CONCEPTUAL MODEL DEVELOPMENT
GROUNDWATER AND CONTAMINANT TRANSPORT MODELING EFFORT
TOW WAY FUEL FARM
NAVAL STATION ROOSEVELT ROADS, PUERTO RICO
APRIL 27, 2001

1.0 INTRODUCTION

This document presents the conceptual model for the groundwater and contaminant transport modeling effort for Solid Waste Management Unit (SWMU) 7/8, Tow Way Fuel Farm (TWFF), Naval Station Roosevelt Roads (NSRR), Ceiba, Puerto Rico. This document has been prepared by Baker Environmental, Inc. (Baker) under contract to the Naval Facilities Engineering Command, Atlantic Division (LANTDIV) Contract Number N62470-95-D-6007, Contract Task Order (CTO) 034.

1.1 Purpose of the Model

There are four basic objectives for the groundwater flow and contaminant transport modeling at the Tow Way Fuel Farm (TWFF), Naval Station Roosevelt Roads (NSRR) site:

- provide a basic understanding of the groundwater flow system with regard to the groundwater flow directions and velocities;
- provide a basic understanding of the mass transfer of contaminants of concern (COCs) from the light non-aqueous phase liquid (LNAPL) phase to the dissolved phase and vapor phase, including transport of the dissolved phase COCs;
- assist in development and implementation of remedial technologies; and
- estimate remedial times and calculate mass recovery rates.

The steps involved in developing the conceptual and numerical groundwater flow and fate and transport model include the following:

- Collection and review of site information including geology, hydrogeology, precipitation, and site-specific water source and sink information.

- Development of a steady state groundwater flow model. Calibrate the model to average groundwater elevations.

- Development of a transient groundwater flow model using site-specific precipitation information. Calibrate the model to transient groundwater elevations.

- Development of a flow model for the LNAPL on top of the water table.

- Collection and review of site information regarding LNAPL removal volumes and current thickness at well locations. Calculate the estimated volume of LNAPL for use in source zones in the fate and transport model.

- Development of a contaminant transport model for the COCs using mass transfer from the LNAPL to the dissolved phase as the source.

1.2 Report Organization

This conceptual model report is organized into five sections, including this introduction. The second section discusses the collection and review of TWFF information related to the modeling effort. The third section describes the numerical groundwater model conceptualization and implementation. Section 4 discusses the numerical contaminant transport model, including the LNAPL and dissolved phase flow. The last section discusses potential data gaps in the knowledge at the TWFF and suggestions for incorporation of these data gaps into the upcoming field event.

2.0 SITE DATA COLLECTION AND REVIEW

This section discusses the collection and review of TWFF information related to the modeling effort.

2.1 Site Location and Background

Roosevelt Roads is an active U.S. Naval Station and is located near the town of Ceiba on the eastern end of Puerto Rico. The approximate location of the Naval Station is 18°15'00" latitude and 65°39'30" longitude.

The TWFF is bounded on the north by undeveloped land comprised of hills and forest and on the south by Ensenada Honda. Currently, seven fuel storage tanks, 82, 83, 84, 85, 1080, 1082, and 1088, comprise the TWFF. Figure 2-1 is a site map showing the topography and location of the fuel tanks at TWFF. In 1984 two underground storage tanks (USTs), 56A and 56B were removed. These were located near the Pump House. Since 1957, spills, leaks, and sludge disposal have resulted in releases of product. This discharge has impacted soil and groundwater at the site. According to the latest Quarterly Progress Report (Baker, 2001) there are areas of phase separated hydrocarbons (PSH) on the water table around several monitoring wells, including UGW3, MW01, and in most of the UGW and Recovery Wells (RW) along Forrestal Drive between Palau Street and Card Street. Thirty wells at TWFF have had product measured in them at some point or continually throughout the past four years.

2.2 Climatology and Recharge

The climate of the Roosevelt Roads area is characterized as warm and humid, with frequent showers occurring throughout the year. A major factor affecting the weather is the pattern of trade winds associated with the Bermuda High, the center of which is in the vicinity of 30° North, 30° West. Uniform temperatures prevail, with small diurnal ranges as a result of insular exposure and the relatively small land area. The warmest months are August and September, while the coolest are January and February. Mean annual maximum temperatures range from 82° Fahrenheit (° F) in January to 88.2° F in August. The mean annual minimum temperatures vary from 64.0°F in January to 73.2°F in June. Rain usually occurs at least nine days in every month, with an average of 60 to 75 inches per year, although a dry winter season occurs from December through April. The rainy season occurs during the months of August through November. About

22 thunderstorm-days occur per year, with maximum frequencies of three days per month from May through October. Approximately two tropical storms per year occur in the study area, one of which usually reaches hurricane intensity.

Table 2-1 shows the shows the rainfall data at the NSRR airfield for the period of 1942-1997. Also shown on this table is the average rainfall at Fajardo, north of NSRR at an elevation of 30 feet above mean sea level (MSL) (Owenby, and Ezell, 1992).

In the immediate area of the TWFF, elevations range from sea level to approximately 270 feet. Slopes of up to 60 degrees are common. Recharge to the aquifer is dependent on topography, soil type, and ground cover. In the area of the tanks, the slopes are fairly steep and runoff of rainwater to low spots and drains is common. As a result, it is expected that very little recharge to the aquifer due to rainfall would occur in this area except in the areas of drains and low spots. Downhill from the fuel tank area but still north of Forrestal Drive and in the entire area south of Forrestal Drive the land is flat, and the land cover is minimal. Therefore, more recharge of rainwater is expected to occur here.

2.3 Geology and Hydrogeology

The underlying geology of the area at NSRR is predominantly volcanic as well as sedimentary. The volcanic rocks and interbedded limestones have been complexly faulted, folded, metamorphosed and variously intruded by dioritic rocks. The primary geologic formations on and near NSRR are various beach deposits, alluvium, quartz diorite and granodiorite, aquartz keratophyre, the Daguao Formation, and the Figuera Lava.

The geology in the area of TWFF can be divided into three categories: an upper zone of fill material, a zone of residual soil (weathered rock), and bedrock. The upper zone of fill material is composed of fine to medium grained sand with varying amounts of silt and clay. The fill material is generally encountered at the ground surface to depths below the ground surface ranging from 2 feet to over 25 feet, but may also be locally absent. The source of the fill material has not been definitively determined but it is most likely either natural soil excavated during tank construction or dredge material from Ensenada Honda.

Underlying the fill zone is a relatively thick layer of residual soil formed in place by the in-situ decomposition of bedrock. This residual soil was encountered at all of the soil borings and

monitoring wells advanced at the site. This zone is comprised of clayey silt, silty clay, with fine to course and rock fragments. With depth the percentage of rock fragments steadily increases until the zone grades to weathered rock fragments with occasional clay seams and eventually to competent bedrock. The thickness of this unit is variable and in places is in excess of 40 feet.

The third zone identified consists of bedrock. The bedrock is described as a gabbro, very broken to broken, massively bedded, hard to very hard and highly fractured due to tectonic deformation and subsequent weathering.

In addition to these three zones, a fourth zone of unconsolidated material was identified during the Corrective Measures Investigation (Baker, 2000) near the Ensenada Honda. This material consists of naturally occurring marine sediments, primarily silt with lesser amounts of sand and clay with coral and shell fragments.

It should be emphasized that there is not a well-defined contact between the residual soil and bedrock; rather, there is a gradational change of decreased weathering and fracturing with increasing depth. A collection of the cross-sections developed during the various investigations is found in Appendix A.

Because there is no distinct physical or hydraulic boundary between the residual soil and the bedrock, they are therefore considered as one hydrogeologic unit. The pattern of groundwater flow in the residual soil/bedrock hydrogeologic unit is shown in Figure 2-2. This figure shows the average water table elevations at the site over a four-year period beginning in January, 1997. (It should be noted that these elevations have been corrected for free product presence where applicable according to the principle of Archimedes. The equation used in this correction can be found in Appendix B. All water level data is from the latest Quarter Progress Report, 2001.) In general, the direction of flow in the upper Tow-Way area is toward the west with an average hydraulic gradient of 0.0063 ft/ft, with radial flow to the northwest and southwest because of a local high average water table elevation at 7MW03. The direction of flow in the lower Tow-Way area is toward Ensenada Honda. The average calculated hydraulic gradient in the lower Tow-Way is 0.0067 ft/ft.

A tidal study was conducted during the RCRA Facilities Investigation (Baker, 1997) to determine the effects of the tide on the groundwater flow patterns at TWFF. Fluctuations between high and

low readings in the wells in the study were generally less than 0.1 feet, indicating that tidal changes do not significantly affect the flow of groundwater at TWFF.

Several slug tests and two limited pump tests have been performed on wells at TWFF. Hydraulic conductivity values ranged from 0.0113 ft/day to 13.685 ft/day. In general the pump tests yielded smaller hydraulic conductivity values than the slugs tests, primarily because they were conducted on wells that are screened in the bedrock. The weathered bedrock would be expected to exhibit a higher hydraulic conductivity than the competent bedrock. The results of the slug and pump tests can be found in the RCRA Facilities Investigation (Baker, 1997), and the Corrective Measures Investigation (Baker, 1999).

2.4 Summary of Previous Investigations and Reports

Several reports have been reviewed for the development of the conceptual groundwater and contaminant transport model at Tow-Way Fuel Farm. These include:

- "Underground Fuel Investigation, Final Report (1992) by O'Brien and Gere
- "Site Characterization, Site 1995" (1995), by Blasland, Bouck, and Lee, Inc.
- "Corrective Action Plan," Blasland, Bouck, and Lee, September, 1994
- "Site Characterization Report", Blasland, Bouck, and Lee, April, 1994
- "Hydraulic Characteristics Evaluation", McLaren/Hart, Inc., August, 1999
- "Draft Report of Findings Quantification of Product Release, Pier 1- TWFF," McLaren/Hart, March, 2000
- "Revised Draft RCRA Facility Investigation Report for Operable Unit 2," Baker, 1997
- "Final Corrective Measures Investigation Report," Baker, 1999
- "Quarterly Progress Reports for Tow-Way Fuel Farm" Baker, 1997-et seq.

3.0 GROUNDWATER MODEL

This section describes the numerical groundwater model conceptualization and implementation.

3.1 Description of Numerical Groundwater Model

The code that is proposed for this work is MODFLOW-SURFACT (HydroGeoLogic, 1998). This code is essentially MODFLOW (McDonald and Harbaugh, 1988), but includes an enhanced matrix solution scheme, an enhanced recharge and cell re-wetting package, a fractured well package, and a robust contaminant transport package. The code is publicly available and interfaces with Groundwater Vistas®, which is a widely used pre- and post-processor for MODFLOW and other modeling packages. The code is used and accepted within the EPA. Many of the modules are the same as MODFLOW without any modifications. Initial set-up of the input files for the MODFLOW model will be done with the Groundwater Modeling System® software because of user familiarity. When the additional packages incorporated into the MODFLOW-SURFACT software become necessary for use, the model will be transferred to the MODFLOW-SURFACT code.

MODFLOW-SURFACT is a fully integrated groundwater flow and solute transport code developed by HydroGeoLogic, Inc. It is based on the U.S. Geological Survey modular 3-dimensional groundwater flow modeling code, MODFLOW.

The SURF acronym in MODFLOW-SURFACT denotes the following:

- S – robust and efficient (matrix solution, nonlinear iterations with adaptive time stepping, output control and axi-symmetric) **S**chemes.
- U – rigorous treatment of **U**nconfined flow.
- R – non-ponding **R**echarge and seepage face boundary conditions.
- F – **F**racture well representation to provide rigorous treatment of well conditions.

The MODFLOW code utilizes a block-centered finite-difference approach to solve the groundwater flow equation. The flow domain is discretized into rows, columns, and layers such that each node represents a rectangular block of porous material that is referred to as a cell. A node in the resulting finite difference grid represents a no-flow, variable-head, or constant-head cell, and any hydraulic property associated with a cell is specified with respect to the corresponding node. A typical MODFLOW grid is depicted below in Figure 3-1.

The MODFLOW-SURFACT code is recommended because it is based upon the widely accepted MODFLOW software, but has additional features that make implementing the conceptual model easier. For example, the high-conductivity zones (fractures) adjacent to low-conductivity zones (matrix) creates extreme numerical convergence problems that are handled relatively easily by MODFLOW-SURFACT but not by other codes (e.g., MODFLOW). Also, the fracture well package allows wells to be screened across multiple layers and assigns the flow within a particular cell in that layer according to the induced hydraulic gradient and transmissivity within the cell. This well package ensures that the flows across multiple layers add up to the total flow that is assigned to a particular well. The recharge package is also convenient because it allows recharge to be assigned to the top of the model and it finds the first cell that is saturated. With MODFLOW and many other codes, this is a trial-and-error process that is the responsibility of the user.

An important aspect of MODFLOW-SURFACT is that it will allow for the simulations of PSH migration and recovery in the unsaturated and saturated zones. Only one phase (i.e., gas, water), however, can be specified as the mobile phase during the simulation. Therefore, the transport simulations in the unsaturated and saturated zones are done separately. Two phases (water and PSH) will be modeled. However, only one phase will be modeled at a time. Water will be modeled first, followed by the PSH phase. This will be accomplished in an iterative fashion.

