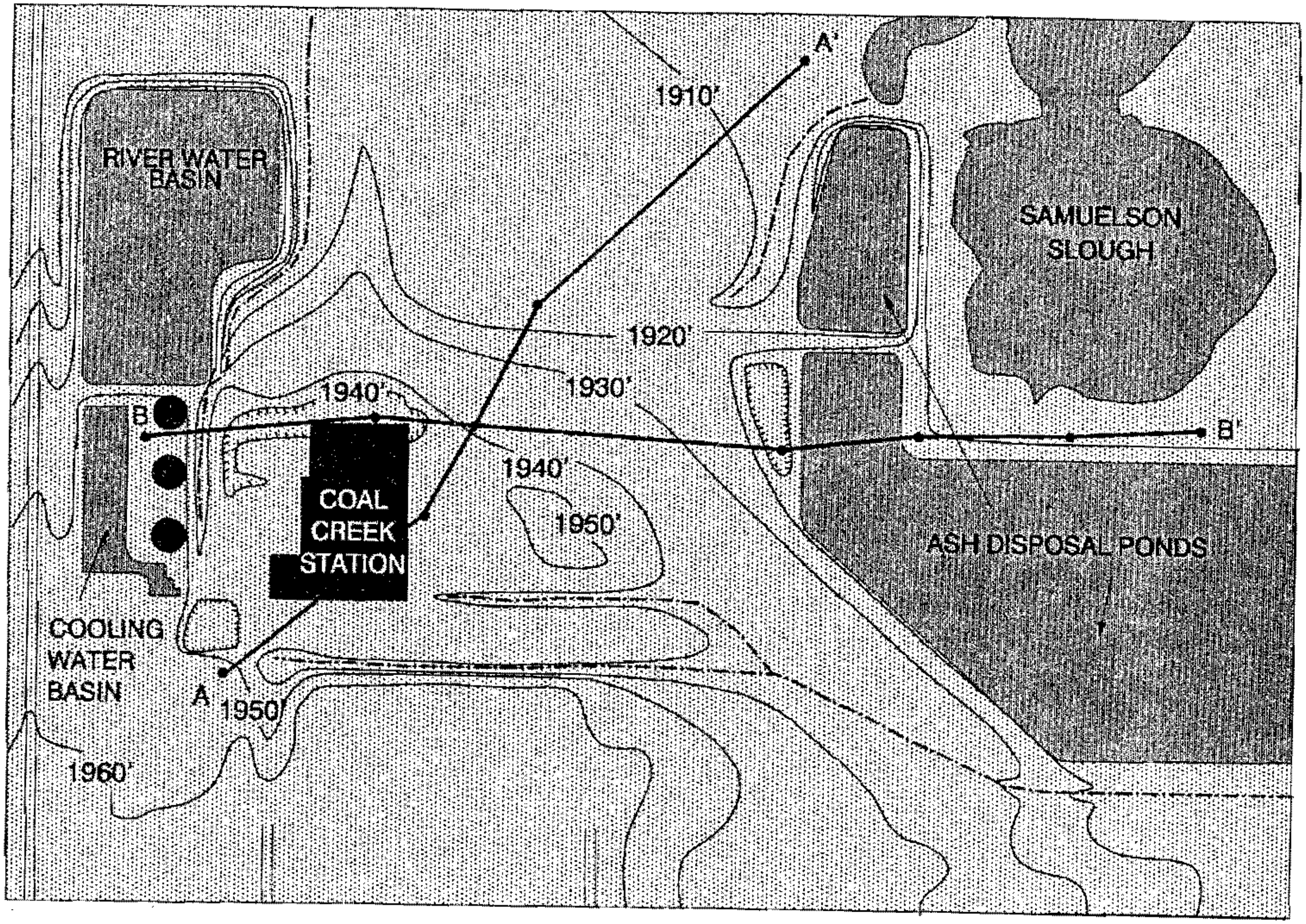
Approximately 90 percent of the precipitation for the area falls in the form of rain; the remainder falls as snow. Mean annual precipitation values vary temporally. Long term precipitation data from 1931 to 1960 indicate an average annual precipitation of 17 inches (430 mm). Annual precipitation during the study was 13 inches (330 mm).

Physiography

The study site is situated in the Coteau Slope physiographic area of the Great Plains physiographic province (Bluemle, 1971). The Coteau Slope is an area characterized by moderate local relief (less than 24 feet (8 m)), although relief as great as 91 feet (30 m) can occur in the vicinity of major valleys. Drainage on the Coteau Slope is well developed with small intermittent streams draining southward and westward into the Missouri River (Bluemle, 1971).

The project site is on an upland bedrock high bounded to the north and east by a buried valley. Topography throughout most of the site has been modified by human activity (Figure 2). In preparation for the

Figure 2. Topography of the Coal Creek Station site showing location of cross-sections, surface water impoundments and CCS.


A'
1910'
RIVER WATER BASIN
SAMUELSON SLOUGH
1920'
1930'
1940'
B
B'
1940'
COAL CREEK STATION
1950'
ASH DISPOSAL PONDS
COOLING WATER BASIN
A
1950'
1960'

construction of Coal Creek Station (CCS), approximately 25 acres were leveled. An additional excavation to a depth of 24 feet (8 m) beneath the leveled surface was required for the placement of footings beneath the power plant. Consequently, large volumes of material consisting of glacial till and bedrock were removed from the original topographic high in and around the plant site. Most of these fill materials were used to construct holding ponds; the remaining fill was redistributed around the site, primarily in the vicinity of the buried valley. Any suitable clay units intercepted during the excavation process were utilized as pond liner materials. The site was engineered so that surface water drainage is primarily eastward into the Samuelson Slough area. Samuelson Slough represents the only significant naturally occurring body of water at the site. The changes in drainage resulting from the most recent construction activities, combined with reduced precipitation, have depleted moisture supply to many intermittent surface water ponding sites.

In the study area there are several large artificial water impoundments (Figure 2). In the northwest corner of the site is a lined basin for the containment of Missouri River water obtained through an underground pipeline (River Water Basin). Immediately to the south is an unlined basin used for recirculating water for cooling plant operations (Cooling Water Basin). There are several lined fly ash evaporation ponds on the eastern side of the study area. The ash ponds overlie the western boundary of the buried valley and, depending on precipitation, may contain standing water. Situated above the central portion of the buried valley is an intermittent stream connecting a series of sloughs, including Samuelson Slough. Surface water in this wetland complex drains to the east and south into the Missouri River.

Stratigraphy

Subsurface units in the upland portion of the study area consist of Paleocene bedrock of the Sentinel Butte and Bullion Creek Formations of the Fort Union Group (Rehm, Groenewold, and Peterson, 1982). The buried valley has a complex glacio-fluvial stratigraphy comprised of units of the Pleistocene Coleharbor Formation (Rehm, Groenewold, and Peterson, 1982). Throughout most of the area the original glacial and uppermost bedrock stratigraphy has been altered by construction. The fill (disturbed) unit, because of its similarity to glacial till, is delineated primarily on the basis of information obtained during plant construction.

Stratigraphy in the buried valley is characterized by an alternating sequence of till and alluvium. The buried valley originates beneath Lake Sakakawea 12 miles

(20 km) north of the site and terminates .5 miles (1 km) southeast of the site. Throughout its 13 mile (21 km) course the buried valley averages 1 mile (1.5 km) in width, underlying an area of approximately 12 square miles (30 km^2). The buried valley thickens toward the north to a maximum of 295 feet (90 m) near Lake Sakakawea. In the vicinity of the plant site its known thickness averages 246 feet (75 m). Subsurface data in the southeastern portion of the study area indicate that the upper section of the buried valley consists of 9 feet (3 m) of till or fill materials directly overlying a unit of coarse alluvium averaging 13 feet (4 m) in thickness. In the northern portion of the site alluvium exists from a depth of 6.5 feet (2 m) to within 1.5 feet (.5 m) of the surface. Alternating units of till and alluvium continue through the intermediate depths of the buried valley, alluvium becoming more prevalent toward the base (Klausing, 1974). The buried valley, or Wellers Slough Aquifer (Klausing, 1974) is capable of yielding in excess of 1000 gpm (6 x 10-2 m^3/sec).

Paleocene units are composed of sandy, silty, and clayey sediments interbedded with lignite. These units vary in thickness from 1 foot to 50 feet (.3 m to 15 m). A majority of the units encountered in the study area consist of a mixture of fine to very fine sand and clay with variable amounts of silt. Lithologies are similar throughout much of the stratigraphic profile. Lignite is a minor constituent at the study area, comprising less than 5% of the stratigraphic column.

Hydrogeology

The depth to the water table at the site ranges from 52 feet (16 m) in the south to 6 feet (2 m) in the northern portion of the site. This variation is a direct response to changes in stratigraphy, topography, and drainage. In comparison to the northern portion, the southern part of the site is topographically higher with well developed drainage, and is underlain by low permeability bedrock; consequently it receives less infiltration and the water table is lower. Surface water and ground water from upland areas discharges into the buried valley. These sources of water, combined with permeable subsurface units lead to a higher water table in the buried valley than is found in upland areas.

Most of the Paleocene bedrock in the study area have low hydraulic conductivities. At a site adjacent to the northern edge of the buried valley, Rehm, Groenewold, and Peterson (1982) reported hydraulic conductivities ranging from 3×10^{-5} ft/sec (1×10^{-5} m/sec) to 1.6×10^{-10} (5×10^{-11} m/sec) for clay-rich bedrock units other than lignite. The variability in hydraulic conductivity is attributed to fractures. Hydraulic conductivity values for bedrock units encountered during the present investigation averaged 9×10^{-6} ft/sec (3×10^{-6} m/sec)

(Appendix A). Saturated sand and/or lignite units with appreciably higher hydraulic conductivity are scarce in the study area; where present they are generally less than 1.5 feet (.5 m) thick and are laterally discontinuous.

Units of alluvium within the Coleharbor Formation have a mean hydraulic conductivity of 1.6 x 10^{-4} ft/sec (5 x 10^{-5} m/sec), and are the most permeable units in the study area. Till exhibits a wide range of hydraulic conductivities. Unfractured till has a very low hydraulic conductivity; however fractures can increase the hydraulic conductivity by several orders of magnitude. The mean hydraulic conductivity for till in the area is 2.3 x 10^{-8} ft/sec (7 x 10^{-9} m/sec) (Rehm, Groenewold, and Peterson, 1982). All units of till and alluvium at the site are in the buried valley.

Pavement and Slurry Characterization

The concrete and slurry backfill installed during the present study used fly ash as a replacement material for Portland cement. Approximately 70% of the Portland cement in concrete was replaced with fresh fly ash from CCS. A total of 5288 cubic yards (4835 m^3) of concrete was installed in 8 inch (20 cm) slabs at the site (Figure 3). Two different concrete batch mixes and one slurry mix were used (Table 1). The first concrete mix was abandoned because of problems with strength gain

Figure 3. Detailed site map showing instrument and concrete locations. (See Figures 1 and 2 for setting)

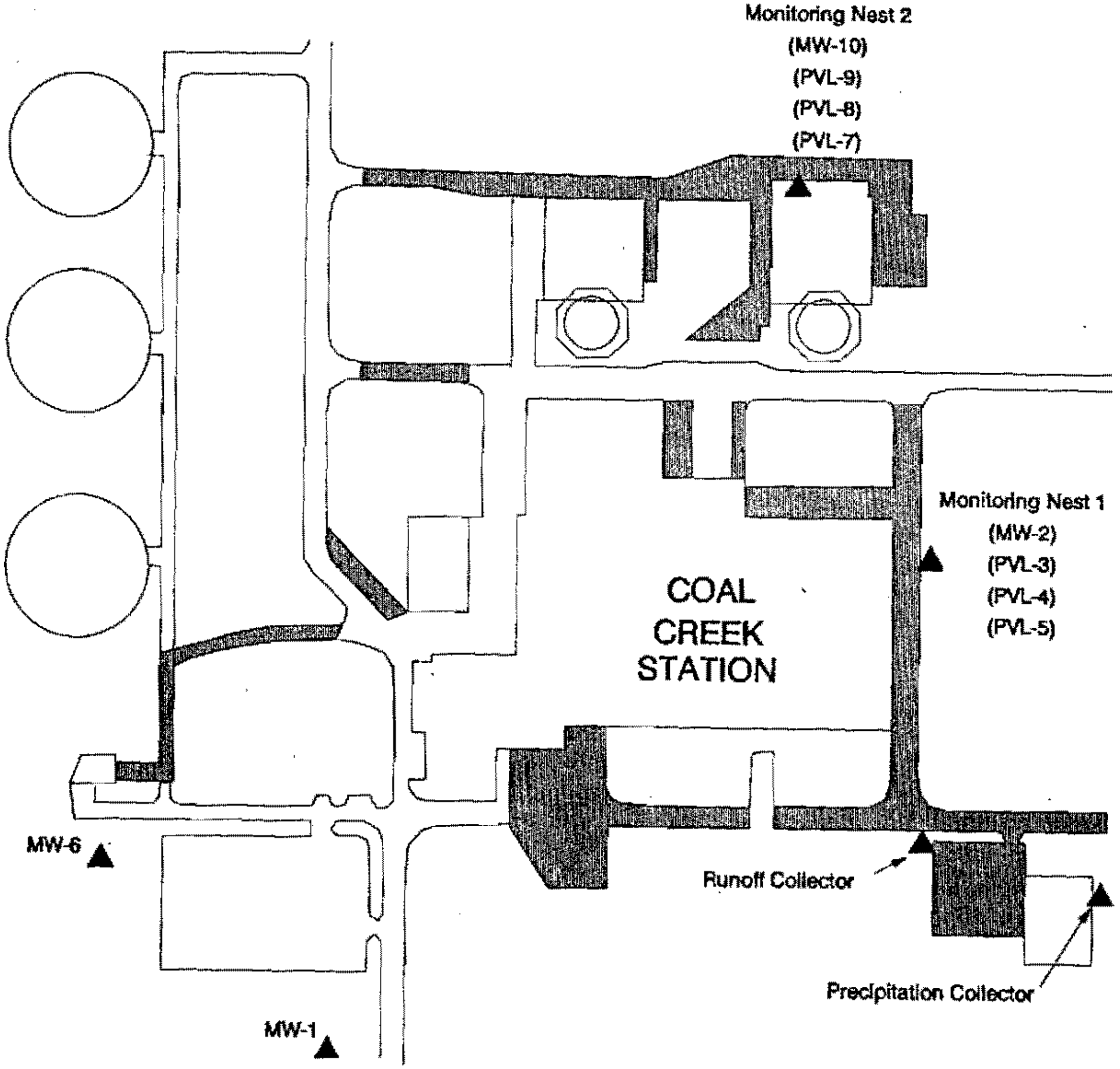

Monitoring Nest 2
(MW-10)
(PVL-9)
(PVL-8)
(PVL-7)
Monitoring Nest 1
(MW-2)
(PVL-3)
(PVL-4)
(PVL-5)
COAL CREEK STATION
MW-6
Runoff Collector
Precipitation Collector
MW-1

TABLE 1

MATERIALS

Cement	ASTM C150, Type I.
Fly Ash	Coal Creek Station, ASTM C-618
Fine Aggregate	Clean natural sand, ASTM C33
Coarse Aggregate	Crushed stone, washed gravel, or other acceptable inert granular material conforming to ASTM C33
Water	Clean and free from mud, oil, organic matter or other substances per ASTM C-94

MIX DESIGNS

	Concrete #1	Concrete #2	Slurry
Cement	170 lbs.	194 lbs.	0-25 lbs.
Fly Ash	394 lbs.	394 lbs.	250 lbs.
Fine Aggregate	1330 lbs.	1250 lbs.	3000 lbs.
Coarse Aggregate	1830 lbs.	1860 lbs.	0 lbs.
Water, net	240 lbs.	240 lbs.	ND
Water/Cement Ratio	0.43	0.41	ND
Air Content	6.0 %	6.25 %	ND
Slump	4 ins	4 ins	ND

ND - not determined

discovered in August, 1988. The reason for the low strengths has yet to be determined. However, these problems were alleviated with the use of the second mix design. Fly ash was used as a total replacement for cement in the slurry mix which was designed as a flowable mixture to be used for backfilling around culverts and other similar construction uses. It was also designed to achieve relatively low strengths (compressive strength 150 psi) to facilitate easy removal, allowing repair work at a later date.

The suitability of a particular fly ash for cement replacement is a function of its chemical composition, mineralogy, and physical properties. The chemical composition of fly ash is dependent on the composition of the coal burned. Variations in the composition of coal within a single seam can lead to large compositional differences in the fly ash. Fly ash generated from both combustor units at CCS is a good cement replacement because of its high SiO_2 and lime content (Table 2). The type of combustion and environmental control technology dictates the physical properties of the ash and also influences ash mineralogy. CCS utilizes a pulverized coal combustor which operates at a lower temperature than other combustion procedures, consequently little ash fusion is produced and the resulting ash has a fine consistency similar to cement. There is a general consensus that the finer the fly ash, the higher the

TABLE 2

COAL CREEK STATION FLY ASH ANALYSES

	Weight Percent (Ignited Basis)			
	Combustor Unit 1		Combustor Unit 2	
Oxide Components	Run 1	Run 2	Run 1	Run 2
SiO_2	42.68	42.68	39.83	39.83
Al_2O_3	15.01	14.99	16.18	15.96
TiO_2	0.55	0.55	0.61	0.63
Fe_2O_3	9.33	9.58	10.09	9.58
CaO	21.88	22.40	23.20	24.04
MgO	5.72	5.24	5.76	5.52
K_2O	1.90	1.73	1.60	1.73
Na_2O	0.82	0.72	0.74	0.82
SO_3	1.26	1.50	1.77	1.74
P_2O_5	0.18	0.07	0.08	0.08
Undetermined	0.67	0.54	0.14	0.07
	100.00	100.00	100.00	100.00

pozzolanic activity (Manz and McCarthy, 1986). The combustion and collection technology at CCS produce an ash possessing excellent physical properties for cement replacement.

The American Society of Testing and Materials (ASTM) has developed a classification system, dependent on coal type for fly ash used as cement replacement, in which fly ash is classified as either class C or class F. Ash from bituminous coal is classified F, whereas lignite and subbituminous ashes are classified C. Fly ash from CCS is an excellent class C ash, nearly meeting the criteria for class F ashes. Each class of ash must meet minimum chemical and physical specifications prior to acceptance as a cement replacement material. These specifications are virtually identical for both classes, with the exception of the SiO_2, Fe_2O_3, and Al_2O_3 content, which must total no less than 70% by weight for class F and 50% by weight for class C fly ash. This classification system was developed in an attempt to standardize the classification of fly ash in the same manner in which other construction materials are regulated.

Characterization of fly ash mineralogy is very important to evaluating its potential as a cement replacement and predicting its leaching behavior. Fly ash is composed of an iron aluminosilicate matrix with a highly soluble oxide-trace element phase located on the particle surfaces (Daly, Groenewold, and Manz, 1982).

Roughly 30% of a fly ash particle is crystalline. Predominant crystalline phases in CCS fly ash are anhydrite ($CaSO_4$), periclase (MgO), melilite ($(Ca_2(Mg,Al)(Al,Si)_2O_7)$, quartz ($SiO_2$), ferrite spinel ($((Mg,Fe)(Fe,Al)_2O_4)$, dicalcium silicate ($Ca_2SiO_4$), and lime (CaO) (Table 3). Fly ash from CCS is both pozzolanic (self-hardening reaction occuring when ash is reacted with calcium hydroxide released as concrete hardens) and cementitious (self-hardening upon contact with water alone). The original ash mineralogy can change during these self-hardening hydration reactions by the formation of minerals such as ettringite (McCarthy et al., 1987). The end result of the incorporation of fly ash as an active ingredient in concrete is a synthetically created rock in which constituents of the ash are physically and/or chemically bonded within the concrete matrix.

The environmental concerns over the use of fly ash concrete and slurry result from the high fly ash content (70%) and the documented leaching potential of free fly ash (Beaver, 1986). The leaching potential of a material such as fly ash is proportional to the permeability of the ash or the material it is contained in. According to Kosmatka and Panarese (1988) typical permeability values for mature concrete without fly ash average 3.3×10^{-12} ft/sec (1×10^{-12} m/sec). The addition of fly ash decreases the permeability of concrete through hydration

TABLE 3

COAL CREEK STATION FLY ASH MINERALOGY
(after Manz et al., 1989)

Quantitative XRD[1] Analysis (wt%)

Ah	Qz	Ml	C_2S	Sp	Lm	Pc	SUM
0.9	5.7	1.7	3.2	2.2	1.2	2.9	20.8

Mineralogy Codes and Nominal Compositions

Code	Name	Nominal Composition
Ah	Anhydrite	$CaSO_4$
C_2S	Dicalcium Silicate	Ca_2SiO_4
Lm	Lime	CaO
Ml	Melilite	$Ca_2(Mg,Al)(Al,Si)_2O_7$
Pc	Periclase	MgO
Qz	Quartz	SiO_2
Sp	Ferrite Spinel	$(Mg,Fe)(Fe,Al)_2O_4$

[1] Mineralogy determined by X-ray diffraction (XRD)

and the pozzolanic-reaction process. Most of the research documenting fly ash leaching is based on fly ash disposed of in landfills, mine spoils, and other similar settings (Spencer and Drake, 1987). The permeability of ash in these disposal environments would average roughly 1 x 10^{-5} ft/sec (1 x 10^{-6} m/sec), many orders of magnitude higher than it is for fly ash concrete (Moretti, personal communication, 1990). Therefore it is likely that the incorporation of fly ash as an active ingredient in concrete will reduce the potential for leaching.

METHODOLOGY

The primary focus of this study is to document any impact on water quality resulting from the use of concrete containing a high replacement of fly ash for cement. To meet this objective, the physical and chemical interrelationships between the surface water, the unsaturated zone, and the saturated zone must be thoroughly assessed. Instrumentation was designed and implemented to monitor water quality, as well as gather information regarding water flow and occurrence in these three zones. The data will be used to interpret the hydrogeology and hydrogeochemistry of the shallow subsurface of the site and document any possible degradation in water quality caused by the concrete.

Monitoring and sampling of the saturated zone was accomplished with the use of shallow water table wells. These were used to monitor any changes in either water level or water quality. The unsaturated zone was instrumented with pressure vacuum lysimeters at different depths to document changes in moisture content and water quality. The lysimeters were situated to provide early detection of any possible leachate generation. Surface water runoff and precipitation sampling was necessary to ascertain water quality both before and after its contact with the concrete. Climate and precipitation data were used to calculate potential evapotranspiration which allowed the estimation of seasonal recharge rates.

Saturated Zone

Instrumentation

Instrumentation of the saturated zone consisted of the placement of 4 monitoring wells, two for background monitoring and two for downgradient detection (Figure 3). All wells were constructed in accordance with standard US EPA guidelines (Appendix B). Each borehole was drilled using an air rotary drill rig with a 5 5/8 inches (14.28 cm) bit. Borehole sediments were sampled at 5 foot (1.5 m) intervals for the preparation of stratigraphic logs. Sediment samples were sealed in plastic bags and indexed according to well number, location, and depth. Every attempt was made to avoid the introduction of drilling fluids, but drilling conditions mandated the injection of an air-water mist in two boreholes (MW-6, MW-2). Borehole samples were logged following the procedures outlined in ASTM (1983) and are included in Appendix C.

Monitoring wells were constructed using 2 inch (5.08 cm) flush threaded schedule 40 PVC. Screened intervals were constructed out of 2 inch (5.08 cm) flush-threaded PVC with a .010 inch (.025 cm) slot size. Threaded pipe was used to eliminate the need for solvent welds, which may impact water quality (Driscoll, 1986, p. 724). Size 1230 washed silica sand was tremmied into the annulus of screened intervals to form the sand pack. A granular bentonite seal 2 feet (.6 m) thick was placed above the sand pack. A 6% bentonite grout (neat cement), pumped from the bottom up, was used to fill the remainder of the annular space. At the surface of each well a concrete pad was poured. Completion summaries for these monitoring wells are presented in Appendix B.

Shortly after installation, the wells were developed with a bailer. The low permeability of the sediments permitted most of the wells to be purged dry. Each well was either purged dry or one well volume was removed. The process was repeated 6 times prior to the first sampling event in an attempt to reduce turbidity in the wells. Recovery times were so slow that often a day was required between purging events.

Sampling

Collection of ground water samples was made on a quarterly basis. Prior to each sampling event wells were either bailed dry or a total of 3 well volumes was removed. Each sample was removed with a Teflon bailer and placed in a 1 liter plastic transfer bottle. One bail volume provided a sufficient quantity of sample to fill a 1 liter sample bottle. The bailer was cleaned and rinsed with reagent-grade water before sampling each well. Temperature, specific conductance, and pH were recorded as quickly as possible, usually within 10 minutes of sample removal. All time intervals between measurements were recorded on field sheets. Conductivity was always measured prior to pH to eliminate any possible interference created by buffer solution contamination. Temperatures were recorded immediately upon removal of the sample from the well.

Once field measurements were complete, the samples were filtered through a 0.45 micron membrane filter. Prefiltering with a coarse 8 micron glass filter was necessary for some turbid samples. The filtering apparatus consisted of a 1 liter bottle containing the sample connected with a 3-foot (1 m) piece of 3/8 inch Tygon tubing to a standard 142mm filtering unit. The filtering unit was positioned to discharge directly into the final sample bottle. Two additional bottles identical to the sample bottle were used in this procedure; one was filled with reagent grade water, the other was used to force air through the sampling apparatus. This filtering apparatus was used to minimize sample aeration and agitation. Standard inline filtering units using a peristaltic pump create turbulence which can break up ferric hydroxide particles, allowing them to pass through a 0.45 micron filter (RMT Inc., 1985).

Upon placing a new filter in the filtering unit, approximately 500 ml of reagent-grade water was used to prerinse the unit. Air was then forced through the unit with the second bottle moving most of the remaining reagent-grade water through the filtering apparatus. Next, the bottle containing the sample was attached to the unit and elevated, a slight pressure was exerted on the bottle moving the sample through the filter and into the awaiting sample bottle. With this procedure it was necessary to discard only the first 50ml of sample. Other procedures utilizing a peristaltic pump result in a much larger quantity of reagent-grade water remaining in the tubing after prerinsing and/or a large volume of sample in the tubing during filter replacement. Both of these problems require that a significant amount of sample be flushed through and discarded. It became very important to conserve sample volume when sampling the unsaturated zone where sample volume was often limited.

Immediately after filtering, each sample was split into two 250 ml polysulfone bottles, one unpreserved, the other preserved, to 1% HNO_3. Following preservation the samples were placed in a refrigerator. Upon completion of sampling, the samples were transferred from the refrigerator to a cooler for transport. When required, ice was used to maintain the samples at approximately 40°F (4°C). The samples were transported to the lab as soon as possible. A minimum of 5 hours were generally required to transport the samples to the Energy and Environmental Research Centers (EERC) Analytical Research Laboratory, where all the water samples were analyzed (Appendix D). For quality assurance and control, duplicate analyses were performed on some of the samples by GAI Consultants, Inc. of Monroeville, Pennsylvania.

Unsaturated Zone

Instrumentation

Pressure vacuum lysimeters equipped with a porous ceramic cup (Soilmoisture Equipment Corporation, Model 1920) were chosen to instrument the unsaturated zone (Figure 4) because of a proven ability to provide an unbiased, representative sample of unsaturated zone moisture (RMT Inc., 1987; Creasey and Dreiss, 1988). A total of 6 lysimeters was installed at the site in two different locations (Figure 3). In each of the two locations, three lysimeters were installed in a nested position, along with one monitoring well, to form a monitoring nest (Figure 5). In each monitoring nest the lysimeters were installed at depths of 5, 10, and 15 feet (1.5 m, 3.0 m, and 4.5 m). The purpose of this configuration was to provide a sample record of water migrating from the surface towards the water table.

The same air rotary drill rig used to install the monitoring wells was also employed in the installation of the lysimeters. Sediment samples were obtained at 5-foot (1.5 m) intervals for the preparation of stratigraphic logs. Boreholes constructed for lysimeter installations were drilled without the introduction of drilling fluids. All the lysimeters in each nest were installed at the same time.

The lysimeters were prepared in the lab prior to installation in the field. Approximately one liter of a

Figure 4. Pressure-vacuum lysimeter schematic diagram.

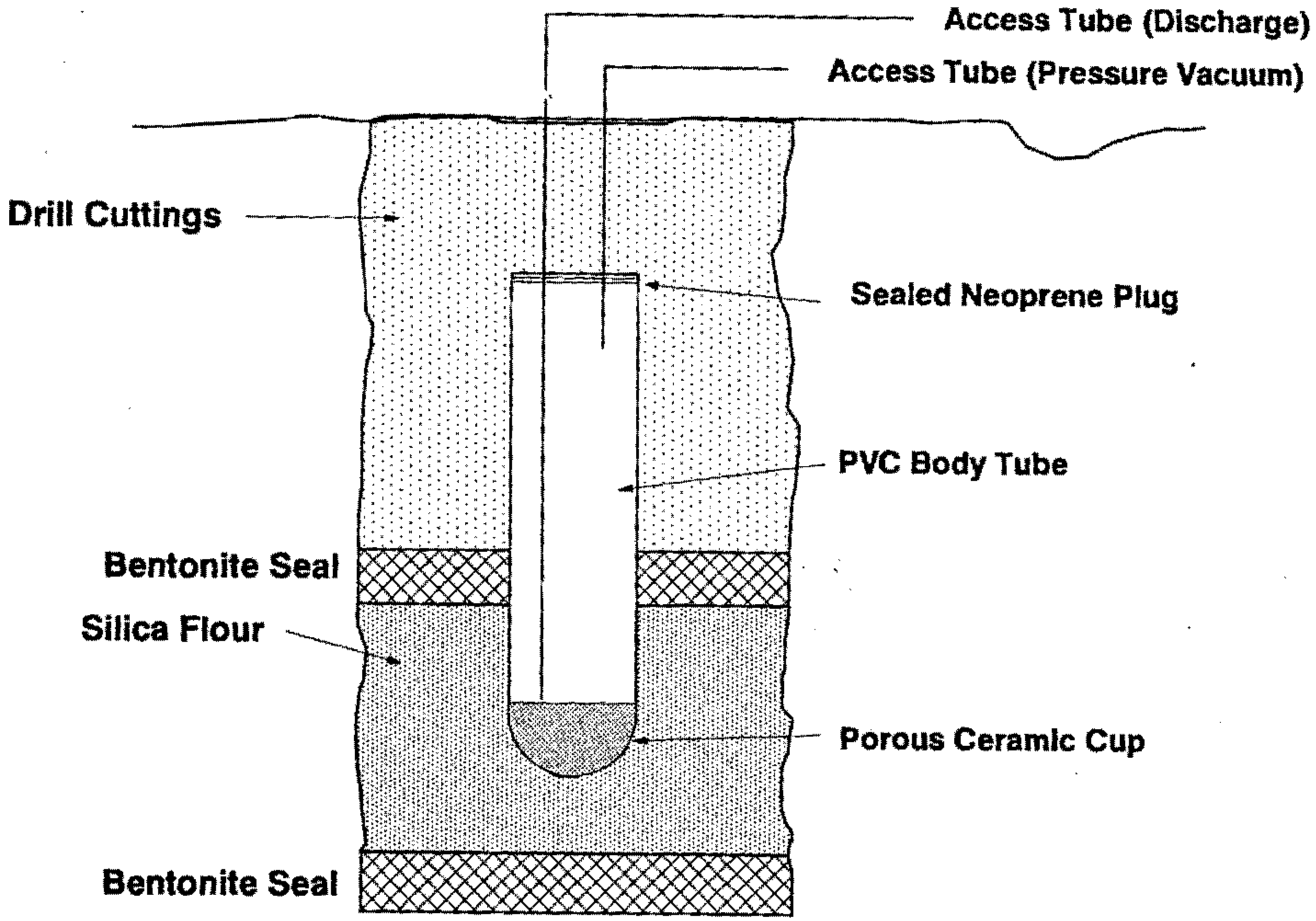
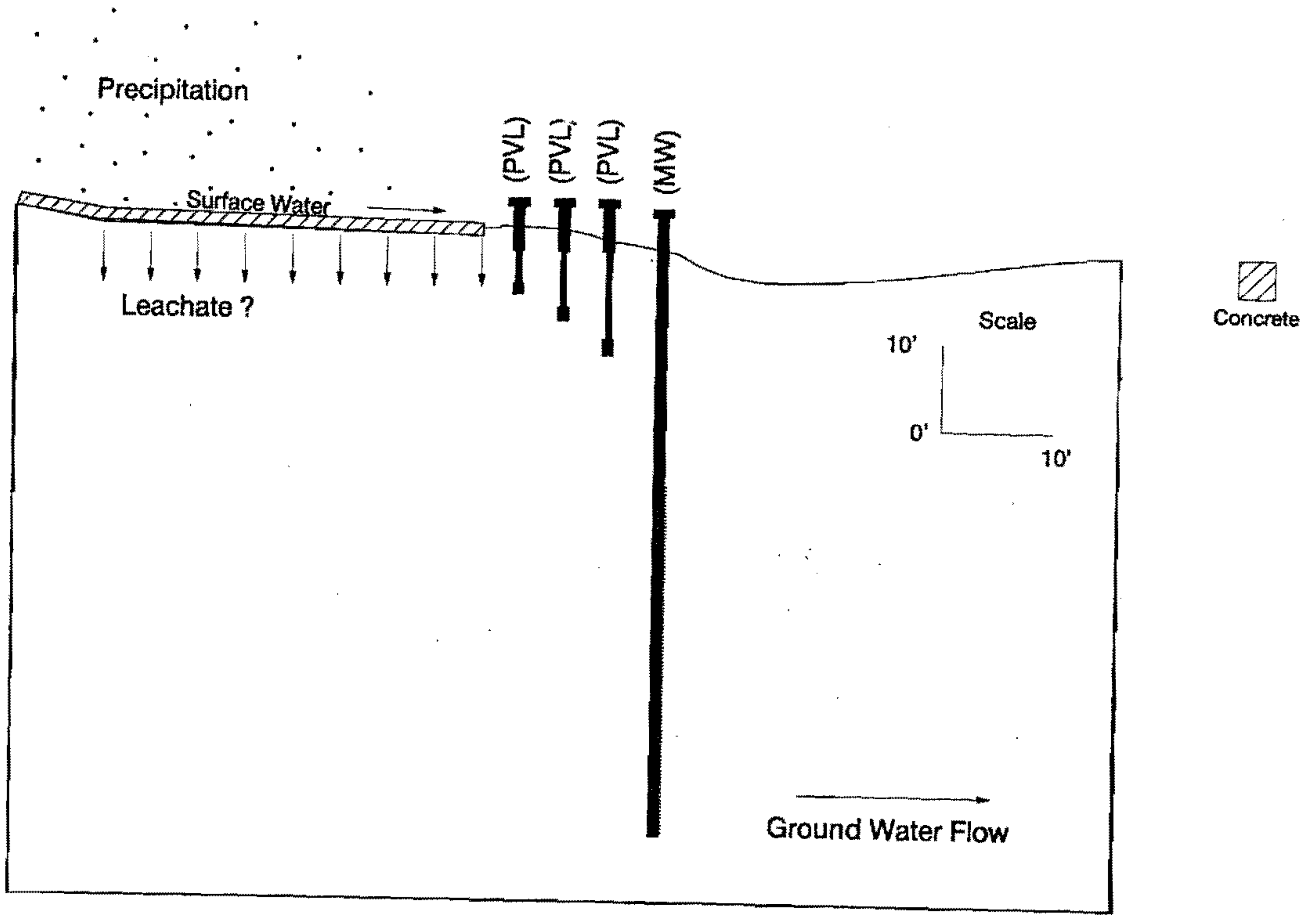

Access Tube (Discharge)
Access Tube (Pressure Vacuum)
Drill Cuttings
Sealed Neoprene Plug
PVC Body Tube
Bentonite Seal
Silica Flour
Porous Ceramic Cup
Bentonite Seal

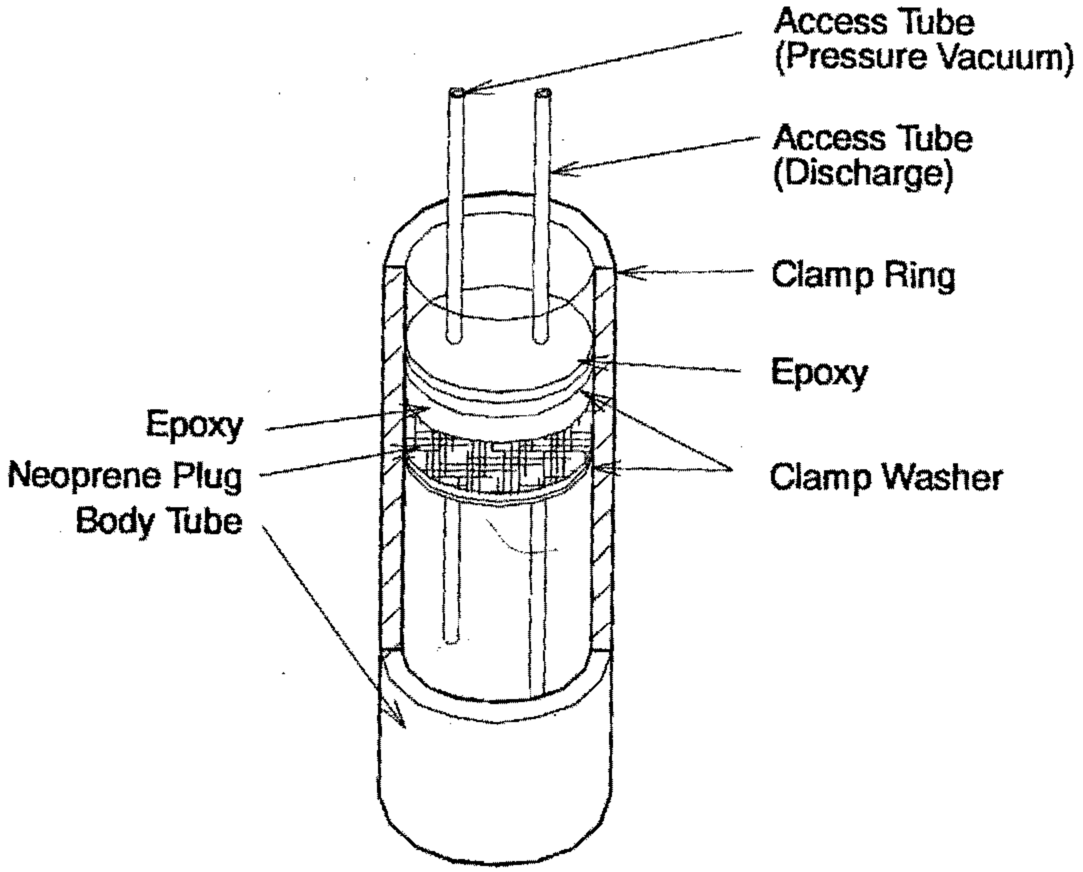
Figure 5. Monitoring nest schematic diagram. (PVL= pressure-vacuum lysimeter; MW= monitoring well)


Precipitation
Surface Water
Leachate ?
(PVL)
(PVL)
(PVL)
(MW)
Scale
10'
0'
10'
Ground Water Flow
▨ Concrete

10% HNO_3 solution was leached through each lysimeter. Reagent-grade water was used to rinse each lysimeter until the pH stabilized. The leaching process required a minimum of 1 week to complete. Following leaching, the lysimeters were assembled according to manufacturers' instructions. The access tubes were potted (sealed) in epoxy at the point where they entered the body tube (Figure 6). Potting creates a better seal on the lysimeter, lessening the risk of vacuum leaks (Soilmoisture Equipment Corp., 1988). It is important that each lysimeter is capable of maintaining a vacuum, otherwise the instrument will not function. After potting, and dependent on the installation depth, the appropriate lengths of tubing were attached to each lysimeter. Finally, the instruments were labelled and sealed in plastic bags for protection from contamination prior to installation.

Boreholes for each lysimeter were drilled to 6 inches (15 cm) beyond the target installation depth. Granular bentonite was placed in the base of the each borehole to a thickness of 6 inches (15 cm). The bentonite was prewetted with 250 milliliters of reagent-grade water. One lysimeter was placed into each borehole and embedded within 25 pounds of silica flour. An additional bentonite seal was placed above the silica flour in a similar fashion. Drill cuttings were used to backfill the borehole to the surface. The cuttings were

Figure 6. Pressure-vacuum lysimeter potting procedure.

