SCREENING EVALUATION OF REMEDIAL TECHNOLOGIES
Martin State Airport: Middle River, Maryland

LOCKHEED MARTIN

Tetra Tech
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Screening Evaluation of Remedial Technologies
Martin State Airport
Middle River, Maryland

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APPENDIX

SECTION 1

Section 1

Introduction

On behalf of Lockheed Martin Corporation, Tetra Tech, Inc. has prepared the following report that provides identification and screening of remedial technologies for the southeast portion of Martin State Airport in Middle River, Maryland. This document contains a summary of site conditions, preliminary remedial action objectives developed for the site, and screening of viable technologies and process options to identify potential remedial alternatives for feasibility / treatability studies and remedial action plan (RAP) development.

This report is organized as follows:

- Section 2 – Site Background: Presents a brief description of the site, soil and groundwater conditions, and description of the previous investigations;
- Section 3 – Preliminary Remedial Action Objectives: Describes the remedial action objectives;
- Section 4 – Identification and Screening of Remedial Technologies: Presents a range of potential remedial technologies and process options, and a screening evaluation based on effectiveness, implementability, and cost;
- Section 5 – Viable Remedial Alternatives: Summarizes the viable remedial alternatives based on screening evaluation;
- Section 6 – Remedial Alternatives and Proposed Treatability Studies: Proposes site-specific remedial alternatives for each chemical plume and treatability studies to evaluate site-specific effectiveness; and
- Section 7 – References: Cites references used to compile this report.

SECTION 2

Section 2

Site Background

2.1 SITE LOCATION

Martin State Airport is located at 701 Wilson Point Road in Middle River, Maryland, and is bounded by Frog Mortar Creek to the east and Stansbury Creek to the west. Both creeks join into Chesapeake Bay at the south side of the airport. With large surface water bodies surrounding most of the perimeter, the setting can be considered a small peninsula. The project site is located at the southeast portion of the Martin State Airport and is bounded by Frog Mortar Creek to the east, and the main airport runway to the west. The site location is shown in Figure 2-1 in Appendix A.

2.2 SUBSURFACE CONDITIONS

2.2.1 Geology

Martin State Airport is located in the Western Shore of the Coastal Plain Physiographic Province. Based on geologic mapping of Baltimore County, the property is underlain by the Potomac Group, a Cretaceous age interbedded gravel, sand, silt, and clay unit ranging in thickness from 0 to 800 feet. The Potomac Group is composed of three units: the Raritan and Patapsco Formations, the Arundel Clay, and the Patuxent Formation. The Raritan and Patapsco Formations range up to 400 feet thick and are composed of a gray, brown, and red variegated silt and clay unit with lenticular lenses of sand and few gravels. The Arundel Clay is composed of dark gray and maroon lignitic clays and ranges in thickness from 0 to 100 feet. The Patuxent Formation is described as a white or light gray to orange brown, moderately sorted sand unit with quartz gravels, silts and clays and ranges up to 250 feet in thickness.

Based on lithologic logging of soil borings within the project site, the subsurface soils are highly heterogeneous, consisting of gravels, sands, silts, and clays. While some soil zones were consistently observed throughout the project site, generally the soil lithology varied considerably between soil borings. The soils consist of an upper layer of fill materials that overlies native soils of the Potomoc Group. The maximum depth of the logged borings (110 feet below ground surface [bgs]) identified interbedded sands, silts, and clays of the Patapsco Formation. During the data gap investigation (Tetra Tech, May 2004), additional deep borings were completed to provide more comprehensive soil lithology information across the project site. A summary of the dominant soil types at each monitoring well location is shown in Figure 2-2 in Appendix A. This figure also presents the monitoring well screen elevations and thicknesses for comparison purposes. Subsurface characteristics are further illustrated in seven cross sections prepared for the site. A site map showing the cross section locations is presented in Figure 2-3 in Appendix A. Cross sections A-A′, B-B′, C-C′, and D-D′ (Figures 2-4 through 2-7 in Appendix A) depict subsurface conditions along a northwest to southeast axis. Cross sections X-X′, Y-Y′, and Z-Z′ (Figures 2-8 through 2-10 in Appendix A) depict subsurface conditions along a northeast to southwest axis. These cross sections are described in Data gap and Hyrogeologic Investigation and Modeling (Tetra Tech, May 2004).

Based on soil boring log data and the cross sections, shallow subsurface were divided into three layers:

- Upper Surficial Aquifer, -15 feet msl above, consists of artificial fill that occurs within the uppermost 10 to 20 feet bgs, and native sediments beneath the fill materials. The uppermost native soils are heterogeneous sands, silts, and clays.

- Intermediate Surficial Aquifer is defined from -15 to -45 feet msl. In general, coarser-grained materials (well graded sands and poorly graded fine sands) were dominant in the layer.

- Lower Surficial Aquifer defined from -45 to -75 feet msl, consists of well graded sands and finer-grained materials, primarily low to medium plastic clay, occur from approximately -65 to -75 feet msl, which is the maximum logged depth at the site.

2.2.2 Hydrogeology

The uppermost water-bearing zone in the region is known as the Patapsco Formation. Available regional well log data indicate that the Patapsco Formation may extend to a depth of approximately 120 feet bgs beneath the site. The Patapsco Formation is underlain by the Arundel Formation, a thick red clay aquiclude. Regional lithologic information indicates that the Arundel Formation is approximately 120 feet thick and serves as the aquiclude overlying the water-bearing Patuxent Formation. Based on this information, the Arundel Formation may extend from 120 to 240 feet bgs at Martin State Airport.

Based on the physiographic setting as a narrow peninsula, surficial groundwater will tend to flow away from topographic rises and toward open water (i.e., toward Chesapeake Bay). The Patapsco aquifer is recharged directly by rainfall in the unpaved portions of the site. Annual precipitation is approximately 42 to 46 inches.

Figures 2-11 through 2-13 are groundwater elevation (head) contours for the Upper Surficial Aquifer, Intermediate Surficial Aquifer and Lower Surficial Aquifer, respectively. Groundwater contours were based on the field measurements of groundwater elevation taken on October 14, 2003. Groundwater flow direction in the surficial aquifer is northeast toward Frog Mortar Creek. Horizontal groundwater gradients were calculated at 0.003 in the Upper Surficial Aquifer, 0.002 in

Intermediate Surficial Aquifer, and 0.0018 in the Lower Surficial Aquifer. Vertical groundwater gradients range from 0.001 to 0.006. Hydraulic conductivities range from 5 ft/day to 20 ft/day for sandy soils, and from 0.01 ft/day to 0.2 ft/day for clayey soils. Lateral groundwater linear velocity was estimated at 0.1 ft/day. The calculation is based on groundwater gradient of 0.003, hydraulic conductivity of 10 ft/day, and soil porosity of 0.3.

2.3 SUMMARY OF PREVIOUS INVESTIGATIONS

2.3.1 Investigations Conducted By MAA

From 1992 through 1996, the Maryland Aviation Administration (MAA) conducted several investigations at the southeast portion of Martin State Airport[1]. Results of the investigations identified four areas of concern. The locations of the four areas of concern are described as follows:

1) *Taxiway Tango Median Anomaly Area* – After removal of four buried drums in 1991, a geophysical survey was conducted throughout the area adjacent to Taxiway Tango. Several anomalous zones were identified as potentially containing buried metal.

2) *Drum Area* – During a previous investigation conducted at the site in 1996, several drums were uncovered during surface vegetation clearing.

3) *Two Existing Ponds* – Based on historical records, acids may have been discharged during the 1950's and 1960's at the locations where two ponds currently exist.

4) *Petroleum Hydrocarbon Area* – During a previous investigation conducted at the site in 1996, petroleum hydrocarbons were encountered while drilling a soil boring. The petroleum hydrocarbon area is located approximately 200 feet west of the ponds.

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[1] The previous investigations included the following: (1) Geophysical Survey of Taxiway Tango (Handex 2/92), (2) Preliminary Site Investigation of Taxiway Tango (MES 5/94), (3) Confirmation Investigation of Taxiway Tango (MES 1/95), and (4) Expanded Investigation of Taxiway Tango (MES 7/96).

2.3.2 Investigations Conducted By Lockheed Martin Corporation

Previous sampling and investigation tasks conducted at the site by Lockheed Martin Corporation consisted of:

(1) Sampling existing groundwater monitoring wells in March 1999 (Tetra Tech, May 1999);

(2) Source identification and assessment program at four areas of concern in March through May 2000 (Tetra Tech, September 2000);

(3) Chemical delineation and modeling during December 2001 through December 2002 (Tetra Tech, December 2002); and

(4) Data gap and hydrogeologic investigation and groundwater modeling, April, 2004 (Tetra Tech, May 2004)

These investigation programs have adequately completed the vertical and lateral delineation of the existing groundwater chemical plumes. The site characterization and modeling effort has improved understanding of the surficial aquifer system, resulting in a site conceptual model that explains aquifer characteristics, chemical sources, and plume migration pathways. The important characteristics of groundwater chemical plumes are described in Section 2.5.

2.4 CHEMICALS OF CONCERN

Groundwater

Based on concentration and frequency of detection, three chlorinated VOCs (cis-1,2-DCE, TCE, and vinyl chloride) and one metal (dissolved cadmium) are considered the primary chemicals of concern (COCs). These four primary COCs were detected throughout the investigation area with the highest concentrations in the Upper and Intermediate Surficial Aquifers. Most other chemicals detected above Maryland Department of the Environment (MDE) groundwater cleanup standards, including aromatic VOCs, selected SVOCs, and other metals, were generally found co-located with the four primary COCs.

Soil

Historical soil sampling data reported relatively low concentrations of chemicals, indicating most of the chemical mass was transported from the vadose zone to groundwater during the last 40 years. Based on the analysis of soil samples collected from the source identification and assessment program (Tetra Tech, September 2000), only one volatile organic compound, five semi-volatile organic compounds, and five priority pollutant metals were detected above the EPA Region III industrial soil risk-based concentrations.

2.5 VOC PLUME CHARACTERISITCS AND MIGRATION PATHWAYS

The suite of chlorinated VOCs found in groundwater at the site suggests partial anaerobic degradation of TCE to cis-1,2-DCE and vinyl chloride. The presence of elevated concentrations of breakdown products indicates an old release. Based on current distributions of the plumes, hydrogeological conditions, and chemical and physical properties, the chemical plumes are estimated to have originated approximately 40 to 45 years ago.

The lateral and vertical distribution of chemical concentrations in groundwater indicates that three potential source areas are present at the site contributing to three primary groundwater plumes. These source areas and plumes are as follows:

1) Plume No. 1, originating from the Drum Area
2) Plume No. 2, originating from the Petroleum Hydrocarbon and Pond #1 Area
3) Plume No. 3, originating from the Taxiway Tango median area

The plumes are migrating along the down-gradient groundwater flow path from west to east toward Frog Mortar Creek. While the three plumes represent the primary source areas, the chemicals have commingled, particularly at areas approaching Frog Mortar Creek, to form larger groundwater plumes. Figures 2-14 through 2-25 in Appendix A are depth-specific maps to depict the distribution of chemicals of concern (i.e., TCE, cis-1,2-DCE, vinyl chloride, and dissolved cadmium) in the Upper, Intermediate, and Lower Surficial Aquifers.

Characteristics and predicted movement of these plumes are described below:

Plume No. 1 (Drum Area)

- The former Drum Area is a source of VOCs in groundwater, primarily within the Upper Surficial Aquifer. TCE and cis-1,2-DCE concentrations greater than 10,000 μg/L were reported in monitoring well samples collected to the northeast (immediately down-gradient) of the Drum Area. Due to clay layers serving as barriers, very little vertical transport occurs from the Upper to the Intermediate Surficial Aquifer, and no identifiable vertical transport to the Lower Surficial Aquifer. As a result, plume movement is dominated by lateral transport, which occurs primarily within the Upper Surficial Aquifer.

- Cadmium was detected at low concentrations in the Upper and Intermediate Surficial Aquifers at the Drum Area. There is no vertical transport to the Lower Surficial Aquifer.

Plume No. 2 (Petroleum Hydrocarbon and Pond #1 Area)

- TCE, cis-1,2-DCE and vinyl chloride concentrations greater than 10,000 μg/L were reported in monitoring well samples collected directly east (down-gradient) of the Petroleum Hydrocarbon and Pond #1 Area. Vertical transport occurs from the Upper to the Intermediate Surficial Aquifer around the source area. There is no vertical transport to the Lower Surficial Aquifer. As a result, plume movement is dominated by both vertical and lateral transport, which occurs primarily within the Upper and Intermediate Surficial Aquifer.

- Cadmium was detected at high concentrations in the Intermediate Surficial Aquifer at wells down-gradient of the Petroleum Hydrocarbon and Pond #1 Area.

Plume No. 3 (Taxiway Tango Area)

- TCE and cis-1,2-DCE concentrations greater than 10,000 μg/L were reported in samples at two distinct locations. DMW-11, a suspected VOC source area within the Taxiway Tango median area, is characterized lithologically by thick clay. The presence of clay inhibits chemical movement and accounts for the localized extent of VOCs in the Upper Surficial Aquifer at this source area. The second area near DMW-1 (east of the median area) is characterized with laterally extensive sands in the Intermediate and Lower Surficial Aquifers. Lateral transport of VOCs occurs primarily within the deeper portions of the Aquifer. The presence of abundant fine-grained materials inhibits significant lateral transport in the Upper Surficial Aquifer toward Frog Mortar Creek.

- Cadmium was detected at high concentrations in the Intermediate and Lower Surficial Aquifer at wells down-gradient of the Taxiway Tango median area.

2.6 CHEMICAL MASS ESTIMATION

A total of 200 pounds (lbs) of Cadmium and 40,000 lbs of VOCs are estimated to be present in groundwater. The majority of the VOC mass is TCE, cis-1,2-DCE and vinyl chloride. The mass is estimated at approximately 24,000 lbs for TCE, 13,000 lbs for cis-1,2-DCE and 3,000 lbs for vinyl chloride. Results of the chemical plume mass estimations are presented in Table 2-1.

Table 2-1
Summary of Chemical Mass Estimates

Chemical	Aquifer	Plume 1 (Drum Area)	Plume 2 (Petroleum Hydrocarbon Area)	Plume 3 (Taxiway Tango Area)	Total (lbs)
TCE	Upper	9,700	1,400	3,200	14,300
	Intermediate	370	8,300	450	9,120
	Lower	0	0	580	580
	TCE Total (lbs)	**10,070**	**9,700**	**4,230**	**24,000**
cis-1,2-DCE	Upper	2,800	3,700	850	7,350
	Intermediate	50	3,800	1,400	5,250
	Lower	0	0	400	400
	cis-1,2-DCE Total (lbs)	**2,850**	**7,500**	**2,650**	**13,000**
Vinyl Chloride	Upper	60	1,700	100	1,860
	Intermediate	10	900	150	1,060
	Lower	0	0	80	80
	Vinyl Chloride Total (lbs)	**70**	**2,600**	**330**	**3,000**
Cadmium	Upper	30			
	Intermediate	140			
	Lower	30			
	Cadmium Total (lbs)	**200**			

SECTION 3

Section 3

Preliminary Remedial Action Objectives

The primary purpose of the remedial action is to protect human and ecological receptors from exposure to the site contaminants. The preliminary remedial action objectives are:

- ✓ To mitigate potential impacts to Frog Mortar Creek due to migrations of the groundwater chemical plumes;
- ✓ To mitigate shallow impacted soils (i.e. hot spots) if there are risks to human health and ecological receptors;
- ✓ To treat hotspots (i.e., source areas) of groundwater chemical plumes; and
- ✓ To reduce concentrations of VOCs within the groundwater chemical plumes to action levels established by the human health and ecological risk assessments.

SECTION 4

Section 4

Identification and Screening of Remedial Technologies

4.1 IDENTIFICATION OF TECHNOLOGY TYPES AND PROCESS OPTIONS

The process of developing and screening remedial action alternatives was conducted by dividing treatment technologies into six general categories: 1) no action; 2) institution controls; 3) containment; 4) passive treatment; 5) active ex-situ treatment; and 6) active in-situ treatment. Remedial technologies and process options were further developed based on these general categories. The first step of the alternative development was to identify general remedial technologies, followed by separating them into the six categories. A summary table describing general technologies and possible process options is shown in Table 4-1 and discussed in the following subsections.

Upon identifying a wide-range of potential remedial technologies and process options, a screening evaluation was performed based on the criteria of effectiveness, implementability, and cost. Factors that eliminated certain technologies included cost, treatment time, difficulty to employ (with respect to site conditions), and uncertainty in effectiveness. Based on the screening evaluation, the feasible remedial alternatives are described in Section 5.