3.2 Conceptual Model

3.2.1 Groundwater

The groundwater model domain includes an expanded area around the TWFF and part of Site 1995. Figure 3-2 depicts the boundaries of the groundwater model at this time. Proposed future installation of wells (see Section 5) may expand the boundaries to the north slightly.

The edge of the model domain bounded by the Ensenada Honda, with the exception of the bulkhead areas, is modeled as a constant head boundary with a mean sea level elevation of 0.0 feet. As stated above, no tidal effects are to be included in the model. All other boundaries are modeled as variable head boundaries, allowing groundwater to flow into and out of the model domain. As stated, there are two bulkheads, modeled as horizontal flow barriers, located at the Honda. These are solid concrete walls with a depth of about 20 feet below sea level. They are assumed to have no horizontal hydraulic conductivity.

Recharge areas are shown in Figure 3-3. Initially, no recharge is allowed to occur directly under any of the fuel tanks or large concrete areas. Even in the dry season, ponding is observed in the vicinity of and to the east of UGW14. Initially, more recharge will be assigned to this location, although it may be that this water drains away through the concrete culvert located through the road in this area. Higher recharge will be assumed in the flat areas of the lower TWFF, and less recharge will be assigned to sloped areas. For an initial assumption, 20 percent of the average rainfall will be assumed as recharge to the aquifer in the fuel farm area and on the lower TWFF. On hillsides, the recharge will drop to 10 percent of average rainfall, and at ponding locations, 30 percent of the rainfall will be assumed to infiltrate to the aquifer.

In a three-dimensional model, several vertical layers can be modeled. Usually these are chosen according to stratigraphy at the site. As stated above, there are basically three kinds of formations at the site; fill, weathered bedrock, and unweathered bedrock. An interpolation method will be used to expand the information given through boring logs over the entire site. When the interpolation method produces elevations of layers that don't make physical sense, control points will be added to obtain a realistic conceptual model of the site. Figure 3-4 depicts the locations of two cross sections of the initial layers as determined through interpolation routines on the weathered rock boring information. The layers in the longitudinal and transverse flow directions are given in Figures 3-5 and 3-6. The weathered rock layer was assumed to be 20 feet thick and the bottom elevation of the third layer is -40 feet MSL.

Hydraulic conductivity at the site will vary with the layers. The fill is initially assigned a hydraulic conductivity of 10 feet/day. The weathered bedrock is less with an initial hydraulic conductivity of 1.0 feet/day and the competent bedrock still less at 0.01 feet/day. The results of the slug tests were used as a guide to determine the initial assignments and zones of this hydraulic

conductivity. It is recognized that this parameter will be changed during calibration of the steady-state model.

The saltwater-freshwater interface will not be modeled. In Puerto Rico there is a forty-foot column of freshwater below sea level for every foot of freshwater above sea level (http://capp.water.usgs.gov/gwo/ch_n/N-PR_VItext2.html). Also, the Ghyben-Herzberg equation (Strack, 1993) verifies the relationship of freshwater head to saltwater head (see Appendix C). The depth to the water table at the location of concern along Forrestal Drive is approximately 5 feet above mean sea level. This means that there are approximately 5 x 40 feet, or 200 feet of freshwater below mean sea level at this location. No remedial action or pumping will take place that will affect the interface at that depth, and the saltwater-freshwater interface can safely be ignored.

There are several minor drains located at TWFF. In addition, there is a concrete lined drain in the lower portion of the upper TWFF. These drains will not be included in the initial modeling effort but may be added at a later date. The major impact the drains have is to direct water away from the model domain, although, as seen in the case of the water ponding in the upper TWFF, they may direct water to an area of lower elevation which can then be modeled as an area of higher recharge.

3.2.2 Calibration

The steady-state model will be calibrated to the average water table elevations shown in Figure 2-2. It is anticipated, but not guaranteed, that the modeled water table elevations will match the actual water table elevations to within one standard deviation of the mean.

Once the steady-state model is done, the transient simulation will begin. Rainfall on a month-by-month basis will be input to the model and the modeled groundwater levels calibrated to known groundwater levels for that month. The total simulation time will be four years. The storativity of the different layers will be assumed appropriately for the different soil types.

3.2.3 LNAPL

LNAPL movement over the changing water table may be modeled after the transient simulation is done. Previous modeling studies (TWFF Quarterly Report No. 8, 1999) of the LNAPL movement in two dimensions showed that any water extraction from under the LNAPL only increases the smear zone of the LNAPL, increasing the amount of LNAPL that becomes unrecoverable. In a similar fashion, greater movement of LNAPL can be accomplished under a positive pressure head. If there is negative pore pressure in the soil voids, i.e. the LNAPL is held in place by capillary action, then no movement of the LNAPL can occur. Movement of LNAPL will occur, however, when the negative pore pressure is broken, as in the case of a well screen through the LNAPL, allowing LNAPL to flow into a well casing.

Because the LNAPL can flow into a well casing screened across the layer of LNAPL, the amount of product in the wells with product in them is usually larger than the thickness of the product in the formation. A brief discussion of the various empirical methods used to estimate the actual thickness of LNAPL in the aquifer formation given the product thickness in a well is found in Weidemeier, et al., 1995. In modeling the LNAPL movement over the surface of the water table, a corrected thickness and assumed saturation will be determined. (This effective volume will also be used during the fate and transport model as source zones.) The most likely method to be used for correcting for thickness will be the method of de Pastrovich et al., (1979, from Weidemeier, et al, 1995). The corrected thickness in the formation is given in the following equation:

$$h_f = \frac{h_m(r_w - r_{lnapl})}{r_{lnapl}}$$

Where h_f = height of the product in formation

h_m = height of the product in the monitoring well

D_w = density of water

D_{lnapl} = density of LNAPL

These corrected heights in formation will be used in the model to simulate the LNAPL movement.

It should be noted that in this equation and in the equation for the correction of the water table elevation for a monitoring well with product in it, the density of the water and the LNAPL are the major parameters to be input. If these values are incorrectly assumed, errors can result in the conceptualization of the subsurface conditions. Furthermore, the water at TWFF may not have a density of 1 g/cm^3, as is usually assumed, because of the high salinity of the groundwater in the area. For these reasons, actual density values of water and LNAPL should be obtained in an upcoming field effort.

4.0 FATE AND TRANSPORT MODEL

This section discusses the numerical contaminant transport model, including the LNAPL and dissolved phase flow.

4.1 Description of Numerical Contaminant Transport Model

Key simulation features provided by the Analysis of Contaminant Transport (ACT) modules in MODFLOW-SURFACT include the following:

- Advective-dispersive transport of up to 5 chemical species in steady state or transient flow fields.
- Linear or non-linear retardation for each species.
- First-order decay and biochemical degradation of contaminants in water and soil.
- Generation of transformation products.
- HydroGeoLogic, Inc., has developed compatible transport modules and combined these with the original MODFLOW modules and SURF packages to produce the fully integrated code.
- Mass partitioning of a single or multi-component contaminant with diffusive mass movement in the inactive phase.
- Mass partitioning of a single or multi-component contaminant from a depleting, immobile NAPL phase with advective and dispersive transport in the active phase and diffusive transport in the inactive phase.

MODFLOW-SURFACT uses state of the art numerical schemes for solving the transport equation. Included in the code is Pre-Conditioned Conjugate Gradient (PCG) flux limiting schemes designed to provide accurate, physically correct, and strictly mass-conserved numerical solutions.

4.2 Conceptual Model

4.2.1 Chemicals to be Modeled

During the Corrective Measures Study for the TWFF, benzene and 1,2,4-trimethylbenzene were the two chemicals that triggered human health risk in groundwater. The ecological risk assessment is not complete at this point, but may include other chemicals of potential concern (COPC) at TWFF. Because of its potential degradation product of vinyl chloride, trichloroethylene in the area of 7MW07 will also be modeled.

4.2.2 Source Zones

The source zones for the chemicals will be the areas where LNAPL containing the COPCs has been observed. The mass of the COPCs available to be partitioned into the aquifer will be found from the fingerprinting of the LNAPL to be done in the upcoming field effort. A constant source resulting from dissolution of the contaminants in the LNAPL in contact with the water table will be assumed. At this point there appears to be three different mechanisms through which COPCs can enter the groundwater. The first mechanism is chemical diffusion from LNAPL above the capillary fringe of the water table into the capillary water. Simply put, the chemical diffuses through the capillary zone into the top of the water table. In an area of steady-state LNAPL, this would provide a constant source, although not a strong source because chemical diffusion is a relatively slow process. The second mechanism to be considered is the dissolution of COPCs from trapped LNAPL in the aquifer caused by a rising water table. This source can also be assumed to be continuous, depending on the volume of LNAPL trapped in the groundwater. It is expected that a greater mass of the COPCs would be dissolved through this mechanism than the first. The third mechanism to consider is point sources at monitoring wells that are screened through the LNAPL layer and the water table. In this case the groundwater is in contact with the LNAPL and the appropriate fraction of COPCs would dissolve into the water table from the LNAPL in the well. In this case, as in the first, chemical diffusion would be the primary mechanism, and this is not expected to yield much contaminant mass to the aquifer.

4.2.3 Transport Parameters

One of the largest sources of uncertainty in modeling advection and dispersion of chemicals in an aquifer is the assumption of a value for longitudinal (in the direction of flow) dispersivity. This value can usually be initially estimated through the use of the Xu and Eckstein (1995) equation. The transverse and vertical dispersivities are usually assumed to be some percentage of the longitudinal dispersivity, usually 10 percent and 0.1 percent, respectively. The heterogeneity of the aquifer determines the dispersivities. Different values of dispersivity can be assigned to different locations and layers in the model. Porosity of the aquifer matrix will be assumed at a value typical for that layer. In the case of the fractured bedrock, an equivalent porosity will be given typical of fractured rock.

Biodegradation and adsorption onto the aquifer matrix will be assumed during the contaminant modeling. The main input parameter to the numerical model to determine biodegradation rates is the half-life of the COPC(s). These values will be obtained from the literature, (Mackay, 1999). The parameters associated with adsorption are the organic carbon distribution coefficient (K_{oc}), the fraction organic carbon, and the soil bulk density. The K_{oc} values will be taken from the literature. The fraction organic carbon can be obtained from the total organic carbon test results that were done in previous investigations. The soil bulk density is also available from the Corrective Measures Investigation (Baker, 1999). All of these parameters combine into the distribution coefficient, K_d, to enable calculation of the mass adsorbed onto the soil matrix in the aquifer.

For the case of trichloroethylene, reductive dechlorination may or may not be modeled, depending on the geochemical conditions and presence of daughter products at the site. This information will be gathered in the upcoming field event.

4.2.4 Calibration

An attempt will be made to calibrate the transport model to actual site conditions given various known sources areas and time frames. However, because of the vast uncertainty of the time frames, spill volumes and spill locations, a realistic calibration is not expected. Since the primary purpose of this modeling effort is to enable a realistic expectation of the results of any remedial

scenarios proposed *in the future* at TWFF, a complete historical calibration is not deemed necessary.

4.3 Vapor Movement

In the MODFLOW-SURFACT model the mass of contaminants available to diffuse into the soil vapor can also be modeled, although no movement in the air can occur due to advection while the groundwater is allowed to move. If the soil vapor movement of the COPC is modeled, then only diffusion of the COPC, and not advection or dispersion, can occur in the groundwater. In other words, only one medium, water or air, can be allowed to move advectively during the simulation. It is expected that this option will be used during the remedial scenarios and not during the initial modeling effort.

5.0 RECOMMENDATIONS FOR FUTURE FIELD INVESTIGATION/DATA COLLECTION EFFORT

5.1 Additional Monitoring Wells

In the upper Tow-Way area, the average groundwater table indicates that the direction of groundwater flow is to the northwest. There are no wells in this direction at TWFF to verify this. It would be beneficial to have up to four more wells north of TWFF to confirm hydraulic gradient. If the direction of groundwater flow is indeed to the northwest in this area, chemical analyses of those wells would be used to determine potential contaminant migration in that direction also.

5.2 LNAPL Analyses

There are three different kinds of LNAPL at the site. The density of the LNAPL at all locations is necessary to determine accurate water table elevations at the site. It is also used to establish the thickness of the LNAPL in the aquifer matrix. Fingerprinting of the LNAPL would be used to determine the mass fraction of the COC or COPC that is available from the LNAPL. In addition to fingerprinting, a determination should be made of the viscosity of the LNAPL. and Henry's constant for the COCs.

5.3 Natural Attenuation Specific Monitoring

According to the data taken for the Corrective Measures Investigation (Baker, 1999), natural attenuation (NA) specific parameters indicate that NA is occurring in the area of BTEX compounds. In order to verify this, a second round of NA parameters in the groundwater should be taken in an upcoming field investigation. These parameters include dissolved oxygen, nitrate, ferrous iron, sulfate, methane, alkalinity, and oxidation-reduction potential.