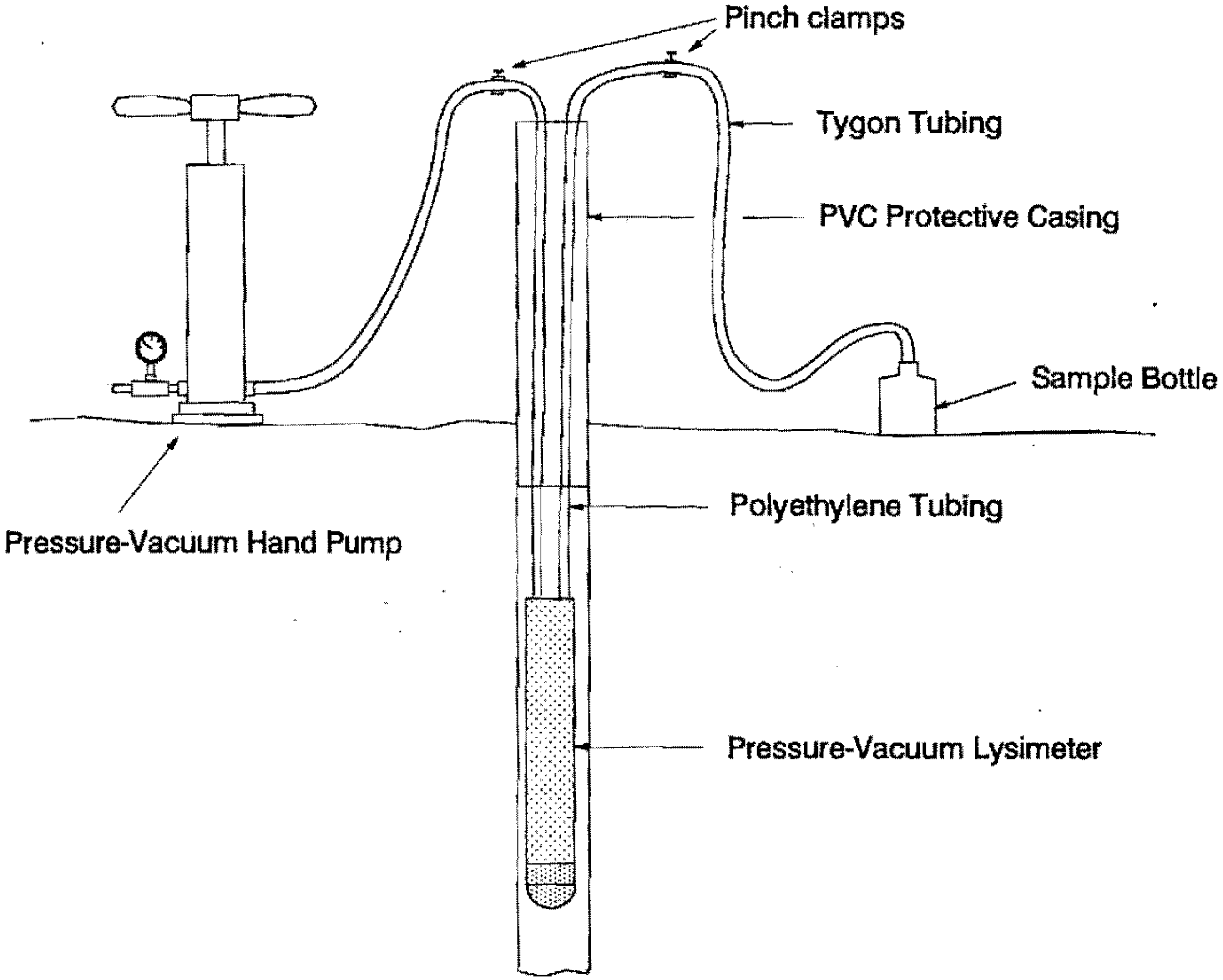

Access Tube
(Pressure Vacuum)
Access Tube
(Discharge)
Clamp Ring
Epoxy
Clamp Washer
Epoxy
Neoprene Plug
Body Tube

tamped into place at 1 foot (.3 m) intervals. A 4-foot (1.3 m) length of 4-inch (10 cm) PVC pipe was installed at the top of the borehole to house the access tubes. A vacuum of 28 inches of mercury (60 centibars) was pulled on the instrument to initiate sample collection. Vacuums were maintained periodically to insure adequate sample collection. Completion summaries for all the lysimeter installations are provided in Appendix B.

Sampling

The lysimeters were sampled following a simplified procedure. First of all, both access tubes were cleaned with reagent-grade water and the clamps were opened. A one liter transfer bottle was attached to the discharge access tube. The pressure/vacuum access tube was secured to a pressure pump, several strokes on a hand pump produced enough pressure to force the sample out of the lysimeter and into the sample bottle (Figure 7). The amount of pressure was minimized in an attempt to reduce sample agitation. This procedure effectively reduced sample removal time and eliminated any direct contact with ambient air. Upon removal from the lysimeters, water samples were exposed to the same set of sampling procedures as described for the saturated zone samples.

Figure 7. Pressure-vacuum lysimeter sampling schematic.


Pinch clamps
Tygon Tubing
PVC Protective Casing
Sample Bottle
Polyethylene Tubing
Pressure-Vacuum Hand Pump
Pressure-Vacuum Lysimeter

Precipitation and Surface Water Runoff

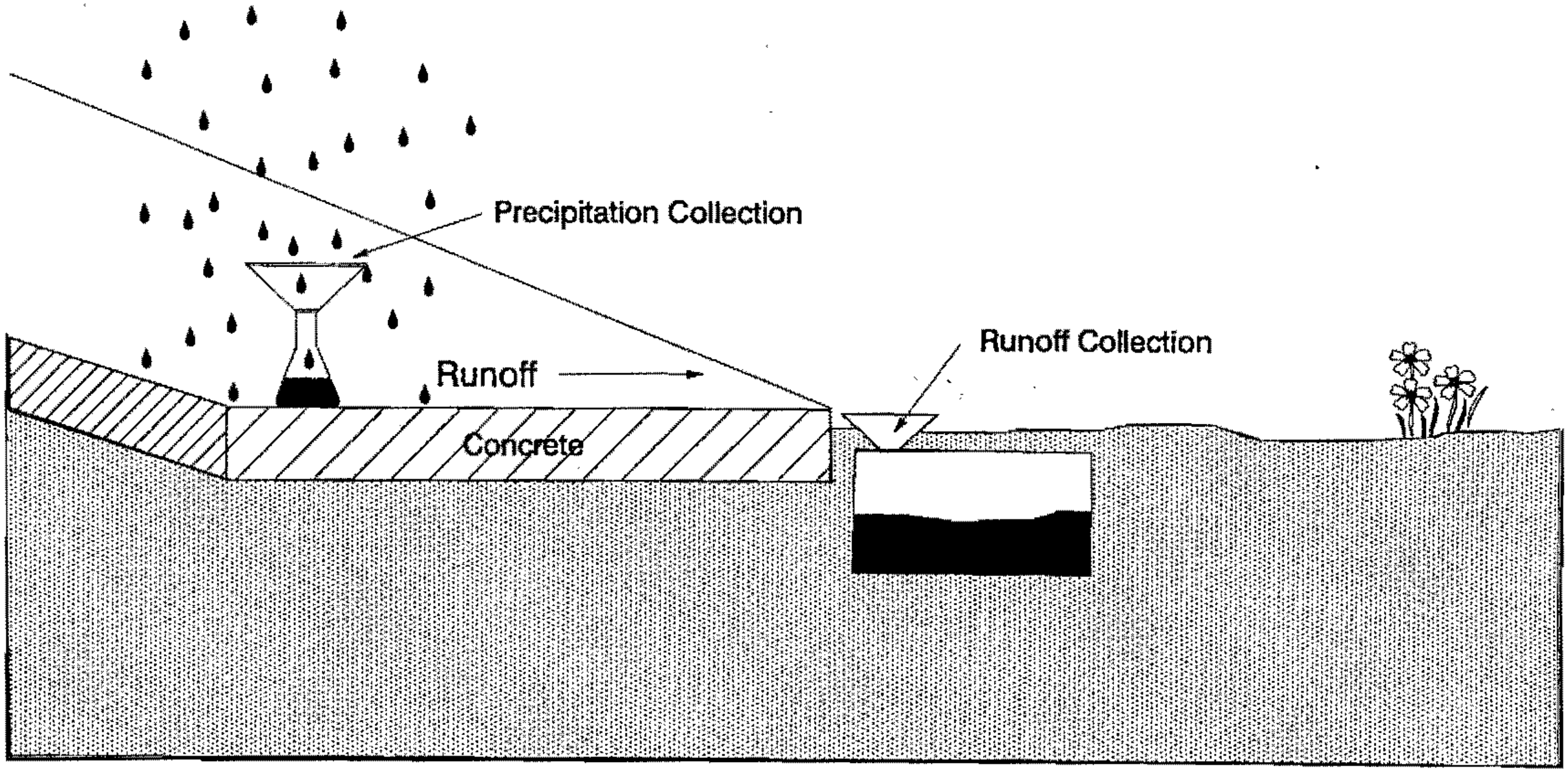
Instrumentation

Precipitation and runoff were collected in simple catchment devices (Figure 8). Runoff collectors were located adjacent to large concrete surfaces to insure that runoff would have a maximum amount of contact with concrete. Instruments were situated to procure a sample of runoff immediately after leaving the concrete slab. Precipitation collectors were located as near to the runoff collector as possible. The distance between precipitation collectors, runoff collectors, and monitoring nests was minimized to reduce the influence of spatially variable atmospheric contaminants such as dust sources and cooling tower precipitate. In addition to the collection of precipitation, weather records were obtained from the US Weather Service Observation Station in Washburn, ND, approximately 5 miles (8 km) southeast of the site.

Sampling

Precipitation and surface water runoff were sampled semi-annually from collection devices. In addition, the cooling water basin was sampled and analyzed to determine any possible influence on saturated zone water quality. Precipitation samples obtained were cumulative over periods of several months and included snowfall as well as rainfall. Runoff samples were also cumulative, and

Figure 8. Surface water monitoring schematic diagram.


Precipitation Collection
Runoff
Runoff Collection
Concrete

reflect primarily the same precipitation events that constitute the precipitation samples. Samples were treated employing the same procedures previously detailed for the ground water samples.

Field Measurements

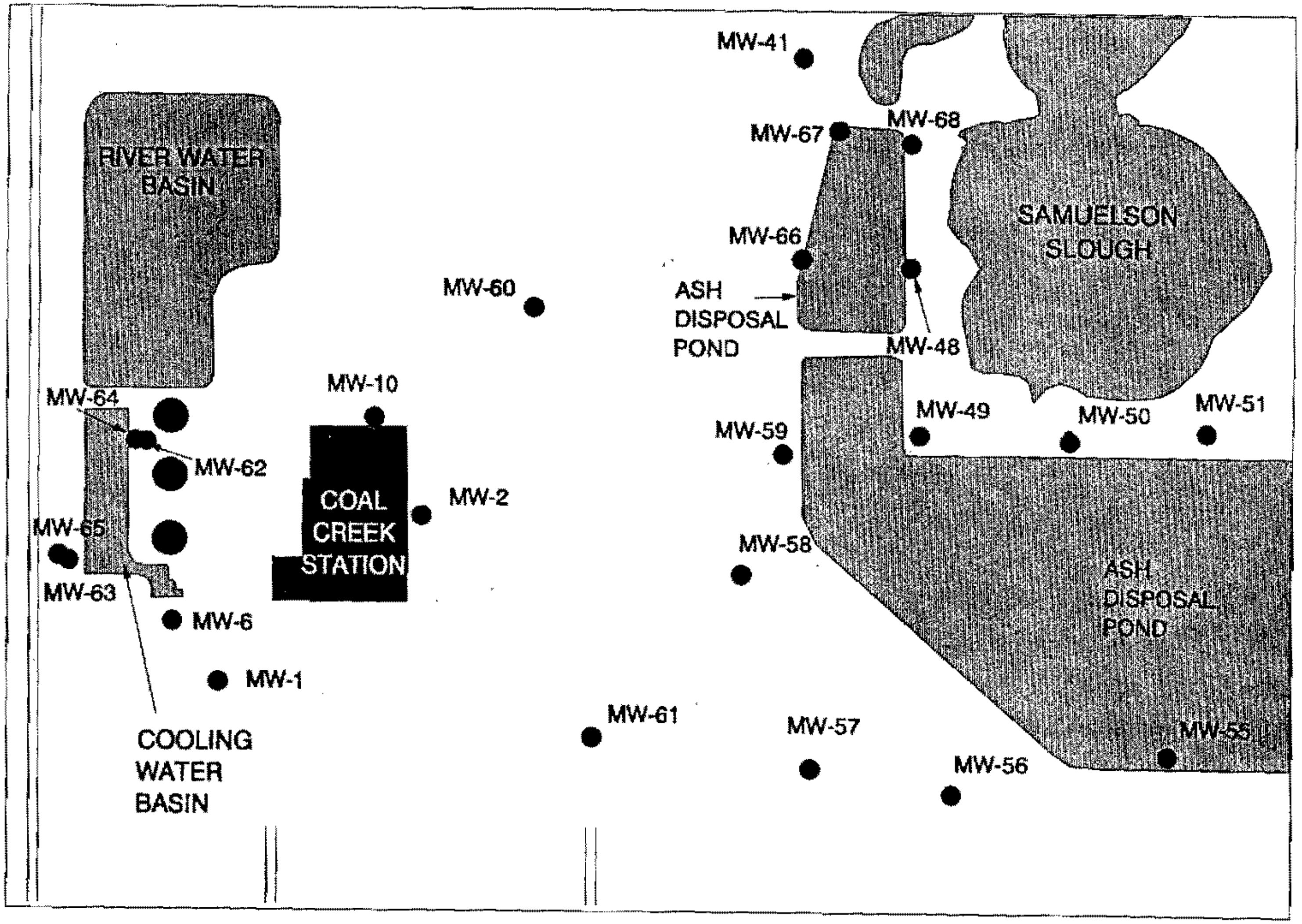
Water Levels

To document ground water occurrence and flow, water levels were measured in 22 monitoring wells using an electric water level tape (Figure 9). Four of the wells monitored were installed for the present study (MW-1, MW-2, MW-6, and MW-10) the remainder consisted of existing wells. Water levels were recorded monthly during the first summer of monitoring and quarterly thereafter. In addition to the measurements gathered for the present study, CCS personnel also have recorded monthly water levels since 1979 for several monitoring wells (Appendix E).

Hydraulic Conductivity Measurements

Hydraulic conductivity determinations were made on two monitoring wells, one screened in bedrock (MW-6), the other screened within units of both bedrock and fill (MW-10). Standard slug tests were performed and analyzed according to Hvorslev (1951) (Appendix A).

Figure 9. Water level monitoring well locations.


MW-41
MW-67
MW-68
RIVER WATER BASIN
SAMUELSON SLOUGH
MW-66
MW-60
ASH DISPOSAL POND
MW-48
MW-10
MW-64
MW-62
MW-59
MW-49
MW-50
MW-51
COAL CREEK STATION
MW-2
MW-65
MW-63
MW-58
ASH DISPOSAL POND
MW-6
MW-1
MW-61
MW-57
MW-55
MW-56
COOLING WATER BASIN

Evapotranspiration Estimate

To evaluate water movement to the shallow subsurface, a study of potential evapotranspiration was undertaken using the Thornthwaite (1948) method. Temperature data were supplied by the U.S. Weather Service, Washburn Station. All data pertaining to these calculations are included in Appendix F. The Thornthwaite method requires the mean monthly temperature and latitude of the site. The method was chosen because it is the most widely employed means of determining potential evapotranspiration.

Leachate Extraction Tests

Samples of concrete and slurry were subjected to leaching after curing for 3 and 28 days. Leachate extraction tests were also conducted on composite fly ash samples. The tests were performed following two standard batch leaching procedures both using a 20:1, liquid to solids ratio: the U.S. Environmental Protection Agency EP-Toxicity (EP-Tox, Method 1310), and the American Society of Testing Materials (ASTM D 3487-85). The two methods differ in the composition of the liquid phase, consequently the results are quite different. The EP test employs a solution consisting of reagent-grade water with the addition of acetic acid, whereas the ASTM procedure uses reagent-grade water alone for the liquid phase. The EP-Tox procedure was designed to simulate acidic conditions typical of municipal landfill settings but ash is typically not disposed under these conditions. The pH is considerably higher in the ASTM procedure, hence only the water-soluble fraction of the fly ash determines the composition of the final leachate. The ASTM procedure most closely approximates conditions likely in a field situation. The differences in the two procedures are reflected in the results (Appendix G).

RESULTS

Precipitation and Surface Water Occurrence

Throughout the course this study the Northern Great Plains experienced a severe drought. These conditions are reflected in the long-term precipitation data for Washburn, North Dakota (Figure 10). During the monitoring period most of the precipitation occurred from April to August (Figure 11). Long-term data indicate that the period from May to September normally provides 75 percent of the total annual precipitation (Jensen, 1972). Discrepancies between long-term data and precipitation observed during the monitoring period are the result of the drought conditions.

Reduced precipitation at the site has diminished the available surface water for recharge. Recent construction activities have also reduced the availability of surface water for recharge by shortening its flow path through the plant site. Many areas that previously contained standing water have been drained and some areas, previously devoid of standing water, have been provided with water.

Prior to construction of CCS, the landscape was quite different. The area that now contains the plant was much higher topographically (Figure 12). Prior to CCS, surface water drainage was well-developed northward through an intermittent stream. Construction of the plant necessitated the removal of material down to the

Figure 10. Long-term total annual precipitation for the period 1980 - 1989.

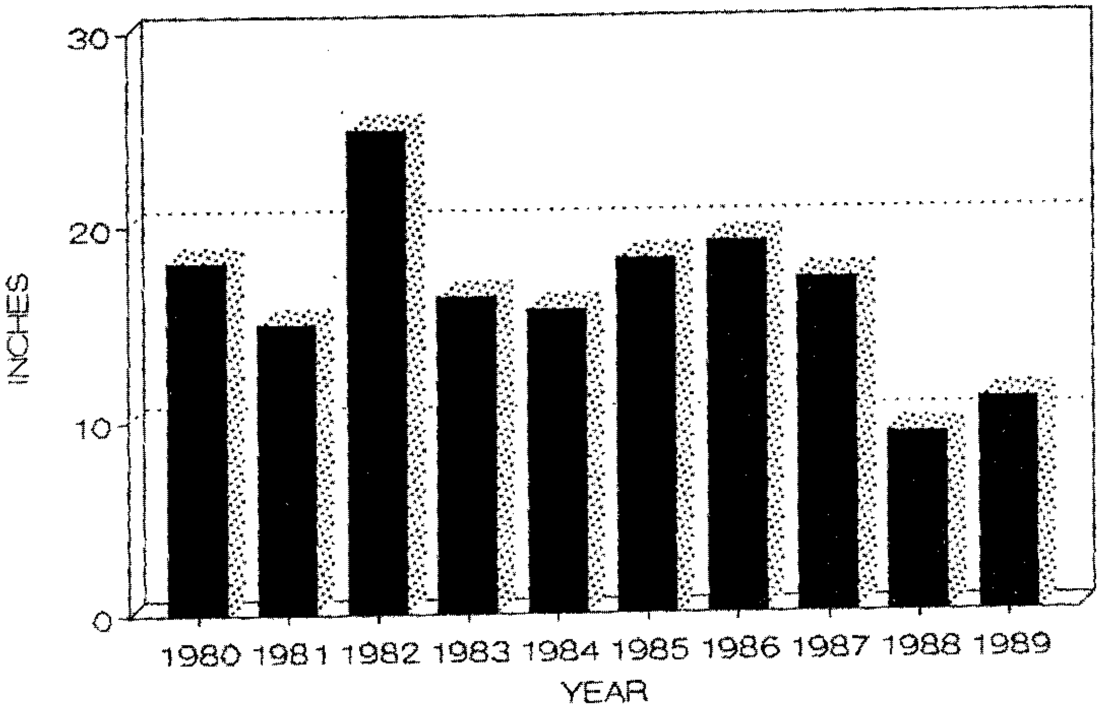

30
20
10
0
INCHES
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
YEAR

Figure 11. Total monthly precipitation for the monitoring period.

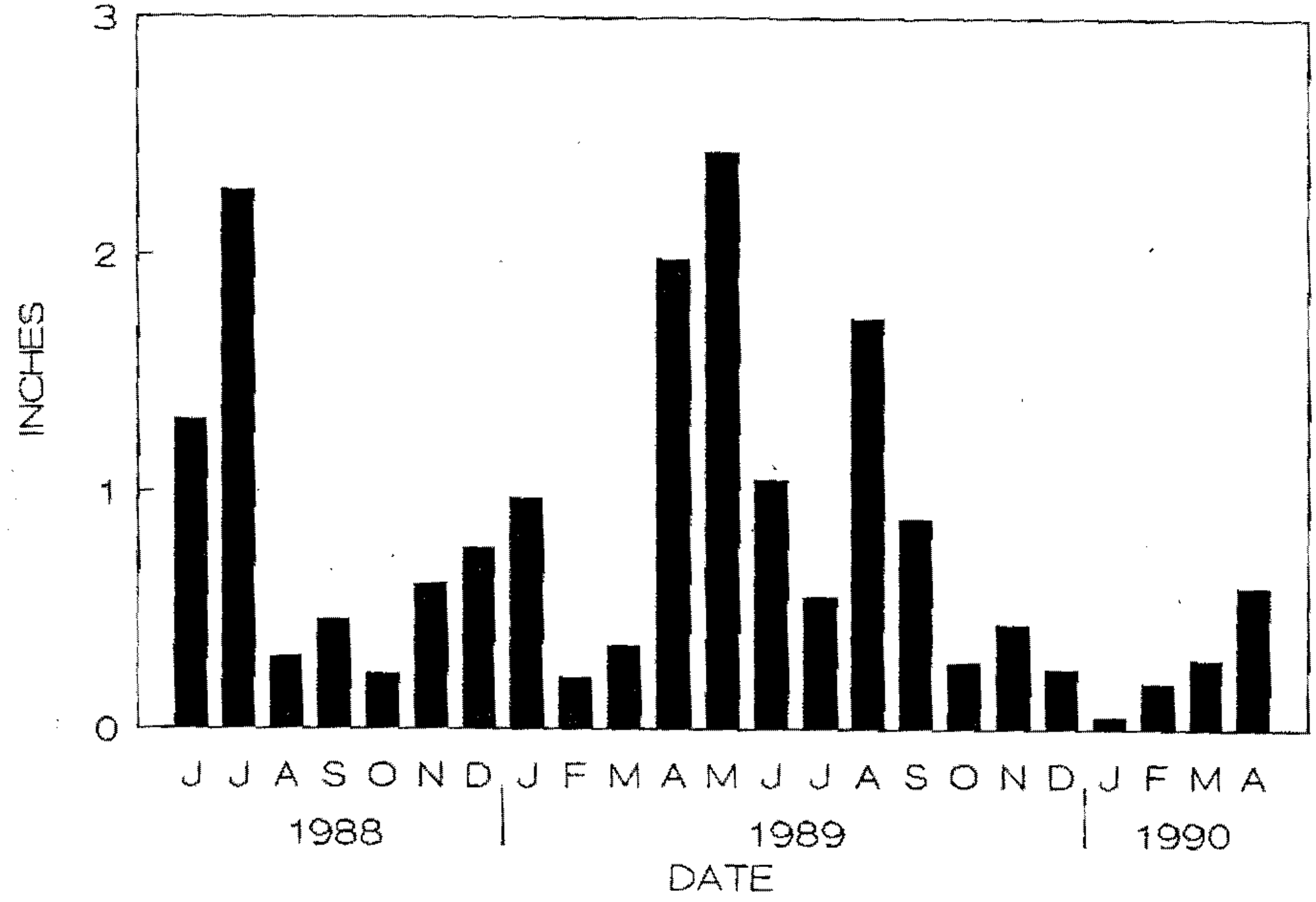
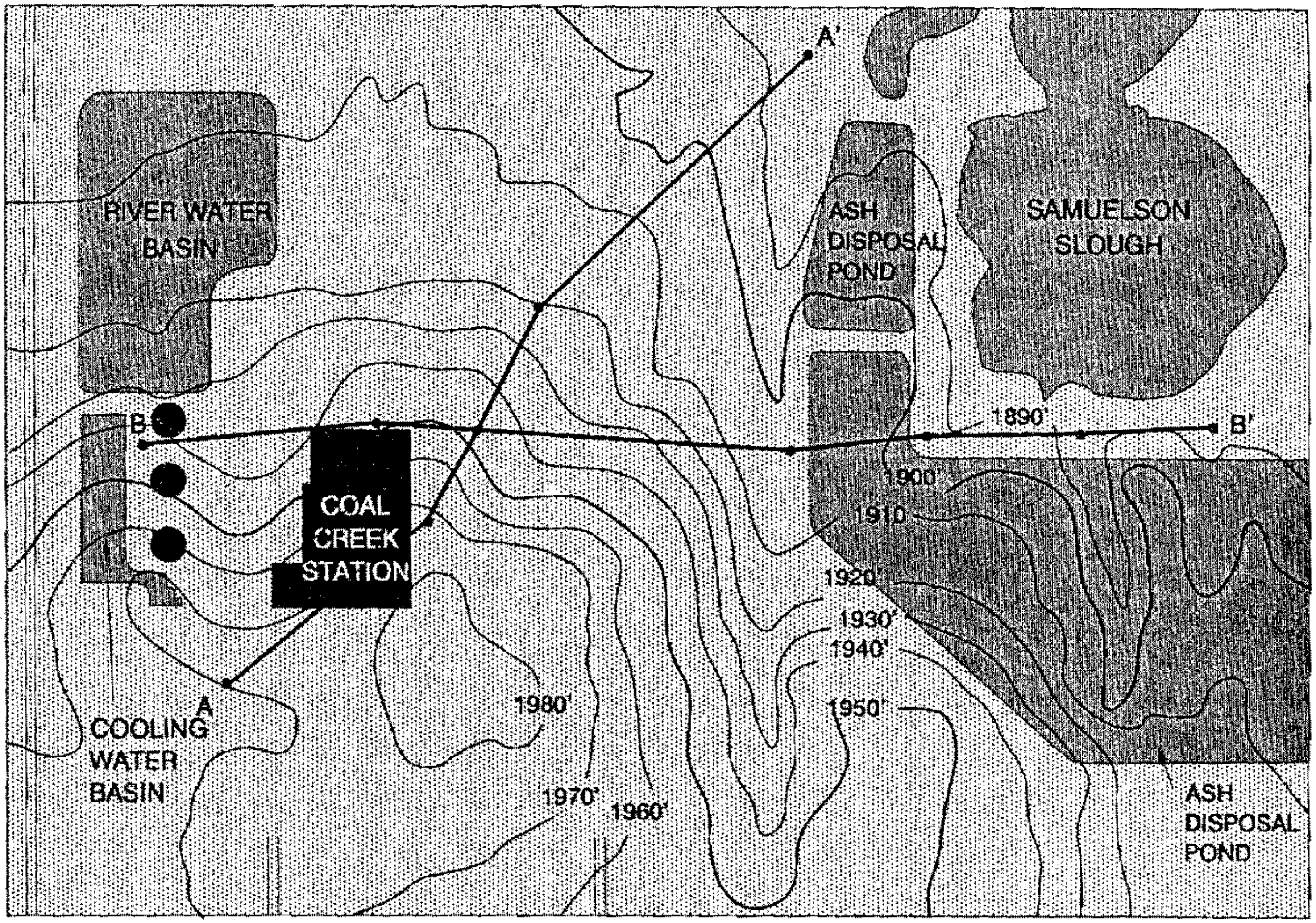

3
2
1
0
INCHES
J J A S O N D J F M A M J J A S O N D J F M A
1988
1989
1990
DATE

Figure 12. Map of topography prior to Coal Creek Station. (from USGS, 1961, Underwood Quadrangle)

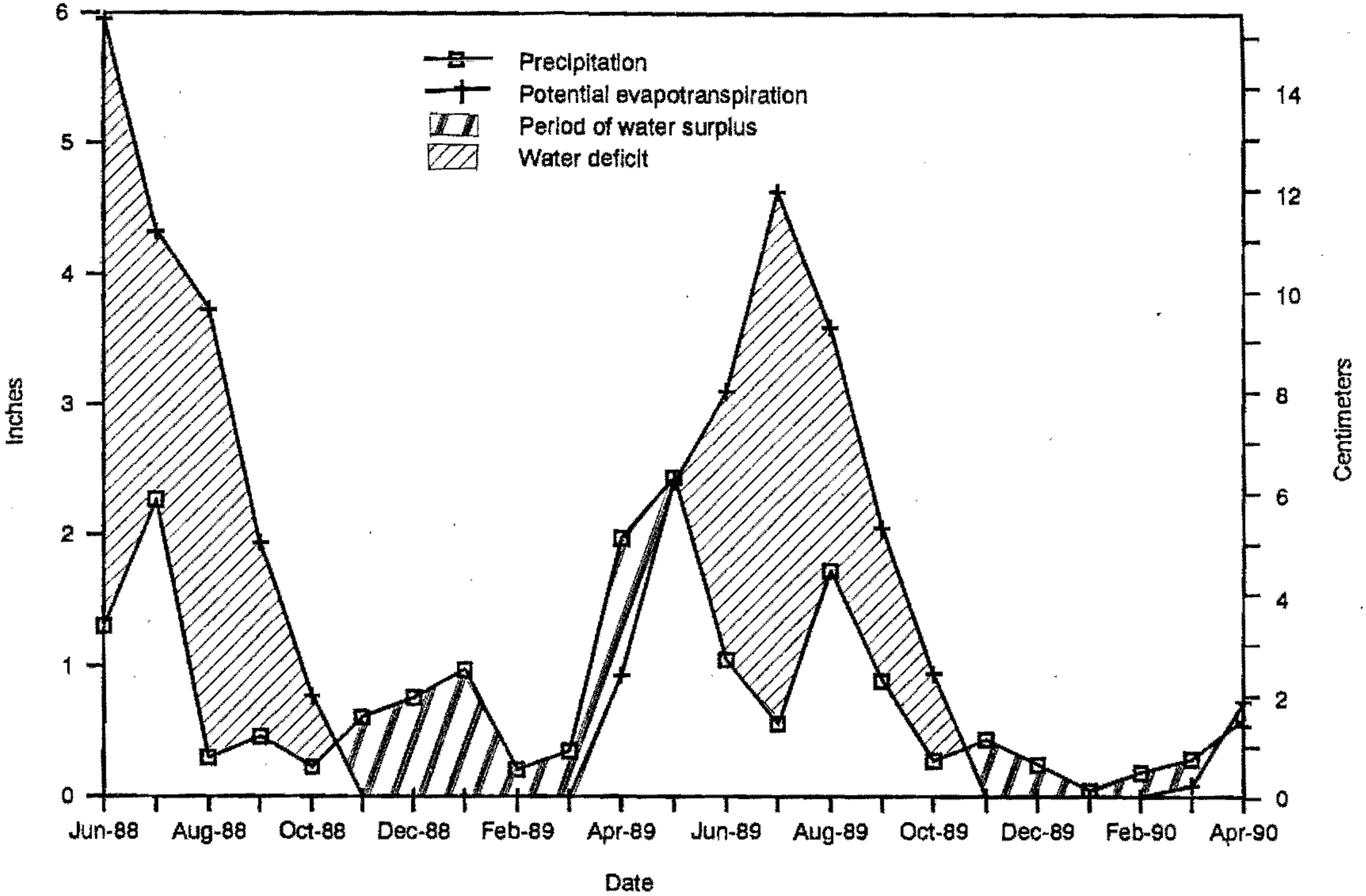

A'
RIVER WATER BASIN
ASH DISPOSAL POND
SAMUELSON SLOUGH
B
1890'
B'
1900'
COAL CREEK STATION
1910
1920'
1930'
1940'
1980'
1950'
A
COOLING WATER BASIN
1970'
1960'
ASH DISPOSAL POND

1940 foot (591 m) MSL, creating a relatively level area, an additional 20 feet (6 m) of excavation was necessary for the placement of footings beneath the plant (Stewart, personal communication, 1990). Present topography at the site causes surface water runoff to flow initially in two directions, although all runoff eventually flows into the Samuelson Slough area (Figure 2). The northern and western portions of the study area drain northward and eventually eastward into Samuelson Slough. The southern and eastern sections of the site drain eastward through two drainage ditches. The drainage ditches in the immediate vicinity of the plant have improved drainage. However, numerous areas of intermittent standing water presently exist (Figure 2).

Evapotranspiration and Recharge

The Thornthwaite method was employed in computing potential evapotranspiration. Precipitation data were compared to those estimates of potential evapotranspiration to approximate recharge. Results indicate that summer months experience the greatest potential evapotranspiration, coincident with the highest precipitation and average temperature (Figure 13). During winter the evapotranspiration potential is low because temperatures are low, however little water is available for recharge. Most of the recharge occurs during periods in spring where precipitation exceeds

Figure 13. Moisture budget for the study area.



Precipitation
Potential evapotranspiration
Period of water surplus
Water deficit
Inches
0
1
2
3
4
5
6
Centimeters
0
2
4
6
8
10
12
14
Jun-88
Aug-88
Oct-88
Dec-88
Feb-89
Apr-89
Jun-89
Aug-89
Oct-89
Dec-89
Feb-90
Apr-90
Date

evapotranspiration (Figure 13). Occasional recharge is likely following exceptionally heavy precipitation events in the summer and fall, although this cannot be concluded from information collected to date. Recharge also is possible during winter through frozen soils (Willis, 1963; Kane, 1981), but the infiltration rate is less than one-half the summer rate.

Ground Water Occurrence and Flow

Saturated Zone

In many geologic settings, including western North Dakota, the water table generally mirrors the surface topography (Ronnie, 1987, p. 63; Fetter, 1988, p. 86). This relationship exists in most portions of the site. However, there are two areas with anomalous water tables (Figure 14). The first area is centered on the eastern edge of the plant, where the water table is lower than would be expected, as there is no associated reduction in topography (Figure 2). However, during construction of MW-1 and MW-2 a color change, often associated with a past water table, was detected 25 to 35 feet (7 to 10 m) above the present water table, which may indicate the original water table prior to construction (Figure 15). The second anomaly occurs adjacent to the Cooling Water Basin (CWB) as a distinctive ground water mound. The mounding developed from the absence of a liner beneath the CWB. Steep gradients adjacent to the CWB attest to

Figure 14. Water table map of the study area. Water levels are from 4/89. Refer to Figure 9 for instrument locations.

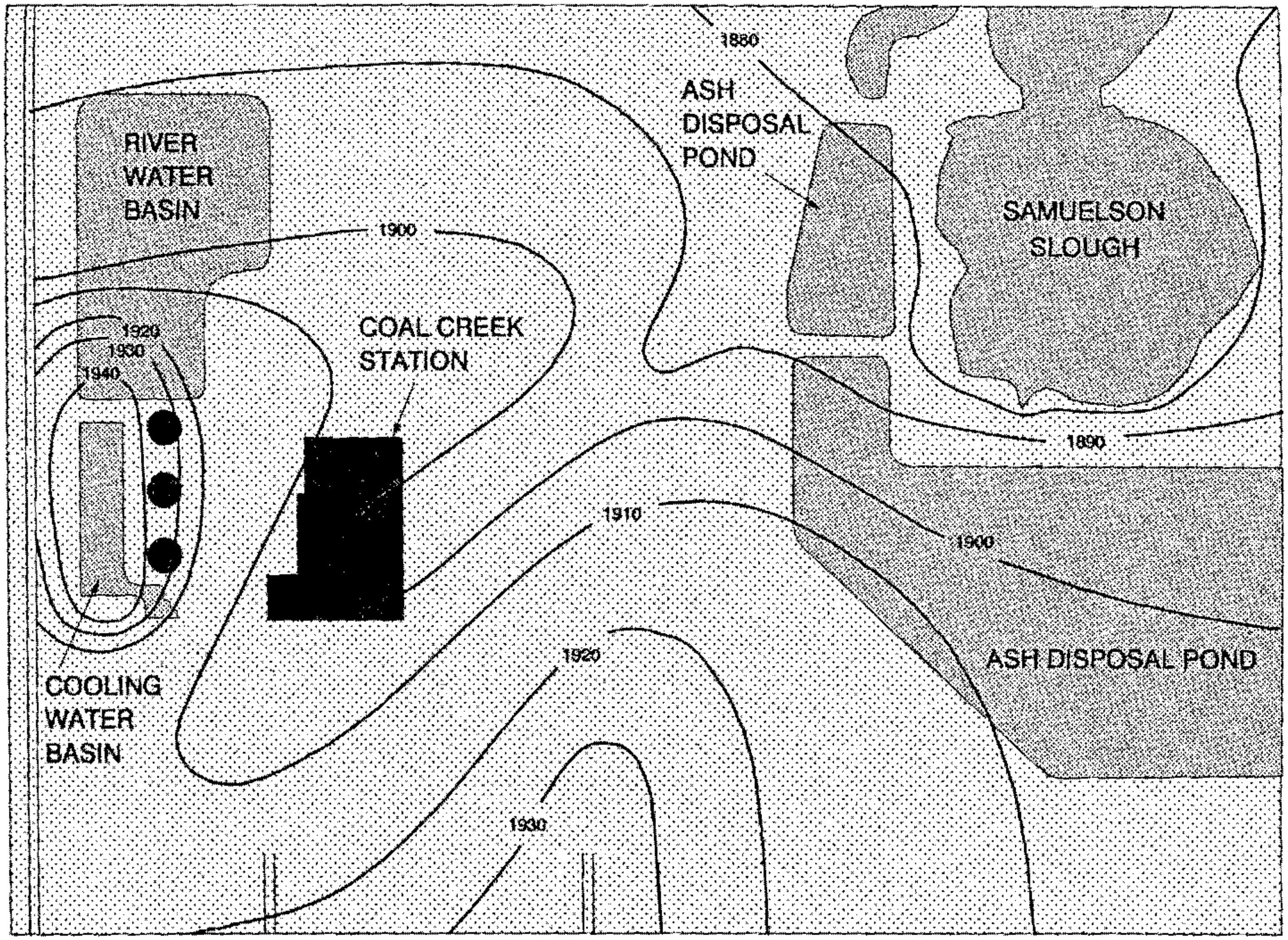
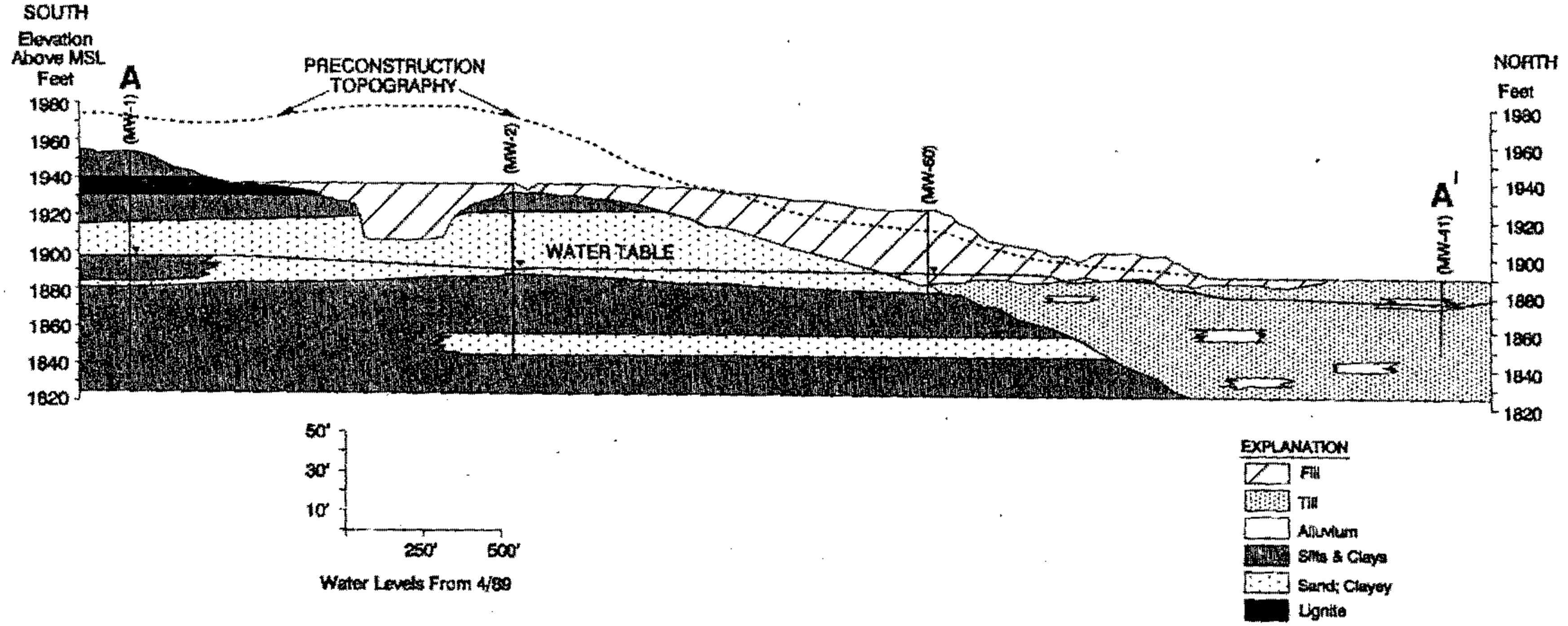

1880
ASH
DISPOSAL
POND
RIVER
WATER
BASIN
SAMUELSON
SLOUGH
1900
COAL CREEK
STATION
1920
1930
1940
1890
1910
1900
ASH DISPOSAL POND
COOLING
WATER
BASIN
1920
1930

Figure 15. Hydrostratigraphic cross-section A-A'. Refer to Figure 2 for location of cross-section.