Table 4-1 Screening of Technologies and Process Options

General Response Action	Remedial Technology	Process Option	Effectiveness	Implementability	Cost	Acceptance for Further Evaluation	
						Yes	No
No action	None	Not Applicable	Does not achieve remedial action objectives	Not Applicable	None		X
Institutional Controls	Access Restriction	Fencing	Prevents direct exposure however does not meet remedial action objectives	Easily implemented	Low		X
Containment	Capping	Geomembrane	Effective in preventing direct contact. Minimizes surface water infiltration. Process is not consistent with remedial action objectives.	Long term maintenance required	Moderate to high		X
		Pavement		Easily implemented and maintained	Low		X
Passive Treatment	Natural Attenuation	Soil, Soil Vapor and Groundwater Monitoring	Based on site-specific conditions of dispersion, dilution, sorption, and biological action	Easily implemented, monitoring for long time	Low	X	
Active Ex-situ Treatment	Removal	Excavation of soil with backhoe	Effective for removal of soil down to 15 feet	Easily implmented	Low	X	
		Pumping Groundwater with wells or trenchs	Effective for removal of groundwater to the surface for treatment	Easily implemented, long time operation	High		X
		Biological, Oxidation, UV, Air Stripping, Activated Carbon	Several methods to treat the extracted groundwater	Easily implemented, long time operation	High		X

Table 4-1 Screening of Technologies and Process Options (Continued)

General Response Action	Remedial Technology	Process Option	Effectiveness	Implementability	Cost	Acceptance for Further Evaluation	
						Yes	No
Active in-situ Treatment	Stabilization	Soil blending with cement, lime and/or pozzolanic agents	Effective for immobilization of metals. Soil blending becomes difficult beyond the shallow soils.	Treatability tests will be required.	Moderate to high for small quantities of soil requiring remediation.		X
Active in-situ Treatment	Fixation	Soil blending with emulsifierand silica	Effective for immobilization of metals in soils	Treatability tests will be required.	Moderate to high for small quantities of soil requiring		X
		Soil blending with polysilcate additives	Very effective for immobilization of metals in soils	Treatability tests will be required.	Moderate to high for small quantities of soil requiring		X
	Biological	Phytoremediation	Effective for VOC and metals in groundwater, however, not effective for deep aquifer.	Not implementable for deep aquifer	Low		X
	Thermal	Steam Injection	Enhance removal of VOCs absorbed to soils.	Requires water, heat source, and extensive piping and aboveground treatment.	High		X
	Physical	Air Sparging/Vapor extraction (AS/VE)	Effective in shallow groundwater and sand	Not implementable for deep aquifer	Medium to high		X
		Air Sparging in Recirculation wells	Effective in shallow groundwater and sand	Not implementable for deep aquifer	High		X

Table 4-1 Screening of Technologies and Process Options (Continued)

General Response Action	Remedial Technology	Process Option	Effectiveness	Implementability	Cost	Acceptance for Further Evaluation	
						Yes	No
Active in-situ Treatment	Chemical	Chemical Oxidation (Fenton's reagent, permanganate)	Effective for VOCs, however, cost prohibitive except within an isolated source area	Easily implemented	High	X	
	Chemical/ Biological	Permeable Recative Barrier (PRB) Zero Valent Iron (ZVI)	Effective for increasing the process for natural biodegradation to take place for chlorinated VOCs in groundwater	Easily implemented for shallow groundwater	Medium to High	X	
		Zero Valent Iron (ZVI) micro- or nano-particles	Suspensions of ZVI injected through chlorinated VOC plumes	Pilot test needed to determine spacing of injection	Medium to High	X	
		Electron donor addition (Proprietary and non-proprietary addition)	Effective to enhance anaerobic reduction of chlorinated compounds	Pilot test needed to determine spacing of injection	Medium to High	X	
		Enhanced Bioremediation (addition of microbes, nutrients, and substrate)	Chemical-specific microorganisms	Pilot test needed to determine spacing of injection	Medium to High	X	

4.1.1 No Action and Institutional Controls

The no action and institutional controls alternatives are options that can be easily implemented and maintained at no to low cost. Under the no action alternative, potential risks to human heath and ecological habitat would remain as identified by the risk assessment. Institutional controls would mitigate the risk to human health by eliminating site access; however, this would not mitigate ecological risks. No action and institutional controls were eliminated since they did not meet the remedial action objectives of mitigating potential impacts to Frog Mortar Creek, and reducing concentrations of COCs within the plumes.

4.1.2 Containment

Containment technologies are generally easy to implement, but have a wide cost range. Surface containment technologies such as capping are generally easy to install and maintain. Costs would vary based on the level of protectiveness, but a low-to-moderate cost option such as paving would provide sufficient protection for the public health by eliminating exposures to vapors and direct soil contact. However, the containment technologies were eliminated for further consideration because they did not meet the remedial action objectives of minimizing potential impacts to the creek, and decreasing concentrations of COCs within the plumes.

4.1.3 Passive Treatment

Passive treatment technology such as natural attenuation is generally easy to implement with low cost. Natural attenuation might, after a long period of time, mitigate human health and ecological risks. However, during the period of attenuation, the contaminants would continue to migrate, and potentially degrade groundwater and surface water quality. Natural attenuation was retained as a viable approach for further consideration because it can be applied in conjunction with other remedial technologies.

4.1.4 Active Ex-situ Treatment

Ex-situ remediation is at a minimum, a two-step process. First the media of concern (i.e., soil, vapors, or groundwater) must be removed from its in-situ condition, and second a treatment process is applied to mitigate the contamination. A final step for the disposal of treatment residuals may also be required. A wide range of ex-situ remedial options was screened preliminarily, including removal, stabilization, biological treatment, and physical treatment. Removal options were considered relevant for this screening.

Removal

Removal options are the first step in an active ex-situ remediation process. They are generally well proven options that are easy to implement and low in cost for surface and near surface contamination, but more difficult and costly for deep contamination. Two options were screened: 1) excavation of shallow subsurface soil, and 2) pumping of groundwater from extraction wells or from an interception trench.

- Excavation would be effective and easy to implement as the first step in mitigation of impacted shallow soils. Excavation would not be effective for subsurface soil or groundwater impacted with VOCs, since these media could not be effectively removed from their in-situ locations. Excavation was retained as an option for shallow soils impacted with VOCs and metals.

- Pumping groundwater from extraction wells or an interception trench is an effective measure and relatively easy to implement as the first step in the remedy for VOC removal at high concentration areas. Pumping groundwater is not a favored technology because it has initial high contaminant removal rates followed by low removal rates in many field cases. Water treatment is required using granular activated carbon, air stripping unit or other viable treatment alternative, prior to discharge. However, to meet the remedial objectives for plume control and treatment at the site, this approach would have high construction and operation and maintenance (O&M) costs and long treatment time and therefore was eliminated from further consideration.

- The ex-situ water treatment technologies, biological, chemical oxidation, UV, air stripping, and activated carbon were not retained for further consideration for the site since pumping groundwater option above was eliminated.

4.1.5 Active In-situ Treatment

In-situ options including stabilization, fixation, biological treatment, thermal treatment, chemical/biological treatment and physical treatment were screened for applicability to the site.

4.1.5.1 Stabilization and Fixation

Stabilization with lime or cementation agents is proven to be effective for immobilizing metals, but not VOCs. Stabilization is difficult to implement at the depth of metal contamination at the site due to the requirement for in-situ blending of the affected soil with stabilization chemicals. In addition, fixation by emulsifiers and silica or polysilicate additives are effective for immobilizing metals, but with unknown or limited success for VOCs. Stabilization and fixation costs would be high for remediating deep soils.

In-situ stabilization and fixation options were eliminated from further consideration due to the site-specific condition that the cadmium plumes are present mainly in the Intermediate Surficial Aquifer.

4.1.5.2 Phytoremediation

Phytoremediation with specific plant species could be effective in removing metals and possible VOCs. Due to depth limitation of the plant roots, phytoremediation would not be effective for the deep impacted soil and groundwater at the site, and therefore was eliminated from further consideration.

4.1.5.3 Thermal – Steam Injection

Thermal in-situ treatment is moderately difficult to implement and expensive. There are several methods for applying heat to the groundwater, such as steam to enhance the removal of contaminants. Steam injection is considered effective in mobilizing and destroying VOCs, but not metals. Thermal treatment would require extensive surface facilities for implementation and high O& M costs, and therefore was eliminated from further consideration.

4.1.5.4 Air Sparging / Vapor Extraction (AS/VE)

Air sparging and vapor extraction (AS/VE) is a process where air is injected into groundwater to effectively remove VOCs by direct volatilization into the air stream, and the vapor phase is removed from the subsurface unsaturated zone by vapor extraction. Further treatment of the vapor phase would be required. The physical processes would not be effective for metals. The effectiveness of air sparging also depends on soil permeability. In general, an intrinsic permeability great than 10^{-9} cm^2 (i.e., a hydraulic conductivity value of 1.8 ft/day) is best for adequate air sparging flow. The hydrogeologic setting of the surficial aquifer at the site has highly stratified low-permeability clay lenses (hydraulic conductivity value of 0.1 ft/day), which is not favorable for the AS/VE option. Since AS/VE is not feasible for the site, it was eliminated from further consideration.

4.1.5.5 Air Sparging in Recirculation Wells

Air sparging in recirculation wells is proven to be effective in removal of chlorinated solvents from groundwater. However, the effectiveness of air sparging depends on soil permeability. Similar to AS/VE, air sparging in recirculation wells was eliminated from further consideration based on the low permeability of soils at the site.

4.1.5.6 Chemical Oxidation

Chemical oxidation methods offer the potential rapid (from a week to a month) removal chemicals of concern. Typical chemical agents such as Fenton reagent or potassium permanganate are injected into the groundwater. The oxidizing reactions destroy the chlorinated compounds effectively. In addition, chemical oxidation is easy to implement. However, because the chemical agents are expensive their applications are usually only practical in limited areas, typically source zones where soils have low-permeability, are highly stratified, or contains dense, non-aqueous-phase liquid (DNAPL). Since hydrogeologic settings of some source areas at the site are low permeability and highly stratified soils, chemical oxidation was retained as an option for further consideration.

4.1.5.7 Permeable Reactive Barrier (PRB) / Zero Valent Iron (ZVI)

Zero valent iron permeable reactive barriers have been used for in-situ remediation of VOCs and metals without the need to continually pump groundwater or add chemical reagents to the subsurface. The barrier can be placed on the migration pathways of VOC and metal plumes to prevent further migration of impacted groundwater. Cost associated with the treatment system is very low after construction is completed. However, periodic addition or regeneration of the reagent material may be required for maintaining performance of the reactive barrier. Since migration toward Frog Mortar Creek is a primary concern, the use of a barrier would be effective to treat both chlorinated VOCs and dissolved metals. Therefore, this technology was retained as an option for further consideration.

4.1.5.8 Zero Valent Iron (ZVI) Micro- or Nano-Particles

ZVI injection is a more recent development. Micrometer to nanometer sized ZVI particles are slurried with water and injected into the groundwater. These particles radiate out from the injection point. This method allows for treatment of the source directly, rather than waiting for the source plume to flow through a barrier. Alternatively, injection points can be placed close together to create a barrier in places where trenching is limited due to depth or interferences. Therefore, ZVI injection was retained as an option for further consideration.

4.1.5.9 Electron Donor Addition

Reductive dehalogenation would be effective in treating dissolved chlorinated solvents in groundwater. Since reductive dehalogenation is the primary natural biodegradation processes associated with the degradation of chlorinated VOCs, electron donors can be added to enhance these degradation reactions. Hydrogen ions are the actual source of electrons that drive the destruction of the chlorinated solvents. Various substances include but are not limited to emulsified vegetable oil, lactate, and ethanol. An engineered hydrogen source, Hydrogen Release Compound^{TM} [HRC^{TM}], is a proprietary polylactate compound manufactured by Regenesis for the specific purpose of groundwater remediation. Based on the effectiveness of electron donors to enhance anaerobic reduction of chlorinated solvents, it was retained as an option for further consideration.

4.1.5.10 Enhanced Bioremediation

Enhanced in-situ bioremediation involves the induction of enhancement agents to the impacted subsurface zones in an attempt to create conditions that can promote degradation of contaminants, which are chlorinated VOCs in this case. The appropriate environment induces anaerobic dechlorination of the primary COCs (TCE, cis-1,2-DCE and vinyl chloride) to innocuous end products (ethane and ethane). In reviewing the concentration ratios of biodegradation parent and daughter products within the plumes at the site, it is evident that degradation has occurred historically and may still be occurring. As a result, enhanced bioremediation was retained as an option for further consideration.

SECTION 5

Section 5

Viable Remedial Alternatives

Based on the screening evaluation presented in Section 4, the following technologies have been retained as viable potential remedial alternatives:

- Natural Attenuation
- Ex-situ Removal (metals in surface soils)
- In-situ Chemical Oxidation
- In-situ Permeable Reactive Barriers (PRB) with Zero Valent Iron (ZVI)
- In-situ Zero-Valent Iron (ZVI) Micro- or Nano-particles
- In-situ Electron Donor (ED)
- In-situ Enhanced Bioremediation (Bio-augmentation)

Further description and evaluation of these technologies are presented in the following subsections.

5.1 NATURAL ATTENUATION

Natural attenuation is defined as "biodegradation, dispersion, adsorption, and dilution" of contaminants in groundwater. Natural attenuation is a viable remediation strategy if site-specific data indicate that process will effectively reduce contaminants in the groundwater to concentrations protective of human health and environment in a timeframe comparable to that which could be achieved through active remediation. Natural attenuation may be appropriate as a stand-alone remedy or in conjunction with "hot spot" treatment. Performance monitoring is required to assure that natural attenuation processes continue and contingency measures may be required in the event that natural attenuation does not progress as expected. Natural processes take a long time, on the order of several years. Groundwater modeling is often performed to estimate the time to reach cleanup goals. The biodegradation component to natural attenuation can also be enhanced by supplementing the groundwater system with agents that are limiting the proliferation of microbes responsible for contaminant degradation.

The primary destructive mechanism associated with natural attenuation of organic contaminants is biodegradation. For chlorinated solvents, degradation proceeds primarily through reductive dehalogenation, resulting in the accumulation of degradation daughter products as shown below:

TCE → DCE → Vinyl Chloride

After reviewing the concentration ratios of biodegradation parent and daughter products within the plumes at the site, it is evident that degradation has occurred historically and may still be occurring. A final design for this approach would require additional sampling for geochemical parameters to evaluate the biological activity at the site. Based on the USEPA guidance document for natural attenuation, the time frame to meet cleanup goals can be estimated using public domain groundwater models.

Regulations may have default maximum concentrations for sites where natural attenuation can be applied as a remedial alternative. The concentrations of the plumes at the source may be higher than the default values; however, natural attenuation can be considered in conjunction with an active treatment system at the site.

5.2 EX-SITU REMOVAL OF SOILS

Soil excavation is a typical ex-situ removal method. Excavation is simply the process of digging up contaminated soil for treatment and / or disposal. It is generally used for removing contaminated soil where other treatment methods may be more expensive. Landfill debris, metals contaminated soils, and semi-volatile organics are contaminants typically addressed by excavation. Excavation may be considered in areas where potential risks may exist to human health and ecological receptors. Excavation to remove the contamination typically involves scrapping or removing the shallow subsurface soil using earth moving equipment.

5.3 IN-SITU CHEMICAL OXIDATION

Fenton's Reagent

The Fenton's applications for in-situ groundwater treatment have been developed since 1990's. Fenton's reagent generates hydroxyl radicals through the reaction of ferrous iron and hydrogen peroxide:

$$Fe^{+2} + H_2O_2 \Longrightarrow {}^{\cdot}OH + Fe^{+3} + OH^{-}$$

The process is self-replicating since the reaction of ferric iron with hydrogen peroxide to generate the perhydroxyl radical also occurs:

$$Fe^{+3} + H_2O_2 \Longrightarrow Fe^{+2} + {}^{\cdot}OOH + H^{+}$$

The perhydroxyl radical is a weaker oxidizer (between hydrogen peroxide and permanganate). However, more importantly the process generates ferrous ions that in turn stimulate further reaction with hydrogen peroxide to produce more hydroxyl radials. The hydroxyl radical can react with almost any hydrocarbon to produce carbon dioxide as a final product (and chlorides if a chlorinated hydrocarbon is treated). The key application issues are delivery of the reagents in-situ and pH control. Optimum pH for the reaction, in the range of 3.0 to 4.5, is driven by the iron chemistry. Improper control of the reaction will only generate oxygen and water, not high intensity oxidation.

The technology is ideal for application in source zone areas where there are high concentrations of adsorbed or even interstitial free product. Cost is mostly dependent upon the geochemistry of the geologic matrix and control of the iron chemistry. Soil buffering capacity may limit the ability to obtain optimal subsurface pH conditions. The chemical oxidation process is less efficient in the presence of soil. With regards to the rate of reaction and the degree of completion of the reaction, high concentrations of hydrogen peroxide (10% to 25%) are preferred. The heat generated by exothermic dissociation of hydrogen peroxide promotes contaminant volatilization. Concentrations as low as 11% can cause groundwater to boil. Excess consumption of hydrogen peroxide by reactions with the geologic matrix can be controlled by using multiple applications at concentrations of 5% or less.

Problems may occur when 1) too many iron minerals are present in the soil, 2) if the iron is in a mineralized form not readily available for dissolution under low pH conditions, and 3) the natural catalytic activity of the mineralized iron decomposes the hydrogen peroxide to oxygen and water and does not create the hydroxyl radical.