In addition to these parameters, there are a few additional ones that should be obtained from the wells in the area of the trichloroethylene plume: VOC analyses of cis-1,2 dichloroethylene, trans-1,2 dichloroethylene, and vinyl chloride; dissolved gas analyses of ethene and ethane; chloride should also be measured in the area of the plume and compared to the chloride in areas outside the plume.

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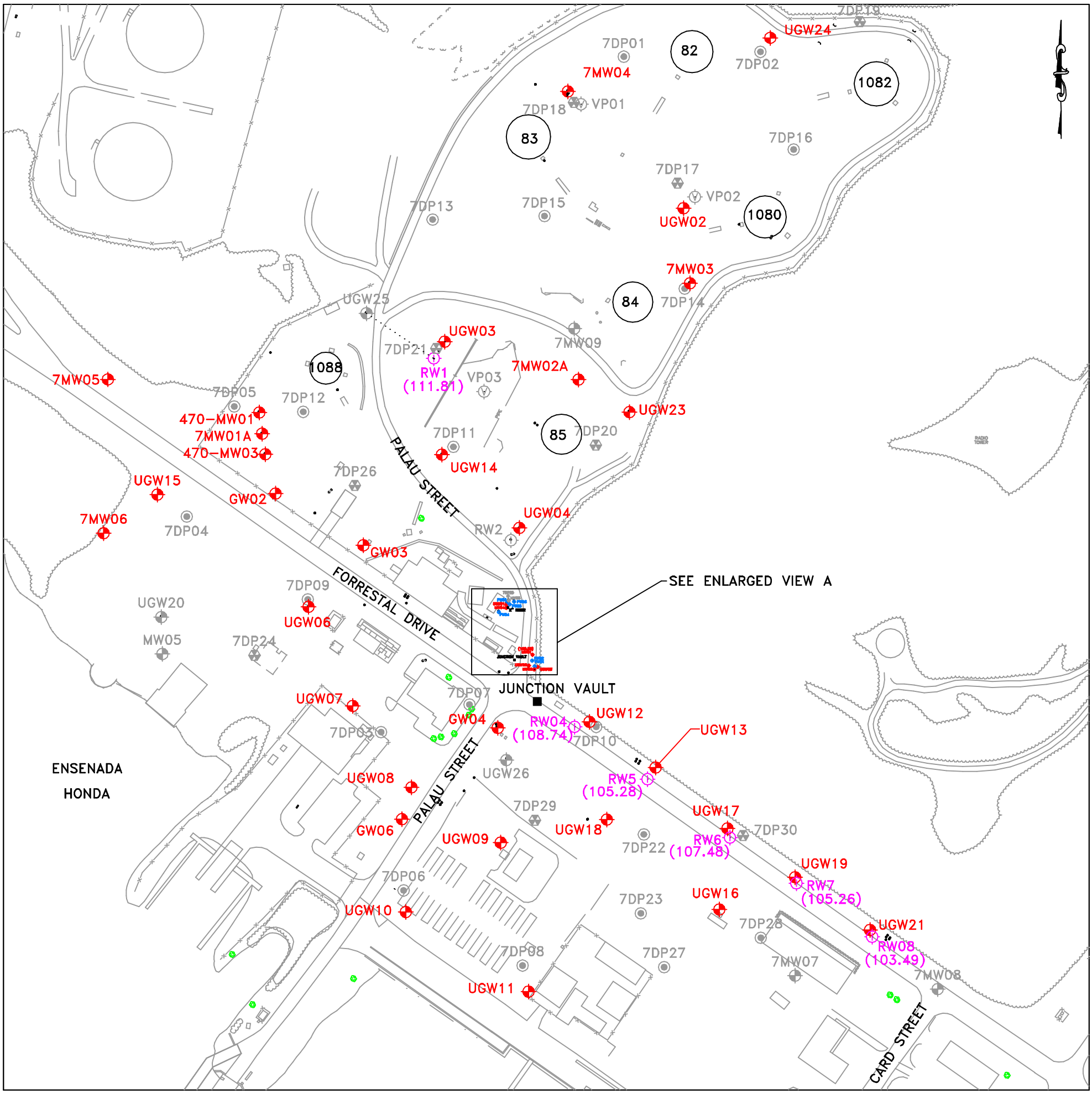
TABLES

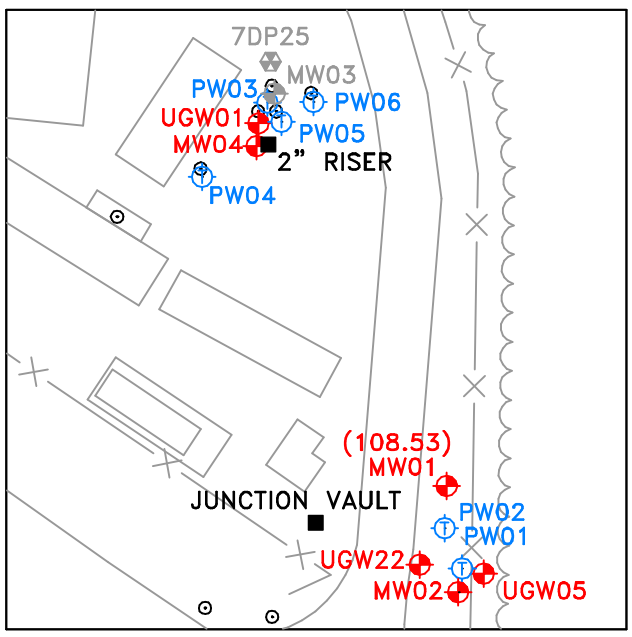
TABLE 2-1
NSRR RAINFALL
1942-1997

Location	YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Roosevelt Roads PU	1942	141	55	203	544	912	878	571	446	763	755	1345	143	6756
Roosevelt Roads PU	1943	473	136	170	165	165	655	310	497	325	685	9999	207	99999
Roosevelt Roads PU	1944	101	9999	42	72	506	523	9999	9999	9999	9999	9999	9999	99999
Roosevelt Roads PU	1945	9999	9999	53	268	9999	506	1274	714	910	9999	9999	9999	99999
Roosevelt Roads PU	1947	9999	9999	9999	9999	9999	9999	9999	9999	9999	9999	384	9999	99999
Roosevelt Roads PU	1948	304	278	294	129	614	458	567	362	886	747	1186	408	6233
Roosevelt Roads PU	1949	263	157	338	113	300	646	825	589	1424	1095	327	610	6687
Roosevelt Roads PU	1950	446	748	92	361	416	276	311	560	568	9999	9999	9999	99999
Roosevelt Roads PU	1959	9999	9999	9999	9999	9999	9999	363	546	645	382	217	496	99999
Roosevelt Roads PU	1960	252	77	566	874	452	572	844	1004	1595	308	676	1128	8348
Roosevelt Roads PU	1961	403	263	183	286	461	230	408	582	457	1008	795	628	5704
Roosevelt Roads PU	1962	349	136	252	557	682	961	455	594	730	679	221	199	5815
Roosevelt Roads PU	1963	200	208	384	640	840	273	375	426	270	203	334	202	4355
Roosevelt Roads PU	1964	192	166	214	424	160	308	636	468	285	444	205	217	3719
Roosevelt Roads PU	1965	169	135	98	180	1118	600	315	674	677	475	534	851	5826
Roosevelt Roads PU	1966	187	134	278	434	338	364	414	424	668	716	696	508	5161
Roosevelt Roads PU	1967	395	154	211	87	319	573	277	243	253	294	834	192	3832
Roosevelt Roads PU	1968	232	170	42	144	359	578	423	369	364	312	458	494	3945
Roosevelt Roads PU	1969	836	331	483	335	1796	421	647	588	802	710	1136	9999	99999
Roosevelt Roads PU	1970	203	183	130	243	1612	740	403	852	421	9999	886	1111	99999
Roosevelt Roads PU	1971	396	285	9999	256	781	375	225	692	9999	747	238	9999	99999
Roosevelt Roads PU	1972	588	137	208	235	195	229	180	257	505	575	186	301	3596
Roosevelt Roads PU	1973	189	124	65	287	48	128	285	597	422	757	230	245	3377
Roosevelt Roads PU	1974	253	9999	270	375	86	75	173	615	714	1772	1944	383	99999
Roosevelt Roads PU	1975	256	103	562	240	421	219	9999	9999	9999	631	599	1021	99999
Roosevelt Roads PU	1976	249	131	207	412	414	206	131	865	626	694	278	223	4436
Roosevelt Roads PU	1977	327	110	319	174	9999	9999	9999	9999	9999	9999	9999	9999	99999
Roosevelt Roads PU	1983	9999	9999	9999	9999	9999	9999	9999	9999	305	511	704	301	99999
Roosevelt Roads PU	1984	202	303	68	108	264	393	196	419	794	527	800	416	4490
Roosevelt Roads PU	1985	239	242	220	153	1036	155	643	690	823	1395	535	174	6305
Roosevelt Roads PU	1986	140	304	212	538	1230	185	262	612	381	721	397	335	5317
Roosevelt Roads PU	1987	9999	225	1806	332	1824	1193	149	406	553	609	1181	9999	99999
Roosevelt Roads PU	1988	222	371	121	320	327	784	738	677	724	779	371	542	5976
Roosevelt Roads PU	1989	186	450	297	91	511	87	617	590	9999	271	130	139	99999
Roosevelt Roads PU	1990	270	302	179	209	161	390	556	222	459	1192	322	447	4709
Roosevelt Roads PU	1991	135	326	215	150	262	596	218	400	433	382	578	242	3937
Roosevelt Roads PU	1992	818	273	175	329	721	449	294	322	748	367	587	820	5903
Roosevelt Roads PU	1993	391	73	136	342	9999	484	1043	266	1110	445	9999	260	99999
Roosevelt Roads PU	1994	214	272	71	70	272	267	180	359	315	612	669	370	3671
Roosevelt Roads PU	1995	108	246	114	120	782	192	542	507	468	531	173	9999	99999
Roosevelt Roads PU	1996	504	236	259	186	325	427	439	385	726	217	926	272	4902
Roosevelt Roads PU	1997	274	388	156	219	399	170	447	265	664	1114	797	137	5030
Average (mm X 10)		**300.19**	**228.67**	**255.08**	**282.10**	**586.36**	**435.95**	**452.32**	**515.78**	**633.69**	**657.28**	**607.75**	**424.91**	
Average (inches)		**1.18**	**0.90**	**1.00**	**1.11**	**2.31**	**1.72**	**1.78**	**2.03**	**2.49**	**2.59**	**2.39**	**1.67**	**79.29**
Fajardo (inches)		**3.91**	**2.88**	**4.1**	**5.08**	**9.21**	**5.92**	**5.64**	**7.77**	**7.09**	**9.83**	**8.65**	**5.68**	**75.76**

Note: The 9999data are believed to be unknown values. The average rainfall calculations were made without the 9999 data.

FIGURES





VIEW A

200 0 100 200
1 inch = 200 ft.

50 0 25 50
1 inch = 50 ft.

NOTE:
DATUM PLAN USED IS MEAN LOW WATER = 100.00 FT. AS ESTABLISHED BY U.S. NAVY SURVEY SECTION AS OF NOVEMBER 1941.