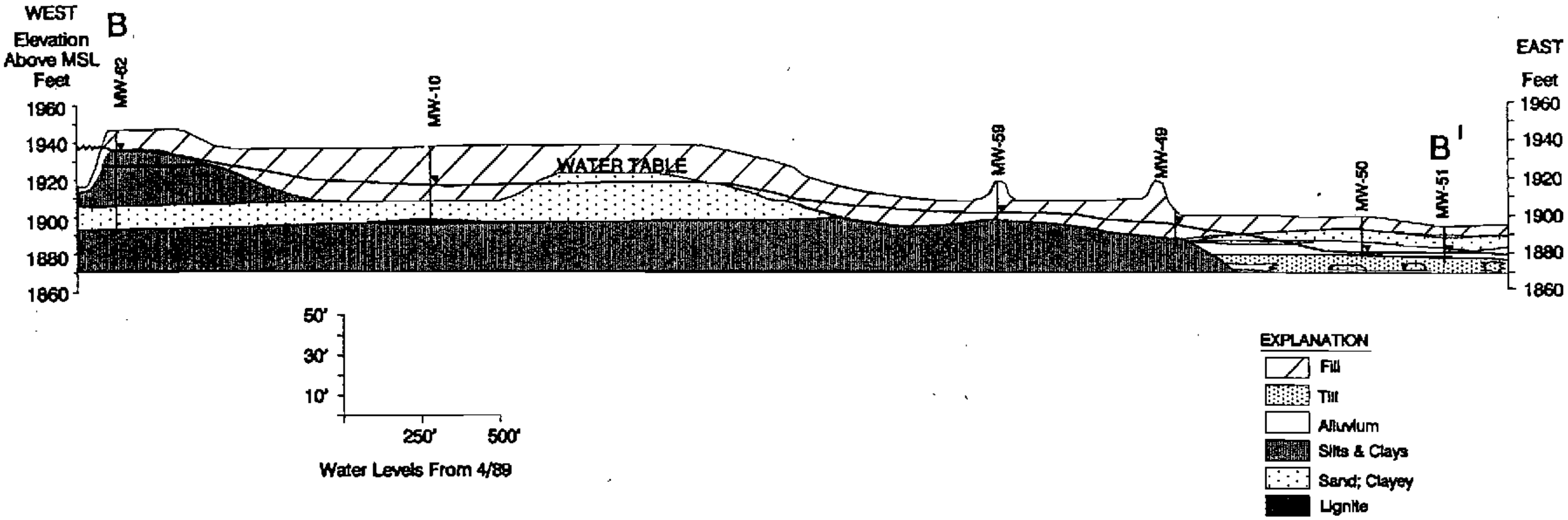

SOUTH
Elevation Above MSL Feet
A
(MW-1)
PRECONSTRUCTION TOPOGRAPHY
(MW-2)
WATER TABLE
(MW-60)
A′
(MW-41)
NORTH
Feet
1980
1960
1940
1920
1900
1880
1860
1840
1820
50′
30′
10′
250′
500′
Water Levels From 4/89
EXPLANATION
Fill
Till
Alluvium
Silts & Clays
Sand; Clayey
Lignite

the low hydraulic conductivity of the bedrock (Figure 16). Consequently, the present influence of the basin on flow is limited to within a 500 feet (150 m) radius.

On a regional scale, shallow ground water flow is towards the northeast, in the direction of the buried valley (Figure 14). Many local flow systems are superimposed upon this regional trend. Nearly all the major subsurface units near the station are of low hydraulic conductivity; flow in these units is primarily downward with a lesser lateral component (Rehm, Groenewold, and Peterson, 1982). The mean hydraulic conductivity of these bedrock units is 1.3×10^{-7} ft/sec (4×10^{-8} m/sec). Lateral flow occurs primarily at the base of fill and through lignite and sand (Figures 15 and 16). However, lignite and sand units do not exert a major influence on flow because they are uncommon and of minimal thickness, generally less than 5 feet (1.5 m).

Water levels in most of the monitoring wells were constant throughout the monitoring period (Figure 17). However, the water level in MW-10 increased significantly throughout this investigation as a result of high rates of recharge and ground water mounding above low permeability bedrock units. The water level in MW-10 rises dramatically in response to summer precipitation events, indicating a low evapotranspiration rate and relatively rapid infiltration (Figure 18). Water levels

Figure 16. Hydrostratigraphic cross-section B-B'. Refer to Figure 2 for location of cross-section.


WEST
B
Elevation Above MSL Feet
1960
1940
1920
1900
1880
1860
MW-62
MW-10
WATER TABLE
MW-59
MW-49
MW-50
MW-51
B'
EAST
Feet
1960
1940
1920
1900
1880
1860
50'
30'
10'
250'
500'
Water Levels From 4/89
EXPLANATION
Fill
Till
Alluvium
Silts & Clays
Sand; Clayey
Lignite

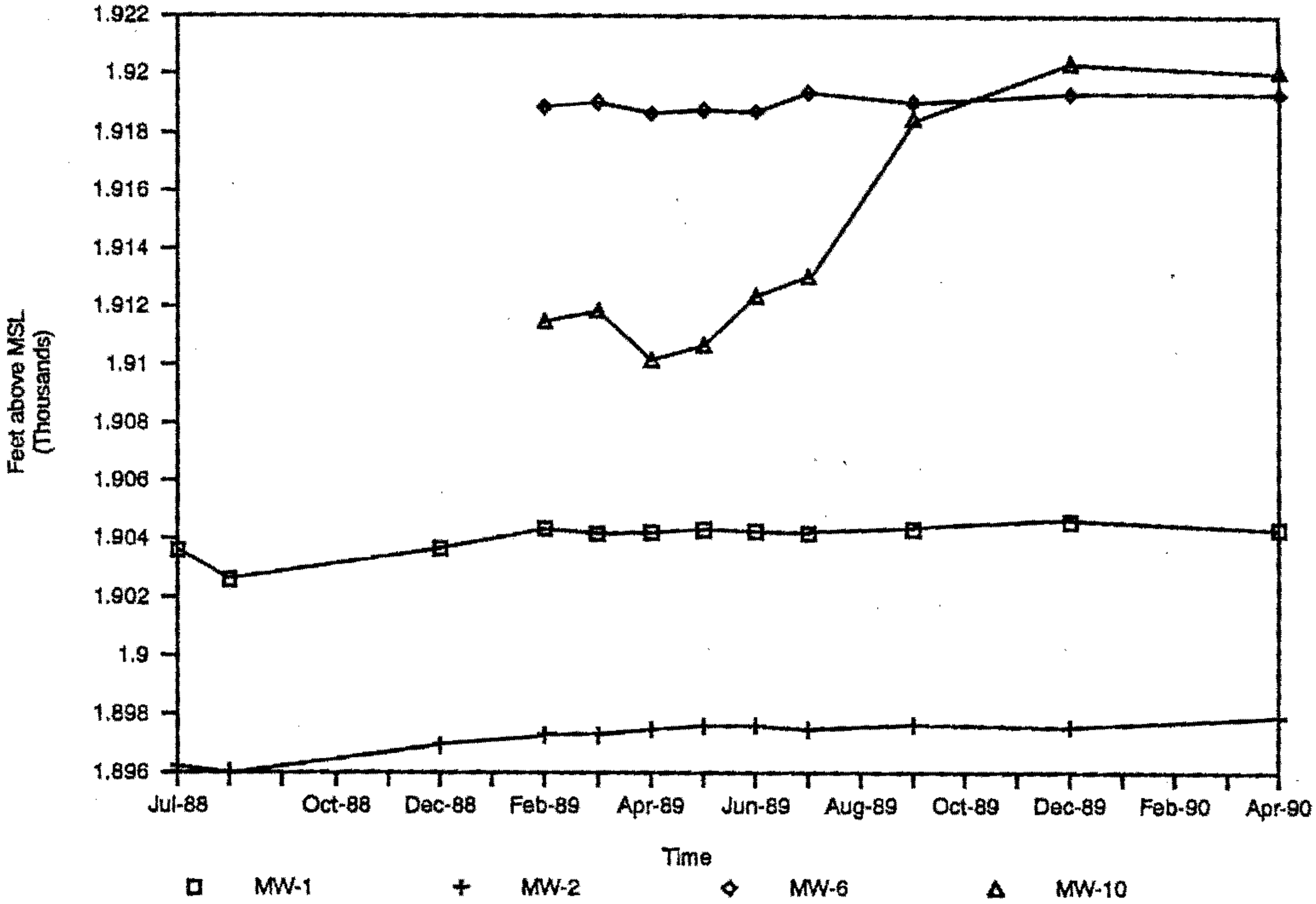
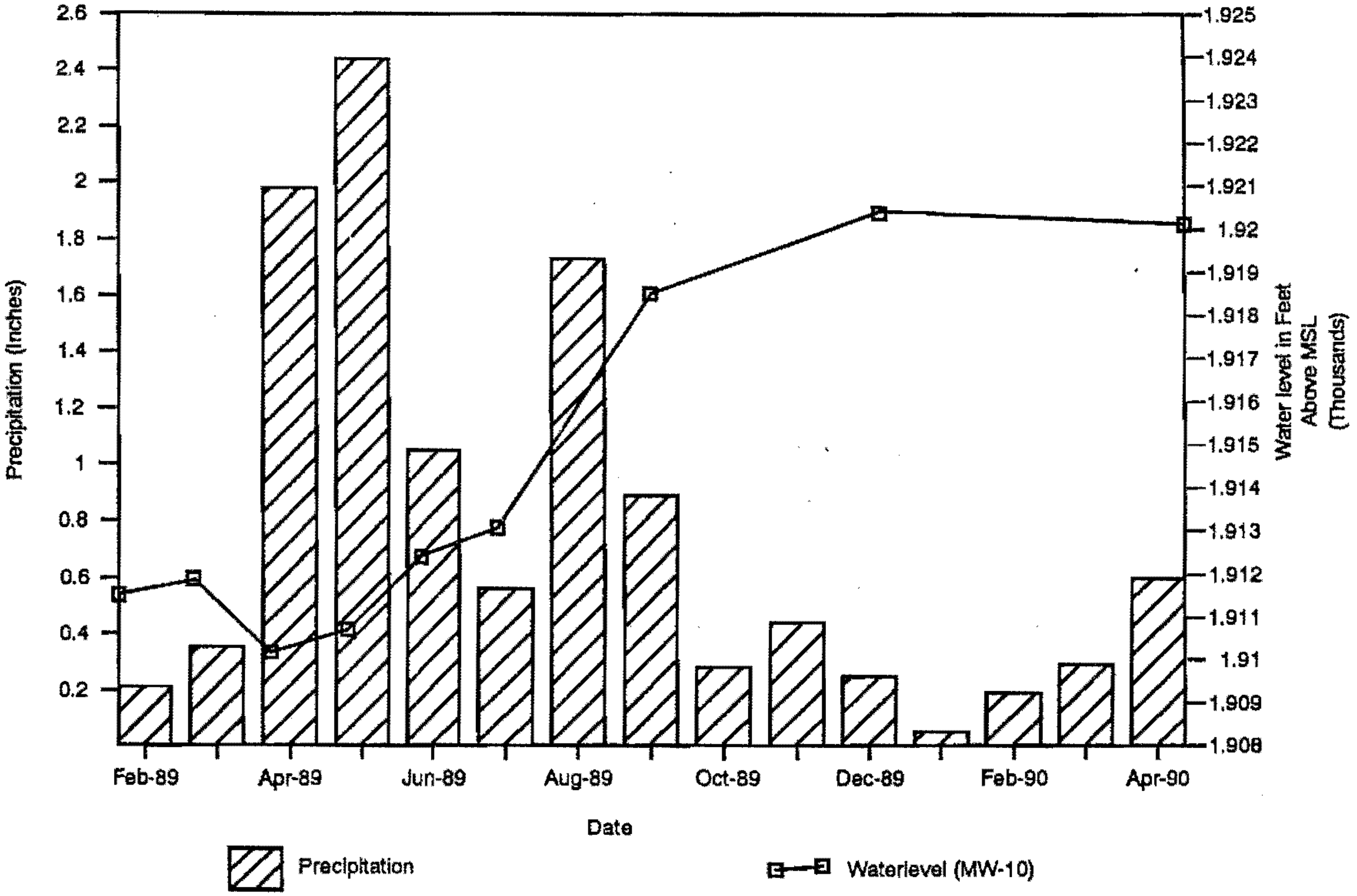

1.922
1.92
1.918
1.916
1.914
1.912
1.91
1.908
1.906
1.904
1.902
1.9
1.898
1.896
Feet above MSL
(Thousands)
Jul-88
Oct-88
Dec-88
Feb-89
Apr-89
Jun-89
Aug-89
Oct-89
Dec-89
Feb-90
Apr-90
Time
□ MW-1
+ MW-2
◇ MW-6
△ MW-10

Figure 18. Hydrograph of MW-10 vs average monthly precipitation. Refer to Figure 3 for well location.



Precipitation (Inches)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
Water level in Feet Above MSL (Thousands)
1.925
1.924
1.923
1.922
1.921
1.92
1.919
1.918
1.917
1.916
1.915
1.914
1.913
1.912
1.911
1.91
1.909
1.908
Feb-89
Apr-89
Jun-89
Aug-89
Oct-89
Dec-89
Feb-90
Apr-90
Date
Precipitation
Waterlevel (MW-10)

in the remaining monitoring wells do not respond to moderate summer precipitation events.

Unsaturated Zone

Monitoring of the unsaturated zone was conducted at two sites (monitoring nest 1 and monitoring nest 2). Both locations contain three nested pressure vacuum lysimeters. Monitoring nest 1 contains lysimeters PVL-3, PVL-4, and PVL-5, installed at 5, 10, and 15 feet, respectively (Figure 19). Nest 1 is located in an area characterized by well developed drainage and minimal subsurface disruption. The setting in which nest 1 is situated closely approximates a natural (undisturbed) environment. Monitoring nest 2 contains lysimeters PVL-7, PVL-8, and PVL-9, located at depths of 5, 10, and 15 feet, respectively (Figure 20). Nest 2 is situated in an artificial recharge zone created by extensive subsurface disruption, abundant surface water, and relatively low evapotranspiration rates due to shading by the 300 foot (98 m) high power plant.

The stratigraphy at nest 1 consists of 5 feet (1.5 m) of fill underlain by bedrock. The bedrock units are of low hydraulic conductivity; therefore water movement through the unsaturated sediments is extremely slow (Rehm, Groenewold, and Peterson, 1982). Pressure-vacuum lysimeter monitoring data confirm the slow infiltration rates. Moisture conditions in the unsaturated zone were

Figure 19. Stratigraphy and instrumentation of monitoring nest 1. Refer to Figure 3 for instrument locations.

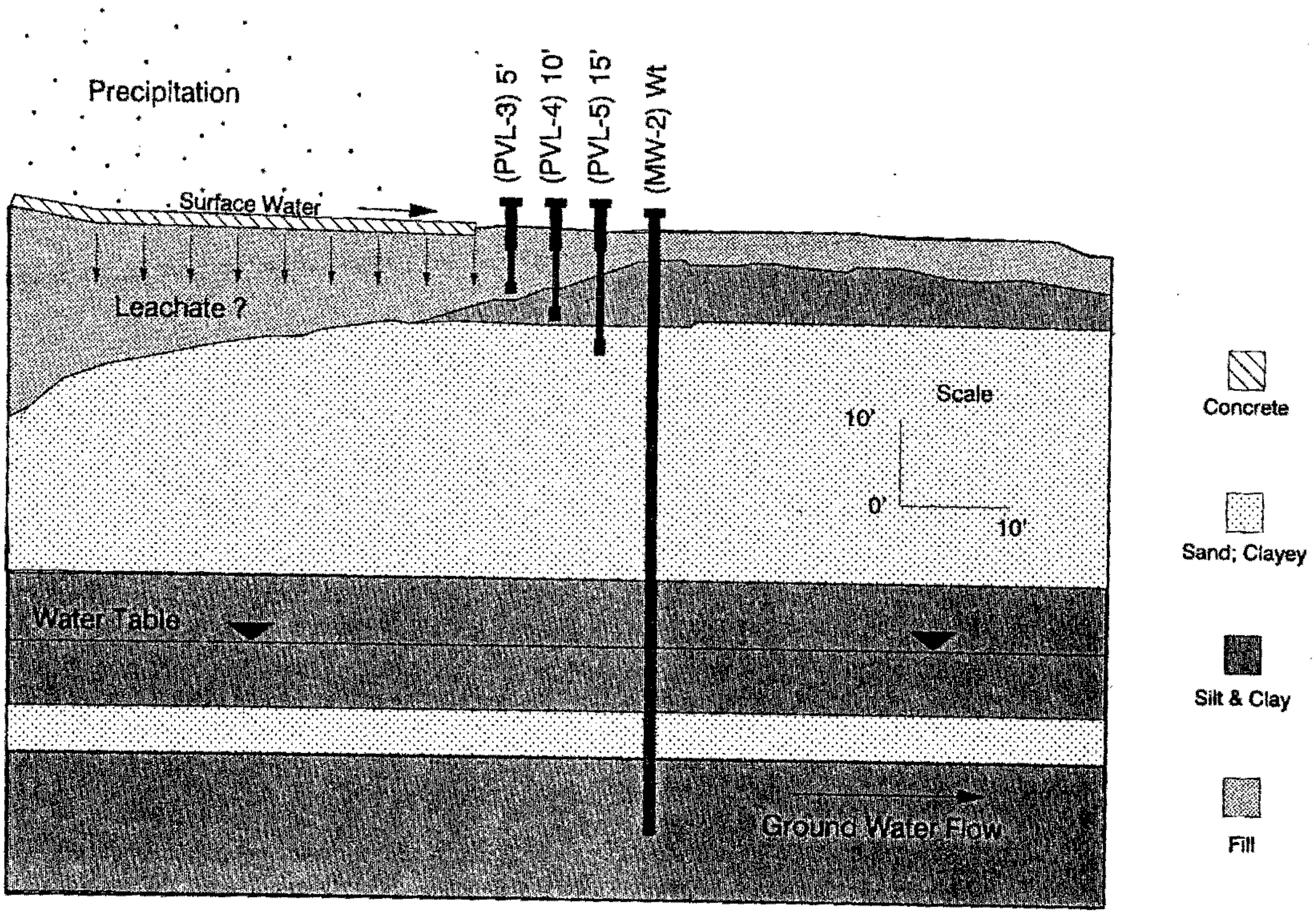
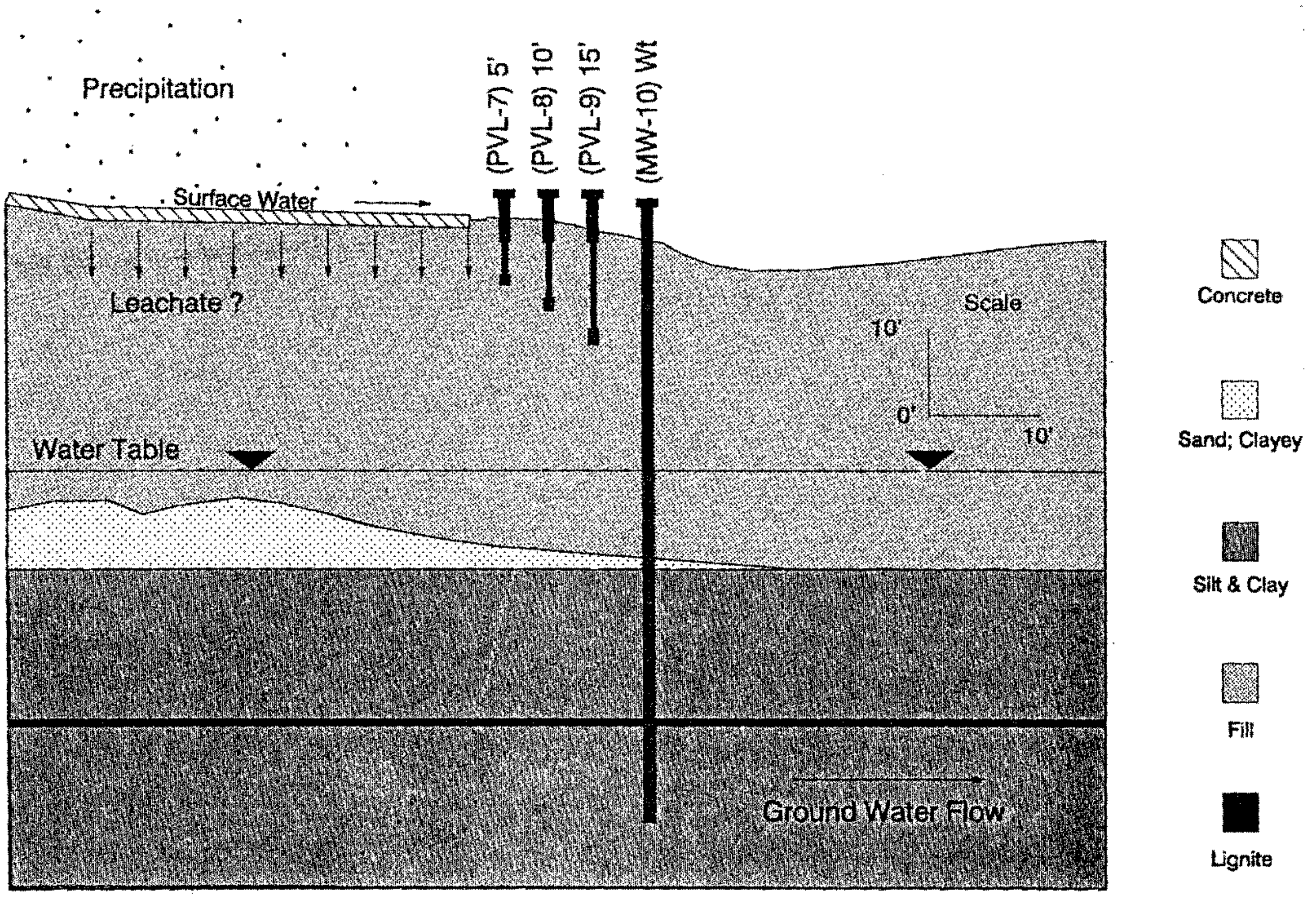

Precipitation
Surface Water
Leachate ?
(PVL-3) 5'
(PVL-4) 10'
(PVL-5) 15'
(MW-2) Wt
Scale
10'
0'
10'
Water Table
Ground Water Flow
Concrete
Sand; Clayey
Silt & Clay
Fill

Figure 20. Stratigraphy and instrumentation of monitoring nest 2. Refer to Figure 3 for instrument locations.


Precipitation
Surface Water
Leachate ?
(PVL-7) 5'
(PVL-8) 10'
(PVL-9) 15'
(MW-10) Wt
Scale
10'
0'
10'
Water Table
Ground Water Flow
Concrete
Sand; Clayey
Silt & Clay
Fill
Lignite

estimated by monitoring vacuum on the lysimeters. The pressure vacuum lysimeter will not maintain a vacuum if moisture is held under a tension greater than 85 centibars. If moisture conditions are such that the tension is greater than 85 centibars, the lysimeters will draw in air and the vacuum will quickly dissipate. Fine-grained sediments such as silts and clays typically have moisture contents ranging from 50% to 15% (dry weight) as tension increases from 0 to 80 centibars. Therefore, monitoring vacuum provides a rough estimate of the moisture conditions around each lysimeter (Fancher, personal communication, 1990).

In the summer of 1988 a wetting front was observed as it moved through the unsaturated zone of nest 1. During installation of nest 1 the sediment was observed to be dry to a depth in excess of 20 feet (6 meters). Precipitation occurred the day following installation and infiltration was monitored by measuring vacuum on the lysimeters. One week was required for the moisture to move through the top 5 feet (1.5 meters) of fill material at monitoring nest 1. An additional two weeks passed before the lysimeter located at the 10-foot (3 meter) level held a vacuum (see Figure 19, PVL-4). The 10-foot (3 meter) level appears to represent the lower limit of moisture originating from moderate summer precipitation events because the lysimeter located at 15 feet (4.5

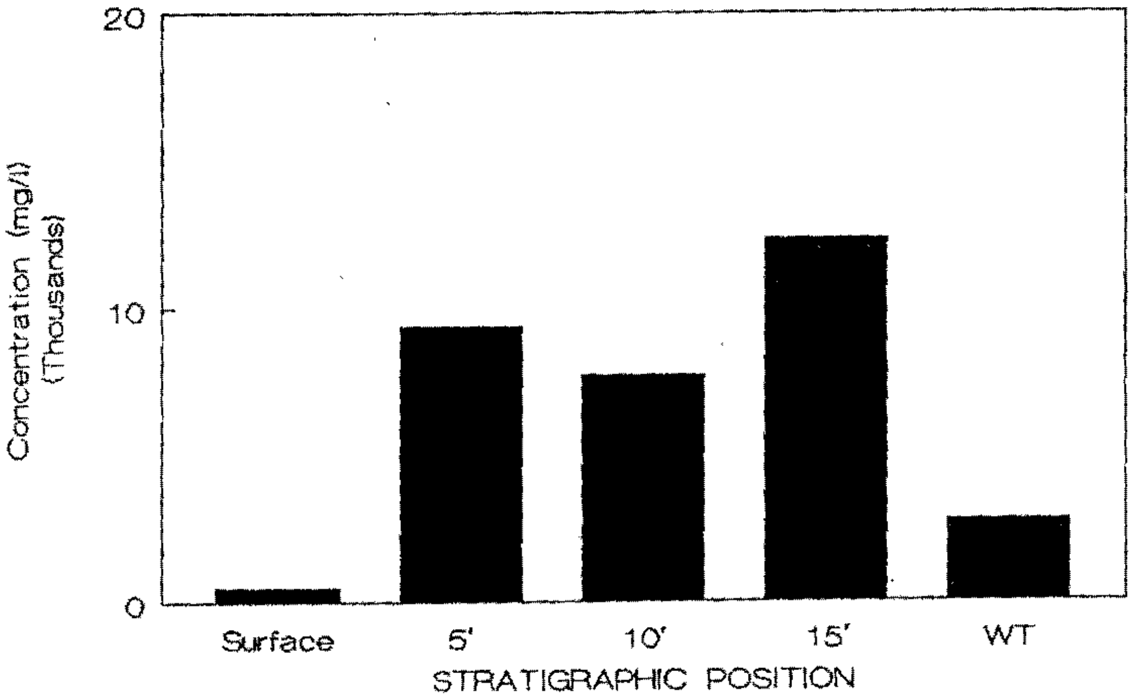
meter) failed to maintain a vacuum until early the following spring (8 months later).

Moisture conditions at nest 2 were quite different from nest 1. Nest 2 has more available surface water, a lower evapotranspiration rate, and contains a thicker horizon of fill materials; these factors combine to increase recharge. There were no instances during which the lysimeters in nest 2 failed to maintain a vacuum. Moisture in the unsaturated zone of nest 2 was abundant during monitoring with all the lysimeters yielding a large volume of sample (1 liter). Only the uppermost lysimeter in nest 1 (PVL-3) had, at times, sufficient moisture available to yield a comparable volume of sample. The persistent rise in the water table of MW-10 (Figure 17) provides further evidence for the consistent moisture conditions throughout the subsurface at monitoring nest 2.

Hydrogeochemistry

Water quality monitoring was performed on surface water (precipitation and runoff), unsaturated zone water, and saturated zone water. At the study area, water in the unsaturated zone is roughly 3 times as mineralized as saturated zone water and 50 times as mineralized as surface water runoff (Figure 21). There is an overall increase in mineralization with depth in the unsaturated zone. However, distinct differences in composition exist

Figure 21: Average TDS by stratigraphic position. The abbreviation WT refers to the water table. Samples at 5, 10, and 15 feet (1.5, 3.0, and 4.5 m) are from pressure-vacuum lysimeters.


20
10
0
Concentration (mg/l)
(Thousands)
Surface
5'
10'
15'
WT
STRATIGRAPHIC POSITION

between the undisturbed (monitoring nest 1) and disturbed sites (monitoring nest 2) (Figure 22).

Surface Water Characterization

The TDS of surface water runoff at CCS average 748 mg/l; the highest and lowest reported values were 1180 mg/l and 317 mg/l, respectively. Precipitation was less mineralized with a mean TDS of 202 mg/l. Average TDS for the runoff samples may not be very indicative of an immediate runoff event because some samples were collected over extended periods during which it is likely that evaporation may have concentrated the samples. The runoff sample taken 3/13/89 provides a more accurate indication of an immediate runoff event (Appendix D). Constituents of the runoff and precipitation include sulfate and bicarbonate as major anions, and sodium, calcium, and magnesium in approximately equal proportions as major cations.

Analyses of the Cooling Water Basin water (CWB) made during this study and obtained from CCS indicate a mean TDS value for the basin of approximately 6000 mg/l, exceeding the 500 mg/l maximum permissible limit by a factor of 12 (Table 4). Major constituents of the cooling water include sulfate (3700 mg/l), chloride (300 mg/l), bicarbonate (350 mg/l), and sodium (800 mg/l), calcium (600 mg/l), and magnesium (275 mg/l) as major cations (Figure 22).

Figure 22. Stiff diagram of all ground and soil water sampling points. The abbreviations MW, PVL and CWB refer to monitoring well, pressure-vacuum lysimeter and Cooling Water Basin, respectively. Refer to Figure 3 for instrument locations.

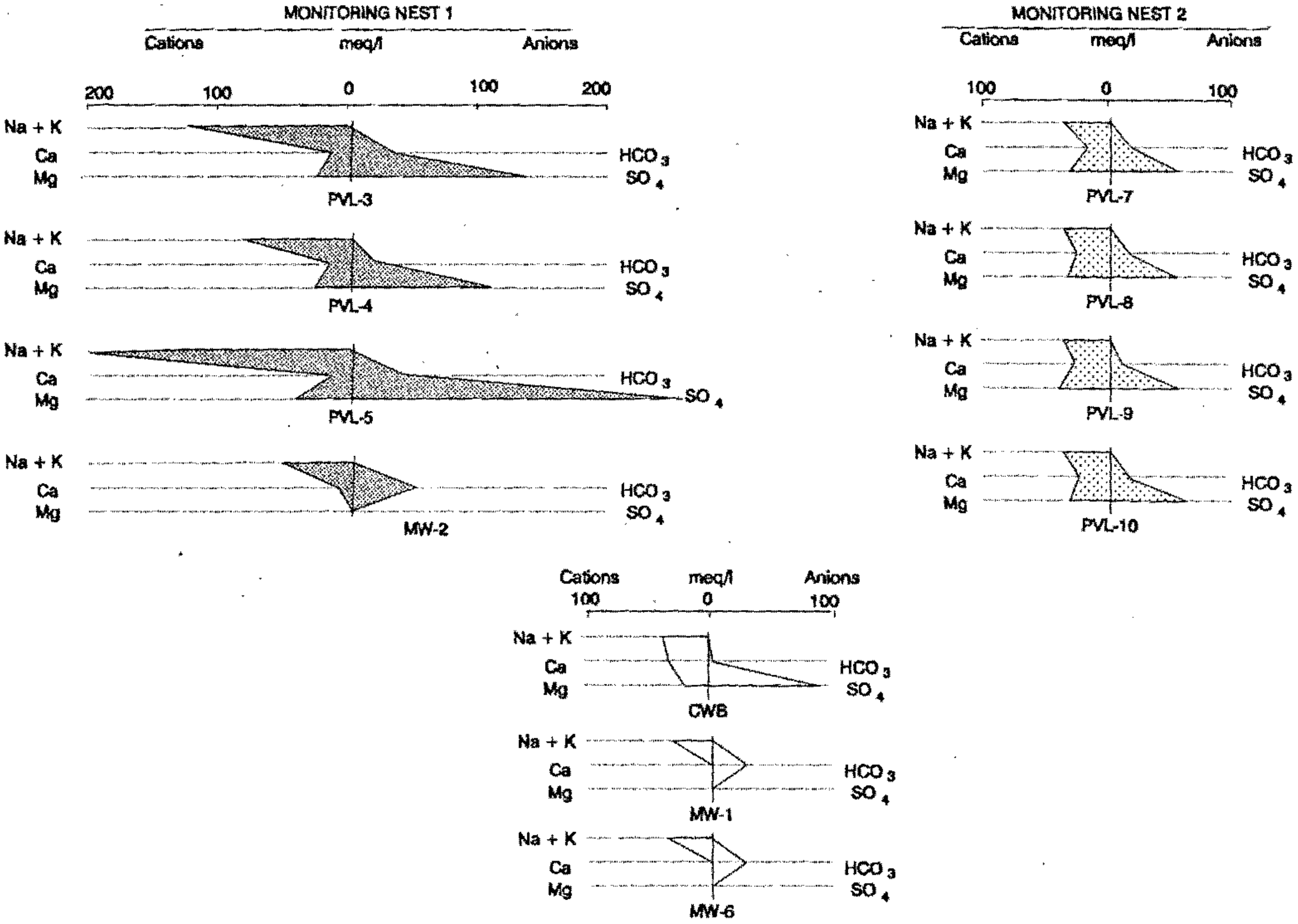

MONITORING NEST 1
Cations
meq/l
Anions
200
100
0
100
200
Na + K
Ca
Mg
HCO 3
SO 4
PVL-3
PVL-4
PVL-5
MW-2
MONITORING NEST 2
Cations
meq/l
Anions
100
0
100
PVL-7
PVL-8
PVL-9
PVL-10
Cations
meq/l
Anions
100
0
100
CWB
MW-1
MW-6

TABLE 4

Federal Interim Water Standards

Maximum Contaminant Levels[1]

Constituent	Safe Drinking Water Act *	Resource Conservation and Recovery Act (RCRA), 1980
Arsenic	0.05 mg/l	5 mg/l
Barium	1 mg/l	100 mg/l
Cadmium	0.01 mg/l	1 mg/l
Chromium	0.05 mg/l	5 mg/l
Lead	0.050 mg/l	5 mg/l
Mercury	0.002 mg/l	0.2 mg/l
Selenium	0.01 mg/l	1 mg/l
Silver	0.050 mg/l	5 mg/l

Secondary Maximum Contaminant Levels [2]

Constituent	Recommended Concentration Limit
Boron	1 mg/l
Copper	1 mg/l
Iron	0.3 mg/l
Manganese	0.5 mg/l
Sulfate	250 mg/l
TDS	500 mg/l
Zinc	5 mg/l

---

[1] Maximum contaminant levels have been promulgated for substances with a health risk.

[2] Secondary contaminant levels were established for constituents that affect the aesthetic quality of water.

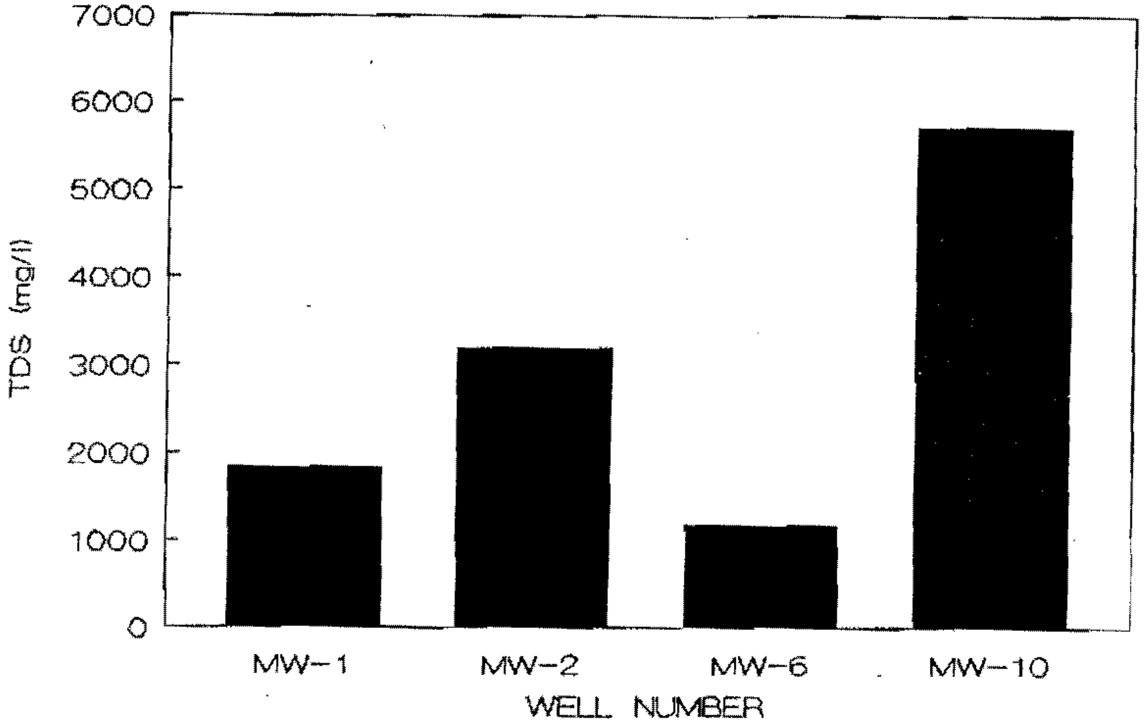
* Code of Federal Regulations: 40 CFR, Part 141.

Saturated Zone Characterization

Measurements of pH, specific conductance, and temperature were all in the expected range for saturated zone water from the region with the exception of MW-10. Values for pH ranged between 7.1 and 8.35, specific conductance varied between 1.85 mmhos/cm and 6.26 mmhos/cm, and temperature averaged 8°C. On the basis of composition, saturated zone water at the CCS site can be categorized into two groups (Figure 22). Water from all wells, with the exception of MW-10, is sodium bicarbonate-type water typical of the region (Groenewold et al., 1983; Beaver, 1986). Water from MW-10 is more mineralized, containing sodium, magnesium, and calcium in approximately equal proportions as dominant cations and sulfate as the dominant anion.

Klausing (1974, p. 14) reported a range of TDS from 206 mg/l to 3550 mg/l for 65 different water samples from wells screened within the Fort Union Group. TDS concentrations from the CCS site are highly variable, ranging between 1750 mg/l and 6020 mg/l (Figure 23). The highest TDS occurred in MW-10. All values of TDS reported from monitoring wells at the site exceed the maximum permissible limit of 500 mg/l for drinking water. Because of the high TDS, sodium, and sulfate ground water from the CCS site would be considered unfit for human consumption (Table 4).

Figure 23. Average TDS for all monitoring wells. MW-1 and MW-6 were installed for continuous background monitoring of the saturated zone. Refer to Figure 3 for well locations.


7000
6000
5000
4000
3000
2000
1000
0
TDS (mg/l)
MW-1
MW-2
MW-6
MW-10
WELL NUMBER

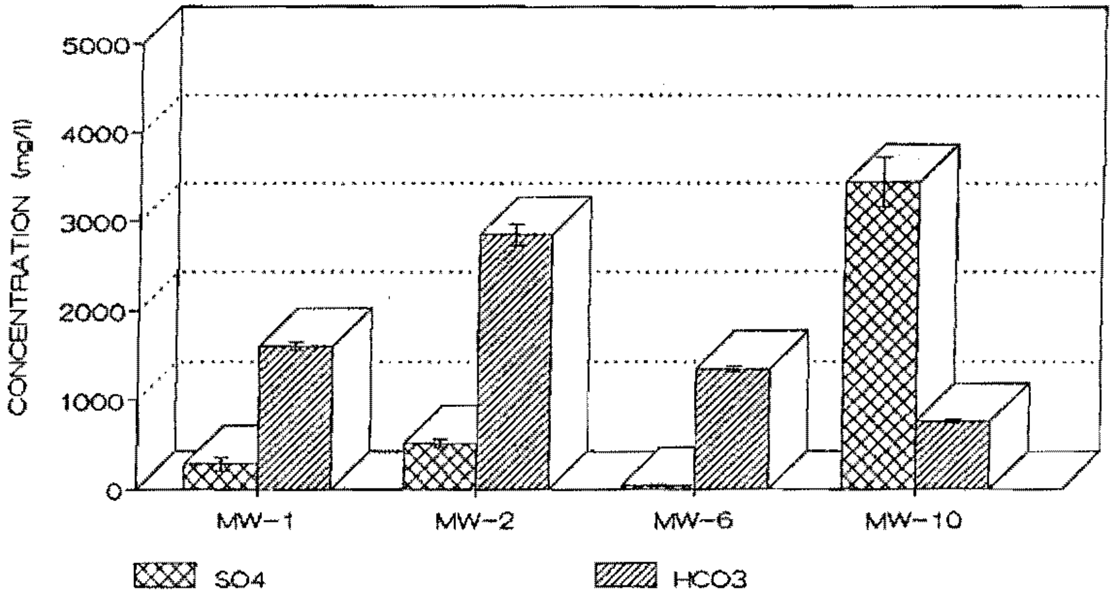
The two major anions in ground water at the CCS site are sulfate and bicarbonate. Both these constituents vary spatially at the site (Figure 24). The concentration of sulfate ranges from a low of 35 mg/l in MW-6 to a high of 3691 mg/l in MW-10. Wells completed in the Fort Union Group can be expected to have sulfate concentrations from 3 mg/l to 2000 mg/l (Klausing, 1974). The lowest recorded value for bicarbonate occurred in MW-10 (741 mg/l); the highest value was recorded in MW-2 (2965 mg/l). All wells with the exception of MW-10 have bicarbonate as the dominant anion. MW-10 has little bicarbonate in comparison with its sulfate concentration.

