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# US Army Corps of Engineers

## Toxic and Hazardous Materials Agency

FINAL

POLELINE ROAD DISPOSAL AREA  
REMEDIAL INVESTIGATION  
TECHNICAL PLAN

CONTRACT NO. DAAA15-90-D-0020  
TASK ORDER #0006

Prepared for:

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY  
ABERDEEN PROVING GROUND, MARYLAND 21010-5401

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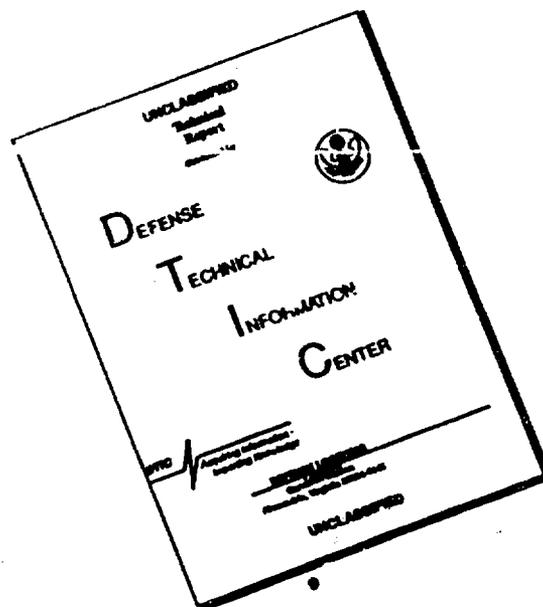


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**POLELINE ROAD DISPOSAL AREA  
REMEDIAL INVESTIGATION  
FORT RICHARDSON, ALASKA**

**TECHNICAL PLAN**



Prepared for:

**U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY  
Installation Restoration Division  
Aberdeen Proving Ground, MD 21010-5401**

Prepared by:

**ENVIRONMENTAL SCIENCE & ENGINEERING, INC.  
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**AUGUST 1991**

## TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
1.0 INTRODUCTION .....	1-1
1.1 <u>INSTALLATION HISTORY</u> .....	1-1
1.2 <u>BACKGROUND</u> .....	1-4
1.2.1 LOCATION AND SITE PHYSIOGRAPHY .....	1-12
1.2.2 REGIONAL AND LOCAL GEOLOGY .....	1-12
1.2.3 REGIONAL AND LOCAL HYDROGEOLOGY .....	1-14
1.2.4 NATURE AND EXTENT OF THE PROBLEM .....	1-17
1.3 <u>DEFINITION OF BOUNDARY CONDITIONS</u> .....	1-17
2.0 SAMPLING DESIGN PLAN .....	2-1
2.1 <u>SUPPORT FACILITIES</u> .....	2-1
2.2 <u>SOIL GAS SURVEY</u> .....	2-1
2.3 <u>TRENCHING AND SOIL SAMPLING INVESTIGATION</u> .....	2-3
2.3.1 TRENCHING AND SOIL SAMPLING TECHNIQUE .....	2-3
2.3.1.1 <u>Positive Results From The Field Screening Method</u> .....	2-7
2.3.1.2 <u>Negative Results From The Field Screening Method</u> .....	2-7
2.3.2 SAMPLE LOGGING AND HANDLING .....	2-8
2.3.3 CHAIN-OF-CUSTODY .....	2-8
2.3.4 SAMPLE SHIPMENT .....	2-8
2.4 <u>MONITORING WELL INSTALLATION</u> .....	2-8
2.4.1 CRITERIA FOR WELL LOCATIONS AND WELL COMPLETION .....	2-8
2.4.2 WELL DRILLING .....	2-10
2.4.3 WELL CONSTRUCTION .....	2-10
2.4.3.1 <u>Well Screens, Casings, and Fittings</u> .....	2-10
2.4.3.2 <u>Gravel/Sand Pack</u> .....	2-14
2.4.3.3 <u>Bentonite Seal</u> .....	2-14
2.4.3.4 <u>Grout Seal</u> .....	2-14
2.4.3.5 <u>Protective Casing</u> .....	2-14
2.4.4 WELL DEVELOPMENT .....	2-15
2.4.5 SURVEYING .....	2-15

TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
2.5	2-15
<u>GROUNDWATER SAMPLING</u> .....	2-15
2.5.1	2-15
GROUNDWATER SAMPLING PROTOCOL .....	2-15
2.5.1.1	2-16
<u>Documentation</u> .....	2-16
2.5.1.2	2-16
<u>Decontamination Procedures and</u> <u>Instrument Calibration</u> .....	2-16
2.5.1.3	2-17
<u>Well Inspection and Field Measurements</u> .....	2-17
2.5.1.4	2-17
<u>Well Purging</u> .....	2-17
2.5.1.5	2-18
<u>Sample Collection</u> .....	2-18
2.5.2	2-18
SAMPLE PACKAGING AND SHIPPING .....	2-18
2.5.3	2-19
CHAIN-OF-CUSTODY .....	2-19
2.6	2-19
<u>AQUIFER TESTING</u> .....	2-19
3.0	3-1
<u>PRELIMINARY RISK ASSESSMENT</u> .....	3-1
3.1	3-1
<u>PRELIMINARY ECOLOGICAL RISK AGREEMENT</u> .....	3-1
3.1.1	3-1
HABITAT CHARACTERIZATION .....	3-1
3.1.2	3-2
SELECTION OF CHEMICALS OF CONCERN .....	3-2
3.1.3	3-2
IDENTIFICATION OF INDICATOR SPECIES .....	3-2
3.1.4	3-2
TOXICITY ASSESSMENT .....	3-2
3.1.5	3-2
EXPOSURE ASSESSMENT .....	3-2
3.1.6	3-2
RISK CHARACTERIZATION .....	3-2
3.2	3-3
<u>PRELIMINARY HUMAN RISK ASSESSMENT</u> .....	3-3
3.2.1	3-3
SELECTION OF CHEMICALS OF CONCERN .....	3-3
3.2.2	3-3
EXPOSURE ASSESSMENT .....	3-3
3.2.3	3-4
TOXICITY ASSESSMENT .....	3-4
3.2.4	3-4
RISK CHARACTERIZATION .....	3-4
4.0	4-1
<u>REFERENCES</u> .....	4-1
APPENDIX A	FIELD DATA FORMS
APPENDIX B	FIELD TEST METHOD

## LIST OF TABLES

<u>TABLE</u>	<u>PAGE</u>
1-1	Results of Groundwater Sampling 1991 ..... 1-10
2-1	Chemical Analyses to be Performed at the Poleline Road Site, Fort Richardson, Alaska ..... 2-9
2-2	Chemical Analyses to be Performed on Approved Water, PRDA, Fort Richardson, Alaska ..... 2-11

## LIST OF FIGURES

<u>FIGURE</u>	<u>PAGE</u>
1-1	Area Location Map ..... 1-2
1-2	Site Location Map ..... 1-3
1-3	Areas of Conductivity Anomalies ..... 1-6
1-4	Poleline Road Total Magnetic Survey Fort Richardson, Alaska ..... 1-7
1-5	Areas of Apparent Site Excavation ..... 1-8
1-6	Site Map ..... 1-9
1-7	Potential Disposal Areas - Trench Locations ..... 1-13
1-8	Groundwater Contour Map 10/90 ..... 1-16
2-1	Proposed Trailer and Site Office Location ..... 2-2
2-2	Soil Gas Collector Locations ..... 2-4
2-3	Proposed Trenching Locations ..... 2-5
2-4	Unified Soil Classification System (USCS) ..... 2-6
2-5	Schematic of Monitoring Well Nest ..... 2-13

## LIST OF ACRONYMS

ARARS	Applicable or Relevant and Appropriate Requirements
COC	Chemicals of Concern
COE	U.S. Army Corps of Engineers
DOT	Department of Transportation
EM	Electromagnetic
EOC	emergency operations center
EOD	Explosive Ordnance Disposal
ESE	Environmental Science & Engineering, Inc.
ESI	Expanded Site Investigation
FRA	Fort Richardson Army Installation
GPR	ground-penetrating radar
H&S	Health and Safety
LOAEL	Lowest Observed Adverse Effects Levels
MSL	mean sea level
NOAEL	No Observed Adverse Effects Levels
OVA	organic vapor analyzer
PID	photoionization detector
PRDA	Poleline Road Disposal Area
QCP	Quality Control Plan
RfD	Reference Doses
RfC	reference concentrations
RI	Remedial Investigation
SEE	Small Enplacement Excavator
USARPAC	U.S. Army Pacific Command
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency
USCS	Unified Soil Classification System
VOCs	Volatile Organic Compounds

## **1.0 INTRODUCTION**

## 1.0 INTRODUCTION

The Poleline Road Disposal Area (PRDA) is located on Fort Richardson Army Installation (FRA), approximately five miles northeast of Anchorage, Alaska (Figure 1-1). PRDA is centered on a longitude of E 145,000 and a latitude of N 134,000. The site, as known at this time, encompasses a 300 foot by 500 foot area of wooded land on FRA approximately two miles southwest of the town of Eagle River and approximately one mile west of the Glen Highway (Figure 1-2). PRDA was identified by a former soldier who believes hazardous substances were buried there during his tour of duty at FRA in the 1950's. An U.S. Army Corps of Engineers map dated July 15, 1954, further confirmed the potential existence of this disposal area.

An Expanded Site Investigation conducted for the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) by Environmental Science & Engineering, Inc. (ESE) in 1990, confirmed the presence of Volatile Organic Compounds (VOCs) in soil and shallow groundwater at the PRDA. This Technical Plan presents the field investigation procedures to conduct a Remedial Investigation (RI) at the PRDA in 1991 as authorized by USATHAMA.

The general purpose of the RI is to conduct a comprehensive site evaluation to determine the location of contaminant sources and the extent of both groundwater and soil contamination. The investigation will also collect data required to determine whether the site conditions warrant remedial action or no further action. Specific objectives of the expanded site investigation are:

- Determine site and contamination boundaries using soil gas survey;
- Characterize the contamination occurring in, and the interrelationship between, the shallow and deep aquifers at the PRDA; and
- With trenching and soil sampling operations, characterize source areas identified in the ESI which have the potential of impacting media at the PRDA.

### 1.1 INSTALLATION HISTORY

Fort Richardson encompasses approximately 64,000 acres of land within the municipality of Anchorage in south-central Alaska. Fort Richardson is bounded on the west by the city of Anchorage and Elmendorf Air Force Base, on the north by Eagle Bay and the Knik Arm of Cook Inlet, and on the south and southeast by Chugach State Park. The town of Eagle River is located due east of the northeastern section of the installation.

Fort Richardson was built during 1940-1941 and named after Brigadier General Wilds P. Richardson, a pioneer explorer who served in the territory between 1897 and 1917. As head of the War Department's Alaska Road Commission from 1905 through 1917, Richardson was responsible for much of the surveying and building of early

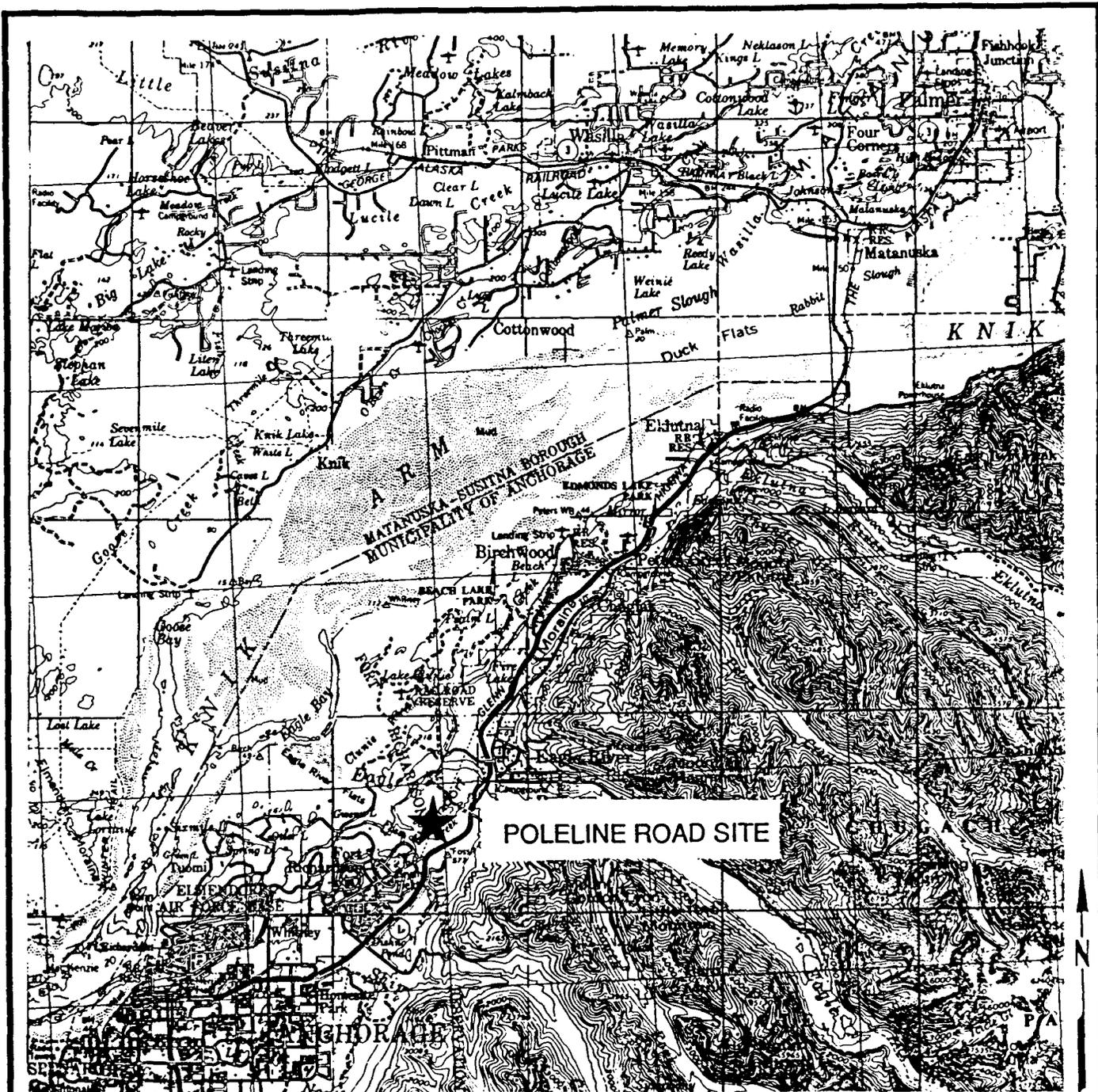
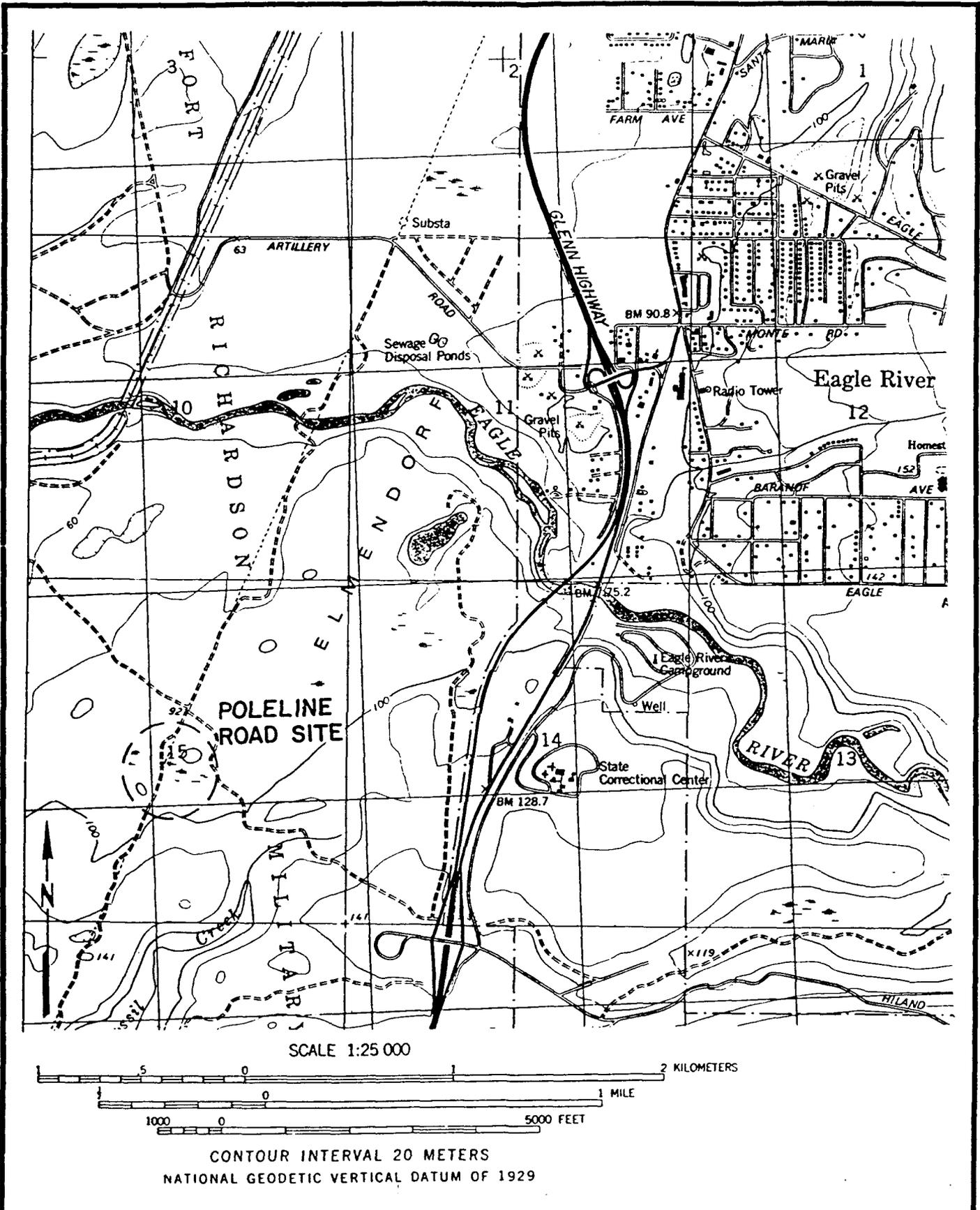


Figure 1-1  
AREA LOCATION MAP

SOURCE: U.S.G.S., 1985

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Materials Agency

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**Figure 1-2**  
**SITE LOCATION MAP**

SOURCE: U.S.G.S., 1985

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Materials Agency**

**Aberdeen Proving Ground, Maryland**

transportation roads and rails that facilitated the state's settlement and growth.

Fort Richardson was established as the key defense post in Alaska and headquarters of the United States Army, Alaska. Fort Richardson's primary mission was defending Alaska against the attack of foreign invaders. During World War II, Fort Richardson was used as a staging area and supply point to enable the United States to launch a successful counter-attack against the Japanese in the Aleutian Islands. Although originally built on the site of what is now the post's sister installation of Elmendorf Air Force Base, Fort Richardson was moved to its present location in 1950.

Most of Fort Richardson's facilities were built during the early 1950's. During the late 1940's and early 1950's, military landholdings in the Anchorage area were extensive, stretching all the way to Turnagain Arm. In 1959, three Nike Hercules missile sites were built at permanent facilities off post. One of these missile locations was at Site Summit, on top of the mountains overlooking the post. That missile unit, the 1st Battalion, 43rd Air Defense Artillery, was inactivated in July 1979. Today, the command at Fort Richardson continues training to maintain its readiness and to provide combat-ready forces for the ground defence of Alaska and the initial defence of the Aleutian Islands. Fort Richardson currently operates under the U.S. Army Pacific Command (USARPAC) and is home for the three major installations located in Alaska (Ft. Richardson, Ft. Greeley, Ft. Wainwright), as well as home of the 6th Infantry Division (light).

## 1.2 BACKGROUND

Prior to 1990 little information existed about the PRDA other than the defined location on the U.S. Army Corps of Engineers (COE) map dated 1954 and interviews conducted by Army personnel with two ex-soldiers. One ex-soldier led the Army to the site in February 1990. He stated that chemicals were buried there in the 1950's. No known documentation exists detailing what types of chemicals were buried, however, a former Army chemical officer, stationed at Fort Richardson from 1951 to 1953, thought most of the compounds buried were solvents and decontaminants (chemicals used to neutralize and clean up hazardous chemicals). In addition, the officer reported that the 266th Chemical Detachment disposed of FS smoke and Japanese cluster bombs by wrapping them in detonation cord, placing the bombs in a trench (along the eastern edge of the site), and detonating them. FS smoke is 41 percent chlorosulfonic acid, 54 percent sulfur trioxide, and 5 percent sulfuric acid, which becomes smoke when exposed to moisture. The cluster bombs described by this officer were identified by Explosive Ordinance Disposal (EOD) as Japanese Army type-2 one-third kg bombs in a 76-bomb container. The disposal of these bombs consisted of delayed action fuses that would detonate the bombs. Apparently, many duds were scattered throughout the site and never retrieved. Type-2 bombs have arming vanes that need to rotate a certain number of times to arm the bomb. Not all of the bomblets would have been subjected to enough velocity and distance to become armed, which could account for a high dud rate.

In April 1990, ESE, Inc. was authorized by USATHAMA to conduct an Expanded Site Investigation (ESI) of the PRDA. The ESI was conducted between June and October 1990, and the ESI Final Report submitted in February 1991. A surface geophysical survey was conducted, five groundwater monitoring wells (4 in a shallow aquifer and 1 in a deeper aquifer) were drilled, installed, and sampled, and 10 soil shallow borings were drilled to a depth of 8 feet and sampled.

Three geophysical investigation methods Electromagnetic (EM) conductivity, magnetometer and ground-penetrating radar (GPR) were utilized at PRDA in 1990.