Baker

cad\rroads\arp\277520CM

LEGEND

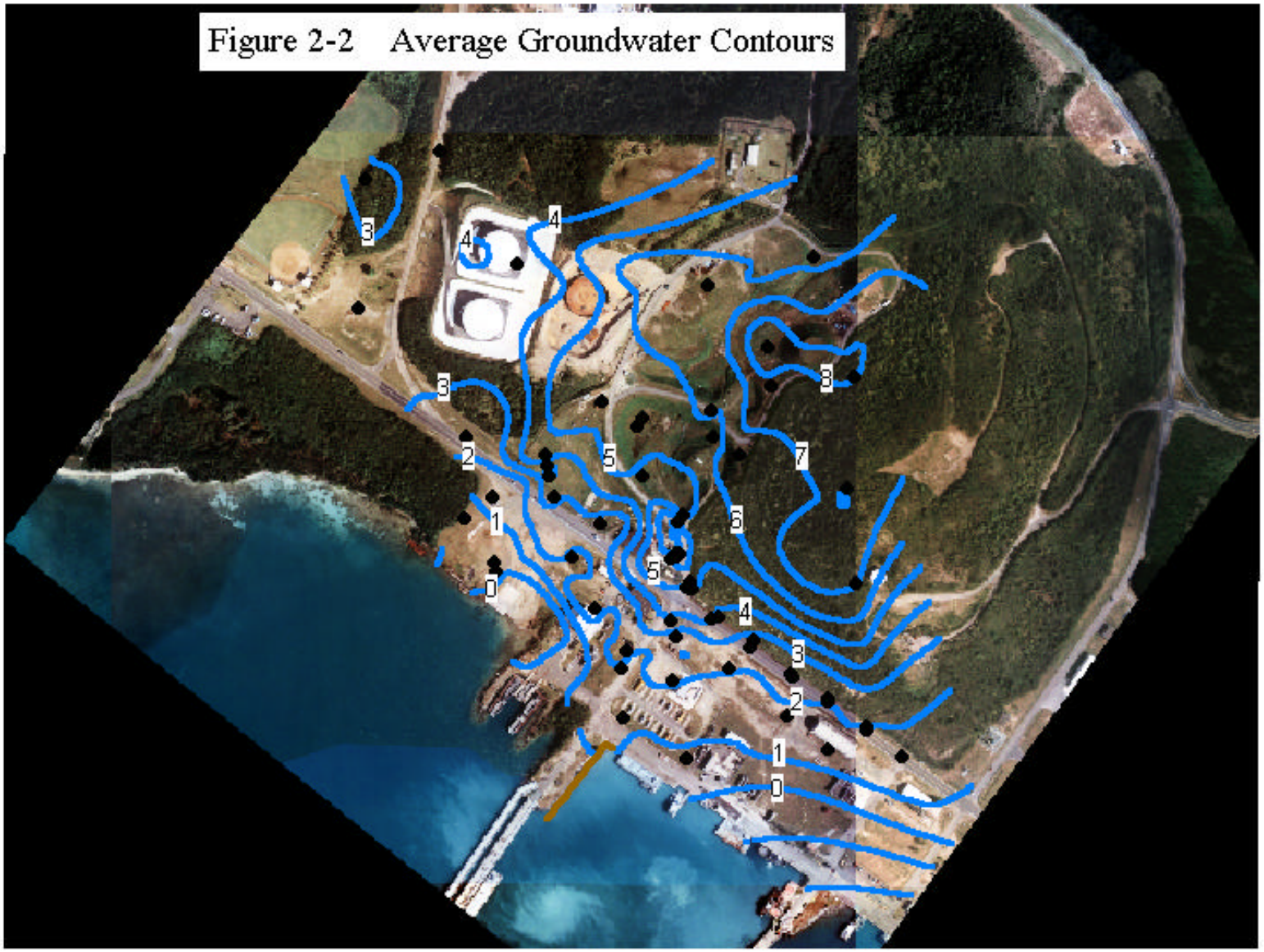
- MONITORING WELL LOCATION
- VERTICAL PERMEABILITY SAMPLE LOCATION
- SOIL BORING LOCATION
- SOIL BORING AND SOIL GAS SAMPLE LOCATION
- TERRAVAC PRODUCT RECOVERY WELL LOCATION
- ICHOR PRODUCT RECOVERY WELL LOCATION

SOURCE: LANTDIV, FEB. 1992/1997

FIGURE 2-1
SITE MAP
TOW WAY FUEL FARM

NAVAL STATION ROOSEVELT ROADS
PUERTO RICO

Figure 2-2 Average Groundwater Contours



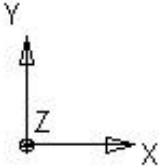


Figure 3-1-- Typical MODFLOW Grid

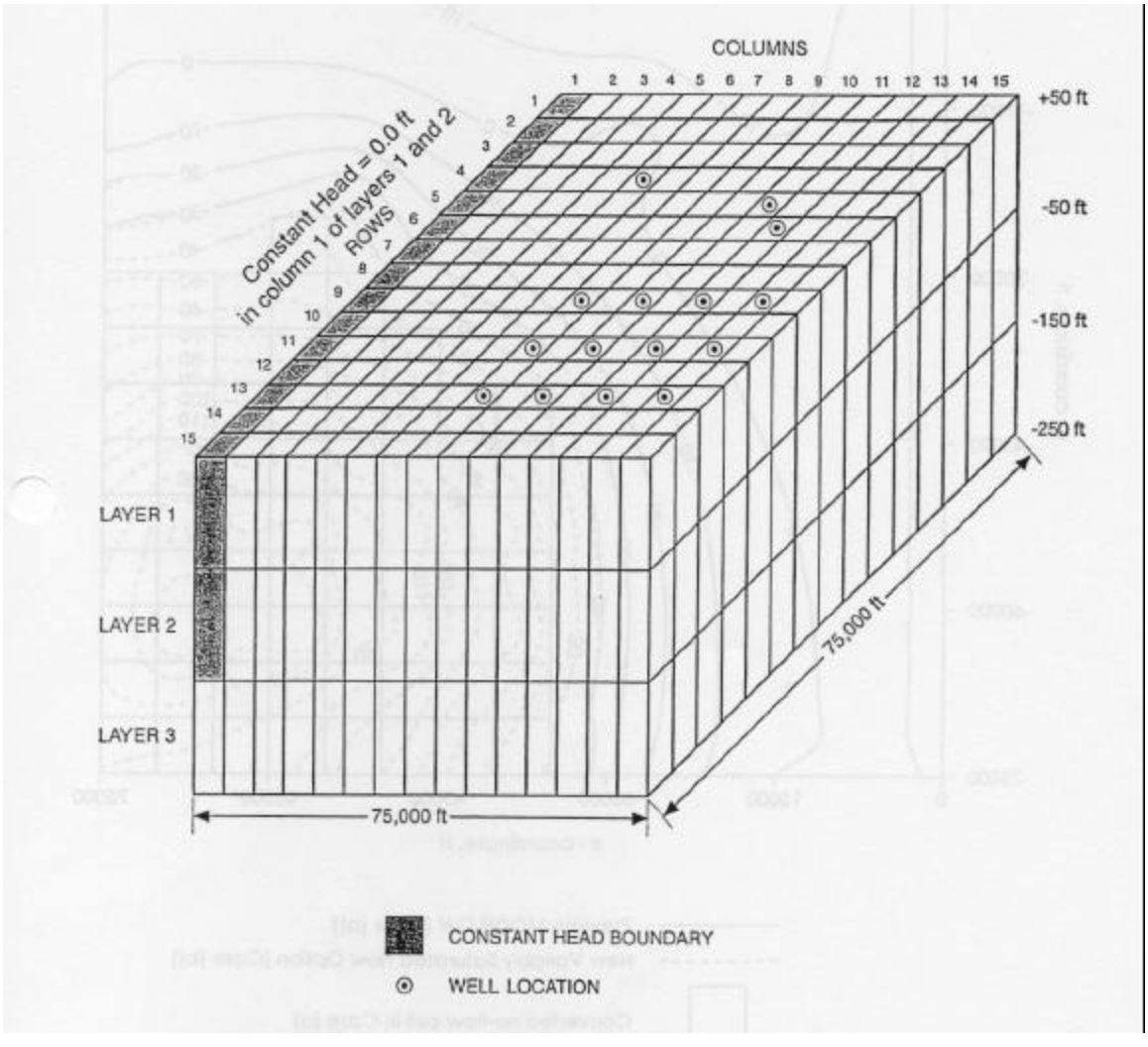
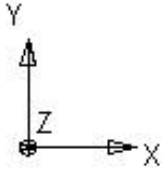


Figure 3-2
Boundaries of the Model



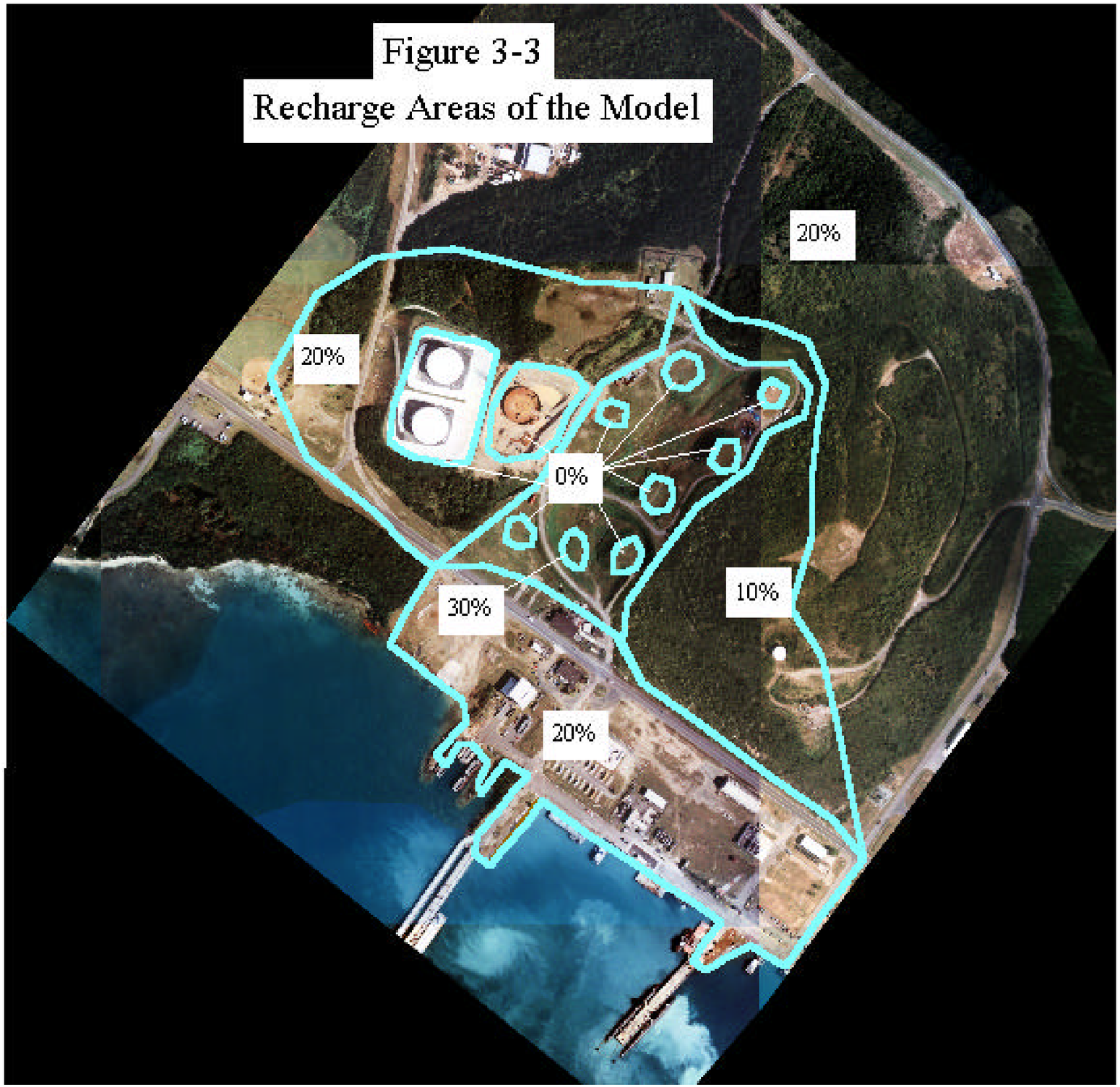


Figure 3-3
Recharge Areas of the Model

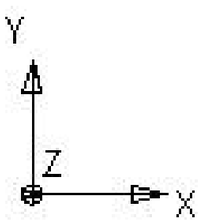
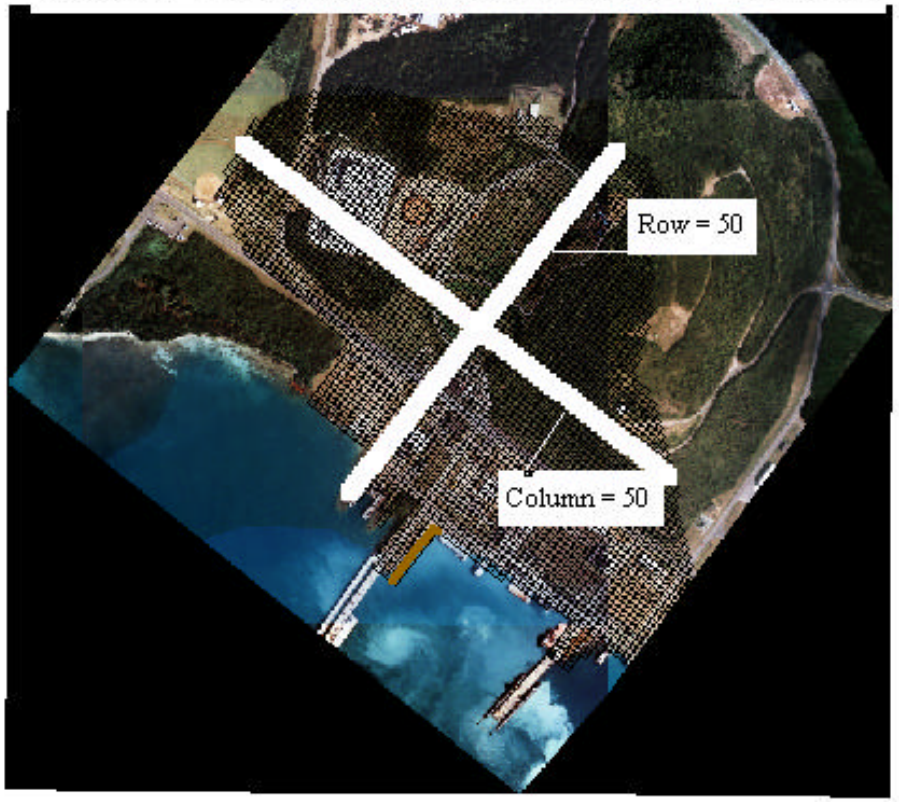
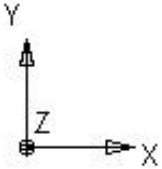