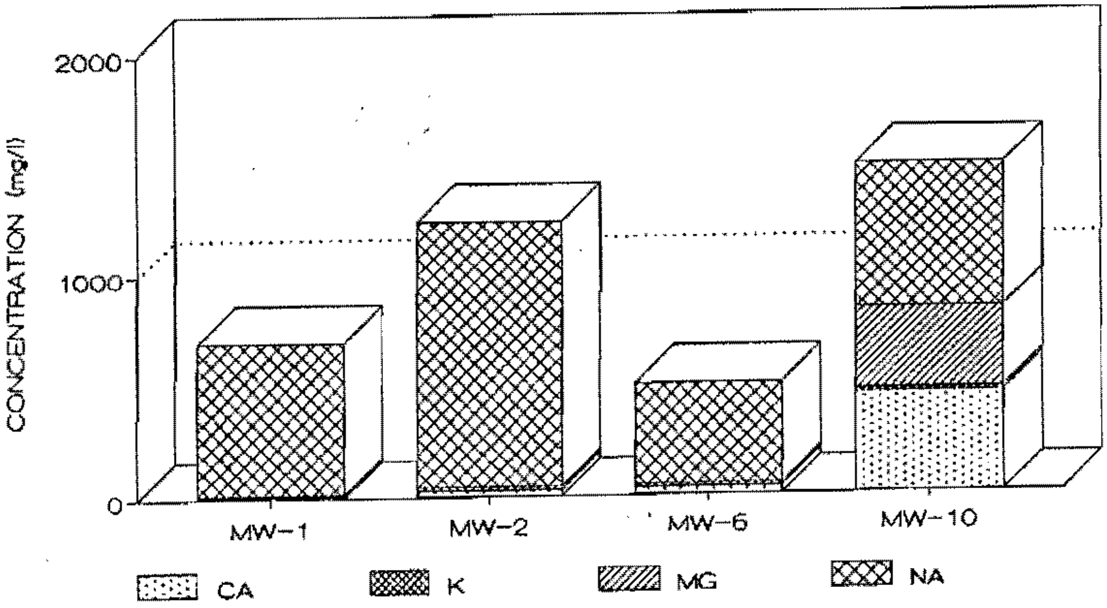
The dominant cation in saturated zone waters from the CCS site is sodium (Figure 25). The highest reported value is 1257 mg/l, occurring in MW-2; the lowest value is 406 mg/l from MW-6. Groenewold, Rehm, and Cherry (1981) reported sodium concentrations ranging from 9.5 mg/l to 620 mg/l for wells completed in shallow (less than 225 feet (75 m)) lignite aquifers at the Falkirk site, approximately 4000 feet (1200 m) north of CCS.

Concentrations of both calcium and magnesium are relatively low over most of the study area (Figure 25). Monitoring wells MW-1, MW-2, and MW-6 all have calcium concentrations less than 40 mg/l and magnesium concentrations less than 20 mg/l. The highest reported value for both calcium (470 mg/l) and magnesium (428 mg/l) occur in MW-10. Calcium and magnesium in MW-10 are

Figure 24. Average anion concentrations for all monitoring wells. MW-1 and MW-6 were installed for continuous background monitoring of the saturated zone. Error bars show standard deviation. Refer to Figure 3 for well locations.

Figure 25. Average cation concentrations for all monitoring wells. MW-1 and MW-6 were installed for continuous background monitoring of the saturated zone. Refer to Figure 3 for well locations.


CONCENTRATION (mg/l)
5000
4000
3000
2000
1000
0
MW-1
MW-2
MW-6
MW-10
SO4
HCO3


CONCENTRATION (mg/l)
2000
1000
0
MW-1
MW-2
MW-6
MW-10
CA
K
MG
NA

higher than the expected range for background levels reported by Groenewold, Rehm, and Cherry (1981).

Selenium is the only trace element found in the saturated zone water in concentrations exceeding the maximum permissible limit of 10 ug/l for drinking water. All of the exceedences were observed in MW-10 (Figure 26). In most cases, reported selenium concentrations for the remaining wells were below detection limits. Average selenium concentrations in MW-10 exceed drinking water standards by a factor of 30.

Arsenic concentrations in the saturated zone waters of the CCS site were all below the maximum permissible limit (Figure 26). The highest concentrations occurred in MW-1, which also recorded the highest pH. In MW-1 the arsenic concentrations ranged from 16 ug/l to 42 ug/l. Arsenic levels in ground water at the site are generally greater at higher pH (Figure 27). This is expected because the solubility of arsenic is strongly pH-dependent, increasing at higher pH (Ferguson and Gavis, 1972; Hassett and Groenewold, 1986).

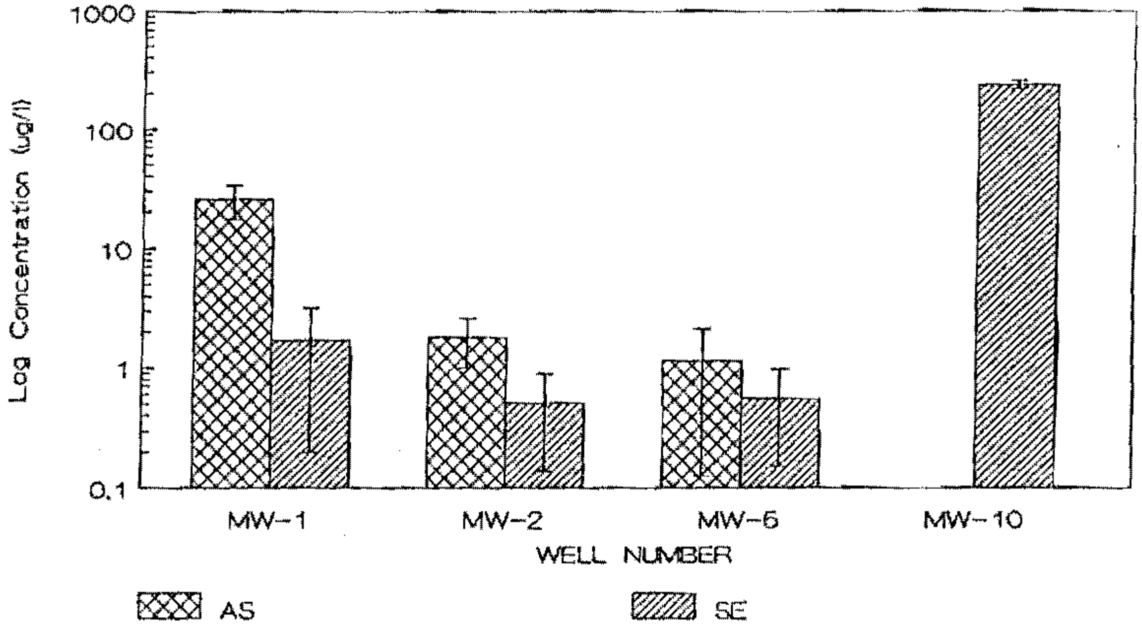
The remaining trace elements were detected at concentrations below their maximum permissible limits and many were below detection limits (Appendix D).

Unsaturated Zone Characterization

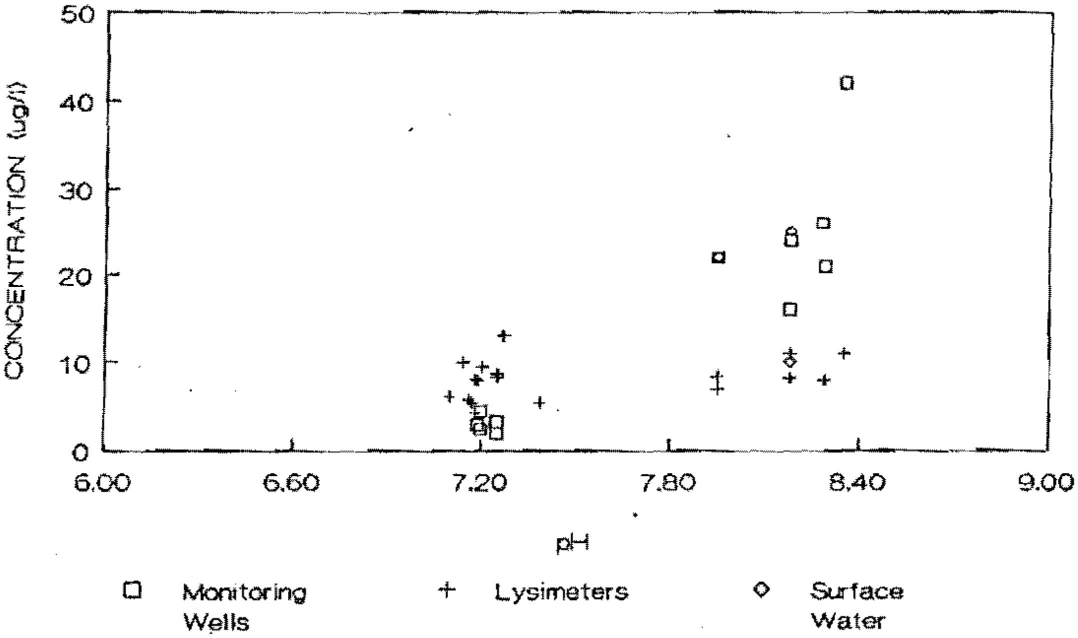
Two contrasting unsaturated environments have been instrumented at the site. The first site is in a

Figure 26. Average arsenic and selenium concentrations for all monitoring wells. MW-1 and MW-6 were installed for continuous background monitoring of the saturated zone. Error bars show standard deviation. Refer to Figure 3 for well locations.

Figure 27. Arsenic concentration vs field pH for all sampling points. Refer to Figure 3 for instrument locations.



Log Concentration (ug/l)
1000
100
10
1
0.1
MW-1
MW-2
MW-6
MW-10
WELL NUMBER
AS
SE



CONCENTRATION (ug/l)
50
40
30
20
10
0
6.00
6.60
7.20
7.80
8.40
9.00
pH
Monitoring Wells
Lysimeters
Surface Water

relatively undisturbed setting with respect to recharge and subsurface disruption (monitoring nest 1). The other site is located where the subsurface has been disrupted at depth and recharge rates have been elevated by topographic changes (monitoring nest 2). Both sites are downgradient of fly ash concrete installations. Each site contains three pressure-vacuum lysimeters installed at depths of 5 feet (1.5 m), 10 feet (3 m), and 15 feet (4.5 m) and one monitoring well screened at the water table.

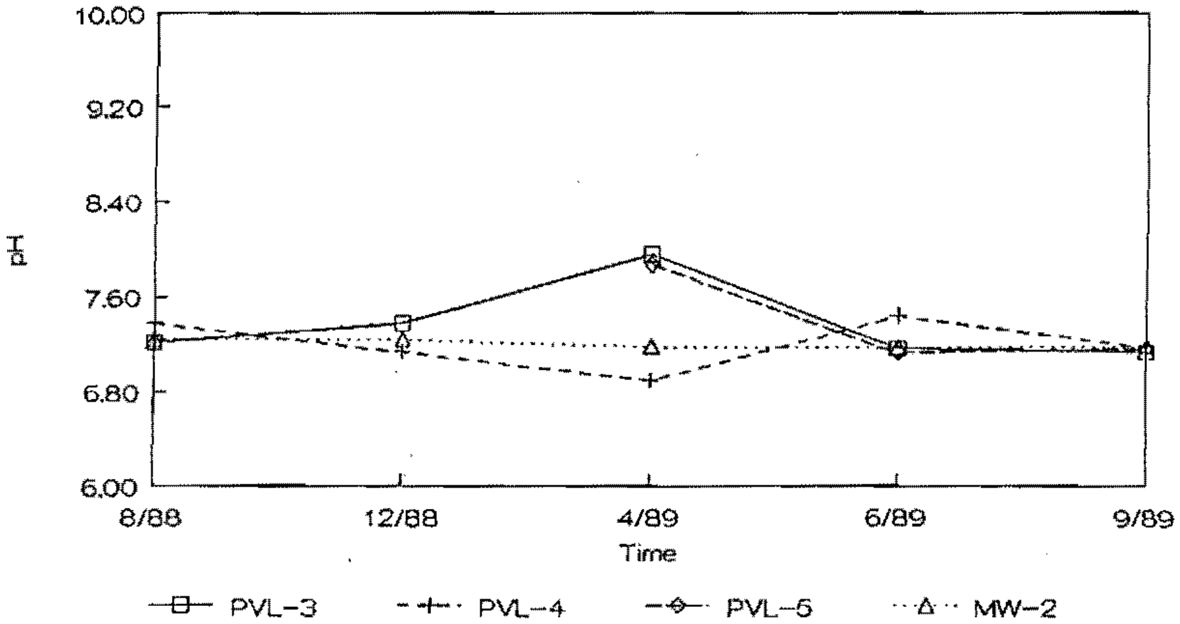
Undisturbed Setting (monitoring nest 1)

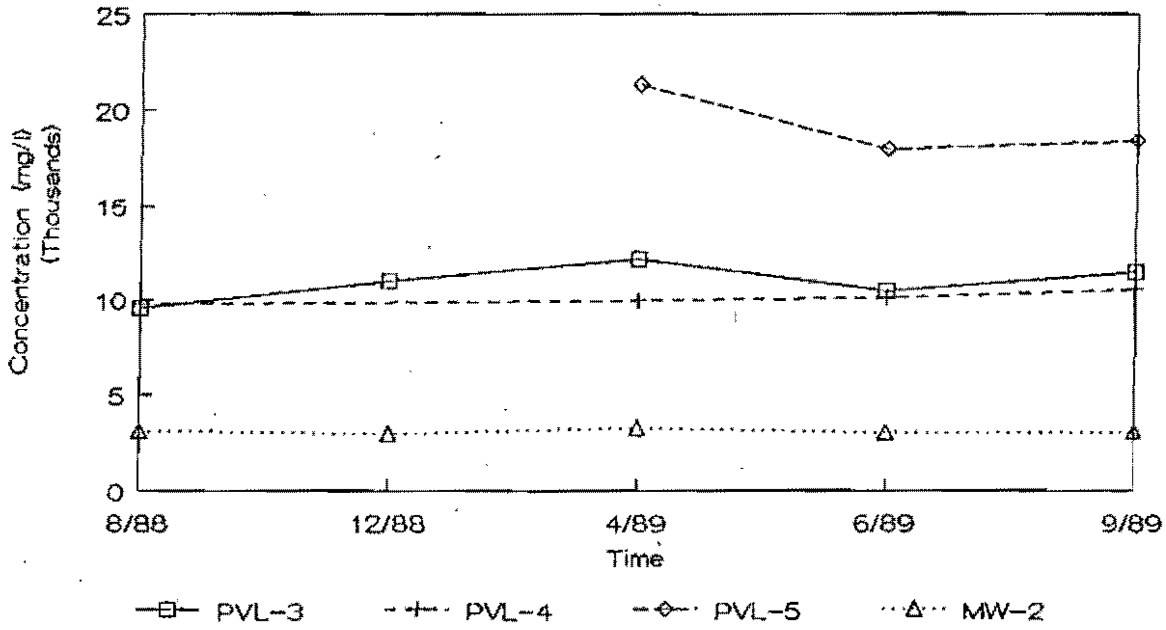
Field measurements of pH, temperature, and specific conductance were taken on all unsaturated zone samples. Measurements of pH fell between 6.90 and 7.95 in the undisturbed setting (Figure 28). Temperature readings were highly variable, as expected, ranging from frozen conditions in winter to 18.9°C in late summer (Appendix D). Variability in the temperature readings decreased with increasing depth. The high summer temperature readings at depths of 5 feet (1.5 m) and 10 feet (3 m) for both monitoring nests indicate a large temperature gradient in the upper 10 feet (3 m) of the column (Appendix D).

Calculated total dissolved solids (TDS) ranged between 21329 mg/l and 9891 mg/l in monitoring nest 1 (Figure 29). The highest TDS concentration was recorded

Figure 28. Monitoring nest 1 (undisturbed site) - field pH vs time. Pressure-vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 29. Monitoring nest 1 (undisturbed site) - TDS vs time. Pressure-vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.


10.00
9.20
8.40
7.60
6.80
6.00
pH
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2


25
20
15
10
5
0
Concentration (mg/l)
(Thousands)
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2

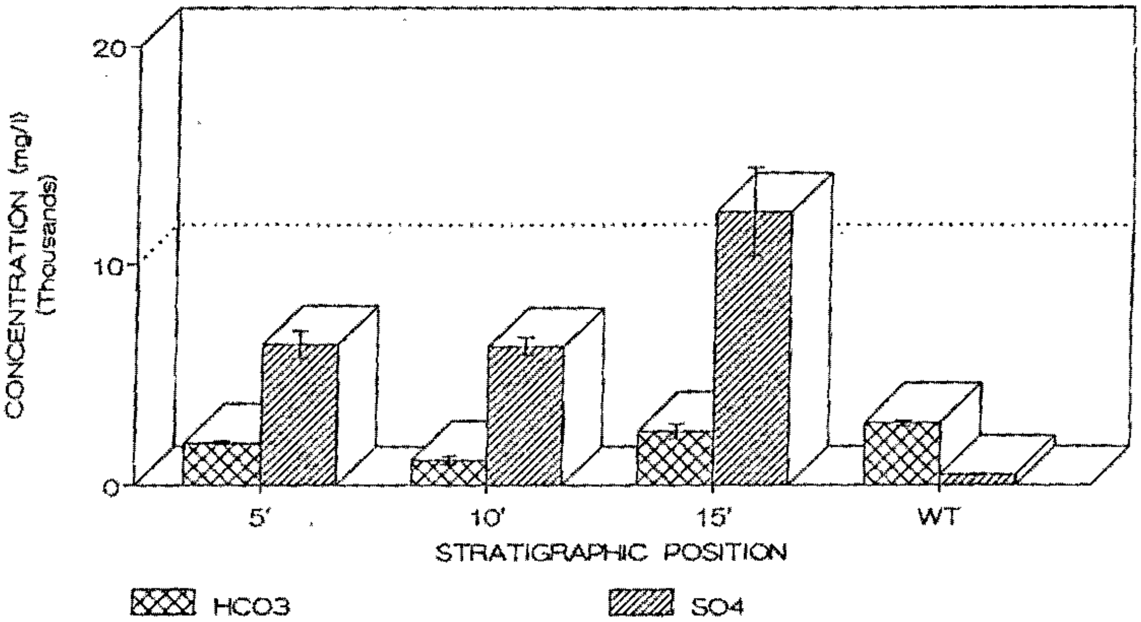
at the 15 foot level (4.5 m). The lowest TDS occurred in the saturated zone (MW-2). Pore water in nest 1 was at least twice as mineralized as saturated zone water (Figure 22). Both TDS and pH were more variable with respect to depth and time in the unsaturated zone than in the saturated zone (Figures 28 and 29).

Major anions in monitoring nest 1 are bicarbonate and sulfate (Figure 30). Sulfate is the dominant anion in the unsaturated zone whereas bicarbonate prevails in the saturated zone. Pore water concentrations of bicarbonate and sulfate in nest 1 are highest at the 15-foot (4.5 m) level (Figures 31 and 32). Sulfate concentrations in the unsaturated zone range from 5480 mg/l at 5 feet (1.5 m) to 15400 mg/l at a depth of 15 feet (4.5 m). Sulfate decreases by a factor of 23 at the water table. Bicarbonate increases to the water table and is less variable with depth and time than sulfate.

The dominant cation in all subsurface waters at the site is sodium. However, sodium concentrations are more variable in the unsaturated zone than other cations, particularly in the undisturbed setting (monitoring nest 1). At nest 1, sodium concentrations increase steadily with depth before falling sharply at the water table (Figure 33). In contrast to the unsaturated zone, sodium concentrations are chronologically consistent in the saturated zone (Figure 34). The greatest deviation in

Figure 30. Monitoring nest 1 (undisturbed site) - average anion concentrations by stratigraphic position. Pressure-vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Error bars show standard deviation. Refer to Figure 3 for instrument locations.

Figure 31. Monitoring nest 1 (undisturbed site) - bicarbonate concentration vs time. Pressure-vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.


20
10
0
CONCENTRATION (mg/l) (Thousands)
5'
10'
15'
WT
STRATIGRAPHIC POSITION
HCO3
SO4

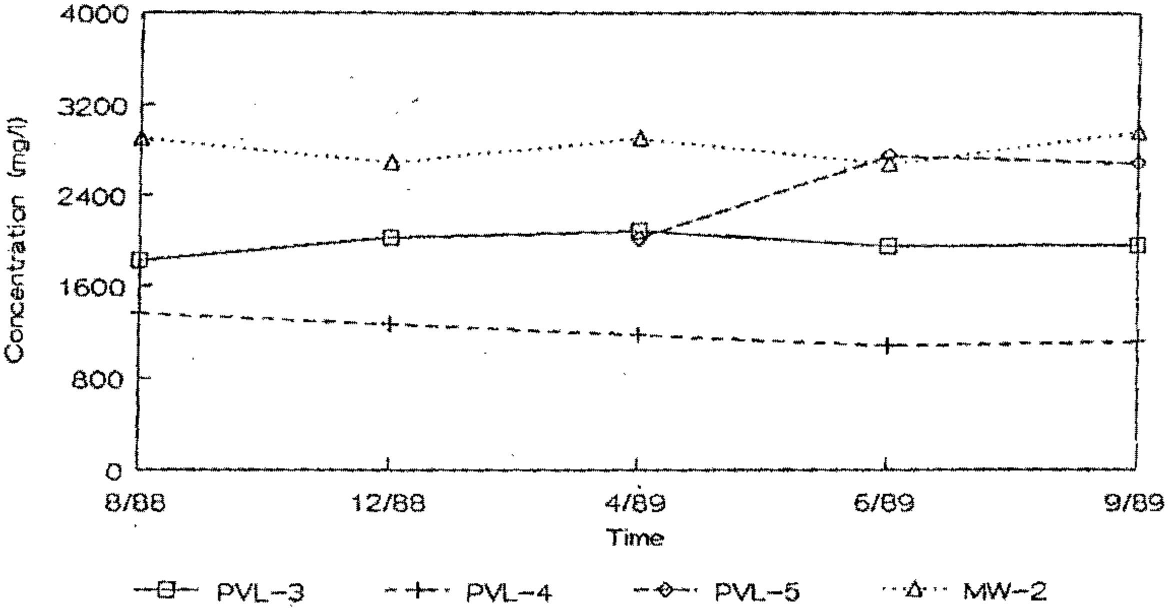
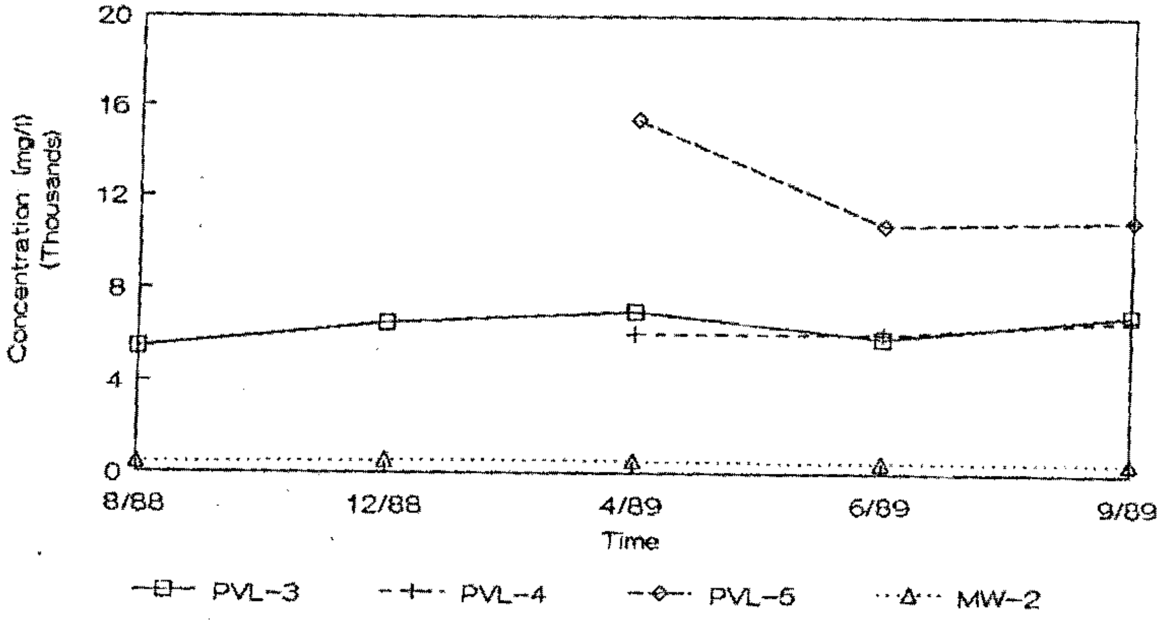

4000
3200
2400
1600
800
0
Concentration (mg/l)
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2

Figure 32. Monitoring nest 1 (undisturbed site) - sulfate concentration vs time. Pressure- vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 33. Monitoring nest 1 (undisturbed site) - average cation concentrations by stratigraphic position. Pressure-vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Error bars show standard deviation. Refer to Figure 3 for instrument locations.


Concentration (mg/l) (Thousands)
20
16
12
8
4
0
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2

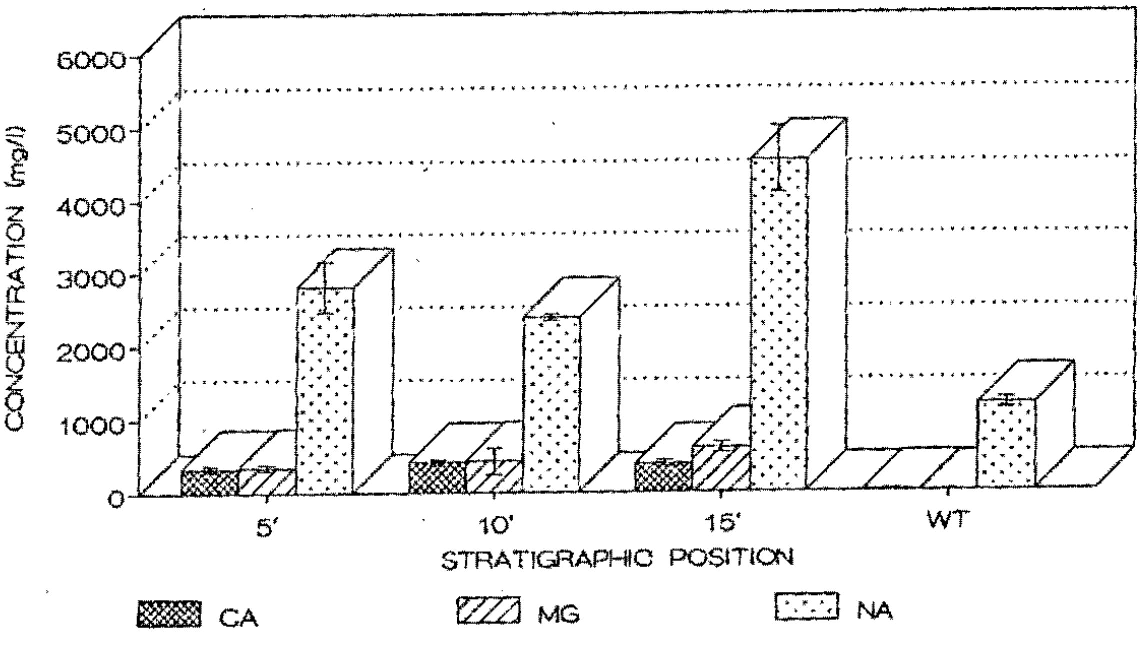
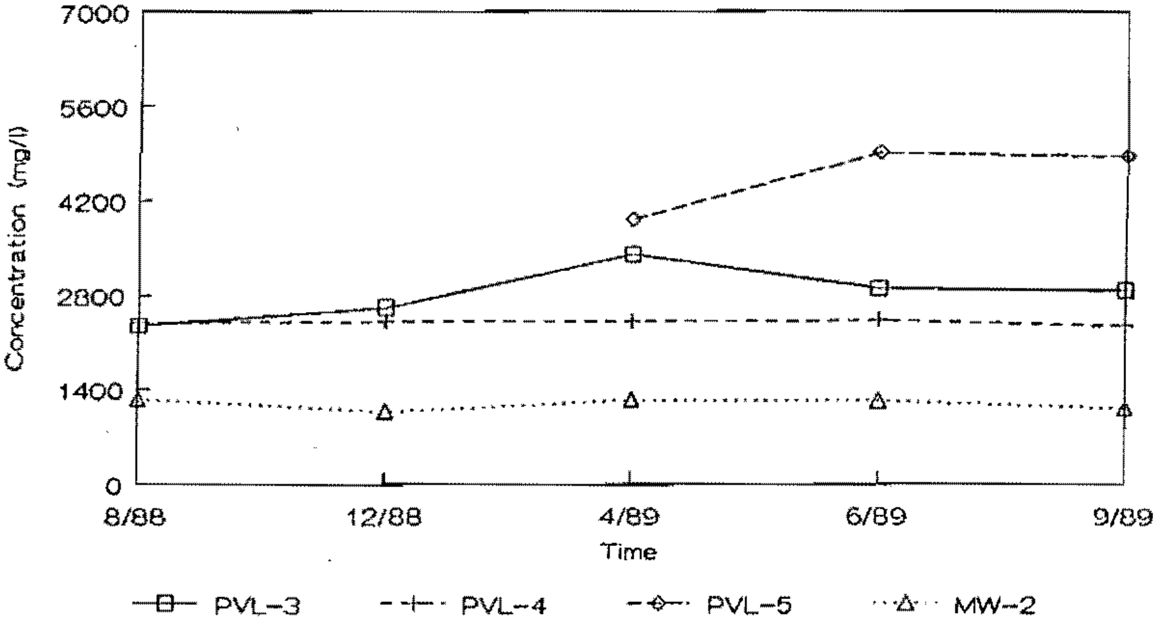
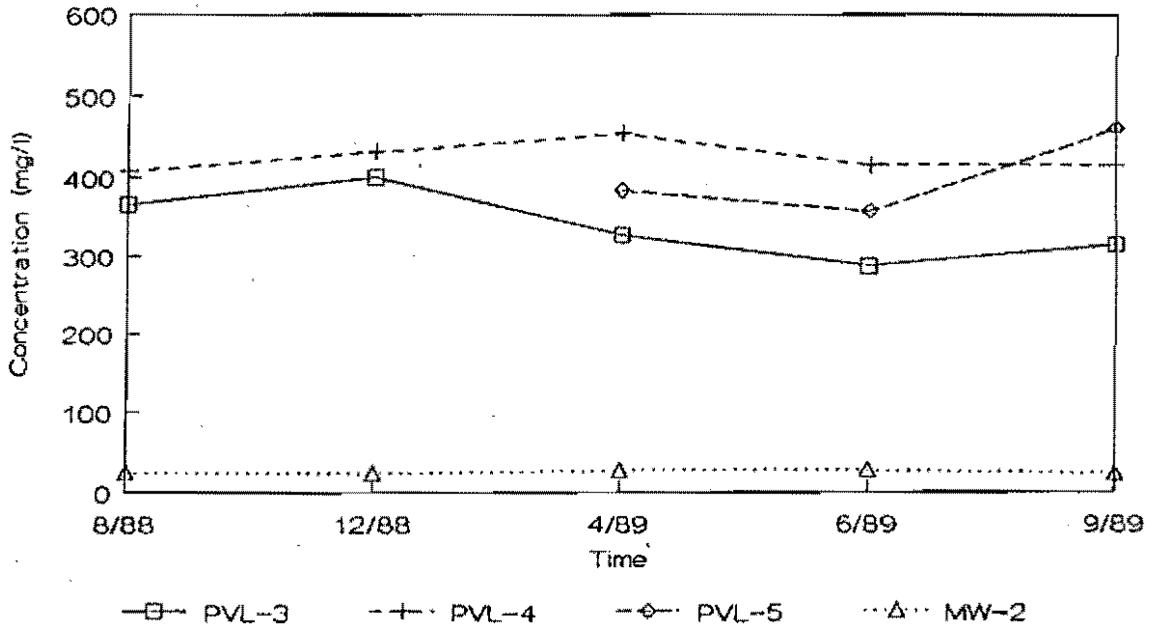

CONCENTRATION (mg/l)
6000
5000
4000
3000
2000
1000
0
5'
10'
15'
WT
STRATIGRAPHIC POSITION
CA
MG
NA

Figure 34. Monitoring nest 1 (undisturbed site) - sodium concentration vs time. Pressure- vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 35. Monitoring nest 1 (undisturbed site) - calcium concentration vs time. Pressure- vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.


7000
5600
4200
2800
1400
0
Concentration (mg/l)
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2


600
500
400
300
200
100
0
Concentration (mg/l)
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2

sodium was observed at the 5-foot (1.5 m) level during spring thaw.

Both calcium and magnesium throughout the unsaturated profile occur in nearly equal proportions, increasing slightly with depth (Figure 33). Both constituents decrease by an order of magnitude at the water table. The 15-foot (4.5 m) level recorded the highest concentrations of calcium and magnesium in the undisturbed setting, 462 mg/l and 710 mg/l, respectively. The lowest concentration of calcium (24 mg/l) and magnesium (11 mg/l) occur in the saturated zone (MW-2).

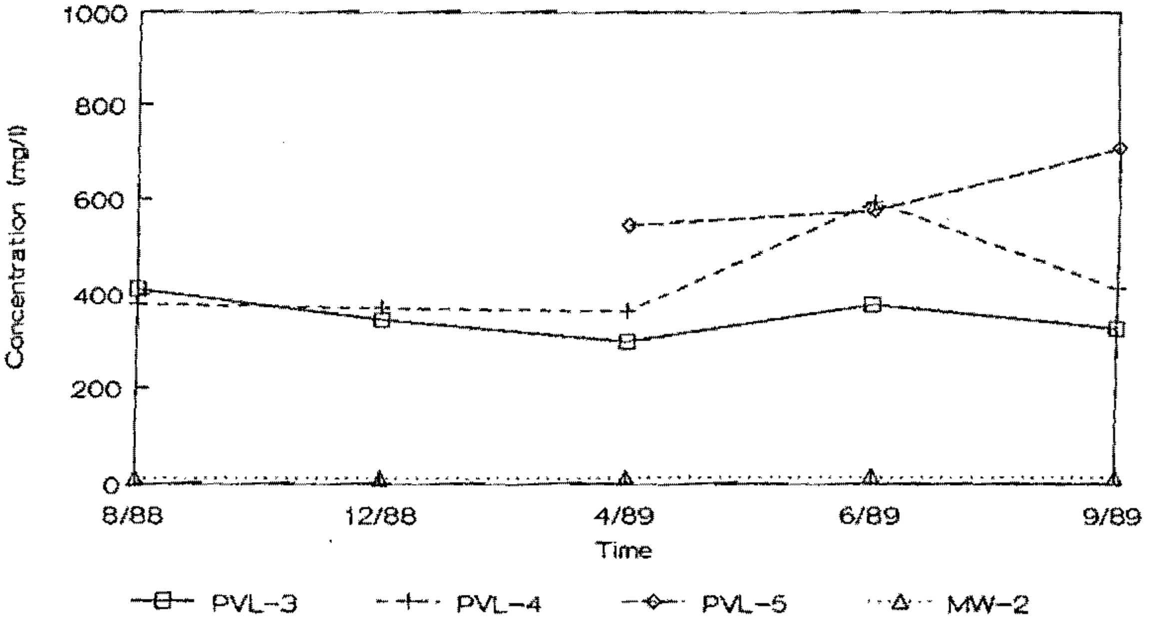
In the undisturbed setting, changes in calcium and magnesium with time follow one another at the 15-foot (4.5 m) level (Figures 35 and 36). Calcium and magnesium concentrations at 5 feet (1.5 m) and 10 feet (3 m) show more deviation, which may reflect increasing moisture variability at these depths.

Trace elements are of principal concern in this study because many of them, such as arsenic, selenium, and molybdenum, have a tendency to leach from fly ash (Hassett and Groenewold, 1986). Monitoring of the unsaturated zone was designed to provide early detection of these and other contaminants that may or may not originate from fly ash concrete.

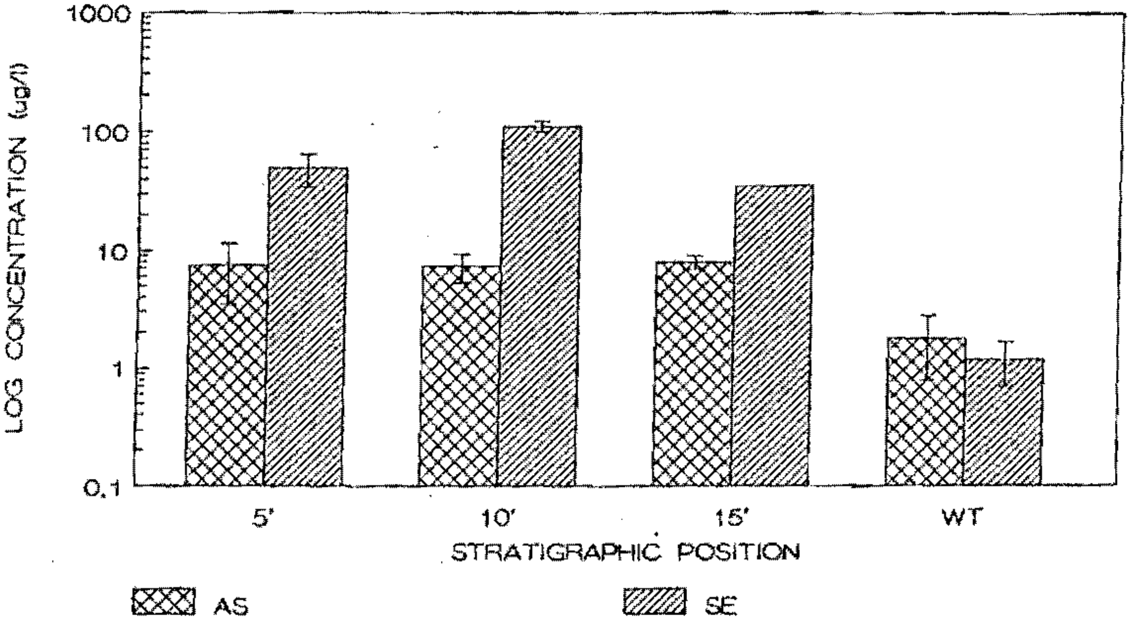
Arsenic concentrations in the undisturbed setting averaged 7 ug/l throughout the unsaturated profile, but decreased to 1 ug/l at the water table (Figure 37).

Figure 36. Monitoring nest 1 (undisturbed site) - magnesium concentration vs time. Pressure-vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 37. Monitoring nest 1 (undisturbed site) - average arsenic and selenium concentrations by stratigraphic position. Pressure-vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Error bars show standard deviation. Refer to Figure 3 for instrument locations.



1000
800
600
400
200
0
Concentration (mg/l)
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2



1000
100
10
1
0.1
LOG CONCENTRATION (ug/l)
5'
10'
15'
WT
STRATIGRAPHIC POSITION
AS
SE

Selenium concentrations were more variable in the unsaturated zone with the 10-foot (3 m) level recording concentrations twice those at the 5-foot (1.5 m) and 15-foot (4.5 m) level. Reported arsenic concentrations ranged from a high of 11 ug/l at 5 feet (1.5 m) to below detection limits in the saturated zone (MW-2). Selenium ranged from 30 ug/l to 122 ug/l in the unsaturated zone and decreased to below 2 ug/l at the water table.

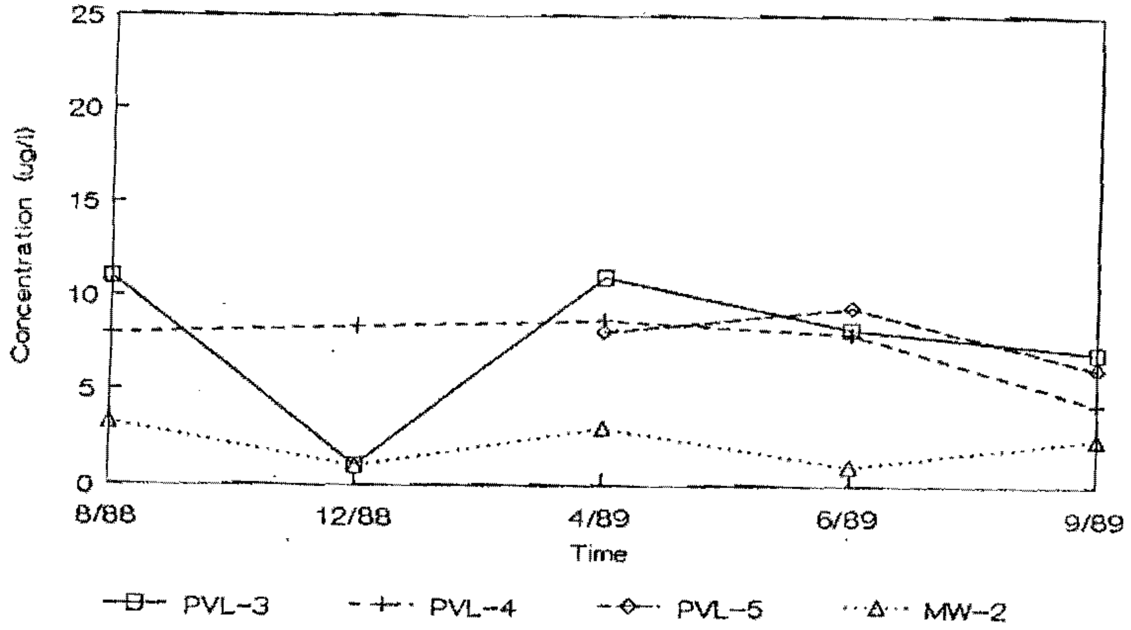
Arsenic was variable over time in the unsaturated zone (Figure 38). However, arsenic concentrations changed little between the saturated and unsaturated zones. Selenium was uniform over time, increasing slightly in the uppermost lysimeters (Figure 39). The deepest lysimeter (PVL-5) and MW-2 have static selenium concentrations. The remaining trace elements were generally at concentrations below expected levels for fly ash leachate.