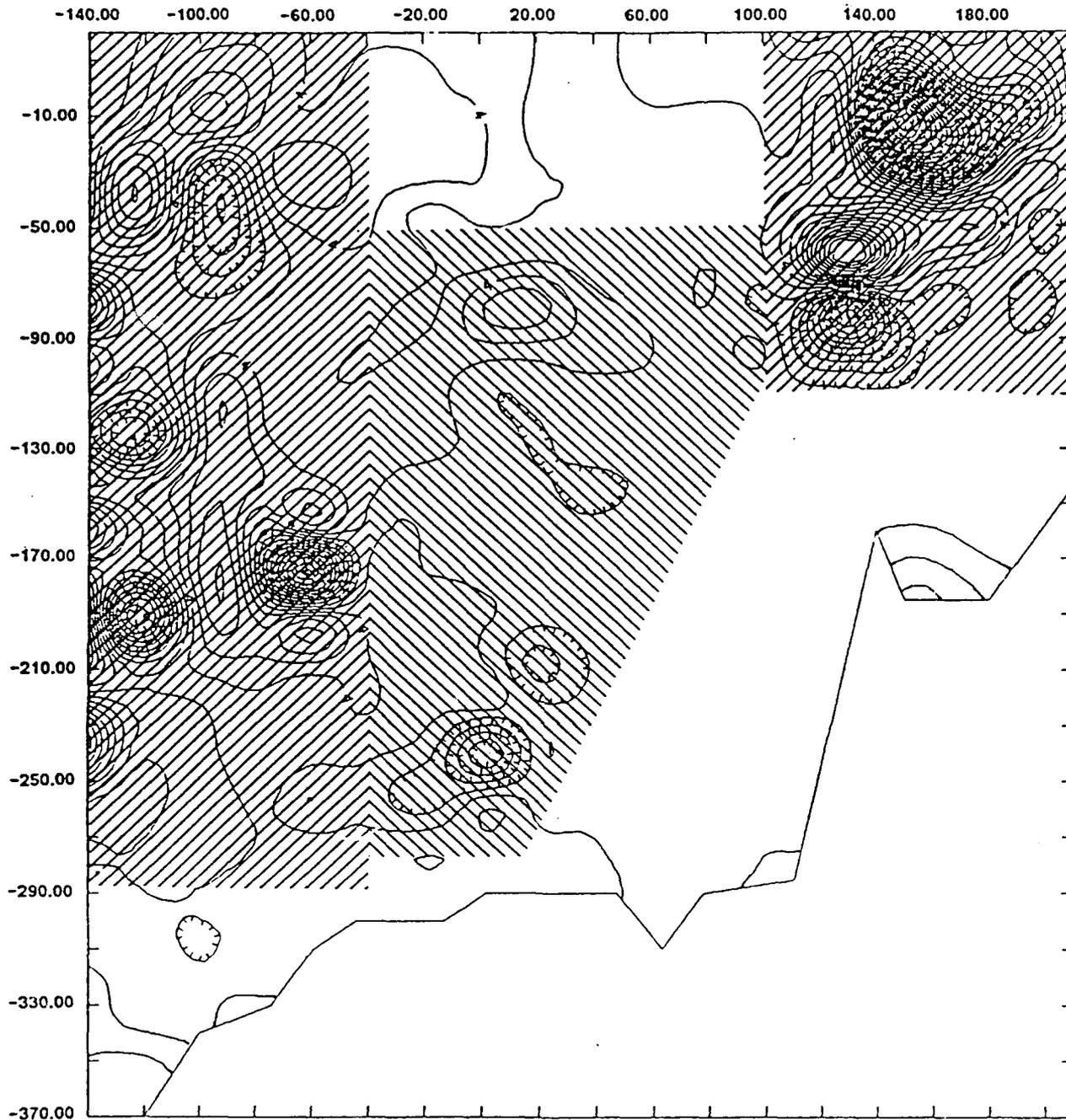
The EM survey indicated that two strong conductivity anomalies were present on the site. The most predominate anomaly exists along the western edge of the site along the crest of a hill. This anomalous area coincides with surface disruptions that are presumed to be related to a disposal trench. A second anomaly is located in the northeast corner of the site. This area also coincides with a surface disruption that may be the trench where the Japanese cluster bombs were disposed. Scattered conductivity anomalies were also observed in the central and south-central portions of the site. These scattered anomalies do not fit any identifiable pattern (Figure 1-3).

The magnetometer survey indicated that metallic objects may have been buried in the two locations identified in the EM survey (Figure 1-4).

The GPR records indicate that the western anomaly has subsurface reflections consistent with an excavation. GPR transects were not conducted over the anomaly in the northeastern edge of the site due to vegetation. GPR reflections recorded over the central area of the site may also represent excavations, however, no strong conductivity or magnetic anomalies are associated with these reflections (Figure 1-5).

The five groundwater monitoring wells installed at PRDA in 1990 were sampled twice (Figure 1-6). Table 1-1 lists the results of these samplings. The shallow groundwater beneath PRDA contains VOCs. Well MW-4, located downgradient from the site, contained the most elevated levels of VOCs. Well MW-5, located upgradient of the site, also contained VOCs. Well MW-5's concentrations were, however, much less than the concentrations present in MW-4. Well MW-3, located on the eastern side of the site, also contained VOC compounds. The lower concentrations observed at well MW-3 are consistent with an expected lower concentration at this site since it lies lateral to the groundwater gradient direction and lateral to the suspected disposal trench. Well MW-2, located near the disposal trench in the northeast corner of the site did not contain any compound detections. Well MW-1, the only monitoring in the bedrock aquifer, contained trace concentrations of VOCs. Apparently interconnection between the shallow and bedrock aquifers exists at the PRDA site.

At the 1991 PRDA kick-off meeting on July 10, surface disruptions consistent with collapsing drums were observed near the toe of the hill on the western edge of the site. This area is coincident with the main suspected



**LEGEND**

-  AREA OF SIGNIFICANT CONDUCTIVITY ANOMALIES
-  AREA OF MODERATE CONDUCTIVITY ANOMALIES

SCALE 1:40

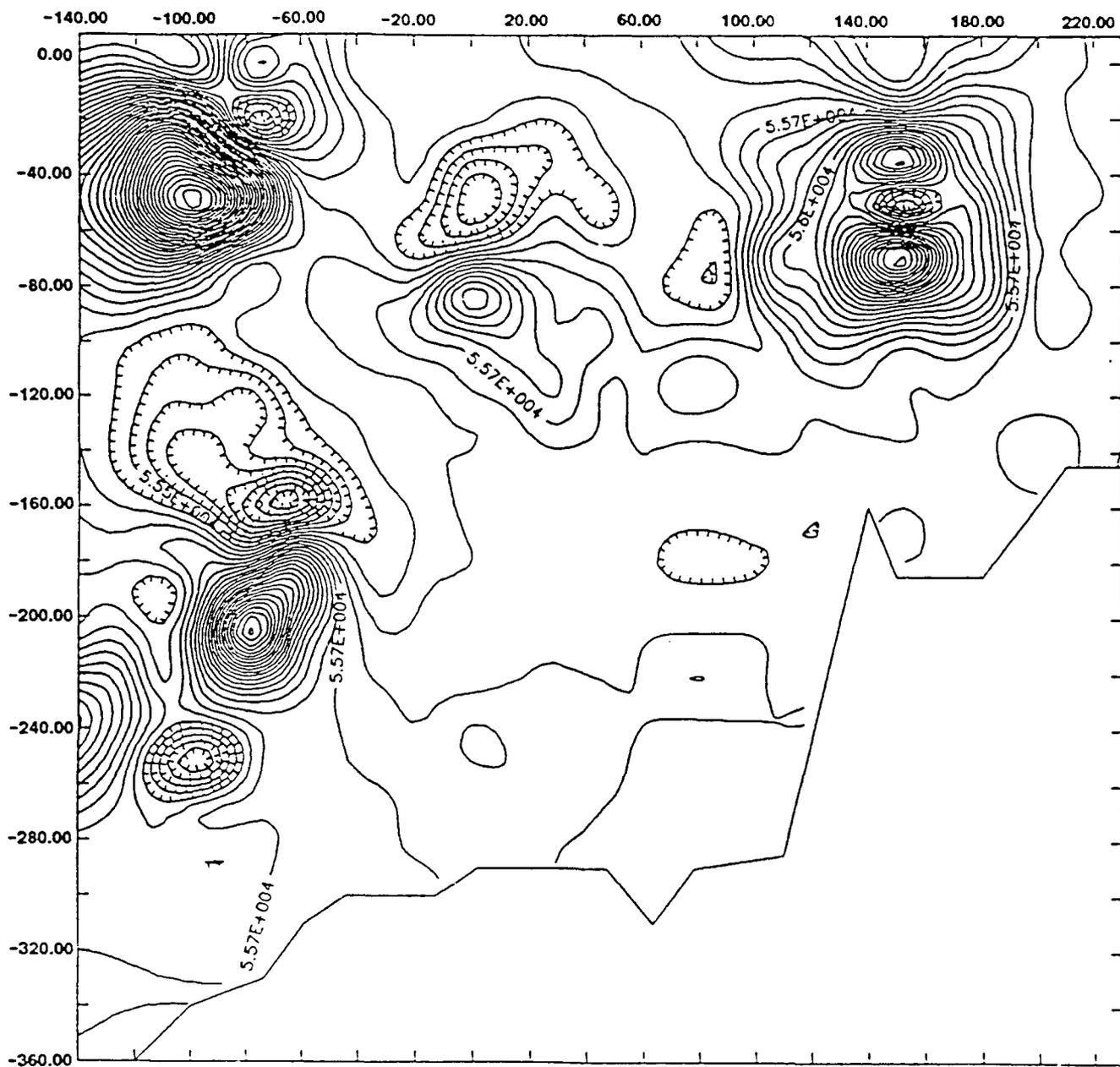


CONTOUR INTERVAL = 1 MMOH/METER MAGNETIC

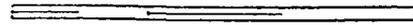
Figure 1-3  
 AREAS OF CONDUCTIVITY ANOMALIES  
 FT. RICHARDSON, ALASKA  
 SOURCE: ESE, 1991

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SCALE 1:40



CONTOUR INTERVAL = 100 GAMMAS

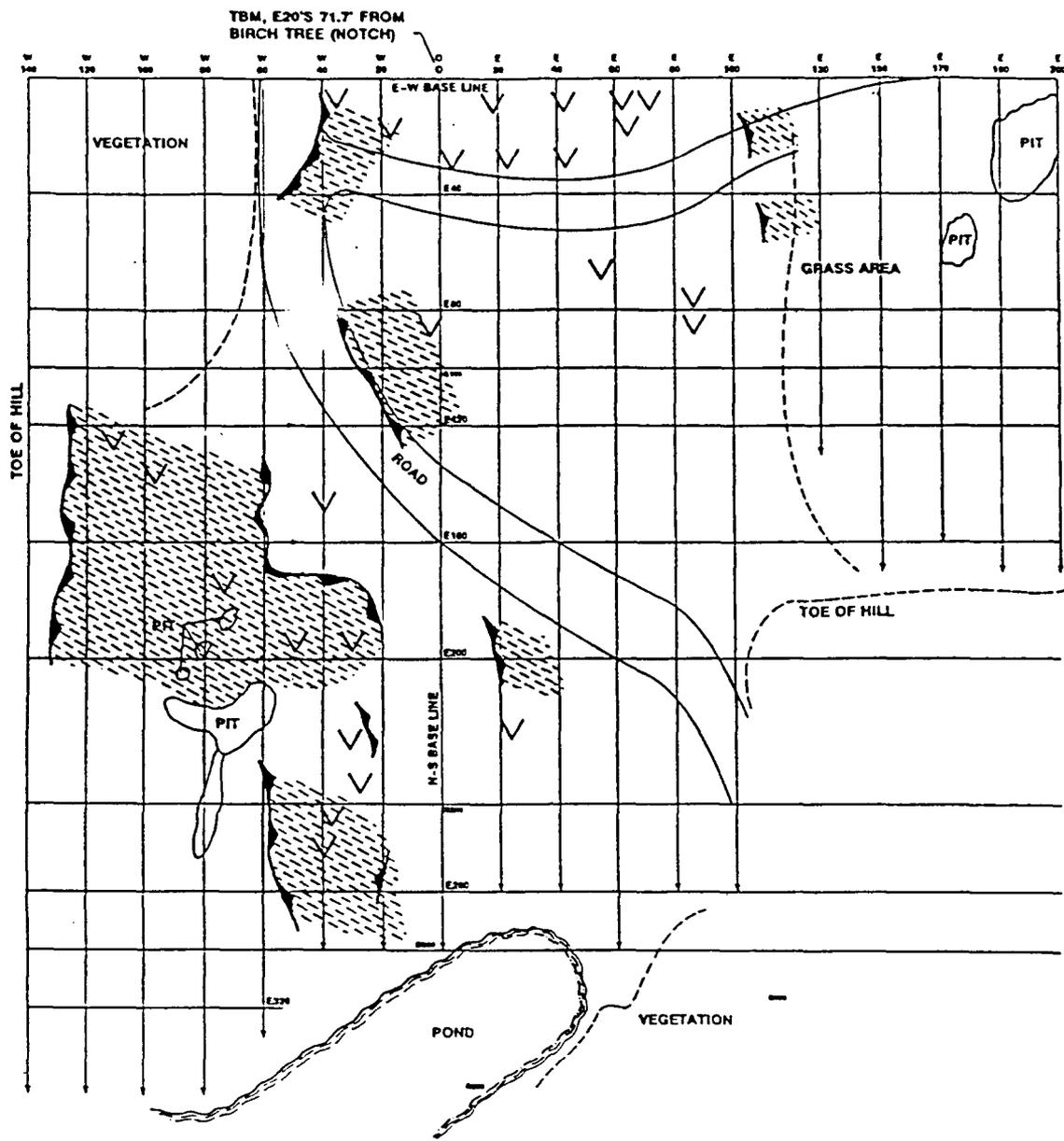


MAGNETIC

Figure 1-4  
 POELINE ROAD TOTAL MAGNETIC SURVEY  
 FT. RICHARDSON, ALASKA  
 SOURCE: ESE, 1991

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**LEGEND**

-  APPARENT EXCAVATIONS
-  APPARENT LIMIT OF EXCAVATIONS FROM GPR SURVEY
-  STRONG GPR ANOMALY



MAGNETIC

Figure 1-5  
 AREAS OF APPARENT SITE EXCAVATION  
 FT. RICHARDSON, ALASKA  
 SOURCE: ESE, 1991

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Table 1-1. Summary of Analysis Groundwater, PRDA (Concentrations  $\mu\text{g/L}$  [ppb]) (Page 1 of 2)

Site	Analyte	Sept	Oct
PRDA-MW-1	Carbon tetrachloride	4.3	1.9
	1,1,2,2-Tetrachloroethane	ND	5.6
	Arsenic	27.4	8.85
	Beryllium	20.2	ND
	Chromium	235	31.6
	Copper	282	30.1
	Lead	79.9	18
	Mercury	0.5	ND
	Nickel	239	ND
	Zinc	646	98.2
PRDA-MW-2	Arsenic	30.7	11.4
	Beryllium	6.5	ND
	Chromium	46.2	22.5
	Copper	79.7	28
	Lead	26.7	7.0
	Mercury	0.2	0.2
	Nickel	94.7	48.1
	Zinc	368	62.7
PRDA-MW-3	1,2-Dichloroethane	6.1	ND
	1,1,2,2-Tetrachloroethane	48.0	49.0
	Trichloroethene	28.1	36.9
	Arsenic	7.25	ND
	Chromium	15.5	ND
	Copper	17.4	ND
	Lead	11.4	1.8
	Zinc	52.9	ND
PRDA-MW-4	Benzene	8.98	< 250
	Carbon tetrachloride	49.0	< 290
	Chloroform	28.0	< 250
	1,1-Dichloroethene	5.02	< 250
	1,2-Dichloroethane	1,600	< 250
	1,1,2,2-Tetrachloroethane	43,000	36,000
	1,1,2-Trichloroethane	210	< 600
	Trichloroethene	9,990	9,790
	Hexachloroethane	6.6	9.3
	Lead	3.9	ND
	Mercury	ND	0.2
	Zinc	46.3	49.9

Table 1-1. Summary of Analysis Groundwater, PRDA (Concentrations  $\mu\text{g/L}$  [ppb]) (Page 2 of 2)

Site	Analyte	Sept	Oct
<b>PRDA-MW-4 Duplicate</b>	Benzene	11.6	< 250
	Carbon tetrachloride	53.0	< 290
	Chloroform	28.0	< 250
	1,2-Dichloroethene	1,400	< 250
	1,1,2,2-Tetrachloroethane	47,000	44,000
	1,1,2-Trichloroethane	230	< 600
	Trichloroethene	9,220	11,200
	Hexachloroethane	6.5	ND
	Arsenic	ND	3.94
	Copper	ND	9.71
	Lead	8.5	3.1
	Mercury	ND	0.5
	Zinc	41.5	65.8
<b>PRDA-MW-5</b>	1,2-Dichloroethene	190	< 100
	1,1,2,2-Tetrachloroethane	7,500	17,000
	1,1,2-Trichloroethane	35	< 600
	Trichloroethene	3,390	5,870
	RDX	2.84	ND
	Arsenic	50.9	30.6
	Chromium	30.1	8.23
	Copper	44.6	16.4
	Lead	11.2	6.6
	Nickel	68.2	ND
	Zinc	91.4	33.9
<b>Equipment Blank</b>	Hexachloroethane	ND	9.9
	Arsenic	4.80	
	Copper	6.90	
	Lead	ND	7.2
<b>Trip Blank</b>		ND	ND

disposal pit and lends support to the hypothesis that drummed materials have been disposed at this location.

Along the northeastern side of PRDA is a depression which coincides with a geophysical anomaly suggestive of buried metallic objects. This depression and the surface disruptions observed along the western edge of PRDA will be further investigated by trenching as described in Section 3.3.

The results of the 1990 ESI indicate the presence of VOCs in the subsurface beneath the site. In April 1991, USATHAMA authorized ESE to conduct a RI to further define the nature and extent of contamination at PRDA.

#### 1.2.1 LOCATION AND SITE PHYSIOGRAPHY

PRDA is located on Fort Richardson approximately 1.1 miles southwest of the Eagle River and 0.80 miles northeast of the Anchorage municipal landfill, along a dirt road extending from the landfill to Poleline Road (Figure 1-2). The site itself is bisected by this dirt road. One area of potential disposal is located southwest of the road and north of the marsh (Figure 1-7). This was the first area identified as a potential disposal site for chemicals. Although this area contains a significant amount of vegetation, there are portions that have no vegetation or obviously stressed vegetation. There are also discernable areas where pits were dug and filled in. A potential borrow area is also present about 50 feet north of the marsh.

Another area (Figure 1-7) located northeast of the road is related to the bomb disposal activities described by the ex-soldier stationed at Fort Richardson in the mid to late 1940's. This area has an extensive vegetative cover and is low lying and swampy in areas. There are areas of noticeable subsidence corresponding to the described areas of the pits that were dug for bomb disposal. These pits are located in the northeast corner of this portion of the PRDA.

The site is a low lying, relatively flat wooded area with evidence of disturbance characterized by juvenile vegetation growth. There is a hill with about 80 feet of relief due north-northwest of the site and another hill south-southeast with similar relief. The remaining area surrounding the site is of low relief and boggy.

#### 1.2.2 REGIONAL AND LOCAL GEOLOGY

The PRDA is in the Susitna Lowland physiographic division of south-central Alaska (Reger and Updike, 1989). Most of the lowland is below 500 feet elevation, although isolated uplands such as Mt. Susitna reach 4,396 feet above mean sea level (MSL). Local relief generally ranges from 50 to 250 ft. The region was glaciated repeatedly in Quaternary time and remains glaciated today (Reger and Updike, 1989). The surficial deposits of this area are Quaternary age alluvium consisting of fluviially reworked glacial sediments and glacial tills from a few feet to thousands of feet in thickness. Underlying the glacial deposits are Tertiary age clastic sedimentary strata, a mixture of conglomerates, sandstones, siltstones, claystones, and coal. These sediments range in

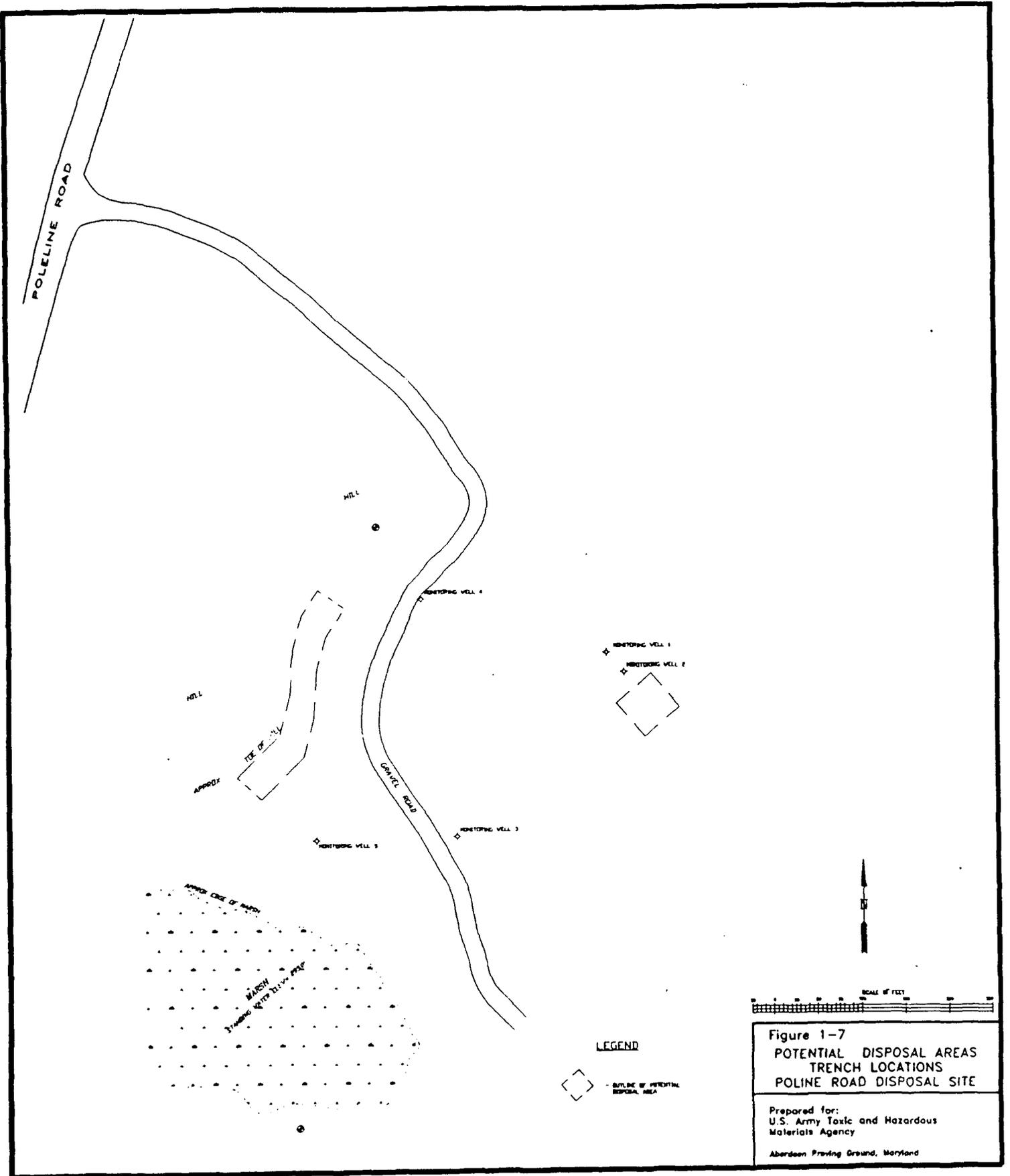


Figure 1-7  
 POTENTIAL DISPOSAL AREAS  
 TRENCH LOCATIONS  
 POLINE ROAD DISPOSAL SITE

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thickness from 300 to 11,000 ft (Evans *et al.*, 1972).