Figure 3-4 Location of 3-D Grid Cross-Sections





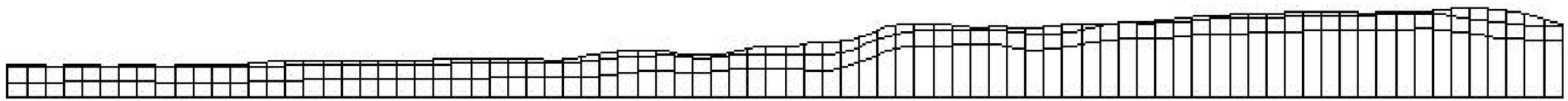


Figure 3-5 Row = 50

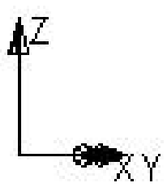
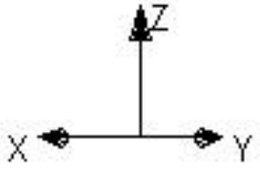
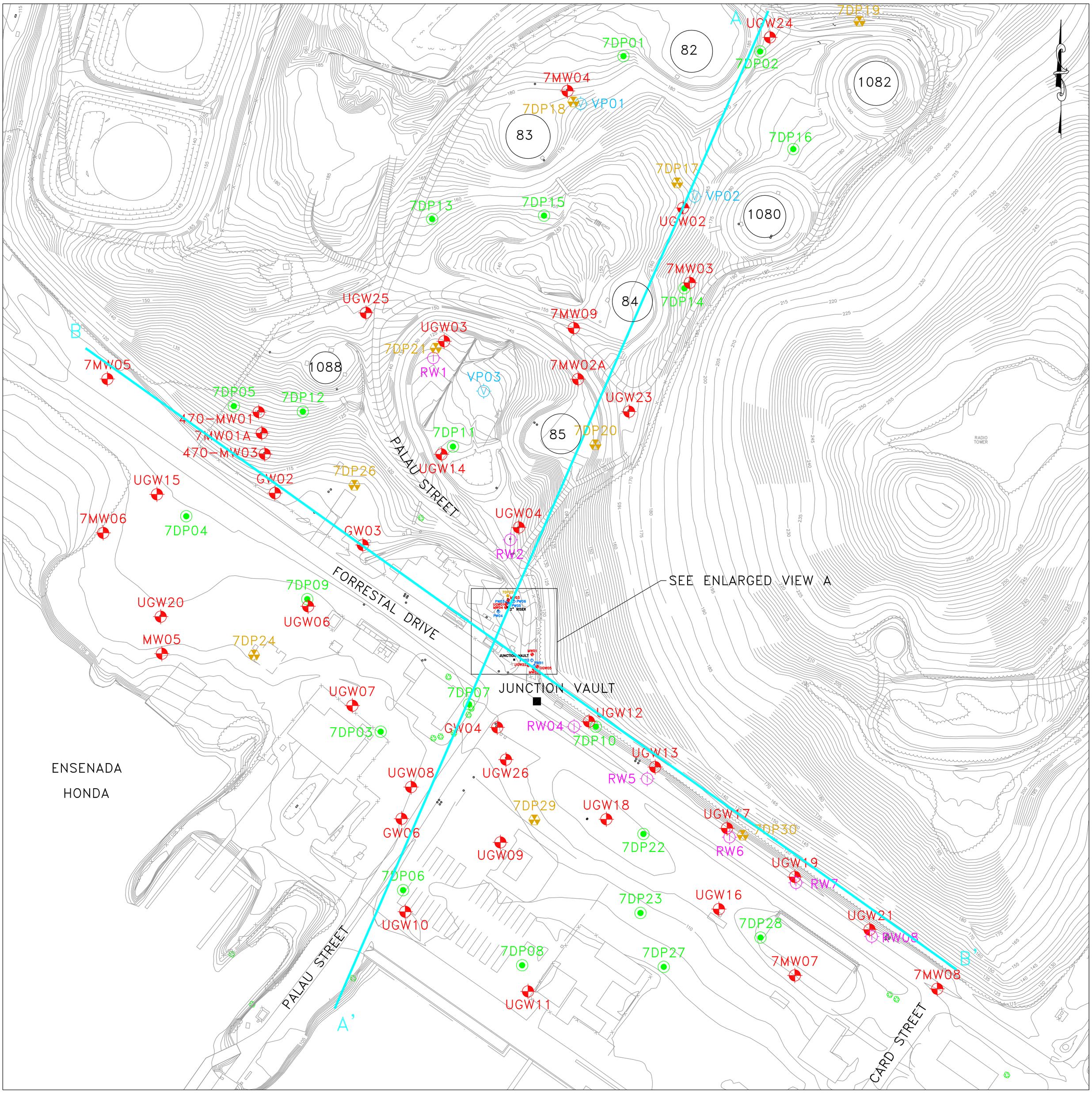
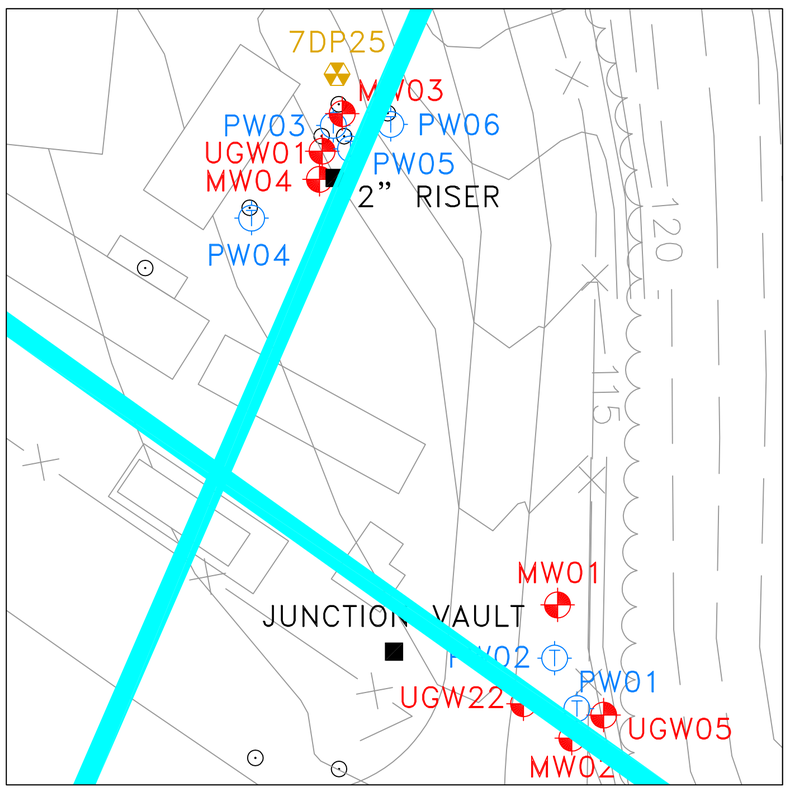


Figure 3-6 Column = 50



APPENDIX A
BORING CROSS-SECTIONS FROM TOW-WAY FUEL FARM INVESTIGATIONS





VIEW A

NOTE:
DATUM PLAN USED IS MEAN LOW WATER = 100.00 FT. AS ESTABLISHED BY U.S. NAVY SURVEY SECTION AS OF NOVEMBER 1941.

Baker

277800WP

LEGEND

- MONITORING WELL LOCATION
- VERTICAL PERMEABILITY SAMPLE LOCATION
- SOIL BORING LOCATION
- SOIL BORING AND SOIL GAS SAMPLE LOCATION
- TERRAVAC PRODUCT RECOVERY WELL LOCATION
- ICHOR PRODUCT RECOVERY WELL LOCATION

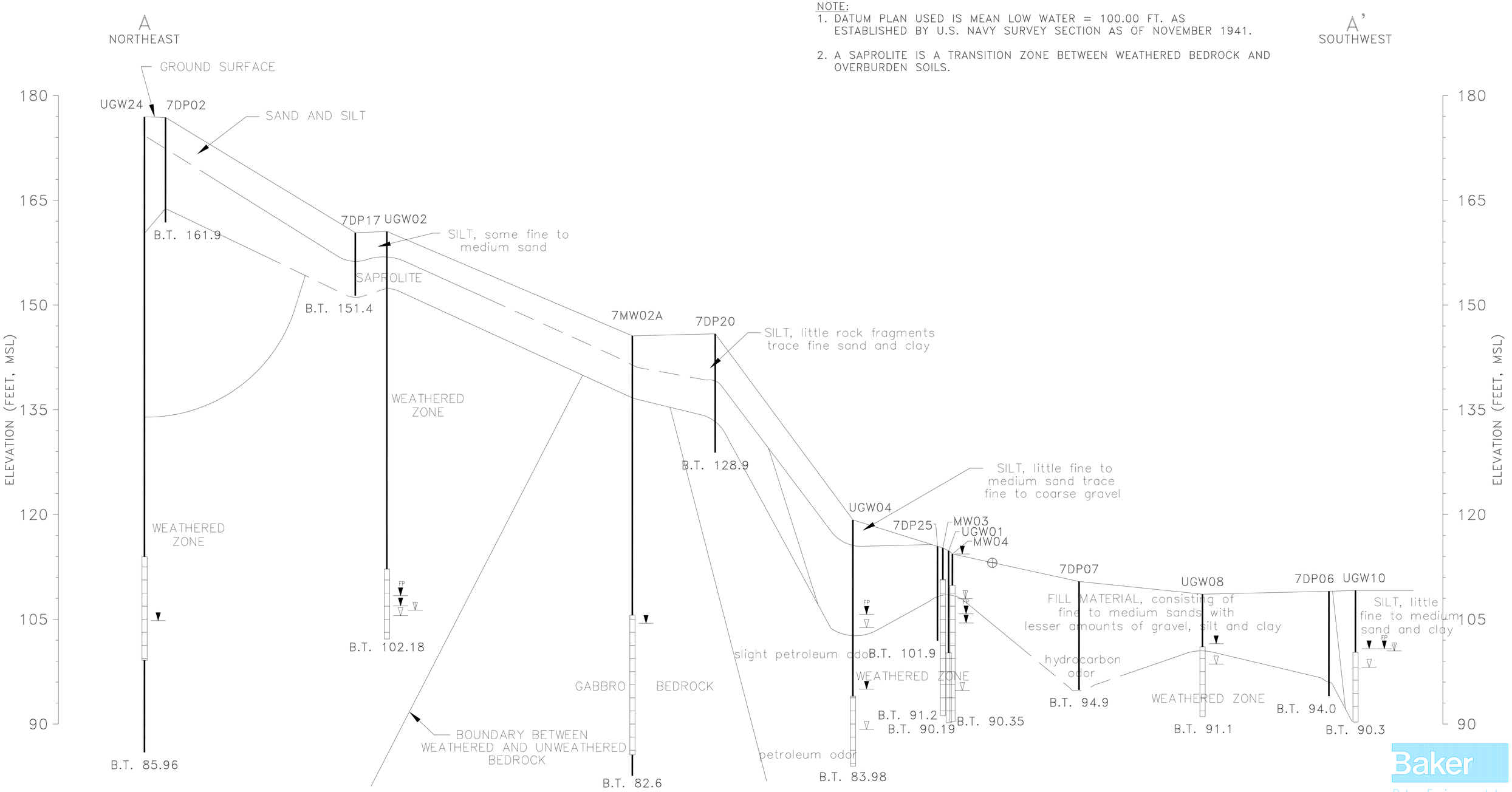
SOURCE: LANTDIV, FEB. 1992/1997

FIGURE 3-1
CROSS SECTION TRAVERSE LOCATIONS FOR A-A' AND B-B'
TOW WAY FUEL FARM

NAVAL STATION ROOSEVELT ROADS
PUERTO RICO

277807WP

NOTE:
1. DATUM PLAN USED IS MEAN LOW WATER = 100.00 FT. AS ESTABLISHED BY U.S. NAVY SURVEY SECTION AS OF NOVEMBER 1941.
2. A SAPROLITE IS A TRANSITION ZONE BETWEEN WEATHERED BEDROCK AND OVERBURDEN SOILS.



Baker
Baker Environmental Inc.

LEGEND

- GROUNDWATER ELEVATION (4/15/98 THROUGH 4/21/98)
- CORRECTED GROUNDWATER ELEVATION (4/21/98)
- GROUNDWATER ENCOUNTERED DURING DRILLING
- FREE PRODUCT ELEVATION (4/15/98 THROUGH 4/21/98)
- B.T. X' — BORING TERMINATED, ELEVATION MSL
- WELL SCREEN INTERVAL
- INTERSECTION OF CROSS-SECTION B-B'
- ESTIMATED — — — PROJECTED

150 0 75 150 300
Horizontal Scale: 1 inch = 150 ft.

15 0 7.5 15 30
Vertical Scale: 1 inch = 15 ft.