<u>Disturbed Setting</u> (monitoring nest 2)

The field pH readings for instruments in the disturbed setting were temporally uniform and in the range of 6.99 to 7.53 (Figure 40). Calculated TDS showed a declining trend with time until 6/89, after which it increased slightly, possibly the result of increasing evapotranspiration (Figure 41). In comparison to the undisturbed setting, the TDS levels in nest 2 were lower and more uniform with respect to both depth and time. In

Figure 38. Monitoring nest 1 (undisturbed site) - arsenic concentration vs time. Pressure- vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 39. Monitoring nest 1 (undisturbed site) - selenium concentration vs time. Pressure-vacuum lysimeters (PVL) 3, 4, and 5 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.


25
20
15
10
5
0
Concentration (ug/l)
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2

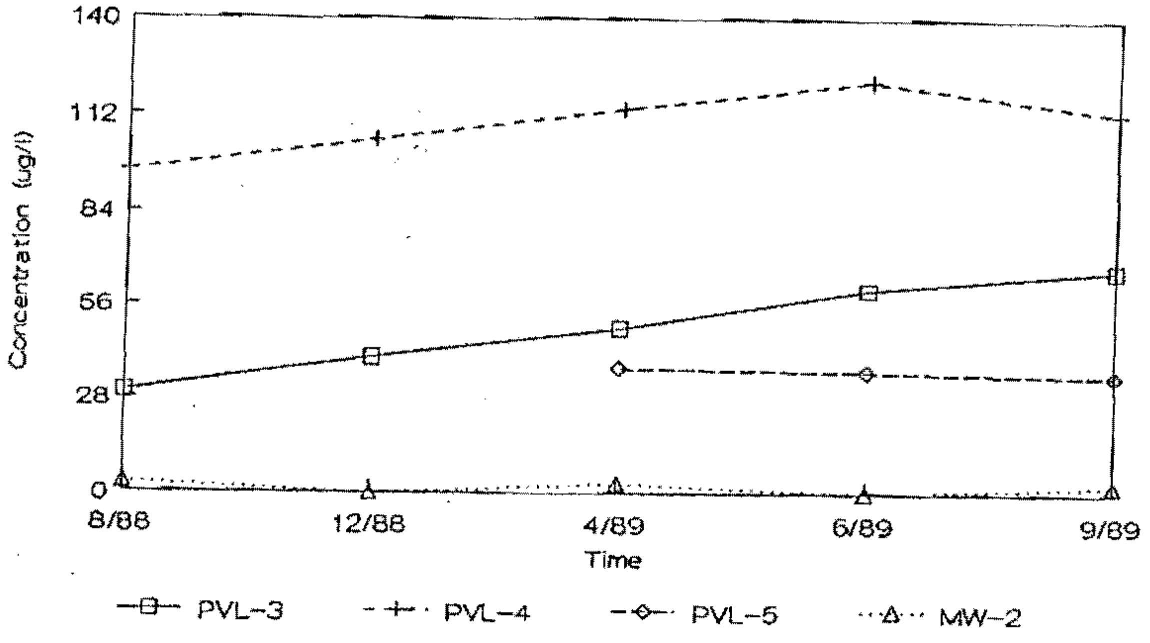
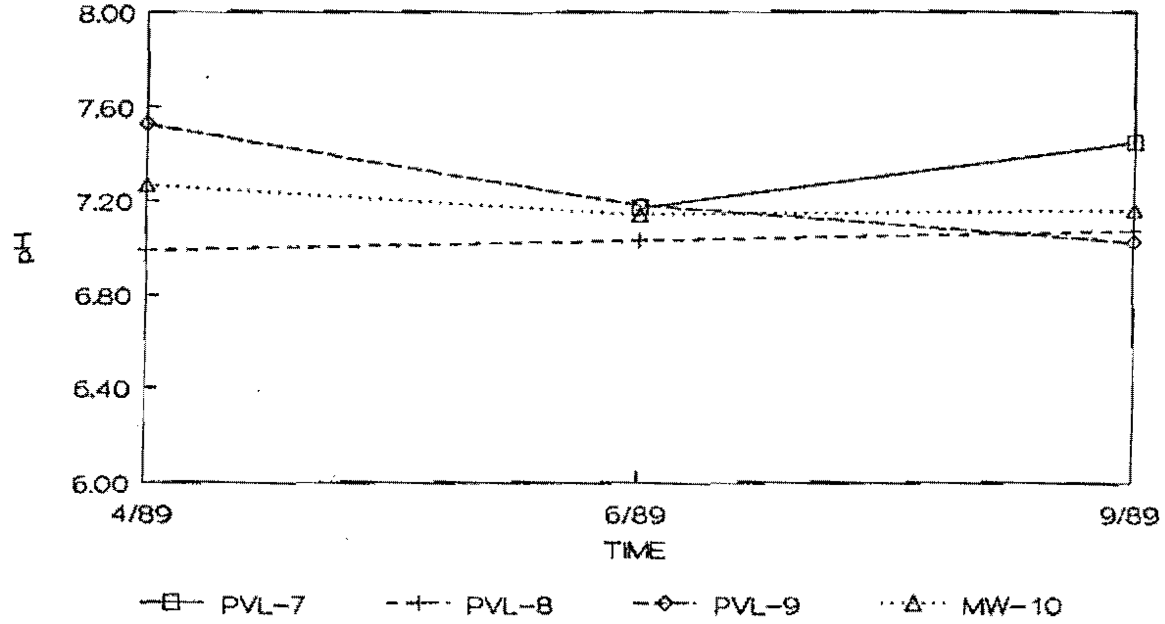
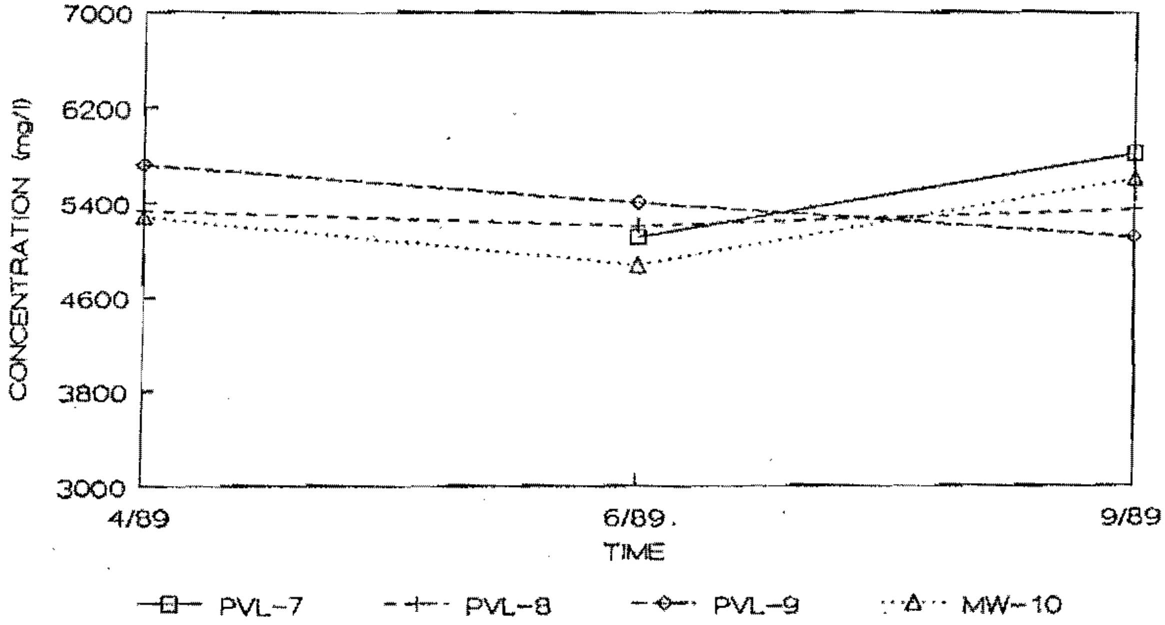

140
112
84
56
28
0
Concentration (ug/l)
8/88
12/88
4/89
6/89
9/89
Time
PVL-3
PVL-4
PVL-5
MW-2

Figure 40. Monitoring nest 2 (disturbed site) - field pH vs time. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 41. Monitoring nest 2 (disturbed site) - TDS vs time. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.


8.00
7.60
7.20
6.80
6.40
6.00
pH
4/89
6/89
9/89
TIME
PVL-7
PVL-8
PVL-9
MW-10


7000
6200
5400
4600
3800
3000
CONCENTRATION (mg/l)
4/89
6/89
9/89
TIME
PVL-7
PVL-8
PVL-9
MW-10

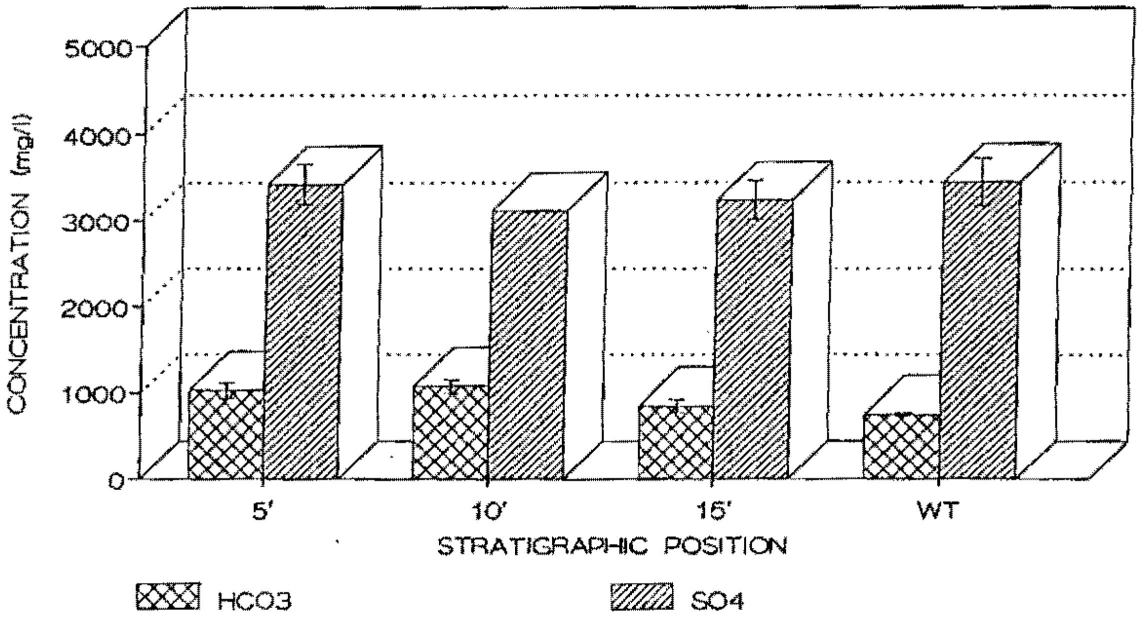
contrast to the undisturbed setting, water mineralization remained relatively constant throughout nest 2.

The uniform composition of water through the unsaturated zone to the water table is also evident in the anion concentrations (Figure 42). Sulfate, averaging over 3000 mg/l at all sampling points, is the dominant anion in nest 2. The highest sulfate concentration (3691 mg/l) was recorded in MW-10; the lowest (2978 mg/l) occurred at 15 feet (4.5 m) (Figure 43). Average bicarbonate concentrations in nest 2 decrease slightly with depth, from 1027 mg/l at 5 feet (1.5 m) to 758 mg/l at the water table (MW-10). However, no distinct drop exists between the unsaturated and saturated zones, as observed in nest 1. Throughout the monitoring period bicarbonate increased with time at all depths (Figure 44)

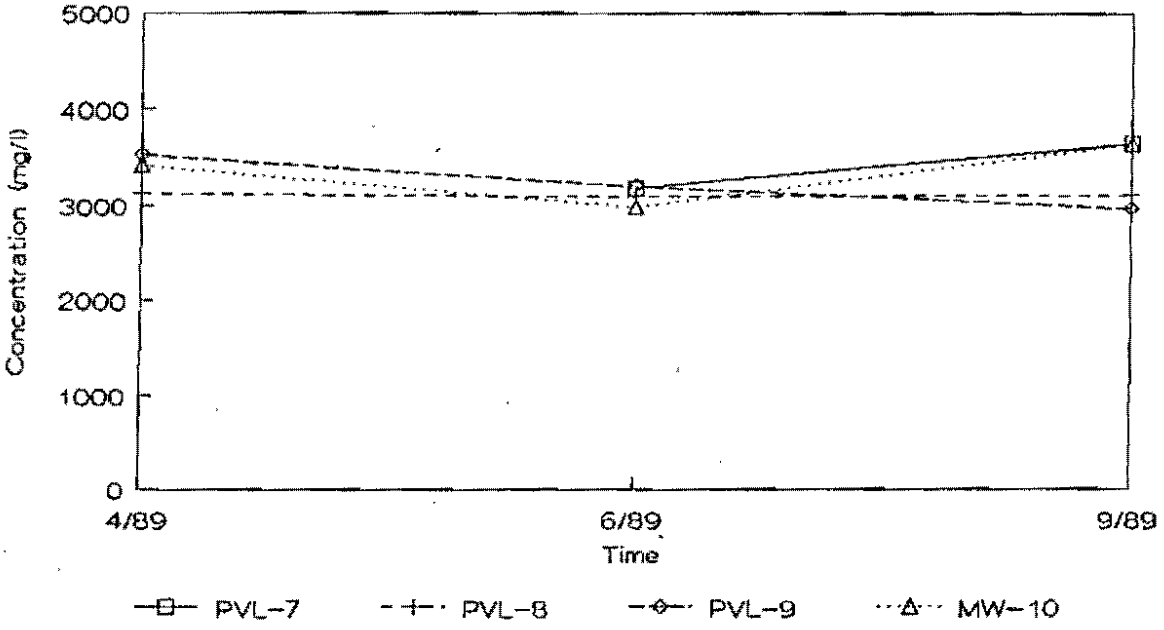
Of the three principal cations, sodium is dominant and ranges from 589 mg/l at the water table to 845 mg/l at 10 feet (3 m) (Figure 45). Sodium concentrations are more variable than calcium or magnesium (Figure 46). In comparison to the undisturbed setting (monitoring nest 1), sodium averages 5 times less at the disturbed site. Calcium is secondary in abundance at most all monitoring levels (Figure 45). The concentration of calcium at the disturbed site remained essentially constant through time. However, with depth calcium concentrations were more variable (Figure 47). Magnesium concentrations

Figure 42. Monitoring nest 2 (disturbed site) - average anion concentrations by stratigraphic position. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Error bars show standard deviation. Refer to Figure 3 for instrument locations.

Figure 43. Monitoring nest 2 (disturbed site) - sulfate concentration vs time. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.



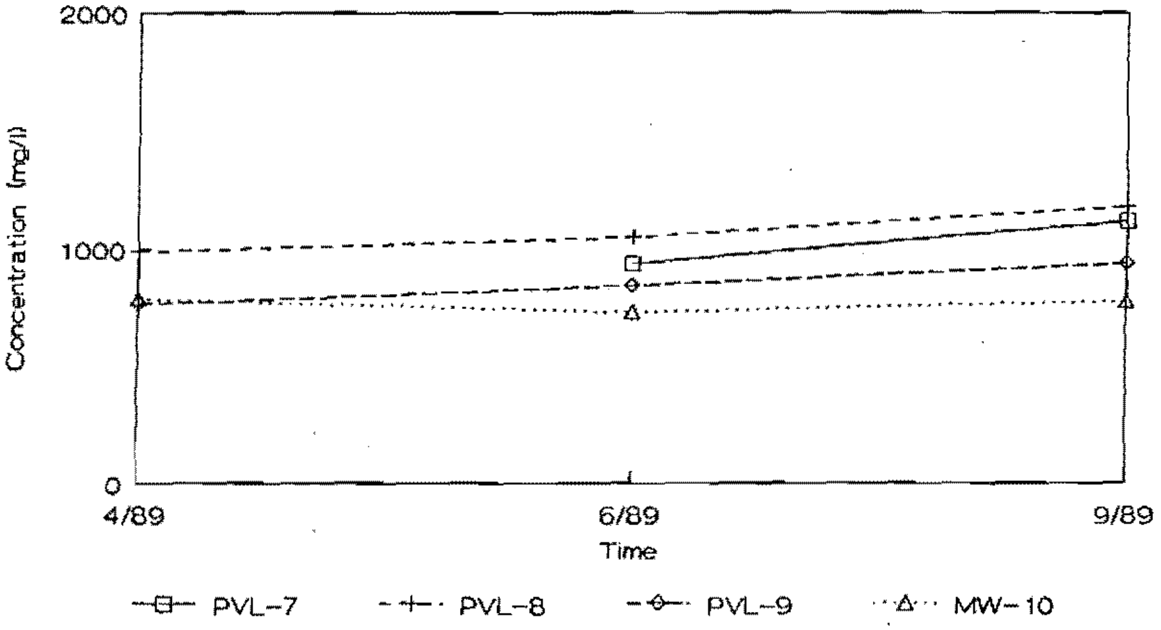
5000
4000
3000
2000
1000
0
CONCENTRATION (mg/l)
5'
10'
15'
WT
STRATIGRAPHIC POSITION
HCO3
SO4



5000
4000
3000
2000
1000
0
Concentration (mg/l)
4/89
6/89
9/89
Time
PVL-7
PVL-8
PVL-9
MW-10

Figure 44. Monitoring nest 2 (disturbed site) - bicarbonate concentration vs time. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 45. Monitoring nest 2 (disturbed site) - average cation concentrations by stratigraphic position. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Error bars show standard deviation. Refer to Figure 3 for instrument locations.


2000
1000
0
Concentration (mg/l)
4/89
6/89
9/89
Time
PVL-7
PVL-8
PVL-9
MW-10

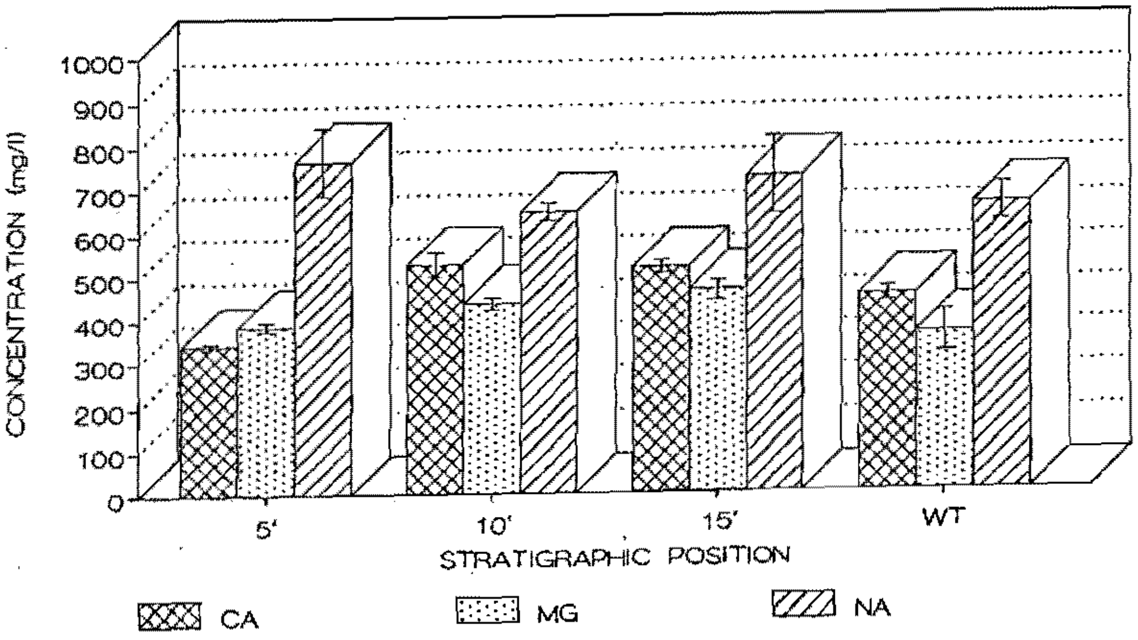
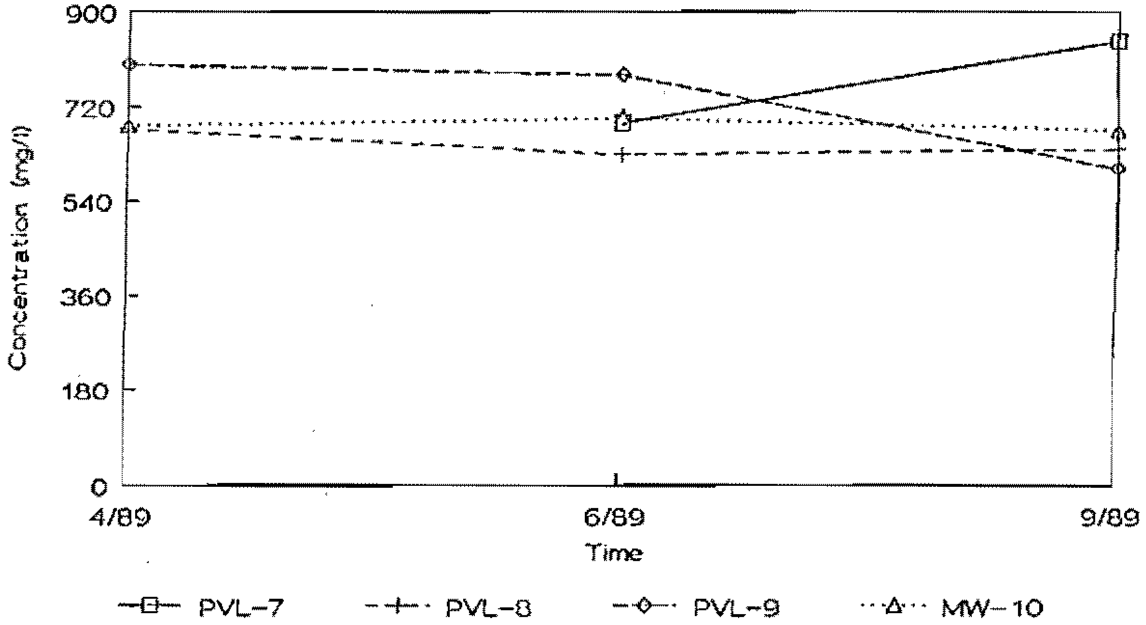
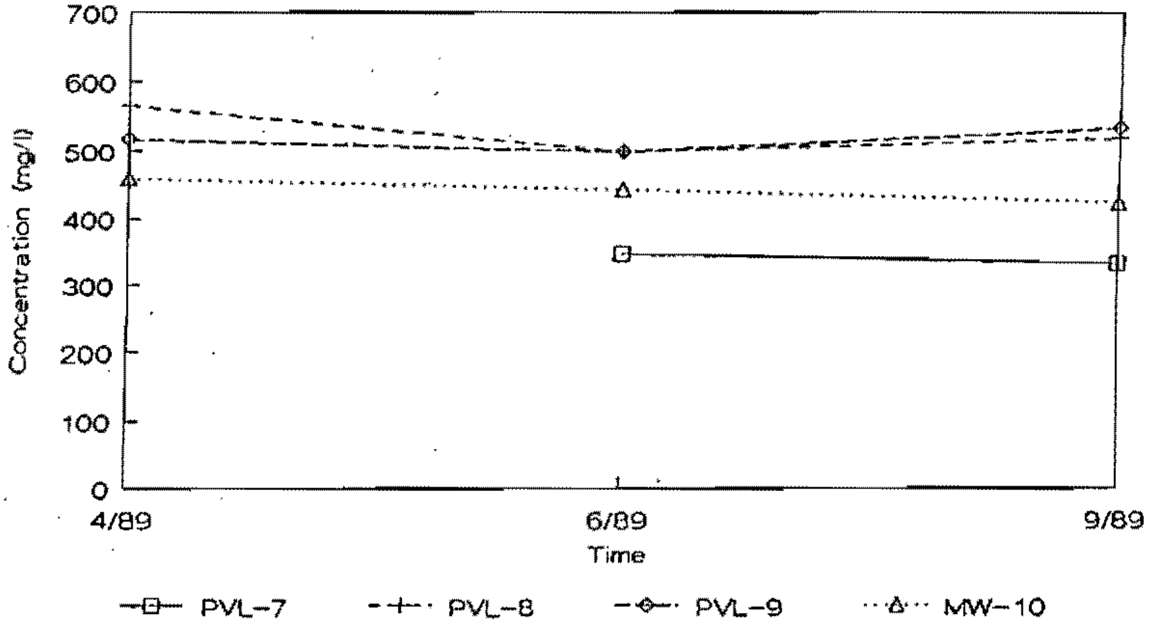

1000
900
800
700
600
500
400
300
200
100
0
CONCENTRATION (mg/l)
5'
10'
15'
WT
STRATIGRAPHIC POSITION
CA
MG
NA

Figure 46. Monitoring nest 2 (disturbed site) - sodium concentration vs time. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 47. Monitoring nest 2 (disturbed site) - calcium concentration vs time. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.


900
720
540
360
180
0
Concentration (mg/l)
4/89
6/89
9/89
Time
PVL-7
PVL-8
PVL-9
MW-10

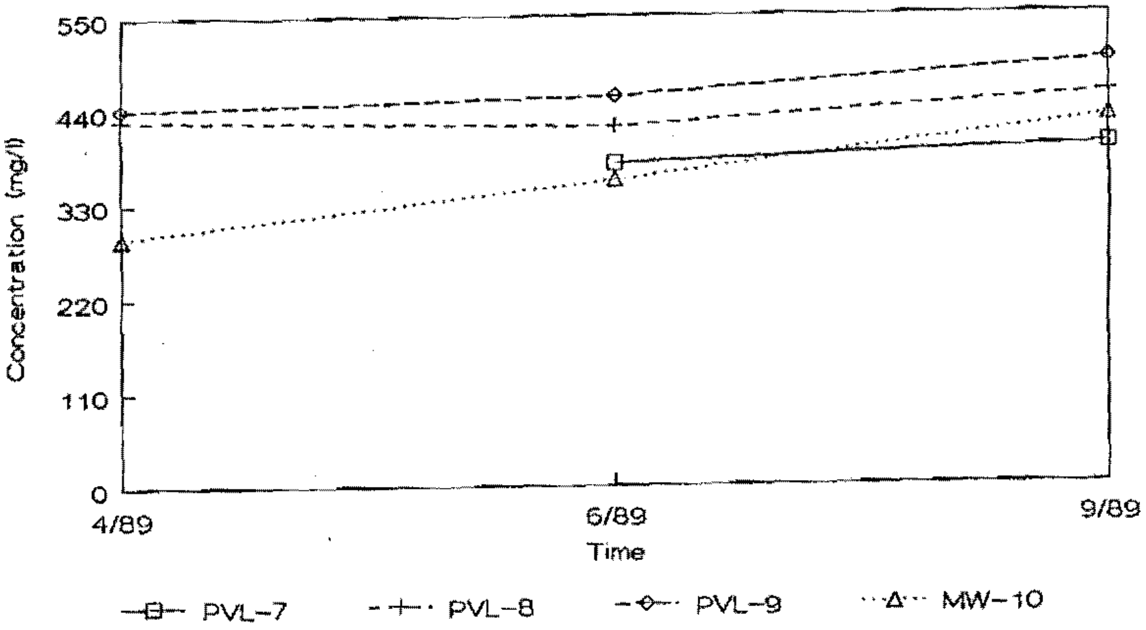

700
600
500
400
300
200
100
0
Concentration (mg/l)
4/89
6/89
9/89
Time
PVL-7
PVL-8
PVL-9
MW-10

parallel calcium with depth and increase with respect to time (Figure 48).

Selenium concentrations at monitoring nest 2 vary greatly, ranging from 422 ug/l at the 5-foot (1.5 m) level to 2.4 ug/l at a depth of 15 feet (4.5 m) (Figure 49). However, through time selenium concentrations were uniform at each depth (Figure 50). Arsenic concentrations were erratic with respect to both depth and time (Figure 51). Arsenic was not detected below the water table in the disturbed setting (Figure 49). Most of the other trace elements occurred near or below detection limits.

Figure 48. Monitoring nest 2 (disturbed site) - magnesium concentration vs time. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 49. Monitoring nest 2 (disturbed site) - average arsenic and selenium concentrations by stratigraphic position. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Error bars show standard deviation. Refer to Figure 3 for instrument locations.


550
440
330
220
110
0
Concentration (mg/l)
4/89
6/89
9/89
Time
PVL-7
PVL-8
PVL-9
MW-10

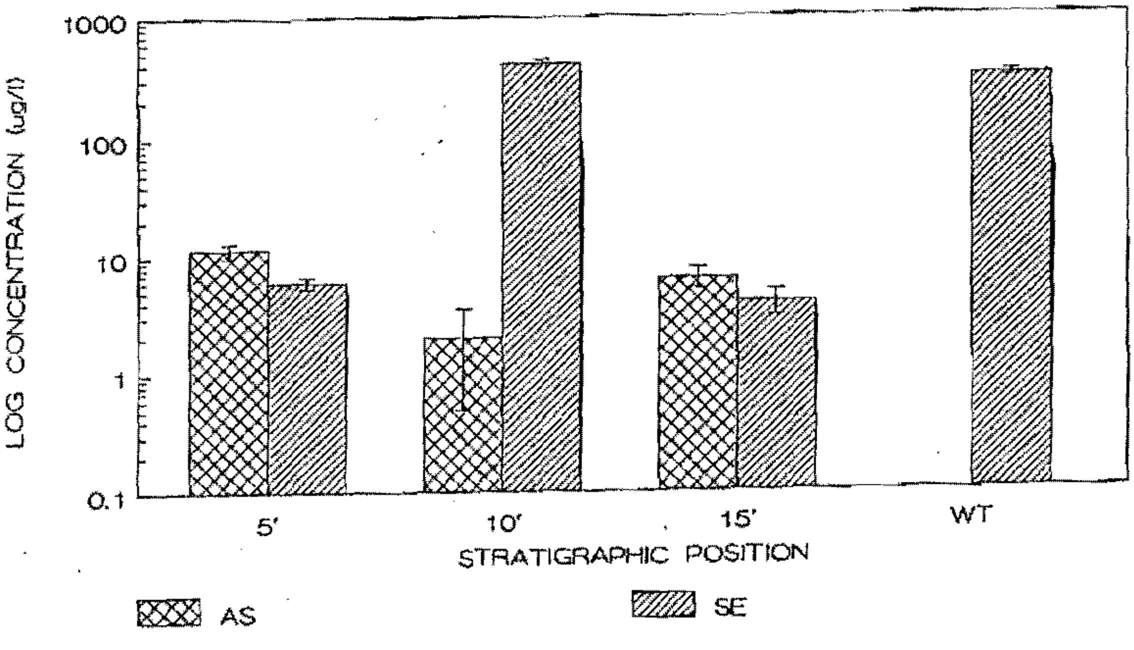
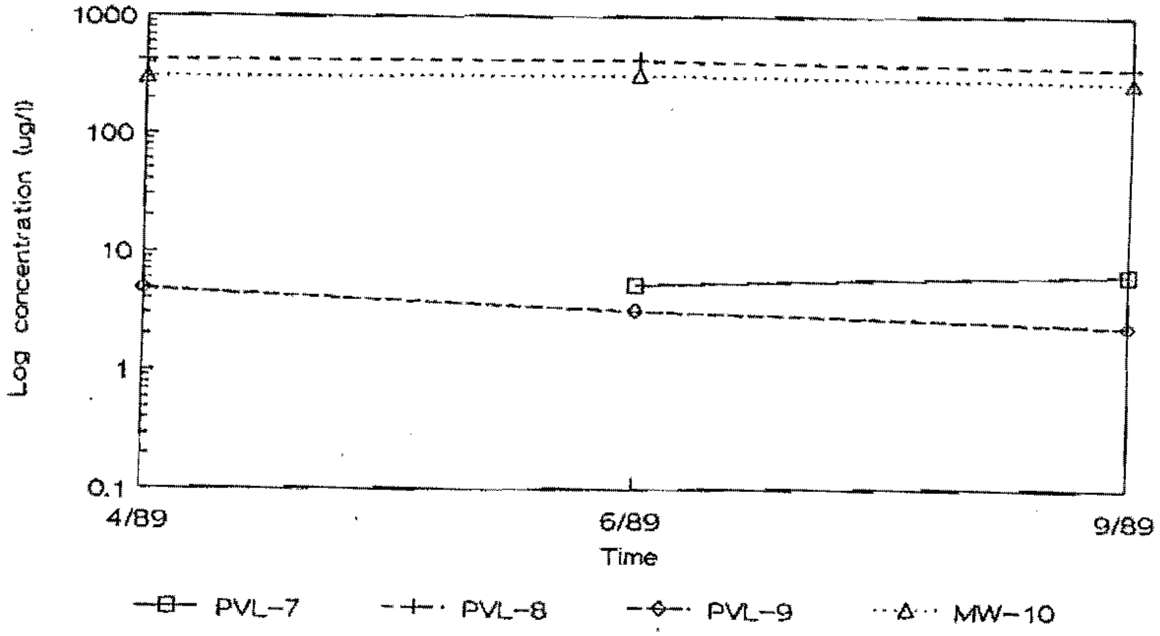
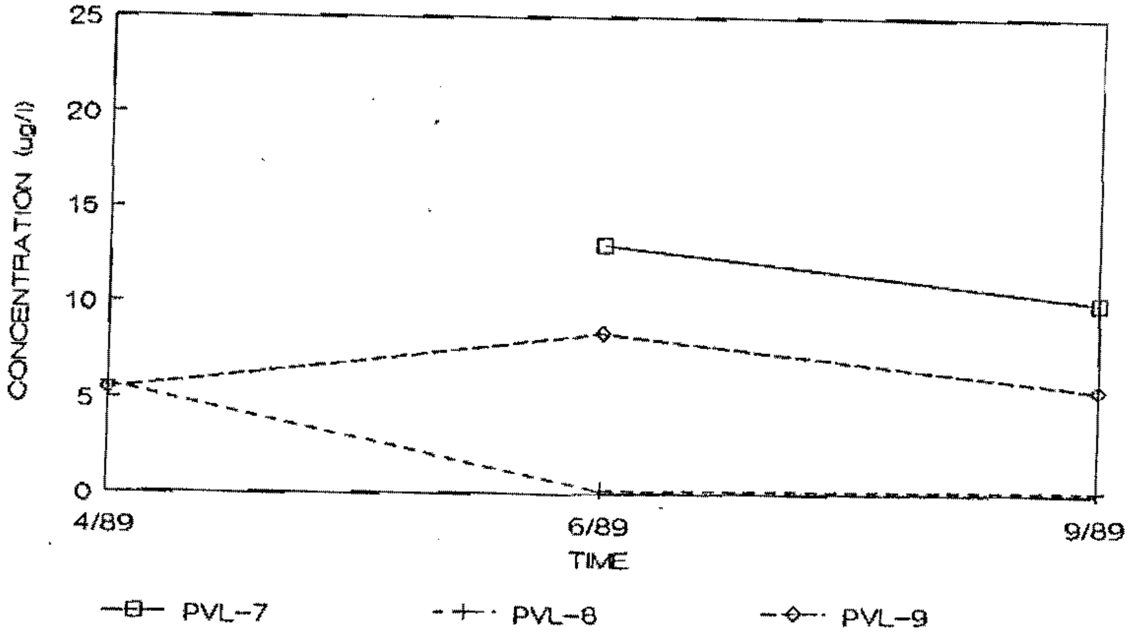

1000
100
10
1
0.1
LOG CONCENTRATION (ug/l)
5'
10'
15'
WT
STRATIGRAPHIC POSITION
AS
SE

Figure 50. Monitoring nest 2 (disturbed site) - selenium concentration vs time. Pressure-vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.

Figure 51. Monitoring nest 2 (disturbed site) - arsenic concentration vs time. Pressure- vacuum lysimeters (PVL) 7, 8, and 9 are located at depths of 5, 10, and 15 feet (1.5, 3.0, and 4.5 m), respectively. Refer to Figure 3 for instrument locations.



1000
100
10
1
0.1
Log concentration (ug/l)
4/89
6/89
9/89
Time
PVL-7
PVL-8
PVL-9
MW-10



25
20
15
10
5
0
CONCENTRATION (ug/l)
4/89
6/89
9/89
TIME
PVL-7
PVL-8
PVL-9

DISCUSSION

The purpose of this investigation was to characterize the hydrogeology to determine if concrete, containing 70% replacement of Portland cement with fly ash, will degrade soil water or ground water quality. A thorough analysis of the occurrence, physical movement, and geochemistry of ground water, in combination with laboratory leaching data is necessary to evaluate the potential impact to subsurface water.

Hydrogeology

Saturated Zone

Ground water occurrence and flow at the site is primarily a result of topography, recharge, and the thickness and extent of fill. Changes in topography appear to have exerted the most influence on the configuration of the present water table (Figure 2 and Figure 14). In settings similar to the study area, the water table generally reflects the surface topography. Because this relationship does not exist in some portions of the site indicates the water table has yet to reach steady-state with respect to recent topographic changes and continues to react to changes in artificial recharge.

The water table depression beneath and slightly downgradient of CCS (Figure 14) may be the result of a 30-foot (10 m) reduction in topography by levelling (Figure 15). The original position of the water table, as estimated from borehole color changes (MW-1 and MW-2), was approximately 30 feet (10 m) higher than the present water table. As climatic data suggest there has been no substantial change in recharge during the last 10 years, it is concluded that in low permeability sediments with a relatively deep water table (> 30 feet (10 m)) a significant alteration in topography may cause a similar, although subdued change in the water table. The degree of response will depend on factors such as recharge, permeability, and unsaturated zone thickness. The lower the permeability the longer it will take for the water table to adjust to changes in recharge and/or topography because of slower flow rates.

Ground water occurrence at the site has also been altered by the deposition of permeable units of fill material and the disruption of surface water flow. In areas near the plant where thick units of fill coincide with surface water ponding sites, such as occurs in the vicinity of monitoring nest 2, artificial recharge zones have been created. These zones, where underlain by less permeable bedrock, can result in temporary conditions of saturation above the water table.

Unsaturated Zone

Liquid-phase transport in the unsaturated zone occurs in response to infiltration events and evapotranspiration. The degree of recharge is dependent on the magnitude and duration of the infiltration event, the initial soil moisture content, evapotranspiration, and properties of the sediment, such as matric potential, hydraulic conductivity and specific moisture capacity (Freeze, 1969). In the study area, the unsaturated zone averages over 30 feet (10 m) in thickness, the tension-saturated zone or capillary fringe is included in the unsaturated zone because the pressure head is negative. The capillary fringe can rise several feet above the water table in fine-grained sediments typical of those encountered at the site (Fetter, 1988, p. 91). This may provide a pathway where saturated zone water is discharged through evapotranspiration and/or vapor-phase transport. Lysimeter monitoring data suggest that moisture movement in the upper portion of the unsaturated zone moves up and down in response to evapotranspiration and the advance of additional wetting fronts; only following substantial precipitation events of long duration and/or spring thaw does moisture migrate below this zone.

The 10-foot (3 meter) level appears to represent the lowest extent for moisture originating from summer precipitation events of moderate duration. Rehm, Groenewold, and Peterson (1982) reported that upon reaching a depth of 10 feet (3 m), infiltrating water cannot be returned directly to the atmosphere through liquid phase transport. However, in fine grained sediments with a high temperature gradient and low moisture content, transport in the vapor-phase may outweigh liquid-phase transport (Fetter, 1988, p. 91). The climate of the site causes high temperature and humidity gradients in the unsaturated zone, which are the key factors in promoting vapor phase transport (Ripple, Rubin and Van Hylckama, 1972). High temperature gradients were observed from lysimeter monitoring data during mid-summer throughout the monitoring period (Appendix D). Consequently, vapor-phase transport may be responsible for the observed reductions in both the water table and moisture content of the unsaturated zone during mid-summer.