The sediments encountered during the ESI when drilling the shallow monitoring wells confirm the presence of glacial deposits at the site. They consist of unstratified to poorly stratified clays, silts, sands, gravels, and boulders. These sediments range widely in size, shape, and distribution, and were deposited chiefly by direct action of glacial ice and/or meltwater. The deposits are likely part of the Elmendorf Moraine deposits and were laid down during the latest glaciation phase of the Naptowne Glaciation event (Reger and Updike, 1989). The age of these deposits is 11,690 to 13,690 years (Schmoll *et al.*, 1972). Identification of the fine details of Elmendorf Moraine stratigraphy during groundwater monitoring well drilling is difficult due to the air-rotary drilling method necessary to drill in this material.

The deep monitoring well installed during the ESI encountered bedrock at 123 feet below ground surface. The bedrock consisted of black hard claystone with grey interbeds. This bedrock is likely part of the Tertiary age Kenai group (Evans *et al.*, 1972).

### 1.2.3. REGIONAL AND LOCAL HYDROGEOLOGY

Unconsolidated materials in the Anchorage area are of glacial, lacustrine, fluvial, or glaciofluvial origin. These sediments consist of glacial tills, alluvial fan deposits, lacustrine clays and silts, and valley alluvial deposits which are very complexly interlayered. The hydraulic properties of these sediments vary greatly. The extent and communicative properties of the unconsolidated materials are locally oriented and are difficult to generalize on a regional basis. The ability of these materials to produce water is dependent on the percent of sands and gravels within the deposits and the lateral extent of these sands and gravels. There are no defined continuous water table aquifers in this area. Groundwater in the alluvial deposits may occur in many different zones throughout the strata as zones of perched occurrence, confined zones, and unconfined zones.

The results of the 1990 PRDA ESI indicate that a shallow groundwater aquifer exists in the glacial till at PRDA and extends from approximately 18 to 60 feet below ground surface. It is underlain by a water free zone of fine grained silts and clays that extends from 60 to approximately 120 feet deep where bedrock and another water zone is encountered. The saturated zone of the glacial till (shallow aquifer) occurs under water table conditions, and the underlying fine grained sediments below appear to be acting as a semiconfining layer between the shallow alluvium and the underlying bedrock. The deeper saturated zone (bedrock) also appears to be under water table conditions. The thickness of the deeper water zone is unknown.

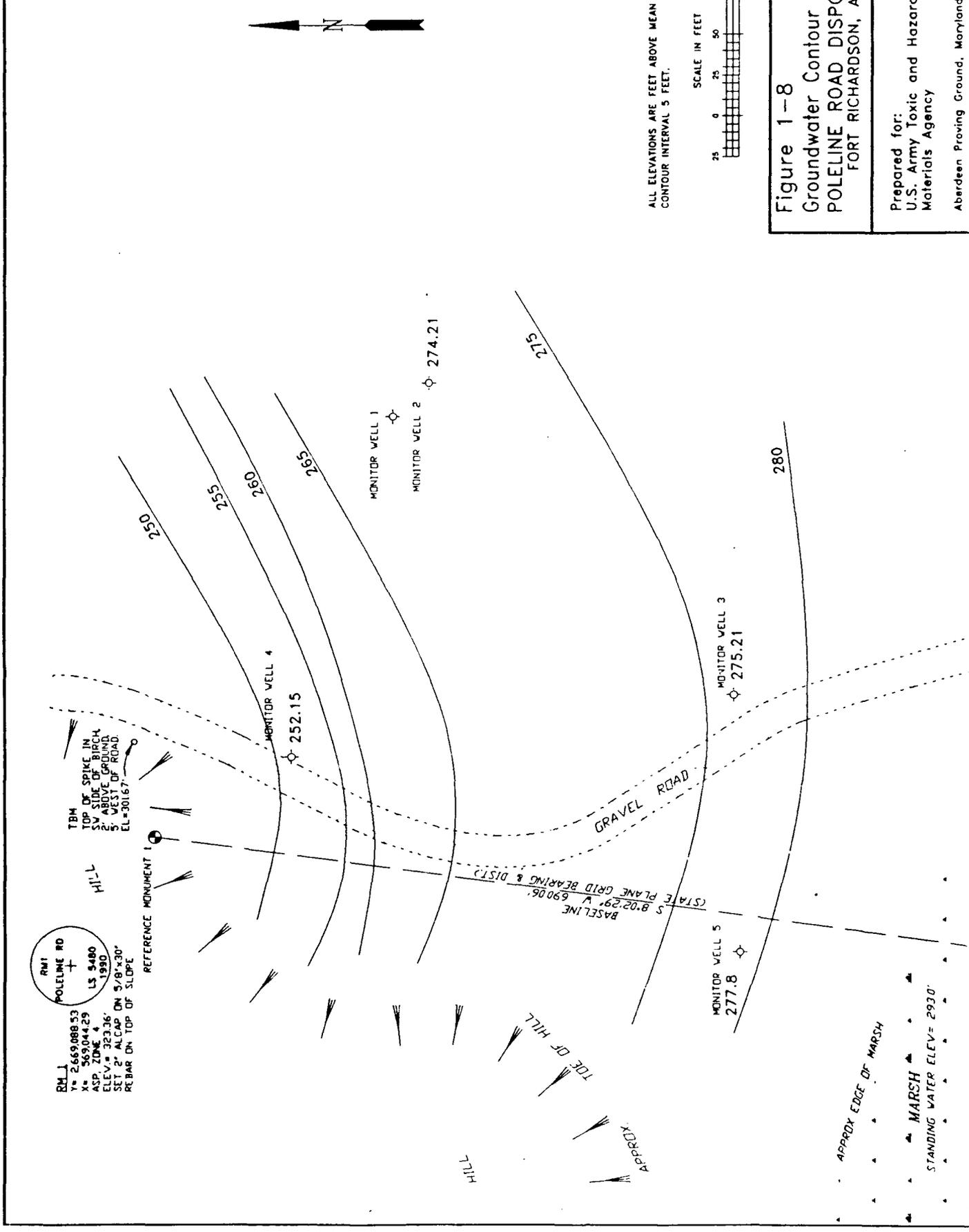
The alluvium and glacial deposits forming the surficial sediments of PRDA and the surrounding area comprise an unconfined aquifer system. Based on the monitoring well borings drilled for the ESI, the surficial deposits

consist of poorly sorted clays, silts, gravels, cobbles, and boulders. Shallow groundwater was encountered in these wells 18-32 feet below ground surface. Water levels in this aquifer range from elevation 252 ft to 277 ft above MSL. Shallow groundwater flow is in a northerly direction, with perhaps a component of flow in a northwesterly direction (Figure 1-8)

RM 1  
 POLELINE RD  
 Y= 2669.08853  
 X= 5650.4429  
 ASP. ZONE 4  
 ELEV. = 323.36'  
 SET 2" ALCAP ON 3/8"x30"  
 REBAR ON TOP OF SLOPE

TBM  
 TOP OF SPIKE IN  
 SIDE OF BRICK  
 3' WEST OF ROAD  
 EL=301.67'

REFERENCE MONUMENT 1  
 HI-L



ALL ELEVATIONS ARE FEET ABOVE MEAN SEA LEVEL.  
 CONTOUR INTERVAL 5 FEET.

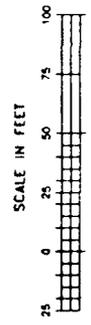


Figure 1-8  
 Groundwater Contour Map 10/90  
 POLELINE ROAD DISPOSAL SITE  
 FORT RICHARDSON, ALASKA

Prepared for:  
 U.S. Army Toxic and Hazardous  
 Materials Agency  
 Aberdeen Proving Ground, Maryland

The upper unconfined aquifer at the site is underlain by a bedrock aquifer consisting of claystone with siltstone interbeds. At PRDA, the unconsolidated surficial materials tend to be very fine grained clays and silts in the 60 feet immediately overlying the bedrock. These fine grained materials were not saturated in the deep well and may act as a confining zone. Groundwater was encountered in the deep zone at 121 feet below ground surface, at an elevation of 171 ft above MSL. No groundwater flow directions can be determined for this deep zone, since only one deep well was installed. There are obvious fluctuations in the water levels in the deep well which may be attributed to tidal fluctuations in Cook Inlet.

#### 1.2.4 NATURE AND EXTENT OF THE PROBLEM

Soil boring data collected during the ESI indicate 1,2-dichloroethene, tetrachloroethane, tetrachlorethane, and trichloroethylene were present in the 8-foot interval from which the samples were collected. Data from the five groundwater monitoring wells indicated that carbon tetrachloride, 1,1,1,2-tetrachloroethane, 1,2-dichloroethane, trichloroethylene, 1,1-dichloroethene, 1,1,2-trichloroethane, benzene, and hexachloroethane are present in water quality samples of groundwater in both the shallow and deep groundwater zones. This indicates a release of chemicals has occurred at PRDA that may pose a potential threat to the environment based upon the existence of exposure pathways (ESE, 1991). The nature and extent of this contamination in the soils and groundwater will be better defined during the RI.

#### 1.3 DEFINITION OF BOUNDARY CONDITIONS

Based on the information available at the time this plan was prepared, the site for the purpose of this investigation is delineated as 300 feet by 500 feet. A buffer zone 2400 feet in radius originally designated at the site has been dropped due to the absence of surity compounds detected during the 1990 ESI at PRDA. Information obtained during this investigation may require amending these boundaries.

## **2.0 SAMPLING DESIGN PLAN**

## 2.0 SAMPLING DESIGN PLAN

The 1991 geotechnical program for the PRDA will provide high quality data to further expand the initial database developed in 1990 for the site. The program will conduct the necessary activities to complete this data to meet the objectives defined in Section 1.0. The geotechnical program is designed to be dynamic, and may be modified in response to actual site conditions encountered. This program is divided into four categories; soil gas survey, trenching and soil sampling program, monitoring well installation and groundwater sampling, and aquifer testing. Each of these programs is described in detail below.

### 2.1 SUPPORT FACILITIES

After the soil gas survey and prior to commencing field activities (trenching and soil sampling investigation and monitoring well installation), the following onsite facilities will be set-up and/or identified:

- Exclusion/Contamination Reduction/Clean Zones as defined in the APSP, decontamination facilities; and
- Onsite office/sample and equipment storage facility.

Decontamination facilities will be located onsite within the area designated as the contamination reduction zone. This area will contain all emergency equipment and decontamination supplies. Decontamination of large equipment, such as drill rigs, will be performed on a decontamination pad constructed onsite. The decontamination pad will be used to avoid creating muddy conditions during equipment decontamination operations.

Onsite offices will consist of a mobile trailer which will have a designated office area and a sample preparation and storage area. The proposed location for the trailer office will be near the intersection of Poleline Road and the gravel spur road which bisects the site (Figure 2-1). Sample preparation and storage areas will include an area for storage of samples in a chilled environment while awaiting shipment and an area to process samples for shipment. A thorough description of support facility activities, including site personnel decontamination procedures and the definition of the site zones, are found in the APSP.

### 2.2 SOIL GAS SURVEY

A soil gas survey was conducted at PRDA using the Petrex™ soil gas technique to determine subsurface contaminant distribution(s). A Petrex™ soil gas collector consists of an activated charcoal coated ferromagnetic wire enclosed in a capped glass tube filled with an inert atmosphere. The collector tubes were uncapped, placed in small holes about 2 to 3 inches in diameter and approximately 1 foot deep, and allowed to equilibrate with soil gases for a period of 1 week (7/15/91 to 7/22/91). Time test collectors, periodically removed and analyzed, indicated that 1 week exposure was adequate to characterize soil gas constituents at the site. The tubes were

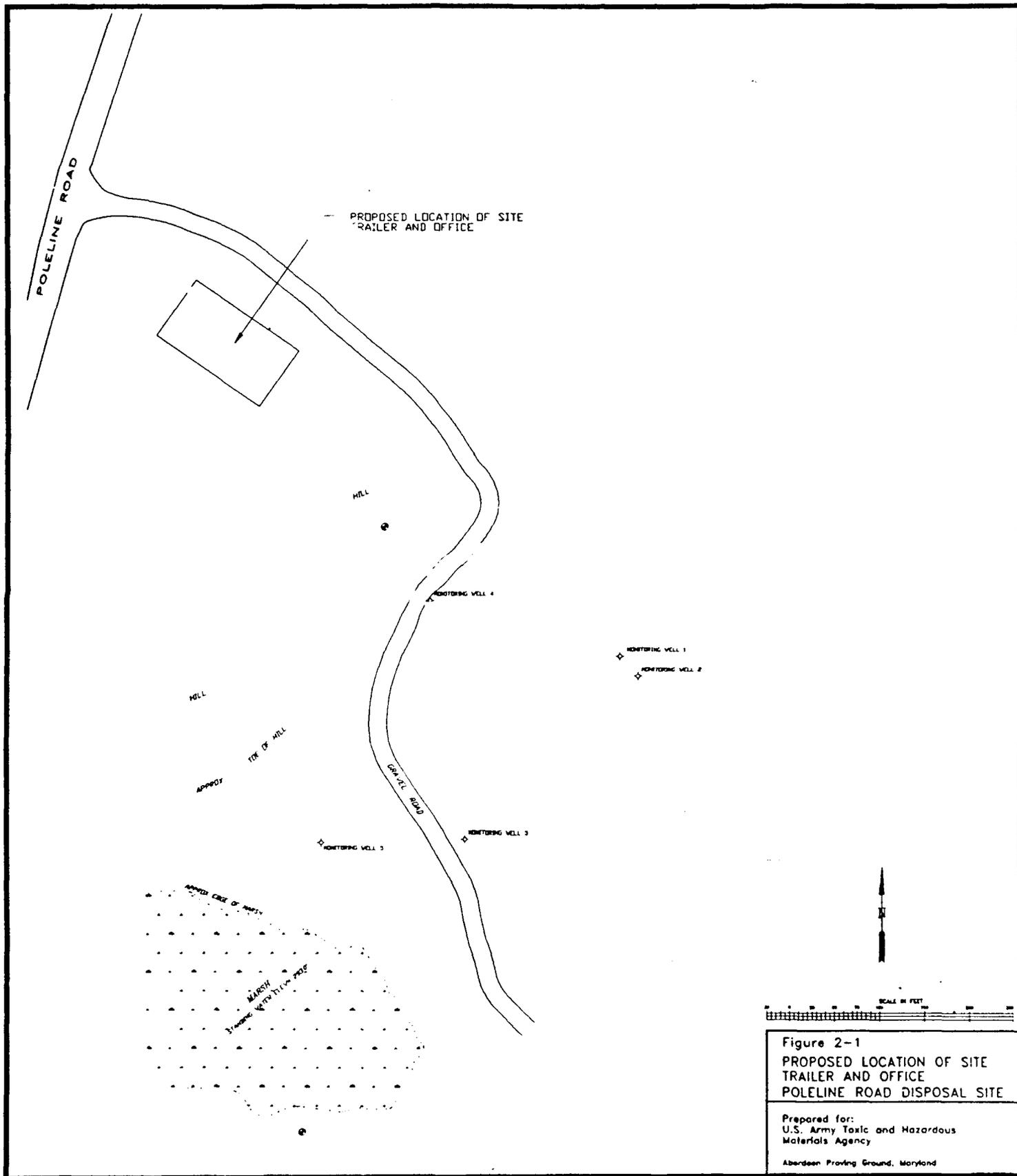


Figure 2-1  
 PROPOSED LOCATION OF SITE  
 TRAILER AND OFFICE  
 POLELINE ROAD DISPOSAL SITE

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retrieved, capped, and sent to Petrex of Lakewood, Colorado, for Curie point desorption mass spectrometry analysis. This analysis identifies the relative ion counts of volatile and semivolatile compounds.

The soil gas survey used soil gas sampling locations placed on a grid with variable spacing (50 to 100 ft) to provide required site coverage to help determine placement of additional groundwater monitoring wells and to delineate the downgradient extent of groundwater contamination northwest of the site toward Poleline Road. Figure 2-2 shows the locations of these collectors.

Data collected by the Petrex™ soil gas method will be displayed in the form of isopleth contour maps based upon the ion count flux recorded for each compound or mixture of compounds identified at each sample location. Although a relationship between high and low ion flux counts and high and low compound concentrations in groundwater and soils does exist, the actual concentration of a compound in the subsurface cannot be judged solely by ion flux counts. The isopleth contour maps of ion flux counts, therefore, should not be confused with actual soil gas concentration but should be considered only as an indication of relative compound concentration.

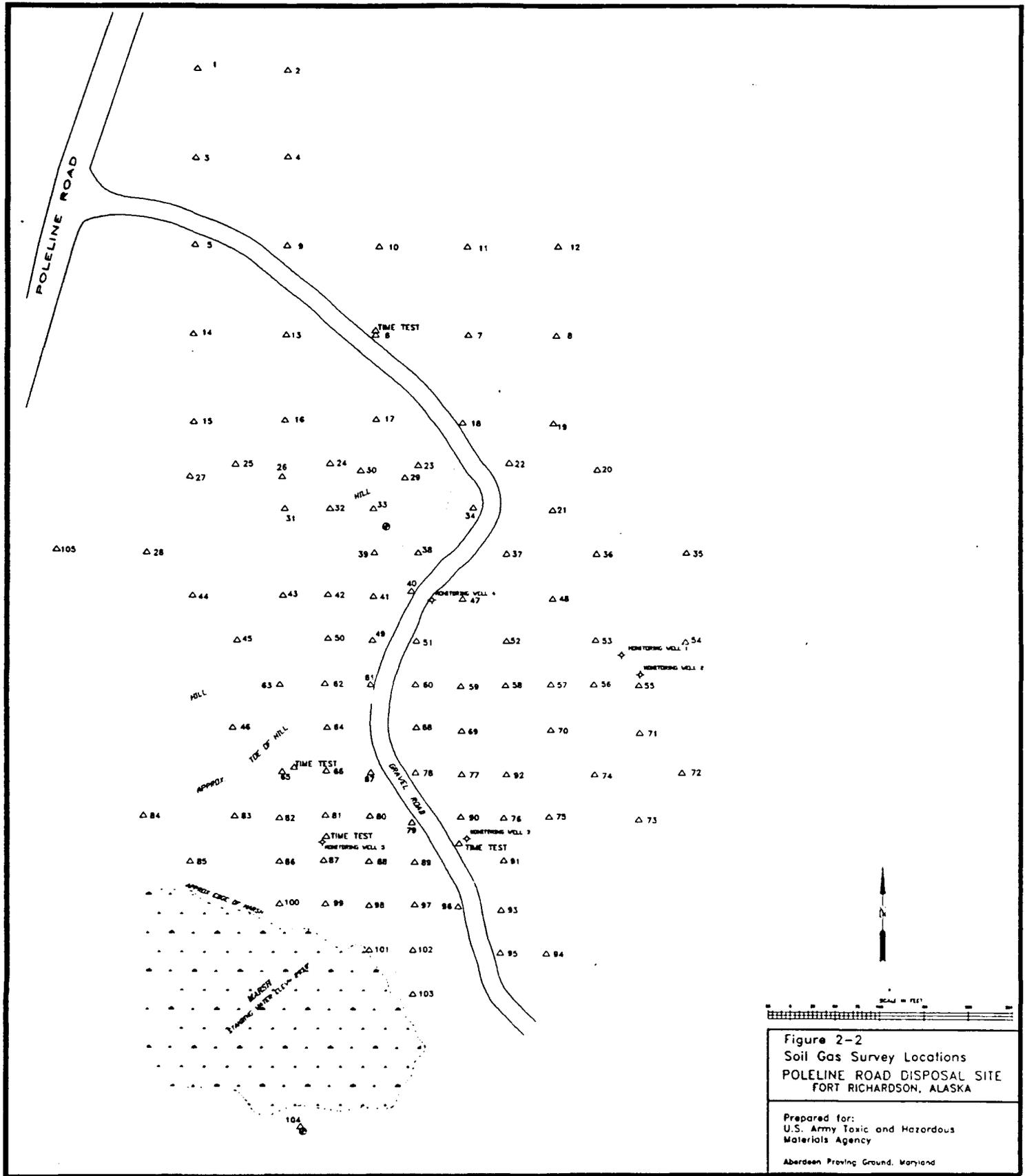
### 2.3 TRENCHING AND SOIL SAMPLING INVESTIGATION

