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FINAL

GROUNDWATER MODELING REPORT
OPERABLE UNIT NO. 9
SITE 73 - AMPHIBIOUS VEHICLE MAINTENANCE FACILITY

MARINE CORPS BASE
CAMP LEJEUNE, NORTH CAROLINA

CONTRACT TASK ORDER 0312

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LIST OF ACRONYMS AND ABBREVIATIONS

AFCEE	Air Force Center for Environmental Excellence
AME	Absolute Mean Error (see Absolute Residual Mean)
ARM	Absolute Residual Mean
b	Aquitard Thickness
BC	Boundary Conditions (MODFLOW)
BRAGS	Base-Wide Remediation Assessment Groundwater Study
C_{drn}	Drain Cell Conductance (MODFLOW)
C_{riv}	River Cell Conductance (MODFLOW)
CA	Corrective Action
CCLs	Ceiling Concentration Limits
CCP	Central Coastal Plain
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)
cfd	Cubic Feet per Day
cis-1,2-DCE	cis-1,2-dichloroethene
cm/sec	Centimeters per Second
CMS	Corrective Measure Study
CTO	Contract Task Order
DCE	cis and trans-1,2-dichloroethene
DNAPLs	Dense Non-Aqueous Phase Liquids
DoN	Department of the Navy
ESE	Environmental Science and Engineering, Inc.
FFA	Federal Facilities Agreement
ft^2/day	Square Feet/Day (unit of transmissivity)
ft/day-s	Feet/Day (unit of velocity or hydraulic conductivity)
ft/day/ft	Feet/Day/Feet (unit of leakance)
FS	Feasibility Study
G3CTM	G-3 Contaminant Transport Model (for groundwater discharge to surface water -- NC DENR)
gpm	Gallons per Minute
GWQ	Groundwater Quality
HFB	Horizontal Flow Barrier (MODFLOW)
HPIA	Hadnot Point Industrial Area
IP	Implementation Plan
IR	Installation Restoration

LIST OF ACRONYMS AND ABBREVIATIONS
(Continued)

K	Hydraulic Conductivity (ft/day)
K_{ii}	Hydraulic Conductivity Tensor in the i direction (MODFLOW)
K_v	Vertical Hydraulic Conductivity (ft/day)
L	Length of Cell (MODFLOW)
m	Thickness of River or Stream Sediments (MODFLOW)
ME	Mean Error (see Residual Mean)
MCB	Marine Corps Base
mi^2	Square Mile
MSL	Mean Sea Level
n	Sample Size
NC	North Carolina
NC DENR	North Carolina Department of Environment and Natural Resources
NPL	National Priorities List
OU	Operable Unit
PCE	Tetrachloroethene (perchloroethylene)
ppb	Parts per Billion
RASA	Regional Aquifer System Analysis
RCRA	Resource Conservation and Recovery Act
RF	Retardation Factors
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
RSD	Residual Standard Deviation
RM	Residual Mean
RMS	Root Mean Square
RMSE	Root Mean Square Error (see Root Mean Square)
SMP	Site Management Plan
TCE	Trichloroethene
trans-1,2-DCE	Trans-1,2-dichloroethene
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UST	Underground Storage Tank
VC	Vinyl Chloride
VOC	Volatile Organic Compound
W	Width of Cell (MODFLOW)
WAR	Water and Air Research, Inc.

LIST OF ACRONYMS AND ABBREVIATIONS
(Continued)

X	X Axis of Cartesian Coordinates associated with Hydraulic Conductivity (MODFLOW)
Y	Y Axis of Cartesian Coordinates associated with Hydraulic Conductivity (MODFLOW)
Z	Z Axis of Cartesian Coordinates associated with Hydraulic Conductivity (MODFLOW)
°F	Degrees Fahrenheit

EXECUTIVE SUMMARY

This Groundwater Modeling Report was prepared to support the evaluation of remedial alternatives in the Feasibility Study (FS) for Operable Unit No. 9, Amphibious Vehicle Maintenance Facility at Marine Corps Base (MCB) Camp Lejeune, North Carolina. Specifically, the modeling effort provided data interpretation to assist in evaluating the impact on groundwater contaminants of various remedial options and the risk mitigating effects of those options on adjoining Courthouse Bay. This report describes the several steps taken to:

1. Define the three-dimensional groundwater flow directions beneath the site (using MODFLOW).

2. Determine the fate of the identified dissolved contaminants (by advection using MODPATH).

3. Estimate concentration in surface water after discharge into Courthouse Bay (using G3CTM).

4. Assess the need for remediation based on appropriate objectives in three different scenarios.

5. Optimize the remedial measures (using MODFLOW and MODPATH).

6. Compare the efficacy of the various remedial scenarios (e.g., wells versus trench using MODFLOW and MODPATH).

Groundwater flow modeling played a major role in accomplishing the above objectives. The combination of numerical (MODFLOW) and analytical (G3CTM) models was used to conceptualize and illustrate the exposure pathway of a contaminant from groundwater to surface water. There were several specific objectives and two major objectives of the modeling effort. The first major objective was to develop a site-specific, steady-state, three-dimensional, calibrated groundwater flow model (using MODFLOW and MODPATH) that would be used to:

- Predict the fate (and perhaps suggest source area locations) of the groundwater contaminants at Site 73 by simulating the existing three-dimensional patterns of groundwater flow at Site 73 in the surficial hydrologic unit and the Castle Hayne Aquifer including the interaction of groundwater and surface water (Courthouse Bay).

- Assess the potential for contaminant migration toward water supply wells across Courthouse Bay toward BB-44 or other Courthouse Bay area wells.

- Compare the efficacy of various remediation schemes for Site 73 in order to protect potential human and/or ecological receptors from groundwater contaminants (particularly trichloroethene and its degradation products: cis-1,2-dichloroethene and vinyl chloride).

- Evaluate the potential hydrologic effects of the remedial scenarios on the groundwater regime.

- Support the design of the selected remedial alternative.

The groundwater flow model has proved useful in predicting the ultimate fate of the groundwater contaminants and helped in answering many questions regarding the associated risk. Based on the conceptual model (as described in Section 2.3) and within the limitations of its calibration, the Site 73 model describes how groundwater flows beneath the Amphibious Vehicle Maintenance Facility (Objective 1). It also demonstrated that the groundwater contaminants at Site 73 are not likely the source of trace contamination in water supply well BB-44 (Objective 2). The Site 73 model demonstrates the effects of remedial groundwater withdrawals on the surficial water table and the Castle Hayne Aquifer (Objective 3). The model demonstrates that the relatively low-volume withdrawal rates of the extraction wells will have an extremely localized effect on the water levels in the surficial unit and the Castle Hayne Aquifer (Objective 4). The model can also be used to help design and optimize the remediation system(s) if necessary (Objective 5).

The second major objective was to develop a steady-state, single-species contaminant transport model (using MT3D with the results from MODFLOW) that would be used to predict the fate of trichloroethene (TCE) in the subsurface beneath Site 73 and to evaluate the risk to Courthouse Bay (the only receptor) associated with the TCE concentrations under several remedial scenarios. However, the risk associated with the degradation products of TCE [especially vinyl chloride (VC)] in groundwater is actually greater than that posed by the TCE. This meant that the concentrations of the single-species (TCE) predicted by MT3D would not provide adequate information to evaluate the risks posed by vinyl chloride (VC) and cis-1,2-dichloroethene (DCE).

Therefore, instead of completing the MT3D calibration, the proposed Draft Risk Analysis Framework (NC DENR, 1996) was used to estimate the surface water concentrations of TCE and VC from groundwater discharge (class G-3, Method II). Using site-specific input values and conservative assumptions it was determined that the allowable "source" concentrations in the surficial unit were 0.818 mg/L TCE, 16,200 mg/l DCE and 1.21 mg/L VC. In the Castle Hayne Aquifer, the values were 0.994 mg/L TCE, 5.53e+6 mg/L DCE and 6.7 mg/L VC. These "source" concentrations are considered protective of the applicable surface water quality standards (0.0924 mg/L TCE, 7.0 mg/L DCE and 0.525 mg/L VC). However, according to the Draft Risk Analysis Framework Document, the allowable "source" concentrations may not be higher than the Ceiling Concentration Limits (CCLs). The CCLs for VC are defined as either 1,000 times the groundwater quality standard (1,000 x 0.000015 mg/L = 0.015 mg/L) or half of the solubility limit (½ x 1,100 mg/L = 550 mg/L). The lowest of the three types of values for VC is 0.015 mg/L. The calculated "source" values for TCE and DCE did not exceed either of their CCLs.

Finally, the data from the RI (Baker, 1997) indicate that TCE may be degrading to DCE and VC and that the VC may be further degrading to harmless compounds before it reaches Courthouse Bay. In this case, the actual risk to Courthouse Bay would be zero. Additional data collection would be necessary over a period of years to prove that such natural bioattenuation is actually occurring. The parameters and monitoring locations necessary for this are beyond the scope of this effort but have been documented (AFCEE, 1996).

Therefore, there are three possible strategies to remediate the affected areas beneath Site 73:

1. Use groundwater quality (GWQ) standards as cleanup levels protective of drinking water and actively remediate those areas that exceed them.

2. Use the "source" concentrations (as calculated by the model G3CTM) as clean-up levels protective of SA surface water quality and actively remediate those areas that exceed them.

3. Passively remediate the affected areas on-site by gathering data to support the natural bioattenuation option to reach one or both of the above clean up levels.

Baker believes that the best alternative to remediate the risk at Site 73 is to collect additional data that will support the hypothesis that the VC is being completely naturally bioattenuated before it reaches Courthouse Bay.

1.0 INTRODUCTION

Marine Corps Base (MCB), Camp Lejeune was placed on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) National Priorities List (NPL) on October 4, 1989 (54 Federal Register 41015, October 4, 1989). Subsequent to this listing, the United States Environmental Protection Agency (USEPA) Region IV; the North Carolina Department of Environment and Natural Resources (NC DENR); and the United States Department of the Navy (DoN) entered into a Federal Facilities Agreement (FFA) for MCB, Camp Lejeune. The primary purpose of the FFA is to ensure that environmental impacts associated with past and present activities at MCB, Camp Lejeune are thoroughly investigated and appropriate CERCLA response/Resource Conservation and Recovery Act (RCRA) corrective action alternatives are developed and implemented, as necessary, to protect public health, welfare, and the environment (FFA, 1989).

The Fiscal Year 1996 Site Management Plan (SMP) for MCB, Camp Lejeune, the primary document referenced in the FFA, identified 33 sites that require Remedial Investigation/Feasibility Study (RI/FS) activities. In addition to the RI/FS sites, 108 underground storage tank (UST) sites have also been identified. Based on information obtained from the SMP and from Base personnel, over 15 of these RI/UST sites are currently undergoing or are proposed for groundwater remediation actions (i.e., groundwater pumping and treatment).

Under contract N62470-89-D-4814, this modeling effort was performed under Modification 05 to Contract Task Order 0312 (CTO-0312). The objective of this modification was to perform groundwater modeling at Operable Unit (OU) No. 9 also known as the Amphibious Vehicle Maintenance Facility (Site 73) to support the evaluation of remedial alternatives in the Feasibility Study (Baker, 1997) and to provide information necessary for the design and implementation of the selected remedial alternative.

In order to evaluate of the potential effects of site-specific groundwater remediation alternatives, a three-dimensional groundwater flow and contaminant transport model was developed for Site 73. This site-specific model was constructed on the foundation laid by the Base-Wide Remediation Assessment Groundwater Study (BRAGS) groundwater flow model (Draft BRAGS Report, Baker, 1996) using data gathered during the Remedial Investigation of Site 73 (RI, Baker, 1997).

1.1 <u>Modeling Objectives and Limitations</u>

Undocumented leakage and disposal of chlorinated solvents and petroleum products have occurred at Site 73 since 1941. The volume of leakage, spillage, and disposal probably increased during the Vietnam War era (early 1960's to mid 1970's) when the Amphibious Vehicle Maintenance Facility was used very heavily for training in amphibious assault tactics. Heavy demands placed on the facilities and the then-common practice of convenient disposal on the ground most likely resulted in the current subsurface contamination.

While the actual source areas for the groundwater contamination remain for the most part unidentified, the groundwater flow model described herein was used to "project back in time" so that potential source areas were tentatively identified. Of course, such projections are subject to errors in understanding actual subsurface conditions and contaminant behavior, but they are one tool that can be used to understand past waste management practices. This was one of many objectives for the groundwater flow model.

There were multiple specific objectives of this modeling effort. The first major objective was to develop a site-specific, steady-state, three-dimensional, calibrated groundwater flow model (using MODFLOW and MODPATH) that would be used to:

- Predict the fate (and perhaps suggest source area locations) of the groundwater contaminants at Site 73 by simulating the existing three-dimensional patterns of groundwater flow at Site 73 in the surficial hydrologic unit and the Castle Hayne Aquifer including the interaction of groundwater and surface water (Courthouse Bay).

- Assess the potential for contaminant migration toward water supply wells across Courthouse Bay toward BB-44 or other Courthouse Bay area wells.

- Compare the efficacy of various remediation schemes for Site 73 in order to protect potential human and/or ecological receptors from groundwater contaminants (particularly trichloroethene and its degradation products: cis-1,2-dichloroethene and vinyl chloride).

- Evaluate the potential hydrologic effects of the remedial scenarios on the groundwater regime.

- Support the design of the selected remedial alternative.

The second major objective was to develop a steady-state, single-species contaminant transport model (using MT3D with the results from MODFLOW) that would be used to predict the fate of trichloroethene (TCE) in the subsurface beneath Site 73 and to evaluate the risk associated with the TCE concentrations under several remedial scenarios. At the outset of this effort it was known that the applicability of transport modeling would be very limited because of the lack of chemical data over time at Site 73. The best result expected (given the input) would have been an estimate of the concentration (and an associated risk value) of TCE before it discharged into Courthouse Bay. However, at the time the Implementation Plan (IP) for his modeling effort was written, the Remedial Investigation (RI) report was not yet finished and it was not known that there were degradation products actually present in the surficial unit. The risk associated with the degradation products [cis-1,2-dichloroethene (DCE) and especially vinyl chloride (VC)] in groundwater is actually greater than that posed by the TCE. Additionally, the presence of VC so close to Courthouse Bay (within 50 feet at 73-MW09) as reported in the RI (Baker, 1997) suggests that the chlorinated solvents have been actively degrading into degradation products over time as they were migrating toward Courthouse Bay. The data from the RI indicate that the VC may be degrading to harmless compounds before it reaches Courthouse Bay.

Modeling this type of contaminant behavior was beyond the scope of this effort because it is not a single-species problem. The difficulty with such modeling lies in the fact that as the TCE degrades, its concentration diminishes with time and distance from the source; concurrently, the concentrations of DCE and VC increase along the same flow path. MT3D (Zheng, 1990), the mass transport model proposed for this effort, is capable of simulating one dissolved species at a time and is not capable of simulating a series of degradation reactions. There are newer models that are capable of simulating the PCE->TCE->DCE->VC reaction series (e.g., BIOMOD-3D, by Draper Aden Environmental Modeling, Inc.), but the results would be subject to cumulative error in every step of the series unless an extensive calibration effort were attempted for each dissolved species.

For these reasons, it is suggested that an approach other than single-species transport modeling be used to evaluate the groundwater risk at Site 73. Baker believes that the best alternative to evaluate the risk is to collect additional data that will support the hypothesis that the VC is being completely naturally bioattenuated before it reaches Courthouse Bay. One or more wells would probably be necessary to provide enough data to make a good case. A detailed discussion of this approach is provided in a following section.

Another alternative would be to use the methodology put forth in the Draft Risk Analysis Framework Document from the North Carolina Department of the Environment and Natural Resources (NC DENR, 1996). However, there are very restrictive limitations to the concentrations of VC that can be left in place, due to its very low threshold values.

1.2 Report Organization

The Site 73 Groundwater Modeling Report is comprised of one text volume with appendices. The section headings included within this text volume are as follows:

- Geology and Hydrogeology of the Camp Lejeune Area - Section 2.0
- Site 73 Groundwater Flow Model - Section 3.0
- Alternatives to the Site 73 Solute Transport Model - Section 4.0
- Remedial Scenario Simulations - Section 5.0
- Summary and Conclusions - Section 6.0
- References - Section 7.0
- Appendices

1.3 Location and Environmental Setting

MCB, Camp Lejeune is located on the Atlantic Coastal Plain of North Carolina in Onslow County. The facility encompasses approximately 234 square miles and is bisected by the New River. The New River flows in a southeasterly direction through Camp Lejeune and forms a large, meandering estuary before entering the Atlantic Ocean. The southeastern border of Camp Lejeune is the Atlantic Ocean shoreline. The western and northeastern boundaries of the facility are U.S. Route 17 and State Route 24, respectively. The City of Jacksonville borders Camp Lejeune to the north.

1.4 Background and History

Installation Restoration (IR) Site 73, the Amphibious Vehicle Maintenance Facility is located on the northwest shore of Courthouse Bay (see Figure 1-1). Construction of MCB, Camp Lejeune began in April 1941 at the Hadnot Point Industrial Area (HPIA), where major functions of the base are located today. The facility, shown on Figure 1-2, was designed to be the "World's Most Complete Amphibious Training Base." The MCB, Camp Lejeune complex consists of five geographical locations under the jurisdiction of the Base Command. These areas include Camp Geiger, Montford Point, Courthouse Bay, Mainside, and the Rifle Range Area.

1.5 Topography

The relatively flat topography of MCB, Camp Lejeune is typical of seaward portions of the North Carolina Coastal Plain. Elevations on the base vary from sea level to 72 feet above mean sea level (msl); however, most of MCB, Camp Lejeune is between 20 and 40 feet above msl. Drainage at

MCB, Camp Lejeune is generally toward the New River, except in areas near the coast where flow is into the Intracoastal Waterway that lies between the mainland and barrier islands. In developed areas of the facility, natural drainage has been altered by asphalt cover (i.e., roadway and parking areas), storm sewers, and drainage ditches. Approximately 70 percent of MCB, Camp Lejeune is comprised of broad, flat interstream areas with poor drainage (WAR, 1983).

1.6 Surface Water Hydrology

The dominant surface water feature at MCB, Camp Lejeune is the New River. It receives drainage from a majority of the Base. The New River is short, with a course of approximately 50 miles on the central Coastal Plain of North Carolina. Upstream from Camp Lejeune and over most of its length, the New River is confined to a relatively narrow channel in Eocene and Oligocene limestones. South of Jacksonville, the riverbed widens dramatically as it flows across less resistant sand, clay, and marl. At MCB, Camp Lejeune, the New River flows in a southerly direction into the Atlantic Ocean through the New River Inlet. Several small coastal creeks drain the area of Camp Lejeune not associated with the New River and its tributaries. These creeks flow into the Intracoastal Waterway, which is connected to the Atlantic Ocean by Bear Inlet, Brown's Inlet, and the New River Inlet. The New River, the Intracoastal Waterway, and the Atlantic Ocean converge at the New River Inlet.

1.7 Previous Investigations And Computer Simulations

Over 90 RI/UST investigations have been conducted regarding the hydrogeological characteristics of the subsurface at and near MCB, Camp Lejeune. The geology and hydrogeology of the region and of the area adjacent to Camp Lejeune has been described by the USGS in several recent reports from 1989 to 1993. Of particular import were the publications by Cardinell et al (1993), Geise et al (1991), Winner and Coble (1989), and Harned et al (1989). On-site investigative activities conducted by Baker Environmental, Inc. and other firms have added to the existing data with regard to the near-surface geology and hydrogeology.

At least three regional groundwater flow models have been constructed encompassing the Camp Lejeune area. At the outset of the BRAGS effort it was thought that one or more of the existing regional groundwater flow models may be adapted for use on a smaller scale. The Regional Aquifer System Analysis (RASA) program generated two regional groundwater flow models and the North Carolina Geological Survey created a model of the Central Coastal Plain (CCP). These three existing models were examined, but it was subsequently determined that the they were too large in scale and not detailed enough to yield meaningful results for use at MCB, Camp Lejeune (Draft BRAGS Report, Baker, 1996).

The recently constructed BRAGS groundwater flow model encompassed the entire MCB Camp Lejeune area to address water supply issues over the entire base and the Site 82 model dealt with the Piney Green VOC area to address the site-specific remedial design issues. Both models are described in the Draft BRAGS Report (Baker, 1996) and are being updated in response to comments from various authorities.

SECTION 1.0 FIGURES

FIGURE 1 - 1 Location Map for Site 73 Model Grid, MCB, Camp Lejeune, North Carolina

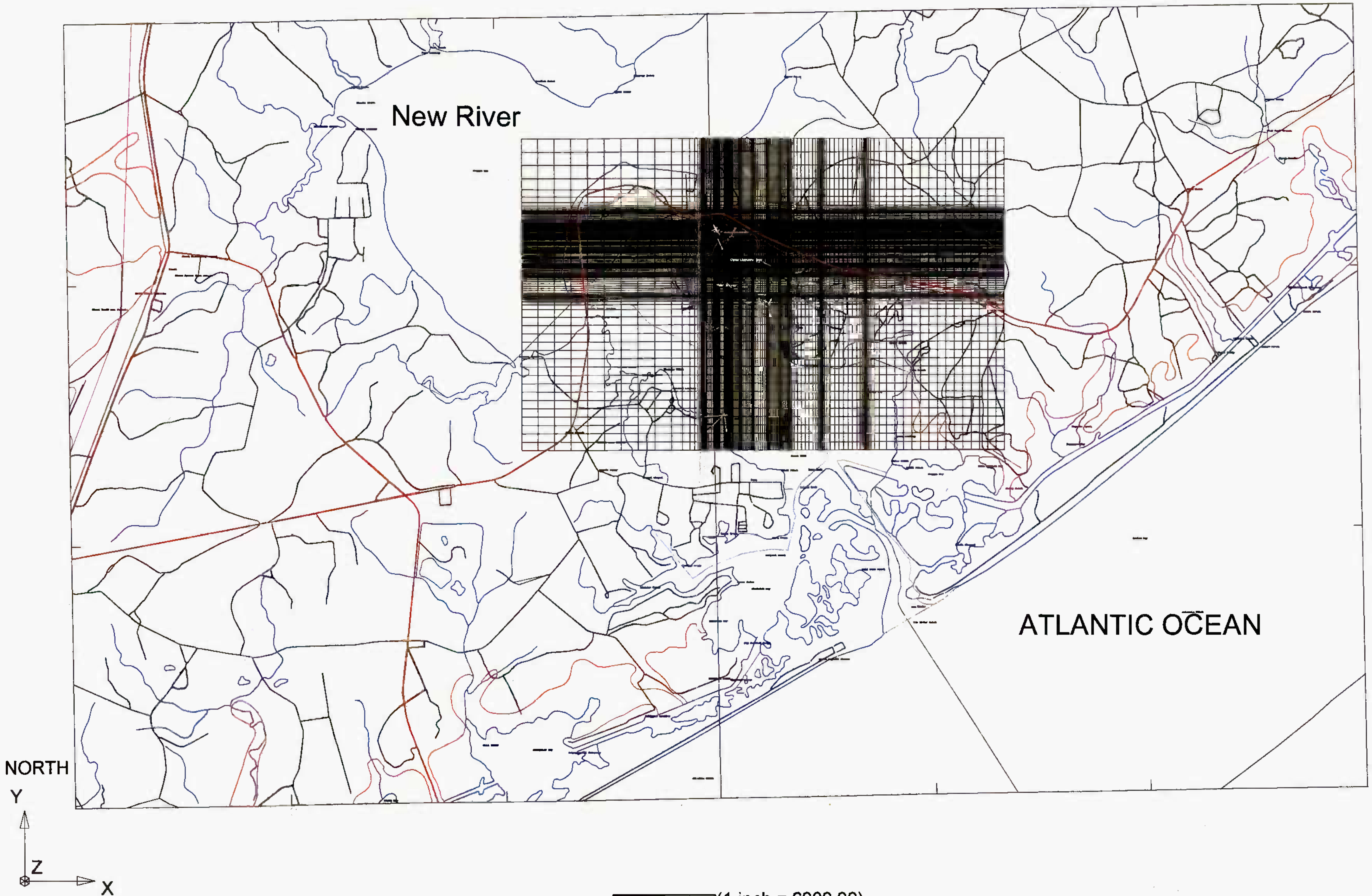

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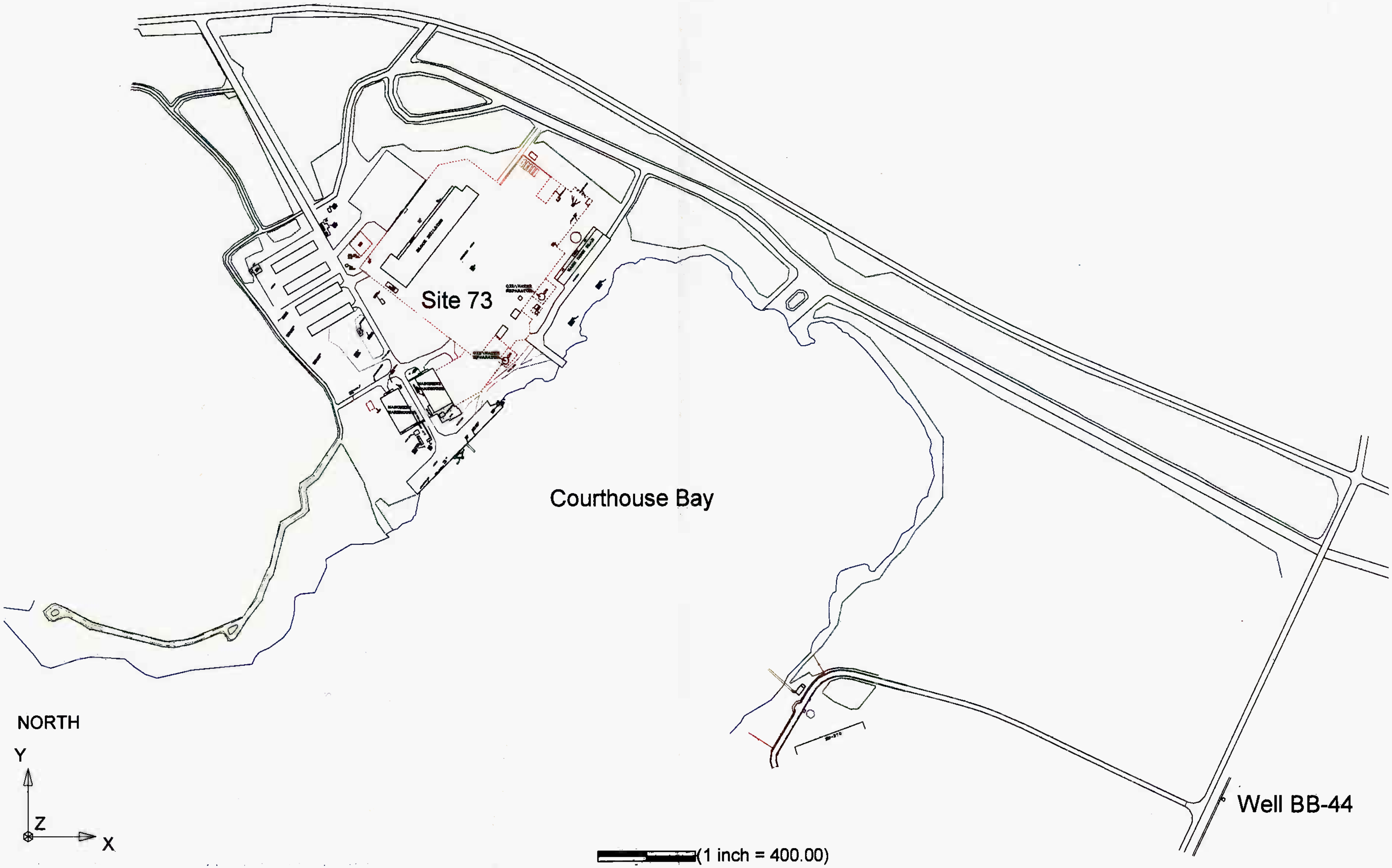
FIGURE 1 - 2 Site Map of the Amphibious Vehicle Maintenance Area -- Site 73