Moisture conditions in the unsaturated zone of the disturbed site are uniform. Recharge is greater at the disturbed site because of an increased infiltration rate and decreased evapotranspiration rate. High recharge rates have resulted in a 10-foot (3 m) rise of the water table in MW-10 during the monitoring period (Figure 17). This has exposed previously unsaturated sediment to conditions of saturation, thus causing dramatic changes in the composition of saturated zone waters (Figure 23). Uniform moisture conditions in the unsaturated zone of the disturbed site have resulted in uniform soil water compositions relative to the undisturbed setting.

There appears to be a direct relationship between moisture content and composition in the unsaturated zone.

Water in the unsaturated zone of the undisturbed site (monitoring nest 1) is more mineralized and variable than in the disturbed setting (monitoring nest 2)(Figure 22). This is a result of lower and more variable moisture conditions in the undisturbed setting. Generally, observed decreases in moisture content cause an increase in mineralization and vice versa. With a change in mineralization there is little change in the proportions of individual constituents to one another, indicating that concentration and dilution is responsible for many temporal changes in composition. Concentration at depth suggests that much of the transport in the unsaturated zone occurs in the vapor-phase. If liquid-phase transport were the dominant process, the composition of unsaturated zone water at a particular level would remain relatively constant with respect to mineralization and this was not observed.

Hydrogeochemistry

Background Water Quality

Water analyses were obtained from the lysimeters in monitoring nest 1 prior to the installation of concrete (8/12/88), for comparison with analyses subsequent to concrete emplacement (Appendix D). Continuous background monitoring of the saturated zone is provided by MW-1 and MW-6 (Appendix D). The background monitoring data were used in conjunction with leaching data to evaluate the likelihood of ground water degradation. Leachate data from the ASTM procedure was preferred over EP data; the high pH required in the EP test simulates conditions that do not exist at the site.

The leachate tests suggest that calcium should provide the best indication of leachate generation, followed by sulfate (Appendix G). Any changes in composition due to leaching should be observed first in the lysimeter located at 5 feet (1.5 m). Monitoring data to date indicate that there has been no increase in any of the above constituents at either monitoring location. In fact, calcium levels in the undisturbed setting (monitoring nest 1) have shown a slight decrease since concrete emplacement (Figure 35). The pH has remained relatively stable at all monitoring locations (Figures 28 and 40). Because background concentrations of calcium are nearly double those observed in the leaching tests, it is doubtful that much of an effect would be observed at depth in the unsaturated zone.

Geochemical Model

Groenewold et al. (1983) presented a conceptual geochemical model applicable for much of western North Dakota. The model considers the evolution of ground water in an undisturbed setting as well as ground water evolution in settings disrupted by surface mining and reclamation. Both such settings exist at the CCS site, although the disruption is a result of construction instead of strip-mining.

According to the model, infiltration events contribute oxygen and other dissolved gases to the subsurface, causing the oxidation of reduced carbon and sulfur, producing SO_4, CO_2 and H^+. The H^+ enables the disassociation of calcite and dolomite and release of Ca^{2+}, Mg^{2+}, and HCO_3^-, concurrent with a reduction in available H^+. At this point, if the system is exposed to evapotranspiration, calcium and/or magnesium sulfates and bicarbonates will be precipitated. However, if additional moisture is contributed Na^+ will be released by exchange with calcium and magnesium on the Na-montmorillonite clays that predominate in the region (Groenewold et al., 1983). These are the processes thought responsible for the sodium sulfate bicarbonate-type ground water encountered in undisturbed settings throughout Interior Plains region (Groenewold et al., 1983).

Groenewold et al. (1983) proposed that in disturbed settings these same processes are operative, although to a much larger extent, resulting in greater water mineralization at disturbed sites. The emplacement of reduced sediments in the zone of oxidation enhances sulfate oxidation; sulfate dissolution/precipitation and ion exchange, resulting in highly mineralized pore and saturated zone water. The most important factor for controlling ground water mineralization is recharge. Associated with a high rate of recharge is the possibility of increased mineralization in the saturated zone, which is the reason for the high TDS in the disturbed setting (Figure 23, see MW-10). The composition of both soil and ground water in the disturbed setting (monitoring nest 2) results from the emplacement of chemically reactive reduced sediments in an oxidizing environment. Similar observations of highly mineralized ground water were made in mine spoil settings near Center, North Dakota (Beaver,1986). The similarity in composition between soil and ground water is a result of high rates of recharge. The ground water mounding that has occurred at the disturbed site rules out contributions due to lateral transport.

Ground Water Chemistry

Mineralization

In the undisturbed setting (monitoring nest 1) pore water is highly mineralized in comparison to saturated zone water (Figure 22). Much of the available mineralization at the undisturbed site is contained in the unsaturated zone and may be in the form of soluble salts (Groenewold et al., 1983). These salts are not regularly flushed to the saturated zone because of the infrequency of recharge. The lack of regular recharge or flushing accounts for the higher degree of mineralization in the unsaturated zone of the undisturbed site in comparison to the saturated zone. Mineralization fluctuations in pore water of the undisturbed site are the result of changing moisture conditions.

The consistent and lower degree of mineralization observed in pore water of the disturbed site (monitoring nest 2) is caused by a relatively constant supply of moisture (Figure 22). Ample recharge flushes soluble salts from the unsaturated zone on a more regular basis than at the undisturbed site. These high rates of recharge have resulted in unique water compositions in the disturbed setting. Recharge appears to be the most important process controlling the composition of ground water at the site.

Carbonate Equilibria and Ion Exchange

Of the three major cations at the site, sodium is most abundant at all monitoring locations. Calcium and magnesium occur in approximately equal proportions throughout the unsaturated zone of the undisturbed site before decreasing abruptly at the water table (Figure 33). Concentrations of all three cations are constant throughout the disturbed site (Figure 45). The key geochemical processes controlling these constituents are carbonate dissolution and ion exchange. These processes also influence pH and HCO_3^- concentration.

The initial concentration of calcium in pore water results from dissolution of calcite and dolomite, which are common minerals in the Fort Union Group (Groenewold et al., 1983). These dissolution reactions consume H^+ (increasing pH) producing HCO_3^-, Ca^{2+}, and Mg^{2+}. Dissolution continues until equilibrium is attained, whereby, further dissolution requires the removal of either Ca^{2+} of Mg^{2+} from solution, often accomplished through exchange with 2:1 layer clays such as Na-montmorillonite. Cation exchange processes preferentially tend to replace monovalent ions with divalent ions because divalent ions are held more strongly at exchange sites. Na-montmorillonite has the highest exchange capacity of the 2:1 layer clays and is the dominant clay mineral in western North Dakota (Groenewold et al., 1983), consequently ion exchange is an important geochemical process. The concentration of Ca^{2+} would be expected to remain relatively stable with depth, because as dissolution releases Ca^{2+} it is continually removed by ion exchange. This is confirmed as both Mg^{2+} and Ca^{2+} concentrations are uniform with depth as Na^+ increases (Figures 33 and 45).

Dissolution of calcite and dolomite is the primary geochemical mechanism for the production of HCO_3^- (Cherry, 1972). Carbonate dissolution is also indirectly responsible for the Na^+ concentrations through ion exchange. In the undisturbed setting, a steady increase is recorded in Na^+ with depth (Figure 33). The Na^+ concentrations are cumulative because there exists no precipitation reaction that controls Na^+ in the same way carbonate precipitation controls Ca^{2+} (Hem, 1985). If carbonate dissolution were the primary process responsible for the release of Na^+ then increases in Na^+ should parallel increases in HCO^{3-}. However, the dissolution of gypsum also releases Ca^{2+} causing an increase in Na^+ accompanied by an increase in $SO_4{}^{2-}$. Therefore, Na^+ concentrations paralled by increases in $SO_4{}^{2-}$ and $HCO_3{}^-$ are an indication of carbonate and gypsum dissolution and continuing ion exchange. Monitoring data confirm these processes in the unsaturated zone of monitoring nest 1 (Figure 22).

In the disturbed setting (monitoring nest 2) concentrations of Na^+, $SO_4{}^{2-}$, and $HCO_3{}^-$ remain stable down to the water table (Figures 42 and 45). This indicates little dissolution of either carbonate or gypsum except at shallow depths (< 5 feet (1.5 m)). The lack of continual dissolution may be caused by the relative absence of Na-montmorillonite in the disturbed setting which results in less exchange of Ca^{2+} for Na^+ . Without the existence of a removal mechanism for Ca^{2+} such as cation exchange, the waters would become saturated and no further dissolution could occur.

Sulfate

There are two significant sources for SO_4^{2-}, reduced sulfur and the dissolution of soluble sulfate salts such as gypsum (Groenewold et al., 1983). Gypsum forms as a result of carbonate dissolution (Ca^{2+}) and framboidal pyrite oxidation (SO_4^{2-}). Sulfur or gypsum is not common at depth in the overburden sediments of western North Dakota. However, Groenewold et al. (1983) reported that gypsum exists at shallow depths (above 20 feet (6 m)) in southwest North Dakota. The occurrence of gypsum there is thought to result from a gradual accumulation with time by the concentration of infiltrating waters through evapotranspiration (Moran et al., 1976). Periodically, gypsum is flushed to the saturated zone by recharge, causing a release of SO_4^{2-} and Ca^{2+}. Decreases in the concentration of SO_4^{2-} at depth are attributed to bacterial sulfate reduction (Beaver, 1986).

Sulfate is a major contributor to overall mineralization at the site. Concentrations of SO_4^{2-} in the undisturbed environment increase dramatically with depth in the unsaturated zone before decreasing abruptly at the water table (Figure 30). The reduction in SO_4^{2-} at the water table of the undisturbed site may result partially from bacterial sulfate reduction because the decrease is too great to be a reflection of overall changes in mineralization alone. Sulfate in the disturbed setting is constant with depth, indicating

SO_4^{2-} acquired in the upper portion of the unsaturated zone is not removed from solution at depth (Figure 42). The lack of a decrease in SO_4^{2-} with depth, suggests that bacterial sulfate reduction may not be operative. High rates of recharge contribute more dissolved oxygen to the subsurface of the disturbed site, which may explain the absence of bacterial sulfate reduction.

Selenium

Selenium in solution can exist in three oxidation states: selenate, +6; selenite, +4; and selenide, -2 (Cutter, 1982). However, selenate and selenite are the predominant forms in solution (Hassett, personal communication, 1990). The oxidation state of dissolved selenium in pore water is dependent on the redox potential. Thermodynamic calculations predict that under anoxic conditions (Eh <0.0) selenide predominates; under moderately oxic conditions (Eh 0.0-0.5) selenium exists as both selenate and selenite in approximately equal proportions, and under oxidizing conditions (Eh >0.5) selenate is the dominant form (Cutter, 1982; Old Dominion University, 1986; Elrashidi et al., 1987). However, these calculations oversimplify selenium complexing because they fail to account for the poorly understood biochemical cycle of selenium and the existence of thermodynamically unstable species of selenium (Geering et al., 1967; Cutter, 1982).

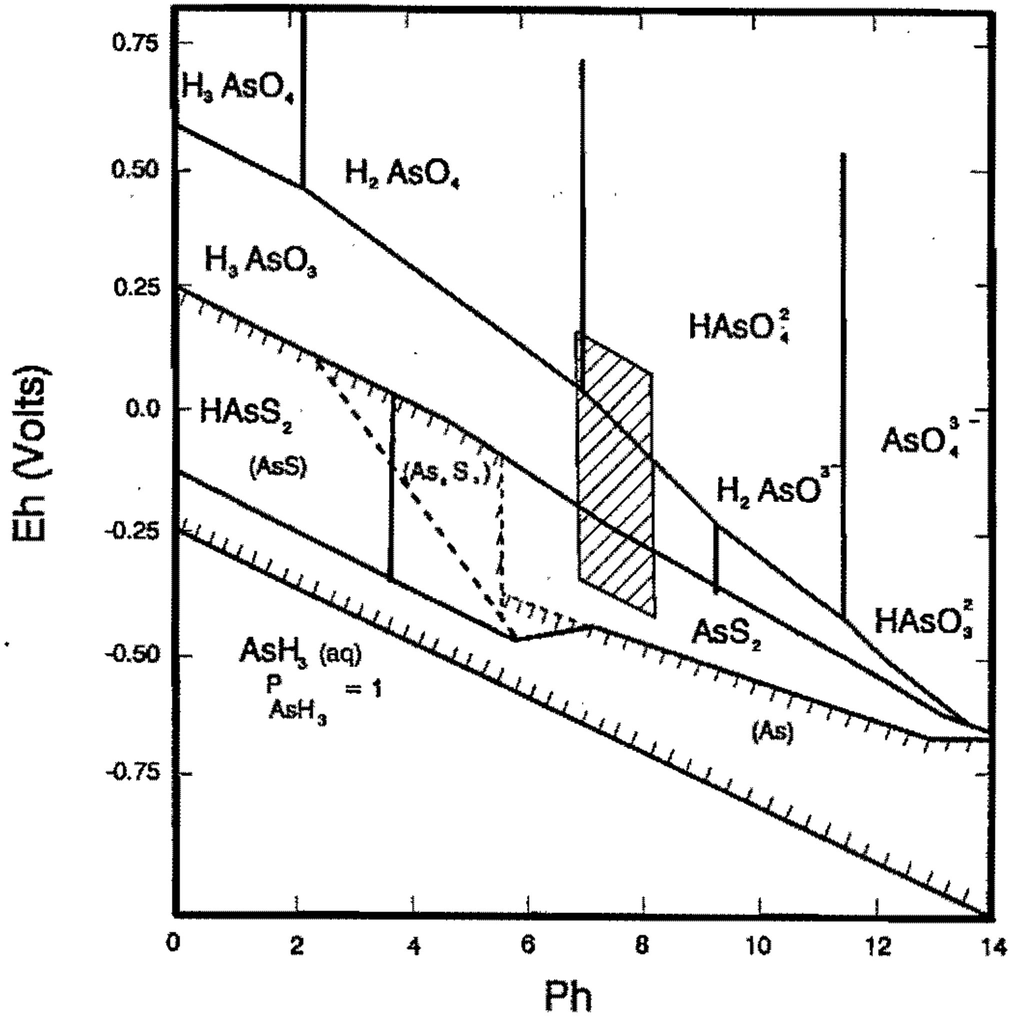
The mobilization of selenium is greatest under oxidizing conditions, because of inorganic and organic oxidation of elemental selenium to more soluble species (Geering, 1967). In strongly reducing environments selenium is precipitated as selenide. Minerals containing selenide are less soluble than selenate or selenite species. Selenides form a major inert sink for selenium under reducing conditions and do not pose a threat to water quality if left undisturbed (Elrashidi et al., 1987). Bar-Yosef and Meek (1987) reported that the primary mechanism whereby selenium is removed from solution is adsorption rather than precipitation. Montmorillonite, the predominant clay at the site, exhibits the greater adsorptive capacity in comparison to kaolinite (Frost and Griffin, 1977; Bar-Yosef and Meek, 1987).

The high selenium concentrations in the disturbed setting are attributed to disruption of the subsurface which lead to increased oxidation and the release of soluble selenate. In the undisturbed site the reduced selenide sink remains intact beneath the water table and most of the soluble selenium is found in the upper portion of the unsaturated zone. The presence of the reduced selenide sink is the primary reason for the lack of selenium in the saturated zone waters of the undisturbed site (Figure 37). This reduction mechanism has been disrupted at the disturbed site, thus selenium levels remain high into the saturated zone (Figure 49).

Arsenic

Arsenic is similar to selenium in that its speciation is controlled by pH and redox potential and it is involved extensively in biochemical processes. Arsenic in aqueous environments can exist in four oxidation states(0, -3, +3, and +5); however, the most common forms are arsenate (+5) and arsenite (+3) (Battelle, 1986). Arsenite will be the dominant form under mildly reducing conditions at low pH (Figure 38). In an oxidizing environment arsenic exists in solution as arsenate with the most abundant species being $HAsO_4^{2-}$ (Figure 38). Mildly reducing waters can contain both arsenate and arsenite. Under strongly reducing conditions arsenic is precipitated as arsenic sulfide or metal-sulfarsenite compounds or coprecipitated with iron sulfides (Hounslow, 1980). Beaver (1986) identified strongly reducing conditions in piezometers near Center, North Dakota, through the presence of hydrogen sulfide gas. Under these conditions, bacteria reduce sulfate to H_2S and HS^-, concurrent with the oxidation of carbon to bicarbonate. Other than precipitation, adsorption is the key mechanism for the removal of arsenic from solution. Bolt and Snel (1986) observed that 95% of arsenate

Figure 52. Eh - pH diagram for arsenic at 25°C and one atmosphere with total arsenic 10^{-5} mol l^{-1} and total sulfur 10^{-3} mol l^{-1}. Solid species are enclosed in the cross-hatched area. The window represents ground waters from the CCS site according to Garrels and Christ (1965, p. 381).



0.75
0.50
0.25
0.0
-0.25
-0.50
-0.75
Eh (Volts)
H_3AsO_4
H_2AsO_4
H_3AsO_3
$HAsO_4^{2}$
AsO_4^{3-}
H_2AsO^{3-}
$HAsO_3^{2}$
$HAsS_2$
(AsS)
(As_2S_3)
AsS_2
AsH_3 (aq)
$P_{AsH_3} = 1$
(As)
0
2
4
6
8
10
12
14
Ph

leached from fly ash bricks was adsorbed in the upper 6 inches (15 cm) of soil.

Arsenic concentrations in the disturbed setting are constant with depth, possibly because oxic conditions prevent precipitation of arsenite compounds (Figure 36B). However, arsenic decreases moderately at the water table which would be expected as conditions become more reducing with greater depth (Hounslow, 1980). In the undisturbed setting arsenic concentrations also fall at the water table as bicarbonate concentrations increase (Figures 30B and 27A), possibly indicating bacterial sulfate reduction. To date, arsenic has not caused degradation of water quality. It is unlikely that if any arsenic were leached from the concrete, it would be detected even at the 5-foot (1.5 m) level because of adsorbtion (Bolt and Snel, 1986).

Maximum Leachate Generation

In order to obtain a worse-case scenario for the leaching potential of fly ash concrete, a series of simple calculations has been made using data from the leachate extraction tests. These data are applied to an arbitrarily chosen unit area of 100 ft^2 (10.8 m^2) extending from the concrete to the saturated zone. If the saturated zone is taken to be 60 feet (20 m) thick with a porosity of 30%, it will contain 1800 ft^3 (50 m^3) of water. Assuming a concrete thickness of 8 inches (.2

m), the unit area would contain 67 ft^3 (1.9 m^3) of concrete. (The ASTM leachate procedure uses a .22 lb (100 g) sample of broken concrete in .07 ft^3 (2×10^{-3} m^3) of water). For illustrative purposes, the leachate produced by the concrete is assumed to be introduced instantaneously into the saturated zone, ignoring attenuation mechanisms operative in the unsaturated zone. The resulting increase in the concentration of calcium, the constituent most indicative of concrete leaching (Appendix G), would be only 63 mg/l. Arsenic and selenium, although found below detection limits in the ASTM leachate were evaluated using a leachate concentration of 1 ug/l. Results indicate neither would increase more than 1 ug/l from leaching. If pH were lowered to the point where the EP leaching test became valid, calcium would be predicted by the calculations to rise over 400 mg/l. However, calculations suggest that even under EP leaching conditions, neither arsenic or selenium concentrations would be expected to rise.

CONCLUSIONS

1. To date, there has been no contamination directly attributable to the use of concrete containing 70% replacement of fly ash for Portland cement.

2. Leachate extraction tests (ASTM) of the concrete also indicate that degradation of ground water is unlikely. In addition, the low permeability of the concrete (3.3×10^{-12} ft/sec (1×10^{-12} m/sec)) will further limit leachate generation. The EP leachate test was not used to evaluate leaching potential because it involves conditions not found at the study site.

3. Changes in ground water quality from the use of fly ash concrete will depend more on changes in recharge and subsurface disruption, associated with concrete installation, than leachate generation from the concrete.

4. The rate of recharge is a key mechanism which controls the geochemistry of subsurface waters. Where rates are high, ground water mineralization will be more uniformly distributed between the saturated and unsaturated zones. In areas with minimal recharge most of the mineralization available to the ground water system will be contained in the unsaturated zone.

5. In localized recharge zones (monitoring nest 2) the composition of water in the saturated zone is largely determined by processes occurring in the unsaturated zone.

6. In zones of intermittent recharge, more typical of the region, the composition of saturated zone water is a result of processes occurring in both the saturated and unsaturated zones.

7. Water quality monitoring data suggest that in areas of low recharge (monitoring nest 1), concentration through evapotranspiration and vapor transfer is the most important factor for determining overall mineralization in the unsaturated zone.

8. It is evident from water quality monitoring data that in high-recharge disturbed areas, oxidation is operative to a greater depth than in undisturbed sites.

9. Water quality monitoring data suggest that in areas of disturbed stratigraphy with abnormally high rates of recharge degradation of saturated zone water quality is probable.

FUTURE RECOMMENDATIONS

Objectives for this project were addressed in a satisfactory manner by the current monitoring network. However, in future studies detailed measurements of moisture content and redox conditions in both the unsaturated and saturated zones would be helpful in interpreting the hydrogeochemistry further.

Further monitoring is suggested as the concrete fractures. Concrete fractures increase with time and may cause increased leaching due to greater permeability.

The use of fly ash as an active ingredient in concrete significantly reduces its potential for ground water degradation. Considering alternate disposal practices and their potential environmental hazards, every attempt should be made to increase utilization of byproducts such as fly ash.

APPENDICES

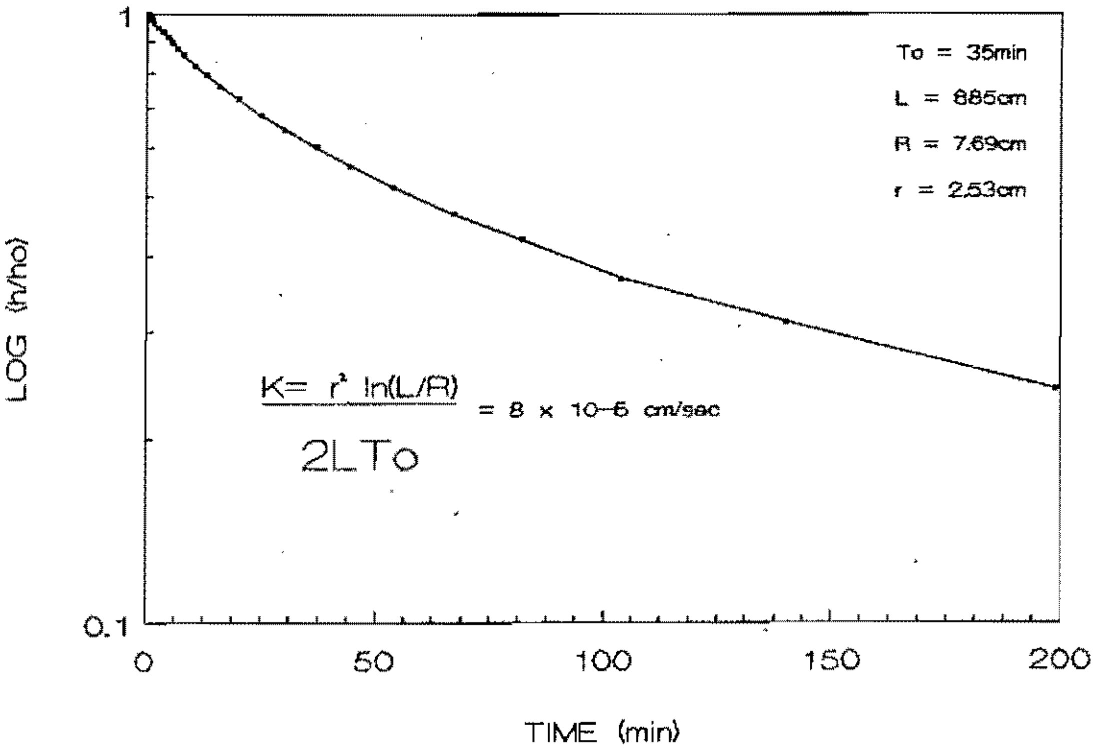
APPENDIX A

Hydraulic Conductivity Data

MW-6 SLUG TEST ANALYSIS (HVORSLEV METHOD)

TIME (min)	WATER LEVEL (m)	HEAD CHANGE (h)	HEAD RATIO (h/ho)	LOG (h/ho)	LOG (pos)	TIME (min)
00:00:00	10.619	0.000	0	0	0	0
00:00:30	9.723	0.896	1	0	0	0.5
00:01:05	9.742	0.877	0.978794	-0.00930	0.009308	1.083
00:01:30	9.753	0.866	0.966517	-0.01479	0.014790	1.500
00:02:30	9.770	0.849	0.947544	-0.02340	0.023400	2.500
00:03:40	9.781	0.838	0.935267	-0.02906	0.029063	3.666
00:04:40	9.799	0.820	0.915178	-0.03849	0.038494	4.666
00:05:40	9.813	0.806	0.899553	-0.04597	0.045972	5.666
00:06:40	9.833	0.786	0.877232	-0.05688	0.056885	6.666
00:08:00	9.851	0.768	0.857142	-0.06694	0.066946	8.000
00:10:30	9.882	0.737	0.822544	-0.08484	0.084840	10.500
00:13:00	9.909	0.710	0.792410	-0.10104	0.101049	13.000
00:16:00	9.938	0.681	0.760044	-0.11916	0.119160	16.000
00:20:00	9.971	0.648	0.723214	-0.14073	0.140733	20.000
00:25:00	10.010	0.609	0.679687	-0.16769	0.167690	25.000
00:30:00	10.040	0.579	0.646205	-0.18962	0.189629	30.000
00:37:00	10.080	0.539	0.601562	-0.22071	0.220719	37.000
00:44:15	10.116	0.503	0.561383	-0.25074	0.250740	44.250
00:54:00	10.154	0.465	0.518973	-0.28485	0.284855	54.000
01:07:00	10.199	0.420	0.46875	-0.32905	0.329058	67.000
01:22:00	10.238	0.381	0.425223	-0.37138	0.371383	82.000
01:44:00	10.290	0.329	0.367187	-0.43511	0.435112	104.000
02:20:00	10.340	0.279	0.311383	-0.50670	0.506703	140.000
03:19:00	10.402	0.217	0.242187	-0.61584	0.615848	199.000

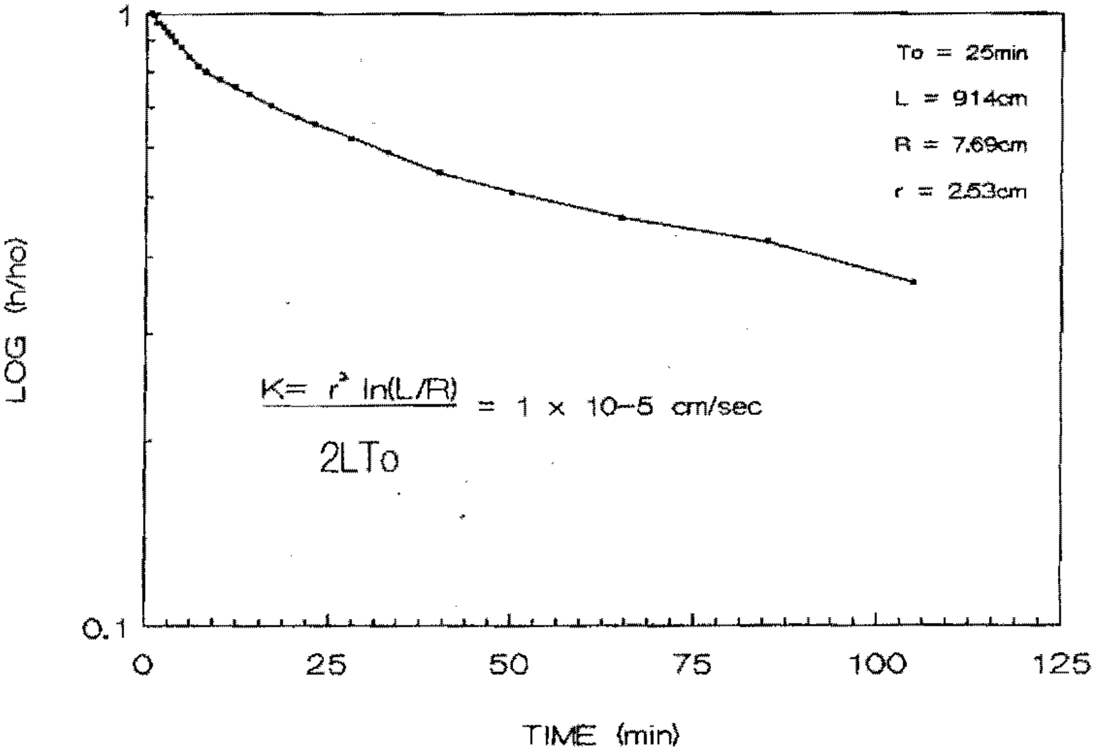
Figure 53. Plot of Hvorslev (1951) slug test data for MW-6. Refer to Figure 3 for well location.


To = 35min
L = 885cm
R = 7.69cm
r = 2.53cm
K= r² ln(L/R) / 2LTo = 8 x 10-6 cm/sec
1
0.1
0
50
100
150
200
TIME (min)
LOG (h/ho)

MW-10 SLUG TEST ANALYSIS (HVORSLEV METHOD)

TIME (min)	WATER LEVEL (m)	HEAD CHANGE (h)	HEAD RATIO (h/ho)	LOG (h/ho)	LOG (pos)	TIME (min)
00:00:00	8.962	0.000	0	0	0	0
00:00:45	8.485	0.477	1	0	0	0.75
00:01:05	8.490	0.472	0.989517	-0.00457	0.004576	1.083
00:01:25	8.502	0.460	0.964360	-0.01576	0.015760	1.417
00:01:45	8.503	0.459	0.962264	-0.01670	0.016705	1.750
00:02:15	8.510	0.452	0.947589	-0.02337	0.023379	2.250
00:02:45	8.519	0.443	0.928721	-0.03211	0.032114	2.750
00:03:15	8.525	0.437	0.916142	-0.03803	0.038036	3.250
00:03:45	8.532	0.430	0.901467	-0.04504	0.045049	3.750
00:04:45	8.544	0.418	0.876310	-0.05734	0.057342	4.750
00:05:45	8.558	0.404	0.846960	-0.07213	0.072137	5.750
00:07:00	8.572	0.390	0.817610	-0.08745	0.087453	7.000
00:08:00	8.580	0.382	0.800838	-0.09645	0.096455	8.000
00:10:00	8.591	0.371	0.777777	-0.10914	0.109144	10.000
00:12:00	8.602	0.360	0.754716	-0.12221	0.122215	12.000
00:14:00	8.612	0.350	0.733752	-0.13445	0.134450	14.000
00:17:00	8.627	0.335	0.702306	-0.15347	0.153473	17.000
00:20:30	8.641	0.321	0.672955	-0.17201	0.172013	20.500
00:23:00	8.649	0.313	0.656184	-0.18297	0.182974	23.000
00:28:00	8.664	0.298	0.624737	-0.20430	0.204302	28.000
00:33:00	8.680	0.282	0.591194	-0.22826	0.228269	33.000
00:40:00	8.700	0.262	0.549266	-0.26021	0.260217	40.000
00:50:00	8.719	0.243	0.509433	-0.29291	0.292912	50.000
01:05:00	8.741	0.221	0.463312	-0.33412	0.334126	65.000
01:25:00	8.760	0.202	0.423480	-0.37316	0.373167	85.000
01:55:00	8.789	0.173	0.362683	-0.44047	0.440472	105.000

Figure 54. Plot of Hvorslev (1951) slug test data for MW-10. Refer to Figure 3 for well location.



1
0.1
LOG (h/ho)
0
25
50
75
100
125
TIME (min)
To = 25min
L = 914cm
R = 7.69cm
r = 2.53cm
K= r² ln(L/R) / 2LTo = 1 x 10-5 cm/sec

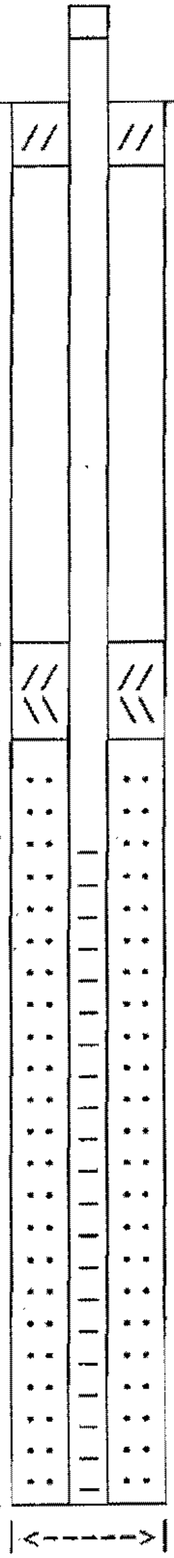
APPENDIX B

Monitoring Well and Pressure-Vacuum Lysimeter Completion Summaries

WELL NUMBER: MW-1
DATE INSTALLED: 7/20/88

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY

ELEV. (MSL)	DEPTH FRM SURFACE
1954.5	0.0'
1889.5	65.0'
1888.0	66.5'
1884.5	70.0'
1854.5	100.0'



Length Above Ground 2.09'

Surface Seal Portland Cement

PIPE:
Diameter 2"
Material PVC
Sch. 40
Joints Flush Threaded
Length 72.09'

BACKFILL MATERIAL:
6% Bentonite Grout

SEAL:
Thickness 1.5'
Type Bentonite

SCREEN:
Diameter 2"
Slot Size .010"
Length 30.00'

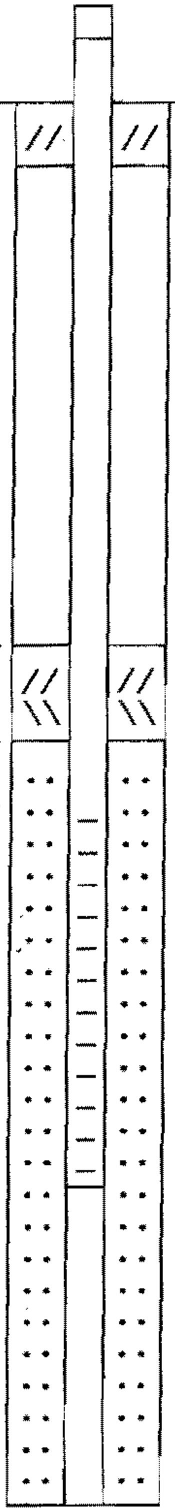
FILTER PACK:
Type Washed Silica Sand
Sand Size 1230
Length 33.50'

--Diameter Of Borehole 5 5/8"

WELL NUMBER: MW-2
DATE INSTALLED: 7/20/88

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY

ELEV. (MSL)	DEPTH FRM SURFACE
1939.6	0.0'
1908.1	31.5'
1906.6	33.0'
1904.6	35.0'
1879.6	60.0'
1859.6	80.0'



Length Above Ground 2.60'

Surface Seal Portland Cement

PIPE:
Diameter 2"
Material PVC
Sch. 40
Joints Flush Threaded
Length 37.60'

BACKFILL MATERIAL:
6% Bentonite Grout

SEAL:
Thickness 1.5'
Type Bentonite

SCREEN:
Diameter 2"
Slot Size .010"
Length 25.00'

FILTER PACK:
Type Washed Silica Sand
Sand Size 1230
Length 47.00'

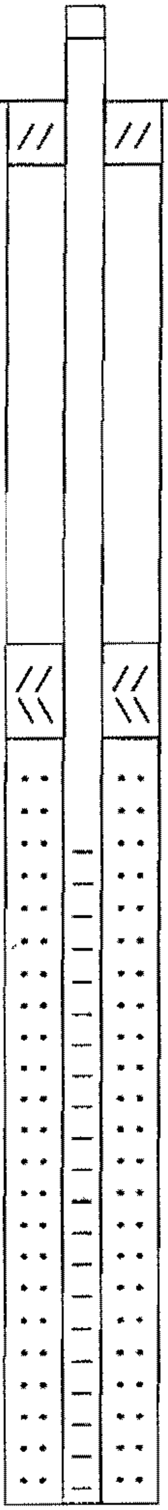
BLANK PIPE:
Diameter 2"
Material PVC
Sch. 40
Joints Flush Threaded
Length 20.00'

|<----->|--Diameter Of Borehole 5 5/8"

WELL NUMBER: MW-6
DATE INSTALLED:12/7/88

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY

ELEV. (MSL)	DEPTH FRM SURFACE
1951.2	0.0'
1922.7	28.5'
1921.2	30.0'
1919.2	32.0'
1894.2	57.0'



Length Above Ground 2.37'

Surface Seal Portland Cement

PIPE:
Diameter 2"
Material PVC
Sch. 40
Joints Flush Threaded
Length 34.37'

BACKFILL MATERIAL:
6% Bentonite Grout

SEAL:
Thickness 1.5'
Type Bentonite

SCREEN:
Diameter 2"
Slot Size .010"
Length 25.00'

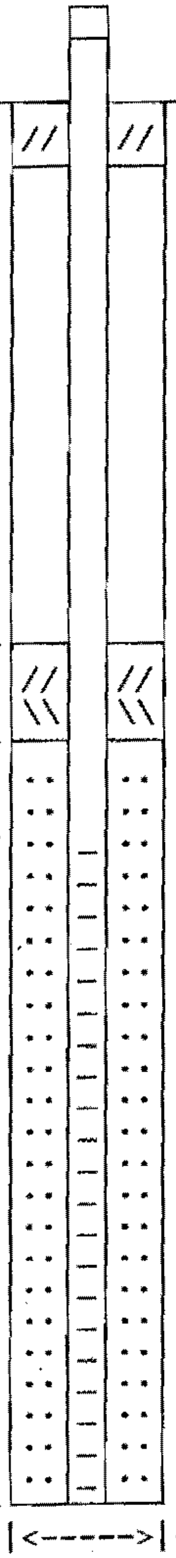
FILTER PACK:
Type Washed Silica Sand
Sand Size 1230
Length 27'

|<----->|--Diameter Of Borehole 5 5/8"

WELL NUMBER: MW-10
DATE INSTALLED:12/8/88

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY

ELEV. (MSL)	DEPTH FRM SURFACE
1940.1	0.0'
1927.1	13.0'
1922.1	18.0'
1920.1	20.0'
1890.1	50.0'



Length Above Ground 2.37'

Surface Seal Portland Cement

PIPE:
Diameter 2"
Material PVC
Sch. 40
Joints Flush Threaded
Length 22.37'

BACKFILL MATERIAL:
6% Bentonite Grout

SEAL:
Thickness 5'
Type Bentonite

SCREEN:
Diameter 2"
Slot Size .010"
Length 30.00'

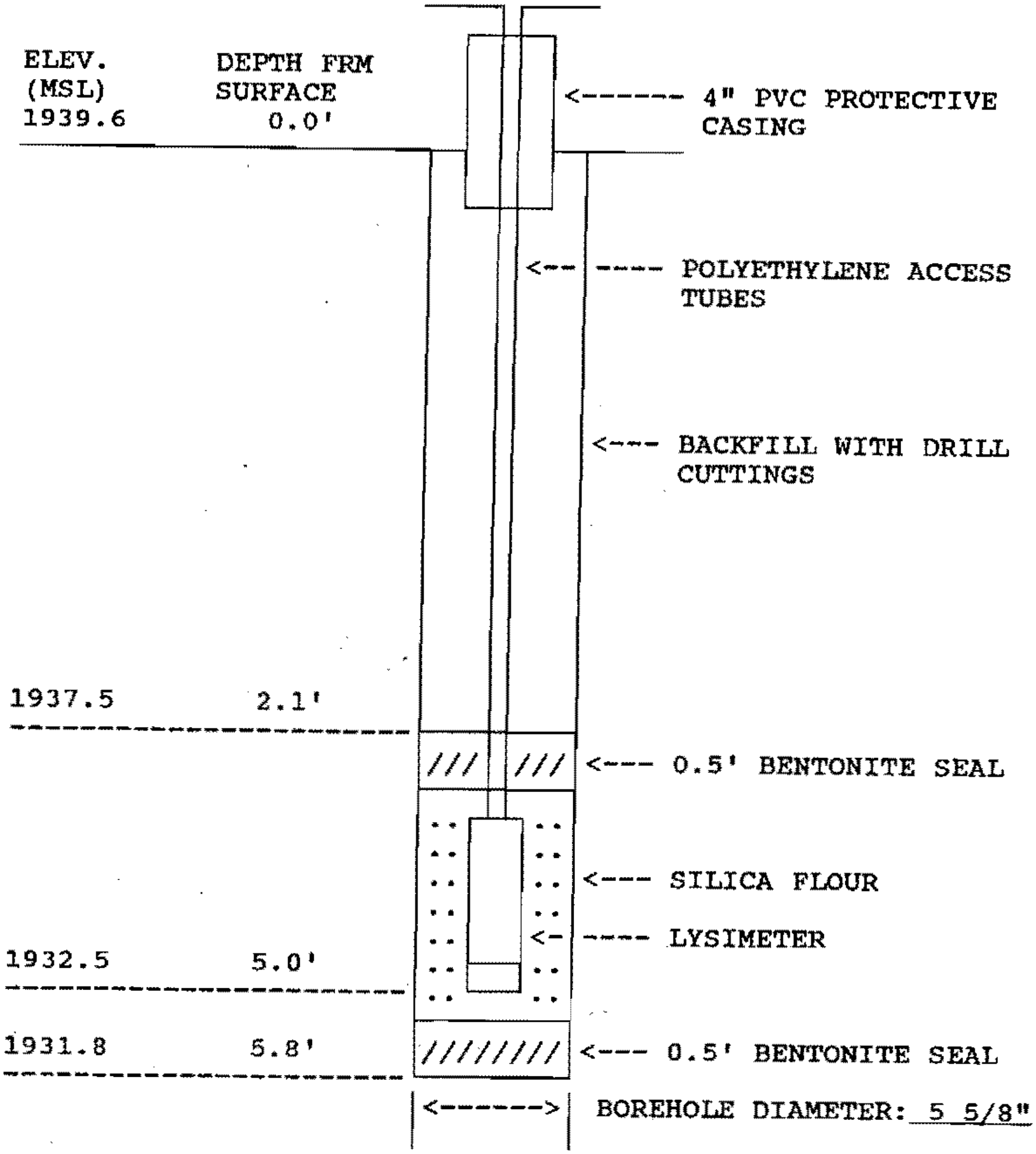
FILTER PACK:
Type Washed Silica Sand
Sand Size 1230
Length 32'

|<----->|--Diameter Of Borehole 5 5/8"