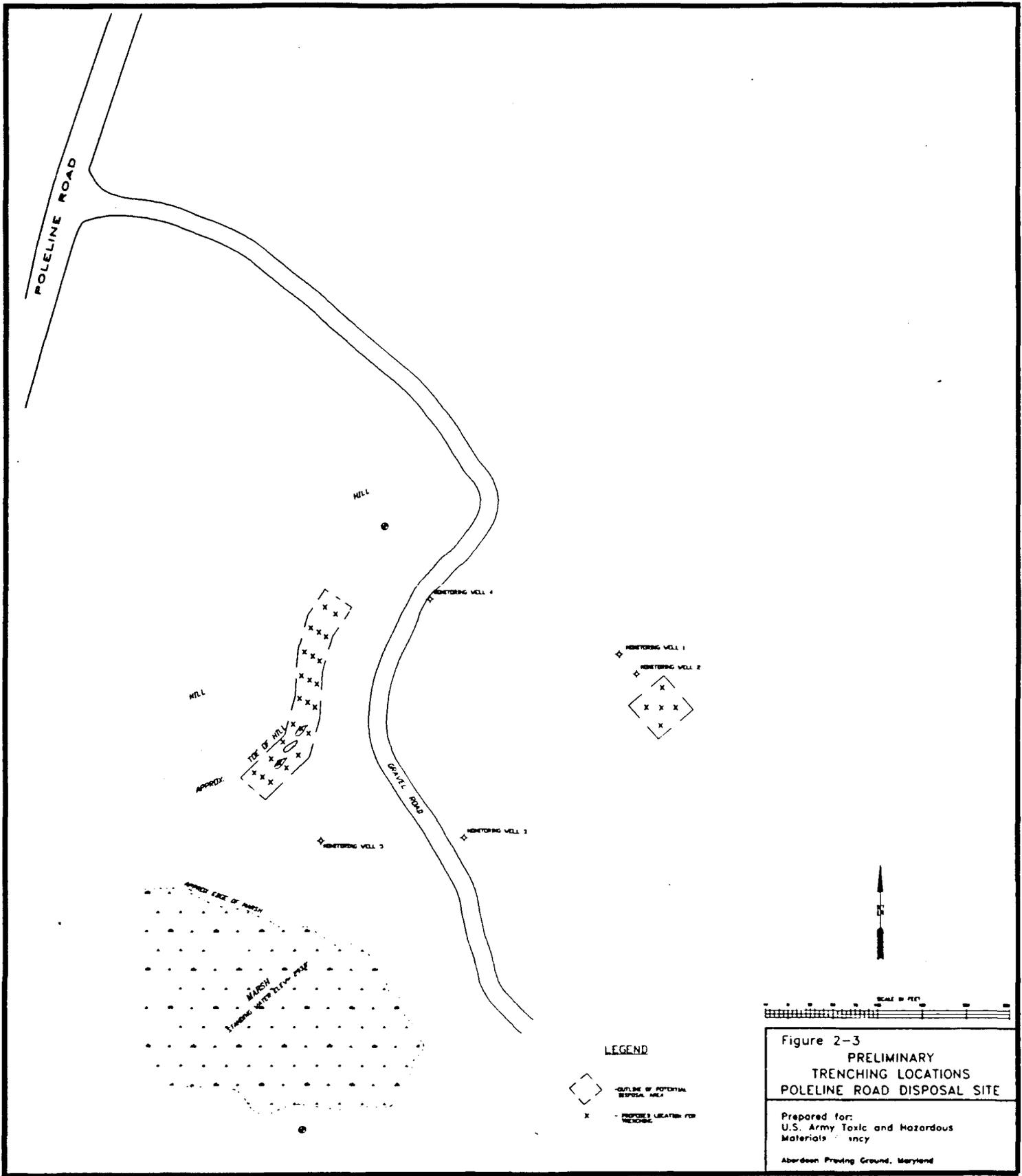
Trenching will be conducted in the two suspected source areas located on the PRDA site. The trenching will be conducted by Fort Richardson EOD utilizing a Small Enplacement Excavator (SEE) and will aid in the characterization of anomalies detected during the ESI geophysical survey. Trenching will be conducted in the suspected disposal areas on the northeastern and northwestern portions of the site. ESE will direct EOD during the trenching activities.

#### 2.3.1 TRENCHING AND SOIL SAMPLING TECHNIQUE

All trenching will be completed using an SEE. The SEE and sampling equipment will be steam-cleaned prior to initial use and between each subsequent trench that is dug. Decontamination and cleaning procedures are described in Section 3.5.1.2. A total of 40 linear feet will be trenched at PRDA. Trenches will be completed to a depth of 6 to 8 feet and logged stratigraphically. Preliminary trenching locations are shown on Figure 2-3. The exact number of individual trenches and their respective lengths will be dependent of site-specific conditions at the time of trenching. A length of 5 feet for individual trenches is proposed.

Data from the trenching will be recorded on log forms and will include, but not be limited to, trench number and location, date, trenching equipment, sampler's name, method of sampling, and lithologic soil descriptions. Example forms are contained in Appendix A. Soils will be classified according to the Unified Soil Classification System (USCS) (Figure-2-4) and standard and lithologic nomenclature for non-soil materials by the site hydrologist. Air emissions from the trenches will be monitored during the trenching operations using either an organic vapor analyzer (OVA) or a photoionization detector (PID) by an onsite ESE Health and Safety (H&S) officer. All air monitoring results will be noted on the log form. If during trenching activities drums are





MAJOR DIVISIONS			GRAPHIC SYMBOL	LETTER SYMBOL	TYPICAL DESCRIPTIONS
COARSE GRAINED SOILS  MORE THAN 50% OF MATERIAL IS LARGER THAN NO. 200 SIEVE SIZE	GRAVEL AND GRAVELLY SOILS	CLEAN GRAVELS (LITTLE OR NO FINES)		GW	WELL-GRADED GRAVELS, GRAVEL SAND MIXTURES, LITTLE OR NO FINES
				GP	POORLY-GRADED GRAVELS, GRAVEL-SAND MIXTURES, LITTLE OR NO FINES
		GRAVELS WITH FINES (APPRECIABLE AMOUNT OF FINES)		GM	SILTY GRAVELS, GRAVEL-SAND-SILT MIXTURES
				GC	CLAYEY GRAVELS, GRAVEL-SAND-CLAY MIXTURES
	SAND AND SANDY SOILS	CLEAN SAND (LITTLE OR NO FINES)		SW	WELL-GRADED SANDS, GRAVELLY SANDS, LITTLE OR NO FINES
				SP	POORLY-GRADED SANDS, GRAVELLY SANDS, LITTLE OR NO FINES
		SANDS WITH FINES (APPRECIABLE AMOUNT OF FINES)		SM	SILTY SANDS, SAND-SILT MIXTURES
				SC	CLAYEY SANDS, SAND-CLAY MIXTURES
FINE GRAINED SOILS  MORE THAN 50% OF MATERIAL IS SMALLER THAN NO. 200 SIEVE SIZE	SILTS AND CLAYS	LIQUID LIMIT LESS THAN 50		ML	INORGANIC SILTS AND VERY FINE SANDS, ROCK FLOUR, SILTY OR CLAYEY FINE SANDS OR CLAYEY SILTS WITH SLIGHT PLASTICITY
				CL	INORGANIC CLAYS OF LOW TO MEDIUM PLASTICITY, GRAVELLY CLAYS, SANDY CLAYS, SILTY CLAYS, LEAN CLAYS
				OL	ORGANIC SILTS AND ORGANIC SILTY CLAYS OF LOW PLASTICITY
	SILTS AND CLAYS	LIQUID LIMIT GREATER THAN 50		MH	INORGANIC SILTS, MICACEOUS OR DIATOMACEOUS FINE SAND OR SILTY SOILS
				CH	INORGANIC CLAYS OF HIGH PLASTICITY, FAT CLAYS
				OH	ORGANIC CLAYS OF MEDIUM TO HIGH PLASTICITY, ORGANIC SILTS
HIGHLY ORGANIC SOILS				PT	PEAT, HUMUS, SWAMP SOILS WITH HIGH ORGANIC CONTENTS

NOTE: DUAL SYMBOLS ARE USED TO INDICATE BORDERLINE SOIL CLASSIFICATIONS

Figure 2-4

UNIFIED SOIL CLASSIFICATION SYSTEM

SOURCE: ESE, 1991

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uncovered and/or damaged, representatives from FRA and USATHAMA will be contacted to provide appropriate guidance.

After the trench is completed, the EOD SEE operator will scoop trench bottom material and raise the bucket to the ground surface to an area away from the trench slope. A total of 4 trench soil samples will be collected from the bucket using a hand auger, placed in appropriate containers and shipped to the laboratory and analyzed for all compounds on the EPA GC/MS volatile organics list and the USATHAMA explosives list.

Prior to release for environmental analysis, onsite EOP personnel will conduct field screening of surety chemicals with the M-18 Kit field test method designed for monitoring these compounds. The following procedures will be used for screening soil samples collected from the trenches.

#### 2.3.1.1 Positive Results From The Field Screening Method

If the M-18 Kit tests are positive, the sample will be considered to contain surety compound(s). Site personnel will:

1. Evacuate from the trenching site to a location declared as safe by the EOD site officer;
2. Immediately notify Fort Richardson emergency operations center (EOC);
3. Notify and request guidance from USATHAMA personnel onsite;
4. Be directed by the 176th EOD which will be responsible for initial emergency response, decontamination, and containment;
5. Refrain from shipping samples offsite;

#### 2.3.1.2 Negative Results From The Field Screening Method

If the field screening method is negative, the sample will be considered as not containing surety compound(s) and will be handled by ESE under the protocol described below and in Section 2.3.2:

- Record location, date, time and other pertinent information on the log forms.
- Commence auguring with a 2-foot hand auger.
- At completion of auguring, the auger will be removed from the bucket and a composite sample collected from the auger. The sample will be sealed and removed to the sample prep area.
- Once the sample is received in the sample prep area, logging and sample shipment preparation will take place.
- After collection of each sample from the auger, the auger and other sampling equipment will be decontaminated in the field prior to moving to the next trench location.
- At the end of the working day all equipment will be decontaminated according to the procedures outlined Section 2.5.1.2.

### 2.3.2 SAMPLE LOGGING AND HANDLING

After each soil sample is collected and received in the sample prep area, descriptions of the soil and other observations will be recorded on boring logs, as described in Section 3.3.1. Samples will be transferred into the appropriate sample bottles and labeled with the sample number, date, project name, number, requested analysis, and sampler's initials. The samples will be examined for visible indications of contaminants. If any contaminants are evident, they will be indicated on the logs. All samples will be preserved in a chilled environment (4°C) until shipped to the laboratory. Samples will be analyzed for the constituents listed in Table 2-1 using EPA and USATHAMA approved methods.

### 2.3.3 CHAIN-OF-CUSTODY

Chain-of-custody forms will be completed and will accompany the samples. The data on the forms will include the boring number, date sampled, requested analysis, project name and number, and signatures of those in possession of the samples. An example chain-of-custody form and a description of chain-of custody protocol is included in the Quality Control Plan (QCP).

### 2.3.4 SAMPLE SHIPMENT

Samples will be shipped to the ESE Denver laboratory for analysis. The sample jars will be wrapped in bubble wrap, placed in plastic bags, and shipped in heavy-duty coolers filled with ice in sealed plastic bags. The corresponding chain-of-custody forms will be placed in plastic bags and taped to the inside lid of the cooler. Details on sample shipment are found in the QCP.

## 2.4 MONITORING WELL INSTALLATION

### 2.4.1 CRITERIA FOR WELL LOCATIONS AND WELL COMPLETION

Groundwater monitoring wells will be installed in areas determined by the soil gas survey to be within the plume. A total of six 4-inch I.D. monitoring wells will be installed at the PRDA. Drilling will not exceed a total of 680 feet. These monitoring wells will consist of four deep and two shallow wells. The deep wells will be installed in conjunction with a new or existing shallow well to form a cluster. One shallow well will be installed upgradient of the anticipated groundwater flow direction at PRDA. All groundwater well locations be finalized after evaluation of the soil gas survey results.

Groundwater well installation conducted during the 1990 ESI revealed a zone of shallow groundwater at a depth of approximately 20 feet exist at the PRDA. Therefore, shallow wells will be constructed to an estimated depth of no greater than 60 feet to evaluate the shallow groundwater zone which exists beneath the site. The deep groundwater wells will be constructed to a maximum estimated depth of no greater than 135 feet within the bedrock aquifer. Actual depths of each of these wells will be determined in the field by the site hydrogeologist based on conditions encountered at the site. The depths of the screened intervals and the length of the screen in each zone may be altered by the hydrogeologist onsite following the recommendations in Section 3.4.3 and

Table 2-1. Chemical Analyses To Be Performed at PRDA, Ft. Richardson, Alaska

PURGABLE ORGANICS

Acrolein  
Acrylonitrile  
Benzene  
Carbon Tetrachloride  
1,2-Dichloroethane  
1,1,1-Trichloroethane  
1,1-Dichloroethane  
1,1,2-Trichloroethane  
1,1,2,2-Tetrachloroethane  
Chloroethylvinyl ether  
2-Chloroethylvinyl ether  
Chloroform  
1,1-Dichloroethene  
trans-1,2-Dichloroethene  
1,2-Dichloropropane  
1,3-Dichloropropane  
Ethylbenzene  
Methylene chloride  
Chloromethane  
Bromomethane  
Bromoform  
Bromodichloromethane  
Fluorotrichloromethane  
Chlorodibromomethane  
Tetrachloroethene  
Toluene  
Trichloroethene  
Vinyl chloride

METALS

Antimony  
Beryllium  
Cadmium  
Chromium  
Copper  
Lead  
Nickel  
Silver  
Thallium  
Zinc  
Mercury  
Arsenic  
Selenium  
Cyanides

EXPLOSIVES AND EXPLOSIVE RESIDUES

Nitrobenzene  
1,3-Dinitrobenzene  
1,3,5-Dinitrobenzene  
2,4-Dinitrotoluene  
2,6-Dinitrotoluene  
2,4,6-Trinitrotoluene  
RDX  
Tetryl

based on field observations during drilling.

## 2.4.2 WELL DRILLING

Shallow monitoring wells will be drilled using a casing advance air rotary method. All drilling equipment, including the rig, water tanks, drill rods, samplers, etc., will be steam-cleaned prior to arrival onsite. Between boreholes, all downhole equipment will be steam-cleaned using an approved water source. This water will be analyzed for volatile organics, semi-volatile organics, total ICAP metals, and USATHAMA explosives. A list of these compounds is provided on Table 2-2.

The deep monitoring wells will also be drilled using a casing advance air rotary method. As with the shallow wells, all drilling equipment, including drill rods, tools, etc., will be steam-cleaned prior to coming onsite and prior to drilling the well. Only non-contaminating lubricants will be used on the threads of downhole drilling equipment. Decontamination and clean-up procedures are described in Section 2.5.1.2.

Geologic materials will be logged according to either USCS classifications for soils or surficial materials or standard lithologic nomenclature for non-soil materials by the site hydrogeologist. The following information will be recorded on the drilling log:

- Dates, times, drilling activities, names of drillers and site geologist;
- Evidence of contamination;
- Lithology;
- Munsell soil color;
- Soil moisture or perched saturated intervals;
- Water levels; and
- Monitor well "as built" diagram.

An example well logging form is found in Appendix A.

## 2.4.3 WELL CONSTRUCTION

### 2.4.3.1 Well Screens, Casings, and Fittings

Figure 2-5 is a schematic diagram showing the well construction details for the well cluster. Schedule 40 PVC flush-threaded blank casing, and well screen (factory-slotted 0.020-inch), couplings and caps (bottom plugs) will be used. All foreign matter (tape, labels, grease, soil, etc.) will be removed from the well materials. Well materials will be steam-cleaned with approved water and stored on plastic sheeting or kept on racks prior to installation. Glues, solvents or cleaners will not be used in construction of the wells. Blank casing in the shallow wells will extend from 2 feet above ground surface to approximately 5 feet above the elevation of the seasonal high water level. Below this, the screen will extend to near the bottom of the borehole and will have a PVC bottom cap or plug. A removable cap will be fitted at the top of the casing. The deeper well will be constructed

Table 2-2. Chemical Analyses Performed at the Poleline Road Site, Ft. Richardson, Alaska (Page 1 of 2)

PURGABLE ORGANICS

Acrolein  
Acrylonitrile  
Benzene  
Carbon Tetrachloride  
1,2-Dichloroethane  
1,1,1-Trichloroethane  
1,1-Dichloroethane  
1,1,2-Trichloroethane  
1,1,2,2-Tetrachloroethane  
Chloroethylvinyl ether  
2-Chloroethylvinyl ether  
Chloroform  
1,1-Dichloroethene  
trans-1,2-Dichloroethene  
1,2-Dichloropropane  
1,3-Dichloropropene  
Ethylbenzene  
Methylene chloride  
Chloromethane  
Bromomethane  
Bromoform  
Bromodichloromethane  
Fluorotrichloromethane  
Chlorodibromomethane  
Tetrachloroethene  
Toluene  
Trichloroethene  
Vinyl chloride

ACID EXTRACTABLES

Phenol  
2-Chlorophenol  
2-Nitrophenol  
2,4-Dimethylphenol  
2,4-Dichlorophenol  
p-Chloro-m-cresol  
2,4,6-Trichlorophenol  
2,4-Dinitrophenol  
4,6-Dinitro-o-cresol  
Pentachlorophenol

BASE/NEUTRAL EXTRACTABLES

N-Nitrosodimethylamine  
Bis(2-chloroethyl) ether  
1,3-Dichlorobenzene  
1,4-Dichlorobenzene  
1,2-Dichlorobenzene  
Bis(2-chloroisopropyl) ether  
Hexachloroethane  
N-Nitroso-n-propylamine  
Nitrobenzene  
Isophorone  
Bis(2-chloroethoxy) methane  
1,2,4-Trichlorobenzene  
Naphthalene  
Hexachlorobutadiene  
Hexachlorocyclopentadiene  
2-Chloronaphthalene  
Acenaphthylene  
Dimethyl phthalate  
2,6-Dinitrotoluene  
Acenaphthene  
2,4-Dinitrotoluene  
Fluorene  
Diethyl phthalate  
4-Chlorophenyl phenyl ether  
N-Nitrosodiphenylamine  
1,2-Diphenylhydrazine  
4-Bromophenyl phenyl ether  
Hexachlorobenzene  
Phenanthrene  
Anthracene  
Di-n-butyl phthalate  
Fluoroanthene  
Benzidine  
Pyrene  
Butyl benzyl phthalate  
Benzo(a) anthracene  
3,3'-Dichlorobenzidine  
Chrysene  
Bis(2-ethylhexyl) phthalate  
Ni-n-octyl phthalate  
Benzo(a)pyrene  
Indeno(1,2,3-cd)pyrene  
Benzo(g,h,i)perylene  
Benzo(b)fluoranthene  
Benzo(k)fluoranthene

Table 2-2. Chemical Analyses Performed at the Poleline Road Site, Ft. Richardson, Alaska (Page 2 of 2)

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METALS

Antimony  
Beryllium  
Cadmium  
Chromium  
Copper  
Lead  
Nickel  
Silver  
Thallium  
Zinc  
Mercury  
Arsenic  
Selenium

EXPLOSIVES AND EXPLOSIVE RESIDUES

Nitrobenzene  
1,3-Dinitrobenzene  
1,3,5-Dinitrobenzene  
2,4-Dinitrotoluene  
2,6-Dinitrotoulene  
2,4,6-Trinitrotoluene  
RDX  
Tetryl

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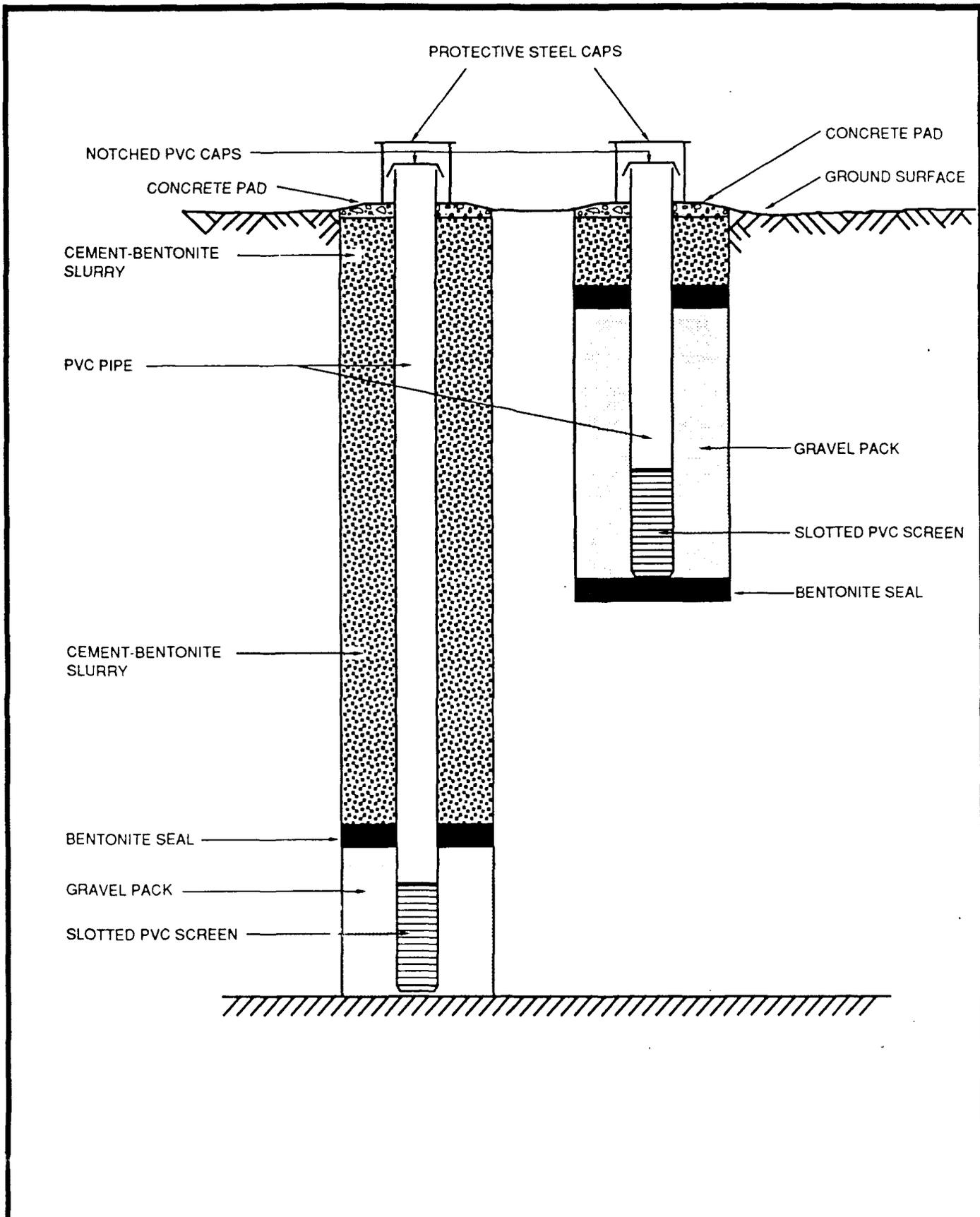


Figure 2-5  
SCHEMATIC OF MONITORING WELL NEST

SOURCE: ESE, 1991

Prepared for:  
U.S. Army Toxic and Hazardous  
Materials Agency

Aberdeen Proving Ground, Maryland

similarly, such that the blank casing extends from 2 feet above ground surface down to the screened interval. This well will be drilled deep enough to allow for a 15-foot screen to extend completely into the water bearing zone. The actual zone to be screened will be determined onsite by the site hydrogeologist as the deep borehole is completed. The screen will extend to the bottom of the borehole and will have a PVC plug. A removable cap will be placed at the top of the casing.