2.0 GEOLOGY AND HYDROGEOLOGY OF THE CAMP LEJEUNE AREA

2.1 Physiography

MCB, Camp Lejeune lies within the Tidewater (tidally-influenced) region of the central Atlantic Coastal Plain physiographic province. The Atlantic Coastal Plain is an eastward-thickening wedge of sediments lying atop the basement of Precambrian bedrock. The strata in the Coastal Plain generally dip toward the east. This wedge varies from a thickness of zero near the Fall Line to more than 10,000 feet under Cape Hatteras (Trapp, 1992; Winner & Coble, 1989). The Tidewater region is the portion of the Atlantic Coastal Plain that is influenced by diurnal ocean tides and is generally low-lying, swampy terrain with elevations ranging from sea level to about 70 ft.

2.2 Geologic and Hydrogeologic Framework

Beneath Camp Lejeune are seven water-bearing hydrostratigraphic units, each comprised of one or more formations: an unnamed surficial unit of recent and Pleistocene age, the Castle Hayne Aquifer of Oligocene and Eocene age, the Beaufort aquifer of Paleocene age, and four Upper Cretaceous aquifers (the Peedee, Black Creek, and the Upper and Lower Cape Fear). For practical purposes, the surficial unit is not considered an "aquifer" since it cannot yield sufficient amounts of water even for domestic use. This limitation of its use is probably due to its small thickness (which limits available drawdown) near Camp Lejeune. The underlying hydrostratigraphic units are much thicker and are capable of yielding adequate supplies of water; therefore, the underlying units can be practically considered "aquifers" and are referred to as such in this report.

Each of the six aquifers mentioned above provide drinking water to many industries, municipalities, and private well owners throughout the eastern Carolinas and have been described in detail by many authors including Cardinell et al (1993), Trapp (1992), and Eimers et al (1990). The surficial unit and the Castle Hayne Aquifer were the only hydrologic units modeled in this effort because: 1) the contaminants beneath MCB Camp Lejeune are either in the surficial unit or in the Castle Hayne Aquifer; 2) only the Castle Hayne Aquifer provides the drinking water for the base; and 3) the underlying aquifers are over 400 feet deep and effectively isolated by the Beaufort confining unit. The other five aquifers were not modeled in this effort and are not discussed further here.

According to the data collected by Baker during the base-wide and site-specific remedial investigation (RI) studies, the surficial unit consists mainly of a fine sand with silt, although medium-grained sand occurs to a lesser extent. Across the base, the thickness of the surficial unit ranges from 0 to 73 feet. These deposits are undifferentiated Pleistocene and recent sediments. Also, sand beds above the confining clay within the Belgrade Formation of Miocene age are considered part of the surficial unit (Cardinell et al, 1993). The bottom of the surficial unit is at or near sea level over most of the base and at Site 73.

The Castle Hayne confining clay unit underlies the surficial unit and overlies the Castle Hayne Aquifer. It is comprised of clay and/or sandy clay from one or more of the following lithologic units: the lower portion of the Miocene Belgrade Formation, the upper portion of the Oligocene River Bend Formation, or the upper portion of the Eocene Castle Hayne Formation (Cardinell et al, 1993). The thickness of this confining unit averages about nine feet near Camp Lejeune and has been breached by the New River and some of its larger tributaries. This observation is one of the keys to understanding groundwater flow near the base: the localized absence of the confining unit near the New River (or a large tributary) allows a strong hydraulic communication between the surficial unit and the Castle Hayne Aquifer. Cardinell et al (1993) graphically contoured the thickness of the Castle Hayne confining unit (Figure 2-1).

In contrast to the classification of lithologic units, the classification of hydrologic units or aquifers depends only on hydraulic conductivity. There must be a distinction between the two types of classification at Site 73: the silty sand bed below the Castle Hayne confining clay may be considered lithologically as part of the Belgrade Formation, but hydrologically it belongs to the same hydrologic unit as the Castle Hayne aquifer. The conceptual groundwater model for Site 73 used only distinctions in hydraulic conductivity to define layers.

The Castle Hayne Aquifer lies beneath the Castle Hayne Confining Unit and consists of the lower portions of the Oligocene River Bend Formation and the Eocene Castle Hayne Limestone. In the vicinity of Camp Lejeune, the Castle Hayne Aquifer consists mainly of fine sand, shell rock and limestone. The upper portions of the aquifer consist of calcareous sand with discontinuous silt and clay beds. The calcareous sand becomes more limy with depth (Cardinell et al, 1993). At Site 73, two or more conspicuous layers of indurated limestone occur at elevations of approximately -30 to -50, and -80 to -100 feet referenced to mean sea level (MSL). These seem to be the most productive layers of the Castle Hayne Aquifer as evidenced by the screened intervals of the Courthouse Bay supply wells (see Table 2-1). Since the apparent limestone "layer" is hydraulically connected to the overlying and underlying sands, data from pumping tests at the site would reflect the average hydraulic conductivity of the entire thickness of the Castle Hayne Aquifer (> 300 feet). The limestone "layer" would have a higher hydraulic conductivity than the average and the overlying and underlying "layers" would have a lower hydraulic conductivity than the average. For the purposes of the model, it was decided that the average hydraulic conductivity value from the entire thickness (as measured by the pumping tests) would be used because it is the only documented value available.

In the vicinity of Camp Lejeune, the Castle Hayne confining unit and the upper Castle Hayne Aquifer have been incised by the meandering of the New River in ages past. Cardinell and others (1993) graphically contoured the top of the Castle Hayne Aquifer (Figure 2-2). The buried channel created by the New River passing almost directly beneath Site 73 is evident in Figure 2-2. The bottom of the Castle Hayne dips to the east across the base at an average gradient 0.004 ft/ft (Cardinell et al, 1993).

2.3 Conceptual Model of Groundwater Flow

Wilder and others (1978) calculated an overall hydrologic budget for a typical location in the eastern Coastal Plain in North Carolina (see Figure 2-3): precipitation averages about 50 inches/year; five inches/year is lost to surface runoff; 34 inches/year is lost due to evaporation and plant transpiration. Total recharge to the water table is then about 11 inches/year. Of this amount, about 10 inches/year is discharged to surface water bodies as base stream flow: this is the amount of recharge used in the Site 73 groundwater model. Because the New River is a regional groundwater discharge zone, and because the inflow must equal the outflow of the model, net recharge to the underlying aquifers will not be visible in the Site 73 (and BRAGS) models. A regional model such as the Central Coastal Plain (CCP) groundwater flow model would be a better tool to estimate recharge to aquifers underlying the Castle Hayne. The remaining one inch/year leaks into the lower units (e.g., the Castle Hayne Aquifer). Other estimates of regional recharge to the water table range from 12 to 20 inches/year (Geise et al, 1991) and also 15 to 22.5 inches/year (Leahy & Martin, 1993).

Precipitation falling on the upland areas of the eastern Coastal Plain generally moves vertically downward and generally flows horizontally toward the nearest groundwater discharge area: stream, river, bay, etc. (see Figure 2-4). As groundwater approaches the nearest discharge point (e.g. a stream or river), it may encounter a low hydraulic conductivity units (silt or clay) in which leakage through the layer is predominantly vertical. Near the discharge area, the head in the surficial water-bearing zone is reduced by the change in the surface relief at the surface water body. However, the pressure in the deeper aquifers remains higher than that in the surface water body. In the immediate vicinity of the discharge area, the particle responds to the vertical gradient in the deeper aquifers and moves vertically upward to the surface water body (see Figure 2-4). The resulting flow path of a "typical" particle of groundwater is a three-dimensional curvilinear path from the recharge area to the discharge area.

The natural groundwater discharge areas around Camp Lejeune are the New River and all of its tributaries (including swamps, wetlands, and streams) and the Atlantic Ocean. Most of these are at or very near mean sea level. Anthropogenic (man-made) discharges include a system of over 100 water supply wells in the Castle Hayne Aquifer at MCB Camp Lejeune. In 1993, 68 of those wells pumped an average of almost 7 million gallons per day. Some of the wells have been taken off-line and/or decommissioned because of high levels of organic contamination (e.g., HP-651), others due to poor well performance. The Courthouse Bay area water supply wells [BB-43 (currently inactive), BB-44, BB-45 (currently inactive), BB-47, BB-218, BB-220, and BB-221] are the closest drinking water supply wells to Site 73. They are approximately 3,200 feet east of Site 73. The five active wells pumped an average of 1.4 million gallons per day (mgd) during 1993. Table 2-1 presents the 1993 groundwater pumping data from the active water supply wells in the Courthouse Bay area. Some volatile organic compounds (VOC's; e.g., TCE) were detected in one or more of these wells and it was suspected that Site 73 may have been a potential source. This modeling effort directly addressed that concern.

2.4 Hydraulic Characteristics

The characteristics of the surficial unit have been measured by slug and pumping tests. The shallow pumping test in the surficial aquifer at Building A-47 (performed in well RW-1 by Baker in February, 1993) indicated an average hydraulic conductivity of 8 ft/day (standard deviation of 4.2 ft/day with a sample size, n, of 2 usable observations, not including the drawdown data from the pumping well). Slug test results in surficial unit wells at Site 73 indicated an average hydraulic conductivity of 1.8 ft/day (standard deviation of 1.5 ft/day with n=14). The average of the pumping and the slug testing was 2.6 ft/day (standard deviation of 2.8 ft/day with n=16). The RI Report for Site 73 (Baker, 1997) contains the data from the Site 73 pumping and slug tests. These data are also presented in Table 2-2.

Between the surficial unit and the Castle Hayne Aquifer lies the Castle Hayne confining unit. Leakance of an aquitard (e.g., a clay confining unit) is defined as the vertical hydraulic conductivity of that aquitard per foot of aquitard thickness (K_v/b). Leakance values for the Castle Hayne confining clay unit found by Trapp (1992) ranged from $1x10^{-6}$ to $1x10^{-4}$ ft/day/ft. Corresponding vertical hydraulic conductivity values for a 10 foot-thick clay unit range from $1x10^{-5}$ to $1x10^{-3}$ ft/day. At Site 73, the vertical hydraulic conductivity of the Castle Hayne confining clay unit was measured to be $2.6x10^{-7}$ cm/sec or $7.3x10^{-4}$ ft/day; the corresponding leakance value for a ten foot-thick clay unit would be $7.3x10^{-5}$ ft/day/ft which is within the stated range of Trapp.

The deeper "B" series wells are actually below the confining clay unit and are probably hydraulically connected to the Upper Castle Hayne Aquifer more than to the surficial unit. The average hydraulic conductivity result in these wells was 0.4 ft/day (standard deviation of 0.24 ft/day with n=6) which corresponds to that of a silty fine sand (Heath, 1983). These data are also presented in Table 2-2.

Aquifer pumping tests were not performed in the lower Castle Hayne Aquifer at Site 73 nor in the Courthouse Bay water supply wells. However, several pumping tests were performed in deep wells in various locations around the base: DRW-1 (Site 82 by Baker/OHM), HP-642 (ES&E Inc.), HP-708 (USGS), and X24s2x (North Carolina DENR). The results of these tests indicated that the hydraulic conductivity of the Castle Hayne Aquifer is very similar to that of the surficial unit with values averaging 4 ft/day ($1x10^{-3}$ cm/sec) and ranging from 2 to 8 ft/day ($7x10^{-4}$ to $3x10^{-3}$ cm/sec). The deep pumping test data from various sites are summarized in Table 2-3.

These hydraulic conductivity values are indicative of fine sand and/or silty sand (Heath, 1983). In contrast, several USGS papers have been published that estimate the regional hydraulic conductivity of the Castle Hayne Aquifer in North Carolina as being one or more orders of magnitude greater than the site-specific values stated above (e.g., an estimated average of 65 ft/day, Winner & Coble, 1989). The highly permeable and relatively thin (10-20 feet thick) layers of limestone within the Castle Hayne may be the reason for such high values. When a highly permeable layer is tested via pumping as the USGS did, the resulting transmissivity value is measured directly, independent of the unit's thickness. The calculation of the hydraulic conductivity value depends upon the interpretation of the thickness of the unit being tested. This may explain the apparent difference between the two sets of hydraulic conductivity data: a single transmissivity value divided by a large thickness (i.e., the entire thickness of the Castle Hayne Aquifer) would yield a lower hydraulic conductivity than for a thinner (limestone) layer. All hydraulic conductivity values calculated in this modeling effort assumed a thickness of 350 feet for the Castle Hayne Aquifer.

Another explanation for the difference between the regional and site-specific data could be the natural variations in hydraulic conductivity that can result from different depositional facies within the same chronostratigraphic unit, or perhaps more likely, post-depositional reworking by fluvial and/or tidal action. The large fraction of fine sand and silt in the upper portion of the Castle Hayne near MCB Camp Lejeune indicates a relatively low to medium energy, shallow water environment of deposition.

SECTION 2.0 TABLES

TABLE 2-1 -- COURTHOUSE BAY WELL DATA SUMMARY

Wells in operation (6/95):	Approximate Surface Elevation (ft msl)	Depth to Water (USGS) ('86-'87) (ft bgs)	Depth of Screen Top (ft bgs)	Depth of Screen Bottom (ft bgs)	Approximate Water Elevation (ft msl)	Approximate Screen Top Elevation (ft msl)	Approximate Screen Bottom Elevation (ft msl)	Maximum Pumping Capacity (GPM):	Average Pumping Rate (GPM):	Average Pumping Rate (cfd):	% Time On
BB 44	18	14	32	62	4	-14	-44	140	62	11936	44%
BB 47	13	NA	40	125	NA	-27	-112	294	131	25219	45%
BB 218	40	NA	64	168	NA	-24	-128	187	83	15979	44%
BB 220	37	10	55	145	27	-18	-108	172	76	14631	44%
BB 221	40	NA	60	155	NA	-20	-115	154	68	13091	44%
								947	420		

TABLE 2-2

MCB CAMP LEJEUNE
SURFICIAL UNIT
HYDRAULIC CONDUCTIVITY
DATA SUMMARY

Well	Hydraulic Conductivity (ft/day)	Test Method
SURFICIAL UNIT		
73-MW01	0.14	FH SLUG
73-MW01	0.18	RH SLUG
73-MW03	4.40	FH SLUG
73-MW03	4.40	RH SLUG
73-MW11	1.10	FH SLUG
73-MW11	1.00	RH SLUG
73-MW13	0.50	FH SLUG
73-MW13	0.35	RH SLUG
73-MW20	1.10	FH SLUG
73-MW20	1.10	RH SLUG
73-MW21	3.50	RH SLUG
73-MW22	1.80	FH SLUG
73-MW22	1.60	RH SLUG
73-MW23	3.60	RH SLUG
MW-15	5.10	PUMPING
MW-17	11.00	PUMPING
Dist/Draw	14.70	PUMPING
Minimum	0.14	
Maximum	14.70	
Average	3.27	Surficial Unit
Standard Deviation	4.00	
UPPER CASTLE HAYNE "B" SERIES		
73-MW01B	0.64	FH SLUG
73-MW01B	0.38	RH SLUG
73-MW11B	0.65	FH SLUG
73-MW11B	0.34	RH SLUG
73-MW15B	0.09	FH SLUG
73-MW15B	0.14	RH SLUG
Minimum	0.09	
Maximum	0.65	
Average	0.37	Upper Castle Hayne
Standard Deviation	0.24	

TABLE 2-3

MCB CAMP LEJEUNE
CASTLE HAYNE AQUIFER
HYDRAULIC CONDUCTIVITY
DATA SUMMARY (1)

Well	Transmissivity (sq ft/day)	Thickness (2) (ft)	Hydraulic Conductivity (ft/day)	Tested by
HP-708 lo	1140	382	3.0	USGS
HP-708 hi	1325	382	3.5	USGS
HP-642 lo	820	355	2.3	ESE, Inc.
HP-642 av	1280	355	3.6	ESE, Inc.
HP-642 hi	1740	355	4.9	ESE, Inc.
X24s2x	900	308	2.9	NC DEHNR
Minimum	820	308	2.3	
Maximum	1740	382	4.9	
Average	1201	356	3.4	
Standard Deviation	332	27	0.9	

(1) - SOURCE: Cardinell et al, 1993, Table 4.
(2) - SOURCE: Cardinell et al, 1993, Table 3.

SECTION 2.0 FIGURES

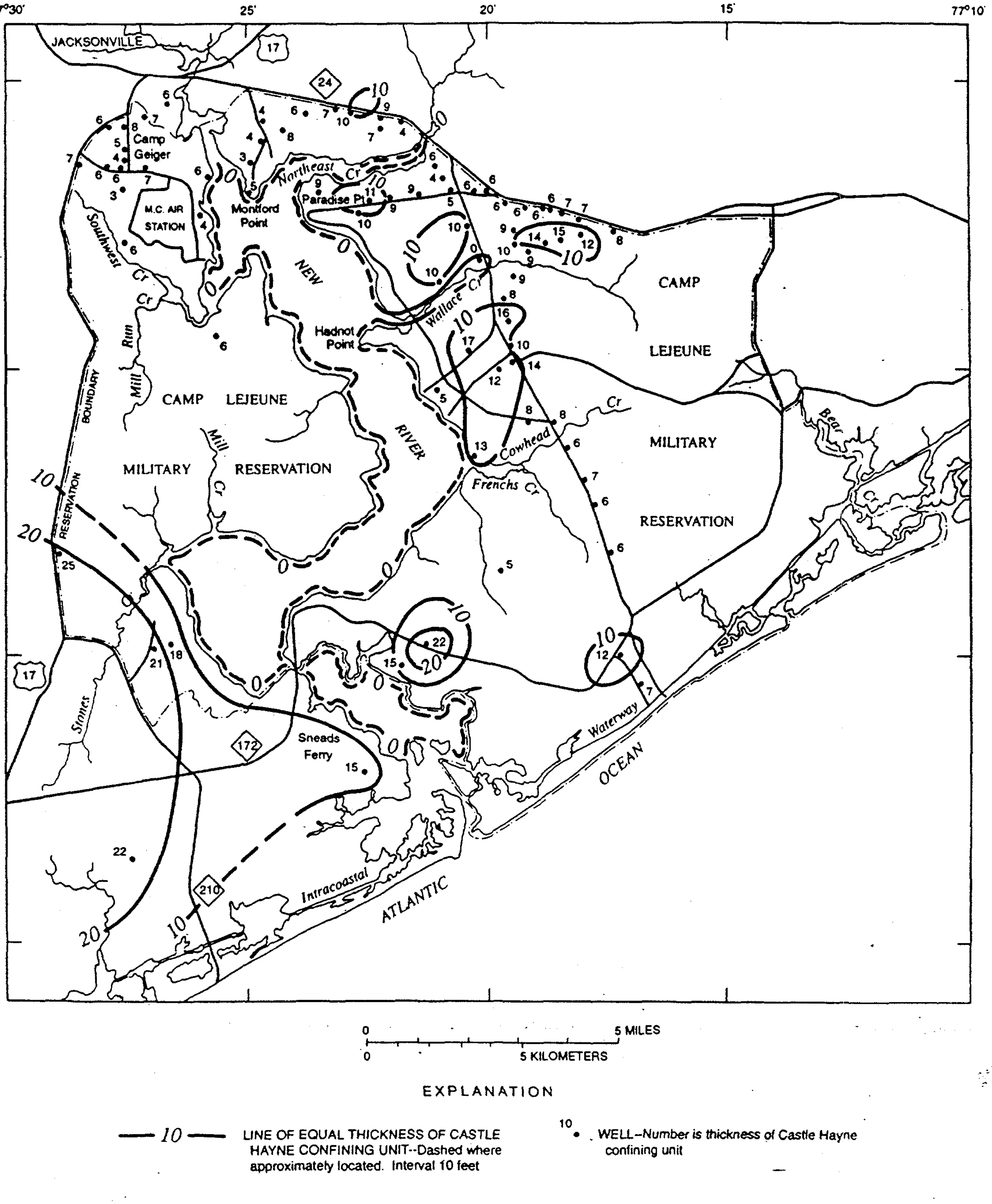
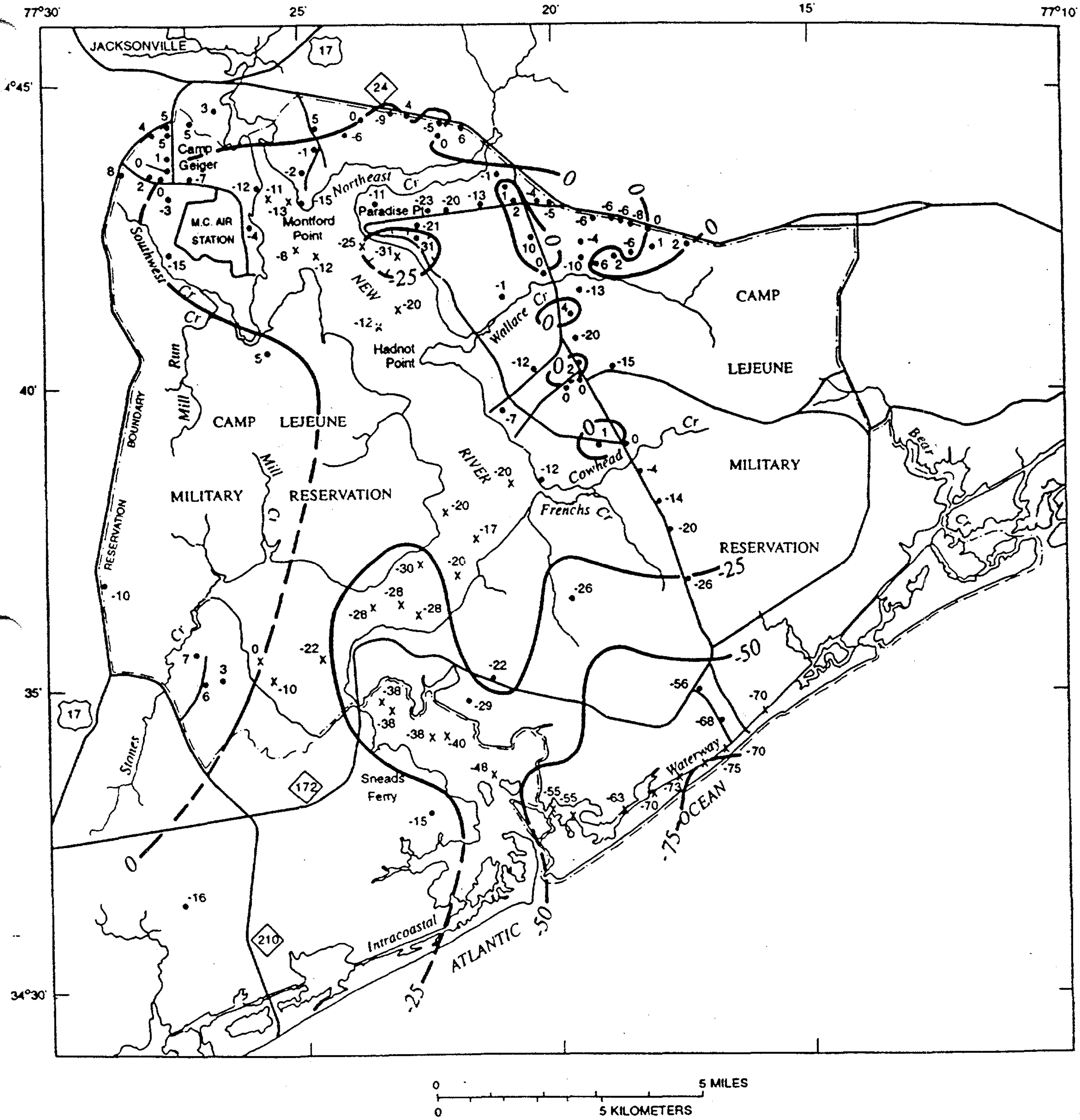