I.D. NUMBER: PVL-3
DATE INSTALLED: 7/20/88
INSTALLATION DEPTH: 5'

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY
BOREHOLE DEPTH: 5.8'

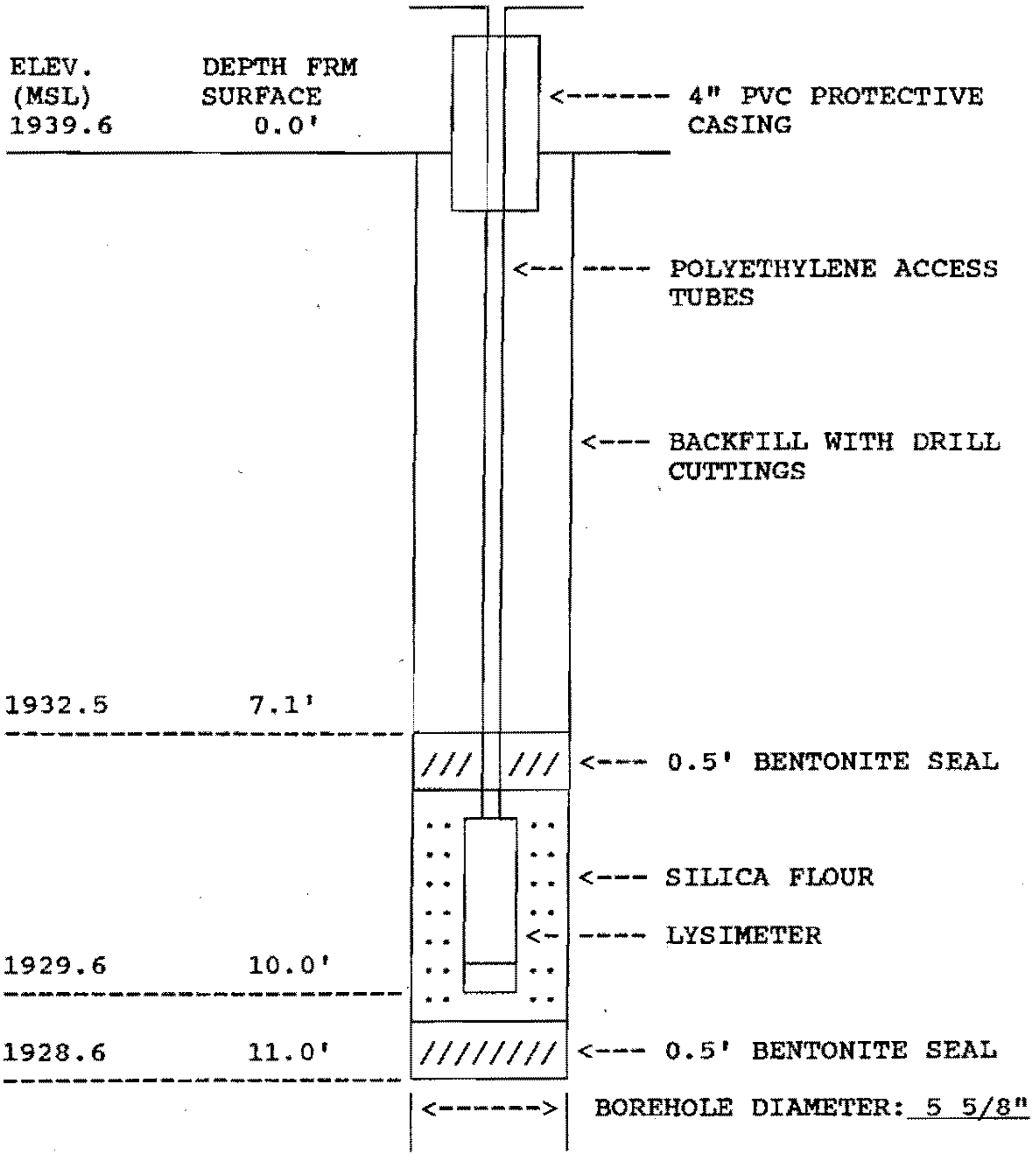
INSTRUMENT TYPE: PRESSURE VACUUM LYSIMETER
MANUFACTURER: SOILMOISTURE EQUIPMENT CORP.
MODEL NUMBER: 1920



I.D. NUMBER: PVL-4
DATE INSTALLED: 7/20/88
INSTALLATION DEPTH: 10'

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY
BOREHOLE DEPTH: 11'

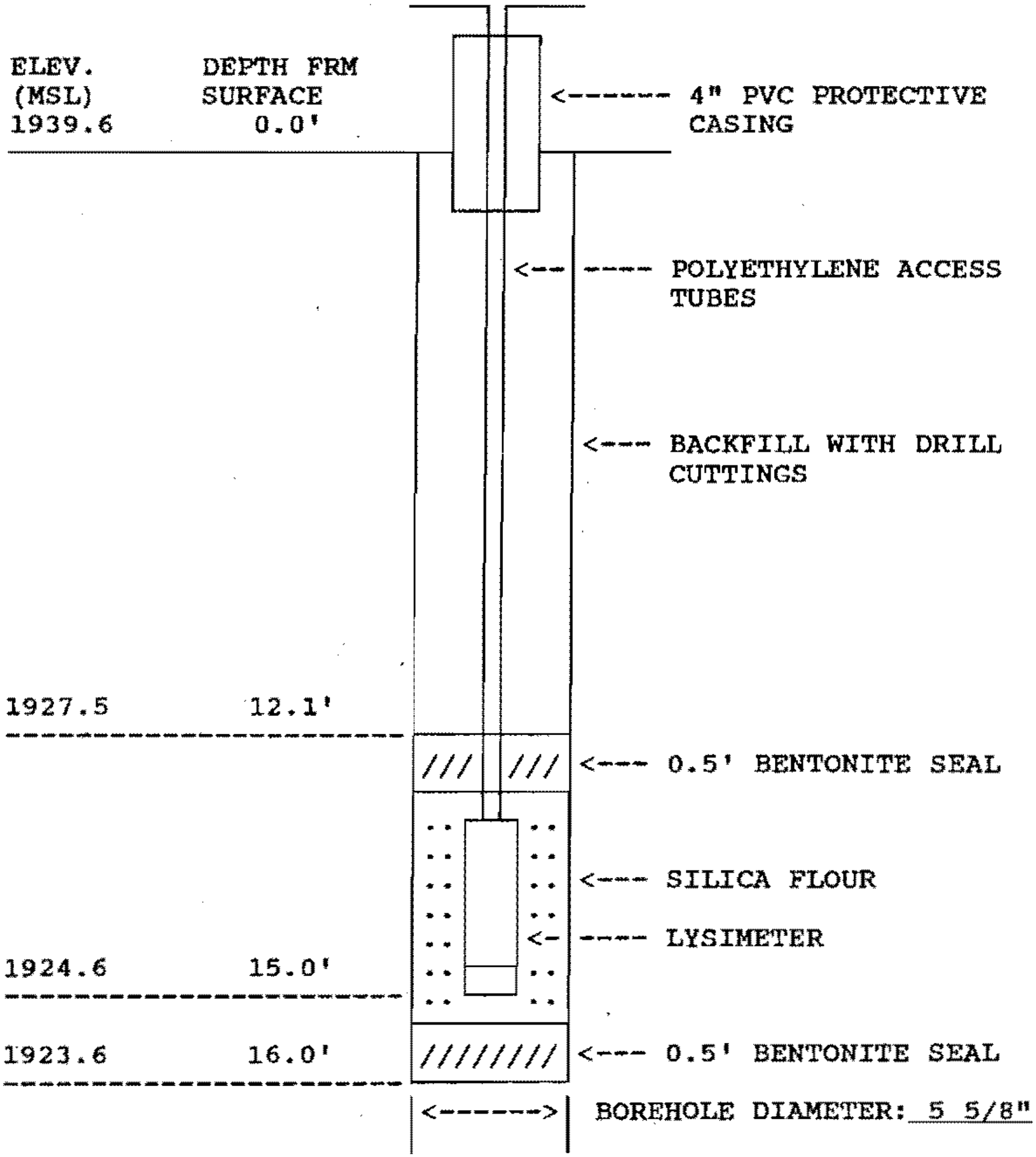
INSTRUMENT TYPE: PRESSURE VACUUM LYSIMETER
MANUFACTURER: SOILMOISTURE EQUIPMENT CORP.
MODEL NUMBER: 1920



I.D. NUMBER: PVL-5
DATE INSTALLED: 7/20/88
INSTALLATION DEPTH: 15'

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY
BOREHOLE DEPTH: 16'

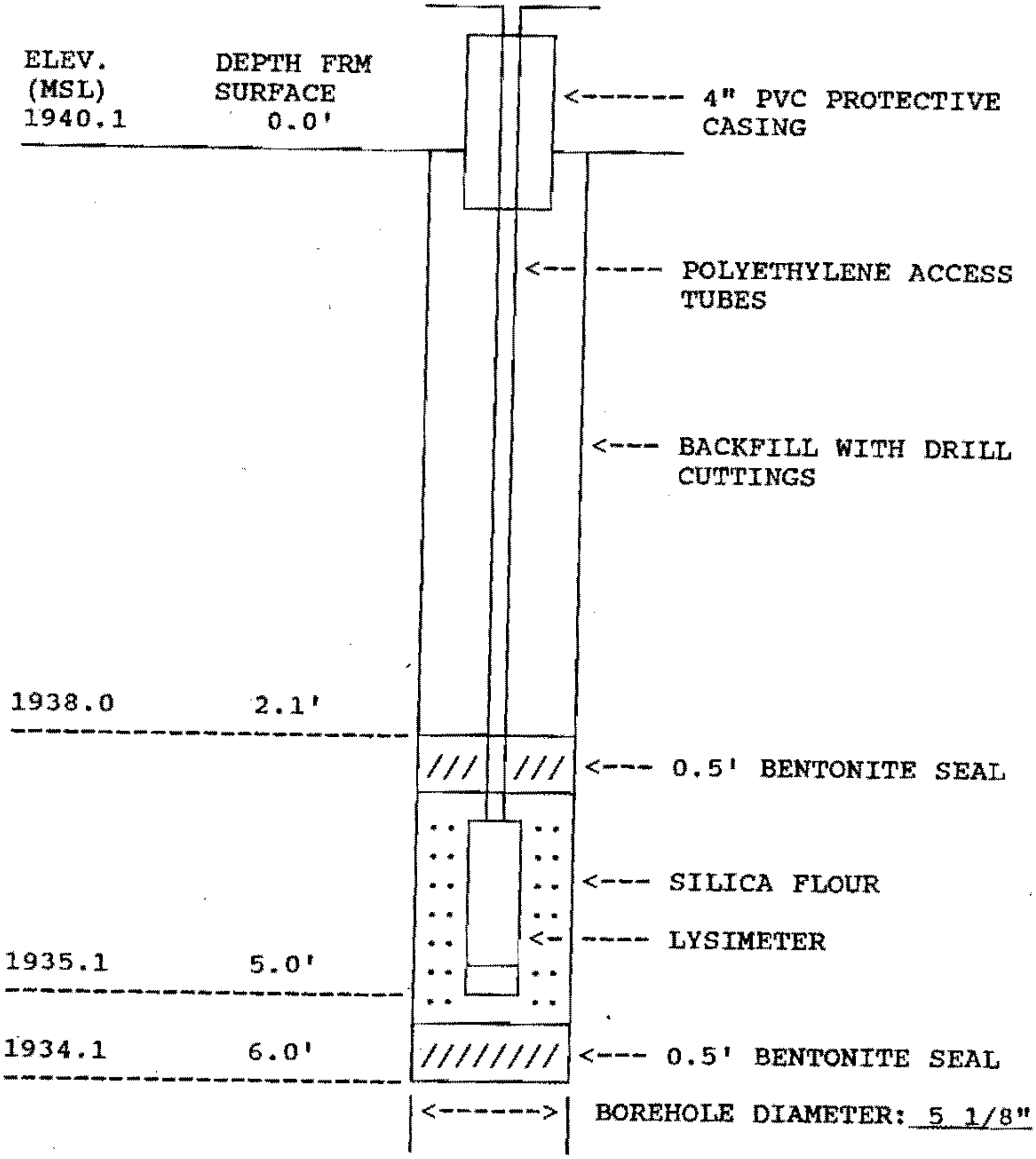
INSTRUMENT TYPE: PRESSURE VACUUM LYSIMETER
MANUFACTURER: SOILMOISTURE EQUIPMENT CORP.
MODEL NUMBER: 1920



I.D. NUMBER: PVL-7
DATE INSTALLED: 12/8/88
INSTALLATION DEPTH: 5'

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY
BOREHOLE DEPTH: 6'

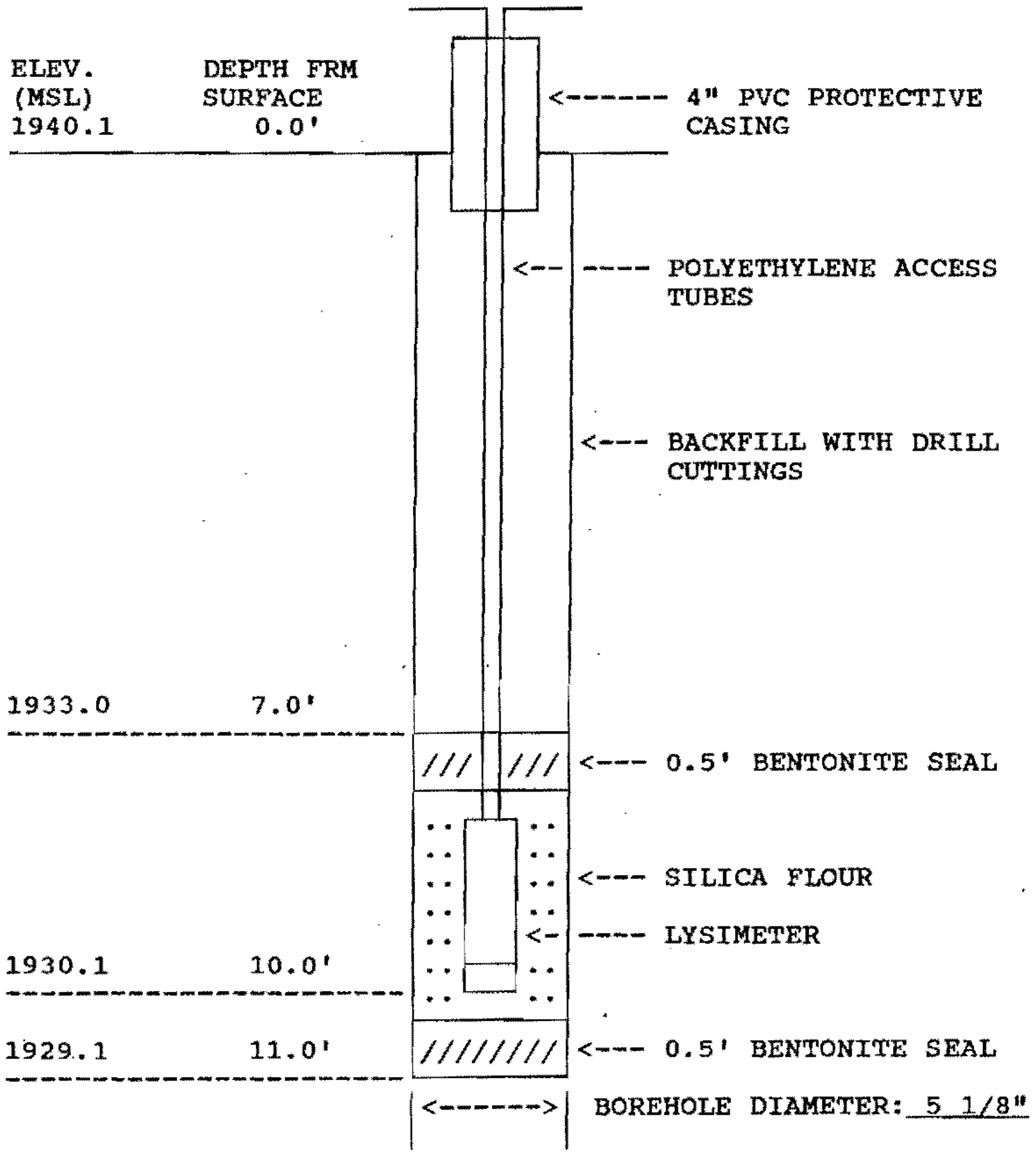
INSTRUMENT TYPE: PRESSURE VACUUM LYSIMETER
MANUFACTURER: SOILMOISTURE EQUIPMENT CORP.
MODEL NUMBER: 1920



I.D. NUMBER: PVL-8
DATE INSTALLED: 12/8/88
INSTALLATION DEPTH: 10'

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY
BOREHOLE DEPTH: 11'

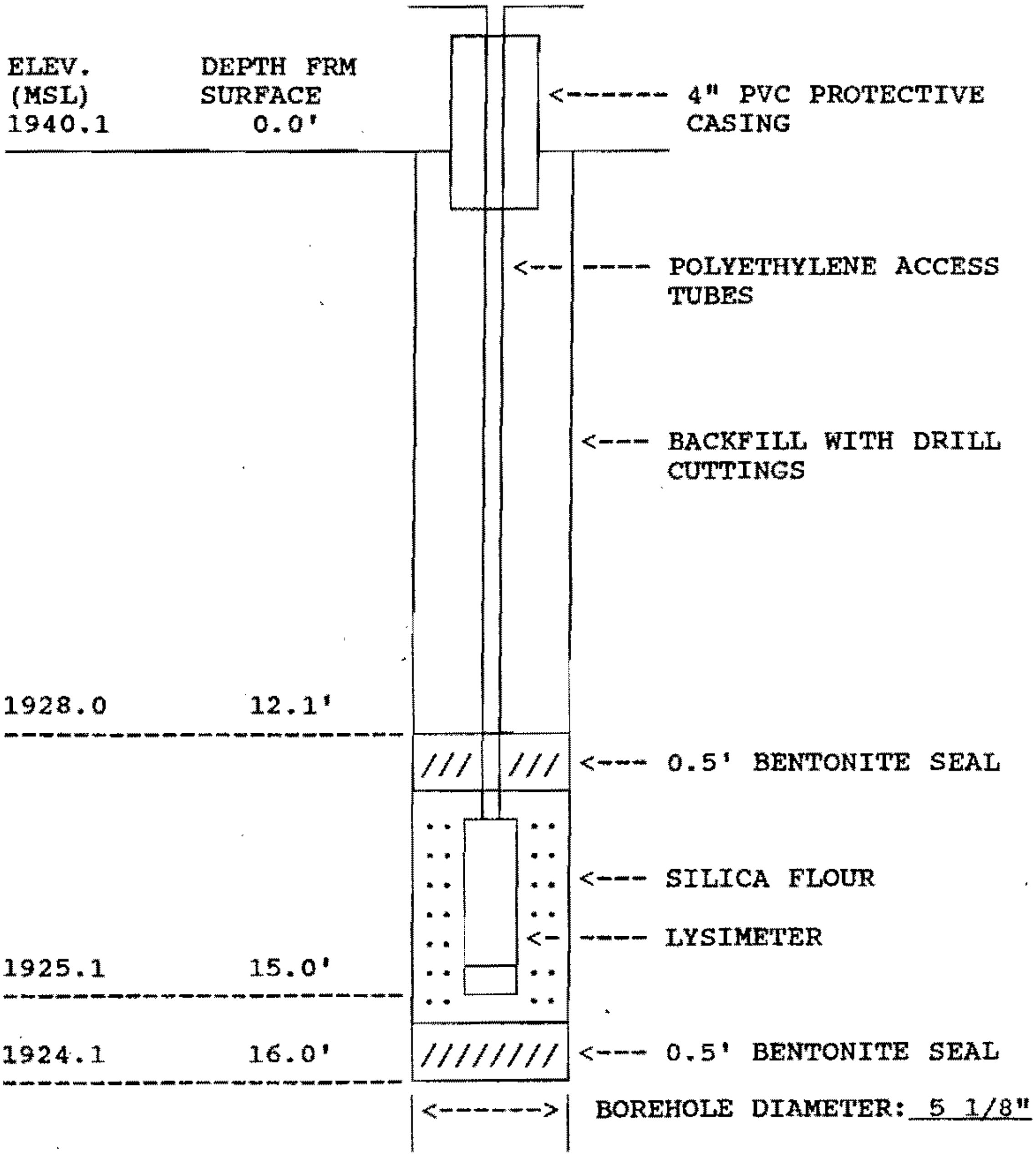
INSTRUMENT TYPE: PRESSURE VACUUM LYSIMETER
MANUFACTURER: SOILMOISTURE EQUIPMENT CORP.
MODEL NUMBER: 1920



I.D. NUMBER: PVL-9
DATE INSTALLED: 12/8/88
INSTALLATION DEPTH: 15'

DRILLER: MOHL DRILLING
DRILLING METHOD: AIR ROTARY
BOREHOLE DEPTH: 16'

INSTRUMENT TYPE: PRESSURE VACUUM LYSIMETER
MANUFACTURER: SOILMOISTURE EQUIPMENT CORP.
MODEL NUMBER: 1920



APPENDIX C

Lithologic Logs of Boreholes

Log of Test Boring No.: MW-1	Surface Elev.: 1954.50
Drilling Contractor: Mohl Drilling	Boring Depth: 100.0'
Drilling Method: 5 5/8" Air Rotary	Start Date:7/19/88
Logged By:TRJ	Completion Date:7/20/88
	Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1954.5	--0	OL	(0.0-0.5) Topsoil, silty, medium brown, low plasticity
		OL	(0.5-5.0) Clay, silty, sandy, medium grey brown, organic, low plasticity
1949.5	--5	OL	Clay, silty, dark brown, organic, low plasticity
1944.5	--10	OH	Clay, medium grey, mottled, organic w/gypsum crystals, low to medium plasticity
1939.5	--15	PT	Weathered coal, black
1934.5	--20	OH	Clay, dark grey brown, medium plasticity
1929.5	--25	MH	Siltstone, clayey, medium grey brown w/shell fragments, low plasticity
1924.5	--30	OH	Clay, silty, medium grey brown, low plasticity
1919.5	--35	SC	Sand, very fine to fine, clayey, medium grey, low plasticity
1914.5	--40	SC	Same as above, (medium plasticity)

MW-1 continued.

1909.5	--45	SC	Sand, fine, clayey, dark grey, low plasticity
1904.5	--50	CL	Clay, sandy, fine, dark grey, medium plasticity
1899.5	--55	CL	Same as above
1894.5	--60	SC	Sandstone, very fine, clayey, light grey, low plasticity
1889.5	--65	CL	Clay, sandy, fine, dark grey brown, medium plasticity
1884.5	--70	CL	Clay, sandy, fine, dark grey, medium plasticity
1879.5	--75	CL	Same as above
1874.5	--80	CL	Same as above
1869.5	--85	CL	Same as above
1864.5	--90	CL	Same as above
	- cont.	CL	(95.0-100.0) Same as above

Log of Test Boring No.: MW-2 Drilling Contractor: Mohl Drilling Drilling Method: 5 5/8" Air Rotary Logged By:TRJ	Surface Elev.: 1939.60 Boring Depth: 80.0' Start Date:7/20/88 Completion Date:7/20/88 Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1939.6	--0	OH	Clay, silty, sandy, medium grey brown, organic, w/shell fragments, low plasticity
1934.6	--5	MH	Siltstone, clayey, medium brown, mottled, w/shell fragments, low plasticity
1929.6	--10	OL SM	(10.0-12.5) Clay, silty, dark brown, mottled, medium plasticity (12.5-15.0) Sand, very fine, silty, medium grey brown
1924.6	--15	SC	Sand, fine, clayey, medium grey, slightly mottled, low to medium plasticity
1919.6	--20	SC	Same as above (low plasticity)
1914.6	--25	SC	Sand, fine, clayey, medium grey, low plasticity
1909.6	--30	SC	Same as above
1904.6	--35	SC	Sand, fine, clayey, medium grey, w/interbedded? silt, medium brown, low plasticity
1899.6	--40	SC	Sandstone, very fine, clayey, light grey, low plasticity

MW-2 continued.

1894.6	--45	CL	Clay, sandy, fine, dark grey, medium plasticity
1889.6	--50	CL	Same as above
1884.6	--55	CL	Same as above
1879.6	--60	CL	Same as above
1874.6	--65	CL	Same as above
1869.6	--70	SC	Sand, fine, silty, clayey, medium grey brown, low plasticity
1864.6	--75	SC	Sand, very fine, clayey, light grey, low plasticity (79.5-80.0) Claystone, medium brown
1859.6	--80		end of boring
	--85		
	--90		

Log of Test Boring No.: MW-6 Drilling Contractor: Mohl Drilling Drilling Method: 5 5/8" Air Rotary Logged By:TRJ	Surface Elev.: 1951.20 Boring Depth: 57.0' Start Date:12/7/88 Completion Date:12/7/88 Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1951.2	--0 - - - -	GC	Clay, light brown, w/sand thru gravel - fill, low plasticity
1946.2	--5 - - - -	GC	Clay, silty, medium grey to brown, w/sand thru gravel - fill, low plasticity
1941.2	--10 - - - -	PT	Weathered coal, black
1936.2	--15 - - - -	OH	Clay, medium grey to brown, mottled, medium plasticity
1931.2	--20 - - - -	CH	Clay, medium grey, high plasticity
1926.2	--25 - - - -	CL	Clay, silty, medium grey, low to medium plasticity
1921.2	--30 - - - -	CL	Same as above
1916.2	--35 - - - -	OL	Clay, silty, sandy, medium grey brown, w/shell fragments, low plasticity
1911.2	--40 - -	SC	Clay, sandy, fine, medium grey, low plasticity

MW-6 continued.

1906.2	--45	SC	Clay, sandy, fine, dark grey, low plasticity
1901.2	--50	SC	Same as above (medium plasticity)
1896.2	--55	SC	Same as above
			end of boring
	--60		
	--65		
	--70		
	--75		
	--80		
	--85		
	--90		

Log of Test Boring No.: MW-10

Drilling Contractor: Mohl Drilling
Drilling Method: 5 5/8" Air Rotary
Logged By:TRJ

Surface Elev.: 1940.10
Boring Depth: 50.0'
Start Date:12/8/88
Completion Date:12/8/88
Sample Interval: 5'

MSL elev	Depth fr lnd surf	ASTM	DESCRIPTION OF MATERIAL
1940.1	--0	GC	Clay, silty, light brown, w/sand thru gravel - fill, low plasticity
1935.1	--5	GC	Clay, silty, medium brown, w/sand thru gravel, clasts of siltstone and shale - fill, low plasticity
1930.1	--10	GC	Same as above
1925.1	--15	GC	Same as above
1920.1	--20	SC	(20.0-24.0) Clay, sandy, medium grey, w/sand thru gravel - fill
		SW	(24.0-25.0) Sandstone, fine, light grey
1915.1	--25	ML	Siltstone, sandy, clayey, medium reddish brown, low plasticity
1910.1	--30	ML	Siltstone, sandy, clayey, medium grey brown, low plasticity
1905.1	--35	ML	(35.0-38.0) Same as above
		PT	(38.0-40.0) Weathered coal, black
1900.1	--40	ML	Siltstone, sandy, clayey, medium grey, mottled, low plasticity

MW-10 continued

1895.1	--45	ML	Siltstone, sandy, clayey, medium reddish brown, low plasticity
1890.1	--50		end of boring
	--55		
	--60		
	--65		
	--70		
	--75		
	--80		
	--85		
	--90		

Log of Test Boring No.: PVL-3	Surface Elev.: 1939.60
Drilling Contractor: Mohl Drilling	Boring Depth: 5.0'
Drilling Method: 5 5/8" Air Rotary	Start Date:7/20/88
Logged By:TRJ	Completion Date:7/20/88
	Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1939.6	--0		
	-	OL	Clay, silty, medium brown to grey mottled, w/sand thru gravel, organic, lignite fragments - fill, low plasticity
	-		
	-		
	-		
1934.6	--5		------------------------------------
	-		end of boring
	-		
	-		
	-		
	--10		
	-		
	-		
	-		
	-		
	--15		
	-		
	-		
	-		
	-		
	--20		
	-		
	-		
	-		
	-		
	--25		
	-		
	-		
	-		
	-		
	--30		
	-		
	-		
	-		
	-		
	--35		
	-		
	-		
	-		
	-		
	--40		
	-		
	-		

Log of Test Boring No.: PVL-4	Surface Elev.: 1939.60
	Boring Depth: 10.0'
Drilling Contractor: Mohl Drilling	Start Date:7/20/88
Drilling Method: 5 5/8" Air Rotary	Completion Date:7/20/88
Logged By:TRJ	Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1939.6	--0		
	-	OL	Clay, silty, medium brown to grey mottled, w/sand thru gravel, organic, lignite fragments - fill, low plasticity
	-		
	-		
	-		
1934.6	--5		
	-	GC	Sand thru gravel, silty, clayey, medium brown - fill, low plasticity
	-		
	-		
	-		
1929.6	--10		--
	-		end of boring
	-		
	-		
	-		
	--15		
	-		
	-		
	-		
	-		
	--20		
	-		
	-		
	-		
	-		
	--25		
	-		
	-		
	-		
	-		
	--30		
	-		
	-		
	-		
	-		
	--35		
	-		
	-		
	-		
	-		
	--40		
	-		
	-		

Log of Test Boring No.: PVL-5 Drilling Contractor: Mohl Drilling Drilling Method: 5 5/8" Air Rotary Logged By:TRJ	Surface Elev.: 1939.60 Boring Depth: 15.0' Start Date:7/20/88 Completion Date:7/20/88 Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1939.6	--0		
	-	GC	Clay, silty, medium brown to grey
	-		mottled, w/sand thru gravel, organic,
	-		lignite fragments - fill, low
	-		plasticity
1934.6	--5		
	-	OL	(5.0-8.0) Clay, silty, medium grey
	-		to brown, mottled, w/shell fragments
	-	OL	(8.0-10.0) Siltstone, clayey,
	-		medium grey to reddish brown,
1929.6	--10		mottled, w/shell fragments
	-		
	-	OL	Siltstone, clayey, medium grey to
	-		reddish brown, mottled, low
	-		plasticity
1924.6	--15		--
	-		end of boring
	-		
	-		
	-		
	--20		
	-		
	-		
	-		
	-		
	--25		
	-		
	-		
	-		
	-		
	--30		
	-		
	-		
	-		
	-		
	--35		
	-		
	-		
	-		
	-		
	--40		
	-		
	-		

Log of Test Boring No.: PVL-7

Drilling Contractor: Mohl Drilling
Drilling Method: 5 5/8" Air Rotary
Logged By:TRJ

Surface Elev.: 1940.10
Boring Depth: 5.0'
Start Date:12/8/88
Completion Date:12/8/88
Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1940.1	--0	GC	Clay, silty, light grey to brown, mottled, w/fine sand thru gravel - fill, low plasticity
1935.1	--5		end of boring
	--10		
	--15		
	--20		
	--25		
	--30		
	--35		
	--40		

Log of Test Boring No.: PVL-8 Drilling Contractor: Mohl Drilling Drilling Method: 5 5/8" Air Rotary Logged By:TRJ	Surface Elev.: 1940.10 Boring Depth: 10.0' Start Date:12/8/88 Completion Date:12/8/88 Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1940.1	--0		
	-	GC	Clay, silty, light grey to brown, mottled, w/fine sand thru gravel - fill, low plasticity
	-		
	-		
	-		
1935.1	--5		
	-	GC	Clay, silty, light grey brown, w/sand thru gravel - fill, low to medium plasticity
	-		
	-		
	-		
1930.1	--10		--
	-		end of boring
	-		
	-		
	-		
	--15		
	-		
	-		
	-		
	-		
	--20		
	-		
	-		
	-		
	-		
	--25		
	-		
	-		
	-		
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	--30		
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	-		
	-		
	-		
	--35		
	-		
	-		
	-		
	-		
	--40		
	-		
	-		

Log of Test Boring No.: PVL-9	Surface Elev.: 1940.10
Drilling Contractor: Mohl Drilling	Boring Depth: 15.0'
Drilling Method: 5 5/8" Air Rotary	Start Date:12/8/88
Logged By:TRJ	Completion Date:12/8/88
	Sample Interval: 5'

MSL elev	Depth fr lnd surf	AS TM	DESCRIPTION OF MATERIAL
1940.1	--0	GC	Clay, silty, light grey to brown, mottled, w/sand thru gravel - fill, low plasticity
1935.1	--5	GC	Clay, silty, medium brown, w/sand thru gravel - fill, medium plasticity
1930.1	--10	GC	Clay, silty, dark brown, w/sand thru gravel, lignite fragments - fill, low plasticity
1925.1	--15		end of boring
	--20		
	--25		
	--30		
	--35		
	--40		

APPENDIX D

Water Quality Data

Well ID	Date mo/da/yr	Field Temp. C	Field pH	Field Cond. mmhos/cm	Ca mg/L	Mg mg/L	Na mg/L
MW-1	08/12/88	12.8	8.35	2.75	8.5	3.7	710
MW-1	12/19/88	5.3	8.28	3.03	6.5	2.6	610
MW-1	03/13/89	5.6	8.18	3.96	7.0	3.5	742
MW-1	06/27/89	12.0	8.18	2.42	6.7	4.3	680
MW-1	09/19/89	5.4	7.95	2.57	19.0	18.0	602
MW-1	12/06/89	6.5	8.29	2.68	7.3	3.4	735
MW-2	08/12/88	14.0	7.25	4.67	26.0	11.0	1257
MW-2	12/19/88	5.5	7.25	5.06	25.0	11.0	1075
MW-2	03/13/89	7.2	7.19	4.85	29.0	14.0	1254
MW-2	06/27/89	12.2	7.18	3.80	29.0	16.0	1230
MW-2	09/19/89	4.7	7.20	4.17	24.0	14.0	1130
MW-2	12/06/89	7.1	7.25	5.00	26.0	12.0	1252
MW-6	03/13/89	5.0	7.18	2.88	35.0	14.0	440
MW-6	06/27/89	14.2	7.20	1.85	24.0	10.0	470
MW-6	09/19/89	4.5	7.10	1.85	29.0	12.0	479
MW-6	12/06/89	7.5	7.21	1.88	38.0	15.0	406
MW-10	03/13/89	6.1	7.27	6.26	460.0	290.0	685
MW-10	06/27/89	13.0	7.14	5.02	445.0	356.0	700
MW-10	09/19/89	3.2	7.16	5.34	425.0	428.0	675
MW-10	12/06/89	8.2	7.10	6.24	470.0	368.0	589
PVL-3	08/12/88	18.9	7.23	10.90	366.0	411.0	2344
PVL-3	12/19/88	3.6	7.39	12.11	400.0	345.0	2620
PVL-3	04/18/89	-	7.95	15.75	327.0	297.0	3400
PVL-3	06/27/89	15.3	7.17	11.35	287.0	378.0	2890
PVL-3	09/19/89	6.0	7.15	17.64	316.0	327.0	2860
PVL-4	08/12/88	17.8	7.39	10.40	409.0	379.0	2403
PVL-4	12/19/88	-	-	-	-	-	-
PVL-4	03/13/89	2.9	6.90	12.19	455.0	365.0	2410
PVL-4	06/27/89	14.3	7.45	10.67	416.0	593.0	2430
PVL-4	09/19/89	5.4	7.19	11.14	416.0	413.0	2340
PVL-5	08/12/88	-	-	-	-	-	-
PVL-5	12/19/88	-	-	-	-	-	-
PVL-5	05/31/89	17.5	7.87	20.30	384.0	544.0	3920
PVL-5	06/27/89	13.1	7.14	16.05	358.0	575.0	4910
PVL-5	09/19/89	5.9	7.18	12.18	462.0	710.0	4850
PVL-7	04/18/89	-	-	-	-	-	-
PVL-7	06/27/89	12.4	7.17	5.46	348.0	376.0	690
PVL-7	09/19/89	8.0	7.45	6.21	334.0	396.0	845
PVL-8	05/31/89	7.7	6.99	7.81	565.0	430.0	680
PVL-8	06/27/89	12.0	7.03	5.20	500.0	420.0	630
PVL-8	09/19/89	14.6	7.07	5.63	520.0	457.0	639
PVL-9	04/18/89	-	7.53	8.18	518.0	442.0	800
PVL-9	06/27/89	10.4	7.18	5.26	500.0	455.0	780
PVL-9	09/19/89	13.3	7.02	5.69	535.0	496.0	601
PRE-1	03/13/89	0.0	6.65	0.07	31.0	6.9	15
RUN-1	03/13/89	1.1	7.20	0.65	46.0	13.0	31
RUN-1	09/19/89	13.3	7.46	1.51	134.0	48.0	110
CWB-1	03/13/89	24.8	8.52	6.42	630.0	290.0	812
CWB-1	12/06/89	18.0	8.58	7.41	596.0	262.0	767

- not reported

Well ID	Date mo/da/yr	Al mg/L	Fe mg/L	Si mg/L	K mg/L	CaCO3 mg/L	HCO3 mg/L
MW-1	08/12/88	0.7	1.4	<10.0	0.5	1352	1648
MW-1	12/19/88	<0.5	<0.2	<10.0	4.2	1263	1540
MW-1	03/13/89	<0.5	<0.2	3.9	4.5	1300	1585
MW-1	06/27/89	<0.5	<0.2	3.4	3.9	1292	1575
MW-1	09/19/89	<0.5	<0.2	4.4	5.2	1331	1623
MW-1	12/06/89	<0.5	<0.2	3.5	4.2	1363	1662
MW-2	08/12/88	<0.5	<0.2	<10.0	7.6	2383	2905
MW-2	12/19/88	<0.5	<0.2	<10.0	7.0	2210	2694
MW-2	03/13/89	<0.5	<0.2	6.2	7.6	2386	2909
MW-2	06/27/89	<0.5	<0.2	6.2	7.4	2194	2675
MW-2	09/19/89	<0.5	<0.2	5.6	6.8	2432	2965
MW-2	12/06/89	<0.5	<0.2	5.9	7.3	2418	2948
MW-6	03/13/89	<0.5	<0.2	5.3	8.4	1098	1339
MW-6	06/27/89	<0.5	<0.2	5.7	6.7	1142	1392
MW-6	09/19/89	<0.5	<0.2	5.3	7.7	1123	1369
MW-6	12/06/89	<0.5	<0.2	5.1	8.6	1073	1308
MW-10	03/13/89	1.8	0.3	12.0	19.0	644	785
MW-10	06/27/89	<0.5	<0.2	12.0	19.0	597	728
MW-10	09/19/89	<0.5	<0.2	12.0	19.0	638	778
MW-10	12/06/89	1.6	<0.2	13.0	19.0	608	741
PVL-3	08/12/88	<0.5	<0.2	31.0	48.0	1495	1823
PVL-3	12/19/88	<0.5	<0.2	<10.0	56.0	1664	2029
PVL-3	04/18/89	1.5	<0.2	33.0	51.0	1711	2086
PVL-3	06/27/89	<1.0	0.3	28.0	44.0	1603	1954
PVL-3	09/19/89	<1.0	<0.4	32.0	48.0	1611	1964
PVL-4	08/12/88	<0.5	<0.2	28.0	53.0	1117	1362
PVL-4	12/19/88	-	-	-	-	-	-
PVL-4	03/13/89	1.6	0.3	32.0	59.0	968	1180
PVL-4	06/27/89	<1.0	0.3	32.0	58.0	888	1083
PVL-4	09/19/89	<1.0	<0.4	33.0	55.0	920	1122
PVL-5	08/12/88	-	-	-	-	-	-
PVL-5	12/19/88	-	-	-	-	-	-
PVL-5	05/31/89	-	<0.2	25.0	62.0	1658	2021
PVL-5	06/27/89	<1.0	<0.4	30.0	73.0	2255	2749
PVL-5	09/19/89	<1.0	<0.4	32.0	71.0	2205	2688
PVL-7	04/18/89	-	-	-	-	-	-
PVL-7	06/27/89	<1.0	<0.4	31.0	16.0	770	939
PVL-7	09/19/89	<1.0	<0.4	28.0	15.0	916	1117
PVL-8	05/31/89	1.8	<0.2	28.0	17.0	812	990
PVL-8	06/27/89	<1.0	<0.4	28.0	16.0	864	1053
PVL-8	09/19/89	<1.0	<0.4	28.0	15.0	967	1179
PVL-9	04/18/89	2.3	<0.2	27.0	21.0	625	762
PVL-9	06/27/89	<1.0	<0.4	32.0	20.0	692	844
PVL-9	09/19/89	<1.0	<0.4	32.0	18.0	773	942
PRE-1	03/13/89	<0.5	<0.2	<1.0	1.3	28	34
RUN-1	03/13/89	<0.5	<0.2	1.6	5.5	59	72
RUN-1	09/19/89	<0.5	<0.2	11.0	18.0	265	323
CWB-1	03/13/89	1.2	0.4	33.0	50.0	385	469
CWB-1	12/06/89	1.3	<0.2	32.0	46.0	269	328