#### 2.4.3.2 Gravel/Sand Pack

The annular space between the casing/screen assembly and the borehole will be filled with a gravel or sand pack compatible with the formation grain size and the screen slot size. The determination of these parameters will be made in the field by the site hydrogeologist based on conditions encountered while drilling. The gravel pack will be installed to a depth of no less than 2 feet above the well screen and will be a clean uniform sand. If water is needed to facilitate placement of the gravel pack, a minimal amount of approved water will be used. The volume of this water will be recorded for subsequent removal during well development.

#### 2.4.3.3 Bentonite Seal

A bentonite seal at least 5 feet thick will be placed above the gravel pack where feasible. The thickness will be measured immediately after placement, without allowance for swelling. The seal will be composed of commercially available 1/4-inch bentonite pellets. The bentonite pellets will be hydrated with approved water, allowing one hour for the pellets to swell. The amount of water added to the pellets for hydration will be recorded on the well activity log and in the field notebook.

#### 2.4.3.4 Grout Seal

The annular space from the bentonite seal to the ground surface will be filled with grout which is pumped through a tremie pipe placed at the top of the bentonite seal. The grout will be composed of 20 parts cement to 1 part bentonite with enough water for a pumpable mixture. The water added to the grout will be approved water. The grout seal will be inspected 24 hours after placement and grout will be added, if necessary, up to the level of the ground surface. 48 hours will elapse after placement of grout before well development will commence. This will allow sufficient time for the grout to set.

#### 2.4.3.5 Protective Casing

A lockable protective casing will be set into the grout seal surrounding the well and will be cleaned of all foreign matter prior to use. The casing will be made of 6-inch diameter iron pipe, 5 feet long, with a lid capable of being locked. It will extend into the grout to about 2.5 feet below the ground surface and will extend about 2.5 feet above the ground surface. The well will be padlocked and all wells will be fitted with locks that are keyed alike. Cement will be poured to a depth of about one-half foot in the annular space inside the protective casing and outside the casing on a pad about 8 square feet and one-half foot thick. The cement will be composed of one part cement to two parts sand with the addition of a minimal amount of water. After installation, the well

number will be marked inside the locking cap. Three 3-inch diameter concrete filled steel guard posts will be installed radially 3 feet away from the well protective casing. The guard posts will be at least 5 feet high and enclosed in concrete to 2 feet below the ground surface.

#### 2.4.4 WELL DEVELOPMENT

Upon completion of the well installation, the monitoring wells will be developed until the water is clear and as sediment-free as possible. Well development will be conducted by means of either a submersible pump, or a bottom discharge bailer with a surge block. A minimum of five times the volume of standing water in the well gravel pack and annulus will be removed. If water was added to aid in the placement of the filter sand, 5 times this volume will be removed as well. All water removed from the monitoring wells during well development will be containerized for disposal.

Measurements obtained and recorded will include static water levels before and after development, field pH, and specific conductance measurements before, during, and after development.

#### 2.4.5 SURVEYING

Once the final well is installed, each well location, the elevations of the ground surface, and the top of the well casing, will be surveyed by McClintock Land Associates, Inc., surveyors registered in the State of Alaska. Well locations will be accurate to within 3 feet using State Plan coordinates. Elevations will be surveyed to within one-tenth foot using the National Geodetic Vertical Datum of 1929. Trench sample locations will also be surveyed following protocols outlined above.

### 2.5 GROUNDWATER SAMPLING

To evaluate the impact that the Poleline Road site may be having on the local groundwater quality, the 6 newly installed wells will be sampled and analyzed for all compounds in the EPA's GC/MS volatile organics list. Only the one upgradient well will be analyzed for dissolved metals in addition to VOC. This sampling effort will be conducted twice. The first sampling effort will occur 14 days after completion of the well development and the second sampling effort will occur 30 days after the first sampling round. During the first groundwater sampling event the 5 existing wells will also be sampled and for the volatile organic compounds listed in Table 2-1.

#### 2.5.1 GROUNDWATER SAMPLING PROTOCOL

Groundwater sampling methodology will include documentation of sample equipment decontamination and calibration, well inspection and field measurements, well purging, sample collection and preservation, and sample packaging and shipping on appropriate field forms.

#### 2.5.1.1 Documentation

Field documentation forms will consists of the following:

- Record of activities at well site;
- Groundwater sample collection log;
- Chain-of-custody form; and
- Sample labels.

All forms will be completed by the following procedures:

- Complete forms in ink, in the field at the place and time the data is collected or the activity is performed. Transcription of data from field books will not be done as an alternative.
- Complete all blanks for requested information or line-out (or mark N.A.) as applicable.

#### 2.5.1.2 Decontamination Procedures and Instrument Calibration

Proper decontamination of sampling equipment before each use is essential for valid sample results. To minimize the potential for cross contamination between wells, all equipment, sampling devices, measuring instruments, and protective gloves will be thoroughly decontaminated before the first sample is collected, between each sampling location, and at the end of the day. Disposable surgical gloves will be worn during all sampling and decontamination activities. The exception is in the case of disposable bailers; they will be disposed without decontamination.

In general equipment decontamination procedures to be observed are as follows:

- Spray off gross contamination with tap water;
- Wash equipment with tap water and non-phosphate detergent;
- Rinse with tap water;
- Air dry;
- Triple rinse with distilled water, the final rinse shall be collected for a rinsate blank when required;
- Air dry; and
- Wrap in clean material (see below).

Decontaminated sampling equipment will be wrapped with clean inert material such as aluminum foil or clean plastic sheeting in order to prevent accidental decontamination by air, soil, or water.

Instruments requiring calibration and the frequency of calibration are:

- Photoionization detector (PID) daily before field activities begin and as necessary, when drift may be suspected;
- pH meter, daily;

- Thermometer is considered calibrated for standard field operations; and
- Specific conductance meter, daily.

The instrument calibration procedures involve calibrating all field equipment periodically according to required frequency of manufacturer's instructions. All calibrations will be documented. If an instrument fails calibration, a back-up will be used.

#### 2.5.1.3 Well Inspection and Field Measurements

Upon arrival at the wellhead, the following protocol will be used:

- Examine the condition of the completed well for evidence of damage of vandalism and document findings;
- Record the well number, sample number, date, time, sampling personnel, and weather conditions on the form;
- Record the PID readings on the form;
- Remove the well cap and monitor the concentration of organic vapors inside the well and in the breathing zone of the sampling team. Adhere to the site APSP procedures for choosing proper respiratory protection; and
- Measure and record the static water level in the well and the total well depth to the nearest 0.01 foot using an electric well sounder or other appropriate measuring device. Measurements should be made from a surveyed measuring point at the top of the well casing. The sounding cable or tape must be decontaminated after each use with a soap and water wash followed by a distilled water rinse.

#### 2.5.1.4 Well Purging

The standing water located in the well and the filter pack must be removed prior to sampling. For high yield wells, five well bore volumes will be evacuated. Purging procedures are as follows: Use the measured I.D. of the well bore, total well depth, the static groundwater depth and the ESE Groundwater Sampling Form to calculate the volume of standing water in the well casing. For a 4 inch I.D. well in an 8 inch borehole, multiply 1.5 gallons by the total feet of water in the well. Multiply that volume by the total volumes to be evacuated (5). If a pump is used to purge the well, lower the pump to a depth equal to the midpoint of the saturated screened interval. For low yield wells, pump or bail dry, allow well to recover (for a minimum of four hours), pump or bail dry again and allow to recover. After the water in the well recovers, a sample will be collected.

If using a bailer, use the volume of the bailer and calculate the number of bails necessary to remove the total evacuation volume (total extracted volume / bailer volume = number of bails). Alternatively, a five-gallon bucket may be used (total volume = number of buckets x five gallons). A groundwater sample for field parameters (pH, temperature, and specific conductance) will be collected before purging begins, after evacuation of each casing volume during purging, and after the analytical samples are collected. Measurements will be made

quickly after obtaining the sample to obtain measurements that are as representative as possible to well bore conditions.

#### 2.5.1.5 Sample Collection

Samples for laboratory analysis shall be collected in order of the volatilization sensitivity of the analytes. The preferred collection order follows:

- VOC
- Dissolved metals
- Explosives and basic parameters

The sample label will be directly affixed to the sample jar (not the cap) and will have any additional required information added using indelible ink. A piece of clear tape will be placed over the label to ensure it remains legible and intact.

The samples will be collected by using a small diameter disposable bailer with a single check valve. Only new nylon or polypropylene rope will be used for bailing at each well. The rope should not touch the ground during bailing. Samples will be transferred directly into sample containers. The bailer should be lowered slowly into and out of the water to minimize groundwater disturbance and possible volatilization. The groundwater may also be poured directly into the sample containers from the bailer.

Samples for organic analysis are collected by transferring water directly from the bailer into the 40 ml VOA vials. Direct the flow to the bottom of the vial and allow the water to overflow, being careful not to aerate the sample. Carefully place the teflon septum lined cap on the bottle, then turn the bottle upside down and tap gently against the palm of the hand. If bubbles are present, discard the sample and resample. If the septum should fall out of the cap during sampling, it will be discarded and replaced with another cap. Place samples immediately on ice. Sample equipment will be decontaminated following the collection of the final sample (including QC samples) at each well.

#### 2.5.2 SAMPLE PACKAGING AND SHIPPING

Samples will be shipped to the laboratory as soon as possible after collection. Samples should be packaged as follows:

- Wrap all glass containers with bubble wrap;
- Place VOA vials together in the can provided by the laboratory;
- Place samples in the ice chest;
- Place two double bags of crushed ice in the cooler;
- Place the original chain-of-custody form in a plastic Ziplock™ bag and tape to the inside lid of the cooler;

- Place chain-of-custody seals (evidence tape) over the lid of the cooler on several sides; and
- Notify the laboratory of the expected arrival time of the samples, and remind the laboratory of any special holding times or required turnaround time. Any samples shipped to the laboratory must be shipped according to Department of Transportation (DOT) standards. In general, most samples will be low hazard samples for non-passenger aircraft which should require only arrows indicating "This End Up" on all sides, "Fragile" on two sides, and an address and return address. Medium hazard samples have additional packaging and labeling requirements. Refer to current DOT regulations before shipping.

### 2.5.3 CHAIN-OF-CUSTODY

Chain-of-custody forms will be completed by the sample collector. Data on these forms will include the sample number, collection date and time, the number and type of bottles, and the types of sample. The sampler will sign and date the form. This form will be transported with the samples at all times and is an inventory of the samples and those persons with access to the samples. The chain-of-custody forms will be reviewed by the Field Team Leader prior to sample shipment.

### 2.6 AQUIFER TESTING

To determine the hydraulic communication between the shallow and deep aquifers as well as the hydraulic conductivity and transmissivity of the deep aquifer, a 72-hour pump test will be conducted. The pump test will be designed after Neuman and Witherspoon, 1972 (Appendix B). Prior experience with well yield in the deep aquifer at PRDA has shown that this aquifer may not be able to produce enough water to be pumped. The pump test, therefore, will only be conducted if the deep aquifer monitoring well can produce water through pumping.

Two observation wells will be installed after determining which deep monitoring well will be used for the pumping well. The observation wells will be installed in the unsaturated zone which occurs approximately 60 to 120 feet below ground surface. The wells will be installed in a radial line from the pumping well. These observation wells will be constructed of 2-inch PVC. The actual construction details will be determined in the field by the project hydrogeologist according to subsurface conditions encountered during the borehole advancement. The observation wells will generally be constructed similarly to the monitoring wells.

Water levels in each well will be measured using downhole pressure transducers. The transducer, as well as all other downhole instruments, will be steam cleaned with approved water prior to use in the well. The transducer is then lowered into the well to a depth which will allow for detection of minimal water level fluctuations. The transducer readings and time will be monitored over the 72-hour period using an Insitu Hermit™ 2000 which stores the data as it is being recorded. The recovery rates will also be monitored for 8 hours after the pump is turned off.

The pump test will be conducted at the PRDA immediately after the second round of groundwater sampling is complete.

### **3.0 PRELIMINARY RISK ASSESSMENT**

### 3.0 PRELIMINARY RISK ASSESSMENT

A preliminary RA will be conducted to identify potential human and nonhuman (ecological) receptors, identify possible exposure pathways from potential onsite sources to the receptors, identify indicator chemicals of concern (COCs) in different media from PRDA, determine exposure point concentrations and qualitatively address the risks associated with exposure to the site. This preliminary RA will determine exposure point concentrations, address the risks associated with exposure to site COCs, and provide recommendations for future evaluations.

#### 3.1 PRELIMINARY ECOLOGICAL RISK ASSESSMENT

An RA will be conducted to assess the current and potential effects of site-related chemicals on potentially affected habitats and biological receptors. The level of detail required to perform an ERA is expected to vary significantly with habitat type; the site's proximity to sensitive habitats such as wetlands, wildlife refuges, and breeding areas; probability of exposure, diversity, and abundance of the area's wildlife; and the biological and physical fate of contaminants of potential concern. The evaluation of ecological risks will include the following investigations.

##### 3.1.1 HABITAT CHARACTERIZATION

The site's general ecology will be described in relation to vegetation types, diversity, and relative abundance of site-specific wildlife, occurrence and classification of surface water, regional topography, and proximity to residential and commercial development. This task will specifically include the characterization of habitat types based on field observations of potential aquatic and terrestrial receptors. Field investigations will include observations of vegetation density and diversity, identification of aquatic species including plants, invertebrates, and vertebrate species, observations of potentially affected avian species including passerines, waterfowl, raptors, and identification of mammals based on small mammal trapping and observations of the area's larger game mammals.

A general biological inventory for the site will be constructed based on the results of field observations and review of existing biological inventories from state wildlife officials, U.S. Fish and Wildlife Service, wildlife and environmental organizations, area universities, and regional identification keys. Emphasis will be placed on the identification of sensitive species, such as threatened or endangered species, resident breeding species, representative top trophic level species, and sensitive aquatic species. The scope of the biological inventory conducted by ESE will be commensurate with the nature of the site's ecology and the extent of environmental contamination.

### 3.1.2 SELECTION OF CHEMICALS OF CONCERN

Selection of COCs will be based on distribution and concentration in soils, sediment, and surface water, frequency of detection; persistence and mobility in the local environment; potential for bioconcentration; and toxicity to ecologically important species. ESE will evaluate these contaminants based on their chemical and physical properties to determine ecological and biological fate, as well as the extent of environmental persistence. The goal of the selection process is to focus on those contaminants that represent the most toxic, mobile, persistent, or frequently occurring onsite. The selection of all COCs will be based on the results of existing analytical data.

### 3.1.3 IDENTIFICATION OF INDICATOR SPECIES

Indicator species will be selected on the basis of their relative abundance and ecological significance within the terrestrial, wetlands, or aquatic habitats of the potentially affected study area(s). Other criteria for the selection of these species include relative sensitivities to the selected COCs, trophic status, mobility, the ability to bioaccumulate selected contaminants, economic importance, and the respective federal/state endangerment status.

### 3.1.4 TOXICITY ASSESSMENT

Relevant criteria will be identified and summarized for selected COCs. These may include: U.S. EPA Ambient Water Quality Criteria; state criteria; proposed dietary and tissue residue guidelines; and sediment quality guidelines. Other Applicable or Relevant and Appropriate Requirements (ARARs) such as LD<sub>50</sub>s and LC<sub>50</sub>s, No Observed Adverse Effects Levels (NOAELs) and Lowest Observed Adverse Effects Levels (LOAELs) for chronic and acute exposures will also be collected from the available literature.

### 3.1.5 EXPOSURE ASSESSMENT

Significant exposure pathways will be determined for the selected indicator species as defined by exposure scenarios for terrestrial, aquatic, and transitional ecosystems. Trophic relationships and dietary exposure pathways for indicator species residing in these habitats are likely to include direct contact with and/or ingestion of contaminated physical media (i.e. water, sediment, and soils), consumption of plants, and carnivorous consumption of prey representative of lower trophic levels.

Exposure point concentrations will be compiled from the existing analytical data for air, surface water, groundwater, and sediment pathways. All appropriate site concentrations will be used.

### 3.1.6 RISK CHARACTERIZATION

The primary emphasis of this task will be to determine the probable magnitude, duration, and frequency of indicator species' exposures to the COCs. ESE will estimate the potential for bioaccumulation in localized

species and biomagnification throughout respective food webs. The characterization of biological and ecological risks will consist of qualitative methods.

The potential impacts of contaminants on the site's ecosystem will be discussed qualitatively based on an analysis of toxicological effects, contaminant fate and transport, and sound ecological principles. This analysis will include an evaluation of both short- and long-term effects on local ecosystem structure and function. Emphasis will be placed on critical habitats such as wetlands, wildlife breeding areas, and aquatic habitats.

The ecological risk assessment will provide the context within which to predict short- and long-term biological and ecosystem impacts from site-derived contamination. Recommendations will be made regarding future onsite and offsite remediation needs and environmental monitoring which may be necessary to verify the actual ecological impacts related to the site.

### 3.2 PRELIMINARY HUMAN HEALTH RISK ASSESSMENT

Based on the existing analytical data, ESE will also perform a preliminary human health risk assessment. This assessment will include the following tasks: data evaluation and selection of contaminants of concern, exposure assessment, toxicity assessment, and risk characterization.

#### 3.2.1 SELECTION OF CHEMICALS OF CONCERN

Selection of contaminants of concern will be based on frequency of detection environmental concentration, toxicity, comparison to site-specific or region-specific background concentrations, and mobility and persistence in various media. The rationale for selecting or eliminating any chemical from the quantitative risk assessment will be clearly documented.

#### 3.2.2 EXPOSURE ASSESSMENT

The exposure assessment will involve the analysis of contaminant releases, identifying exposed populations, identifying potential pathways of exposure, calculating exposure point concentrations, and calculating contaminant intakes for each pathway. Potential pathways for human exposure onsite and/or offsite may include: ground water (ingestion, dermal contact, inhalation of volatiles via household uses of water); soils (dermal contact, incidental ingestion, inhalation of dusts, and indirect exposure, such as ingestion of garden crops, ingestion of game, and ingestion of fish); surface water (dermal contact, incidental ingestion, inhalation of volatiles, and ingestion of fish); and air (inhalation of volatiles). As suggested by EPA guidance, ESE will estimate exposures based on the 95th percentile of the mean concentrations for each applicable media. Chemical exposures will be calculated for each pathway using standard equations which include variables such as exposure concentration, contact rate, exposure time, exposure frequency, exposure duration, receptor weight, and averaging time. Uptake into the food chain may be modeled if contaminants may be contacted by fish or wildlife, or if homegrown produce is used by nearby residents.

### 3.2.3 TOXICITY ASSESSMENT

Toxicity values developed by the EPA, such as observed dose-response relationships in animal laboratory studies or human epidemiological studies, will be used to estimate the potential for adverse effects in humans. In evaluating carcinogenicity, no level of exposure is assumed to be without risk. Exposure to any quantity of a carcinogen poses a finite probability of producing a carcinogenic response. For carcinogenic effects, the EPA has developed values, referred to as slope factors, to determine the cancer causing potential of a compound. The slope factor is used in risk assessments to determine an upper-bound lifetime probability of an individual developing cancer as a result of exposure to a potential carcinogen.