Figure 2-1 Isopach Contour Map -- Castle Hayne Confining Unit

(Taken from Cardinell et al, 1993)



EXPLANATION

—— -25 —— STRUCTURE CONTOUR--Shows altitude of top of Castle Hayne aquifer. Dashed where approximately located. Contour interval 25 feet. Hachured to indicate depression in top of aquifer. Datum is sea level

• -15 WELL--Number is altitude of top of Castle Hayne aquifer in feet above or below (-) sea level

X -38 NAVIGATION FIX POINT ALONG SEISMIC PROFILE LINE (FIG. 5) --Number is estimated altitude of top of Castle Hayne aquifer in feet below (-) sea level

Figure 2-2 Elevation Contour Map -- Top of Castle Hayne/Bottom of Confining Unit (Taken from Cardinell et al, 1993)

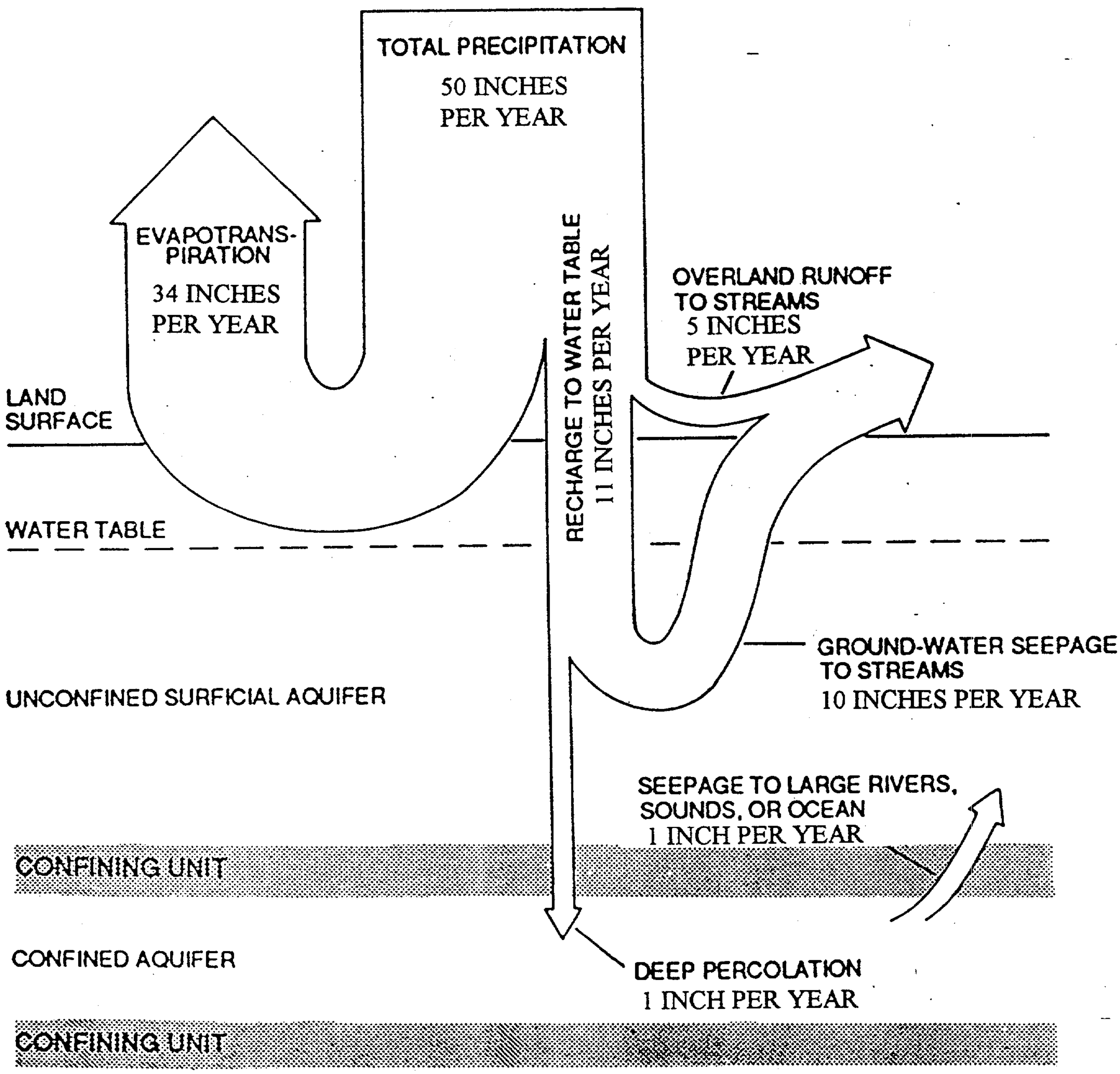


Figure 2-3 Annual Hydrologic Budget Schematic - Central Coastal Plain in North Carolina (Taken from Giese et al, 1991)

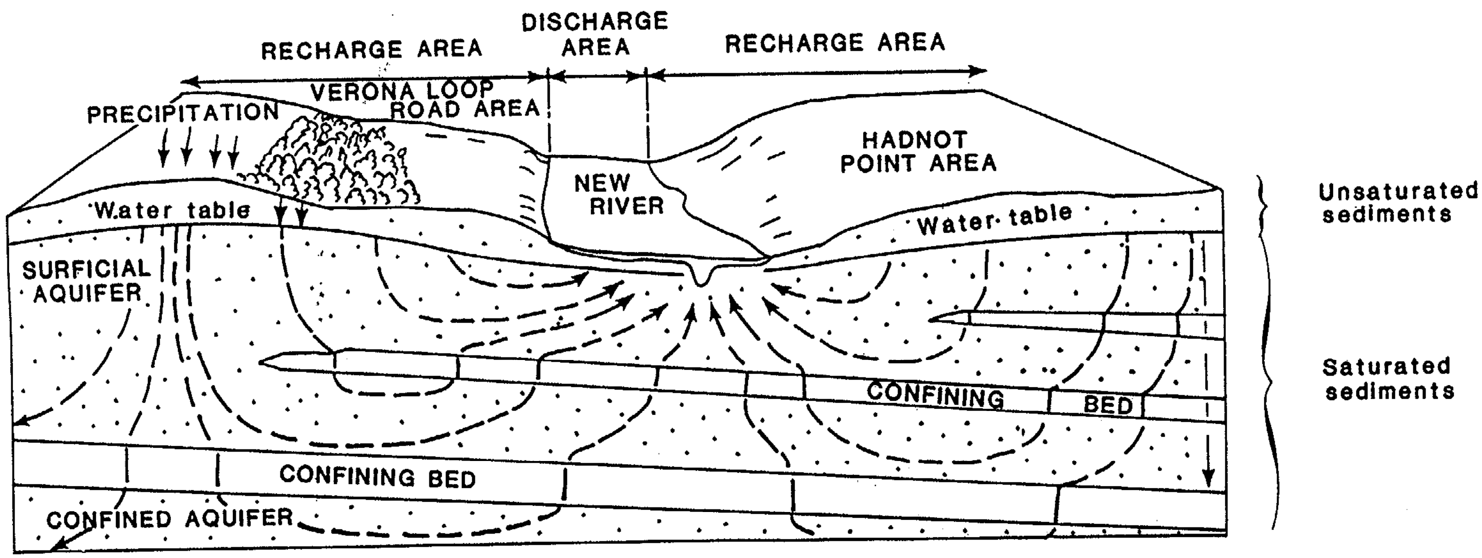


Figure 2-4 Idealized Groundwater Flow Schematic - Central Coastal Plain in North Carolina (modified from Winner, 1981).

3.0 SITE 73 GROUNDWATER FLOW MODEL

The groundwater flow regime at Site 73 was simulated by using the three-dimensional, finite-difference flow code referred to as "MODFLOW" (McDonald & Harbaugh, 1988). MODFLOW is a numerical groundwater flow code initially developed by the U.S. Geological Survey and modified to run on IBM-compatible computers. This code was chosen because it is very flexible in its application and has been extensively documented. It was determined to be the most appropriate model for this complex, three-dimensional groundwater flow system.

The simplified governing (partial differential) equation used by the numerical model (MODFLOW) is:

$$\delta(K_{xx}\delta h/\delta x)/\delta x + \delta(K_{yy}\delta h/\delta y)/\delta y + \delta(K_{zz}\delta h/\delta z)/\delta z - W = S_s\delta h/\delta t$$

where:

x, y, and z are Cartesian coordinates aligned with the major axes of hydraulic conductivity
K_{ii} is the hydraulic conductivity in the i direction
h is the potentiometric head or water table elevation
W is a volumetric flux per unit volume of aquifer and represents sources and/or sinks of water
S_s is the specific storage capacity of the porous material and,
t is time.

This equation describes the movement of water through a porous medium. For a steady-state model such as this, the right side of the equation becomes zero because the change in head with time is zero. Together with the specification of initial and boundary conditions, this equation constitutes a mathematical model of groundwater flow.

MODFLOW can accommodate confined or unconfined conditions and uses input parameters of hydraulic conductivity, aquifer thickness, recharge, evapotranspiration, storativity, and specific yield to calculate water levels at various locations within the model boundaries. Each of the inputs can be varied temporally and/or spatially so that by changing the parameters, a match to actual field conditions can be accomplished.

3.1 Site Data Collection and Review

Baker collected and reviewed the existing groundwater data from the RI and from existing UST reports at Site 73, as well as data from other nearby IR sites. Other available sources, such as USGS reports, detailed topographic maps, and MCB Camp Lejeune potable water supply well data were also reviewed. Data collection focused on information useful for input and calibration of the groundwater model. The following were reviewed in detail:

- Historical and current water level information - statistical analyses for three rounds of water level measurement were performed; no long-term monitoring data were available.

- Contaminant concentration data (spatial and temporal distributions) for confirmation of flow directions.

- Location, pumping rates and pumping schedules of nearby water supply wells, if known.

- Pumping and/or slug test data (transmissivity, hydraulic conductivity, and/or storativity).

- Infiltration data (recharge from precipitation).

- Well/piezometer construction diagrams (including surveyed well location and elevation data on the NC planar grid coordinate system).

- Stream/ditch/swamp elevations from surveys or detailed maps.

- Geologic cross-sections and/or profiles.

- Soil bulk densities.

- TCE, DCE, VC and benzene concentrations in groundwater.

- Soil porosities.

- Organic fraction of soil.

After the data were reviewed, they were to prioritized with regard to reliability, frequency, and proximity to the site. The data deemed to be most important to the model were used as model input. The flow portion of the model was calibrated to measured head data collected by Baker from 1995 to 1996. The transport portion of the model could not be calibrated because of the lack of temporal chemical data necessary for such a calibration. A more detailed discussion of the limited application of transport modeling at Site 73 is included in a following section.

3.2 Finite-Difference Layered Grid

Baker used MODFLOW to simulate the three-dimensional groundwater movement in the subsurface at Site 73. In order to use MODFLOW, it was necessary to discretize the model domain into cells, each of which had a "node" containing the properties (e.g., hydraulic conductivity) and/or boundary conditions (e.g., rivers, wells) that approximated the conditions found at the site. For example, a well was simulated by a specified flux or "well" cell that maintains a constant flow into (recharge) or out of (discharge) the cell. Similarly, rivers, streams, swamps, and no flow boundaries were represented by one of the internal boundary cell types within MODFLOW.

The finite-difference grid superimposed over Site 73 had variable spacing: square and rectangular cells range from 25 to 1,000 feet in length (see Figure 3-1). The grid was comprised of 134 rows (about 18,100 feet north to south) and 165 columns (about 28,200 feet east to west) over an area of approximately 18 mi^2. Even though this model domain is very large compared to the area of Site 73 (approximately 0.08 mi^2), it was necessary in that there were questions regarding the influence of the Courthouse Bay water supply wells upon the fate of the identified TCE in the Castle Hayne Aquifer (well 73-DW03). The large distances from the pumping wells to the model boundaries were necessary so that the pumping influences from the water supply wells would not intersect the model boundaries which would have artificially influenced the amount of simulated drawdown.

Figure 3-2 shows a close-up of the grid around Site 73. The grid spacing is more dense near the site and is also more dense around each of the water supply wells. This denser spacing yields a more accurate depiction of the drawdown cone associated with each well. As shown on the figure, the closest water supply well (BB-44) lies about 3,200 feet east of Site 73 and across Courthouse Bay. One of the objectives of the modeling effort was to demonstrate whether the TCE could have migrated under Courthouse Bay to well BB-44, since this was suggested as a possibility in preliminary studies.

The model consisted of four layers (see Figure 3-3). From top to bottom they represent the surficial unit (Layer 1), the confining clay unit (Layer 2), and the upper and lower portions of the Castle Hayne Aquifer (Layers 3 & 4, respectively). The Castle Hayne Aquifer was divided into two portions at elevation -60 MSL because the 73-DW-series (intermediate depth) monitoring wells were screened in the Castle Hayne Aquifer at elevations of -30 to -60 feet MSL while the 73-GW-series (deep) monitoring wells were generally screened from -140 to -150 feet MSL. Additionally, TCE in one intermediate well (73-DW03 at elevation -60 MSL) would require at least one intermediate-depth extraction well in one of the remedial scenarios. Therefore, the intermediate well data were used to calibrate Layer 3 and the deep well data were used in Layer 4.

3.3 Model Boundary Conditions

Boundaries in MODFLOW include external and internal boundaries. External boundaries can include specified (constant) head, general head boundary, or no-flow (where specified flux = 0) cells. Internal boundaries can include well, river, stream, and drain cells. For the Site 73 groundwater flow model, no specified head, general head boundary or stream cells were used. External boundaries were no-flow cells and internal boundaries were well, river and drain cells.

The elevations and characteristics of the internal boundaries (wells, drains, rivers) and external boundaries of the Site 73 groundwater model were taken from several sources, including the BRAGS model, the Site 73 Remedial Investigation Report, surveyed site maps, USGS 7.5 minute quadrangles, and some were inferred or estimated where no field data exist.

3.3.1 Well Cells

Wells cells are specified (constant) flux boundaries which keep a constant flow rate throughout the specified time period. For this steady-state model, the time period is assumed to be an average day. MODFLOW assumes that each well fully penetrates the layer in which it is placed. Positive values of flow associated with a particular well cell represent recharge to groundwater and negative values represent discharge (withdrawal) from groundwater. As in the BRAGS steady-state, base-wide model, the wells were assigned average daily pumping rates (negative) in cubic feet per day.

Well cells were placed at the locations of the water supply wells and assigned negative (discharge) pumping rates in cubic feet per day. The state planar coordinates of the water supply wells were converted from the latitude and longitude as recorded in Harned et al (1989) and Cardinell et al (1993). It was found that some of the latitudes and longitudes were in error; in those cases estimated locations were used based on existing base-wide mapping. Table 2-1 summarizes the well data for the Courthouse Bay supply wells.

The average pumping rates of the Courthouse Bay supply wells were estimated and graciously supplied by MCB Camp Lejeune personnel from the 1993 total pumping data. This steady-state approach to modeling assumes that 1993 was a typical year for groundwater withdrawals and that the supply wells were pumping constantly at the average rate rather than the actual variable rates. The table shows that the wells are actually pumped 44% of the time or 10.6 hours per day. Table 2-1 presents the average daily pumping rates that were calculated for every well in gallons per minute and cubic feet per day.

3.3.2 River Cells

River cells are head-dependant flow cells in which the elevations of the surface water and river bottom are held constant (at surveyed or mapped elevations) and the thickness and conductance of the sediments control the flow rate of water to or from the cell. If the stream or pond level is higher than the surrounding groundwater, the river cell allows water to recharge the groundwater. Conversely, if the water level in the stream or pond is lower than the groundwater, the groundwater discharges to the surface water body.

The equation for river conductance C_{riv} (ft^2/day)is given by:

$$C_{riv} = (KLW)/M$$

where:

K = hydraulic conductivity of the river sediments (ft/day)
L = length of the river in each cell (ft)
W = width of the river in each cell (ft)
M = thickness of the river sediments (ft)

River cells were used to represent Courthouse Bay near Site 73 where its elevation is mean sea level.

3.3.3 Drain Cells

Drain cells function similarly to river cells except that they cannot recharge the groundwater when the ambient water table drops below the drain elevation. Streams and swamps were represented by drain cells because it was reasonably assumed that they only receive groundwater discharge and were not recharging groundwater. Ephemeral streams (that dry up in summer) can also be represented by drain cells. The elevations of the drain cells were the approximate elevations of the streams as determined by topographic mapping of the streams and swamps.

3.3.4 Horizontal Flow Barrier Cells

A relatively new addition to MODFLOW is the Horizontal Flow Barrier package (Hsieh and Freckleton, 1993). The barriers can be inserted into cells to represent a slurry wall or sheet piling or other kinds of flow barriers. The dock structure adjacent to Courthouse Bay shown on (Figure 3-2) likely is acting as a barrier to horizontal groundwater flow. In order to simulate this, barriers were inserted into several cells to approximate the location of the dock. The package assumes that the barriers completely penetrate the layer (vertically) in which they are placed. The conductance of the dock was assumed to be very low, $1x10^{-6}$ ft/day/ft, which is equivalent to a 3 foot-thick wall with a hydraulic conductivity of $3x10^{-6}$ ft/day ($1x10^{-9}$ cm/sec).

3.4 Parameter Inputs

3.4.1 Input for Layer 1 - Surficial Unit

A value of recharge of 10 inches per year was used over most of the area in the Site 73 model. Lesser recharge rates were applied to concrete and asphalt paved areas and over footprints of buildings. Recharge was applied only to Layer 1. The top elevation of Layer 1 was not defined because the surficial unit is unconfined; the top will vary with the elevation of the water table. The bottom elevations in Layer 1 reflect the top of the confining clay and ranged from -12 feet to -2 feet msl (see Figure 3-4).

Because the results of the slug and pumping tests were relatively similar and consistent, Layer 1 was assigned a homogenous horizontal hydraulic conductivity value of 3 ft/day (the average was 3.3 ft/day as shown in Table 2-2). The homogeneous vertical hydraulic conductivity in Layer 1 was assumed to be one tenth of the horizontal (0.3 ft/day). The approach was to keep the model as simple as possible: the spatial variability would have been adjusted if necessary during the calibration process but it was not necessary as other parameters were adjusted to accomplish the calibration.

River cells were used to represent Courthouse Bay and the New River and the average elevations of both were assumed to be mean sea level. The values of C_{riv} in each river cell varied depending upon the size of the cells but represented permeabilities of silty sediments. For example, using the input values of a typical 60' x 50' cell in Courthouse Bay, the following hydraulic conductivity value is calculated as:

$$C_{riv} = 28.9 \text{ ft}^2/\text{d}$$

where:

L = 50 feet (typical length of river cell in Courthouse Bay)
W = 60 feet (typical width of river cell in Courthouse Bay)
M = 2 feet (estimated thickness of river/bay sediments)

By rearranging the equation for river cell conductance,

$$K = 0.019 \text{ ft/d (or } 7\text{x}10^{-6} \text{ cm/sec)}$$

which is equivalent to that of a silty clay sediment which is reasonable to assume for the bottom of Courthouse Bay. This value is similar to that used in the Draft BRAGS model (Baker, 1996).

The elevations of the drain cells were the approximate elevations of the streams as determined by topographic mapping. The values of C_{drn} in each drain cell varied depending upon the size of the cells but represented hydraulic conductivities of silty sediments. For example, using the input values of a typical 85' x 50' cell in a nearby stream, the following hydraulic conductivity value is calculated as:

$$C_{drn} = 430 \text{ ft}^2/\text{d}$$

where:

L = 50 feet (typical length of drain cell)
W = 85 feet (typical width of drain cell)
M = 2 feet (estimated thickness of stream sediments)

By rearranging the equation for drain cell conductance (same as that for river cells),

$$K = 0.2 \text{ ft/d (or } 7 \times 10^{-5} \text{ cm/sec)}$$

which is equivalent to that of a silt sediment which is reasonable to assume for the bottom of low energy streams around Site 73.

Drain cells were also used to simulate three areas of near-shore wetlands by assigning estimated elevations (0.5 feet msl) and using the input values of a typical 55' x 30' cell in a nearby wetland, the following hydraulic conductivity value is calculated as:

$$C_{drn} = 1{,}000 \text{ ft}^2\text{/d}$$

where:

L = 30 feet (typical length of drain cell)
W = 55 feet (typical width of drain cell)
M = 1 foot (estimated thickness of wetland sediments)

By rearranging the equation for drain cell conductance,

$$K = 0.6 \text{ ft/d (or } 2 \times 10^{-4} \text{ cm/sec)}$$

which is equivalent to that of a sandy silt sediment which is reasonable to assume for the wetlands around Site 73.

3.4.2 Input for Layer 2 - Castle Hayne Confining Clay Unit

Figure 3-5 shows the bottom elevations of Layer 2. As discussed above, these elevations coincide with the bottom of the confining clay unit and not necessarily with the top of the Eocene Castle Hayne Formation.

The horizontal and vertical hydraulic conductivity of the confining layer was assigned a value of 7.3×10^{-4} ft/day (2.6×10^{-7} cm/sec as measured in 73-MW12). In the areas to the east of the site where the confining unit has been breached by the New River, the horizontal and vertical hydraulic conductivity of Layer 2 was made equal to that of Layer 1 (3 ft/day horizontal and 0.3 ft/day vertical). Figure 3-6 shows the areal distribution of the hydraulic conductivity (which represents the extent of the breached clay unit) in the Site 73 model. This representation was assumed for the purposes of the model and may not be accurate at distances from the site where no data exist; however, it is in general agreement with the thicknesses of the confining unit as represented by Cardinell et al (1993).

3.4.3 Input for Layers 3 and 4 - Castle Hayne Aquifer

Layers 3 and 4 together represent the entire thickness of the Castle Hayne Aquifer. Under at least one of the anticipated remedial scenarios, there was an expected need for one or more extraction wells to remediate the levels of TCE in monitoring well 73-DW03. Therefore, the finite-difference grid was vertically discretized at an elevation of -60 feet msl so that Layer 3 was above and Layer 4 below -60 feet msl. In this way the extraction well installed in Layer 3 could represent pumping to that depth.

The top elevations of Layer 3 were the same as those at the bottom of Layer 2. The bottom of Layer 3 and top of Layer 4 was planar at -60 feet msl (see above discussion). The bottom of Layer 4 was at -350 feet msl.

Layer 3 and 4 were assigned a homogenous horizontal hydraulic conductivity of 8 ft/day. Even though an average of 3.37 ft/day was calculated in Table 2-2, a slightly higher input value was necessary to calibrate the model to observed conditions. The homogeneous vertical hydraulic conductivity in Layers 3 and 4 was assumed to be one tenth of the horizontal (0.8 ft/day). Again, the approach was to keep the model as simple as possible: the spatial variability would have been adjusted if necessary during the calibration process but it was not necessary as other parameters (notably the position of the clay breach) were adjusted to accomplish the calibration.