An additional problem with soil mineralogy comes from soils rich in carbonate minerals or with high alkalinity. These soils produce groundwater with a high pH. This can require unacceptable amounts of acid to buffer the pH down to the required range. Carbonate minerals respond to low pH so rapidly that the geologic matrix itself will consume acid. Lastly, the carbonate ion preferentially scavenges hydroxyl radicals before they have a chance to react with the COCs.

Permanganate

The reduction of the permanganate ion proceeds to Mn(II) at low pH conditions by the following reaction:

$$MnO_4^- + 8H^+ + 5e^- ==> Mn^{+2} + 4H_2O$$

The Mn (II) cation is soluble in water at concentrations above the 50 ppb when chloride or sulfate counter anions are present. Examples of complete reactions of permanganate with VOCs are as follow:

- PCE $C_2Cl_4 + 2MnO_4^- ==> 4Cl^- + 2CO_2 + 2\ MnO_{2(s)}$
- TCE $C_2HCl_3 + 2MnO_4^- ==> 3Cl^- + 2CO_2 + H^+ + 2MnO_{2(s)}$
- DCE $C_2H_2Cl_2 + 2MnO_4^- ==> 2Cl^- + 2CO_2 + 2H^+ + 2MnO_{2(s)}$

In contrast to Fenton's reagent, the presence of carbonate minerals in the geologic matrix has generally positive effects on permanganate oxidation: Mn reduction stops at Mn(IV) (insoluble) rather than proceeding to potentially soluble Mn (II). Trace minerals are co-precipitated and immobilized with the manganese oxide. Consumption of permanganate by reaction with reduced mineral such a magnetite is minimized because the rates of these reactions increase with decreasing pH. Oxidant demand from the matrix can be attributed to natural organic matter, reduced metals, carbonates and sulfides. Permanganate demand rates can vary from a few grams of permanganate per kilogram of soil (clean sand with dissolved COC) to as much as several hundred grams of permanganate per kilogram of soil (organic clays with 6% organic carbon content and NAPL). Typical dosage range (by weight) is 1.5% to 5% permanganate in the targeted treatment zone.

Immobile reduced metals such as chromium, uranium, vanadium, selenium and molybdenum (all of which are soluble as oxidized oxyanionic complexes) can be oxidized and mobilized by permanganate oxidation.

Under neutral to basic pH conditions, manganese dioxide (MnO_2) is the end product of the reduction of the permanganate oxyanion. A potential limitation of permanganate usage is that MnO_2 particles will cause permeability loss.

5.4 PERMEABLE REACTIVE BARRIER (PRB)/ZERO VALENT IRON (ZVI)

Permeable reactive barriers (PRB) have been widely tested and used to intercept and treat migrating contaminants in-situ. The reactive barriers can be built by mixing natural materials with one or several types of reactive materials. When contaminants migrate downstream in groundwater through the reactive barrier, they will react with the reactive materials contained in the reactive barrier. By using different reactive materials as filling for the barrier, various inorganic and organic contaminants can be treated in-situ. As a result, the contaminants can be passively fixed in-situ by sorption, reductively degraded, and/or directly precipitated (for inorganics) from the solution phase.

Zero-valent iron (ZVI), a strong chemical reductant, has been used for degradation of a variety of chlorinated solvents. ZVI through several mechanisms allows for hydrogen to replace chlorine in chlorinated compounds. For example, TCE is converted to ethene. ZVI can be brought into contact with VOC-impacted groundwater in two ways, barriers and injection. ZVI/PRBs are (1) installed by excavating trenches and filling them with porous iron material that is the form of iron filings, pellets, and iron-coated sand; (2) installed by injection of colloidal Fe^0 into a series of wells used to create a reactive barrier that can be installed much deeper than trenches.

5.5 ZERO VALENT IRON (ZVI) MICRO- OR NANO-PARTICLES

Injection of ZVI micro, or nano-meter particles is a more recent development. Micrometer to nanometer sized ZVI particles create large reactive surface area; therefore, a much smaller amount of total iron mass may be required to achieve the desired treatment efficiency. ZVI particles with water are injected into the groundwater. The particles radiate out from the injection point. This method allows for treatment of the source directly, rather than waiting for the source plume to flow through a barrier. Alternatively, injection points can be placed close together to create a barrier in places where trenching is limited due to depth or interferences. The injection points spacing for ZVI must be determined through a pilot/treatability test. Depending on the subsurface conditions, the spacing can vary from 5 to 25 feet.

5.6 IN-SITU ELECTRON DONORS

Electron donors (EDs) generally enhance anaerobic biological activity and degrade chlorinated VOCs under anaerobic, reducing conditions. ED compounds can be injected into the groundwater to enhance the biological activity. Application of EDs can occur in different ways, depending on the remedial goals. For example, the compounds can be injected in a series of points across the plume, perpendicular to the groundwater flow, both near the source and downgradient. Then, remediation takes place as the groundwater flows through the injected material. Injection points can also be at the source so that the high-concentration areas are treated within a shorter timeframe. A combination of injection locations, both at the source and downgradient can be considered. Further, these compounds fall into two general categories: slow-release and aqueous as discussed below.

- Slow-release EDs include Hydrogen Release Compound (HRC), vegetable oil, and chitin. HRC (a proprietary compound by Regenesis) is a polymeric compound that slowly releases lactic acid into the groundwater. The lactic acid is metabolized by microorganisms that reduce the chlorinated compounds. Vegetable oil and chitin are naturally occurring materials that can be similarly used by microorganisms during the reduction of chlorinated compounds. Many of these EDs persist for months before being exhausted.

- Aqueous EDs include lactate, ethanol, and similar short-chain hydrocarbons. These materials dissolve in water and are typically used quickly by the microorganisms.

EDs have been applied and demonstrated at numerous sites. As noted, some compounds like HRC are proprietary, while other compounds are available on the open market.

The injection point spacing for EDs must be determined through a pilot/treatability test. Injection point spacings of 5 to 10 feet are typical for viscous materials, while spacings of 15 to 25 feet have been observed for the more soluble materials. In general, the injection points spacing is a function of the subsurface conditions. In addition, multiple injections are often required. The initial injection may not be sufficient to completely degrade all of the contaminants, so follow-up injections may need to be conducted. A final design for this approach would require additional sampling for geochemical parameters to evaluate the biological activity at the site.

5.7 IN-SITU ENHANCED BIOREMEDIATION (BIOAUGMENTATION)

Bioaugmentation consists of injecting microorganisms into the groundwater that are efficient at degrading specific VOCs. These microorganisms are typically used with nutrients and/or other substrates (such as HRC^{TM}) to co-metabolize the VOCs. The initial increase in the microbial population also serves to speed up the remedial process.

Chemical-specific microorganisms have been applied and demonstrated at numerous sites. The organisms are mixed in water and applied using conventional direct push technology equipment.

There are several variations of the application. One method involves injection of the microorganisms, nutrients, and substrate directly into the groundwater, usually at the source. A combination of injections, both at the source and downgradient can be considered. A second variation withdraws groundwater, mixing in microorganisms, nutrients, and substrate above ground and then reinjecting the water. Finally, a permeable barrier can be installed across the path of the groundwater where the growth of the contaminant-specific microorganism is promoted. For this particular site, the injection method would be most applicable.

The injection point spacing for microorganisms must be determined through a pilot/treatability test. The injection point spacing of 15 to 25 feet would be expected in this case. In general, the number of injection points is a function of the subsurface conditions. In addition, multiple injections are often required. The initial injection may not be sufficient to completely degrade all of the contaminants, so follow-up injections may need to be conducted.

SECTION 6

Section 6

Remedial Alternatives and Proposed Treatability Studies

6.1 PROPOSED SITE-SPECIFIC REMEDIAL ALTERNATIVES

In order to accomplish the remedial action objectives for the southeast portion of Martin State Airport, the remedial technologies presented in the Section 5 were retained as viable alternatives. These alternatives can be considered in developing the following remedial strategy for the southeast portion of Martin State Airport site:

Plume No. 1

- Prevent migration of the groundwater chemical plume:

  The main focus will be on the plume in the Upper Surficial Aquifer. ZVI/PRB, ED and Bioaugmentation are the remedial alternatives proposed for treating the Upper Surficial Aquifer. VOC concentrations in the Intermediate Surficial Aquifer are relatively lower; therefore, the proposed remedial alternatives are bioaugmentation and natural attenuation.

- Remove metals in shallow subsurface soils:

  Excavation using earth moving equipment, may be applied to remove metal impacted soils.

- Treat VOCs hotspots:

  If treatment of VOC hotspots is necessary, the proposed remedial alternatives are ED, ZVI micro-or nano-particles and chemical oxidation.

Plume No. 2

- Prevent migration of the groundwater chemical plume:

  The main focus will be on the plume in the Upper and Intermediate Surficial Aquifers. ZVI/PRB, ED and Bioaugmentation are the proposed remedial alternatives.

- Remove metals in shallow subsurface soils:

  Excavation using earth moving equipment, may be applied to remove metal impacted soils.

- Treat VOCs hotspots:

  If treatment of VOC hotspots is necessary, the proposed remedial alternatives are ED, ZVI micro-or nano-particles and chemical oxidation.

Plume No. 3

- Prevent migration of the groundwater chemical plume:

  The main focus will be on the plume in the Intermediate and Lower Surficial Aquifers. ZVI/PRB, ED and Bioaugmentation are the proposed remedial alternatives.

- Remove metals in shallow subsurface soils:

  Excavation using earth moving equipment, may be applied to remove metal impacted soils.

- Treat VOCs hotspots:

  If treatment of VOC hotspots is necessary, the proposed remedial alternatives are ED, ZVI micro-or nano-particles and chemical oxidation.

Table 6-1 summarizes the proposed remedial alternatives for plumes and surficial aquifers.

Table 6-1 Proposed Remedial Alternatives for Plumes and Surficial Aquifers

Plumes	Surficial Aquifers	Metals in Surface Soils	Plume Migration			Hot Spot (VOCs)			Reduce VOC Concentrations in Groundwater	
		Removal Soils (up to 3 feet bgs)	ZVI PRB (VOCs+Metals)	Electron Donor (VOCs)	Bio-augmentation (VOCs)	Chemical Oxidation	ZVI Micro- or nano-particles	Electron Donor	Bio-augmentation	Natural Attenuation
Plume 1	Upper	√	√	√	√	√	√	√	√	√
	Intermediate	–	–	–	–	–	–	–	√	√
	Lower	–	–	–	–	–	–	–	–	–
Plume 2	Upper	√	√	√	√	√	√	√	√	√
	Intermediate	–	√	√	√	√	√	√	√	√
	Lower	–	–	–	–	–	√	√	√	√
Plume 3	Upper	√	–	–	–	√	√	–	–	√
	Intermediate	–	√	√	√	–	√	√	√	√
	Lower	–	√	√	√	–	√	√	√	√

6.2 PROPOSED TREATABILITY STUDIES

Based on the screening of remedial technologies, in-situ methods (i.e., electron donor addition, bioaugmentation, and ZVI injection) appear applicable at the site and will require treatability studies to evaluate their site-specific effectiveness. The following three treatability studies will be performed on-site in order to support final selection of the remedial technologies and design of the remedial action plan:

1) The first treatability study will consist of injecting a proven electron donor in an effort to enhance anaerobic biological activity at the site.

2) In the second treatability study, a specific microorganism will be added to evaluate whether increasing the microbial population will expedite remediation.

3) The third treatability study will consist of injecting zero valent iron into the groundwater to evaluate effectiveness in treating the COCs.

Details of the treatability studies will be presented in separate letter work plans that will be prepared and submitted to MDE. Data collected from the treatability studies will be evaluated as part of the RAP / design process.

SECTION 7

Section 7
References

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   Tetra Tech, May 2004

FIGURES

FIGURE 2-1
SITE LOCATION MAP

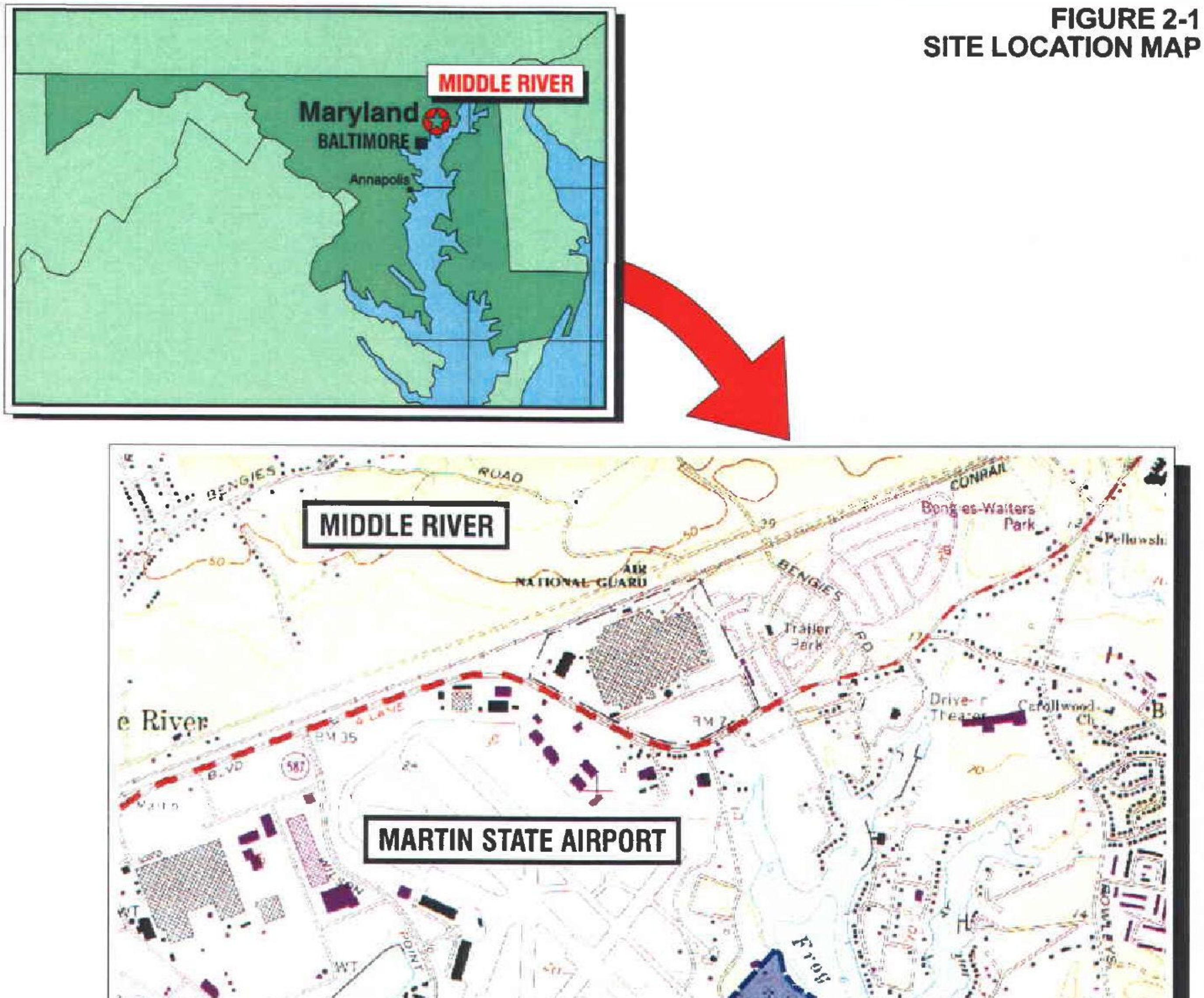
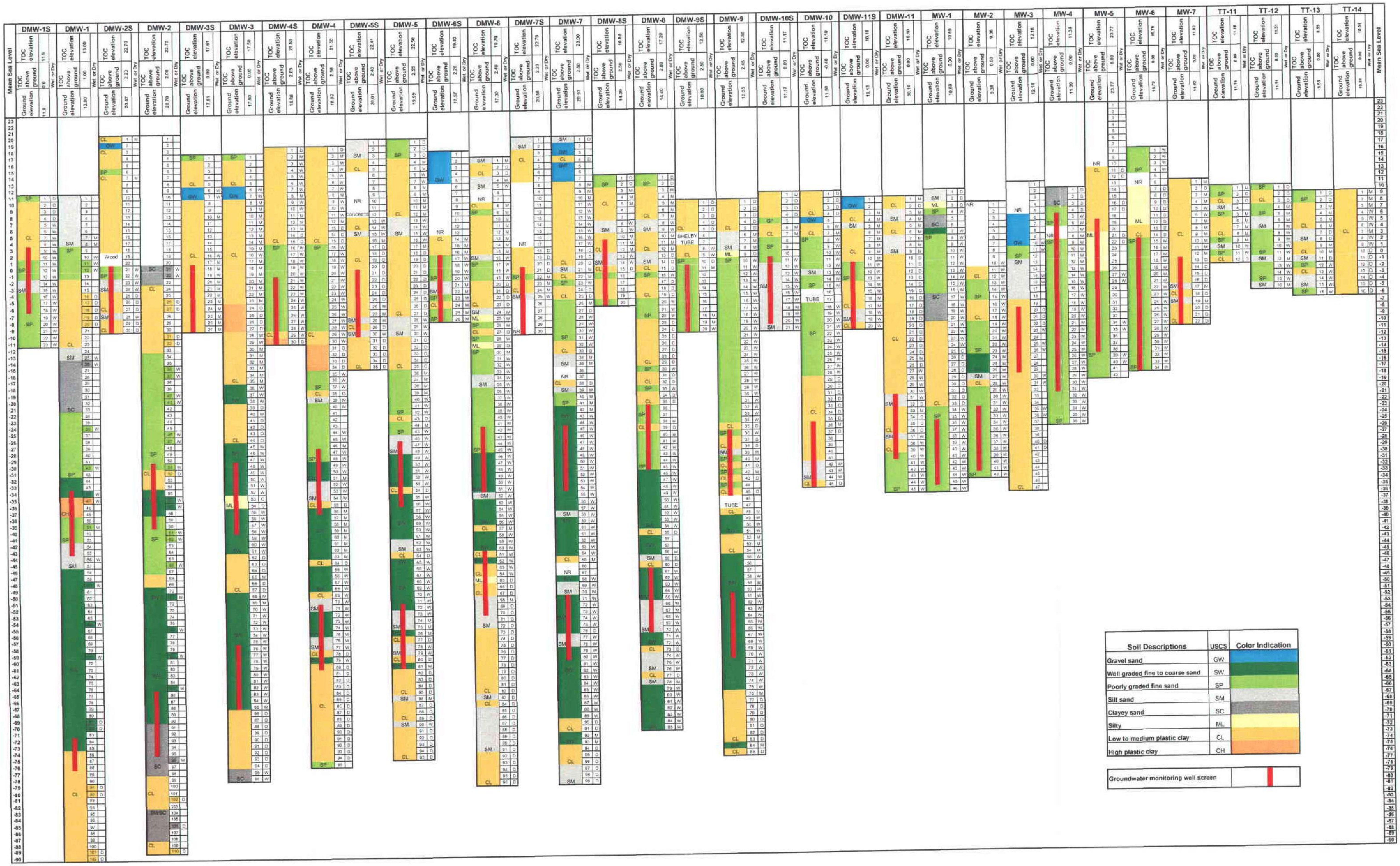