Toxic effects other than cancer are assumed to have a threshold, which must be exceeded before adverse effects are experienced by the organism. The EPA's toxicity values for noncarcinogenic effects are referred to as reference doses (RfD) (oral exposures) or reference concentrations (RfC) (inhalation exposures). These values estimate the level of a compound to which humans (including sensitive subpopulations) can be exposed daily without risk of detrimental effects.

When no EPA values are available, additional methods to evaluate the toxicity of compounds may include in-depth literature searches to derive toxicity values or use of alternative toxicity evaluations.

### 3.2.4 RISK CHARACTERIZATION

The risk characterization will involve calculation of potential carcinogenic and noncarcinogenic risks. Risk characterization will include an extensive discussion of the uncertainties in the risk estimates.

#### 4.0 REFERENCES

#### 4.0 REFERENCES

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**APPENDIX A**  
**FIELD DATA FORMS**











Environmental  
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FIELD ACTIVITY DAILY LOG

DAILY LOG	DATE			
	NO			
	SHEET		OF	

PROJECT NAME:		PROJECT NO.:	
FIELD ACTIVITY SUBJECT:			
DESCRIPTION ON DAILY ACTIVITIES AND EVENTS:			
VISITORS ON SITE:		CHANGES FROM PLANS AND SPECIFICATIONS, AND OTHER SPECIAL ORDERS AND IMPORTANT DECISIONS:	
WEATHER CONDITIONS:	AM	PM	IMPORTANT TELEPHONE CALLS:
WIND DIRECTION	_____	_____	
WIND VELOCITY	_____	_____	
RELATIVE HUMIDITY	_____	_____	
TEMPERATURE	_____	_____	
PERSONNEL ON SITE:			
(FIELD ENGINEER) DATE:			



Borehole: \_\_\_\_\_

Well: \_\_\_\_\_

Depth-Feet	Soil/Rock Type	Well Completion	Description

Drill Site Geologist: \_\_\_\_\_

Date: \_\_\_\_\_

Reviewed By: \_\_\_\_\_

Date: \_\_\_\_\_



WELL CONSTRUCTION SUMMARY

Borehole \_\_\_\_\_ Well \_\_\_\_\_

Project Name and Location \_\_\_\_\_ Project Number \_\_\_\_\_

Drilling Company \_\_\_\_\_ Driller \_\_\_\_\_ Rig Number \_\_\_\_\_

Drilling Method(s) \_\_\_\_\_

Borehole Diameter \_\_\_\_\_ in. \_\_\_\_\_ cm. \_\_\_\_\_ ft. \_\_\_\_\_ cm. to \_\_\_\_\_ ft. \_\_\_\_\_ cm.  
\_\_\_\_\_ in. \_\_\_\_\_ cm. \_\_\_\_\_ ft. \_\_\_\_\_ cm. to \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Size(s) and types of Bit(s) \_\_\_\_\_

Sampling Method(s) \_\_\_\_\_

Size and Type PVC \_\_\_\_\_

Date/Time Start Drilling \_\_\_\_\_

Total Borehole Depth \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Date/Time Finish Drilling \_\_\_\_\_

Depth to Bedrock \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Date/Time Start Completion \_\_\_\_\_

Depth to Water \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Date/Time Cement Protective Casing \_\_\_\_\_

Water Level Determined By \_\_\_\_\_

Materials Used \_\_\_\_\_

Length Plain PVC (total) \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Plain PVC \_\_\_\_\_

Length of Screen \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Slotted PVC \_\_\_\_\_

Total Length of Well Casing \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Bentonite Pellets \_\_\_\_\_

PVC Stick Up \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Bentonite Granular \_\_\_\_\_

Depth to Bottom of Screen \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Cement \_\_\_\_\_

Depth to Top of Screen \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Sand \_\_\_\_\_

Depth to Top of Sand \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Water added during completion \_\_\_\_\_

Depth to Top of Bentonite \_\_\_\_\_ ft. \_\_\_\_\_ cm.

Water added during drilling \_\_\_\_\_

Total Gallons of water added \_\_\_\_\_

Drill Site Geologist \_\_\_\_\_

Date \_\_\_\_\_

Date/Time/Personnel Internal Mortar, Cement Pad, and Weep Hole Installed \_\_\_\_\_

Date/Time/Personnel Casing Painted \_\_\_\_\_

Date/Time/Personnel Numbers Painted \_\_\_\_\_

Materials Used \_\_\_\_\_

Top of Protective Casing to Top of PVC \_\_\_\_\_ ft. \_\_\_\_\_ cm. COMMENT/NOTES

Top of Protective Casing to Weep Hole \_\_\_\_\_ ft. \_\_\_\_\_ cm. \_\_\_\_\_

Top of Protective Casing to Internal Mortar \_\_\_\_\_ ft. \_\_\_\_\_ cm. \_\_\_\_\_

Top of Protective Casing to Top of Cement Pad \_\_\_\_\_ ft. \_\_\_\_\_ cm. \_\_\_\_\_

Top of Protective Casing to Ground Level \_\_\_\_\_ ft. \_\_\_\_\_ cm. \_\_\_\_\_

Reviewed By \_\_\_\_\_ Date \_\_\_\_\_

Drill Site Geologist \_\_\_\_\_ Date \_\_\_\_\_





WELL DEVELOPMENT DATA

Bore \_\_\_\_\_ Well \_\_\_\_\_

Project \_\_\_\_\_ Project Number \_\_\_\_\_

Date(s) Developed \_\_\_\_\_ Date Installed \_\_\_\_\_

Personnel (Name/Company) \_\_\_\_\_ Well Diameter (I.D.) \_\_\_\_\_ in.

\_\_\_\_\_ Anulus Diameter \_\_\_\_\_ in. \_\_\_\_\_ ft. to \_\_\_\_\_ ft.

\_\_\_\_\_ Rig Used \_\_\_\_\_ \_\_\_\_\_ in. \_\_\_\_\_ ft. to \_\_\_\_\_ ft.

\_\_\_\_\_ Pump (Type/Capacity) \_\_\_\_\_ Screen Interval \_\_\_\_\_ ft. to \_\_\_\_\_ ft.

\_\_\_\_\_ Bailer (Type/Capacity) \_\_\_\_\_ \_\_\_\_\_ ft. to \_\_\_\_\_ ft.

\_\_\_\_\_ Water Source \_\_\_\_\_ Casing Height (Above G.L.) \_\_\_\_\_ ft.

Measured Well Depth TOC (Initial) \_\_\_\_\_ ft. Bottom of Screen (Below G.L.) \_\_\_\_\_ ft.

(Final) \_\_\_\_\_ ft.

Water Level TOC/Date/Time (Initial) \_\_\_\_\_

(after 24 hrs.) \_\_\_\_\_

Feet of Water in Well \_\_\_\_\_ ft. x \_\_\_\_\_ gallons/foot = \_\_\_\_\_ gallons casing/anulus volume

Drilling Fluid Lost \_\_\_\_\_ gallons One Purge Volume \_\_\_\_\_ gallons

Purge Water Lost \_\_\_\_\_ gallons Minimum Purge Volume \_\_\_\_\_ gallons

Added Water \_\_\_\_\_ gallons Total Purge Volume \_\_\_\_\_ gallons

Casing/Anulus Volume \_\_\_\_\_ gallons Volume Measured By \_\_\_\_\_

Surge Technique \_\_\_\_\_

Calibration: pH Meter Used: \_\_\_\_\_

pH 7.00 = \_\_\_\_\_ at \_\_\_\_\_ °C, pH 10.00 = \_\_\_\_\_ at \_\_\_\_\_ °C

Conductance Meter Used: \_\_\_\_\_

Standard \_\_\_\_\_ umhos/cm at 25°, Reading \_\_\_\_\_ umhos/cm at \_\_\_\_\_ °C

Purge Volume	Time	Temp. °C	pH	Conductance at 25°C	Physical Characteristics (clarity, odor, sand content, color)
Initial					
Final					

Remarks: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Collected by \_\_\_\_\_ Signature \_\_\_\_\_ Date \_\_\_\_\_

Checked by \_\_\_\_\_ Signature \_\_\_\_\_ Date \_\_\_\_\_



SOIL/SEDIMENT SAMPLING FORM

Station ID \_\_\_\_\_

Date \_\_\_\_\_

\_\_\_\_\_

Sampling Time \_\_\_\_\_

Collected by \_\_\_\_\_

ESE Sample Number \_\_\_\_\_

Sample Splits Collected for \_\_\_\_\_

Fraction Sampled    SV    SS    \_\_\_\_\_

Visual Appearance of Sample \_\_\_\_\_

\_\_\_\_\_

Sampling Location \_\_\_\_\_

\_\_\_\_\_

Sampling Method \_\_\_\_\_

Weather Conditions Now \_\_\_\_\_

Precipitation Past Day \_\_\_\_\_

Comments/Remarks \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Collected by \_\_\_\_\_  
Signature Date

Checked by \_\_\_\_\_  
Signature Date



**Environmental  
Science &  
Engineering, Inc.**

DATE							
TIME							
PAGE	___ OF ___						
PAGE							
PROJECT NO.							

**SAMPLE COLLECTION LOG**

PROJECT NAME \_\_\_\_\_

SAMPLE NO. \_\_\_\_\_

SAMPLE LOCATION \_\_\_\_\_

SAMPLE TYPE \_\_\_\_\_

COMPOSITE \_\_\_\_\_ YES \_\_\_\_\_ NO

COMPOSITE TYPE \_\_\_\_\_

DEPTH OF SAMPLE \_\_\_\_\_

WEATHER \_\_\_\_\_

CONTAINERS USED	AMOUNT COLLECTED

COMMENTS:

PREPARED BY: \_\_\_\_\_

**APPENDIX B**  
**FIELD TEST METHOD**

## Field Determination of the Hydraulic Properties of Leaky Multiple Aquifer Systems

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**Abstract.** A new field method is proposed for determining the hydraulic properties of aquifers and aquitards in leaky systems. Conventional methods of analyzing leaky aquifers usually rely on drawdown data from the pumped aquifer alone. Such an approach is not sufficient to characterize a leaky system: our new method requires observation wells to be placed not only in the aquifer being pumped but also in the confining layers (aquitards) above and/or below. The ratio of the drawdown in the aquitard to that measured in the aquifer at the same time and the same radial distance from the pumping well can be used to evaluate the hydraulic properties of the aquitard. The new method is supported by theory and has been applied to the coastal groundwater basin of Oxnard, California. The field results are in good agreement with laboratory measurements.

Traditionally, groundwater hydrologists have tended to focus their attention on the more permeable aquifer layers of a groundwater basin in developing water supplies. However, sedimentary groundwater basins usually consist of a series of aquifers separated by confining layers of relatively low permeability, which may act as conduits for the vertical migration of water from one aquifer to another. Since fine-grained sediments often tend to be much more compressible than associated coarse-grained aquifer materials, they also can release large quantities of water from storage and thereby increase the supply available to the aquifer. The combined effects of these phenomena are known as leakage.

Usually, when the effects of leakage can be detected by observing drawdown in the aquifer being pumped, the confining beds are called 'aquitards,' and the aquifer is referred to as being 'leaky.' When such effects cannot be easily detected in the aquifer, the confining beds are called 'aquicludes,' and the aquifer is termed 'slightly leaky' [Neuman and Witherspoon, 1968].

Aquitards play an important role in the

hydrology of multiple aquifer systems, and we shall mention here only a few examples. Although groundwater recharge is often believed to occur in areas of aquifer outcrops, Gill [1969] has recently reported that substantial amounts of water produced from the Potomac-Raritan-Magothy aquifer system are coming through the aquitards. Earlier, Walton [1965] had shown how the Maquoketa formation in Illinois, which is essentially a shale bed, serves as an effective transmitter of water between aquifers. Land subsidence in the San Joaquin Valley and other areas in California has been shown to be associated with water withdrawal from multiple aquifer systems and is generally attributed to the resulting compaction of fine-grained aquitard sediments [Poisson and Davis, 1969]. Similar situations exist in Venice, Japan, and other parts of the world.

For the past 20 years, aquifers at depths below 500 feet have been used for storing natural gas in the United States and Europe. Where the properties of the aquitards were not properly investigated, the gas industry has on occasion witnessed the spectacular and dangerous effects of gas leakage. The storage of other fluids,

as well as the disposal of waste products underground, requires the role of aquitards to be thoroughly understood if the degradation of groundwater supplies and the pollution of the surface environment are to be avoided. The role of aquitards may also be important in determining the rate at which the seawater from a degraded aquifer may migrate vertically to an uninvaded zone. An interesting situation in which the effectiveness of aquitards in preventing seawater intrusion is largely unknown occurs where the construction of shallow harbors and marinas requires the removal of a part of the aquitard that normally provides a natural barrier between the ocean and the freshwater aquifer beneath [*California Department of Water Resources*, 1971, p. 10].

Although the importance of aquitards is being recognized more and more, there is no reliable method for their investigation, and very little is known about their hydraulic properties. This report describes an improved field method for evaluating the hydraulic properties of aquifers and aquitards in leaky multiple aquifer systems. The new approach is simple to use and applicable to a wide range of hydrogeological situations. We shall describe in detail one particular investigation performed in the coastal groundwater basin of Oxnard, California.

#### PROBLEMS IN ANALYZING PUMPING TESTS WITH CURRENT METHODS

In analyzing results of water pumping tests the well-known *Theis* [1935] solution is often used to determine the permeability and the specific storage of the aquifer under investigation. As long as the aquitards do not leak significant amounts of water into the aquifer, this method of analysis produces reliable results.

However, groundwater hydrologists noted many years ago that deviations from the aquifer behavior, as predicted by the *Theis* solution, are not uncommon. These deviations are often caused by water leaking out of the confining beds, and this led to the 'leaky aquifer' theory of *Hantush and Jacob* [1955]. This theory and its later modifications [*Hantush*, 1960] relied only on an examination of aquifer behavior and attempted to relate such behavior to the properties of the adjacent aquitards.

Unfortunately, this approach has not been entirely satisfactory. As has recently been

pointed out by *Neuman and Witherspoon* [1969b], field methods based on the leaky aquifer theory of *Hantush and Jacob* [1955] may often lead to significant errors. These errors are such that one tends to overestimate the permeability of the aquifer and underestimate the permeability of the confining beds. Under some circumstances, one may also get the false impression that the aquifer is inhomogeneous. Furthermore, the method does not provide a means of distinguishing whether the leaking beds lie above or below the aquifer being pumped.

A new theory of flow in multiple aquifer systems has recently been developed by *Neuman and Witherspoon* [1969a; *California Department of Water Resources*, 1971, pp. 24-38]. This theory shows that the behavior of drawdown in each layer is a function of several dimensionless parameters  $\beta_i$  and  $r/B_i$ , which depend on the hydraulic characteristics of the aquitards as well as those of the aquifers. The new theory clearly indicates that the observation of drawdown in the pumped aquifer alone is not always sufficient to determine uniquely the values of  $\beta$  and  $r/B$ . For example, *Hantush's* [1960] modified theory of leaky aquifers provides an analytical solution in terms of  $\beta$  that we know is applicable at sufficiently small values of time. Nevertheless, since this solution relates only to drawdown in the aquifer being pumped, its usefulness in determining uniquely the properties of each aquitard or even in determining a unique value of  $\beta$  is very limited [*California Department of Water Resources*, 1971, p. 327; *Riley and McClelland*, 1970]. Our theory indicates that one should be able to develop improved methods of analysis by installing observation wells not only in the aquifer being pumped but also in the confining layers enclosing it. Indeed, as will be shown later, a series of observation wells in more than one layer is a prerequisite for any reliable evaluation of aquitard characteristics.

The idea of placing observation wells in a low permeability layer (aquiclude) overlying a slightly leaky aquifer was originally proposed by *Witherspoon et al.* [1962] in connection with the underground storage of natural gas in aquifers. Their purpose was to determine how effective a given aquiclude would be in preventing gas leakage from the intended underground storage reservoir. Using results obtained from a

finite difference simulation model, Witherspoon et al. were able to suggest a method for evaluating the hydraulic diffusivity of an aquiclude by means of a pumping test.

Later, a theoretical analysis of flow in aquicludes adjacent to slightly leaky aquifers was developed by Neuman and Witherspoon [1968]. This theory led to an improved method for determining the hydraulic diffusivity of aquicludes under slightly leaky conditions [Witherspoon and Neuman, 1967; Witherspoon et al., 1967, pp. 72-92]. Since the method relies on the ratio between drawdown in the aquiclude and drawdown in the pumped aquifer, it will henceforth be referred to as the 'ratio method.'

A method for evaluating the hydraulic diffusivity of an aquitard under arbitrary conditions of leakage, which also uses observation wells completed in the confining layer itself, was recently described by Wolff [1970]. In his analysis Wolff assumed that, at any given radial distance from the pumping well and at a sufficiently large value of time, one can represent drawdown in the pumped aquifer by a step function. Assuming also that drawdown in the unpumped aquifer remains 0, Wolff arrived at a set of type curves that he recommended for aquitard evaluation.

Although this method gave satisfactory results for the particular site investigated by Wolff, we think that the step function approach may lead to difficulties when it is applied to arbitrary multiple aquifer systems. Fundamentally, drawdown in the pumped aquifer cannot be reliably represented by a single step function unless a quasi-steady state is reached within a sufficiently short period of time. The quasi-steady state will be reached only if the transmissibility of the aquifer is large and if the observation wells are situated at relatively small radial distances from the pumping well. To minimize the effect of early drawdowns, Wolff's method further requires that the duration of the pumping test be sufficiently long and that the vertical distance between the pumped aquifer and the aquitard observation wells not be too small.

From our new theory of flow in multiple aquifer systems, we now know that at large values of time the results in the aquitard may be affected significantly by the influence of an adjacent unpumped aquifer, especially where the aquitard

observation well has been perforated close to such an aquifer. Thus, although the single step function approach renders the method inapplicable at small values of time, the assumption of zero drawdown in the unpumped aquifer introduces an additional restriction at large values of time.

In the special case where the thickness of the aquitard is known, one can determine its diffusivity directly from the step function type curves without the need for graphical curve matching. Quite often, however, the effective thickness of the aquitard is unknown. For example, the aquitard may contain unidentified or poorly defined layers of highly permeable material that act as a buffer to the pressure transient and also as a source of leakage. Another possibility is that the aquitard is situated below the pumped aquifer and that its lower limit has never been adequately defined. Then the step function approach requires the graphical matching of aquitard drawdown data with Wolff's [1970] type curves.

However, the intermediate parts of these type curves are essentially parallel, and therefore they cannot be matched uniquely with field results. On the other hand, neither the early nor the late parts of the type curves can be used with confidence. Thus there may be a significant element of uncertainty when Wolff's [1970] method is applied to real field situations.

Since the currently available direct field methods appear to be limited in their application, there is an obvious need for a new approach that would enable one to determine the characteristics of multiple aquifer systems under a wide variety of field conditions. We shall attempt to demonstrate that a rational basis for such an approach is provided by our new theory of flow in multiple aquifer systems [Neuman and Witherspoon, 1969a]. We will start by showing that the ratio method, which we originally thought was limited in application only to aquicludes under slightly leaky conditions, can in fact also be used to evaluate the properties of aquitards under very leaky conditions.

#### APPLICABILITY OF THE RATIO METHOD TO LEAKY CONDITIONS

To develop a method for determining the hydraulic properties of aquitards, we shall first

consider a two-aquifer - complete solution for the down in such a system. In Neuman and Witherspoon aquifer the solutions depend parameters  $\beta_{11}$ ,  $r/B_{11}$ ,  $\beta_{21}$ . In aquitard the solution in parameter  $z/b_1'$ . This large less parameters makes it to construct a sufficient to cover the entire range of field application. For a useful, they are normally not more than two independent parameters.

One way to significantly parameters is to restrict data to small values of want to focus our attention effects that occur prior discernible pressure transient pumped aquifer. At such pumped aquifer does not the rest of the system. are independent of the parameters. Furthermore, the aquitard thickness were infinite. the parameters  $r/B_{11}$  influence on the drawdown equation will depend on additional parameter 'b.'

In the pumped aquifer given by Hantush's [1966] [Neuman and Witherspoon

$$s_1(r, t) = \frac{Q_1}{4\pi T_1} \int_{1/b_1}^{\infty} \frac{e^{-u}}{u} \operatorname{erfc} \left( \frac{r}{y(4T_1 t)} \right) dy$$

In the aquitard the solution

$$s_1'(r, z, t) = \frac{Q_1}{4\pi T_1} \int_{1/b_1}^{\infty} \frac{e^{-u}}{u} \operatorname{erfc} \left( \frac{\beta_{11} + \beta_{21}}{y(4T_1 t)} \right) dy$$

Theoretically, (1) and small values of time

$$t_0 \leq 1.6c$$

In terms of real time

consider a two-aquifer system (Figure 1). A complete solution for the distribution of drawdown in such a system has been developed by Neuman and Witherspoon [1969a]. In each aquifer the solutions depend on five dimensionless parameters  $\beta_{11}$ ,  $r/B_{11}$ ,  $\beta_{21}$ ,  $r/B_{21}$ , and  $t_{D1}$ . In the aquitard the solution involves one additional parameter  $z/b_1'$ . This large number of dimensionless parameters makes it practically impossible to construct a sufficient number of type curves to cover the entire range of values necessary for field application. For a set of type curves to be useful, they are normally expressed in terms of not more than two independent dimensionless parameters.

One way to significantly reduce the number of parameters is to restrict the analysis of field data to small values of time. In particular, we want to focus our attention on those early effects that occur prior to the time when a discernible pressure transient reaches the unpumped aquifer. At such early times the unpumped aquifer does not exert any influence on the rest of the system, and therefore drawdowns are independent of the parameters  $\beta_{21}$  and  $r/B_{21}$ . Furthermore, the aquitard behaves as if its thickness were infinite, which simply means that the parameters  $r/B_{11}$  and  $z/b_1'$  also have no influence on the drawdown. Thus the resulting equation will depend only on  $\beta_{11}$ ,  $t_{D1}$ , and an additional parameter  $t_{D1}'$ .