The locations of the Courthouse Bay supply wells (BB-44 is about 3,200 feet east of Site 73) are shown on Figure 3-2 and their pumping rates were presented in Table 2-1. Average discharge rates for each well are shown in gpm and in cubic feet per day. The average discharges from 4 of the 5 wells were divided equally between Layers 3 and 4, according to the screened intervals for each well. The only well that was pumping only in Layer 3 was BB-44 which is screened from -14 to -44 MSL (see Table 2-1) and lies within the range of elevation represented by Layer 3 (bottom elevation of -60 msl).

3.5 Steady-State Modeling Process

In a steady-state groundwater flow model all values of drawdown are assumed to have reached equilibrium. That is, enough time is supposed to have passed with the wells pumping at constant (average) rates that no more drawdown is occurring over time. While rarely true in reality, this assumption is considered valid when average pumping rates are applied over a long time frame (years or decades) to understand how groundwater flows within the regime. The most important assumption of this approach is that the diurnal pumping schedule of the water supply wells has been averaged as if pumping were a continuous event.

In general, the degree to which the model assumptions match the actual subsurface conditions dictates the accuracy of any subsequent predictions. In order to get a realistic model, it was necessary to calibrate the model to match actual measured values of head in each layer. The "targets" of the calibration were based on the statistics of the historical water level data where possible.

The targets included the average (mean) values of head in 40 surficial wells in layer 1; 18 intermediate wells in the upper Castle Hayne Aquifer, and 5 deep wells in the lower Castle Hayne Aquifer. Table 3-1 presents the data collected during the three rounds in the target wells. Because there was no way of knowing whether the water levels measured by the USGS in the Courthouse Bay supply wells were truly at "static" conditions at the time of collection, the data collected from these wells were used qualitatively but not as calibration targets.

Appendix A contains the MODFLOW input and output files from the calibrated Site 73 flow model.

3.5.1 Calibration Method

The calibration process used the "trial and error" method in which the results of each run were examined statistically to determine the degree of "fit" of the results. Statistics on the error (residual) between computed and observed used in the calibration process were the following: mean, standard deviation, absolute mean, and sum of squares. After each run, one or more input values (e.g., recharge, or horizontal or vertical hydraulic conductivity in one or more layers) and/or their spatial distributions were changed within reasonable ranges and the model rerun. Changes were made to those areas of the grid where the error (or residual) between simulated and measured water levels was large. In this "trial and error" method, not all changes were for the better; some had to be changed many times to find a "better" value or distribution pattern. This process continued until a reasonable fit was achieved. The model was considered to be calibrated when the simulated values of head at each monitoring well matched the observed values within a one-foot tolerance level.

3.5.2 Statistical Evaluation of Calibration

The difference between the target (the average observed groundwater elevation) and a simulated value is called residual (or error). The average of the all the errors should be close to zero for an accurate model because that indicates that the errors higher than the targets are balanced by the errors below the targets. A highly positive or negative residual mean (RM) would indicate an inaccurate model in which the water levels are all too low or too high. The RM is a good indication of statistical accuracy but not of precision. As long as the model errors are balanced (RM near zero) a model can be considered statistically accurate, but the fit is better measured by the more useful indicators of precision. These include the absolute residual mean (ARM), and the root mean square (RMS). These statistical values are better indicators of fit than the residual mean alone because they indicate the shape of the data distribution about the mean. Smaller values of these statistics indicate that the simulated values match the targets more closely.

Generally, the degree of fit was deemed acceptable when the residuals matched the targets within a maximum tolerance of 2 foot in all targeted layers (i.e, Layers 1, 3 & 4). The tolerance level for each site can differ greatly depending on the amount and type of data available. Sites with many data may have more (or even less) stringent tolerances than those with few data. All data points were within 1.7 feet of the mean.

3.6 Calibrated Results of Simulation

Table 3-2 presents the residuals of each target in the Site 73 model. The bottom of the table shows the statistics for each layer. The residual (or error) at a well is defined as the difference between the measured value (of head) and the simulated (modeled) value. In a calibrated model, the residual mean (the average of the errors) should be close to zero, that is, the positive errors should be balanced by the negative errors. However, the residual mean does not describe the "spread" of data around the mean. The Root Mean Square (RMS) error is a standard deviation of the errors which describes how the error is distributed around the mean. A large RMS indicates that the error values are rather large and widely spread; a small value indicate a "clustering" of small errors close to the average.

3.6.1 Output for Layer 1 -- Surficial Unit

Figure 3-7 shows the interpreted water table contours across Site 73 as per the RI Report (Baker, 1997). Figure 3-8 shows the simulated water table contours across Site 73 in the surficial unit. Both maps show that Courthouse Bay is the groundwater discharge area from the surficial unit at Site 73. All of the simulated water levels at the 40 targets in Layer 1 were within 1.7 feet of their targets. Table 3-2 shows that the RM in Layer 1 was 0.03 feet, the ARM was 0.62 feet, and the RMSE was 0.75 ft.

Figure 3-9 shows a graph of computed values as a function of observed values for Layer 1. As is shown on the graph, all simulated points are within 1.7 feet of the diagonal representing the mean at each well. Figure 3-10 shows the residual at each well in Layer 1 graphed as a function of the observed values. All residuals were within 1.7 foot of the mean (horizontal line at y=0) in a seemingly random pattern. The spatial distribution of error in Layer 1 is shown in Figure 3-11. The error bars indicate an error of ± 1 standard deviation from the mean at each well. No pattern of residuals is obvious.

As noted on the figure, some of the error bars are red, indicating that the simulates heads were greater than 200% of the mean at a particular well. With a limited data set, some of the wells had very little variability in water levels so that an error of, for example, 0.2 feet may have been greater than 200% from the mean. Generally, the fit of the model to the data was good.

Because no data exist regarding potentiometric heads in the Castle Hayne confining clay unit with which to measure the "fit" of the inputs in Layer 2, no discussion of output for Layer 2 is included. Even though the assumed predominant flow direction within the clay is vertical, the pattern of hydraulic heads in Layer 2 (not shown) is very similar to that of Layer 1. This is reasonable since the confining clay appears to be the major controlling factor over the water levels in Layer 1.

3.6.2 Output for Layer 3 -- Upper Castle Hayne Aquifer

Figure 3-12 shows the interpreted potentiometric head contours in the upper Castle Hayne across Site 73 as per the RI Report (Baker, 1997). Figure 3-13 shows the simulated contours across Site 73 in the upper Castle Hayne. Both maps show that Courthouse Bay and the New River are the dominant groundwater discharge areas for groundwater in the upper Castle Hayne Aquifer at Site 73. Figure 3-13 also shows that the capture zone of supply well BB-44 extends upgradient to the northeast, away from, and not toward Site 73. It does not indicate that supply well BB-44 draws any water from Courthouse Bay or from the vicinity of Site 73. If these contours are accurate, then the source of VOC in well BB-44 as reported by Greenehorne and O'Mara (1992) was not Site 73.

All of the simulated water levels at the 18 targets in Layer 3 were within 1.5 feet of their targets. Table 3-2 shows that the RM in Layer 3 was -0.04 feet, the ARM was 0.31 feet, and the RMSE was 0.45 ft.

Figure 3-14 shows a graph of computed values as a function of observed values for Layer 3. As is shown on the graph, all simulated points are within 0.9 feet of the diagonal representing the mean at each well. Figure 3-15 shows the residual at each well in Layer 3 graphed as a function of the observed values. All residuals were within 0.9 feet of the mean (horizontal line at y=0) in a seemingly random pattern. The spatial distribution of error in Layer 3 is shown in Figure 3-16. The error bars indicate an error of ±1 standard deviation from the mean at each well. No pattern of residuals is obvious.

3.6.3 Output for Layer 4 -- Lower Castle Hayne Aquifer

Figure 3-17 shows the interpreted potentiometric head contours in the lower Castle Hayne Aquifer across Site 73 as per the RI Report (Baker, 1997). Figure 3-18 shows the simulated contours across Site 73 in the lower Castle Hayne. Both maps show that Courthouse Bay is the groundwater discharge area from the lower Castle Hayne Aquifer at Site 73. All of the simulated water levels at the 5 targets in Layer 4 were within 0.9 foot of their targets. Table 3-2 shows that the RM in Layer 4 was - 0.57 feet, the ARM was 0.57 feet, and the RMSE was 0.61 ft..

Figure 3-19 shows a graph of computed values as a function of observed values for Layer 4. As is shown on the graph, all simulated points are within 0.9 foot of the diagonal representing the mean at each well. Figure 3-20 shows the residual at each well in Layer 4 graphed as a function of the observed values. All residuals were within 0.9 foot of the mean (horizontal line at y=0). The spatial distribution of error in Layer 4 is shown in Figure 3-21. The error bars indicate an error of ± 1 standard deviation from the mean at each well.

3.7 Sensitivity Analysis

A sensitivity analysis was performed on the Site 73 model. This included changing the values of input parameters (one at a time) from the calibrated values and observing the effects of each change. Values of ±20% and 50% of the calibrated values of the five input parameters (recharge, horizontal hydraulic conductivity, leakance, drain conductance, and river conductance) were used as input and the resulting statistics were graphed to illustrate the effect of each change.

In a calibrated model, the residuals should cluster closely about a mean of zero. Several statistics were used to measure the "fit" of the data about the mean. The residual mean (RM, the average of all the residuals) should approach the value of zero. While this indicates the relative accuracy of the model (i.e., the average of the residuals have a value of zero), it says nothing regarding the precision of the simulation (i.e., the actual differences between the simulated and the target values). Therefore, two other statistics were used to determine the fit of the simulated heads to their observed targets: the root mean square (RMS) and the absolute residual mean (ARM) are better indicators of the fit of the simulation to reality. The calibration attempted to minimize the values of the RMS and ARM while keeping the RM as close to zero as possible.

3.7.1 Model Sensitivity to Changes in Recharge

Figure 3-22 graphically depicts the effects of changes to recharge on the residuals (measured values minus simulated values of head). From the figure it is apparent that changes in recharge values significantly affect the values of simulated head. Values of RMS and ARM were minimized (the downwardly curved lines are at their lowest value) at the calibrated value of recharge where the RM is close to zero (0.03 feet).

3.7.2 Model Sensitivity to Changes in Horizontal Hydraulic Conductivity

Figure 3-23 shows the effects of changes to horizontal hydraulic conductivity on the residuals. From the figure it is apparent that changes in horizontal hydraulic conductivity values affect the values of simulated head. Values of RMS and ARM were minimized at the calibrated values of horizontal hydraulic conductivity where the RM is close to zero.

3.7.3 Model Sensitivity to Changes in Leakance

Figure 3-24 presents the effects of changes to leakance on the residuals. From the figure it is apparent that changes in leakance values affect the values of simulated head. Values of RMS and ARM were minimized at the calibrated values of leakance where the RM is close to zero.

3.7.4 Model Sensitivity to Changes in Drain Conductance

Figure 3-25 shows that changes to drain cell conductance had only a slightly measurable effect on the simulated head values. The RM values approached zero when the conductance of the drain cells was increased by about 30%. This would not be unreasonable: a 30% increase in the current value of drain material hydraulic conductivity (K = 0.6 ft/d = $2x10^{-4}$ cm/sec) would yield a value of 0.78 ft/day or $2.8x10^{-4}$ cm/sec--still within the range for a silty sand. However, this change would be minor and as seen on Figure 3-25, the changes to drain conductance had little to no effect on the RMS and the ARM.

3.7.5 Model Sensitivity to Changes in River Conductance

Figure 3-26 shows that changes to river cell conductance also had only a slightly measurable effect on the simulated head values. Also, as shown on Figure 3-26, the changes to river conductance had a minimal effect on the RMS and the ARM. Due to comments on the Draft Site 73 Modeling Report by the State of North Carolina, C_{riv} was reduced by a factor of 100 so that the values are similar to those used in the BRAGS model (Baker, 1996). The overall pattern of groundwater flow did not change and the heads in Layer 1 were dropped by about one foot overall. This change actually caused a better statistical fit of the data and was used in the final model.

3.7.6 Model Sensitivity Analysis Summary

According to this sensitivity analysis, and as shown on Figures 3-27 through 3-29, the model is most sensitive to recharge, followed by (in order of decreasing effect on the model) horizontal hydraulic conductivity, leakance, river conductance and is least sensitive to changes in drain conductance. The value of recharge over most of the model domain was not changed because previous studies indicated what the average value should be. However, on-site values of recharge were adjusted to compensate for the buildings, asphalt and concrete covering the surface.

Changes were also made to horizontal K and leakance values during the calibration. The values were kept homogeneous throughout each layer with the exception of the dichotomy in Layer 2 where the low K and low leakance zones indicate the presence of the clay unit. Adjustments to the lateral extent of the clay breach were made based on the well and boring logs. Early on in the calibration process, it was found that the location of the clay breach was one of the controlling factors in matching the observed the water levels in the surficial unit and in the Castle Hayne Aquifer at Site 73.

Although the calibrated flow model for Site 73 is not a unique solution, it appears to be a reasonable one given the input parameters and the resulting predictions can also be considered reasonably accurate.

3.8 MODPATH Pathline Analysis

The results of the MODFLOW simulations were used to generate three-dimensional particle traces (pathlines) for the calibrated model using MODPATH (Pollock, 1989). MODPATH is a three-dimensional particle-tracking code developed by the USGS that uses the results of MODFLOW to generate particle traces (or pathlines) that result from groundwater advection (flow) as if a dissolved contaminant were carried along with no dispersion, retardation or degradation. The combination of groundwater flow modeling with particle tracking was used to illustrate the direction of groundwater flow and the conservative (worst-case) fate of dissolved contaminants (assuming no degradation and dispersion).

Values of porosity are necessary for MODPATH to calculate travel times. A value of 0.3 (30%) was used as the effective porosity for Layer 1, 3, and 4. Effective porosity in Layer 2 (confining clay unit) was assigned a value of 0.1 (10%).

Although no dispersion, reaction, or degradation of particles is possible with this type of program, it can be used to indicate the ultimate fate of groundwater in three dimensions, to place monitoring wells in contaminant pathways, and to generate three-dimensional capture zones around individual wells to demonstrate contaminant capture under various remedial scenarios.

Appendix B contains the MODPATH input and output files for the Site 73 pathline analyses.

3.8.1 Backward Pathline Simulation

If it is assumed that the contaminants reached their present locations only by advection in a dissolved phase, and not by density-driven movement in a non-aqueous phase, the particles can be projected backwards in time toward potential source locations. This assumes that the average groundwater flow conditions have remained at the mean water levels as measured in the RI Report (Baker, 1997). Figure 3-30 shows a plan view of the results of a pathline analysis run backwards in time from the existing locations of dissolved benzene, TCE, DCE, and VC contamination. The results indicate three main source areas of solvents at the site. The following is a discussion of the potential source areas.

Potential source Area A was indicated from particles run backward from existing contamination in several surficial unit wells and in upper Castle Hayne well 73-DW03. This large area is east and south of Building A-47. This potential source area is reasonable since Area A encompasses areas near the former and existing main operating buildings and the UST area.

Figure 3-31 shows a cross-section (south at left) of the pathlines that were projected backwards from the existing location of TCE in upper Castle Hayne well 73-DW03 and from surficial wells (A47/3-8, 73MW-13, and 73MW-27) toward the source Area A. During the RI, there were indications of residual soil and groundwater contamination in this area by soil gas survey, groundwater screening, and soil samples. The highest groundwater TCE, DCE, and VC concentrations in the surficial unit are in Area A. Note the predominantly horizontal movement in Layers 1 and 3 while the predominant flow in Layer 2 is vertical. This is consistent with movement through a clay unit in which the hydraulic conductivity is much lower than in sand units.

Potential source Area B was indicated by existing contamination in well 73-DW02 and from 73-MW11B (upper Castle Hayne wells). Area B includes Buildings A-8, A-9 and A-10 and the area surrounding them. This area was not indicated on the soil gas survey or the shallow groundwater screening as a potential source area. Figure 3-32 shows a cross-section of the pathlines from Area B (south at left) to the present locations of TCE.

Potential source Area C was projected backwards as the source for the contamination in surficial unit well 73-MW09. Part of Area C (close to the bay) was indicated as one or more possible source areas of solvent contamination by the shallow groundwater screening (Baker, 1997). Figure 3-32 shows a cross-section of the pathlines (south at left) from Area C to the present location of DCE and VC in 73-MW09. Near the existing location of 73-MW09 the pathlines are migrating vertically downward in response to the dock structure which was represented in the model by horizontal flow barrier (HFB) cells.

The average advective travel time for the pathlines from Areas A, B and C was approximately 21 years. This time frame may be reasonable for TCE if a range of retardation factors, (R_f = 1.0 to 2.4) is assumed. The contaminants would have had to travel from source areas starting no later than 1974 (R_f= 1.0) or as early as 1941 (R_f= 2.4) to reach present position as measured in 1996-7. Even though these retardation factors seem relatively low, a larger retardation factor would extend the source time earlier than the 1940's when the use of TCE was not widespread.

While these backwards projections are not definitive of source areas, they are one tool to indicate possible sources of groundwater contamination. Coupled with the analysis of travel times, the pathlines reveal that certain locations of potential sources are more plausible than others.

It should be noted that the behavior of non-aqueous phase liquids would not be accounted for by these pathlines. As an example of non-aqueous behavior not simulated by the model, actual travel times of dense non-aqueous phase liquids (DNAPLs), if residual in the aquifer matrix, would tend to be of shorter duration because the vertical movement of residual DNAPLs are density-driven and would tend to move faster downward than a dissolved constituent by advection. However, the current concentrations of TCE, DCE and VC do not indicate that DNAPLs exist at Site 73.

3.8.2 Forward Pathline Simulation

Figure 3-33 shows a plan view of the forward simulation from the current locations of identified solvent contamination toward Courthouse Bay. This figure and the cross-sections in Figures 3-34 and 3-35 answer the question posed at the outset: "Is the solvent contamination at Site 73 migrating beneath Courthouse Bay toward well BB-44?" The answer, based on the model and all its assumptions, is "no". The influence of Courthouse Bay (and the New River) as the regional groundwater discharge zone is overwhelming compared to the drawdown of the nearby supply wells. According to the calibrated flow model, the groundwater contamination is constrained by naturally-occurring vertical gradients to discharge to Courthouse Bay. Furthermore, if such gradients did not exist, the advective travel time for groundwater (regardless of contaminant retardation) to supply well BB-44, at a distance of 3,200 feet (0.6 mile), would be on the order of centuries (and contaminant travel times even longer with a retardation factor greater than unity).

Figure 3-34 shows a south-north cross-section of the pathlines projected forward (right to left) from the present locations of contamination in upper Castle Hayne well 73-DW03 and from surficial wells 73-MW27, 73-MW13 and A47/3-8. One of the key issues at the start of this effort, "How deep will the contaminants migrate?" can be addressed by this figure. Figure 3-34 suggests that the TCE in well 73-DW03 (at elevation -60 feet MSL) is not yet at its deepest point in its "trajectory" toward Courthouse Bay. Assuming advective transport, the contamination is expected to migrate deeper into the Castle Hayne Aquifer (to a maximum depth of about -260 feet MSL) on its way toward the bay. Even though a deep temporary well, 73-TW01, was installed adjacent to 73-DW03 to an elevation of about -140 MSL and found to be "clean," the location of the deepest contamination is projected by the model to be farther south (near the shore of Courthouse Bay) than the location of the temporary well.

Figure 3-35 shows a south-north cross-section of the pathlines projected forward (right to left) from the present location of contamination in upper Castle Hayne wells 73-DW02 and 73-MW11B. Notice that the migration is predominantly horizontal until the pathlines get in the immediate vicinity of Courthouse Bay where the pathlines abruptly change direction from horizontal to vertically upwards. This seems to be typical of groundwater to surface water discharges around the New River: discharge zones are very close to the surface water bodies.

Figure 3-35 also shows the pathlines projected forward from the present location of contamination in surficial well 73-MW09. The pathlines show the vertical component of migration under the dock structure which is represented by HFB cells assumed to completely penetrate the surficial unit.

SECTION 3.0 TABLES

TABLE 3-1
WATER LEVELS AND OTHER IMPORTANT INFORMATION
SITE 73 GROUNDWATER MODEL
CONTRACT TASK ORDER 0312

Well Number	Easting	Northing	MODFLOW Layer	MODFLOW Row	MODFLOW Column	Well Elevation Top of Casing (msl)	Top of Layer 2 Elevation (msl)	Top of Layer 3 Elevation (msl)	Round 1 H2O level (2-25-96)	Round 1 GW Elev. (msl)	Round 2 H2O level (3-25-96)	Round 2 GW Elev. (msl)	Round 3 H2O level (5-14-96)	Round 3 GW Elev. (msl)	Mean	Standard Deviation
Shallow Wells																
73MW-01	2488900.00	310550.00	1	22	29	15.35	0.00	-12.00	5.79	**9.56**	5.30	**10.05**	6.60	**8.75**	9.45	0.656531
73MW-02	2489110.00	309790.00	1	43	32	14.66	0.50	-4.50	5.27	**9.39**	5.18	**9.48**	5.84	**8.82**	9.23	0.357911
73MW-03	2489180.00	309700.00	1	45	33	13.70	-4.10		4.18	**9.52**	4.09	**9.61**	4.58	**9.12**	9.42	0.260832
73MW-04	2489296.22	309935.67	1	40	36	12.86	1.70		2.76	**10.10**	2.51	**10.35**	3.26	**9.60**	10.02	0.381881
73MW-05	2489390.00	309520.00	1	51	38	15.78	-2.00		5.86	**9.92**	5.41	**10.37**	6.50	**9.28**	9.86	0.547753
73MW-06	2489650.00	308970.00	1	63	45	7.32	-3.50	-28.00	6.32	**1.00**	6.36	**0.96**	7.72	**-0.40**	0.52	0.796994
73MW-07	2489480.00	309010.00	1	62	41	13.94	-2.00		8.14	**5.80**	7.77	**6.17**	8.90	**5.04**	5.67	0.576106
73MW-08	2489830.77	309288.30	1	55	48	10.98	-2.50		4.74	**6.24**	4.55	**6.43**	5.08	**5.90**	6.19	0.268514
73MW-09	2489882.00	309178.29	1	58	49	6.94	-2.80	-26.00	4.26	**2.68**	3.17	**3.77**	3.28	**3.66**	3.37	0.600083
73MW-10	2490012.13	309306.18	1	55	42	6.54	-4.20		2.97	**3.57**	2.89	**3.65**	2.97	**3.57**	3.60	0.046188
73MW-11	2489650.00	309790.00	1	43	45	13.14	-2.50	-13.30	4.21	**8.93**	3.92	**9.22**	4.74	**8.40**	8.85	0.415812
73MW-14	2490155.77	310058.74	1	36	56	8.48	-8.10	-12.50	3.79	**4.69**	3.74	**4.74**	3.87	**4.61**	4.68	0.065574
73MW-15	2490339.00	309670.40	1	46	61	5.00	-2.00	-22.20	3.54	**1.46**	3.85	**1.15**	3.91	**1.09**	1.23	0.198578
73MW-16	2489524.00	309971.29	1	40	44	11.13	-2.50	-10.40	2.84	**8.29**	2.60	**8.53**	3.06	**8.07**	8.30	0.230072
73MW-17	2489840.00	310275.00	1	30	48	10.69			7.79	**2.90**	5.76	**4.93**	5.92	**4.77**	4.20	1.128672
73MW-18	2489280.00	310480.00	1	23	35	12.19	-7.00		3.70	**8.49**	---	---	4.82	**7.37**	7.93	0.79196
73MW-19	2489910.00	310780.00	1	19	50	12.73			5.92	**6.81**	5.74	**6.99**	7.28	**5.45**	6.42	0.841982
73MW-20	2490050.00	310570.00	1	21	53	7.70	-1.20	-2.00	2.46	**5.24**	2.39	**5.31**	3.60	**4.10**	4.88	0.679289
73MW-21	2490260.00	310660.00	1	20	59	7.26	0.50	-5.50	3.58	**3.68**	3.49	**3.77**	4.40	**2.86**	3.44	0.501431
73MW-23	2488850.00	310040.00	1	37	28	11.67	-0.50		4.05	**7.62**	3.89	**7.78**	4.72	**6.95**	7.45	0.440341
73MW-24	2489420.00	310880.00	1	18	39	6.59			2.94	**3.65**	2.93	**3.66**	---	---	3.66	0.007071
73MW-25	2489767.08	309205.23	1	57	46	11.09	0.40		4.36	**6.73**	4.22	**6.87**	4.70	**6.39**	6.66	0.246847
73MW-26	2489532.00	309961.00	1	39	42	16.04	0.00	-10.40	7.02	**9.02**	6.69	**9.35**	7.34	**8.70**	9.02	0.325013
73MW-27	2489910.00	310070.00	1	36	50	9.52	-8.50		3.92	**5.60**	3.82	**5.70**	4.02	**5.50**	5.60	0.1
73MW-28	2489901.43	309311.94	1	55	50	11.45			6.03	**5.42**	5.84	**5.61**	6.25	**5.20**	5.41	0.205183
73MW-29	2490090.00	309820.00	1	43	54	8.76	-7.74		3.08	**5.68**	3.06	**5.70**	3.15	**5.61**	5.66	0.047258
73MW-30	2488990.00	309750.00	1	44	30	9.13	-9.40		2.67	**6.46**	2.65	**6.48**	3.80	**5.33**	6.09	0.658255
73MW-31	2489289.15	308730.40	1	68	35	12.06	0.10	-22.40	---	---	9.69	**2.37**	10.51	**1.55**	1.96	0.579828
73MW-32	2488768.39	309585.84	1	49	26	6.73	-4.90	-5.90	---	---	3.98	**2.75**	5.20	**1.53**	2.14	0.86267
73MW-33	2488696.98	310453.64	1	24	23	14.32	-0.30	-8.50	---	---	5.70	**8.62**	7.02	**7.30**	7.96	0.933381
73MW-34	2488582.65	311080.75	1	12	18	12.90	-10.10	-20.10	---	---	6.25	**6.65**	7.50	**5.40**	6.03	0.883883
73MW-35	2490182.59	311002.91	1	15	56	12.89	-9.90	-9.90	---	---	7.60	**5.29**	8.78	**4.11**	4.70	0.834386
73MW-36	2491493.04	308349.40	1	75	81	8.40	-0.80	-16.80	---	---	5.35	**3.05**	7.04	**1.36**	2.21	1.19501
73MW-37	2489855.67	310308.48	1	29	48	11.12			---	---	5.89	**5.23**	6.01	**5.11**	5.17	0.084853
A47/3-11	2490640.00	310080.00	1	36	67	8.10			7.06	**1.04**	7.09	**1.01**	7.12	**0.98**	1.01	0.03
A47/3-13	2490380.00	310230.00	1	31	62	8.54			4.94	**3.60**	4.87	**3.67**	4.88	**3.66**	3.64	0.037859
A47/3-8	2490350.00	310060.00	1	36	62	6.87			4.64	**2.23**	4.61	**2.26**	4.72	**2.15**	2.21	0.056862
MW-08	2489650.00	310660.00	1	20	45	12.98			5.96	**7.02**	4.76	**8.22**	7.54	**5.44**	6.89	1.394322
MW-09	2489370.00	310090.00	1	35	38	14.92			5.34	**9.58**	4.96	**9.96**	4.72	**10.20**	9.91	0.312623
MW-16	2489740.00	310520.00	1	24	46	12.15			5.58	**6.57**	5.41	**6.74**	6.67	**5.48**	6.26	0.683691
Hybrid - Surficial and Castle Hayne																
DW-02	2489430.00	310350.00	?	28	40	15.78	-1.60	-11.60	12.28	**3.50**	---	---	10.60	**5.18**	4.34	1.187939
Intermediate Wells																
73MW-01B	2488900.00	310550.00	3	21	29	15.86	0.00	-12.00	12.88	**2.98**	12.79	**3.07**	13.80	**2.06**	2.70	0.558957
73MW-02B	2489110.00	309790.00	3	43	32	14.39	0.50	-4.50	11.75	**2.64**	11.68	**2.71**	12.00	**2.39**	2.58	0.168226