FIGURE 2-2 SUMMARY OF BORING LOGS AND WELL SCREENS



Soil Descriptions	USCS	Color Indication
Gravel sand	GW	🟦
Well graded fine to coarse sand	SW	🟩
Poorly graded fine sand	SP	🟩
Silt sand	SM	⬜
Clayey sand	SC	⬛
Silty	ML	🟨
Low to medium plastic clay	CL	🟨
High plastic clay	CH	🟧

Groundwater monitoring well screen	🟥

FIGURE 2-3
BORING LOCATIONS AND CROSS SECTION LAYOUT

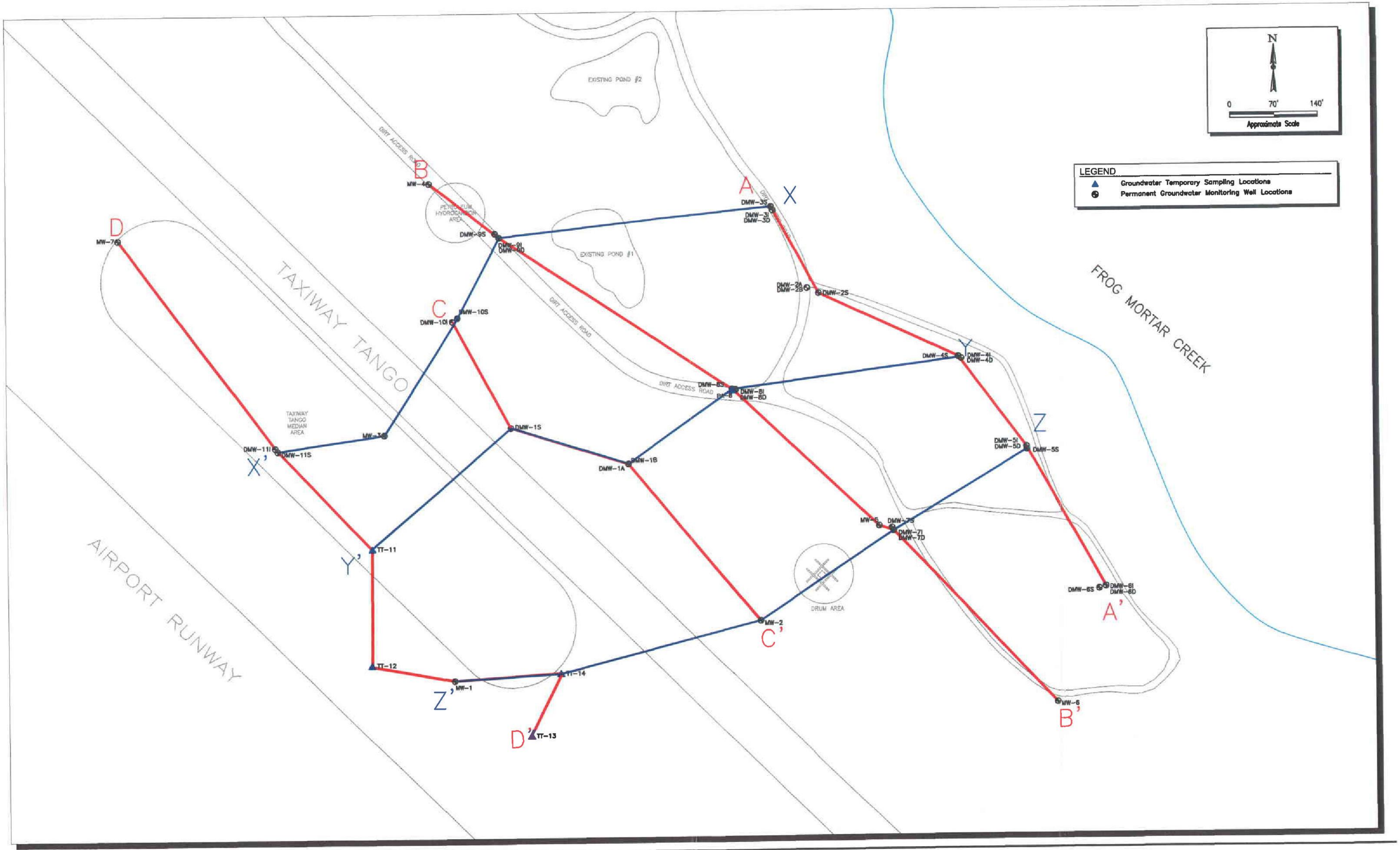
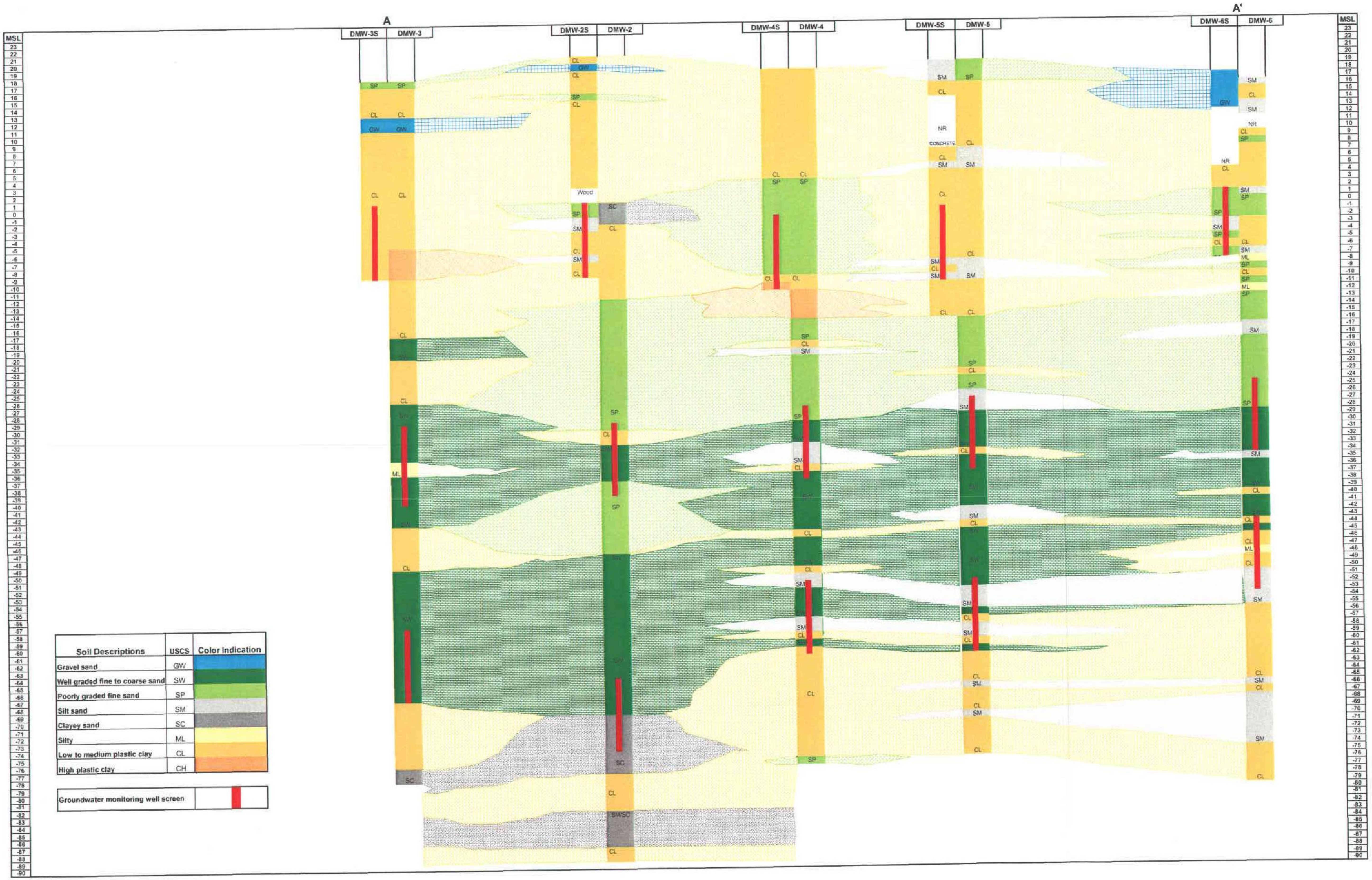


FIGURE 2-4 CROSS SECTION A-A'



Soil Descriptions	USCS	Color Indication
Gravel sand	GW	🟦
Well graded fine to coarse sand	SW	🟩
Poorly graded fine sand	SP	🟩
Silt sand	SM	⬜
Clayey sand	SC	⬛
Silty	ML	🟨
Low to medium plastic clay	CL	🟧
High plastic clay	CH	🟧

Groundwater monitoring well screen	🟥

FIGURE 2-5 CROSS SECTION B-B'

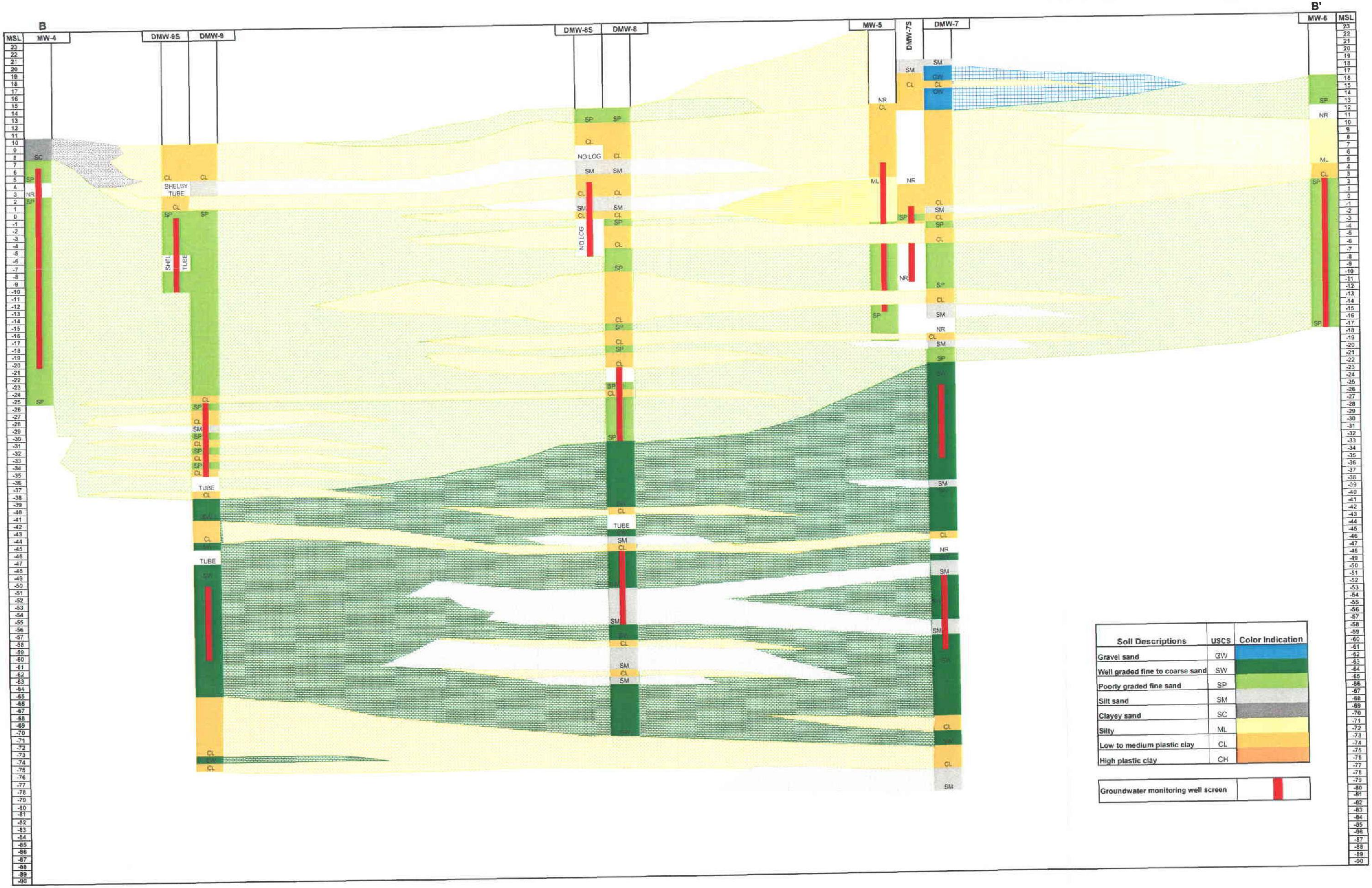


FIGURE 2-6 CROSS SECTION C-C'