In the pumped aquifer, drawdown is then given by Hantush's [1960] asymptotic equation [Neuman and Witherspoon, 1969a].

$$s_1(r, t) = \frac{Q_1}{4\pi t_1} \int_{1/4t_{D1}}^{\infty} \frac{e^{-y}}{y} \cdot \operatorname{erfc} \left( \frac{\beta_{11}}{[y(4t_{D1}y - 1)]^{1/2}} \right) dy \quad (1)$$

In the aquitard the solution is

$$s_1'(r, z, t) = \frac{Q_1}{4\pi T_1} \int_{1/4t_{D1}}^{\infty} \frac{e^{-y}}{y} \cdot \operatorname{erfc} \left( \frac{\beta_{11} + y(t_{D1}/t_{D1}')^{1/2}}{[y(4t_{D1}y - 1)]^{1/2}} \right) dy \quad (2)$$

Theoretically, (1) and (2) are limited to those small values of time that satisfy the criterion

$$t_{D1} \leq 1.6\beta_{11}^2/(r/B_{11})^2 \quad (3)$$

In terms of real time this criterion may also be

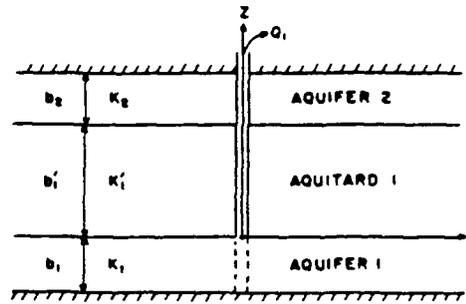


Fig. 1. A schematic diagram of a two-aquifer system.

expressed by

$$t \leq 0.1 S_{11}' b_1'^2 / K_1' \quad (4)$$

indicating that the limiting value of time is independent of the radial distance from the pumping well.

From a practical standpoint the criterion given by (3) or (4) is overly conservative. For example, Figures 2-8 in Neuman and Witherspoon [1969a] reveal that the effect of the unpumped aquifer is felt in the rest of the system at times that are always greater than those predicted by (3). Note further that in these figures the effects of  $\beta_{21}$  and  $r/B_{21}$  are negligible as long as the log-log curve of drawdown versus time for the unpumped aquifer does not depart from its initial steep slope.

This effect of the unpumped aquifer provides a useful criterion for determining the time limit beyond which the asymptotic solutions may no longer be applicable. If an observation well can be provided in the unpumped aquifer, a log-log plot of drawdown versus time should enable the hydrologist to identify this time limit.

Note that there may be field situations in which the procedure above is not applicable. For example, when the transmissibility of the unpumped aquifer is large in comparison to that of the aquifer being pumped, drawdowns in the unpumped aquifer will be too small to measure, and one would not be able to determine the time limit as outlined above. This procedure may also fail when the water levels in the unpumped aquifer are fluctuating during the pumping test owing to some uncontrolled local or regional effect. Then a more conservative estimate of the time limit can be established from drawdown data observed in one of the

been perforated close to although the single step lers the method inappli- of time, the assumption the unpumped aquifer at restriction at large

ere the thickness of the can determine its diffu- he step function type ed for graphical curve however, the effective d is unknown. For ex- y contain unidentified s of highly permeable buffer to the pressure rce of leakage. Another itard is situated below that its lower limit has fined. Then the step es the graphical match- wn data with Wolff's

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RATIO METHOD  
ITIONS

or determining the onds, we shall first

aquitard wells. In general, the smaller the vertical distance between the perforated interval in the aquitard well and the boundary of the pumped aquifer is, the more conservative the time indicated by the procedure above is.

Having established a practical method for estimating the time within which (1) and (2) are valid, we can now proceed to show how these equations lead to the ratio method for evaluating aquitards. Remember that Hantush's equation does not by itself lead to a reliable method for determining a unique value of  $\beta_{11}$  from field results. The same can be said of (2), because it involves three independent parameters  $\beta_{11}$ ,  $t_{D1}$ , and  $t_{D1}'$ . However, the usefulness of these two equations becomes immediately evident when one considers  $s_1'/s_1$ , i.e., the ratio of drawdown in the aquitard to that in the pumped aquifer at the same elapsed time and the same radial distance from the pumping well.

In the discussion that follows we shall be dealing with only one aquifer and one aquitard, and for the sake of simplicity we shall omit all subscripts. Figure 2 shows the variation of  $s'/s$  versus  $t_D'$  for a practical range of  $t_D$  and  $\beta$  values. Note that at  $t_D = 0.2$  changing the

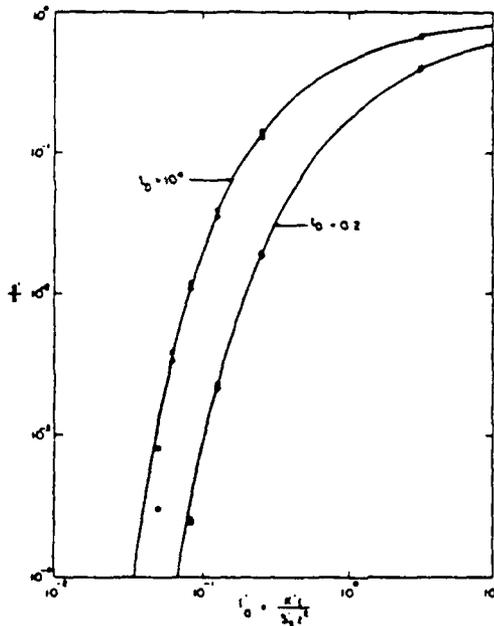


Fig. 2. The variation of  $s'/s$  with  $t_D'$  for  $\beta = 0.0$  (solid lines),  $\beta = 0.01$  (squares), and  $\beta = 1.0$  (circles).

value of  $\beta$  from 0.01 to 1.0 has practically no effect on the ratio  $s'/s$ . The same is true as  $t_D$  increases, and this relationship is shown by the additional results for  $t_D = 10'$ .

If we now use our theory for slightly leaky situations [Neuman and Witherspoon, 1968] where  $s'$  is given by

$$s'(r, z, t) = \frac{Q}{4\pi T} \frac{2}{r^{1/2}} \int_{1/(4t_D)'}^{\infty} -\text{Ei} \left( -\frac{t_D' y^2}{t_D(4t_D' y^2 - 1)} \right) e^{-y^2} dy \quad (5)$$

and  $s$  is obtained from the Theis solution, we have in effect the special case where  $\beta = 0$ . This is represented by the two solid lines in Figure 2.

We also examined the case where  $\beta = 10.0$  and found that the values of  $s'/s$  deviate significantly from those shown in Figure 2. Thus one may conclude that for all practical values of  $t_D$  the ratio  $s'/s$  is independent of  $\beta$  as long as  $\beta$  is of order 1.0 or less. Since  $\beta$  is directly proportional to the radial distance from the pumping well, its magnitude can be kept within any prescribed bounds simply by placing the observation wells close enough to the pumping well. A quick calculation will show that distances of the order of a few hundred feet will be satisfactory for most field situations.

Thus we arrive at the very important conclusion that the ratio method, which we originally thought was restricted to only slightly leaky situations, can in effect be used to determine the hydraulic diffusivities of aquitards under arbitrary leaky conditions. We therefore decided to adopt the ratio method as a standard tool for evaluating the properties of aquitards.

USE OF THE RATIO METHOD IN AQUITARD EVALUATION

The ratio method can be applied to any aquifer and its adjacent aquitards, above and below, in a multiple aquifer system (see sketch in Figure 3). The method relies on a family of curves of  $s'/s$  versus  $t_D'$ , each curve corresponding to a different value of  $t_D$ , as obtained from (5) and the Theis equation. The curves in Figure 3 have been prepared from tables of values published previously by Witherspoon et al. [1967, Appendix G].

In the ratio method value of  $s'/s$  at a given pumping well  $r$  and time  $t$ . The next step magnitude of  $t_D$  for the and  $t$  at which  $s'/s$  has  $t_D < 100$ , the curves in minor changes in the meter, and therefore a desirable. When  $t_D > 1$  close to each other than to be practically independent a crude estimate of  $t_D$  ratio method to yield procedure for determining drawdown data in the later in connection with aquifer characteristics.

Having determined  $\alpha'$  Figure 3 should be used one can now read off corresponding to the computed the diffusivity of the from the simple formula

$$\alpha' = \dots$$

Note in Figure 3 the value of  $t_D'$  obtained not very sensitive to As a result the value  $\alpha'$  depends very little on the drawdown in the critical quantity determined a given elevation  $z$  is the start of the test and the observation well begins lag is very important by method one need not extremely sensitive means in the aquitard observation piezometer with a start usually give sufficient for most field situation a change in pressure change in water level so small in comparison the start of the test and that its influence can be

To evaluate the porosity storage of an aquitard diffusivity, one of these determined by means

1 to 1.0 has practically no effect on the relationship shown by the curves. The same is true as  $t_0 = 10^4$ .

theory for slightly leaky aquifers [see, for example, *Walters and Witherspoon, 1968*]

$$\frac{t_D' y^2}{t_D(4t_D' y^2 - 1)} e^{-y^2} dy \quad (5)$$

in the Theis solution. The special case where  $\beta = 0$  is shown by the two solid lines in Figure 2.

In the case where  $\beta = 10.0$ , the curves of  $s'/s$  deviate significantly from those shown in Figure 2. Thus one can use all practical values of  $t_0$  independent of  $\beta$  as long as  $\beta$  is directly proportional to the distance from the pumping well.

The magnitude can be kept within a desired range simply by placing the observation well far enough from the pumping well. Figure 3 will show that distances of several hundred feet will be sufficient in most situations.

It is a very important consequence of this method, which we originated, that only slightly different values of  $S_1'$  need be used to determine the values of  $S_1'$  for different aquitard conditions. We therefore recommend this method as a standard procedure for determining the properties of aquitards.

THE RATIO METHOD IN CALCULATION

This method can be applied to any system of aquifers, above and below the pumping well (see sketch in Figure 1). It relies on a family of curves corresponding to each value of  $t_0$  as obtained from Figure 2. The curves in Figure 3 are compared from tables of values of  $s'/s$  by *Walters and Witherspoon et al.*

In the ratio method, one first calculates the value of  $s'/s$  at a given radial distance from the pumping well  $r$  and at a given instant of time  $t$ . The next step is to determine the magnitude of  $t_0$  for the particular values of  $r$  and  $t$  at which  $s'/s$  has been measured. When  $t_0 < 100$ , the curves in Figure 3 are sensitive to minor changes in the magnitude of this parameter, and therefore a good estimate of  $t_0$  is desirable. When  $t_0 > 100$ , these curves are so close to each other that they can be assumed to be practically independent of  $t_0$ . Then even a crude estimate of  $t_0$  will be sufficient for the ratio method to yield satisfactory results. A procedure for determining the value of  $t_0$  from drawdown data in the aquifer will be discussed later in connection with methods dealing with aquifer characteristics.

Having determined which one of the curves in Figure 3 should be used in a given calculation, one can now read off a value of  $t_0'$  corresponding to the computed ratio of  $s'/s$ . Finally, the diffusivity of the aquitard is determined from the simple formula

$$\alpha' = (z^2/t) t_0' \quad (6)$$

Note in Figure 3 that, when  $s'/s < 0.1$ , the value of  $t_0'$  obtained by the ratio method is not very sensitive to the magnitude of  $s'/s$ . As a result the value of  $\alpha'$  calculated from (6) depends very little on the actual magnitude of the drawdown in the aquitard. Instead, the critical quantity determining the value of  $\alpha'$  at a given elevation  $z$  is the time lag  $t$  between the start of the test and the time when the aquitard observation well begins to respond. The time lag is very important because in using the ratio method one need not worry about having extremely sensitive measurements of drawdown in the aquitard observation wells. A conventional piezometer with a standing water column will usually give sufficiently accurate information for most field situations. The time lag between a change in pressure and the corresponding change in water level in the column is usually so small in comparison to the time lag between the start of the test and this change in pressure that its influence can be safely ignored.

To evaluate the permeability and specific storage of an aquitard from its hydraulic diffusivity, one of these quantities must first be determined by means other than the ratio

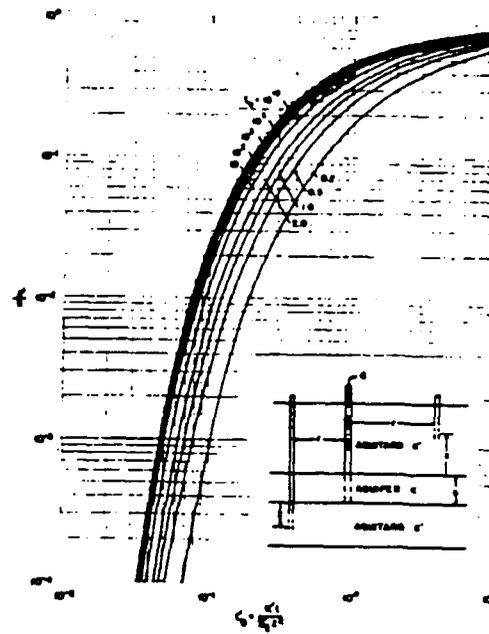


Fig. 3. The variation of  $s'/s$  with  $t_0'$  for a semi-infinite aquitard.

method. Experience indicates that permeability may vary by several orders of magnitude from one aquitard to another and even from one elevation to another in the same aquitard. A much more stable range of values is usually encountered when one is dealing with specific storage.

Recent field measurements in areas of land subsidence (F. S. Riley, personal communication, 1971) have shown that the specific storage of fine-grained sediments depends on the relationship between the load generated by pumping and the past history of loading. When this relationship is such that the sediments react elastically, the value of  $S_1'$  is relatively small. When the sediments are undergoing irreversible consolidation, the value of  $S_1'$  may be larger by 1 or 2 orders of magnitude. Presently, the most reliable measurements of  $S_1'$  are performed in the field by using borehole extensometers. Another way to determine approximate values of  $S_1'$  is to perform standard consolidation tests on core samples in the laboratory. In the total absence of field and laboratory measurements,  $S_1'$  can be estimated by correlating published results on similar sediments. Once the value of

$S_1'$  has been determined,  $K'$  is easily calculated from  $K' = \alpha'S_1'$ .

We also studied the effects of aquitard heterogeneity and anisotropy on the value of  $K'$  obtained by the ratio method at a given elevation  $a$ . In our investigation we used the finite element method to examine the behavior of a two-aquifer system when: (1) the aquitard was a homogeneous anisotropic layer with a horizontal permeability as much as 250 times greater than the vertical and (2) the aquitard consisted of three different layers, each of which was homogeneous and anisotropic. The results of this study indicated that for homogeneous anisotropic aquitards the ratio method will always give a value of  $K'$  that corresponds to the vertical permeability of the aquitard. For a heterogeneous aquitard,  $K'$  is simply the weighted average vertical permeability over the thickness  $z$ . If there are  $N$  layers of thickness  $b^n$  and vertical permeability  $K_v^n$  inside this interval,  $K'$  represents the average value

$$K' = z / \left( \sum_{n=1}^N \frac{b^n}{K_v^n} \right) \quad (7)$$

*Boulton* [1963] and *Neuman* [1972] have shown that, at early values of time, drawdown in an unconfined aquifer can safely be approximated by the Theis solution. At later values of time, drawdown is affected by the delayed response of the water table, and the effect is similar to that of leakage in a confined aquifer. Thus, if the ratio method is applicable to aquitards adjacent to confined leaky aquifers, it should also be applicable to situations in which the pumped aquifer is unconfined. This conclusion is further supported by the fact that the ratio method depends less on the actual values of drawdown in the aquifer than on the time lag observed in the aquitard. To test this applicability of the ratio method to an unconfined aquifer, we took data from *Wolff* [1970] for a pumping test in which observation wells were placed in a confining layer underneath a water table aquifer. We analyzed these data by using the ratio method, and the results are in excellent agreement with those obtained by *Wolff*.

When we showed that our slightly leaky theory was applicable to the so-called leaky aquifer, our previous discussion was restricted to a two-aquifer system. By now, however, the

reader will recognize that such a restriction is not necessary and that the ratio method is actually applicable to arbitrary multiple aquifer systems. The only requirement is that the sum of the  $\beta_i$  values with respect to the overlying and underlying aquitards be of order 1 or less.

In summary, note once again the following features of the ratio method.

1. The method applies to arbitrary, leaky multiple aquifer situations.
2. The pumped aquifer can be either confined or unconfined.
3. The confining layers can be heterogeneous and anisotropic. Then the ratio method gives the average vertical permeability over the thickness  $z$  of the aquitard being tested.
4. The method relies only on early drawdown data, and therefore the pumping test can be of relatively short duration.
5. The drawdown data in the unpumped aquifer or in the aquitard provide an in situ indication of the time limit at which the ratio method ceases to give reliable results.
6. Since the method is more sensitive to time lag than to the actual magnitude of  $s'/s$ , the accuracy with which drawdowns are measured in the aquitard is not overly critical.
7. The method does not require prior knowledge of the aquitard thickness.
8. The ratio method is simple to use and does not involve any graphical curve-matching procedures. This lack of curve-matching procedures is an advantage because curve matching is often prone to errors due to individual judgment and because a more reliable result can be obtained by taking the arithmetic average of results from several values of the ratio  $s'/s$ .

#### METHOD FOR EVALUATING AQUIFERS

When the pumped aquifer is slightly leaky, one can evaluate its transmissibility and storage coefficient by the usual procedures based on the Theis equation. When leakage is appreciable, these procedures will not always yield satisfactory results. Alternative methods for analyzing the results of pumping tests in leaky aquifers were proposed by *Jacob* [1946] and *Hantush* [1956, 1960]. Still another method based on the  $r/B$  solution has recently been proposed by *Narasimhan* [1968]. All these methods rely on drawdown data from the pumped aquifer alone.

Their purpose is to determine the properties of the aquifer and the leakage factors  $r/B$  characteristics of the aquifer. When the aquifer is leaky, these methods and that they can be used.

Since we have indicated that the ratio method is a means for evaluating multiple aquifer systems, it is a means for evaluating remaining unknowns in a multiple aquifer system. When the aquifer is leaky, the methods based on the ratio method are those whose magnitude is  $r/B$ . A look at *Neuman* [1969a] will reveal that the values of  $\beta$  and  $r/B$  are the characteristics of the pumped aquifer development and therefore the error by such methods are small. We recognize that  $\beta$  and  $r/B$  reflect the amount of leakage in the aquifer. In fact,  $\beta$  is directly proportional to the magnitude of leakage from nearly 0 at the large values further from the extent to which the behavior of the drawdown is a function of the pumping well. Thus, the smaller the deviation from the Theis curve are, the less leakage is obvious in the well where the aquitard are largest at a distance from this well in a given system.  $\beta$  and  $r/B$  distance, whereas the error decreases.

At first glance, we see a paradox: The greater the deviations from the Theis curve are, the more leakage is obvious. However, a close examination of the system will show that the explanation for this is that the drawdown will recognize that, in the aquitard do not, in the aquifer, cannot be said about the aquifer. As a result, the area relative to this

Their purpose is to determine not only the properties of the aquifer but also the so-called leakage factors'  $r/B$  and  $\beta$  that depend on the characteristics of the confining layers as well as on those of the aquifer. We have shown earlier that these methods have a limited application and that they can often lead to erroneous results.

Since we have introduced the ratio method as a means for evaluating aquitards, the only remaining unknowns to be determined are the aquifer transmissibility  $T$  and the storage coefficient  $S$ . When the aquifer is leaky, the use of methods based on the Theis solution will lead to errors whose magnitudes are a function of  $\beta$  and  $r/B$ .

A look at Neuman and Witherspoon [1969a] will reveal that the smaller the values of  $\beta$  and  $r/B$  are, the less the drawdowns in the pumped aquifer deviate from the Theis solution, and therefore the smaller the errors introduced by such methods are. At this point we must recognize that  $\beta$  and  $r/B$  do not necessarily reflect the amount of water that leaks into the aquifer. In fact, both these parameters are directly proportional to  $r$ , which simply means that their magnitude in a given aquifer varies from nearly 0 at the pumping well to relatively large values further away from this well. Thus the extent to which leakage can affect the behavior of the drawdown in any given aquifer is a function of the radial distance from the pumping well. Thus the closer one is to this well, the smaller the deviations of drawdown from the Theis curve are. On the other hand, the rate of leakage is obviously greatest near the pumping well where the vertical gradients in the aquitard are largest and diminishes as the radial distance from this well increases. Therefore, in a given system,  $\beta$  and  $r/B$  increase with radial distance, whereas the actual rate of leakage decreases.

At first glance, we seem to be faced with a paradox: The greater the leakage is, the less the deviations from the nonleaky Theis solution are. However, a closer examination of the flow system will show that there is a simple physical explanation for this phenomenon. The reader will recognize that, although vertical gradients in the aquitard do not vary appreciably with radial distance from the pumping well, the same cannot be said about drawdown in a pumped aquifer. As a result the rate of leakage per unit area relative to this drawdown is negligibly

small in the immediate vicinity of the pumping well but becomes increasingly important at larger values of  $r$ . In addition, the water that leaks into the aquifer at smaller values of  $r$  tends to act as a buffer to the pressure transient. This transient cannot propagate as fast as it otherwise might have had there been no increase in aquifer storage. The effect is to reduce further the drawdown at points farther away from the pumping well. The net result is a situation in which larger values of  $r$  are associated with less leakage but also with greater deviations from the Theis curve.

Thus we arrive at the important conclusion that one can evaluate the transmissibility and storage coefficient of a leaky aquifer by using conventional methods of analysis based on the Theis solution. The errors introduced by these methods will be small if the data are collected close to the pumping well, but they may become significant when the observation well is placed too far away. Therefore a distance drawdown analysis based on the Theis curve is not generally applicable to leaky aquifers and should be avoided whenever possible.