TABLE 3-1
WATER LEVELS AND OTHER IMPORTANT INFORMATION
SITE 73 GROUNDWATER MODEL
CONTRACT TASK ORDER 0312

Well Number	Easting	Northing	MODFLOW Layer	MODFLOW Row	MODFLOW Column	Well Elevation Top of Casing (msl)	Top of Layer 2 Elevation (msl)	Top of Layer 3 Elevation (msl)	Round 1 H2O level (2-25-96)	Round 1 GW Elev. (msl)	Round 2 H2O level (3-25-96)	Round 2 GW Elev. (msl)	Round 3 H2O level (5-14-96)	Round 3 GW Elev. (msl)	Mean	Standard Deviation
73MW-06B	2489650.00	308970.00	3	63	45	6.86	-3.50	-28.00	4.99	**1.87**	4.91	**1.95**	5.02	**1.84**	1.89	0.056862
73MW-11B	2489650.00	309790.00	3	43	45	13.00	-2.50	-13.30	10.33	**2.67**	10.27	**2.73**	10.58	**2.42**	2.61	0.164418
73MW-15B	2490339.00	309670.40	3	47	61	4.68	-2.00	-22.20	2.39	**2.29**	2.37	**2.31**	2.62	**2.06**	2.22	0.138924
73DW-01	2488900.00	310550.00	3	22	29	15.92	0.00	-12.00	12.96	**2.96**	12.89	**3.03**	13.66	**2.26**	2.75	0.425793
73DW-02	2489882.00	309178.29	3	58	49	6.74	-2.80	-26.00	4.84	**1.90**	4.77	**1.97**	4.94	**1.80**	1.89	0.08544
73DW-03	2490185.00	310000.81	3	38	56	8.28	-8.10	-12.50	5.66	**2.62**	5.62	**2.66**	5.89	**2.39**	2.56	0.145717
73DW-04	2490339.00	309670.40	3	46	61	4.68	-2.00	-22.20	2.42	**2.26**	2.39	**2.29**	3.64	**1.04**	1.86	0.713185
73DW-05	2490060.00	310570.00	3	21	53	7.32	-0.70	-2.00	4.42	**2.90**	4.37	**2.95**	4.76	**2.56**	2.80	0.212211
73DW-06	2489286.91	308723.35	3	68	35	11.85	0.10	-22.40	----	----	9.73	**2.12**	9.87	**1.98**	2.05	0.098995
73DW-07	2488769.90	309572.97	3	49	26	6.85	-4.90	-5.90	----	----	4.16	**2.69**	4.56	**2.29**	2.49	0.282843
73DW-08	2488699.41	310462.20	3	24	23	14.33	-0.30	-8.50	----	----	11.26	**3.07**	11.68	**2.65**	2.86	0.296985
73DW-09	2488582.21	311074.63	3	12	18	12.57	-10.10	-20.10	----	----	9.51	**3.06**	9.92	**2.65**	2.86	0.289914
73DW-10	2490180.41	310996.69	3	15	56	13.29	-9.90	-9.90	----	----	10.50	**2.79**	10.46	**2.83**	2.81	0.028284
73DW-11	2489523.85	309971.29	3	39	42	16.15	-2.50	-10.40	----	----	13.34	**2.81**	13.37	**2.78**	2.80	0.021213
73DW-12	2490786.55	310226.76	3	31	70	6.94	-12.70	-12.70	----	----	4.11	**2.83**	4.52	**2.42**	2.63	0.289914
73DW-13	2491497.69	308354.01	3	75	81	8.67	-0.80	-16.80	----	----	6.32	**2.35**	8.20	**0.47**	1.41	1.329361
Deep Wells																
73GW-01	2489531.96	309961.32	4	40	43	15.83	-2.50	-10.40	----	----	13.01	**2.82**	13.37	**2.46**	2.64	0.254558
73GW-02	2489881.76	309178.29	4	58	49	6.69	-2.40	-26.00	----	----	4.66	**2.03**	4.60	**2.09**	2.06	0.042426
73GW-03	2490339.22	309670.40	4	46	61	5.75	-2.00	-22.20	----	----	3.12	**2.63**	3.39	**2.36**	2.50	0.190919
73GW-04	2490775.41	310219.80	4	32	70	6.55	-12.70	-12.70	----	----	3.39	**3.16**	3.70	**2.85**	3.01	0.219203
73GW-05	2491502.60	308358.17	4	75	81	8.40	-0.80	-16.80	----	----	5.58	**2.82**	5.36	**3.04**	2.93	0.155563

TABLE 3-2
CALIBRATED TARGETS AND SIMULATED HEADS

Site 73 - CB, Camp Lejeune, North Carolina

Well Name	Target Head	Model Head	Residual
73MW-01	9.45	9.26	-0.19
73MW-02	9.23	8.86	-0.37
73MW-03	9.42	9.45	0.03
73MW-04	10.02	10.37	0.35
73MW-05	9.86	10.50	0.64
73MW-06	0.52	1.63	1.11
73MW-07	5.67	6.12	0.45
73MW-08	6.19	6.17	-0.02
73MW-09	3.37	2.58	-0.79
73MW-10	3.60	2.64	-0.96
73MW-11	8.85	9.80	0.95
73MW-14	4.68	4.25	-0.43
73MW-15	1.23	1.87	0.64
73MW-16	8.30	9.96	1.66
73MW-17	4.20	5.15	0.95
73MW-18	7.93	7.94	0.01
73MW-19	6.42	5.13	-1.29
73MW-20	4.88	4.41	-0.47
73MW-21	3.44	3.21	-0.23
73MW-23	7.45	7.74	0.29
73MW-24	3.66	2.95	-0.71
73MW-25	6.66	5.47	-1.19
73MW-26	9.02	9.96	0.94
73MW-27	5.60	5.79	0.19
73MW-28	5.41	5.62	0.21
73MW-29	5.66	5.68	0.02
73MW-30	6.09	7.76	1.67
73MW-31	1.96	1.47	-0.49
73MW-32	2.14	2.60	0.46
73MW-33	7.96	8.31	0.35
73MW-34	6.03	5.30	-0.73
73MW-35	4.70	3.82	-0.88
73MW-36	2.21	2.26	0.05
73MW-37	5.17	4.19	-0.98
A47/3-11	1.01	2.25	1.24
A47/3-13	3.64	2.80	-0.84
A47/3-8	2.21	2.51	0.30
MW-16	6.26	5.76	-0.50
MW-8	6.89	6.17	-0.72
MW-9	9.91	10.36	0.45
73MW-01B	2.70	2.75	0.05
73MW-02B	2.58	2.41	-0.17
73MW-06B	1.89	1.47	-0.42
73MW-11B	2.61	2.21	-0.40

TABLE 3-2
CALIBRATED TARGETS AND SIMULATED HEADS

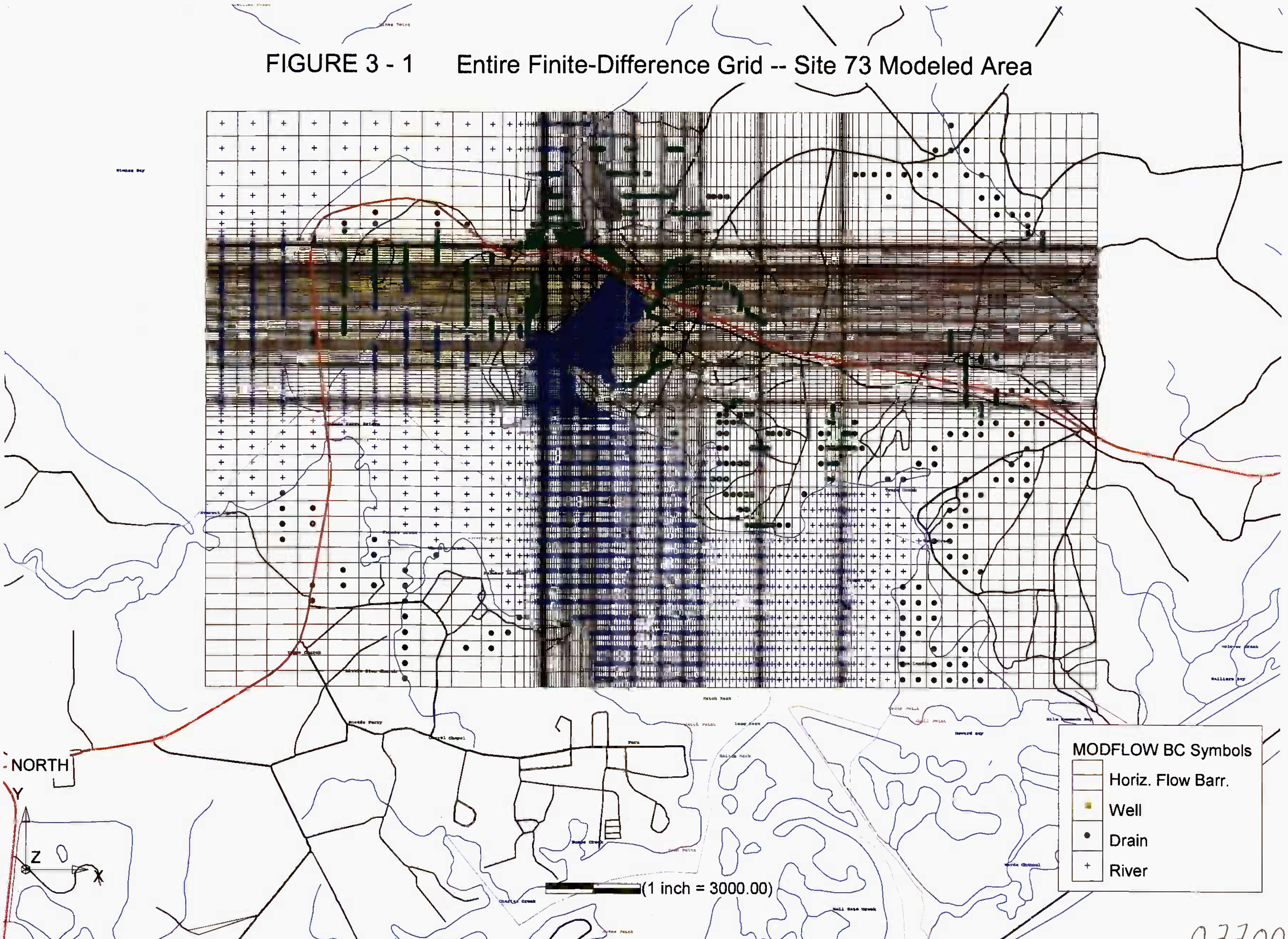
Site 73 - CB, Camp Lejeune, North Carolina

Well Name	Target Head	Model Head	Residual
73MW-15B	2.22	1.83	-0.39
73DW-01	2.75	2.75	0.00
73DW-02	1.89	1.47	-0.42
73DW-03	2.56	2.30	-0.26
73DW-04	1.86	1.83	-0.03
73DW-05	2.80	2.83	0.03
73DW-06	2.05	1.40	-0.65
73DW-07	2.49	2.49	0.00
73DW-08	2.86	2.76	-0.10
73DW-09	2.86	2.73	-0.13
73DW-10	2.81	3.06	0.25
73DW-11	2.80	2.39	-0.41
73DW-12	2.63	2.51	-0.12
73DW-13	1.41	2.25	0.84
73GW-01	2.64	2.38	-0.26
73GW-02	2.06	1.46	-0.60
73GW-03	2.50	1.82	-0.68
73GW-04	3.01	2.57	-0.44
73GW-05	2.93	2.07	-0.86

Statistics for Layer 1	
Number of Targets =	40
Residual Mean (RM) =	0.03
Absolute Residual Mean (ARM) =	0.62
Root Mean Square (RMS) =	0.75
Statistics for Layer 3	
Number of Targets =	18
Residual Mean (RM) =	-0.04
Absolute Residual Mean (ARM) =	0.31
Root Mean Square (RMS) =	0.45
Statistics for Layer 4	
Number of Targets =	5
Residual Mean (RM) =	-0.57
Absolute Residual Mean (ARM) =	0.57
Root Mean Square (RMS) =	0.61

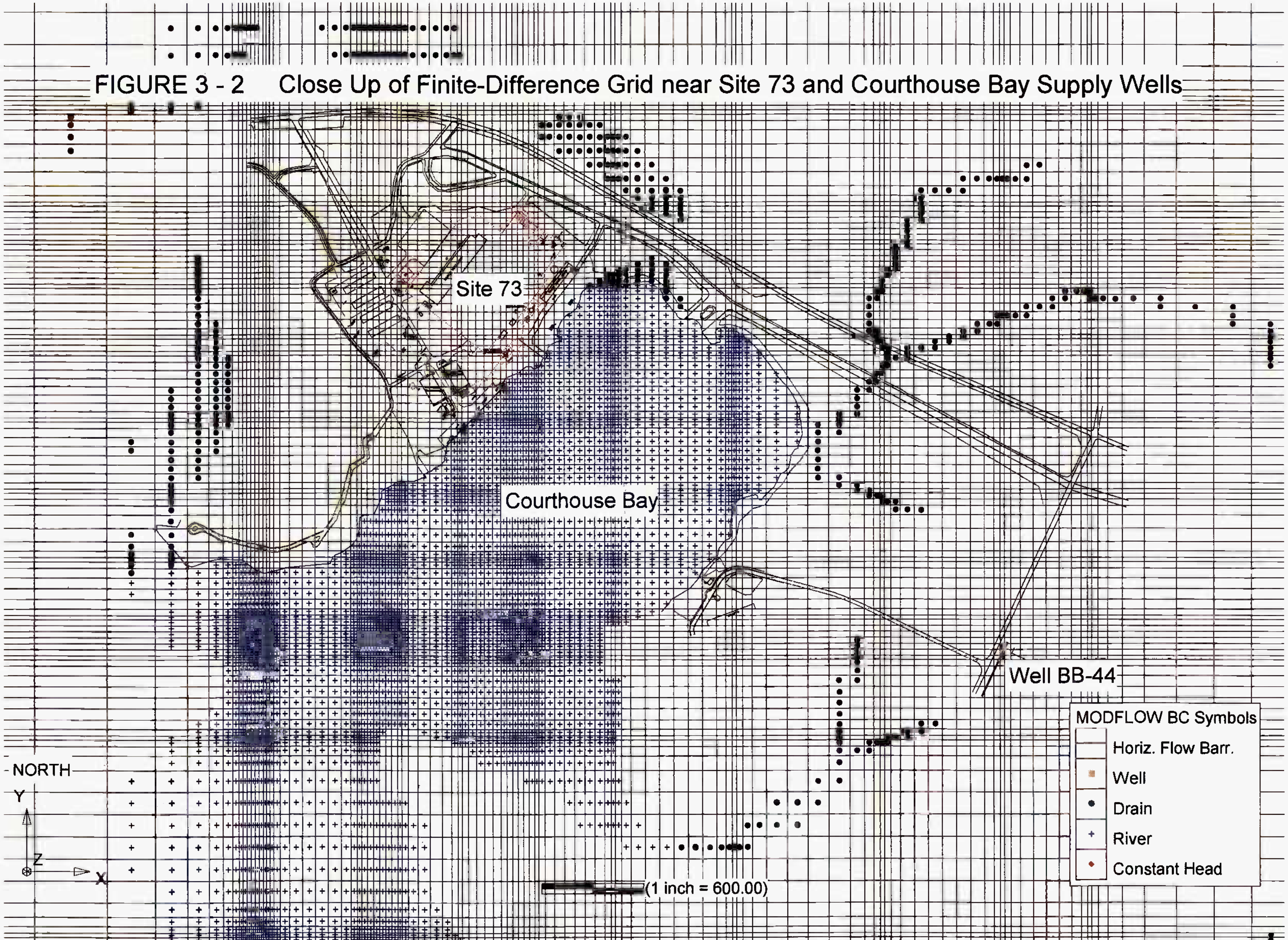
SECTION 3.0 FIGURES

FIGURE 3 - 1 Entire Finite-Difference Grid -- Site 73 Modeled Area



02200DDB2Y

FIGURE 3 - 2   Close Up of Finite-Difference Grid near Site 73 and Courthouse Bay Supply Wells



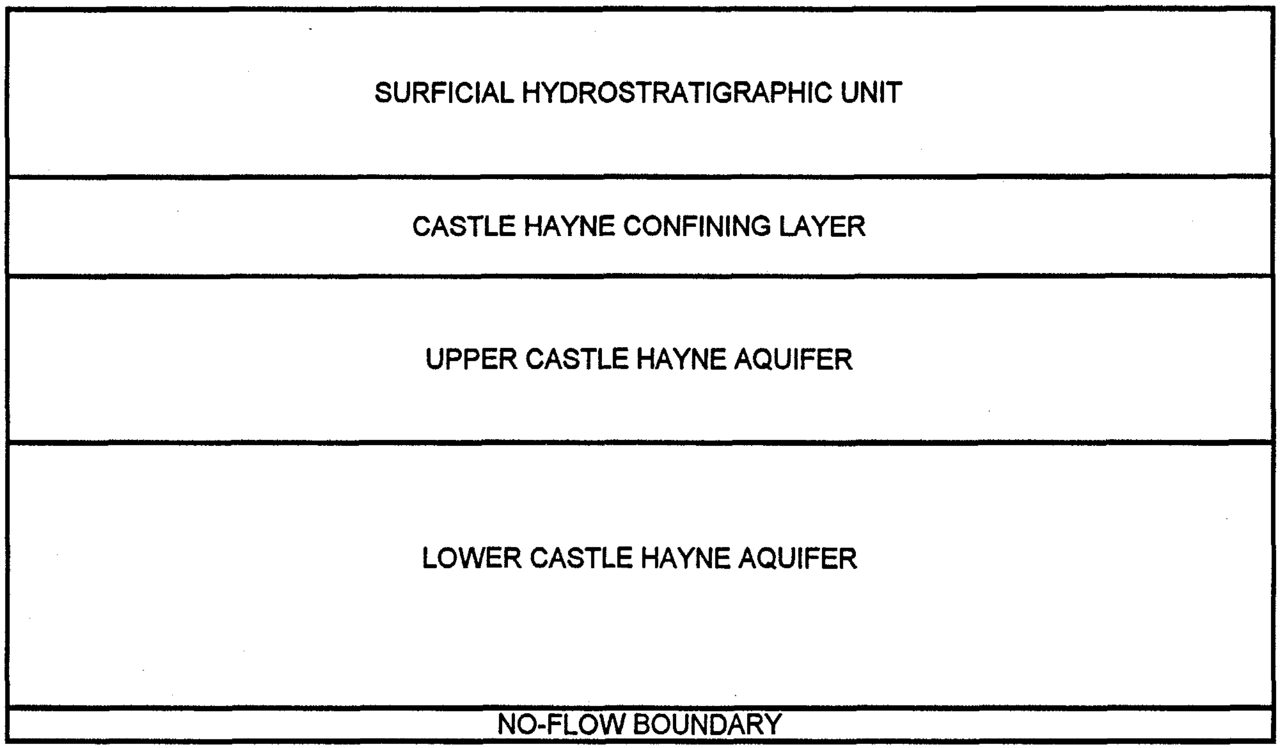


FIGURE 3-3 -- Schematic of Four-Layer Model

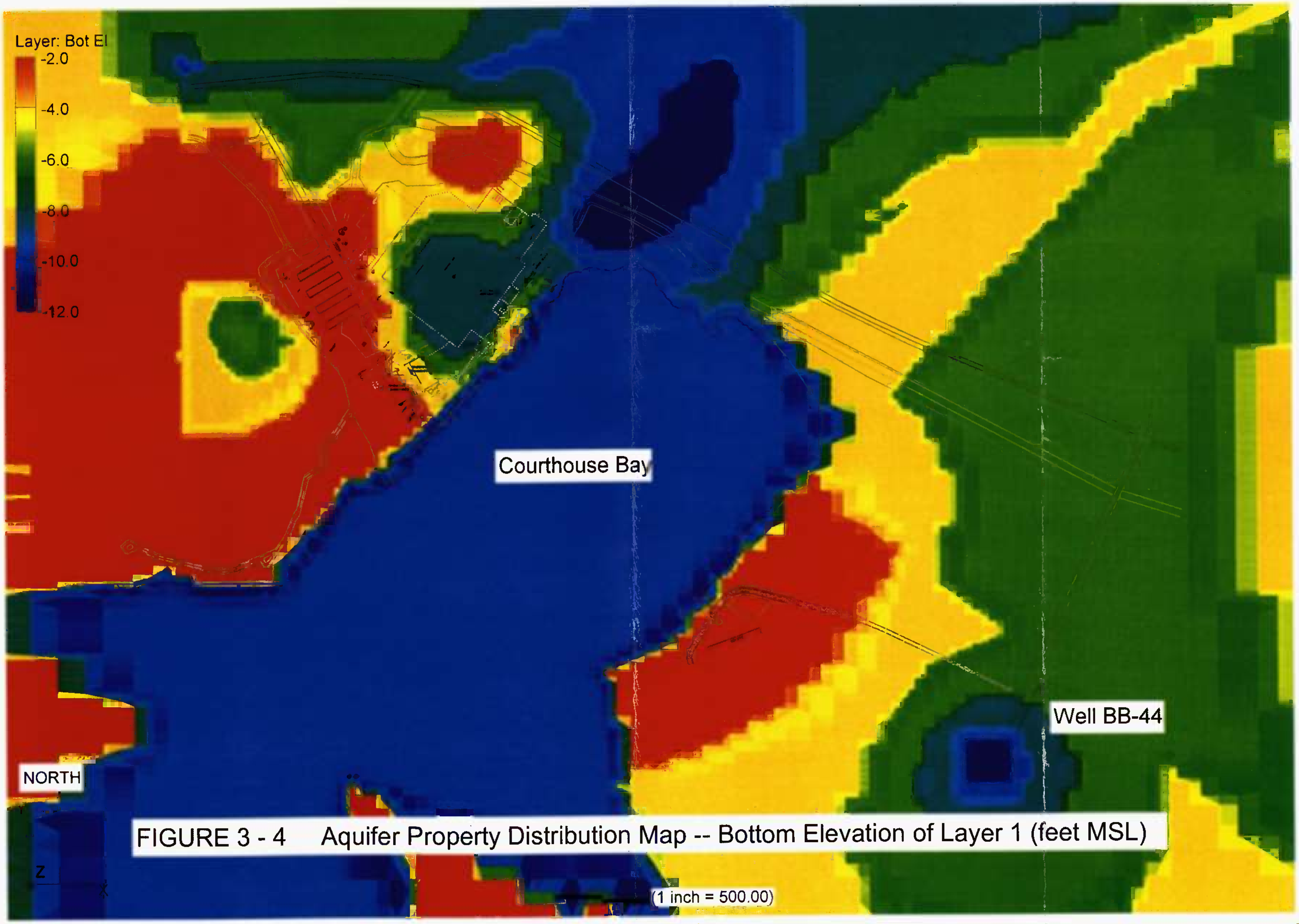


FIGURE 3 - 4 Aquifer Property Distribution Map -- Bottom Elevation of Layer 1 (feet MSL)