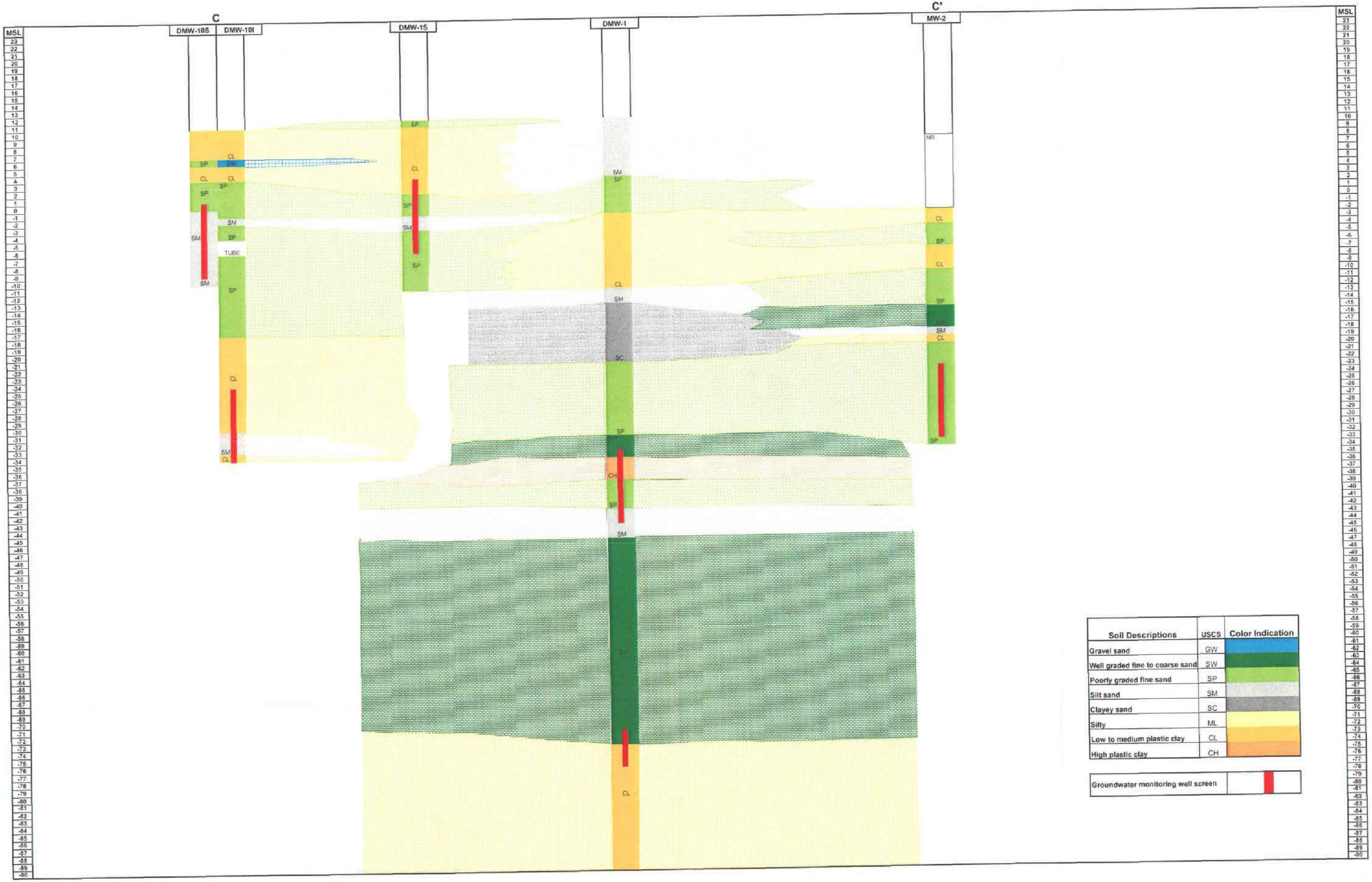
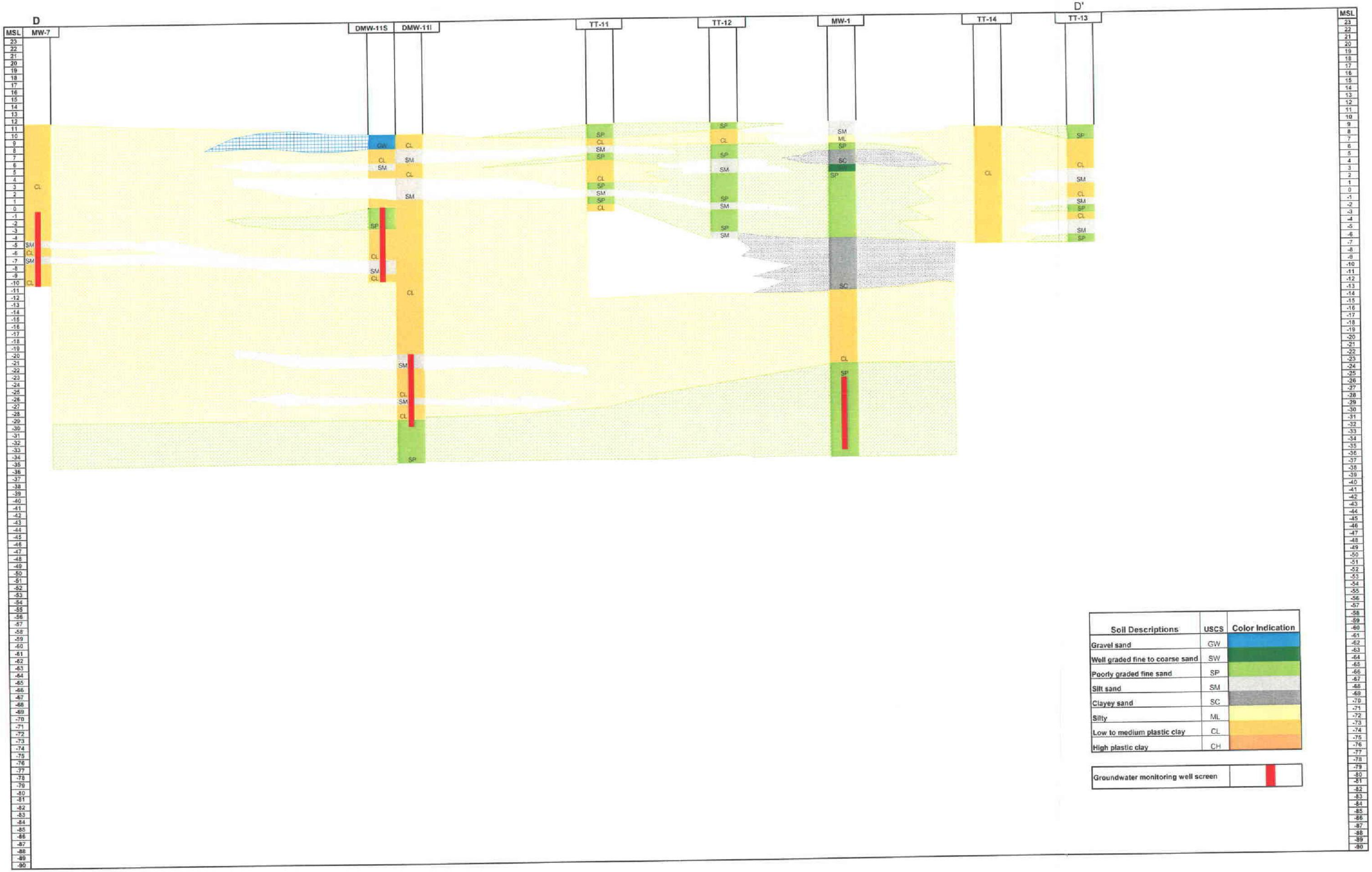


FIGURE 2-7 CROSS SECTION D-D'



Soil Descriptions	USCS	Color Indication
Gravel sand	GW	🟦
Well graded fine to coarse sand	SW	🟩
Poorly graded fine sand	SP	🟩
Silt sand	SM	⬜
Clayey sand	SC	⬛
Silty	ML	🟨
Low to medium plastic clay	CL	🟨
High plastic clay	CH	🟧

Groundwater monitoring well screen	🟥

FIGURE 2-8 CROSS SECTION X-X'

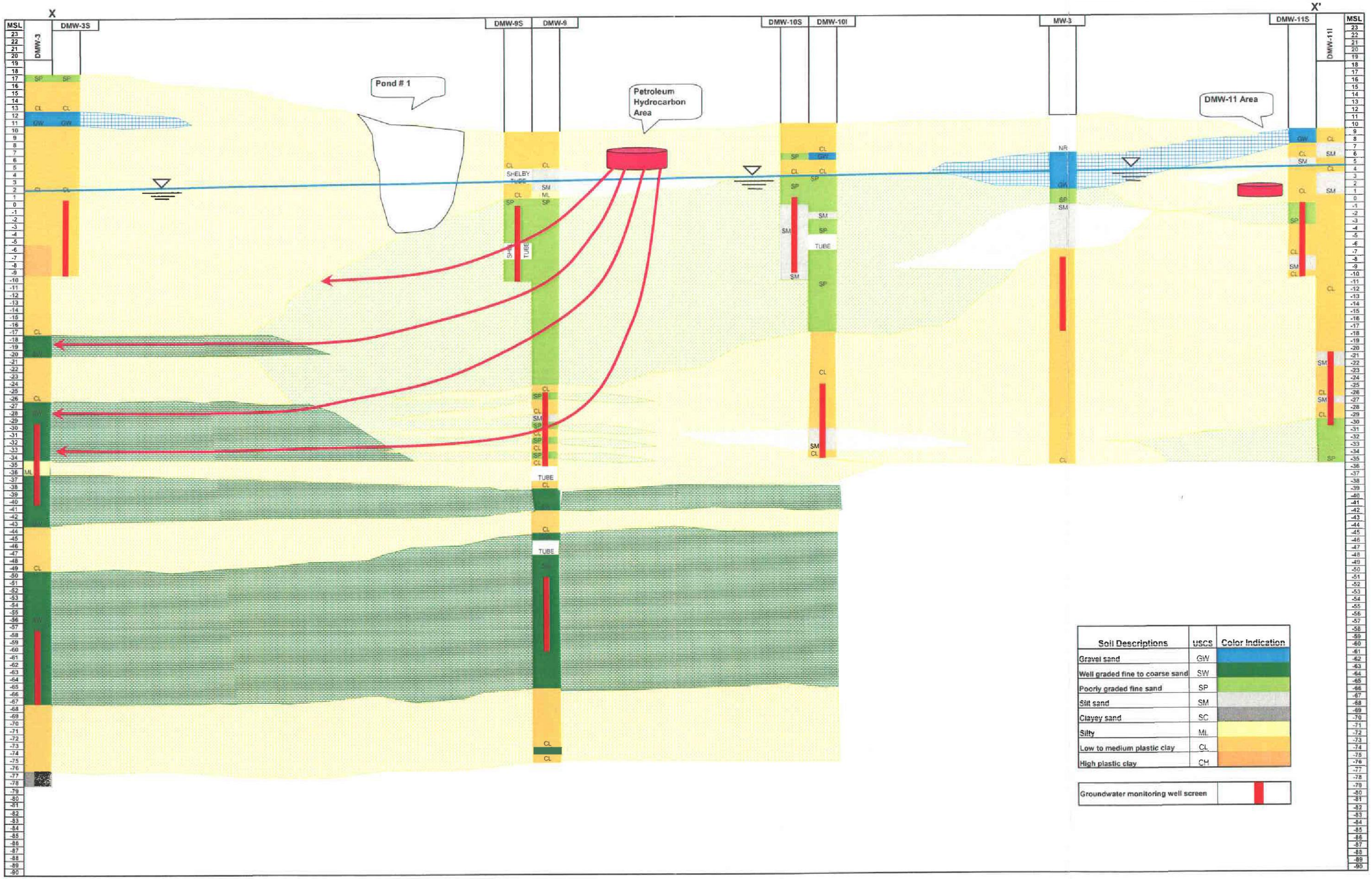


FIGURE 2-9 CROSS SECTION Y-Y'

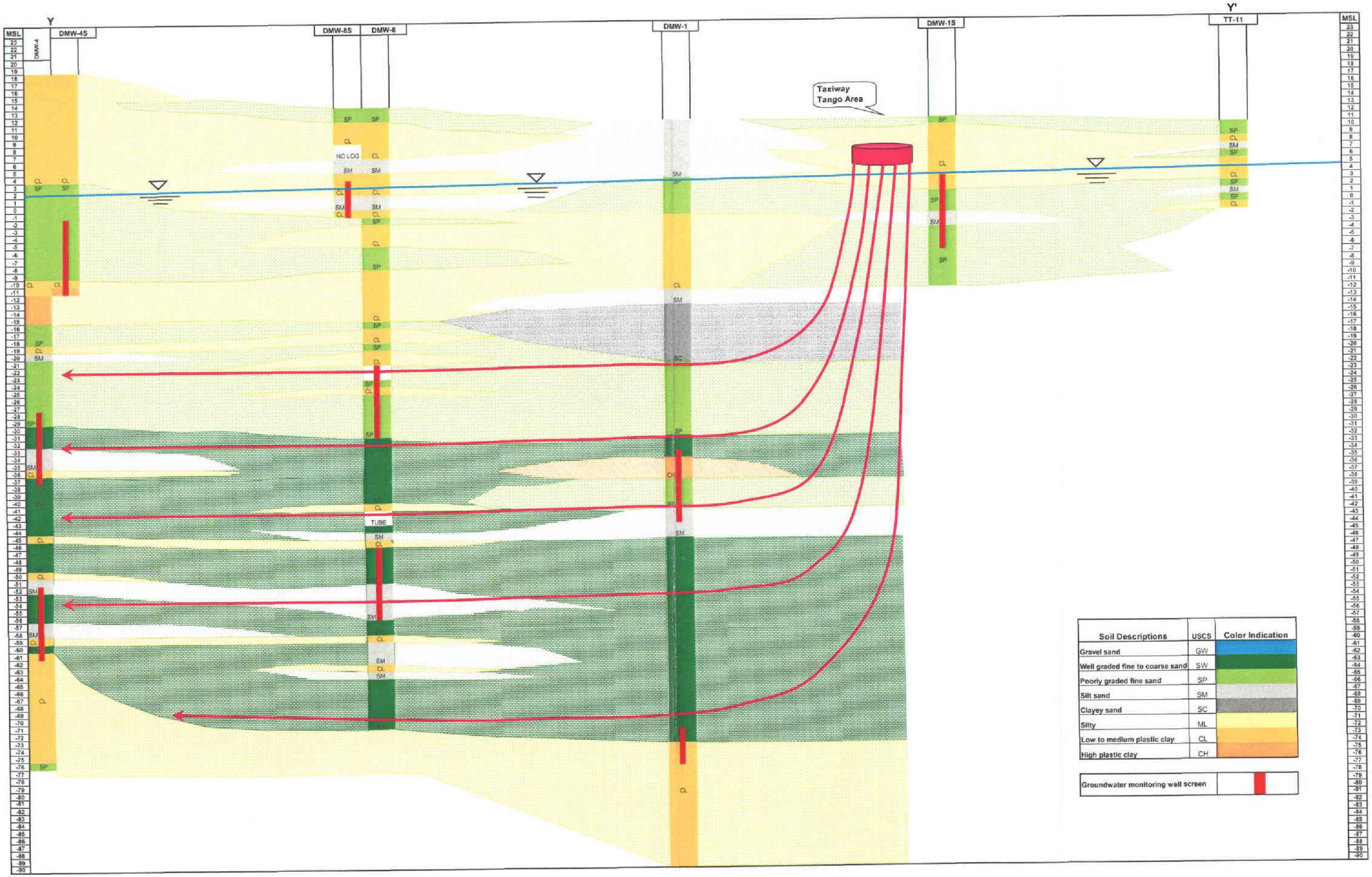
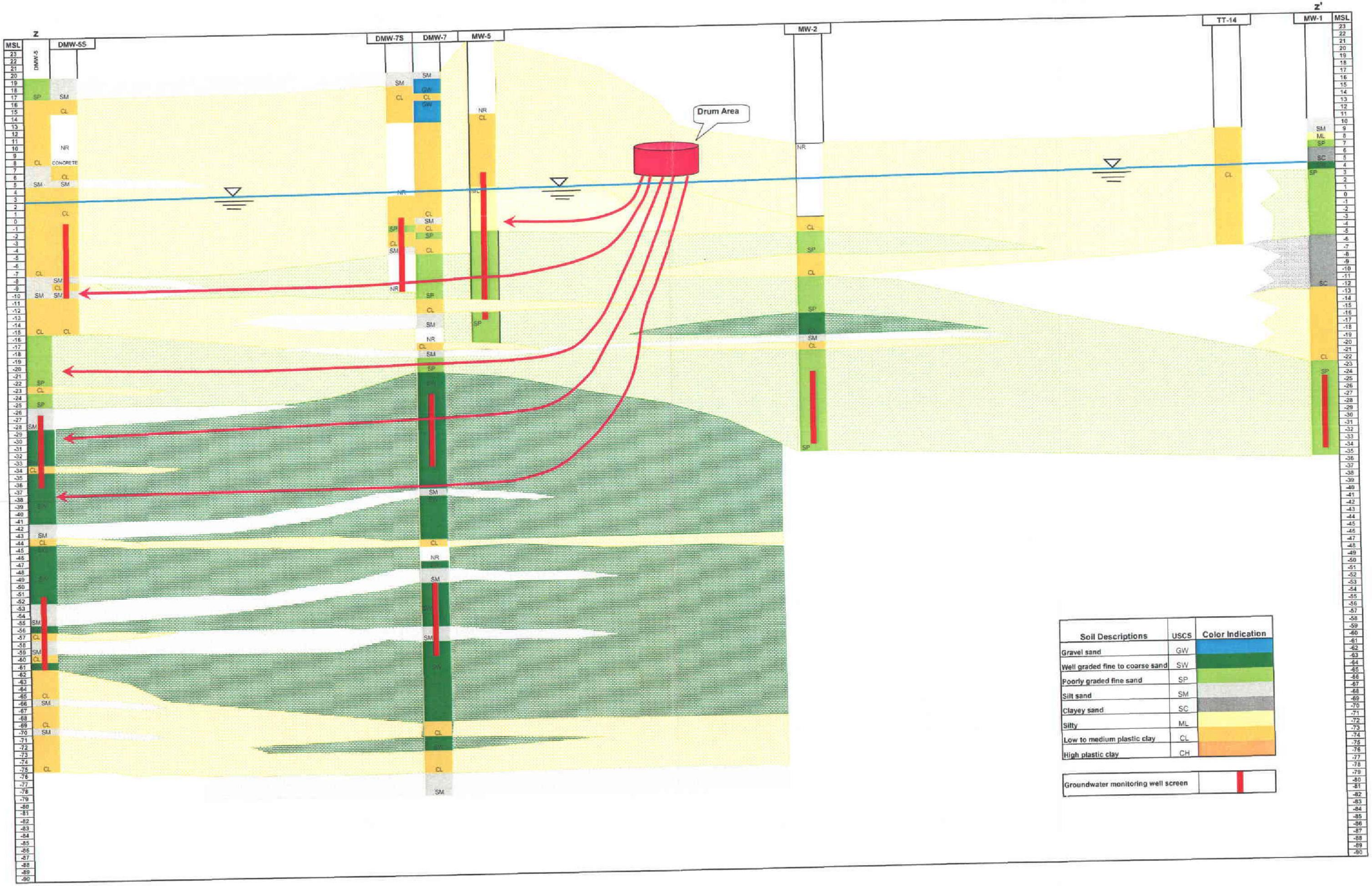


FIGURE 2-10 CROSS SECTION Z-Z'