Ideally, the values of  $T$  and  $S$  should be evaluated by using drawdown or buildup data from the pumping well itself because here the effect of leakage is always the smallest. We recommend this approach whenever the effective radius of the pumping well is known (e.g., wells in hard rock formations). However, when a well derives its water from unconsolidated materials, its effective radius usually remains unknown owing to the presence of a gravel pack. In these situations the approach above can still be used to evaluate  $T$  but cannot be used to determine  $S$ .

As a general rule, early drawdown data are affected by leakage to a lesser degree than data taken at a later time are. Therefore we feel that in performing the analysis most of the weight should be given to the earliest data available, if, of course, there is confidence in their reliability.

Once  $S$  and  $T$  have been determined, one can calculate the dimensionless time at any given radial distance from the pumping well by

$$t_D = Tt/Sr^2 \quad (8)$$

Equation 8 can then be used with the ratio method as we discussed earlier.

that such a restriction is that the ratio method is arbitrary multiple aquifer requirement is that the sum with respect to the overlying aquards be of order 1 or less. We will once again the following method.

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#### ANALYZING LEAKY AQUIFERS

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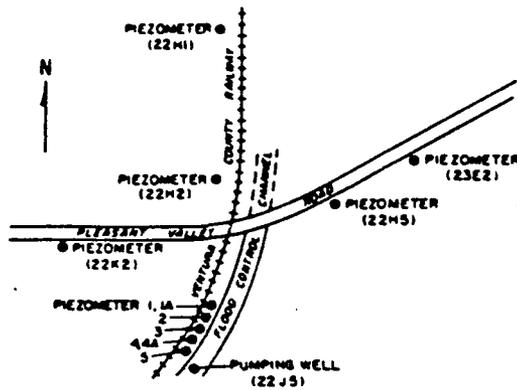


Fig. 4. The locations of the piezometers used in field pumping tests.

FIELD PUMPING TESTS IN THE OXNARD, CALIFORNIA, BASIN

The California Department of Water Resources had previously investigated the Oxnard basin in connection with seawater intrusion problems and constructed several wells at various locations in the basin. For our field studies we selected a particular location in the city of Oxnard where a large capacity pumping well (Figure 4, 22J5) was available to produce water from the Oxnard aquifer. Four additional piezometers (22H2, 22H5, 22K2, and 23E2) were available to monitor water levels in the Oxnard aquifer at radial distances of 502-1060 feet.

In addition, seven new piezometers were installed at various elevations relative to that of the Oxnard aquifer. Table 1 summarizes the vertical distances above and below the Oxnard for each piezometer and also gives the radial distances from pumping well 22J5. Ideally, the

seven piezometers should have been arranged along a circular arc with its center at the pumping well so that responses would be given at various elevations but at only one unique value of  $r$ . However, this arrangement was not possible under the local conditions, and we therefore had to design the well field according to the scheme shown in Figure 4. For details of the construction, the completion, and the development methods, the reader is referred to *California Department of Water Resources* (1971, pp. 63-68).

The following is a brief description of the lithology in the vicinity of the test area. The semiperched zone is composed of fine- to medium-grained sand with interbedded silty clay lenses. The upper aquitard is made up of predominantly silty and sandy clays, mainly montmorillonite. The Oxnard aquifer, which is the most important water producer in the Oxnard basin, is composed of fine- to coarse-grained sand and gravel. Silty clay with some interbedded sandy clay lenses makes up the lower aquitard. The material that forms the Mugu aquifer is fine- to coarse-grained sand and gravel with some interbedded silty clay. Figure 5 shows an electric log through this series of sediments.

ANALYSIS OF PUMPING TEST RESULTS

Two pumping tests were performed in the field. Their purpose was to determine the hydraulic characteristics of the Oxnard aquifer and the confining layers above and below it and to confirm our theoretical concepts [Neuman and Witherspoon, 1969a] regarding the response of multiple aquifer systems to pumping.

The first pumping test lasted 31 days. Figure 6 shows the response in the Oxnard aquifer at

TABLE 1. Location of Piezometers

Piezometer	Distance from 22J5, feet	Depth, feet	Vertical Distance*, feet	Layer
1	100	120	...	Oxnard aquifer
1A	100	239	...	Mugu aquifer
2	91	225	-26	lower aquitard
3	81	205	-6	lower aquitard
4	72	95	+11	upper aquitard
4A	72	58.5	+50	semiperched aquifer
5	62	84	+22	upper aquitard

\* The vertical distance is the distance above the top of the Oxnard aquifer at a depth of 105 feet or below the bottom at a depth of 198 feet.

† Failed to operate satisfactorily.

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various radial distances from the pumping well. Piezometer 1, which is nearest to the pumping well, demonstrated an anomalous behavior during the first 6 of pumping. This was apparently due to a ng effect in the pumping well. At about 6000 min the entire basin started experiencing a general drop in water levels probably due to the beginning of intermittent pumping for irrigation at this time of the year. Table 2 gives the values of  $T$  and  $S$  as calculated from these data by using *Jacob's* [1950] semi-logarithmic approach.

Table 2 shows that in general the values of  $T$  become progressively larger as  $r$  increases. This relationship can be explained as follows. Since the Oxnard aquifer is obviously leaky, the actual drawdown curve at any given well will lie below the Theis solution, as is shown diagrammatically in Figure 7. To demonstrate this positioning, we shall choose a particular point on the data curve that corresponds to some given value of  $s$  and  $t$ . If we could match the data to the true type curve where  $\beta$  and  $r/B$  are not 0, we would obtain the true value of  $s_D$  for the point chosen.

However, such type curves were not available for this investigation, and we used a method that is essentially equivalent to matching the field data to the Theis curve. Therefore the field data are being shifted upward from their true position, and our chosen point will now indicate an apparent value of  $s_D$ ,  $> s_D$ .

From the definition of  $s_D$  it is clear that since  $s$  remains unchanged the value of  $T$  is increased. The greater the radial distance  $r$ , the larger  $\beta$  and  $r/B$  become, and therefore the larger the difference between the true type curve and the Theis curve is. In other words, as  $r$  increases, the magnitude of  $T$  should become more and more exaggerated, which is clearly evident in Table 2.

With regard to errors in  $S$ , the shifting of field data as indicated on Figure 7 may be either to the left or to the right. Thus the effect on the calculated values of  $S$  is not predictable (Table 2). With this unpredictability in mind, we decided to select the results from piezometer 1 of  $T = 130,600$  gpd/ft and  $S = 1.12 \times 10^{-4}$  as being most representative of the Oxnard aquifer, at least in the area of the pumping test.

Having estimated the properties of the pumped aquifer, we shall now consider the results from other parts of this three-aquifer

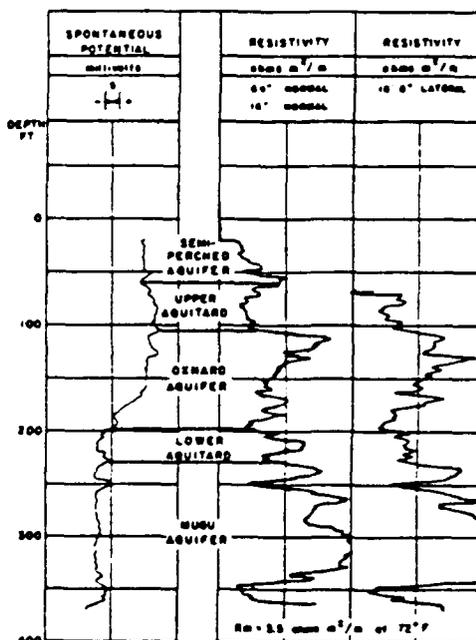


Fig. 5. The electric log from the first exploratory hole.

subsystem. Figure 8 shows the response at one particular point in the lower aquitard (well 3) as well as the responses in the Oxnard above (well 1) and the Mugu below (well 1A). Figure 9 shows the response at two different elevations in the upper aquitard (wells 4 and 5) as well as the response in the overlying semiperched aquifer (well 4A). Since piezometer 1 is located farthest from the pumping well, we do not have the response in the pumped aquifer directly below the piezometers where drawdowns in the upper aquitard were measured. However, from distance-drawdown curves in the Oxnard aquifer and from the behavior of piezometer 4, we concluded that the aquifer response was approximately as shown by the dashed curve in Figure 9. Remember that the ratio method for evaluating aquitards is more sensitive to the time lag than to the actual magnitude of drawdown in the aquifer. Therefore the dashed curve in Figure 9 can be considered sufficiently accurate for our purposes. Note that the shapes of the curves in Figures 8 and 9 are quite similar to those of our theoretical curves [*Neuman and Witherspoon, 1969a*].

To evaluate the lower aquitard, we shall determine the ratio  $s'/s$  at two early values of

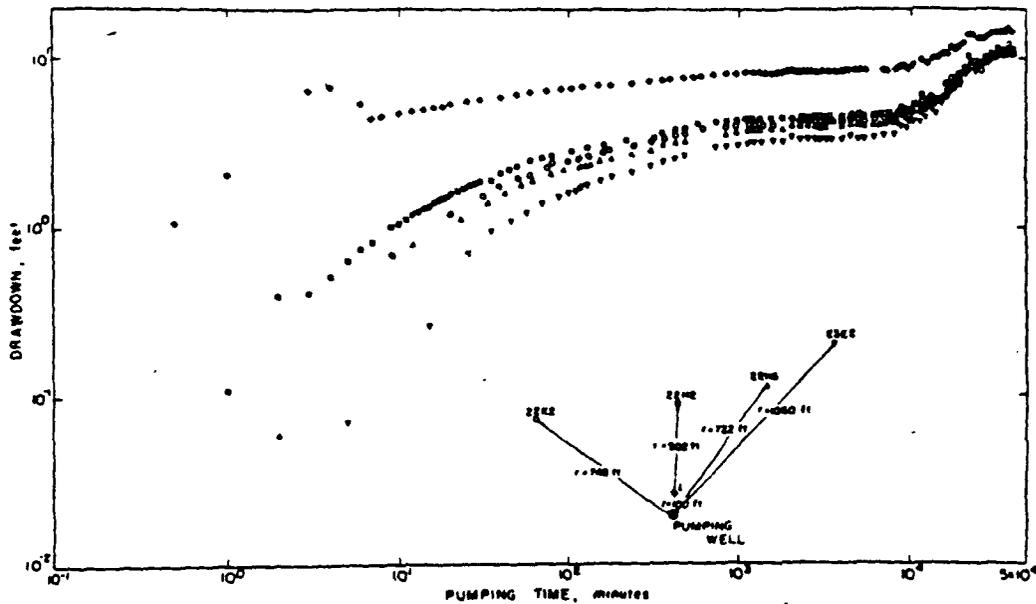


Fig. 6. The fluid levels in the Oxnard piezometers during the first pumping test. The diamonds represent well 1, the squares represent well 22H2, the triangles represent well 22H5, the circles represent well 22K2, and the inverted triangles represent well 23E2.

time,  $t = 80$  min and  $t = 200$  min. At  $t = 80$  min, one can read on Figure 8 that  $s' = 0.078$  and  $s = 6.6$  feet. The ratio is simply  $s'/s = 0.078/6.6 = 1.18 \times 10^{-2}$ . To obtain  $t_D$ , one can use the equation

$$t_D = 9.28 \times 10^{-5} T t / r^2 S \quad (9)$$

where  $T$  is in gallons per day per foot,  $t$  is in minutes, and  $r$  is in feet. Then, using the known values of  $T$  and  $S$  and noting from Table 1 that, at piezometer 3,  $r = 81$  feet, one can calculate

$$t_D = \frac{(9.28 \times 10^{-5})(130,600)(80)}{(81)^2(1.12 \times 10^{-4})} = 1.32 \times 10^3$$

TABLE 2. Results of Oxnard Aquifer Using Jacob's Semilog Method

Well	$r$ , feet	$T$ , gpd/ft	$S$
1	100	130,600	$1.12 \times 10^{-4}$
22H2	502	139,000	$3.22 \times 10^{-4}$
22H5	722	142,600	$3.08 \times 10^{-4}$
22K2	748	136,700	$2.48 \times 10^{-4}$
23E2	1060	157,000	$2.53 \times 10^{-4}$

Referring to Figure 3, one finds that these values of  $s'/s$  and  $t_D$  correspond to  $t_D' = 0.086$ . From the definition of  $t_D'$ , one can verify the formula

$$\alpha' = 1.077 \times 10^4 t_D' z^2 / t \quad (10)$$

where  $\alpha'$  is in gallons per day per foot,  $z$  is in feet, and  $t$  is in minutes. One notes from Table 1 that, for piezometer 3,  $z = 6$  feet, and therefore

$$\alpha' = \frac{(1.077 \times 10^4)(0.086)(6)^2}{(80)} = 4.17 \times 10^3 \text{ gpd/ft}$$

Similarly, one finds that, at  $t = 200$  min,  $\alpha' = 3.39 \times 10^3$  gpd/ft. Since the method gives more reliable results when  $t$  is small, we adopted  $\alpha' = 4.17 \times 10^3$  gpd/ft as the representative value for the top 6 feet of the lower aquitard. The results of similar calculations for both aquitards are summarized in Table 3. Note that the diffusivity of the Oxnard aquifer is

$$\alpha = \frac{T}{S} = \frac{130,600}{1.12 \times 10^{-4}} = 1.17 \times 10^9 \text{ gpd/ft}$$

which is more than 1 million times the values obtained for the aquitards.



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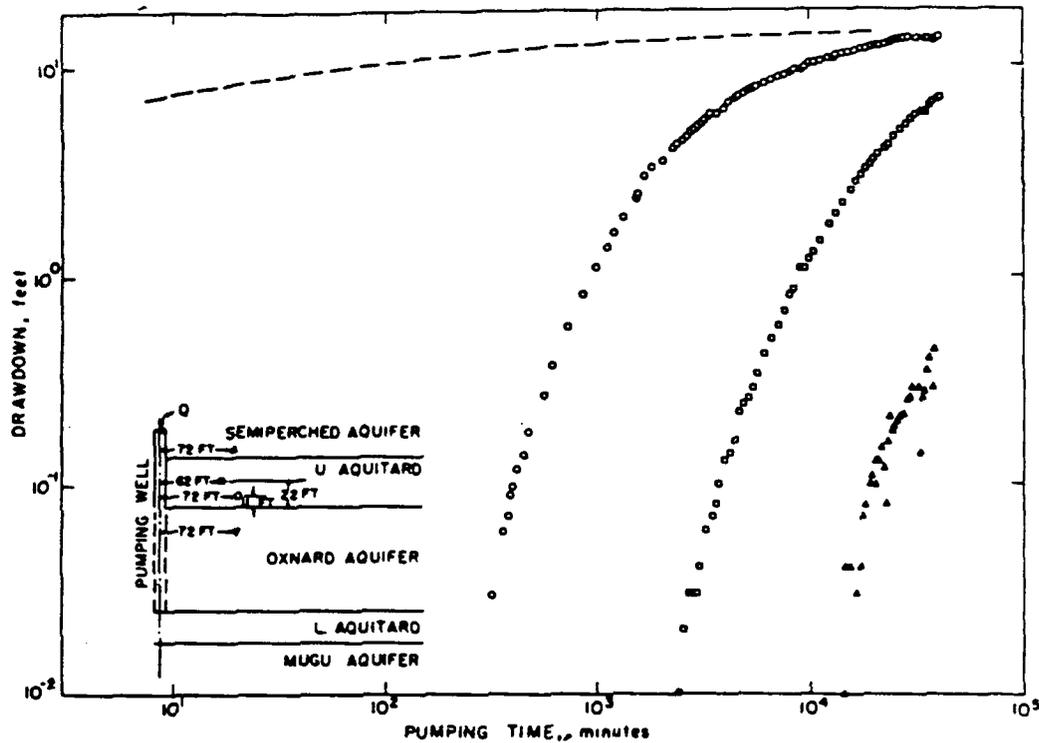


Fig. 9. The response of the piezometers in the upper aquitard (well 4, circles, and well 5, squares) and the semiperched aquifer (well 4A, triangles) during the first pumping test. The broken line indicates the probable response of the Oxnard aquifer at  $r = 72$  feet.

The results of the second pumping test were essentially the same as those of the first test and will therefore not be presented here.

DETERMINATION OF AQUITARD PROPERTIES USING FIELD AND LABORATORY RESULTS

Having determined the hydraulic diffusivities, we can evaluate the permeability  $K'$  of each aquitard if the storage factor is known. The values of  $S_e'$  were calculated from consolidation

TABLE 3. Results for Hydraulic Diffusivity of Aquitards from First Pumping Test

Layer	Section Tested	$K'/S_e'$ , gpd/ft	$K'/S_e'$ , cm <sup>2</sup> /sec
Upper aquitard	bottom 22 feet	$1.02 \times 10^3$	$1.47 \times 10^{-1}$
Upper aquitard	bottom 11 feet	$2.44 \times 10^3$	$3.51 \times 10^{-1}$
Lower aquitard	top 6 feet	$4.17 \times 10^3$	$5.99 \times 10^{-1}$

tests performed in the laboratory [California Department of Water Resources, 1971, pp. 106-110] by using the formula

$$S_e' = \alpha_e \gamma_w / (1 + e) \quad (11)$$

These values were then used to calculate  $K'$  according to

$$K' = \alpha' S_e' \quad (12)$$

and the results are summarized in Table 4.

Direct measurements performed on undisturbed samples in the laboratory indicated that the aquitard permeabilities vary within a range of at least 3 orders of magnitude. The results in Table 4 fall on the high side of this range and thus are an indication that the average permeability in the field cannot always be reliably estimated from laboratory measurements.

It is interesting to compare the specific storage and permeability of the aquitard with those of the Oxnard aquifer. Using an aquifer thickness

Layer  
Upper aquitard  
Upper aquitard  
Lower aquitard

of 93 feet, or

$$K = \frac{r^2 S_e'}{4t}$$

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TABLE 4. Hydraulic Properties of Aquitard Layers

Layer	Section Tested	Specific Storage $S_s'$		Permeability $K'$	
		cm <sup>-1</sup>	ft <sup>-1</sup>	cm/sec	gpd/ft <sup>2</sup>
Upper aquitard	bottom 21 feet	$7.88 \times 10^{-6}$	$2.4 \times 10^{-6}$	$1.11 \times 10^{-6}$	$2.45 \times 10^{-3}$
Upper aquitard	bottom 11 feet	$7.88 \times 10^{-6}$	$2.4 \times 10^{-6}$	$2.66 \times 10^{-6}$	$5.85 \times 10^{-3}$
Lower aquitard	top 6 feet	$3.28 \times 10^{-6}$	$1.0 \times 10^{-6}$	$1.89 \times 10^{-6}$	$4.17 \times 10^{-3}$

of 93 feet, one has

$$K = \frac{T}{b} = \frac{130,600}{93} = 1405 \text{ gpd/ft}^2$$

and

$$S_s = \frac{S}{b} = \frac{1.12 \times 10^{-4}}{93} = 1.20 \times 10^{-6} \text{ ft}^{-1}$$

Thus the permeability of the aquifer exceeds that of the aquitards by more than 4 orders of magnitude. However, note that the specific storage of the aquifer is less than  $S_s'$  in the aquitards above and below by 2 orders of magnitude. In other words, for the same change in head a unit volume of aquitard material can contribute about 100 times more water from storage than a similar volume of the aquifer can. This statistic confirms our belief that storage in the aquitards must be considered when one deals with leaky aquifer systems.

NOTATION

- $\alpha_c$ , coefficient of compressibility, equal to  $-\Delta e/\Delta p$ ,  $LT^2M^{-1}$ ;
- $b_i$ , thickness of  $i$ th aquifer,  $L$ ;
- $b_j'$ , thickness of  $j$ th aquitard,  $L$ ;
- $e$ , void ratio;
- $K_i$ , permeability of  $i$ th aquifer,  $LT^{-1}$ ;
- $K_j'$ , permeability of  $j$ th aquitard,  $LT^{-1}$ ;
- $p$ , pressure,  $ML^{-1}T^{-2}$ ;
- $Q_i$ , pumping rate from  $i$ th aquifer,  $L^3T^{-1}$ ;
- $r$ , radial distance from pumping well,  $L$ ;
- $r/B_{i,j}$ , dimensionless leakage parameter, equal to  $r(K_j'/K_i b_j')$ ;<sup>1/2</sup>
- $s_D$ , dimensionless drawdown, equal to  $4\pi T_i s/Q_i$ ;
- $s_i$ , drawdown in  $i$ th aquifer,  $L$ ;
- $s_j'$ , drawdown in  $j$ th aquitard,  $L$ ;
- $S_{i,j}$ , storage coefficient of  $i$ th aquifer, equal to  $S_{i,b_i}$ ;
- $S_{i,j}'$ , specific storage of  $i$ th aquifer,  $L^{-1}$ ;
- $S_{i,j}'$ , specific storage of  $j$ th aquitard,  $L^{-1}$ ;
- $t$ , pumping time,  $T$ ;

- $t_{D,i}$ , dimensionless time for pumped  $i$ th aquifer, equal to  $K_i t/S_{i,j} r^2$ ;
- $t_{D,j}'$ , dimensionless time for  $j$ th aquitard, equal to  $K_j' t/S_{i,j}' r^2$ ;
- $T_i$ , transmissibility of  $i$ th aquifer, equal to  $K_i b_i$ ,  $L^2T^{-1}$ ;
- $z$ , vertical coordinate,  $L$ ;
- $\alpha_i$ , hydraulic diffusivity of  $i$ th aquifer, equal to  $K_i/S_{i,j}$ ,  $L^2T^{-1}$ ;
- $\alpha_j'$ , hydraulic diffusivity of  $j$ th aquitard, equal to  $K_j'/S_{i,j}'$ ,  $L^2T^{-1}$ ;
- $\beta_{i,j}$ , dimensionless leakage parameter, equal to  $r/4b_i(K_j'/K_i S_{i,j}')^{1/2}$ ;
- $\gamma_w$ , specific weight of water,  $ML^{-1}T^{-2}$ .

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