02200DDB3Y

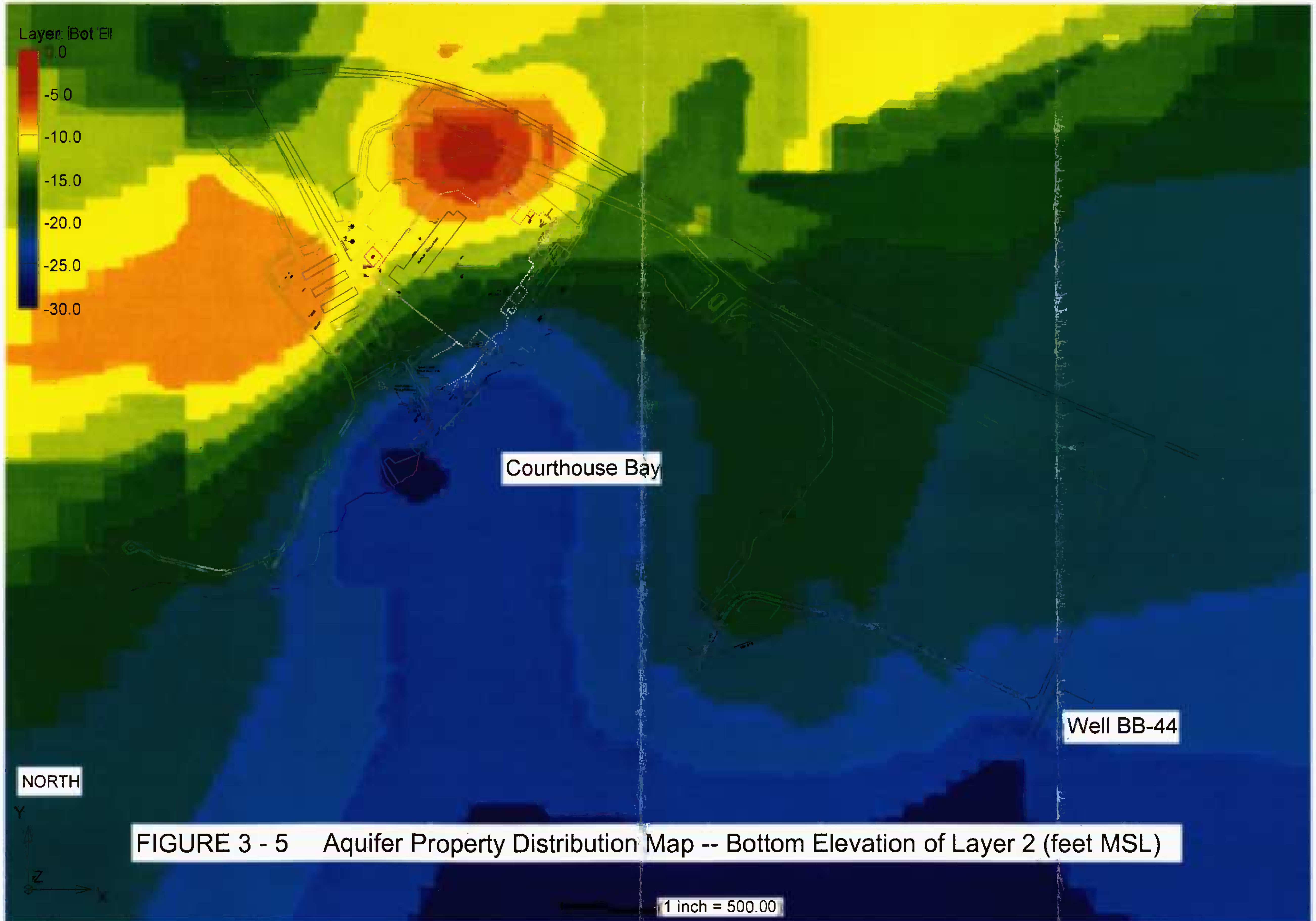
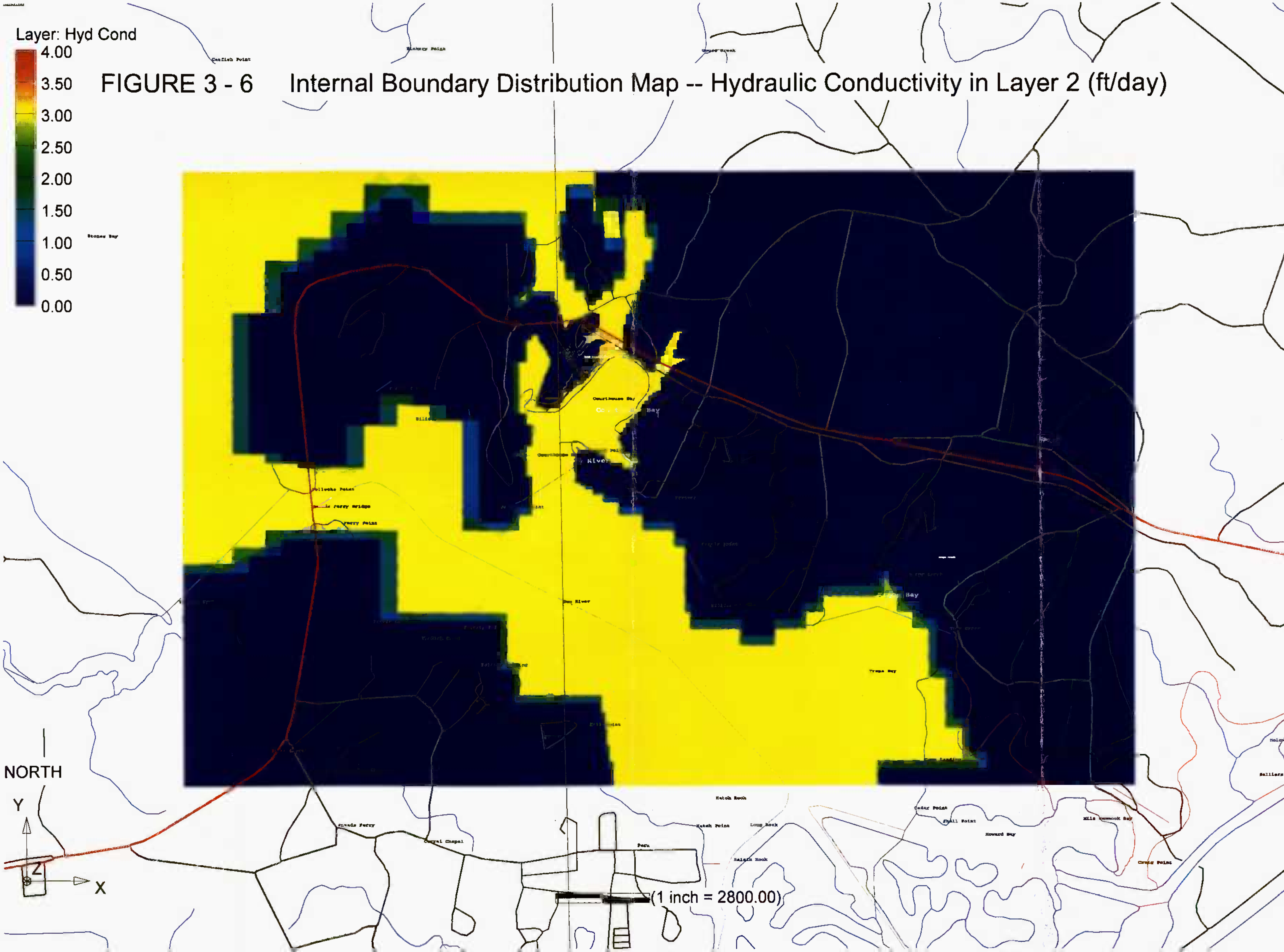
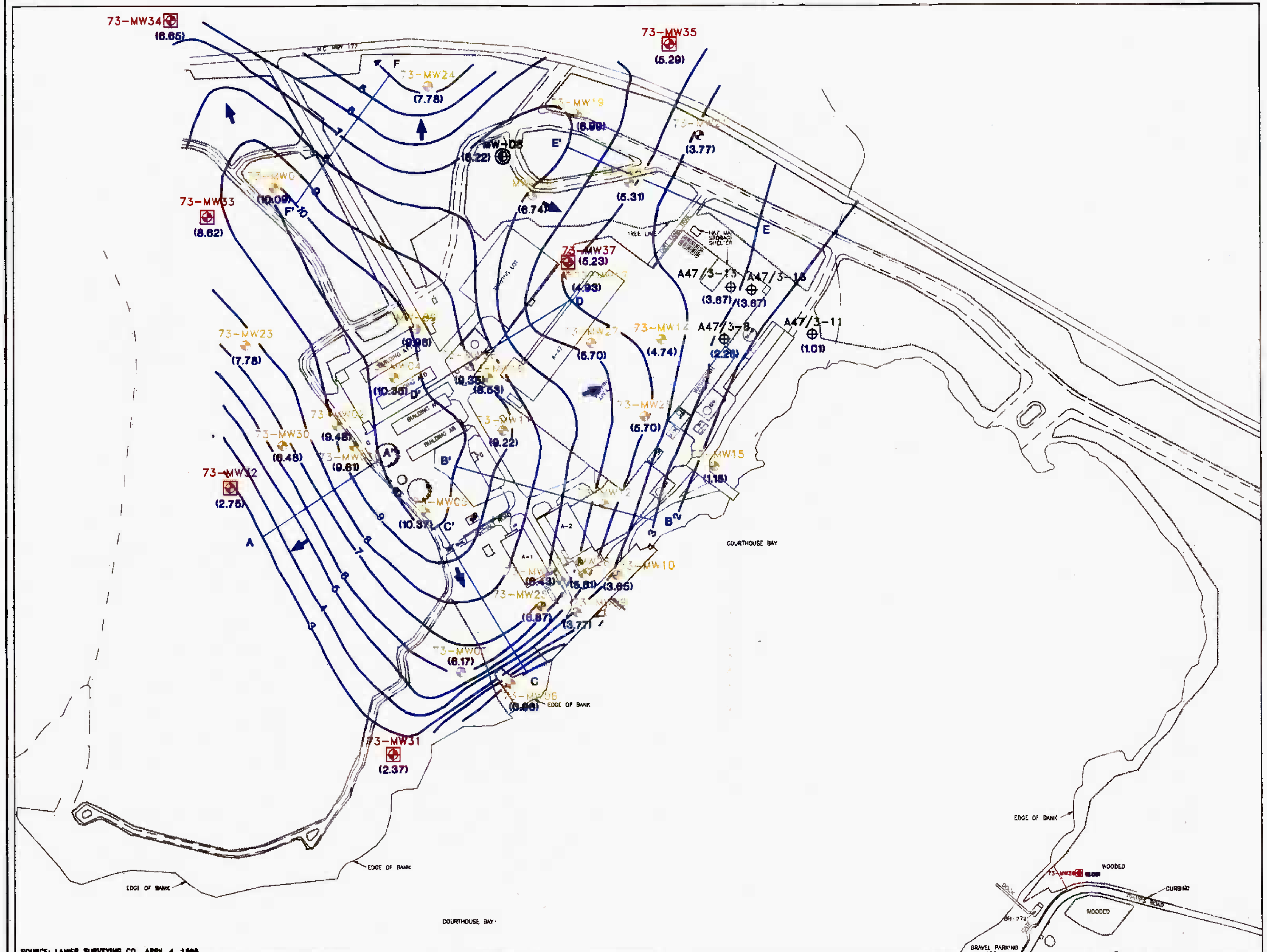


FIGURE 3 - 5 Aquifer Property Distribution Map -- Bottom Elevation of Layer 2 (feet MSL)

FIGURE 3 - 6 Internal Boundary Distribution Map -- Hydraulic Conductivity in Layer 2 (ft/day)





LEGEND

73-MW01	MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE I (APRIL-MAY, 1995)
73-MW31	MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE II (FEBRUARY-MARCH, 1996)
A47/3-8	MONITORING WELLS INSTALLED DURING UST INVESTIGATION BY GSI AND LAW-CATLIN AND ASSOCIATES (1993)
MW-18	MONITORING WELLS INSTALLED BY BAKER DURING UST INVESTIGATION (1992 AND 1993)
MW-D8	MONITORING WELLS INSTALLED DURING A UST INVESTIGATION BY ATEC AND ASSOCIATES (1991)
6.09	GROUNDWATER ELEVATION
	GROUNDWATER CONTOUR LINE
	DIRECTION OF GROUNDWATER FLOW
A'—A	GRADIENT VECTOR

NOTE:
GROUNDWATER LEVELS USED FOR THIS MAP WERE COLLECTED ON MARCH 25, 1996.

GRADIENT CALCULATIONS FOR THE SURFICIAL AQUIFER

A-A' = $\frac{\Delta h}{\Delta L}$ = .018 FT/FT

B-B' = $\frac{\Delta h}{\Delta L}$ = .011 FT/FT

C-C' = $\frac{\Delta h}{\Delta L}$ = .017 FT/FT

D-D' = $\frac{\Delta h}{\Delta L}$ = .010 FT/FT

E-E' = $\frac{\Delta h}{\Delta L}$ = .008 FT/FT

F-F' = $\frac{\Delta h}{\Delta L}$ = .012 FT/FT

REVISIONS		NORTH	SITE 73 – AMPHIBIOUS VEHICLE MAINTENANCE FACILITY		INTERPRETED WATER TABLE CONTOURS (SURFICIAL UNIT)	FIGURE NO.
	DRAWN WJH/REL		GROUNDWATER MODELING REPORT, CTO-0312	Baker		3-7
	REVIEWED JSC		MARINE CORPS BASE, CAMP LEJEUNE	Baker Environmental, Inc.	APPROX. SCALE 1" = 350'	
	S.O.# 62470-312-0000-07000		NORTH CAROLINA		DATE MARCH 1998	
	CADD# 312001GW		BAKER ENVIRONMENTAL, Inc. Coraopolis, Pennsylvania			

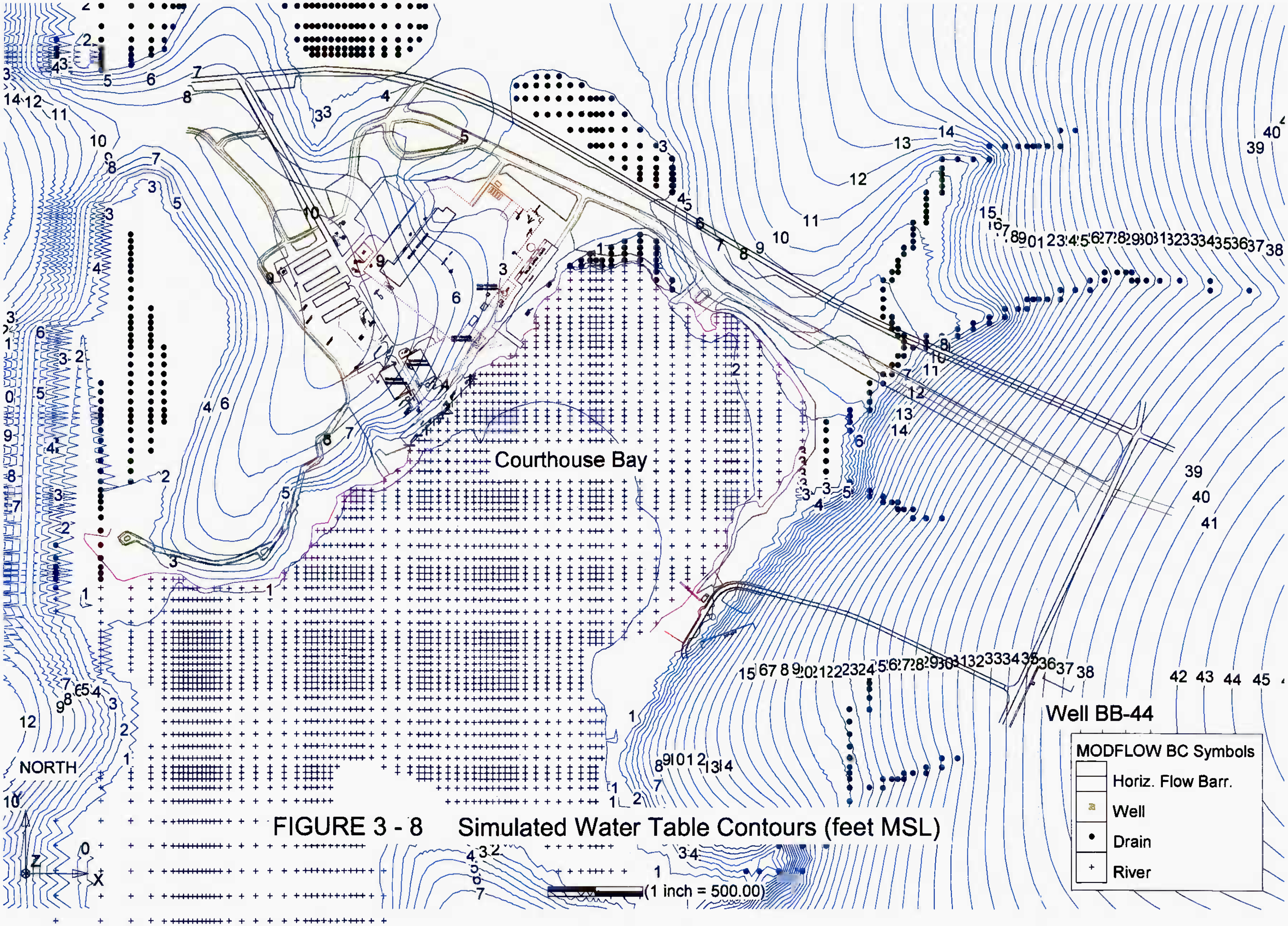


FIGURE 3 - 8 Simulated Water Table Contours (feet MSL)

FIGURE 3-9 Computed vs. Observed Values

Site 73 -- Layer 1 -- Surficial Unit

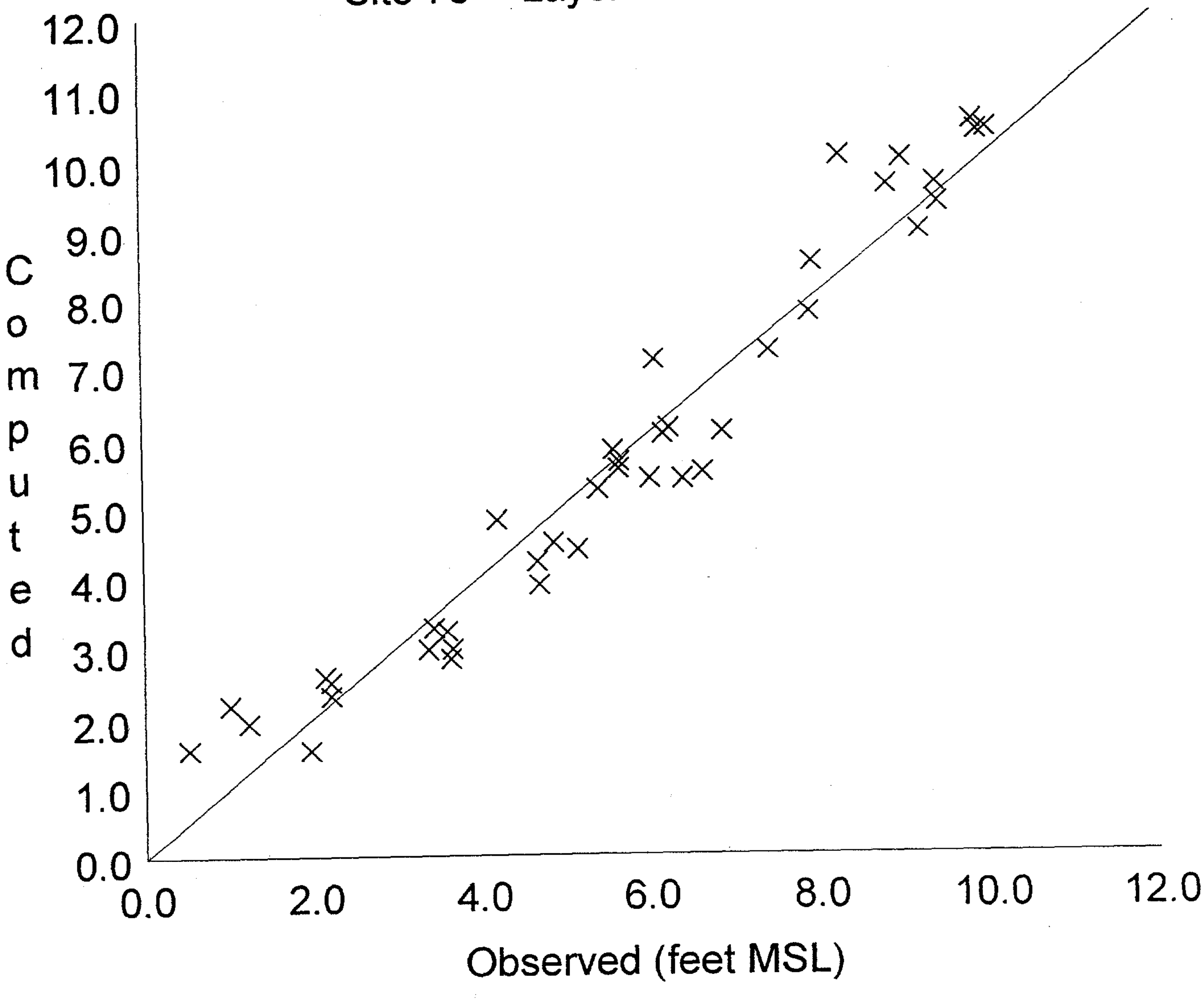
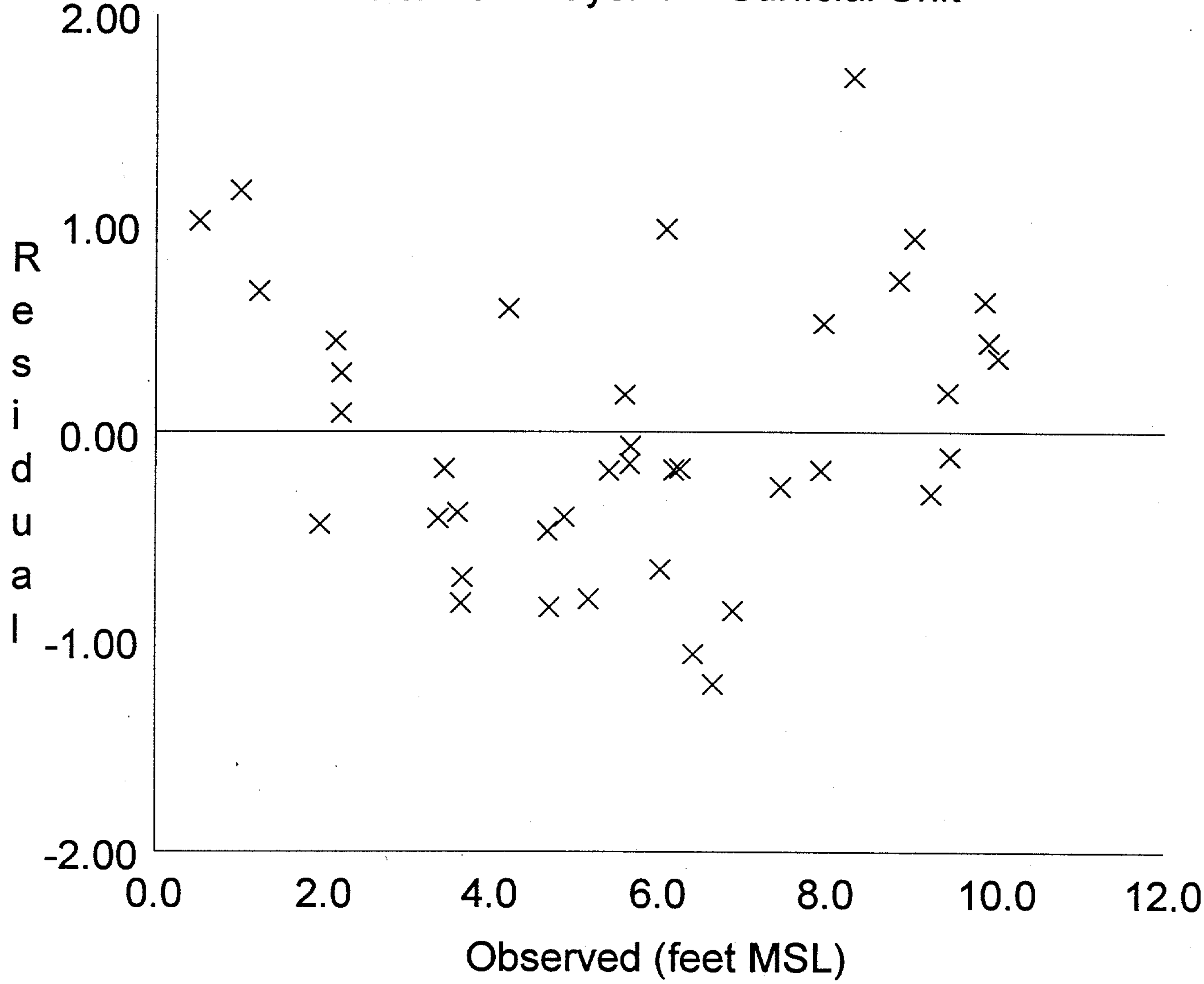