Soil Descriptions	USCS	Color Indication
Gravel sand	GW	🟦
Well graded fine to coarse sand	SW	🟩
Poorly graded fine sand	SP	🟩
Silt sand	SM	⬜
Clayey sand	SC	▨
Silty	ML	🟨
Low to medium plastic clay	CL	🟧
High plastic clay	CH	🟧

Groundwater monitoring well screen	🟥

FIGURE 2-11

GROUNDWATER ELEVATION (HEAD) CONTOURS FOR THE UPPER SURFICIAL AQUIFER (OCTOBER 2003)

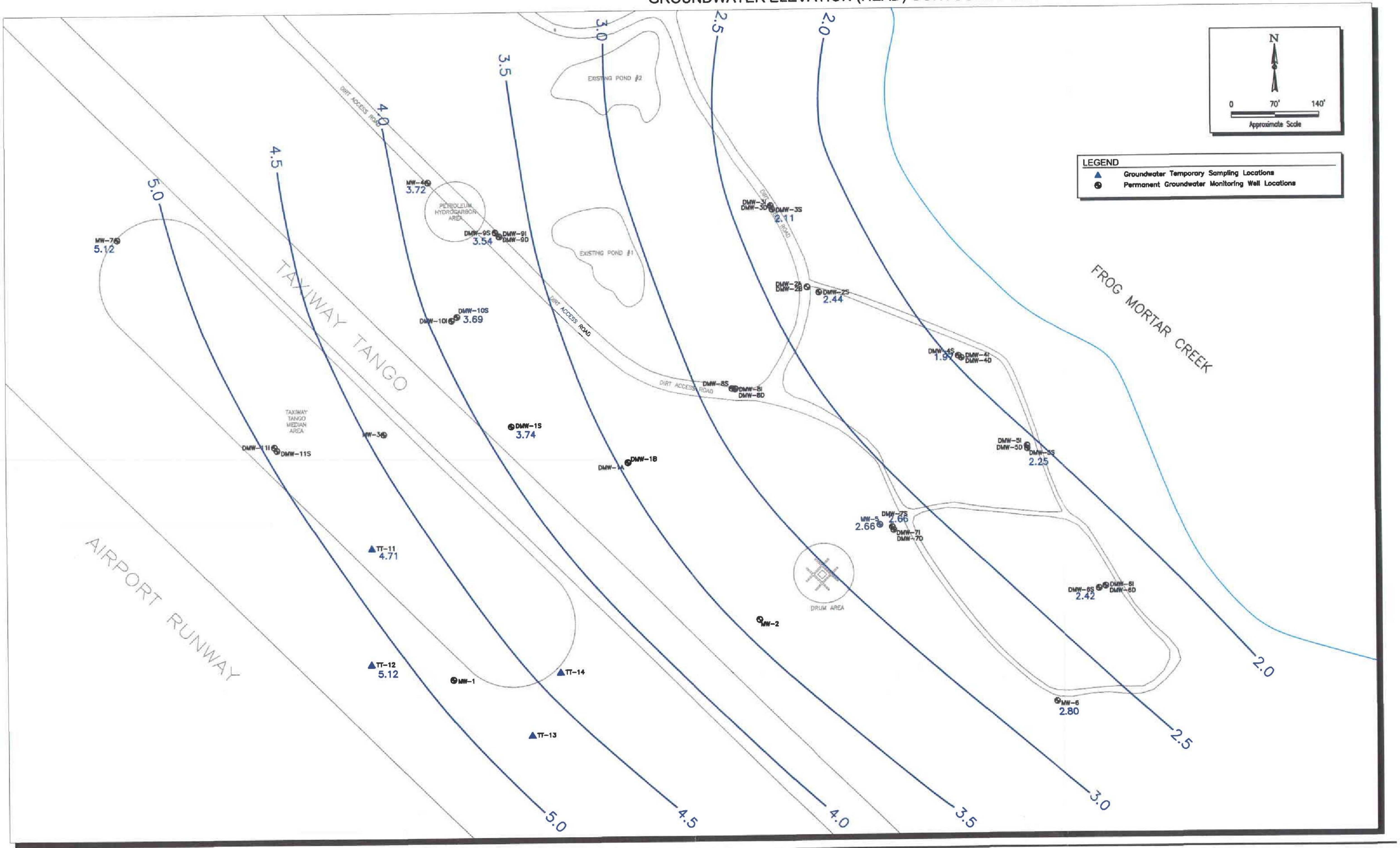


FIGURE 2-12
GROUNDWATER ELEVATION (HEAD) CONTOURS FOR THE INTERMEDIATE SURFICIAL AQUIFER (OCTOBER 2003)

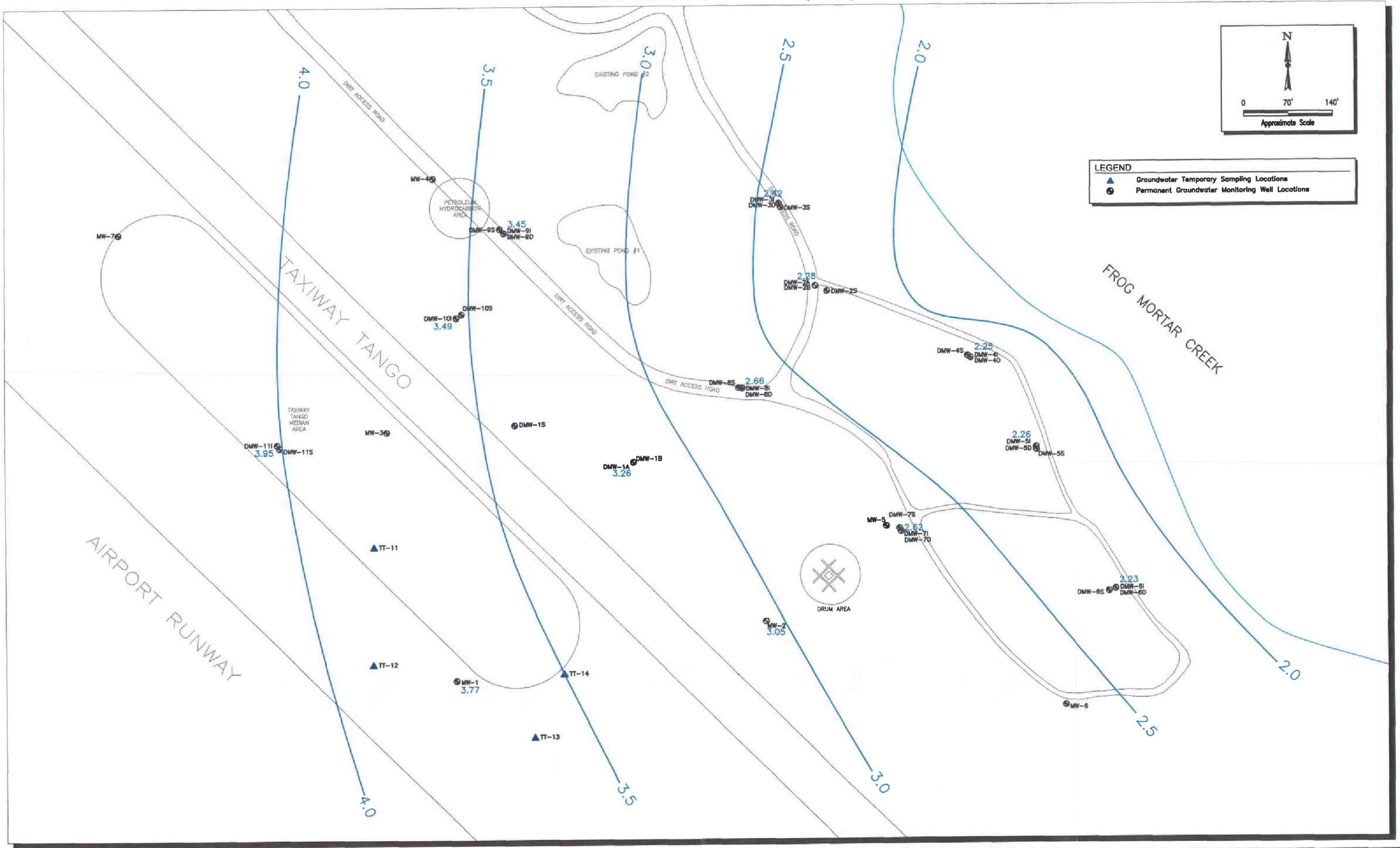


FIGURE 2-13

GROUNDWATER ELEVATION (HEAD) CONTOURS FOR THE LOWER SURFICIAL AQUIFER (OCTOBER 2003)

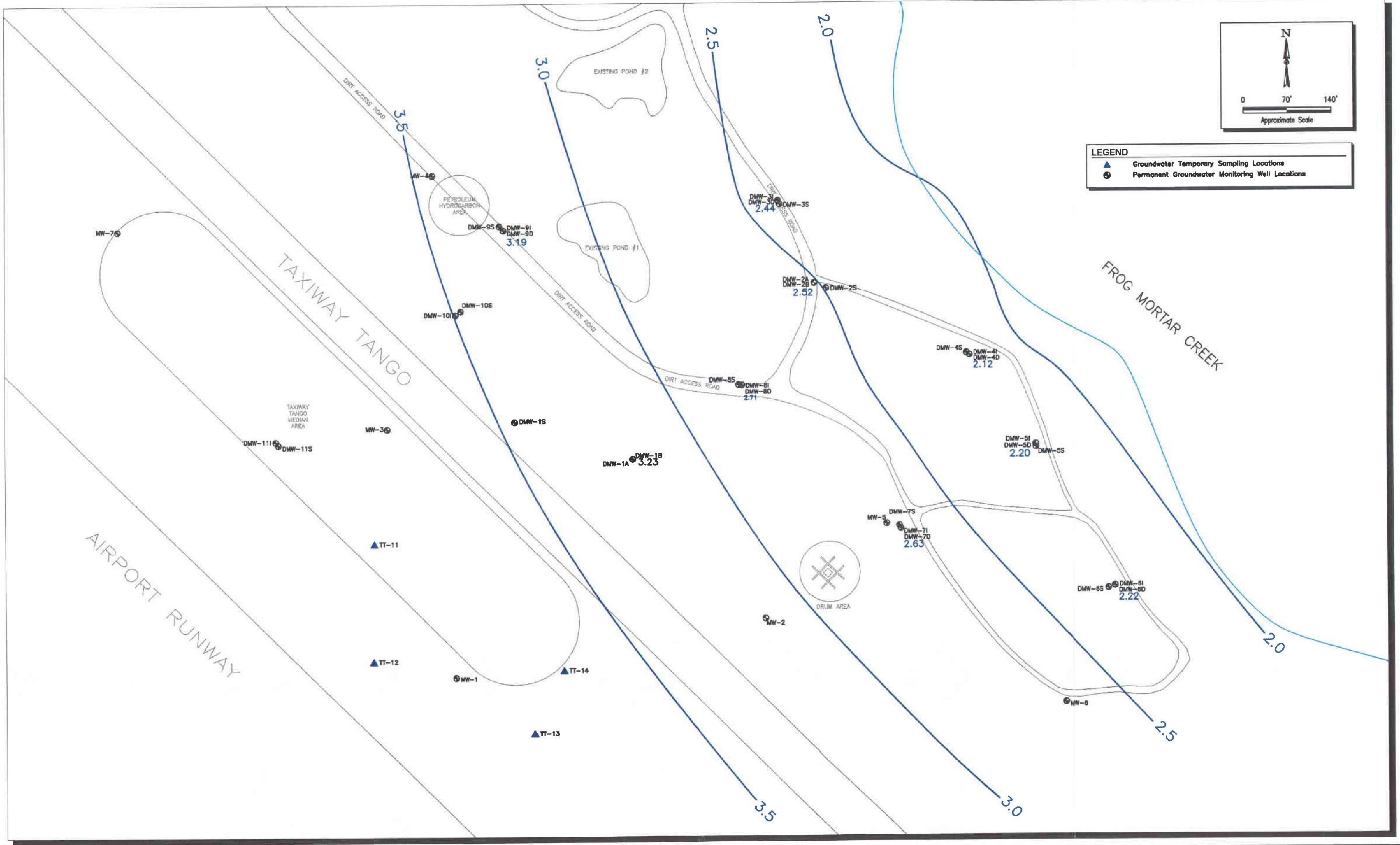


FIGURE 2-14
TCE IN THE UPPER SURFICIAL AQUIFER (SEPTEMBER 2003)

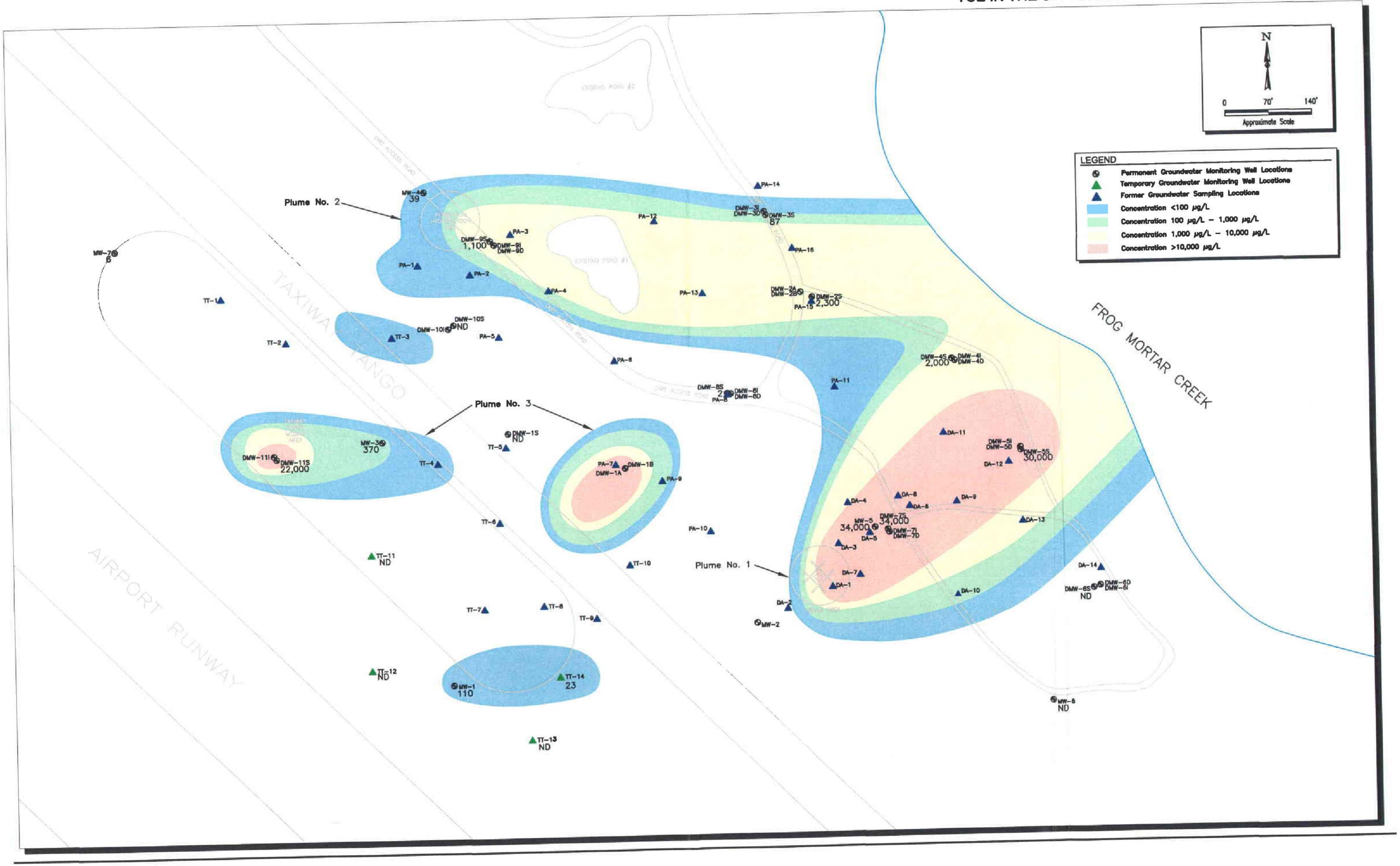


FIGURE 2-15
TCE IN THE INTERMEDIATE SURFICIAL AQUIFER (SEPTEMBER 2003)