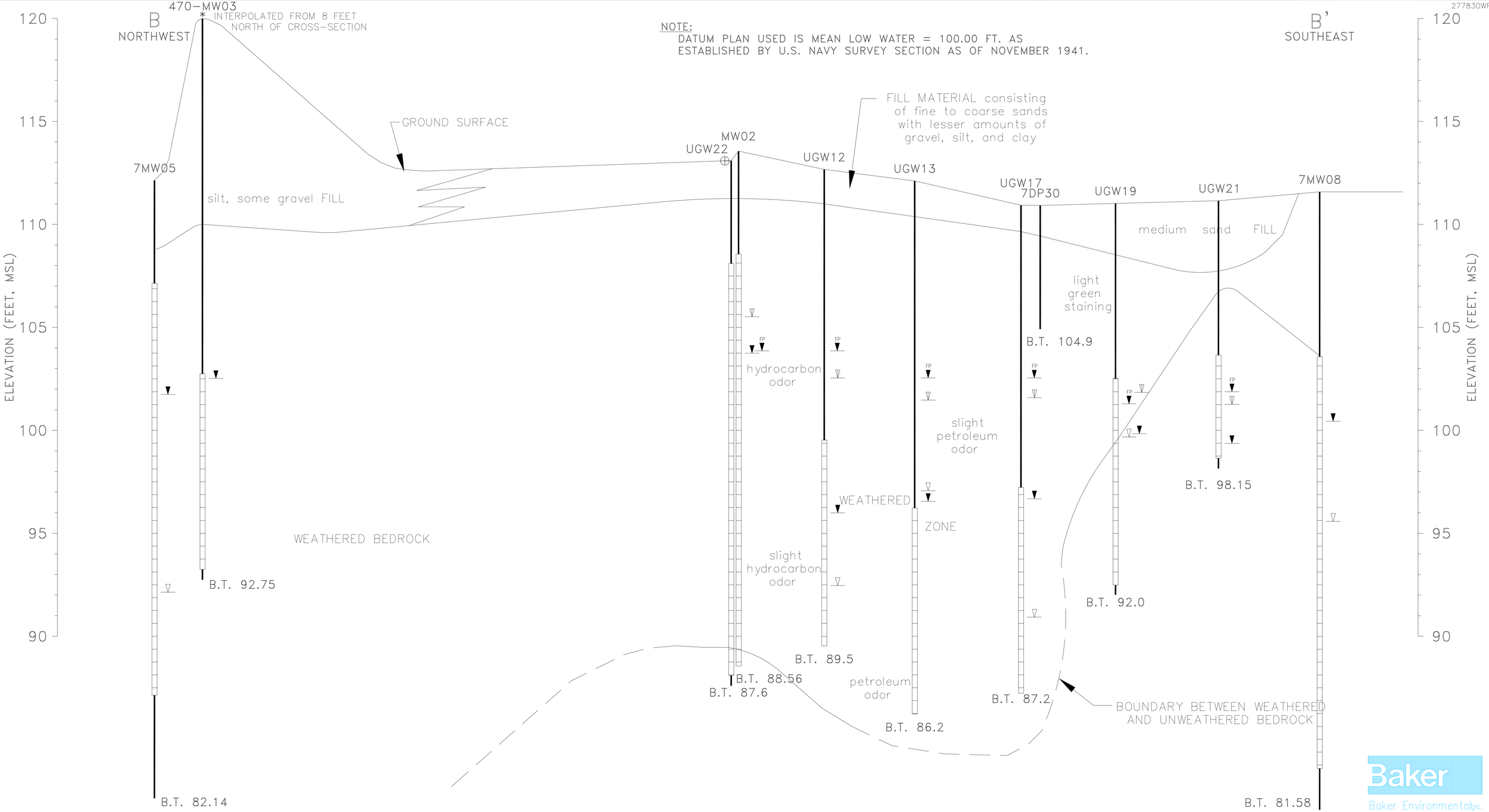
THE SOIL BORING INFORMATION IS CONSIDERED TO BE REPRESENTATIVE OF SUBSURFACE CONDITIONS AT THE RESPECTIVE BORING LOCATIONS. SUBSURFACE CONDITIONS INTERPOLATED BETWEEN BORINGS ARE ESTIMATED BASED ON ACCEPTED SOIL ENGINEERING PRINCIPLES AND GEOLOGIC JUDGEMENT.

FIGURE 3-2
HYDROGEOLOGIC CROSS-SECTION A-A'
TOW WAY FUEL FARM

NAVAL STATION ROOSEVELT ROADS
PUERTO RICO

277830WP

NOTE:
DATUM PLAN USED IS MEAN LOW WATER = 100.00 FT. AS ESTABLISHED BY U.S. NAVY SURVEY SECTION AS OF NOVEMBER 1941.



Baker
Baker Environmental Inc.

LEGEND

- GROUNDWATER ELEVATION (4/15/98 THROUGH 4/21/98)
- CORRECTED GROUNDWATER ELEVATION (4/21/98)
- GROUNDWATER ENCOUNTERED DURING DRILLING
- FP — FREE PRODUCT ELEVATION (4/15/98 THROUGH 4/21/98)
- B.T. X' — BORING TERMINATED, ELEVATION MSL
- WELL SCREEN INTERVAL
- INTERSECTION OF CROSS-SECTION A-A'
- ESTIMATED — — — PROJECTED

160 0 80 160 320

Horizontal Scale: 1 inch = 160 ft.

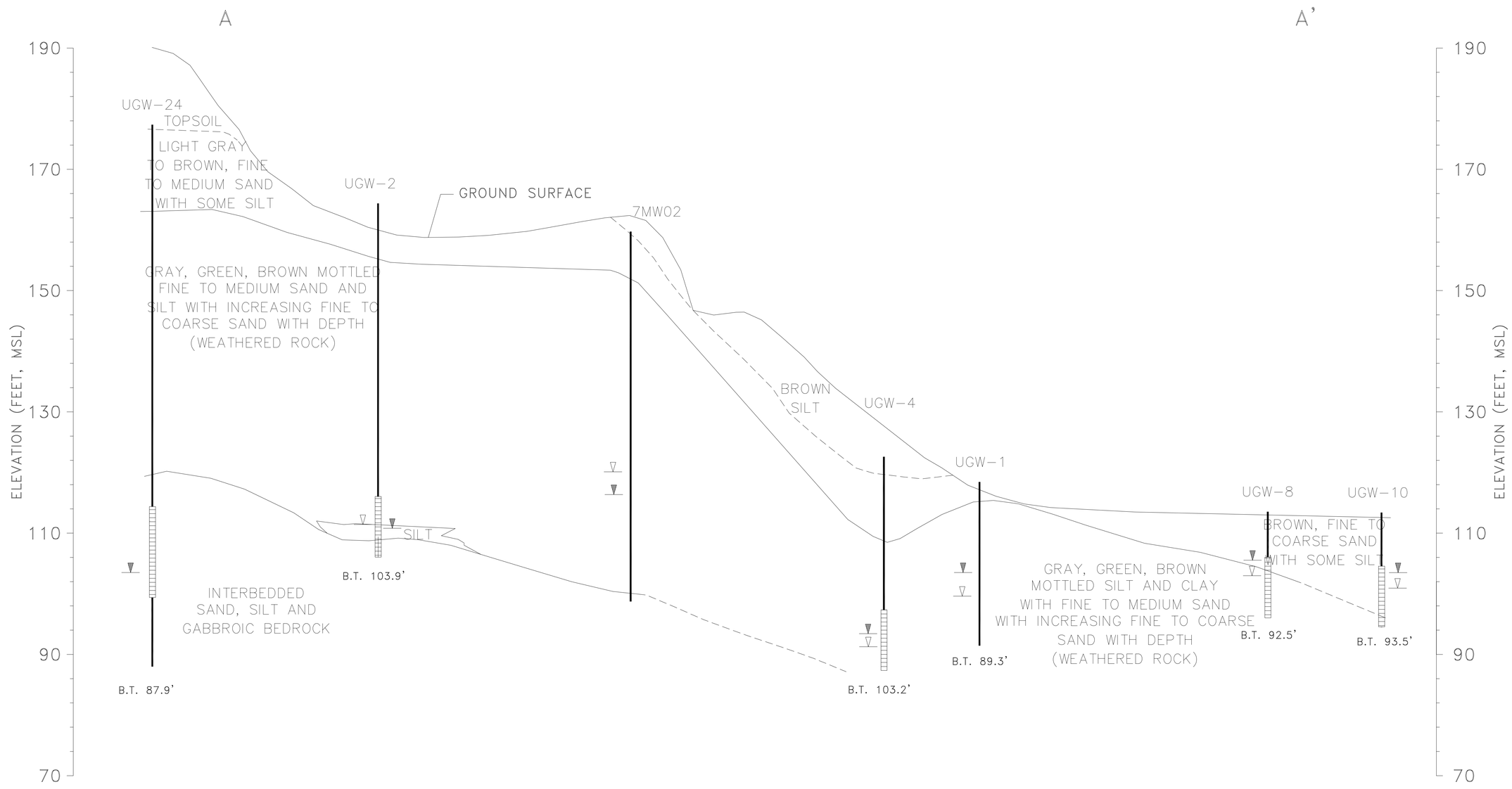
5 0 2.5 5 10

Vertical Scale: 1 inch = 5 ft.

THE SOIL BORING INFORMATION IS CONSIDERED TO BE REPRESENTATIVE OF SUBSURFACE CONDITIONS AT THE RESPECTIVE BORING LOCATIONS. SUBSURFACE CONDITIONS INTERPOLATED BETWEEN BORINGS ARE ESTIMATED BASED ON ACCEPTED SOIL ENGINEERING PRINCIPLES AND GEOLOGIC JUDGEMENT.

FIGURE 3-3
HYDROGEOLOGIC CROSS-SECTION B-B'
TOW WAY FUEL FARM

NAVAL STATION ROOSEVELT ROADS
PUERTO RICO



Baker
Baker Environmental Inc.

LEGEND

- GROUNDWATER ELEVATION
- GROUNDWATER ENCOUNTERED DURING DRILLING
- B.T. X' BORING TERMINATED, ELEVATION, FEET MSL
- WELL SCREEN INTERVAL
- ESTIMATED ----- PROJECTED

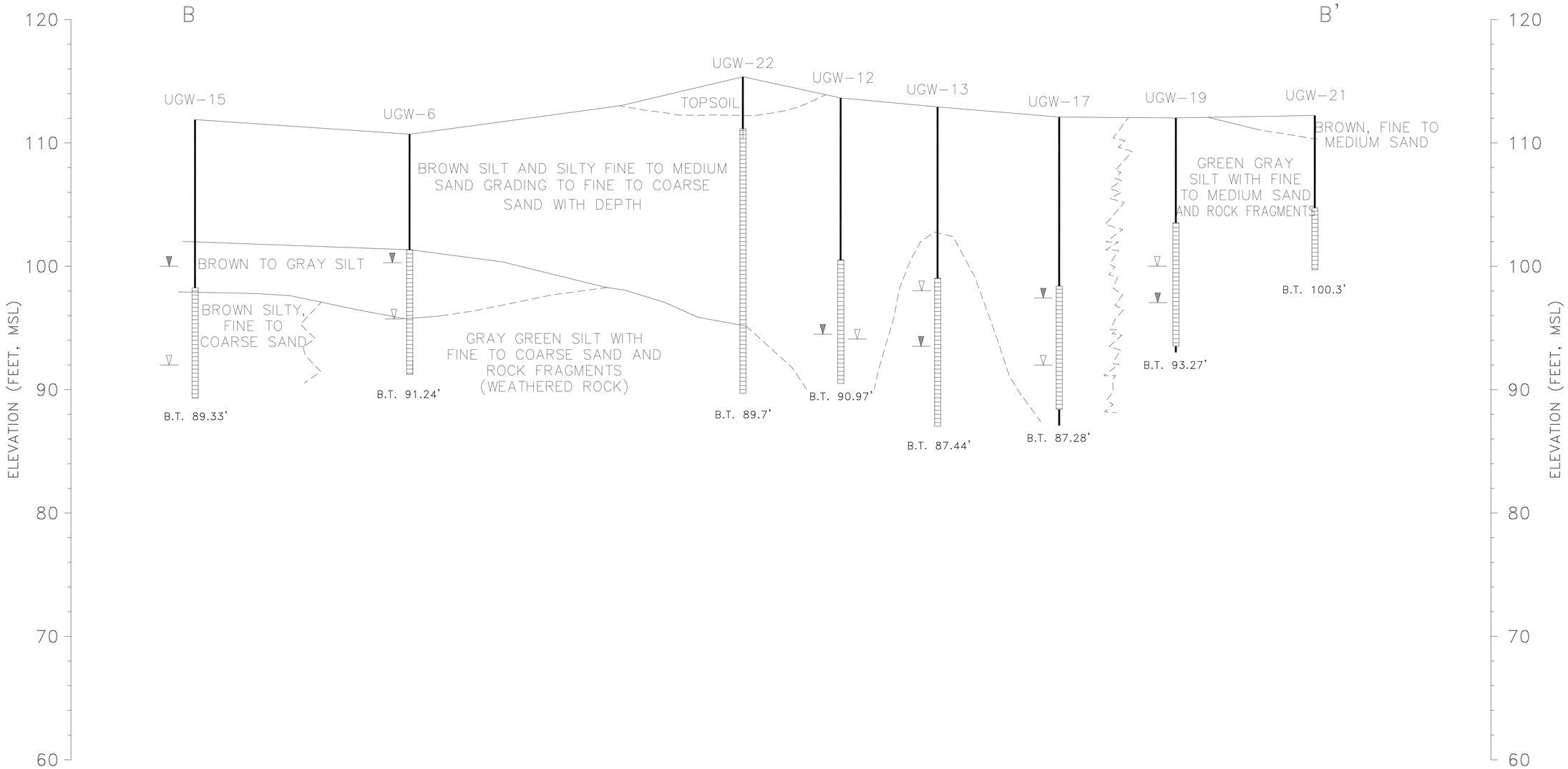
200 0 100 200 400
Horizontal Scale: 1 inch = 200 ft.