FIGURE 3-10 Residual vs. Observed Values

Site 73 -- Layer 1 -- Surficial Unit



O2200DDB4Y

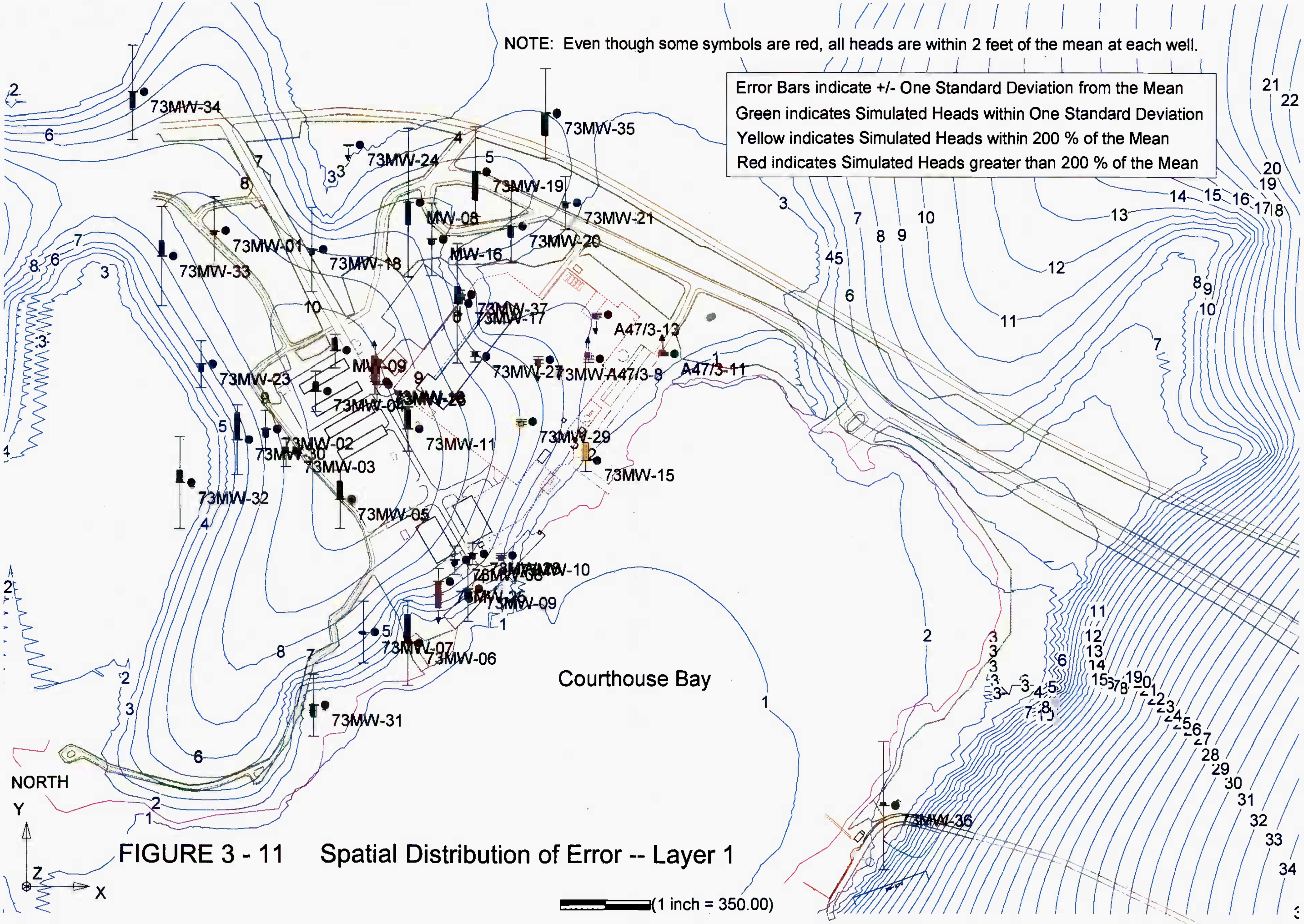
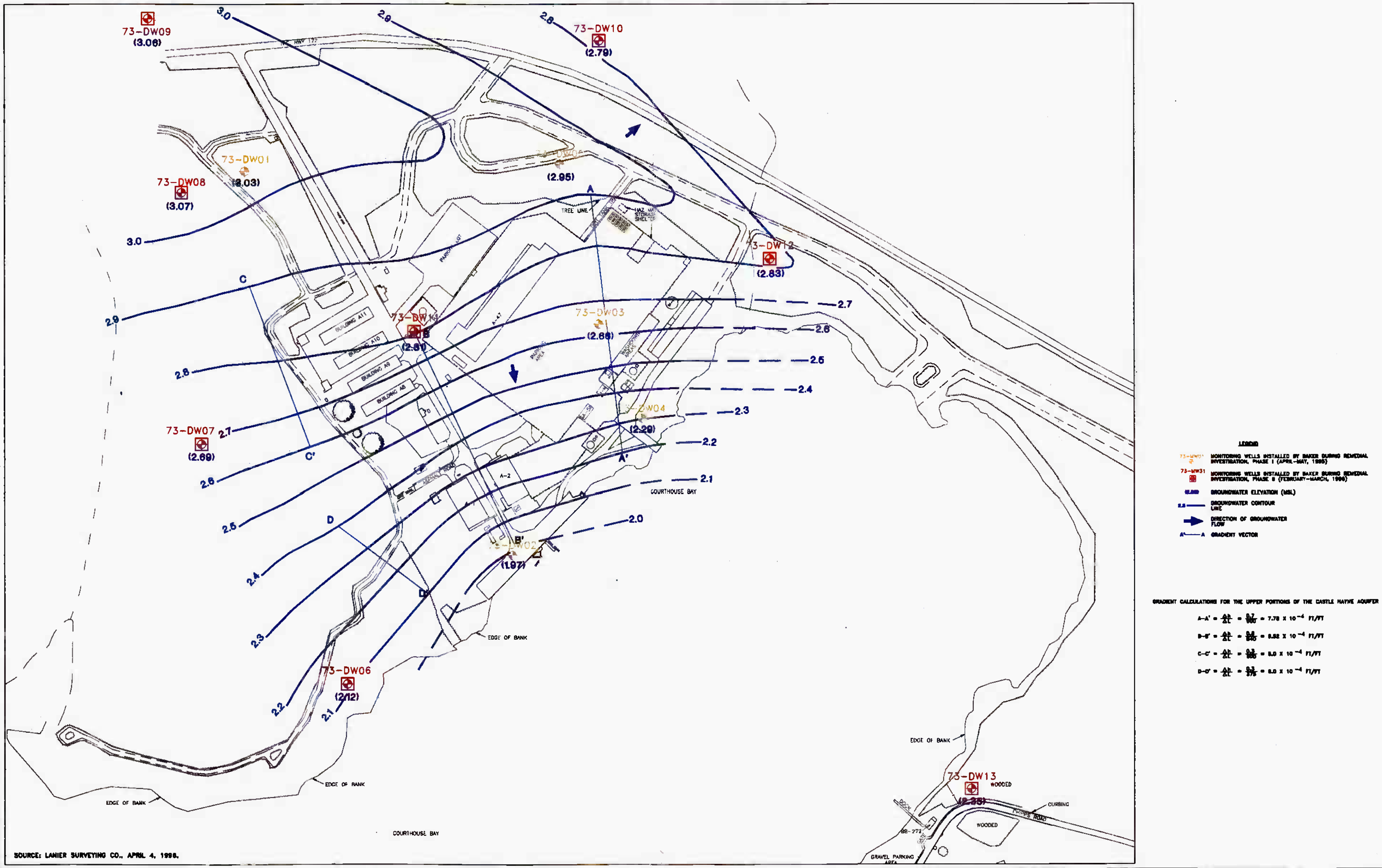


FIGURE 3 - 11 Spatial Distribution of Error -- Layer 1



REVISIONS		NORTH	SITE 73 – AMPHIBIOUS VEHICLE MAINTENANCE FACILITY	INTERPRETED POTENTIOMETRIC CONTOURS (UPPER CASTLE HAYNE AQUIFER)	FIGURE NO.
	DRAWN WJH/REL		GROUNDWATER MODELING REPORT, CTO-0312		3–12
	REVIEWED JSC		MARINE CORPS BASE, CAMP LEJEUNE	APPROX. SCALE 1" = 350'	
	S.O.# 62470-312-0000-07000		NORTH CAROLINA	DATE MARCH 1998	
	CADD# 3120020W		BAKER ENVIRONMENTAL, Inc. Coraopolis, Pennsylvania		

Baker
Baker Environmental, Inc.

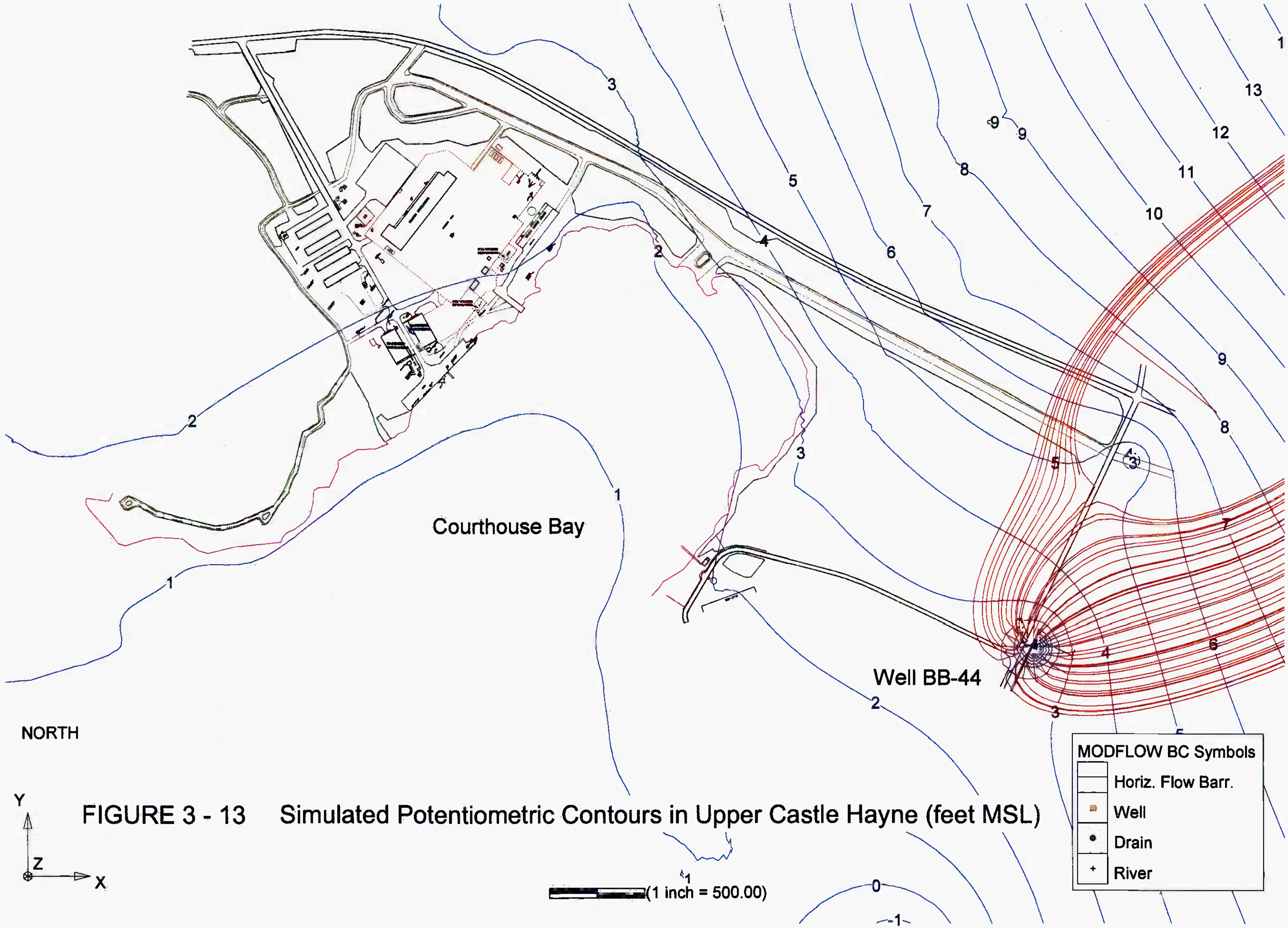


FIGURE 3 - 13 Simulated Potentiometric Contours in Upper Castle Hayne (feet MSL)

FIGURE 3 - 14 Computed vs. Observed Values

Site 73 -- Layer 3 -- Upper Castle Hayne

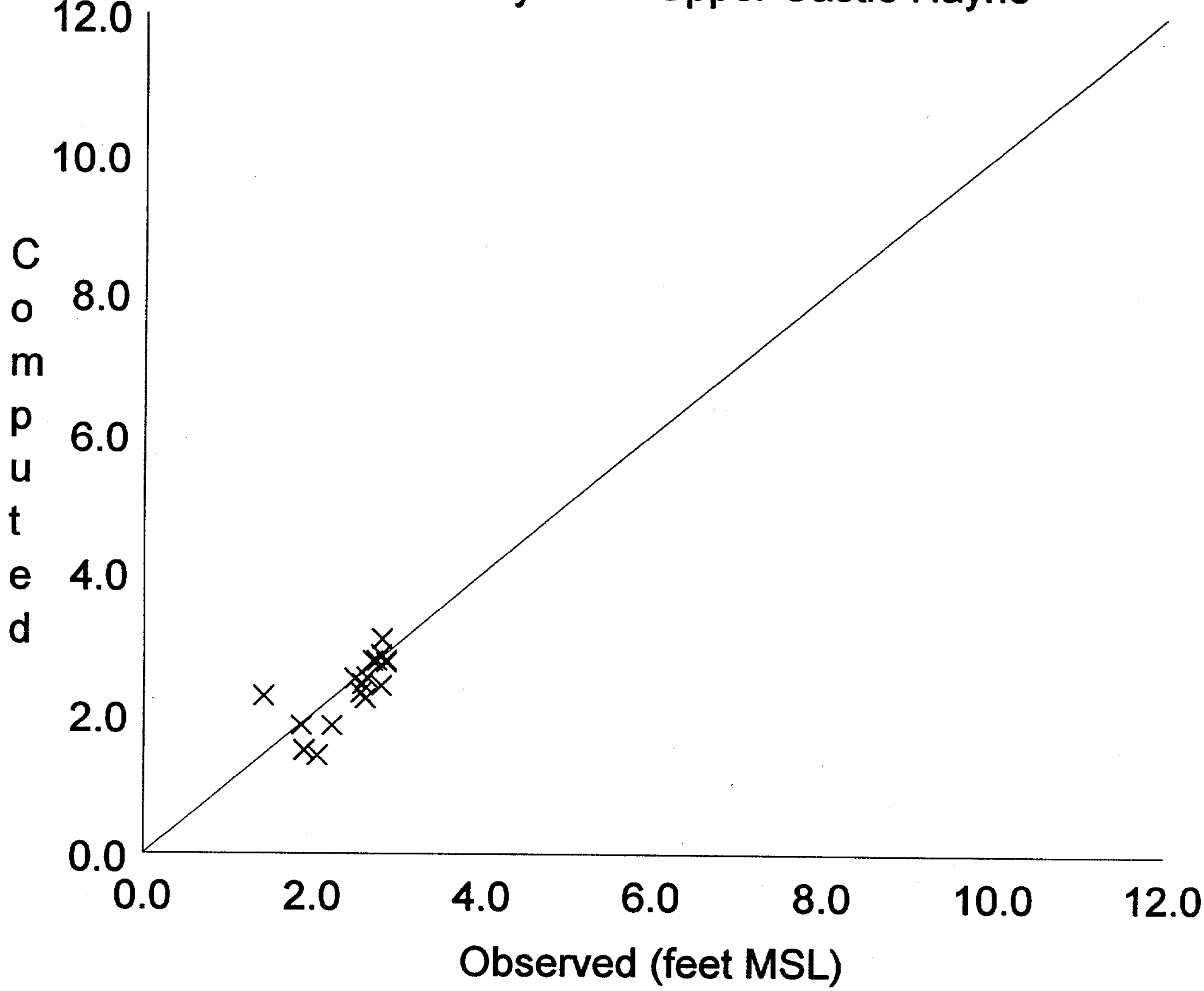
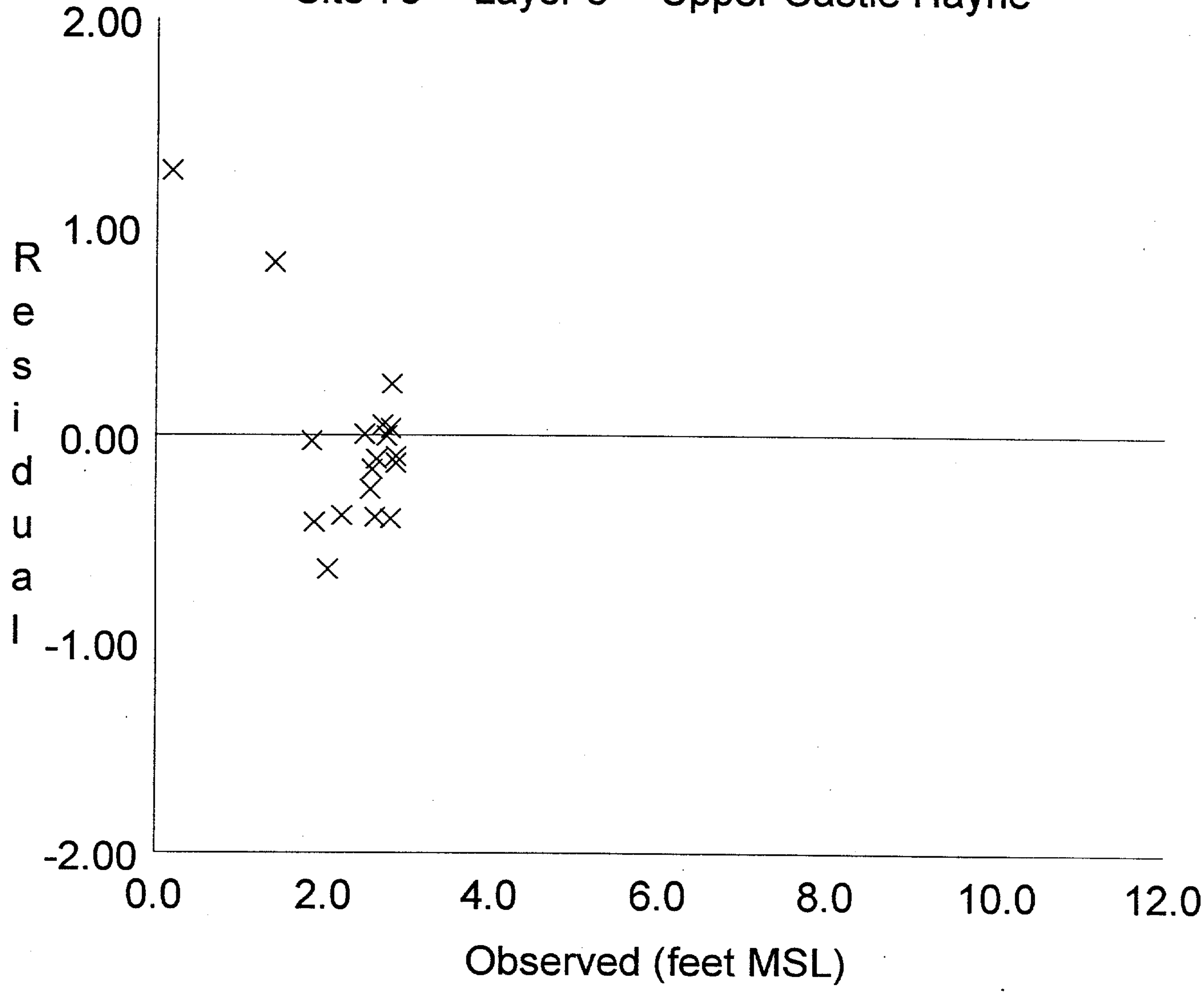