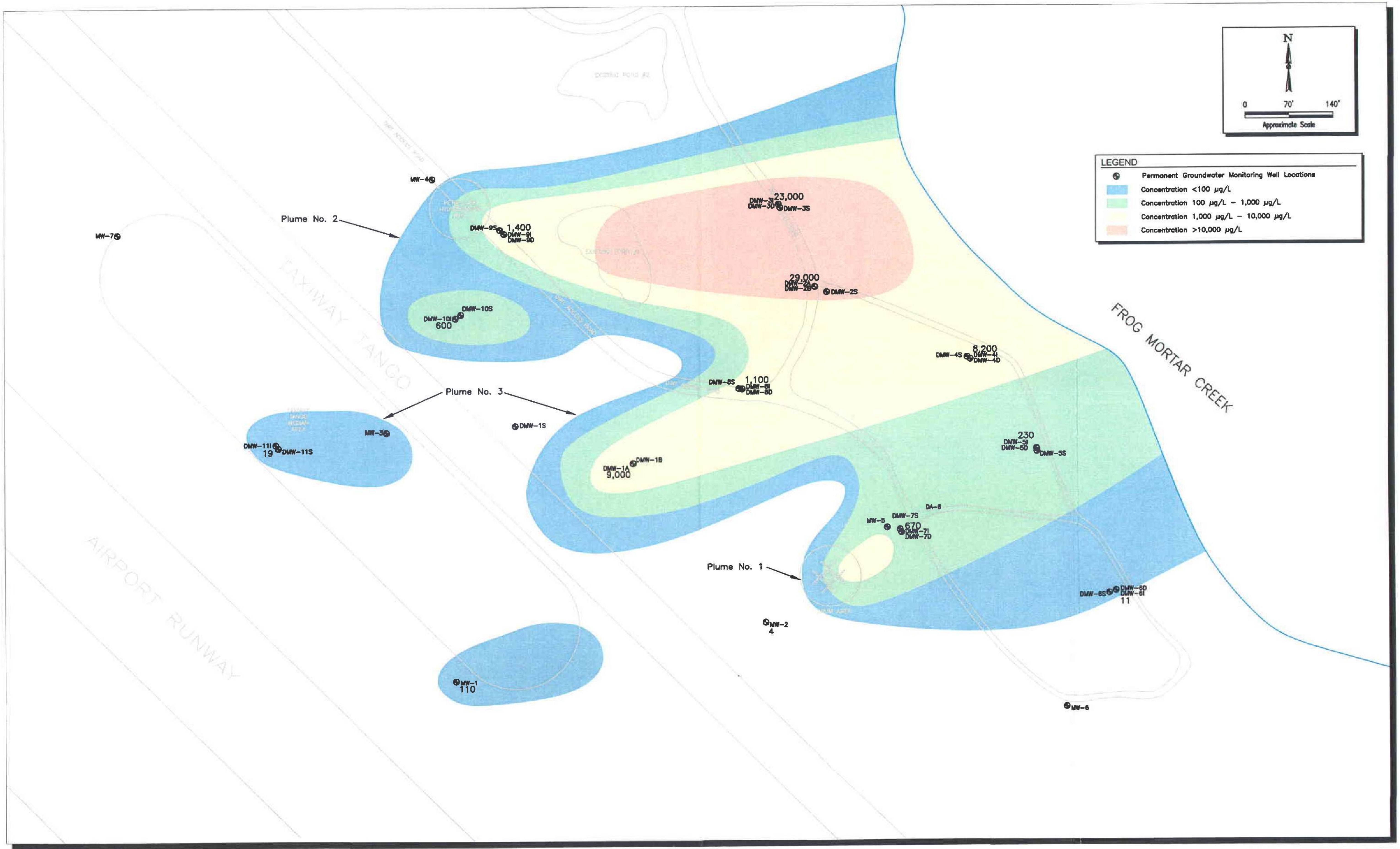


FIGURE 2-16
TCE IN THE LOWER SURFICIAL AQUIFER (SEPTEMBER 2003)

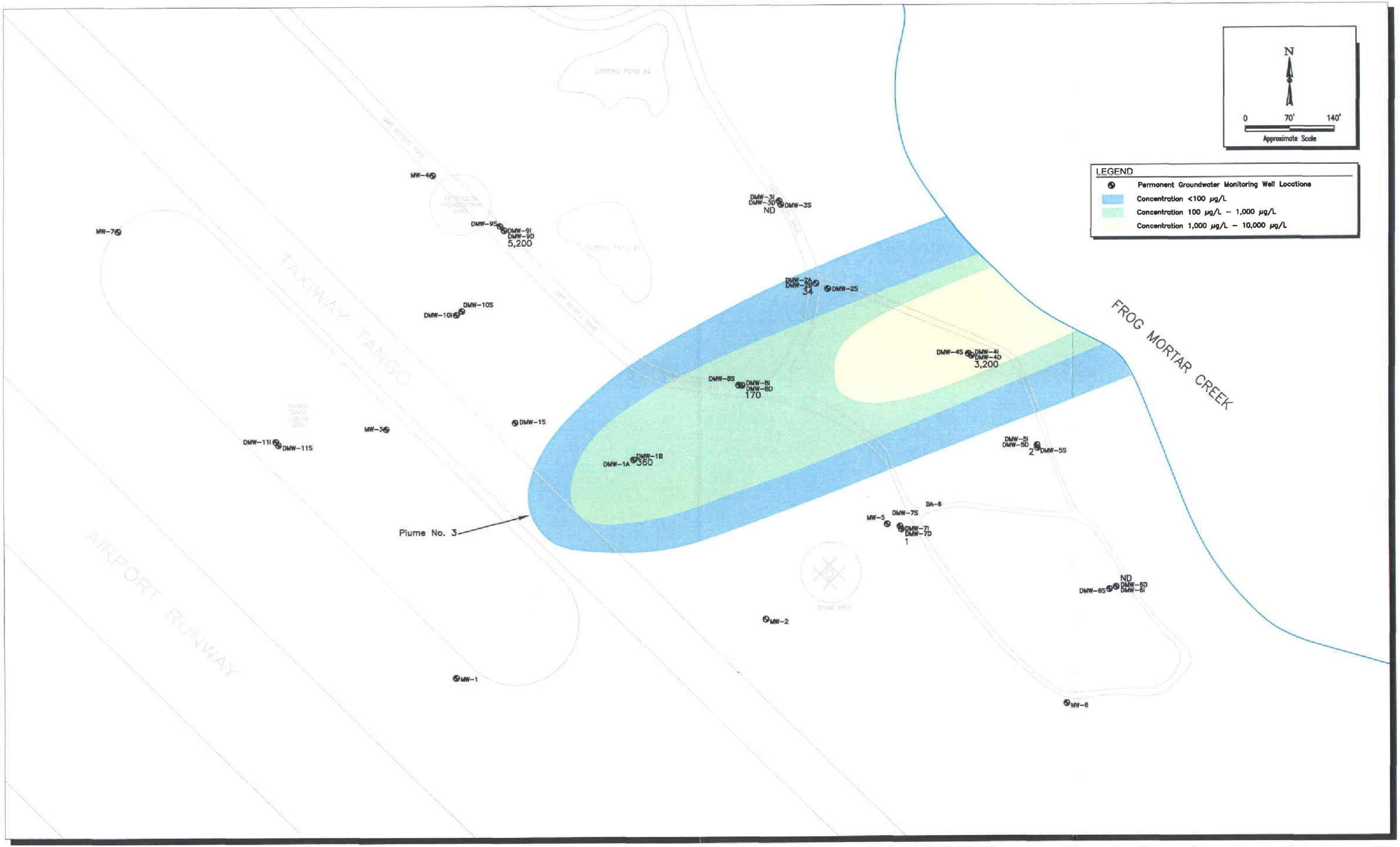


FIGURE 2-17
cis-1,2-DCE IN THE UPPER SURFICIAL AQUIFER (SEPTEMBER 2003)

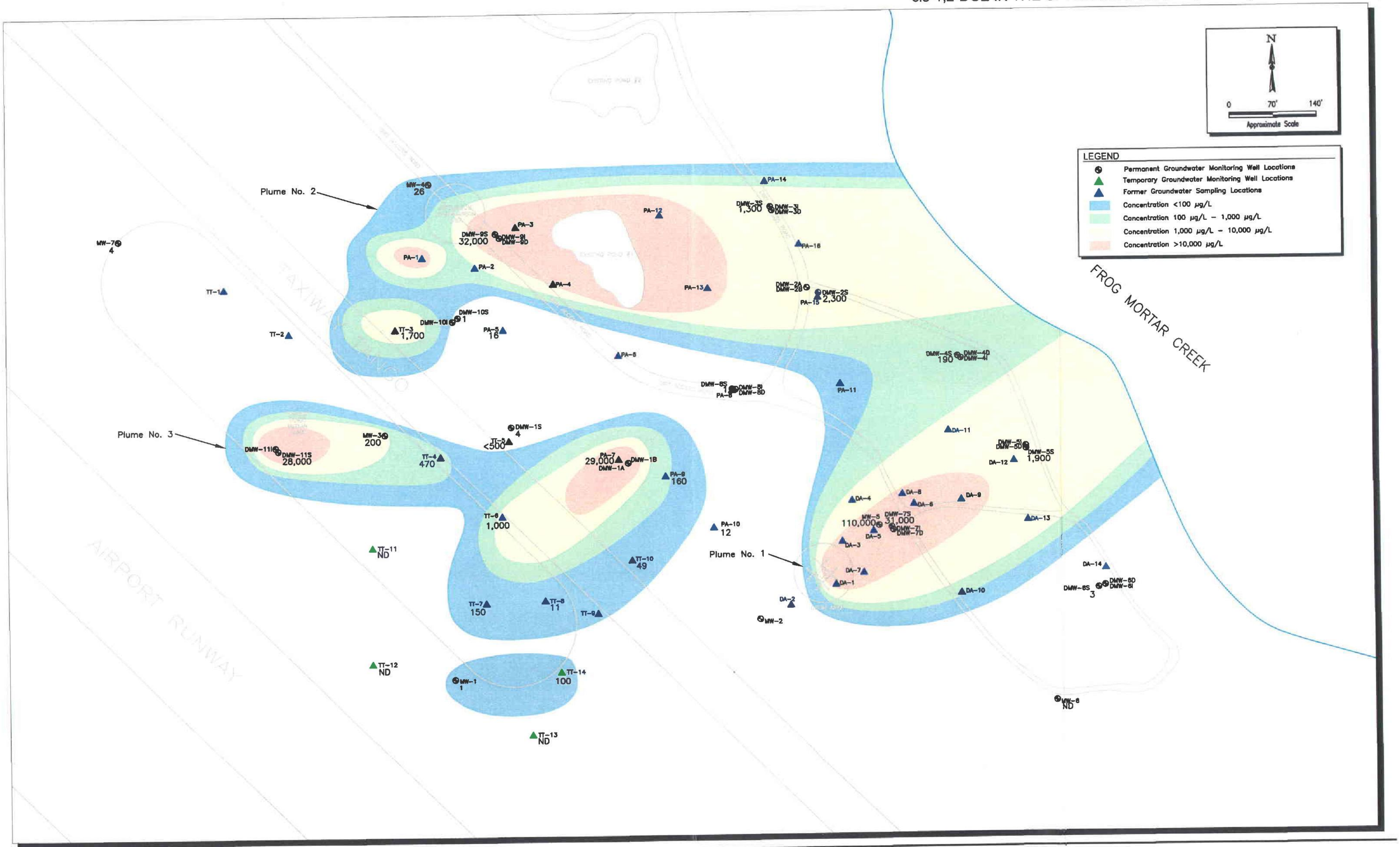


FIGURE 2-18

cis-1,2-DCE IN THE INTERMEDIATE SURFICIAL AQUIFER (SEPTEMBER 2003)

FIGURE 2-19

cis-1,2-DCE IN THE LOWER SURFICIAL AQUIFER (SEPTEMBER 2003)

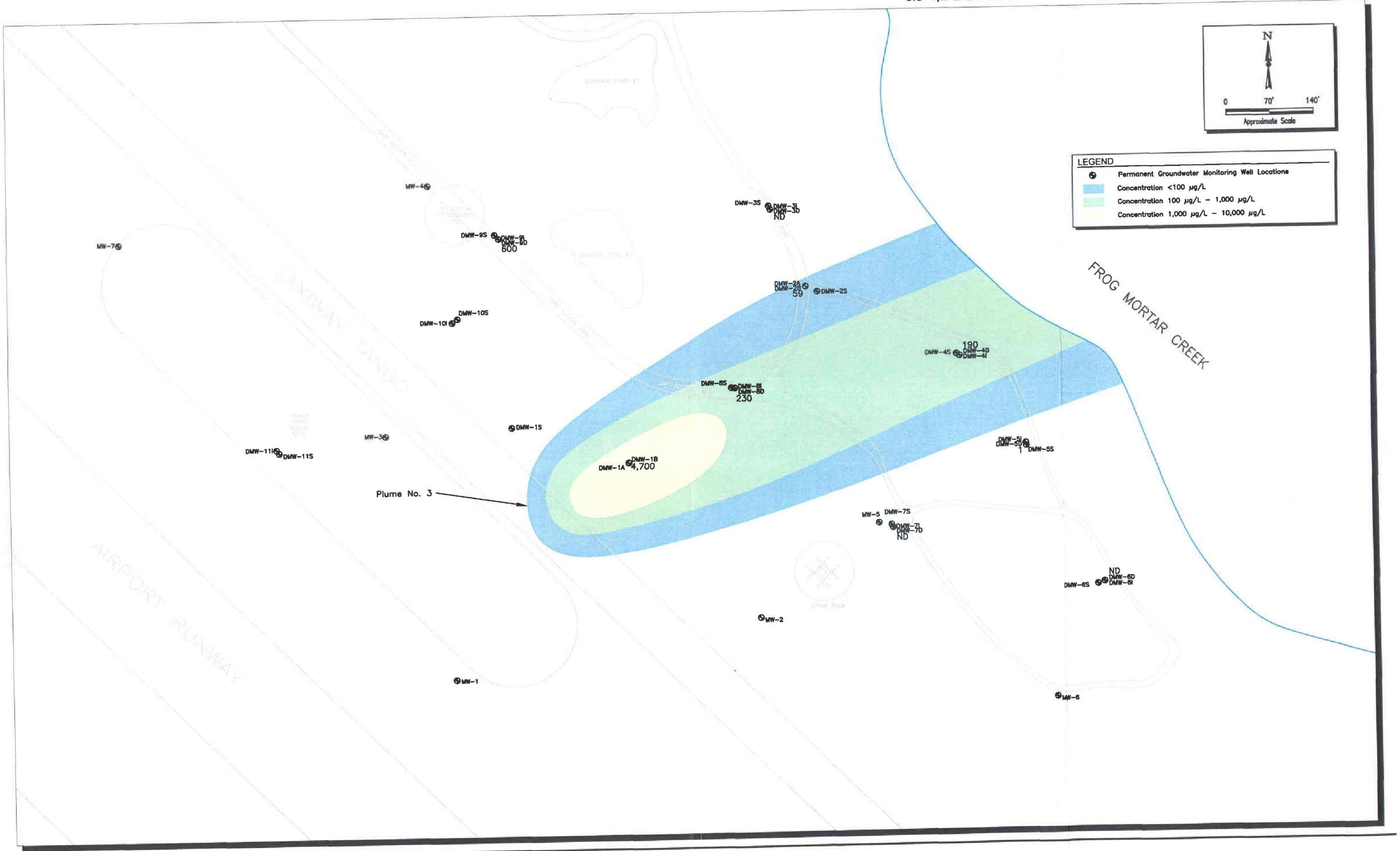


FIGURE 2-20
VINYL CHLORIDE IN THE UPPER SURFICIAL AQUIFER (SEPTEMBER 2003)

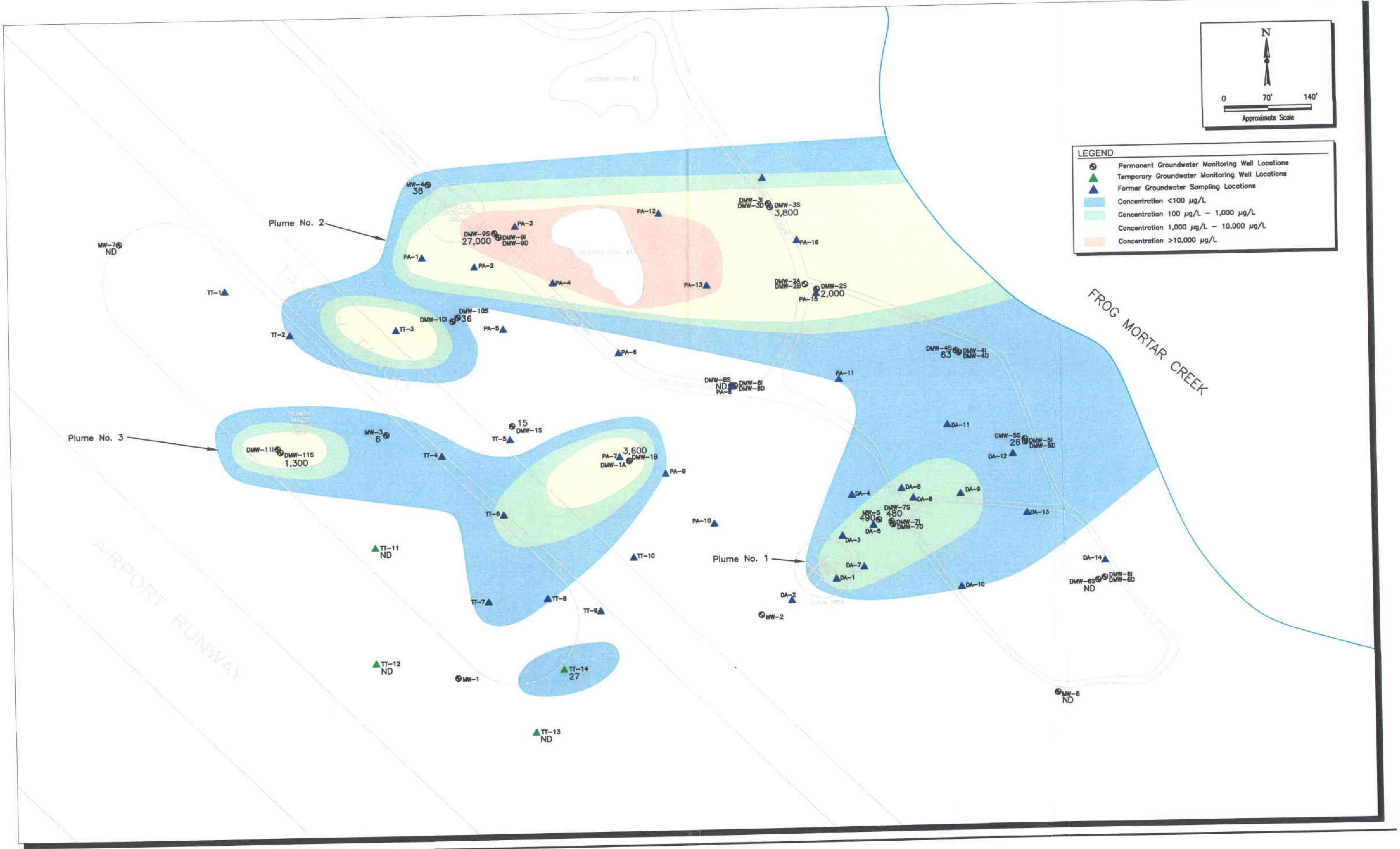


FIGURE 2-21
VINYL CHLORIDE IN THE INTERMEDIATE SURFICIAL AQUIFER (SEPTEMBER 2003)