20 0 10 20 40
Vertical Scale: 1 inch = 20 ft.

THE SOIL BORING INFORMATION IS CONSIDERED TO BE REPRESENTATIVE OF SUBSURFACE CONDITIONS AT THE RESPECTIVE BORING LOCATIONS. SUBSURFACE CONDITIONS INTERPOLATED BETWEEN BORINGS ARE ESTIMATED BASED ON ACCEPTED SOIL ENGINEERING PRINCIPLES AND GEOLOGIC JUDGEMENT.

FIGURE 4-2
CROSS-SECTION A-A'
RFI SWMU 7/8 - TOW WAY FUEL FARM
CTO - 0277

NAVAL STATION ROOSEVELT ROADS
CEIBA, PUERTO RICO



Baker
Baker Environmental Inc.

LEGEND

- GROUNDWATER ELEVATION (X) AS OF MAY 10, 1996
- GROUNDWATER ENCOUNTERED DURING DRILLING
- B.T. X' — BORING TERMINATED, ELEVATION FEET MSL
- WELL SCREEN INTERVAL
- ESTIMATED ----- PROJECTED

100 0 50 100 200
Horizontal Scale: 1 inch = 100 ft.

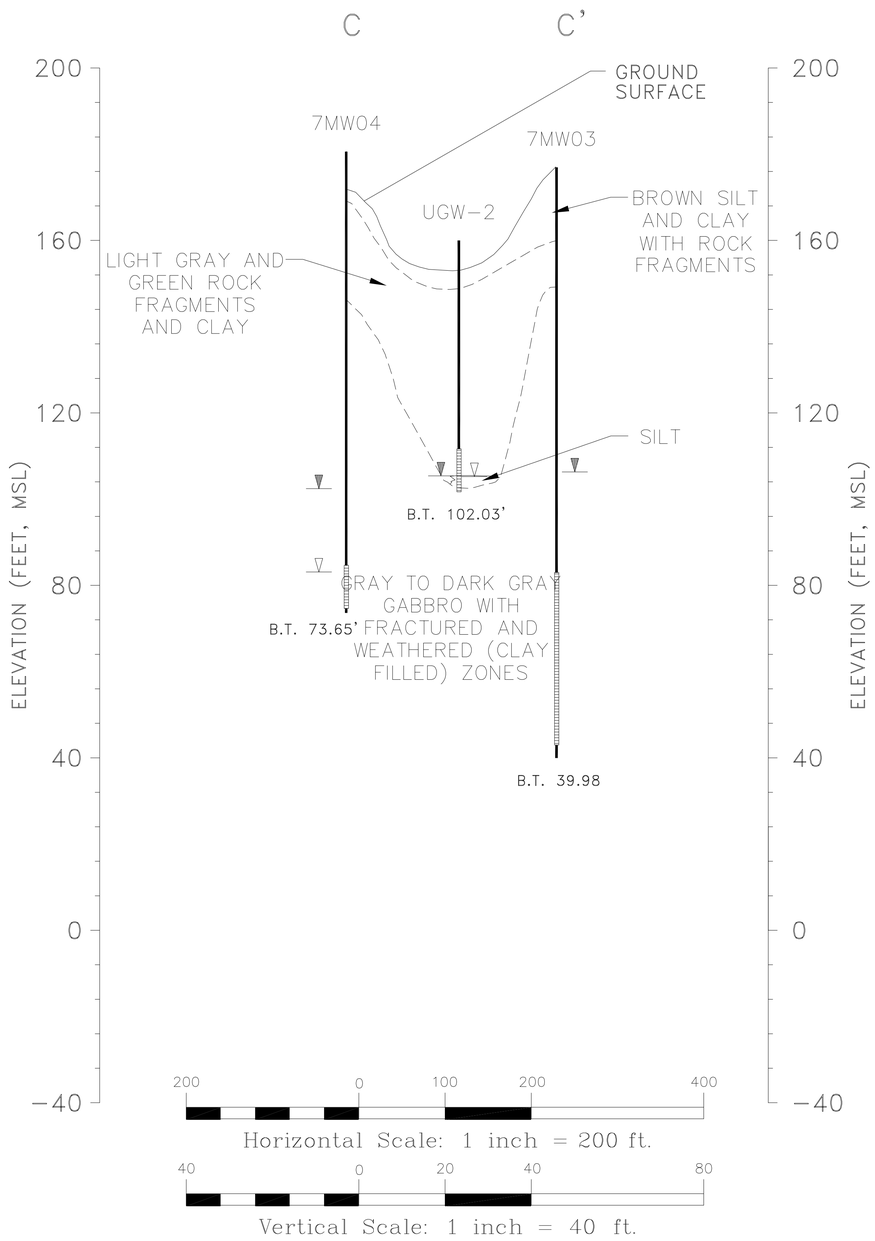
10 0 5 10 20
Vertical Scale: 1 inch = 10 ft.

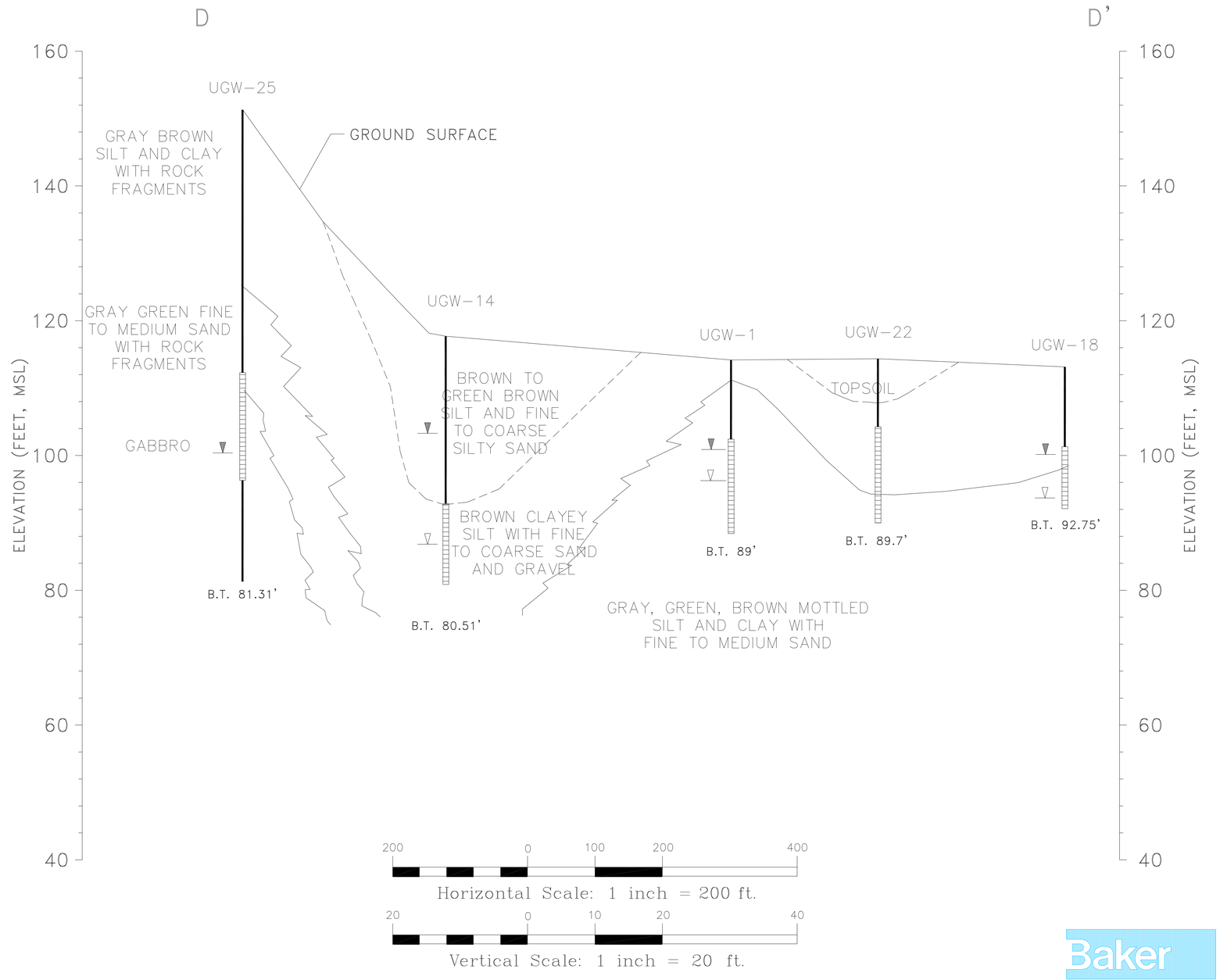
THE SOIL BORING INFORMATION IS CONSIDERED TO BE REPRESENTATIVE OF SUBSURFACE CONDITIONS AT THE RESPECTIVE BORING LOCATIONS. SUBSURFACE CONDITIONS INTERPOLATED BETWEEN BORINGS ARE ESTIMATED BASED ON ACCEPTED SOIL ENGINEERING PRINCIPLES AND GEOLOGIC JUDGEMENT.

FIGURE 4-3
CROSS-SECTION B-B'
RFI SWMU 7/8 - TOW WAY FUEL FARM
CTO - 0277

NAVAL STATION ROOSEVELT ROADS
CEIBA, PUERTO RICO

277914WP





Baker
Baker Environmental Inc.

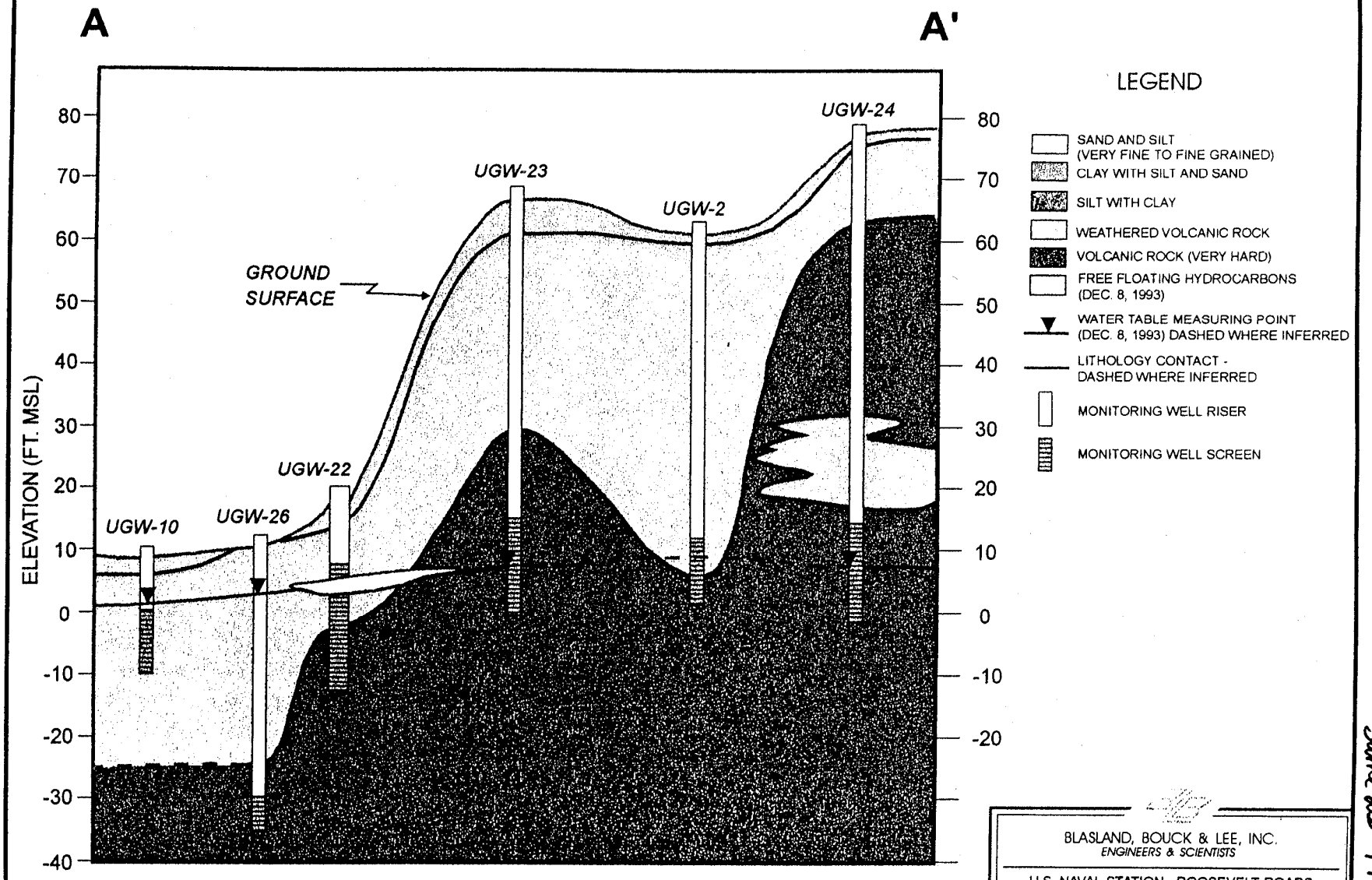
LEGEND

- GROUNDWATER ELEVATION (X)
- GROUNDWATER ENCOUNTERED DURING DRILLING
- B.T. X' BORING TERMINATED, ELEVATION, FEET MSL
- WELL SCREEN INTERVAL
- ESTIMATED ----- PROJECTED
- ASSUMED

THE SOIL BORING INFORMATION IS CONSIDERED TO BE REPRESENTATIVE OF SUBSURFACE CONDITIONS AT THE RESPECTIVE BORING LOCATIONS. SUBSURFACE CONDITIONS INTERPOLATED BETWEEN BORINGS ARE ESTIMATED BASED ON ACCEPTED SOIL ENGINEERING PRINCIPLES AND GEOLOGIC JUDGEMENT.