Well ID	Date mo/da/yr	SO4 mg/L	Total carbon mg/L	TIC mg/L	TOC mg/L	TDS mg/L	TDS CALC
MW-1	08/12/88	331	32.4	3.1	29.3	*	1864
MW-1	12/19/88	372	304.0	287.0	16.0	*	1752
MW-1	03/13/89	191	326.0	311.0	15.6	1750	1731
MW-1	06/27/89	221	344.0	323.0	21.1	1780	1694
MW-1	09/19/89	368	353.0	309.0	43.7	1950	1815
MW-1	12/06/89	230	384.0	354.0	29.8	1840	1801
MW-2	08/12/88	467	14.4	3.0	11.4	*	3197
MW-2	12/19/88	593	529.0	512.0	17.0	*	3036
MW-2	03/13/89	578	603.0	587.0	16.3	3320	3319
MW-2	06/27/89	475	530.0	502.0	28.0	2930	3079
MW-2	09/19/89	505	616.0	584.0	32.1	3280	3143
MW-2	12/06/89	495	582.0	561.0	20.7	3270	3248
MW-6	03/13/89	72	254.0	244.0	9.3	1220	1233
MW-6	06/27/89	35	278.0	256.0	21.8	1220	1236
MW-6	09/19/89	43	303.0	292.0	11.2	1100	1249
MW-6	12/06/89	43	286.0	270.0	16.0	1160	1159
MW-10	03/13/89	3430	164.0	116.0	48.1	6020	5282
MW-10	06/27/89	2989	196.0	135.0	61.1	5310	4879
MW-10	09/19/89	3665	219.0	152.0	67.2	5960	5606
MW-10	12/06/89	3691	224.0	165.0	59.4	5520	5514
PVL-3	08/12/88	5480	452.0	278.0	174.0	*	9576
PVL-3	12/19/88	6560	469.0	296.0	173.0	*	10979
PVL-3	04/18/89	7040	589.0	415.0	174.0	12800	12174
PVL-3	06/27/89	5896	485.0	296.0	189.0	11950	10484
PVL-3	09/19/89	6959	542.0	304.0	238.0	11960	11508
PVL-4	08/12/88	-	-	-	-	-	3942
PVL-4	12/19/88	-	-	-	-	-	-
PVL-4	03/13/89	6070	340.0	240.0	100.0	11870	9971
PVL-4	06/27/89	6093	307.0	179.0	128.0	11020	10154
PVL-4	09/19/89	6771	409.0	275.0	134.0	*	10580
PVL-5	08/12/88	-	-	-	-	-	-
PVL-5	12/19/88	-	-	-	-	-	-
PVL-5	05/31/89	15400	-	-	-	-	21329
PVL-5	06/27/89	10734	528.0	407.0	121.0	20100	18032
PVL-5	09/19/89	11010	426.0	274.0	152.0	*	18457
PVL-7	04/18/89	-	-	-	-	-	-
PVL-7	06/27/89	3189	250.0	117.0	133.0	5460	5112
PVL-7	09/19/89	3658	306.0	216.0	89.7	6040	5825
PVL-8	05/31/89	3130	-	-	-	-	5337
PVL-8	06/27/89	3101	307.0	130.0	177.0	6150	5213
PVL-8	09/19/89	3115	375.0	197.0	178.0	6490	5354
PVL-9	04/18/89	3540	367.0	163.0	205.0	7080	5723
PVL-9	06/27/89	3204	376.0	143.0	233.0	6770	5406
PVL-9	09/19/89	2978	415.0	154.0	261.0	6850	5123
PRE-1	03/13/89	206	11.7	5.8	5.9	202	277
RUN-1	03/13/89	222	17.8	7.3	10.5	172	354
RUN-1	09/19/89	591	101.0	53.6	47.4	1180	1071
CWB-1	03/13/89	3780	87.7	55.6	32.1	6240	5826
CWB-1	12/06/89	3744	102.0	38.0	64.0	5940	5608

* not determined

Well ID	Date mo/da/yr	As ug/L	Ba mg/L	Cd mg/L	Cr mg/L	Cu mg/L	Pb ug/L
MW-1	08/12/88	42.0	0.44	<0.02	<0.02	<0.02	<10.0
MW-1	12/19/88	26.0	0.31	<0.02	0.03	0.06	<10.0
MW-1	03/13/89	16.0	0.16	<0.02	<0.02	<0.05	<10.0
MW-1	06/27/89	24.0	0.70	<0.02	<0.02	<0.05	<10.0
MW-1	09/19/89	22.0	1.00	<0.02	<0.02	<0.05	<10.0
MW-1	12/06/89	21.0	0.02	<0.02	<0.02	<0.05	<10.0
MW-2	08/12/88	3.3	0.14	<0.02	<0.02	<0.02	<10.0
MW-2	12/19/88	<2.0	0.36	<0.02	0.04	<0.05	<10.0
MW-2	03/13/89	3.0	0.13	<0.02	<0.02	<0.05	<10.0
MW-2	06/27/89	<2.0	0.19	<0.02	<0.02	<0.05	<10.0
MW-2	09/19/89	2.5	0.59	<0.02	<0.02	<0.05	<10.0
MW-2	12/06/89	2.0	0.03	<0.02	0.02	<0.05	<10.0
MW-6	03/13/89	<2.0	0.20	<0.20	<0.20	<0.05	<10.0
MW-6	06/27/89	4.5	0.55	<0.02	0.06	<0.05	<10.0
MW-6	09/19/89	<2.0	0.31	<0.02	<0.02	<0.05	<10.0
MW-6	12/06/89	<2.0	0.09	<0.02	0.02	<0.05	<10.0
MW-10	03/13/89	<2.0	0.10	<0.20	<0.02	<0.05	<10.0
MW-10	06/27/89	<2.0	0.14	<0.02	<0.02	<0.05	<10.0
MW-10	09/19/89	<2.0	0.16	<0.02	0.34	<0.05	<10.0
MW-10	12/06/89	<2.0	0.02	0.02	0.34	<0.05	<10.0
PVL-3	08/12/88	11.0	0.16	<0.02	<0.02	0.05	<10.0
PVL-3	12/19/88	<2.0	0.11	<0.02	0.32	0.10	<10.0
PVL-3	04/18/89	11.0	0.92	<0.02	<0.02	0.14	<10.0
PVL-3	06/27/89	8.2	0.11	<0.04	<0.04	0.12	13.0
PVL-3	09/19/89	7.0	<0.04	<0.04	0.35	<0.1	<10.0
PVL-4	08/12/88	8.0	0.04	<0.02	<0.02	0.06	<10.0
PVL-4	12/19/88	-	-	-	-	-	-
PVL-4	03/13/89	8.7	0.05	0.03	<0.02	0.17	<10.0
PVL-4	06/27/89	8.0	0.14	<0.04	<0.04	0.22	<10.0
PVL-4	09/19/89	4.3	<0.04	<0.04	0.39	0.14	<10.0
PVL-5	08/12/88	-	-	-	-	-	-
PVL-5	12/19/88	-	-	-	-	-	-
PVL-5	05/31/89	8.1	<0.02	0.04	<0.02	-	<10.0
PVL-5	06/27/89	9.4	0.04	<0.04	<0.04	0.23	<10.0
PVL-5	09/19/89	6.2	<0.04	<0.04	0.55	0.16	<10.0
PVL-7	04/18/89	-	-	-	-	-	-
PVL-7	06/27/89	13.0	0.04	<0.04	<0.04	0.23	<10.0
PVL-7	09/19/89	10.0	0.32	<0.04	0.34	<0.1	<10.0
PVL-8	05/31/89	5.8	0.03	0.04	<0.02	0.16	<10.0
PVL-8	06/27/89	<2.0	<0.04	<0.04	<0.04	0.24	<10.0
PVL-8	09/19/89	<2.0	0.04	<0.04	0.47	<0.1	<10.0
PVL-9	04/18/89	5.5	0.67	<0.02	<0.02	0.05	<10.0
PVL-9	06/27/89	8.4	0.05	<0.04	<0.04	0.58	<10.0
PVL-9	09/19/89	5.5	<0.04	<0.04	0.50	<0.1	<10.0
PRE-1	03/13/89	<2.0	0.06	<0.02	<0.02	<0.05	<10.0
RUN-1	03/13/89	<2.0	0.10	<0.02	<0.02	<0.05	<10.0
RUN-1	09/19/89	10.0	0.84	<0.02	0.06	<0.05	<10.0
CWB-1	03/13/89	25.0	0.43	<0.02	<0.02	<0.05	<10.0
CWB-1	12/06/89	22.0	0.47	0.02	0.28	0.06	<10.0

- not reported

Well ID	Date mo/da/yr	Mn mg/L	Hg ug/L	Mo mg/L	Se ug/L	Ag ug/L	Zn mg/L	B mg/l
MW-1	08/12/88	0.06	<3.0	<0.05	3.6	<1.0	0.03	-
MW-1	12/19/88	<0.02	<3.0	<0.05	<2.0	<1.0	0.02	-
MW-1	03/13/89	0.06	<1.5	<0.05	<2.0	<1.0	0.04	-
MW-1	06/27/89	0.03	<3.0	<0.05	<2.0	<1.0	0.03	<0.5
MW-1	09/19/89	0.03	1.2	<0.05	7.0	<1.0	0.04	0.5
MW-1	12/06/89	0.04	<3.0	<0.02	<2.0	<1.0	<0.02	-
MW-2	08/12/88	0.13	<1.2	<0.05	<2.0	<1.0	0.04	-
MW-2	12/19/88	0.09	<3.0	0.14	<2.0	<1.0	0.21	-
MW-2	03/13/89	0.12	<1.2	0.09	2.0	<1.0	0.04	-
MW-2	06/27/89	0.12	<3.0	<0.05	3.1	<1.0	0.04	<0.5
MW-2	09/19/89	0.09	<1.2	<0.05	<2.0	<1.0	0.18	<0.5
MW-2	12/06/89	0.09	<3.0	<0.02	<2.0	<1.0	<0.02	-
MW-6	03/13/89	0.15	<1.2	<0.05	<2.0	<1.0	0.03	-
MW-6	06/27/89	0.14	<3.0	<0.05	2.2	<1.0	0.11	<0.5
MW-6	09/19/89	0.10	<1.2	<0.05	<2.0	<1.0	0.07	<0.5
MW-6	12/06/89	0.10	<3.0	<0.02	<2.0	<1.0	<0.02	-
MW-10	03/13/89	0.04	<1.2	0.06	309.0	<1.0	0.08	-
MW-10	06/27/89	0.06	<3.0	<0.05	319.0	<1.0	0.08	<0.5
MW-10	09/19/89	0.06	<1.2	<0.05	278.0	<1.0	0.12	<0.5
MW-10	12/06/89	0.05	<3.0	<0.02	320.0	<1.0	0.08	-
PVL-3	08/12/88	<0.02	<3.0	0.72	30.0	<1.0	0.04	-
PVL-3	12/19/88	0.31	<3.0	0.13	40.0	1.1	0.15	-
PVL-3	04/18/89	0.34	<3.0	0.15	49.0	<1.0	0.14	-
PVL-3	06/27/89	0.38	<3.0	0.17	61.0	<1.0	0.08	<1.0
PVL-3	09/19/89	0.31	<1.2	<0.05	67.0	<1.0	0.05	<1.0
PVL-4	08/12/88	-	<3.0	0.58	96.0	<1.0	<0.02	-
PVL-4	12/19/88	-	-	-	-	-	-	-
PVL-4	03/13/89	0.30	<1.5	0.06	114.0	<1.0	0.09	-
PVL-4	06/27/89	0.19	<3.0	<0.1	122.0	<1.0	0.17	<1.0
PVL-4	09/19/89	0.16	<1.2	<0.05	113.0	<1.0	0.12	<1.0
PVL-5	08/12/88	-	-	-	-	-	-	-
PVL-5	12/19/88	-	-	-	-	-	-	-
PVL-5	05/31/89	0.02	-	-	37.0	<1.0	-	-
PVL-5	06/27/89	1.11	<3.0	0.17	36.0	<1.0	0.18	<1.0
PVL-5	09/19/89	0.97	<1.2	0.10	35.0	1.2	0.22	<1.0
PVL-7	04/18/89	-	-	-	-	-	-	-
PVL-7	06/27/89	0.40	<3.0	0.11	5.3	<1.0	0.12	<1.0
PVL-7	09/19/89	0.27	<1.2	0.08	6.6	<1.0	0.23	<1.0
PVL-8	05/31/89	0.14	<1.5	0.12	422.0	<1.0	0.07	-
PVL-8	06/27/89	0.10	<3.0	<0.1	422.0	<1.0	0.14	<1.0
PVL-8	09/19/89	0.89	<1.2	<0.05	361.0	<1.0	0.12	<1.0
PVL-9	04/18/89	0.75	<3.0	0.19	4.9	<1.0	0.06	-
PVL-9	06/27/89	1.11	<3.0	<0.1	3.2	<1.0	0.12	<1.0
PVL-9	09/19/89	1.15	3.0	<0.05	2.4	<1.0	0.16	<1.0
PRE-1	03/13/89	0.05	<1.5	<0.05	2.5	<1.0	0.04	-
RUN-1	03/13/89	0.06	<1.5	<0.05	2.8	<1.0	<0.02	-
RUN-1	09/19/89	0.64	<1.2	0.07	<2	<1.0	0.11	4.0
CWB-1	03/13/89	<0.02	<0.6	0.17	14.0	<1.0	0.03	-
CWB-1	12/06/89	<0.02	4.4	0.04	13.0	<1.0	0.05	-

- not reported

APPENDIX E

Water Level Data

WELL ID	UND MW-1	UND MW-2	UND MW-6	UND MW-10
GRID COORD. (nearest foot)	N-37505 E-36731	N-38438 E-37638	N-37844 E-36381	N-39019 E-37428
INSTALL. DATE	07/20/88	07/20/88	12/07/88	12/08/88
TOP OF INNER CASING (ft-MSL)	1956.59	1942.22	1953.57	1942.47
GROUND SURFACE ELEV. (ft-MSL)	1954.5	1939.6	1951.2	1940.1
SCREEN INTERVAL ELEV. (ft-MSL)	1888.0-1854.5	1906.6-1859.6	1921.2-1894.2	1922.1-1890.1

WELL ID	CCS MW-48	CCS MW-49	CCS MW-50	CCS MW-51
GRID COORD. (nearest foot)	N-139887 E-1840278	N-138932 E-1840328	N-138919 E-1841117	N-138934 E-1841874
INSTALL. DATE	05/26/88	05/20/88	05/20/88	05/20/88
TOP OF INNER CASING (ft-MSL)	1920.8	1905.9	1902.6	1896.9
GROUND SURFACE ELEV. (ft-MSL)	1919.0	1903.6	1901.1	1895.5
SCREEN INTERVAL ELEV. (ft-MSL)	1876.2-1886.2	1883.7-1893.7	1878.2-1888.2	1876.7-1886.7

WELL ID	CCS MW-55	CCS MW-56	CCS MW-57	CCS MW-58
GRID COORD. (nearest foot)	N-137035 E-1841702	N-136908 E-1840484	N-137053 E-1839717	N-138183 E-1839406
INSTALL. DATE	05/23/88	05/23/88	05/26/88	05/26/88
TOP OF INNER CASING (ft-MSL)	1921.5	1934.9	1943.3	1931.8
GROUND SURFACE ELEV. (ft-MSL)	1918.6	1932.9	1941.2	1929.2
SCREEN INTERVAL ELEV. (ft-MSL)	1900.1-1910.1	1903.7-1913.7	1908.5-1918.5	1906.7-1916.7

WELL ID	CCS MW-60	CCS MW-61	CCS MW-62	CCS MW-63
GRID COORD. (nearest foot)	N-139683 E-1838320	N-137185 E-1838658	N-138934 E-1836221	N-138213 E-1835820
INSTALL. DATE	05/26/88	05/27/88	05/27/88	05/27/88
TOP OF INNER CASING (ft-MSL)	1933.1	1962.0	1952.5	1957.6
GROUND SURFACE ELEV. (ft-MSL)	1930.9	1959.8	1950.2	1955.1
SCREEN INTERVAL ELEV. (ft-MSL)	1889.0-1899.0	1915.7-1925.7	1906.9-1911.9	1912.7-1917.7

WELL ID	CCS MW-64	CCS MW-65	CCS MW-66	CCS MW-67
GRID COORD. (nearest foot)	N-138928 E-1836224	N-138223 E-1835818	N-139966 E-1839694	N-140704 E-1839865
INSTALL. DATE	05/27/88	05/27/88	05/26/88	05/26/88
TOP OF INNER CASING (ft-MSL)	1952.8	1958.3	1921.1	1921.7
GROUND SURFACE ELEV. (ft-MSL)	1950.4	1955.6	1918.6	1918.7
SCREEN INTERVAL ELEV. (ft-MSL)	1925.8-1935.8	1931.6-1941.6	1881.3-1891.3	1877.1-1887.1

WELL ID	CCS MW-68
GRID COORD. (nearest foot)	N-140664 E-1840260
INSTALL. DATE	05/26/88
TOP OF INNER CASING (ft-MSL)	1921.3
GROUND SURFACE ELEV. (ft-MSL)	1919.0
SCREEN INTERVAL ELEV. (ft-MSL)	1875.3-1885.3

DATE	UND MW-1	UND MW-2	UND MW-6	UND MW-10	CCS MW-48	CCS MW-49
07/27/88	1903.59	1896.22			1883.40	
08/10/88	1902.59	1896.02				
12/08/88	1903.67	1896.94				
02/14/89	1904.35	1897.29	1918.89	1911.51	1881.90	1896.49
03/13/89	1904.18	1897.29	1919.05	1911.88	1882.55	1896.51
04/18/89	1904.23	1897.47	1918.65	1910.18	1882.71	1896.68
05/31/89	1904.33	1897.59	1918.79	1910.70	1883.13	1896.25
06/26/89	1904.27	1897.60	1918.73	1912.40	1883.17	1896.37
07/24/89	1904.21	1897.47	1919.40	1913.07	1882.78	1896.13
09/19/89	1904.34	1897.64	1919.06	1918.51		1895.69
12/06/89	1904.62	1897.57	1919.36	1920.39		
05/09/90	1904.37	1897.90	1919.36	1920.13		

DATE	CCS MW-50	CCS MW-51	CCS MW-55	CCS MW-56	CCS MW-57	CCS MW-58
07/27/88	1883.64		1907.00	1911.97	1916.69	1915.03
08/10/88						
12/08/88						
02/14/89	1882.78	1883.67	1904.69	1910.86	1916.63	1915.26
03/13/89	1882.83	1883.93	1912.18	1911.18	1916.67	1915.45
04/18/89	1882.78	1883.02	1910.41	1911.93	1917.31	1916.79
05/31/89	1882.72	1882.66	1909.85	1912.43	1917.31	1917.62
06/26/89	1882.65	1882.09	1908.50	1912.46	1917.17	1917.00
07/24/89	1882.53	1881.59			1916.46	1915.93
09/19/89		1881.48			1914.68	1913.58
12/06/89					1914.67	1913.69

DATE	CCS MW-60	CCS MW-61	CCS MW-62	CCS MW-63	CCS MW-64	CCS MW-65
07/27/88	1903.90	1930.34	1940.04	1930.60	1940.73	1939.70
08/10/88						
12/08/88						
02/14/89	1902.52	NA	NA	1930.01	1940.27	1939.21
03/13/89	1902.73	1929.91	NA	1930.26	NA	1939.56
04/18/89	1902.28	NA	1939.47	1930.14	1940.27	1939.90
05/31/89	1902.26	NA	1939.46	1930.04	1940.37	1939.63
06/26/89	1902.49	1929.98	1939.69	1930.33	1940.39	1939.59
07/24/89	1902.16	1929.88	1939.54	1930.10	1940.21	1939.39
09/19/89	1901.93	NA	1939.54	1929.88	1940.27	1939.27
12/06/89	1901.40	1929.51	1939.34	1929.57	1939.96	1939.07

NA - not accessible

DATE	CCS MW-65	CCS MW-66	CCS MW-67	CCS MW-68
07/27/88	1939.70	1885.63	1881.12	1878.35
08/10/88				
12/08/88				
02/14/89	1939.21	1884.81	1881.61	1878.25
03/13/89	1939.56	1884.29	1881.88	1878.29
04/18/89	1939.90	1885.88	NA	NA
05/31/89	1939.63	1887.20	1883.12	1879.26
06/26/89	1939.59	1886.07	1882.56	1878.80
07/24/89	1939.39	1885.66	1881.57	1878.16
09/19/89	1939.27	1884.48	1880.25	1877.53
12/06/89	1939.07	NA	NA	NA

NA - not accessible

APPENDIX F

Evapotranspiration Data

Thornthwaite's Formula

$$ET = 16(10T/I)^A \times F$$

ET monthly potential evapotranspiration (cm)

T mean monthly temperature

A $[(6.75 \times 10-7)I^3 - (7.71 \times 10-5)I^2 + (1.79 \times 10-2)I + 0.49239]$

I annual heat index, sum of monthly thermal indexes i,

i $(T/5)^{1.514}$

F correction coefficient, function of month and latitude

DATE	MEAN TEMP C	i	UNADJUSTED ET	ADJUSTED ET (cm)	ET (inches)	MEAN PRECIP
Jun-88	29.8	14.918	11.446	15.109	5.948	1.3
Jul-88	22.3	9.618	8.266	10.994	4.328	2.27
Aug-88	21.1	8.846	7.768	9.477	3.731	0.3
Sep-88	13.6	4.549	4.744	4.934	1.943	0.46
Oct-88	6.6	1.522	2.107	1.960	0.771	0.23
Nov-88	-1.5	0.000	0.000	0.000	0.000	0.61
Dec-88	-7.5	0.000	0.000	0.000	0.000	0.76
Jan-89	-9.4	0.000	0.000	0.000	0.000	0.97
Feb-89	-15.9	0.000	0.000	0.000	0.000	0.21
Mar-89	-5.5	0.000	0.000	0.000	0.000	0.35
Apr-89	6.5	1.488	2.071	2.361	0.930	1.98
May-89	13.5	4.499	4.705	6.117	2.408	2.44
Jun-89	16.7	6.208	5.975	7.886	3.105	1.05
Jul-89	23.7	10.547	8.851	11.772	4.635	0.56
Aug-89	20.4	8.405	7.480	9.125	3.593	1.73
Sep-89	14.3	4.908	5.019	5.220	2.055	0.89
Oct-89	7.9	1.999	2.578	2.398	0.944	0.28
Nov-89	-2.2	0.000	0.000	0.000	0.000	0.44
Dec-89	-13.37	0.000	0.000	0.000	0.000	0.25
Jan-90	-4.0	0.000	0.000	0.000	0.000	0.05
Feb-90	-8.7	0.000	0.000	0.000	0.000	0.19
Mar-90	1.0	0.085	0.249	0.231	0.091	0.29
Apr-90	6.3	1.411	1.992	1.852	0.729	0.6

HEAT INDEX $I = 51.648175$

APPENDIX G

Leachate Extraction Test Data

SAMPLE ID	TEST	DATE	pH	Al	Ca	Fe	Mg
88-226 cement	ASTM	Oct-88	11.80	<0.5	1043	<0.2	<0.1
88-274 comp. ash	ASTM	Oct-88	11.62	<0.5	836	<0.2	<0.1
88-275 comp. ash	ASTM	Oct-88	11.44	0.7	516	<0.2	<0.1
88-226 cement	EP	Oct-88	11.82	<0.5	1567	<0.2	8.7
88-274 comp. ash	EP	Oct-88	9.82	<0.5	2084	<0.2	30.0
88-275 comp. ash	EP	Oct-88	8.94	<0.5	2009	<0.2	119.0
3-day concrete	ASTM	Oct-88	11.39	1.4	274	<0.2	<0.1
28-day concrete	ASTM	Oct-88	10.88	3.6	226	0.2	<0.1
3-day concrete	EP	Oct-88	5.26	0.6	1545	<0.2	113.0
28-day concrete	EP	Oct-88	5.59	<0.5	1832	1.4	105.0
3-day slurry	ASTM	Oct-88	10.71	3.0	118	<0.2	<0.1
28-day slurry	ASTM	Oct-88	*	2.4	118	<0.2	<0.1
3-day slurry	EP	Oct-88	5.18	1.7	1626	0.2	123.0
28-day slurry	EP	Oct-88	*	0.6	1700	<0.2	118.0

SAMPLE ID	TEST	DATE	Fe	Mg	K	Si	Na
88-226 cement	ASTM	Oct-88	<0.2	<0.1	144	<10	13.0
88-274 comp. ash	ASTM	Oct-88	<0.2	<0.1	2.8	<10	5.8
88-275 comp. ash	ASTM	Oct-88	<0.2	<0.1	7.7	<10	10.0
88-226 cement	EP	Oct-88	<0.2	8.7	144	<10	12.0
88-274 comp. ash	EP	Oct-88	<0.2	30.0	2.6	24.0	6.1
88-275 comp. ash	EP	Oct-88	<0.2	119.0	8.2	60.0	11.0
3-day concrete	ASTM	Oct-88	<0.2	<0.1	8.9	<10	4.2
28-day concrete	ASTM	Oct-88	0.2	<0.1	6.4	<10	3.6
3-day concrete	EP	Oct-88	<0.2	113.0	9.9	66.0	4.5
28-day concrete	EP	Oct-88	1.4	105.0	8.5	45.0	5.0
3-day slurry	ASTM	Oct-88	<0.2	<0.1	1.8	<10	2.1
28-day slurry	ASTM	Oct-88	<0.2	<0.1	1.6	<10	2.2
3-day slurry	EP	Oct-88	0.2	123.0	3.4	60.0	5.0
28-day slurry	EP	Oct-88	<0.2	118.0	3.3	49.0	4.5

SAMPLE ID	TEST	DATE	SO4	TOTAL CARBON	TIC	TOC	As (ug/l)
88-226 cement	ASTM	Oct-88	378	4.7	1.5	3.2	<2
88-274 comp. ash	ASTM	Oct-88	338	3.7	1.1	2.6	209
88-275 comp. ash	ASTM	Oct-88	306	3.4	1.9	1.5	5
88-226 cement	EP	Oct-88	868	*	*	*	<2
88-274 comp. ash	EP	Oct-88	739	*	*	*	216
88-275 comp. ash	EP	Oct-88	778	*	*	*	300
3-day concrete	ASTM	Oct-88	47	4.2	1	3.2	<2
28-day concrete	ASTM	Oct-88	43	5.9	3	2.9	<2
3-day concrete	EP	Oct-88	121	*	*	*	<2
28-day concrete	EP	Oct-88	145	*	*	*	<2
3-day slurry	ASTM	Oct-88	146	*	*	*	9.5
28-day slurry	ASTM	Oct-88	*	*	*	*	7
3-day slurry	EP	Oct-88	188	*	*	*	<2
28-day slurry	EP	Oct-88	*	*	*	*	<2

* not determined

SAMPLE ID	TEST	DATE	Ba	Cd	Cr	Cu	Pb
88-226 cement	ASTM	Oct-88	0.82	<0.02	0.19	<0.05	<0.6
88-274 comp. ash	ASTM	Oct-88	0.71	<0.02	0.12	<0.05	<0.6
88-275 comp. ash	ASTM	Oct-88	0.75	<0.02	0.16	<0.05	<0.6
88-226 cement	EP	Oct-88	0.68	<0.02	0.27	<0.05	<0.6
88-274 comp. ash	EP	Oct-88	1.00	<0.02	0.32	<0.05	<0.6
88-275 comp. ash	EP	Oct-88	0.97	0.06	0.43	<0.05	<0.6
3-day concrete	ASTM	Oct-88	3.20	<0.02	<0.02	<0.05	<0.01
28-day concrete	ASTM	Oct-88	3.40	<0.02	<0.02	<0.05	<0.01
3-day concrete	EP	Oct-88	2.60	0.06	0.04	<0.05	<0.01
28-day concrete	EP	Oct-88	1.70	<0.02	0.22	0.09	<0.01
3-day slurry	ASTM	Oct-88	1.20	<0.02	0.09	<0.05	<0.01
28-day slurry	ASTM	Oct-88	1.80	<0.02	0.08	<0.05	<0.01
3-day slurry	EP	Oct-88	3.80	0.20	0.38	0.53	<0.01
28-day slurry	EP	Oct-88	3.10	0.06	0.26	0.23	<0.01

SAMPLE ID	TEST	DATE	Mn	Hg (ug/l)	Mo	Se (ug/l)	Ag (ug/l)
88-226 cement	ASTM	Oct-88	<0.02	<1.2	0.10	<2	<1
88-274 comp. ash	ASTM	Oct-88	<0.02	<1.2	0.25	34	<1
88-275 comp. ash	ASTM	Oct-88	<0.02	<1.2	0.22	23	<1
88-226 cement	EP	Oct-88	<0.02	<1.5	0.14	10	<1
88-274 comp. ash	EP	Oct-88	<0.02	<1.2	0.33	116	<1
88-275 comp. ash	EP	Oct-88	<0.02	<1.5	0.41	91	<1
3-day concrete	ASTM	Oct-88	<0.02	<2.0	<0.05	<2	<1
28-day concrete	ASTM	Oct-88	<0.02	<3.0	<0.05	<2	<1
3-day concrete	EP	Oct-88	1.75	<1.5	0.12	<2	<1
28-day concrete	EP	Oct-88	3.99	<3.0	0.12	<2	<1
3-day slurry	ASTM	Oct-88	<0.02	<1.5	0.09	<2	<1
28-day slurry	ASTM	Oct-88	<0.02	<2.0	0.08	2	<1
3-day slurry	EP	Oct-88	2.39	<3.0	0.18	4.4	<1
28-day slurry	EP	Oct-88	2.20	<2.0	1.20	4.4	<1

SAMPLE ID	TEST	DATE	Zn
88-226 cement	ASTM	Oct-88	<0.02
88-274 comp. ash	ASTM	Oct-88	<0.02
88-275 comp. ash	ASTM	Oct-88	<0.02
88-226 cement	EP	Oct-88	<0.02
88-274 comp. ash	EP	Oct-88	<0.02
88-275 comp. ash	EP	Oct-88	<0.02
3-day concrete	ASTM	Oct-88	<0.02
28-day concrete	ASTM	Oct-88	<0.02
3-day concrete	EP	Oct-88	0.84
28-day concrete	EP	Oct-88	0.12
3-day slurry	ASTM	Oct-88	0.02
28-day slurry	ASTM	Oct-88	0.03
3-day slurry	EP	Oct-88	0.16
28-day slurry	EP	Oct-88	0.09

REFERENCES

ASTM, 1983, Classification of soils for engineering purposes: Annual Book of ASTM Standards, Section 4 - Construction, Volume 04.08 Soil and Rock; Building stones, ASTM, Philadelphia, PA, pp. 392-403.

Bar-Yosef, B., and Meek D., 1987, Selenium sorption by kaolinite and Montmorillonite: Soil Science, Vol. 144, No. 1, pp. 11-19.

Battelle, Pacific Northwest Laboratory., 1986, Speciation of selenium and arsenic in natural waters and sediments; volume 2, Arsenic Speciation: Unpublished Report, Electric Power Research Institute, Palo Alto, CA

Beaver, F.W., 1986, The effects of fly ash and flue-gas desulfurization wastes on groundwater quality: University of North Dakota unpublished Doctoral Dissertation, Grand Forks, ND, 225p.

Bluemle, J.P., 1971, Geology of McLean County, North Dakota: North Dakota Geological Survey, Bulletin 60, Part 1, 65p.

Bolt, N., and Snel, A., 1986, Environmental aspects of fly ash application in the Netherlands: Kema Scientific and Technical Reports, Vol. 4, No. 11, pp. 125-140.

Cherry, J.A., 1972, Geochemical processes in shallow groundwater flow systems in five areas in southern Manitoba, Canada: Proceedings of the 24th International Geological Congress, Montreal, Section 11, pp. 208-221.

Creasey, C.L., and Dreiss, S.J., 1988, Porous cup samplers: cleaning procedures and potential sample bias from trace element contamination: Soil Science, Vol. 145, No. 2, pp. 93-101.

Cutter, G.A., 1982, Selenium in reducing waters: Science, Vol. 217, pp. 829-831.

Daly, D., Groenewold, G.H., and Manz, O.E., 1982, Hydrogeological and geotechnical procedures manual for the disposal of fly ash and FGD waste from low-rank coals in western strip mines: University of North Dakota Engineering Experiment Station Bulletin No. 83-04-MMRRI-81, 168p.

Dodd, D.J.R., Golomb, A., Chan, H.T., and Chartier, D., 1981, A comparative field and laboratory study of fly ash leaching characteristics: Hazardous Solid Waste Testing: First Conference, ASTM STP 760, American Society for Testing and Materials, pp. 164-185.

Driscoll, F,G., 1986, Ground Water and Wells: Johnson Division, UOP Inc., St. Paul, MN, 1089p.

Elrashidi, M.A., Adriano, D.C., Workman, S.M., and Lindsay, W.L., 1987, Chemical equilibria of selenium in soils: A theoretical development: Soil Science, Vol. 144, No. 2, pp. 141-152.

Fancher, H., 1990, Personal Communication: Soil Moisture Equiptment Corp., Santa Barbara, CA.

Ferguson, J.F., and Gavis, J., 1972, Review of the arsenic cycle in natural waters: Water Research, Vol. 6, pp. 1259-1274.

Fetter, C.W., 1988, Applied Hydrogeology: Merrill Publishing Company, Columbus, OH, 592p.

Freeze, R.A., 1969, Good Spirit Lake drainage basin, Saskatchewan: Progress Report: Inland Waters Branch Technical Bulletin 14.

Frost, R.R. and Griffin, R.A., 1977, Effect of pH on adsorption of arsenic and selenium from landfill leachate by clay minerals: Soil Science Society of America Proceedings, Vol. 41, pp. 53-57.

Garcez, I., and Tittlebaum, M.E., 1987, Leachability of lignite fly ash enhanced road base: Journal of Environmental Science and Health, Part A, Vol. 22, No. 7, pp. 607-625.

Garrels, R.M., and Christ, C.L., 1965, Solutions, Minerals, and Equilibria: Freeman, Cooper, and Company, San Francisco, CA, 450p.

Geering, H.R., Cary, E.E., Jones, H.P., and Allaway, W.H., 1967, Solubility and redox criteria for the possible forms of selenium in soils: Soil Science Society of America Proceedings, Vol. 32, pp. 35-40.

Groenewold, G.H., Koob, R.D., McCarthy, G., Rehm, B.W., and Peterson, W., 1983, Geological and geochemical controls on the chemical evolution of subsurface water in undisturbed and surface mined landscapes in western North Dakota: North Dakota Geological Survey Report of Investigation No. 79, 151p.

Groenewold, G.H., Rehm, B.W., and Cherry, J.A., 1981, Depositional setting and groundwater quality in coal-bearing strata and spoils in western North Dakota: in F.G. Ethridge and R.M. Flores (eds.), Recent and Ancient Nonmarine Depositional Environments: Models for exploration, SEpm Special Publication No. 31, pp. 157-167.

Hassett, D.J., 1990, Personal Communication: Energy and Environmental Research Center, Grand Forks, ND.

Hassett, D.J., and Groenewold, G.H., 1986, Attenuation capacity of western North Dakota overburden sediments: North Dakota Mining and Mineral Resources Research Institute, University of North Dakota, Grand Forks, ND, 105p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water, United States Geological Survey Water-Supply Paper 2254, 263p.

Hounslow, A.W., 1980, Ground-water geochemistry: arsenic in landfills: Groundwater, Vol. 18, No. 4, pp. 331-333.

Hvorslev, M.J., 1951, Time lag and soil permeability in ground-water observations: Bulletin. number 36, Waterways Experiment Station., Corps of Engineers, U.S. Army, Vicksburg, MS, pp. 1-50.

Jensen, R., 1972, Climate of North Dakota: North Dakota National Weather Service, North Dakota State University, Fargo, ND, 48p.

Kane, D.L., 1981, Groundwater recharge in cold regions: The Northern Engineer, Vol. 13, pp. 28-33.

Klausing, R.L., 1974, Ground-Water Resources of McLean County, North Dakota: North Dakota Geological Survey, Bulletin 60, Part 3, 73p.

Kosmatka, S.H., and Panarese, W.C., 1988, Design and control of concrete mixtures: Portland Cement Association, Skokie, IL, 205p.

Manz, O.E., McCarthy, G.J., Stevenson, R.J., Dockter, B.A., Hassett, D.J., and Thedchanamoorthy, A., 1989, Characterization and classification of North American lignite fly ashes for use in concrete: Proceedings of the Third International Conf. on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, V.M. Malhotra, Ed., American Concrete Institute, Detroit, MI, 17p.

Manz, O.E., and McCarthy, G.J., 1986, Effectiveness of western U.S. high-lime fly ash for use in concrete: Proceedings of the Second International Conf. on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, Vol. 1, pp. 347-365.

McCarthy, G.J., Beaver, F.W., Stevenson, R.J., Groenewold, G.H., and Hassett, D.J., 1987, The essential role of mineralogical characterization in utilization and disposal of coal conversion ashes: In Waste Management for the Energy Industries Proceedings, University of North Dakota, Grand Forks, ND, pp. 41-62.

Moran, S.R., Cherry, J.A., Ulmer, J.H., Peterson, W.M., Somerville, M.H., Schafer, J.K., Lechner, D.O., Triplett, C.L., Loken, G.R., and Fritz, P., 1976, An environmental assessment of a 250 MMSCFD dry ash lurgi coal gasification facility in Dunn County, North Dakota: University of North Dakota Engineering Experiment Station Bulletin 76-12-EES-01, v. V, pt. 1 of 3, 126p.

Moretti, C.J., 1990, Personal communication: Energy and Environmental Research Center, Grand Forks, ND.

Old Dominion University, 1986, Speciation of selenium and arsenic in natural waters and sediments: volume 1, Selenium Speciation; Unpublished Report, Electric Power Research Institute, Palo Alto, CA

Rehm, B.W., Groenewold, G.H., and Peterson, W., 1982, Mechanisms, distribution and frequency of groundwater recharge in an upland area of western North Dakota: North Dakota Geological Survey Report of Investigation No. 75, 72p.

Residuals Management Technology (RMT), INC., 1987, Field evaluation of instruments for the measurement of unsaturated hydraulic properties of fly ash: Electric Power Research Institute, Palo Alto, CA

Residuals Management Technology (RMT), Inc. 1985, Preliminary results on chemical changes in groundwater samples due to sampling devices: Unpublished Report, Electric Power Research Institute, Palo Alto, CA.

Ripple, C.D., Rubin, J., and Van Hylckama, T.E.A., 1972, Estimating steady-state evaporation rates from bare soils under conditions of high water table: U.S. Geological Survey Water-Supply Paper 2019-A, 39p.

Ronnie, 1987, Geohydrologic evaluation of a proposed coal-ash disposal site near Mandan, North Dakota: University of North Dakota Unpublished Masters Thesis, 206p.

Soil Moisture Equiptment Corp., 1988, Operating instructions for the pressure-vacuum soil water sampler: Soil Moisture Equipment Corp., Santa Barbara, CA, 6p.

Southern Company Services, 1989, Use of coal ash in highway construction: Georgia demonstration project: Unpublished Report, Electric Power Research Institute, Palo Alto, CA

Spencer, L.L., and Drake, L.D., 1987, Hydrogeology of an alkaline fly ash landfill in eastern Iowa: Ground Water, Vol. 25, No. 5, pp. 519-526.

Stewart, A., 1990, Personal Communication: Cooperative Power, Eden Prairie, MN.

Thornthwaite, C.W., 1948, An approach toward rational classification of climate: Geographical Review, Vol. 38, pp. 55-94.

USGS, 1961, Underwood Quadrangle, North Dakota: USGS 7.5 Minute Series (Topographic), Scale 1:24,000.

Willis, W.O., Parkinson, C.W., Carlson, C.W., and Haas, H.J., 1963, Water table changes and soil moisture loss under frozen conditions: Soil Science, Vol. 98 pp. 244-248.