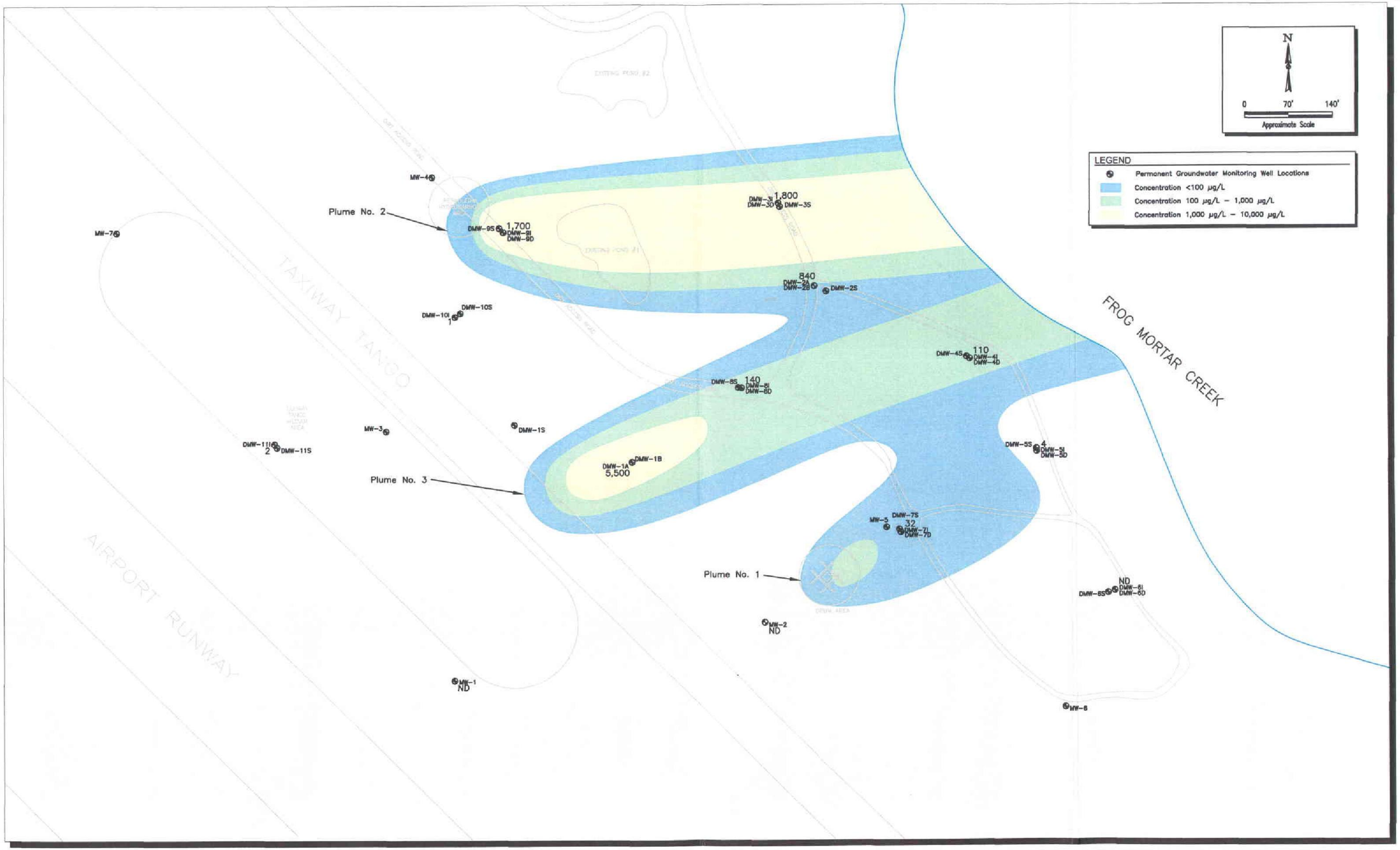


FIGURE 2-22
VINYL CHLORIDE IN THE LOWER SURFICIAL AQUIFER (SEPTEMBER 2003)

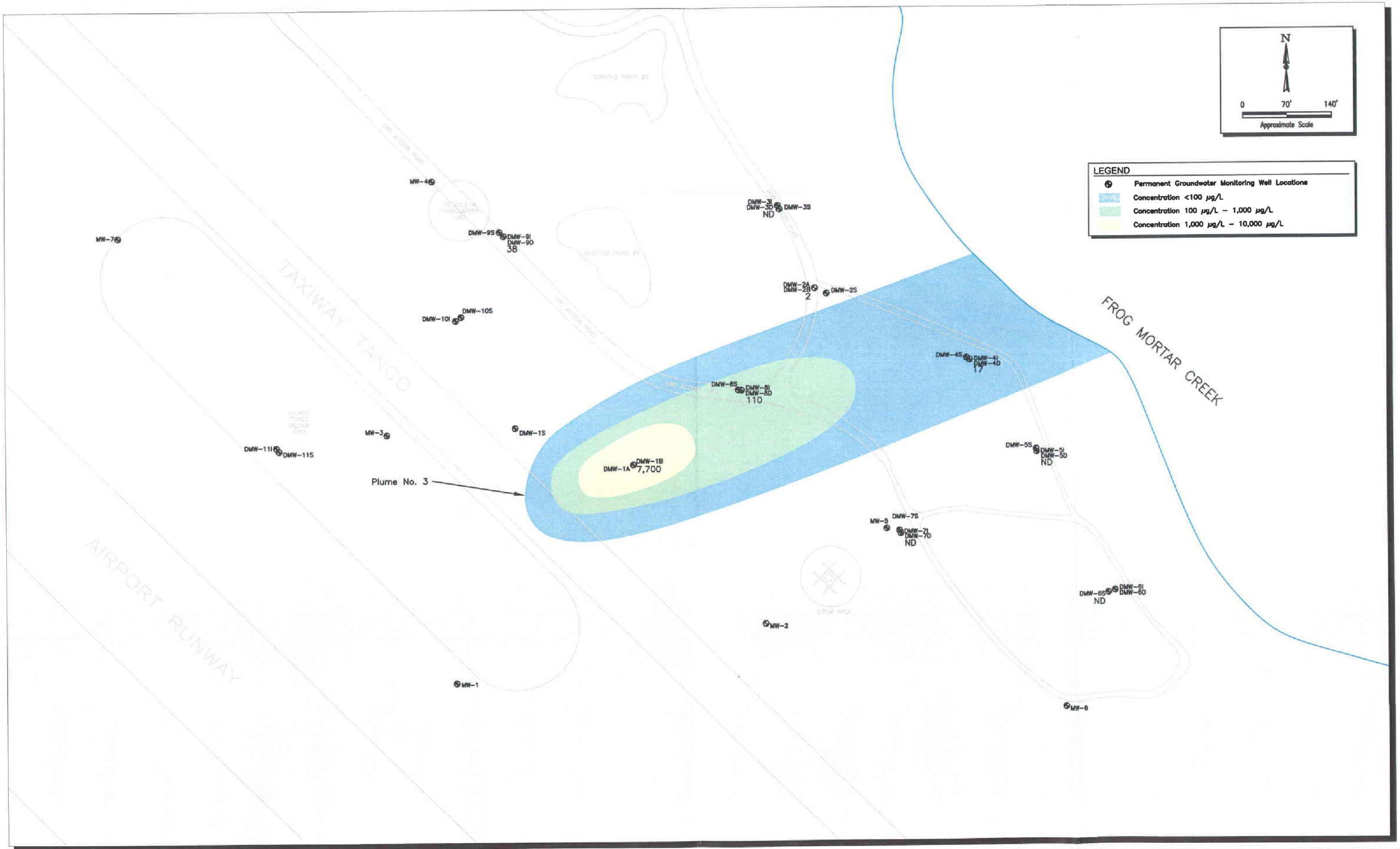


FIGURE 2-23
DISSOLVED CADMIUM IN THE UPPER SURFICIAL AQUIFER (SEPTEMBER 2003)

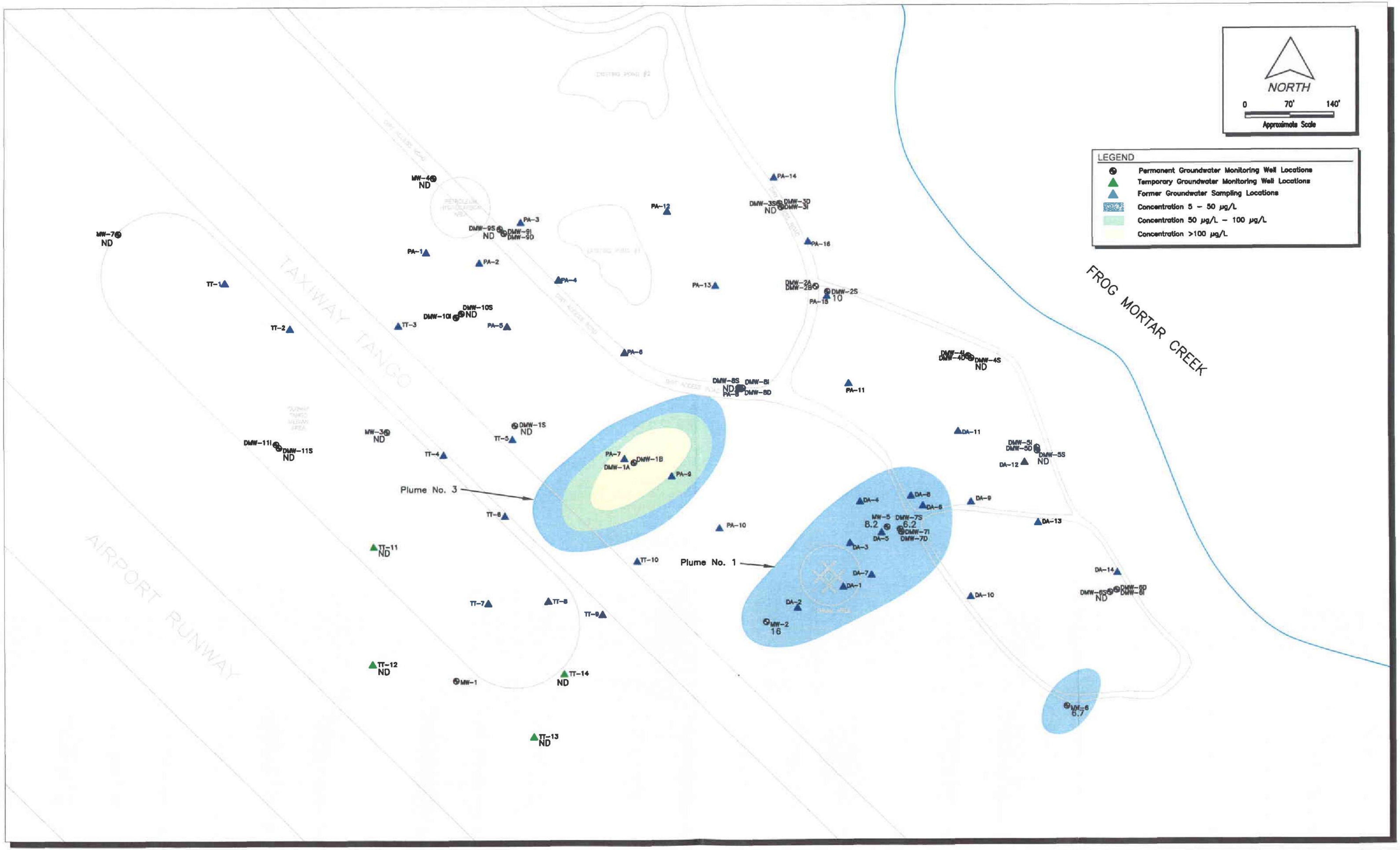


FIGURE 2-24
DISSOLVED CADMIUM IN THE INTERMEDIATE SURFICIAL AQUIFER (SEPTEMBER 2003)

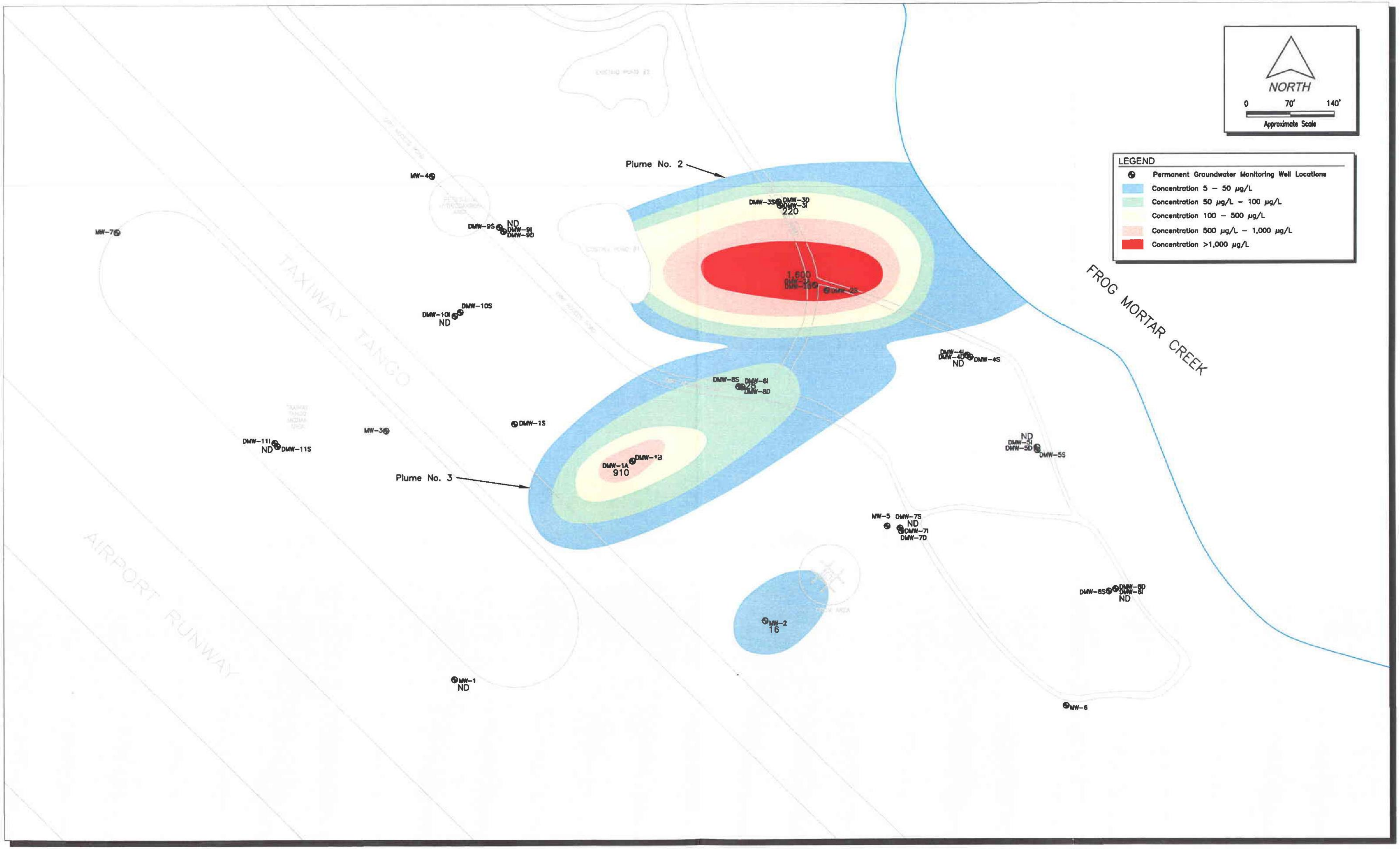


FIGURE 2-25
DISSOLVED CADMIUM IN THE LOWER SURFICIAL AQUIFER (SEPTEMBER 2003)