FIGURE 4-4
CROSS-SECTIONS C-C' AND D-D'
RFI SWMU 7/8 - TOW WAY FUEL FARM
CTO - 0277

NAVAL STATION ROOSEVELT ROADS
CEIBA, PUERTO RICO



VERTICAL EXAGGERATION - x7.5

BLASLAND, BOUCK & LEE, INC.
ENGINEERS & SCIENTISTS

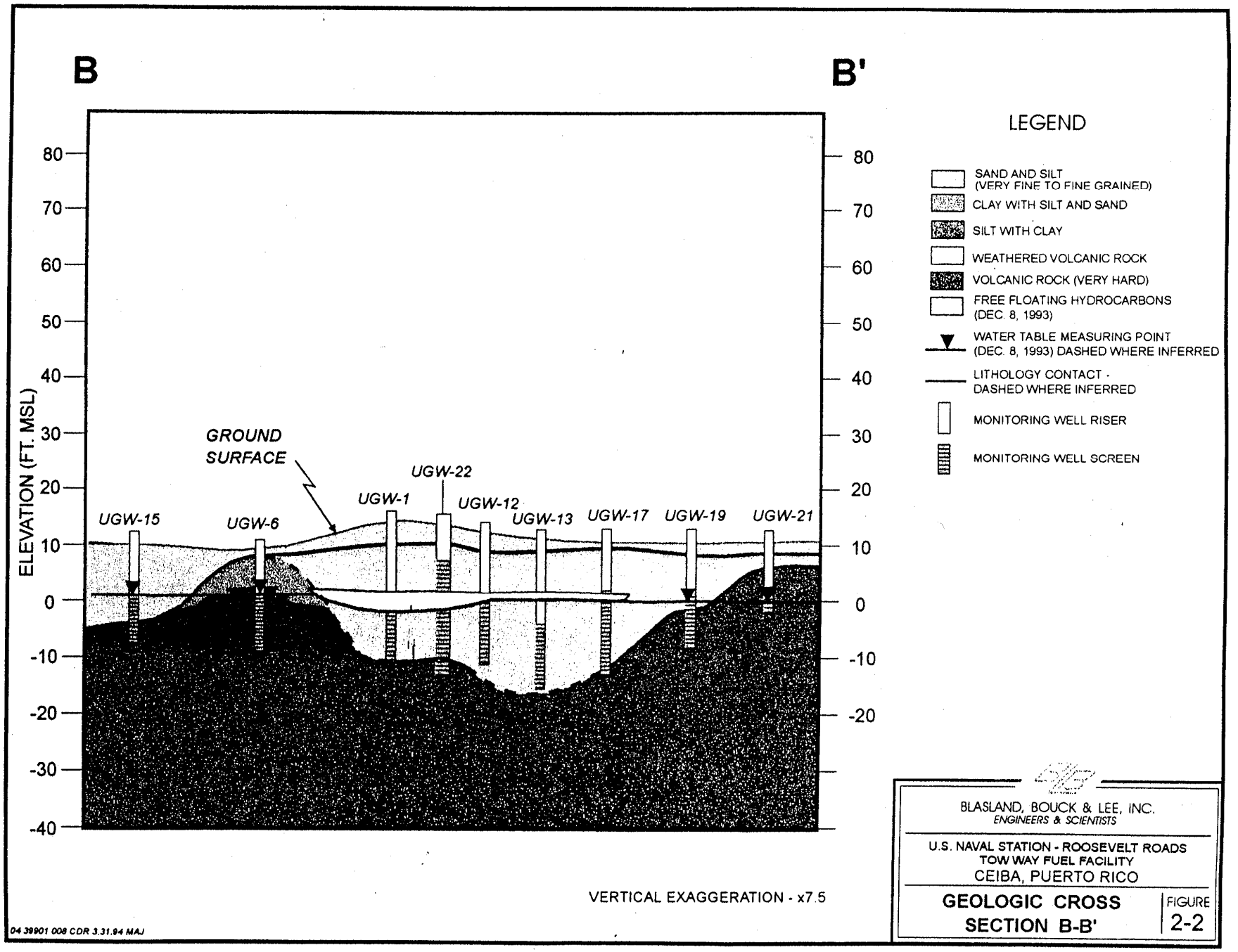
U.S. NAVAL STATION - ROOSEVELT ROADS
TOW WAY FUEL FACILITY
CEIBA, PUERTO RICO

GEOLOGIC CROSS SECTION A-A'

FIGURE 2-1

04 39901 007 CDR 3.31.94 MAJ

1993 Report
Same as 1997 RI


B
B'
ELEVATION (FT. MSL)
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
GROUND SURFACE
UGW-15
UGW-6
UGW-1
UGW-22
UGW-12
UGW-13
UGW-17
UGW-19
UGW-21
LEGEND
SAND AND SILT (VERY FINE TO FINE GRAINED)
CLAY WITH SILT AND SAND
SILT WITH CLAY
WEATHERED VOLCANIC ROCK
VOLCANIC ROCK (VERY HARD)
FREE FLOATING HYDROCARBONS (DEC. 8, 1993)
WATER TABLE MEASURING POINT (DEC. 8, 1993) DASHED WHERE INFERRED
LITHOLOGY CONTACT - DASHED WHERE INFERRED
MONITORING WELL RISER
MONITORING WELL SCREEN
VERTICAL EXAGGERATION - x7.5
04 39901 008 CDR 3.31.94 MAJ
BLASLAND, BOUCK & LEE, INC.
ENGINEERS & SCIENTISTS
U.S. NAVAL STATION - ROOSEVELT ROADS
TOW WAY FUEL FACILITY
CEIBA, PUERTO RICO
GEOLOGIC CROSS SECTION B-B'
FIGURE 2-2

APPENDIX B
EQUIVALENT FRESH-WATER HEAD WATER TABLE CORRECTION EQUATION

Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater

Volume I

By

Todd Wiedemeier
Parsons Engineering Science, Inc.
Denver, Colorado

John T. Wilson and Donald H. Kampbell
U.S. Environmental Protection Agency
Robert S. Kerr Laboratory
Ada, Oklahoma

Ross N. Miller and Jerry E. Hansen
Air Force Center for Environmental Excellence
Technology Transfer Division
Brooks AFB, San Antonio, Texas

Air Force Center for Environmental Excellence
Technology Transfer Division
Brooks AFB, San Antonio, Texas

In areas with measurable mobile LNAPL, a correction must be made for the water table deflection caused by the LNAPL. The following relationship, based on Archimedes' Principle, provides a correction factor that allows the water table elevation to be adjusted for the effect of floating LNAPL.

$$CDTW = MDTW - \frac{\rho_{lnapl}}{\rho_w}(PT) \qquad \text{eq. C.2.1}$$

Where: $CDTW$ = corrected depth to water [L]
$MDTW$ = measured depth to water [L]
ρ_{lnapl} = density of the LNAPL [M/L^3]
ρ_w = density of the water, generally 1.0 [M/L^3]
PT = measured LNAPL thickness [L]

Using the corrected depth to water, the corrected groundwater elevation, CGWE, is given by:

$$CGWE = \text{Datum Elevation} - CDTW \qquad \text{eq. C.2.2}$$

Corrected groundwater elevations should be used for potentiometric surface map preparation. Figure C.2.2 is an example of a groundwater elevation map for an unconfined aquifer. Water table elevation data used to prepare this map were taken from wells screened across the water table.

APPENDIX C
SALTWATER-FRESHWATER INTERFACE EQUATIONS

Groundwater Mechanics

OTTO D.L. STRACK

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Department of Civil and Mineral Engineering
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Minneapolis, Minnesota 55455

PRENTICE HALL ***Englewood Cliffs, New Jersey 07632***

10 SHALLOW INTERFACE FLOW

We will refer to a flow as interface flow when the aquifer contains two fluids that are separated by an interface rather than a transition zone, and when one of the fluids is at rest. Coastal aquifers are often modeled with good approximation by assuming interface flow. The fresh water, then, is assumed to flow over salt water at rest. If the aquifer is sufficiently shallow with respect to its extent so that the resistance to flow in the vertical direction may be neglected, we will call the flow shallow interface flow.

Condition Along the Interface

A cross section through an aquifer with fresh water flowing over salt water at rest is shown in Figure 2.31. The aquifer is bounded above by a phreatic surface and below by an interface that separates the fresh water from salt water at rest. The distances between these surfaces and sea level are denoted as h_f and h_s, where the indices f and s stand for fresh and salt. All heads are measured from a reference level, which lies a distance H_s below sea level. The head in the fresh water, ϕ, is expressed in terms of the pressure p_f by the use of (2.7) as

$$\phi = \frac{p_f}{g\rho_f} + Z \tag{10.1}$$

where ρ_f is the density of the fresh water and the elevation head Z is measured from the reference level. The head ϕ_s in the salt water is written similarly in terms of the pressure p_s in the salt water,

$$\phi_s = \frac{p_s}{g\rho_s} + Z \tag{10.2}$$

where ρ_s is the density of the salt water. The pressure must be single-valued at all points of the interface, such as point $\mathcal{P}$ in Figure 2.31. This gives, with (10.1) and (10.2), and with $Z = H_s - h_s$ at $\mathcal{P}$:

$$g\rho_f(\phi - H_s + h_s) = g\rho_s(\phi_s - H_s + h_s) \tag{10.3}$$

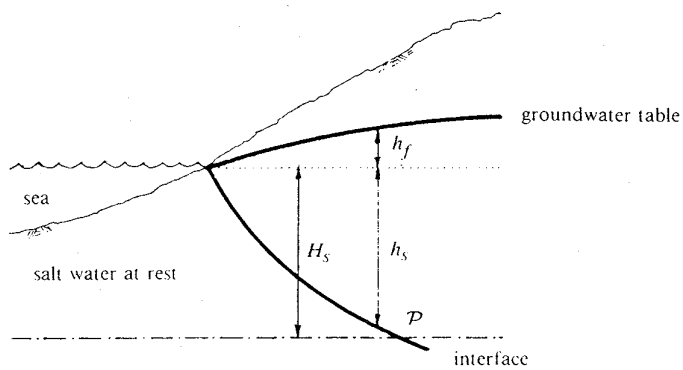

Figure 2.31 The Ghyben-Herzberg equation.

We neglect the resistance to flow in the vertical direction, the Dupuit-Forchheimer assumption, so that the equipotentials are vertical: $\phi = H_s + h_f$. We further limit the analysis to cases where the salt water is at rest so that the head in the salt water equals the elevation of the sea level above the reference level, i.e., $\phi_s = H_s$. This yields with (10.3), after rearrangement of terms and division by $g\rho_f$:

$$\boxed{h_f = h_s \frac{\rho_s - \rho_f}{\rho_f}} \tag{10.4}$$

This equation is known as the Ghyben-Herzberg equation and was derived independently by Badon Ghyben [1888] and Herzberg [1901]. It is of interest to note that Du Commun [1828] should really be credited with the discovery of the Ghyben-Herzberg equation (Carlston [1963]). It may be noted that the Ghyben-Herzberg equation is equally valid when the upper boundary of the aquifer is a horizontal impermeable boundary rather than a phreatic surface. In that case, h_f represents the piezometric head with respect to sea level.