FIGURE 3-15 Residual vs. Observed Values

Site 73 -- Layer 3 -- Upper Castle Hayne



02200DDB5Y

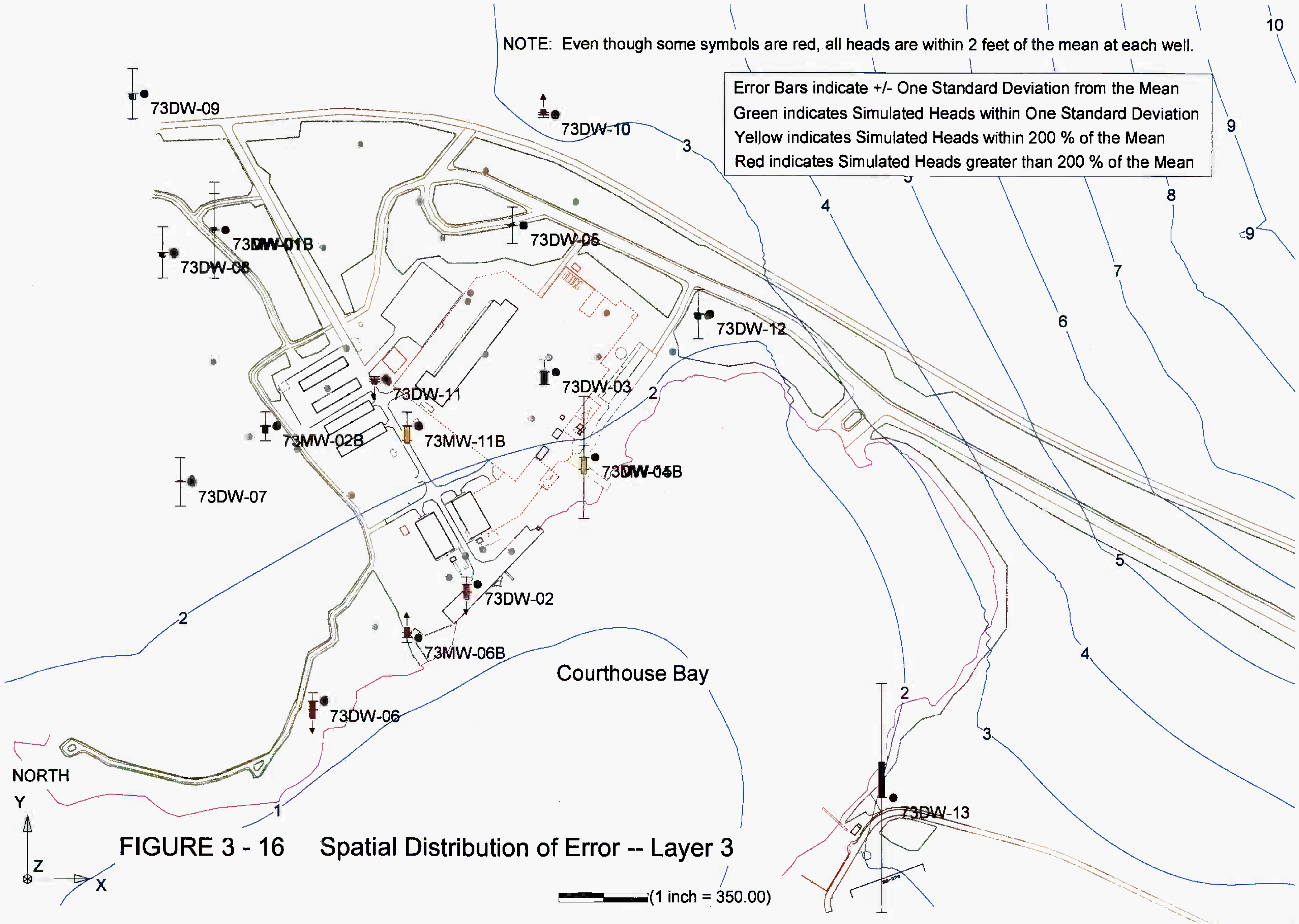
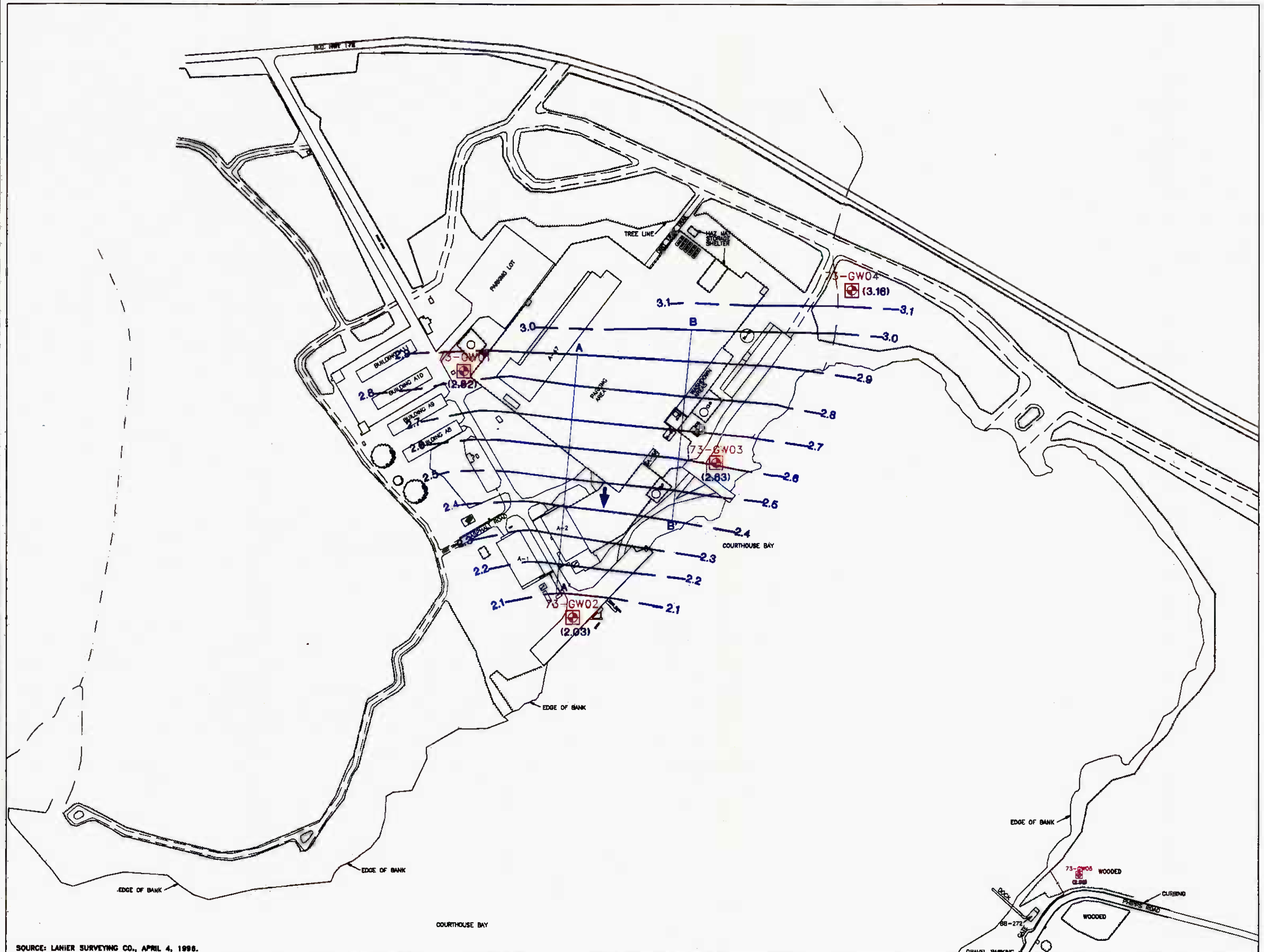


FIGURE 3 - 16 Spatial Distribution of Error -- Layer 3



SOURCE: LANIER SURVEYING CO., APRIL 4, 1996.

LEGEND

73-MW31 MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE II (FEBRUARY-MARCH, 1998)

GROUNDWATER ELEVATION

2.8 GROUNDWATER CONTOUR LINE

DIRECTION OF GROUNDWATER FLOW

A'—A GRADIENT VECTOR

NOTE:
GROUNDWATER LEVELS USED FOR THIS MAP WERE COLLECTED ON MARCH 25, 1998.

GRADIENT CALCULATIONS FOR THE MIDDLE TO LOWER PORTION OF THE CASTLE HAYNE AQUIFER

$$A\text{-}A' = \frac{\Delta h}{\Delta L} = \frac{0.8}{765} = 1.05 \times 10^{-3}$$

$$B\text{-}B' = \frac{\Delta h}{\Delta L} = \frac{0.8}{800} = 1.0 \times 10^{-3}$$

REVISIONS		NORTH	SITE 73 – AMPHIBIOUS VEHICLE MAINTENANCE FACILITY GROUNDWATER MODELING REPORT, CTO-0312 MARINE CORPS BASE, CAMP LEJEUNE NORTH CAROLINA	Baker Baker Environmental, Inc.	INTERPRETED POTENTIOMETRIC CONTOURS (LOWER CASTLE HAYNE AQUIFER)	FIGURE NO.
	DRAWN WJH/REL REVIEWED JSC S.O.# 62470-312-0000-07000 CADD# 312003GW		BAKER ENVIRONMENTAL, Inc. Coraopolis, Pennsylvania		APPROX. SCALE 1" = 350' DATE MARCH 1998	3-17

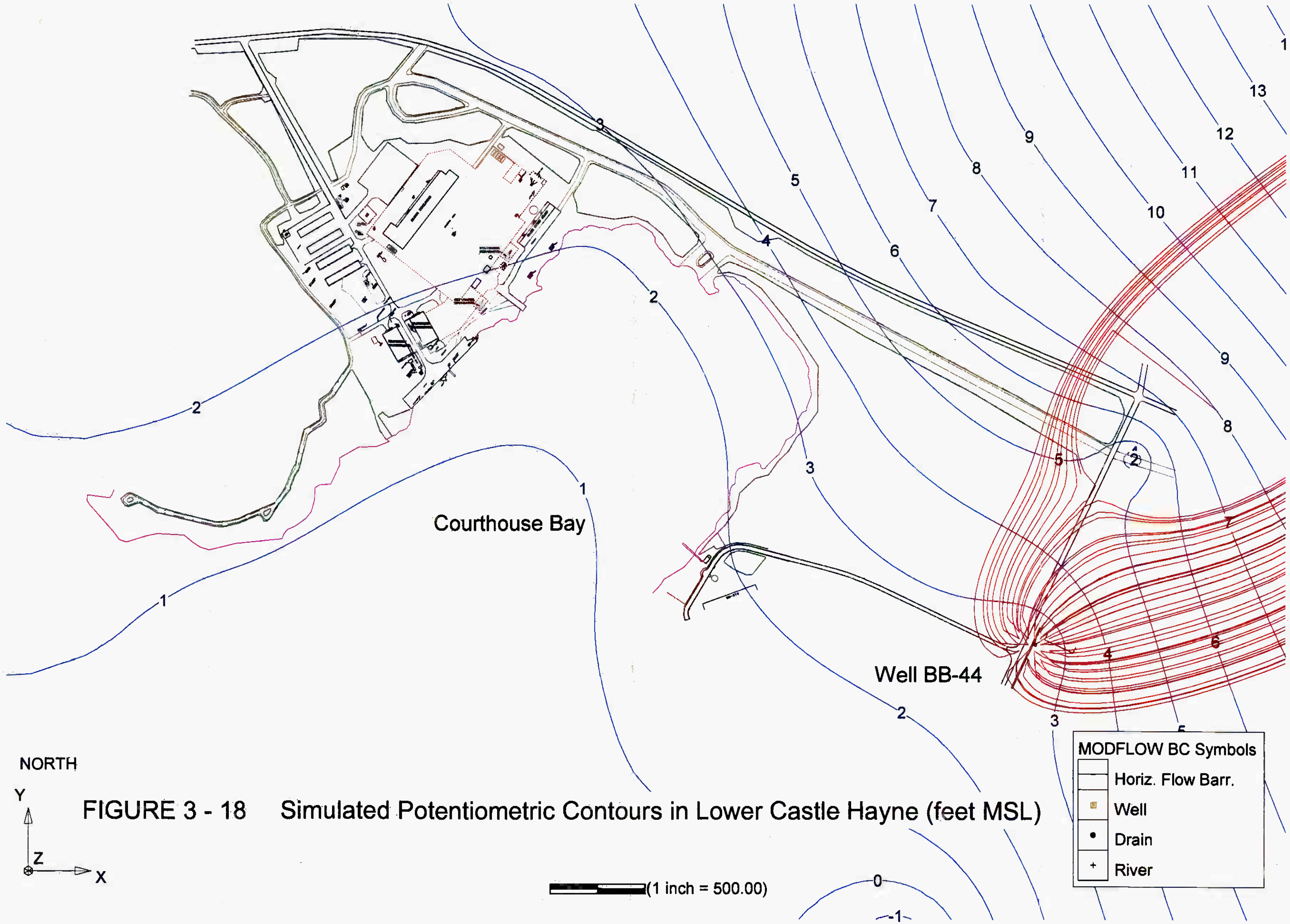


FIGURE 3 - 18 Simulated Potentiometric Contours in Lower Castle Hayne (feet MSL)

FIGURE 3-19 Computed vs. Observed Values

Site 73 -- Layer 4 -- Lower Castle Hayne

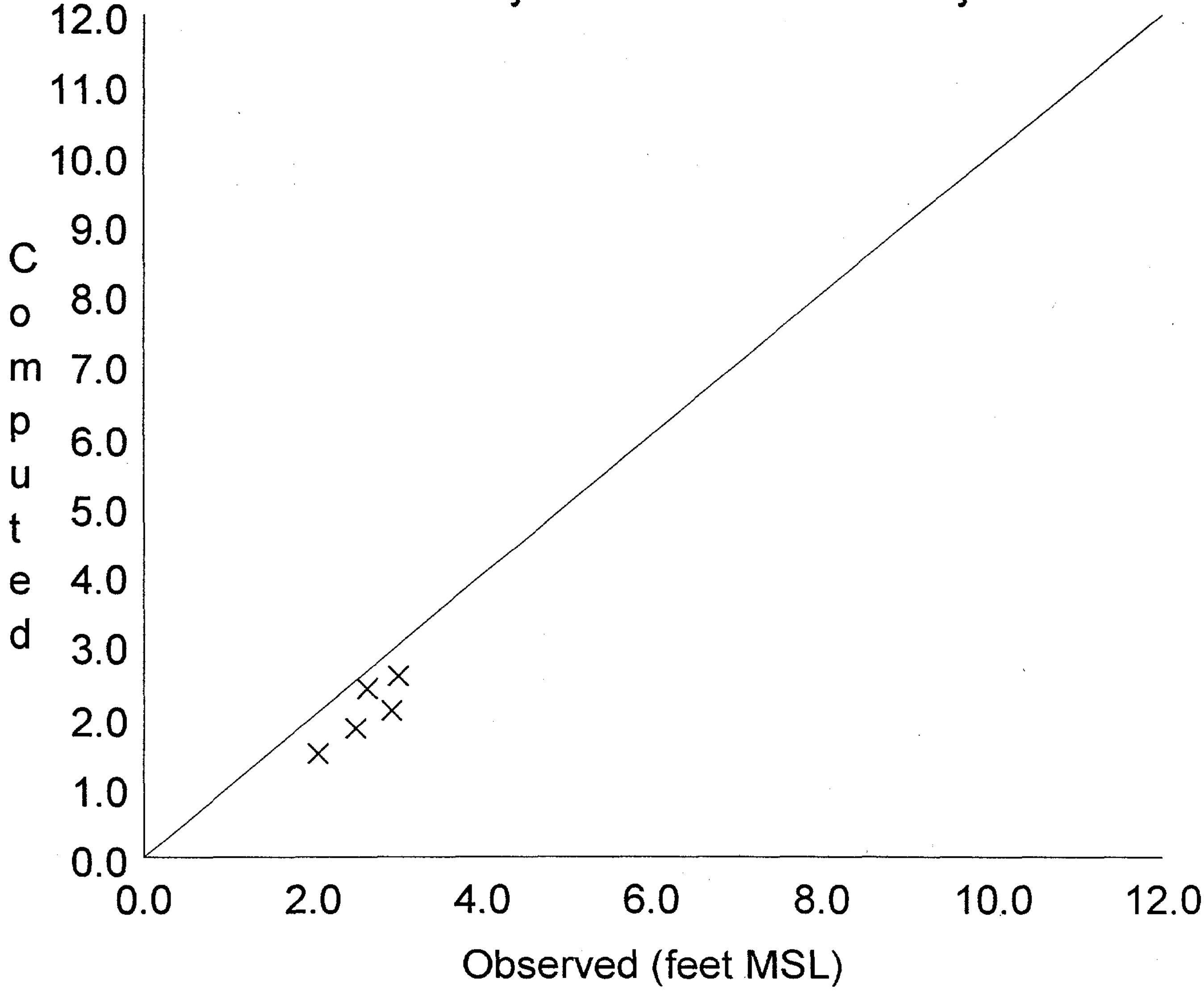
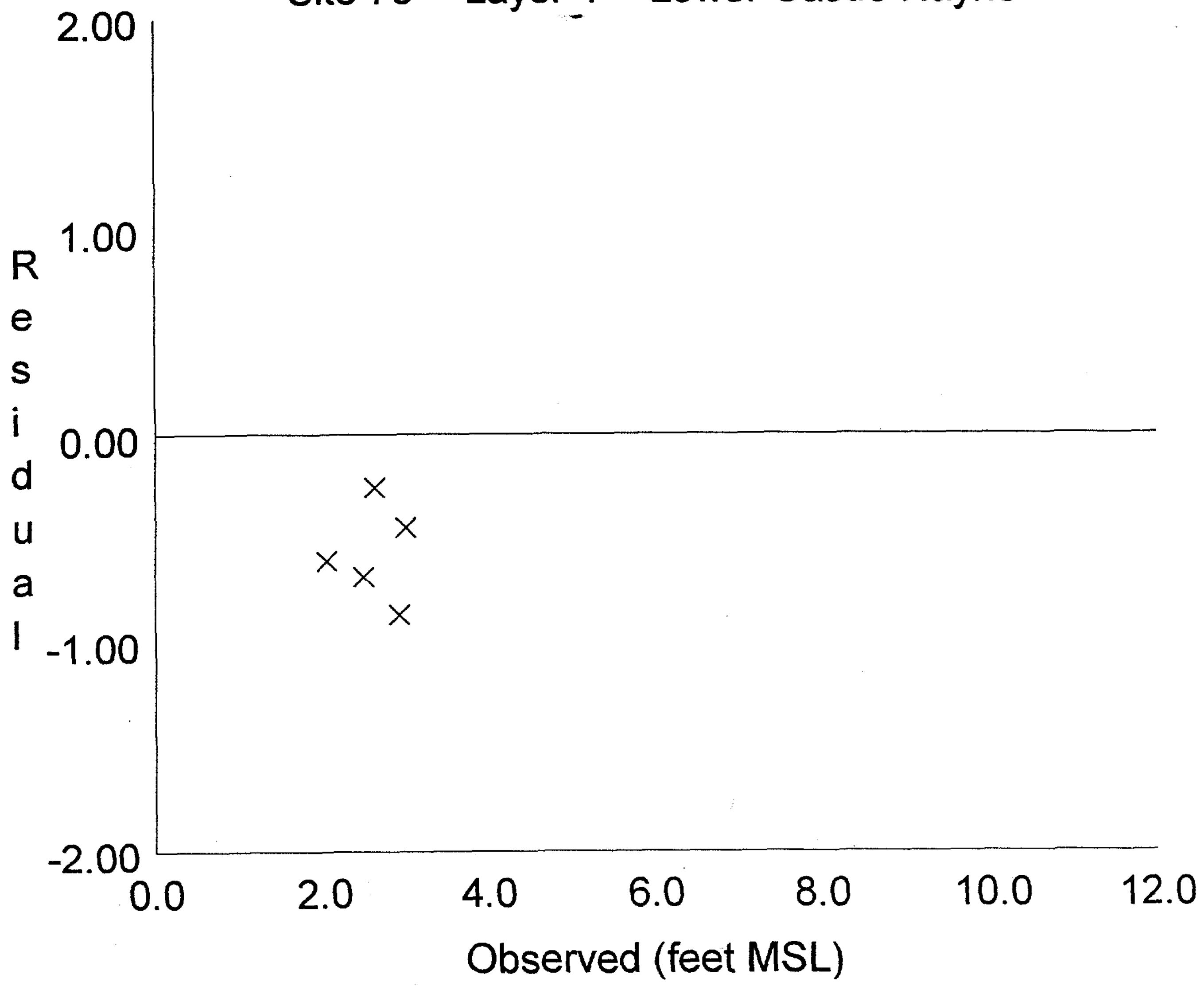


FIGURE 3-20 Residual vs. Observed Values

Site 73 -- Layer 4 -- Lower Castle Hayne



02200DD01Y

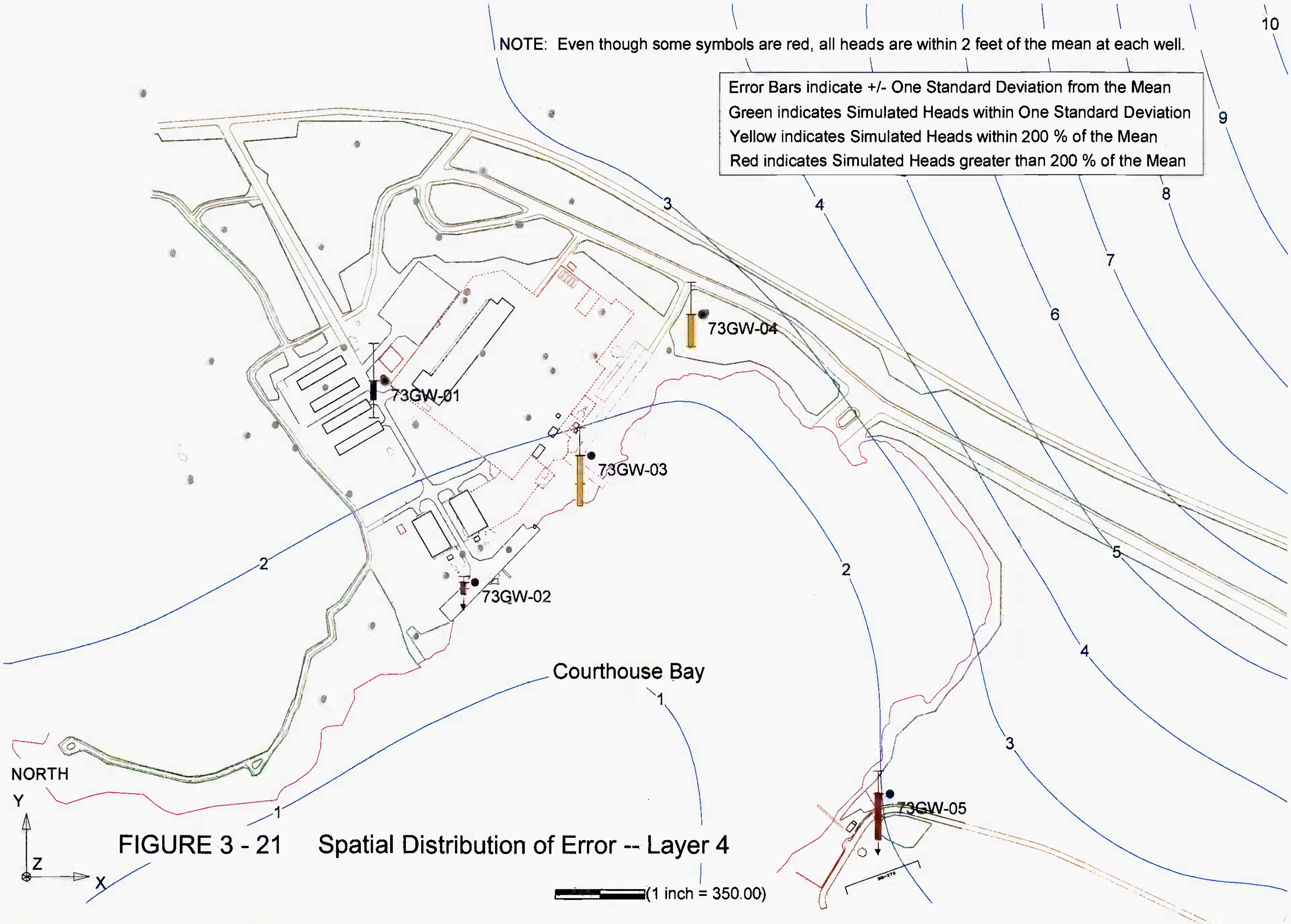


FIGURE 3 - 21 Spatial Distribution of Error -- Layer 4

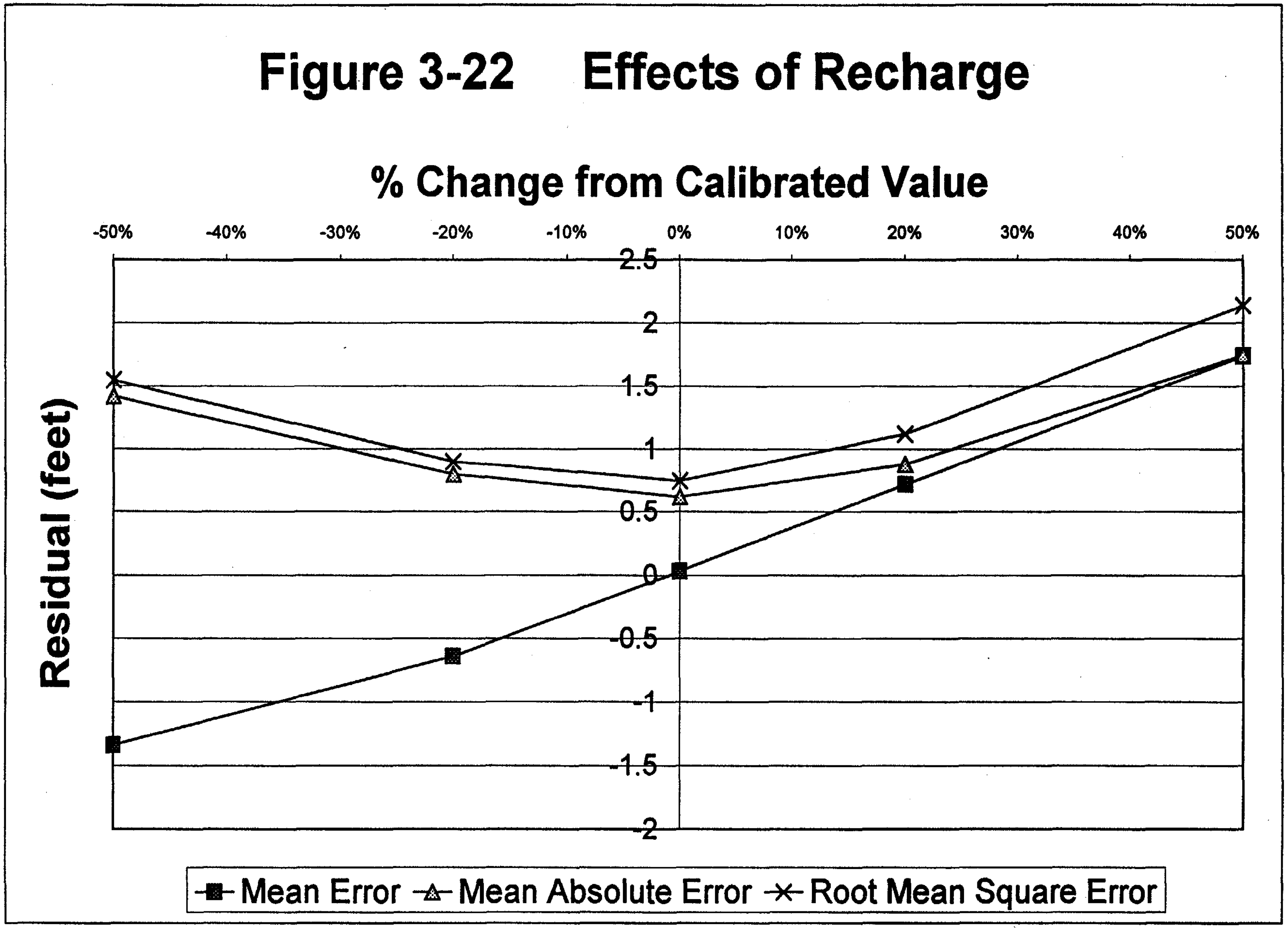
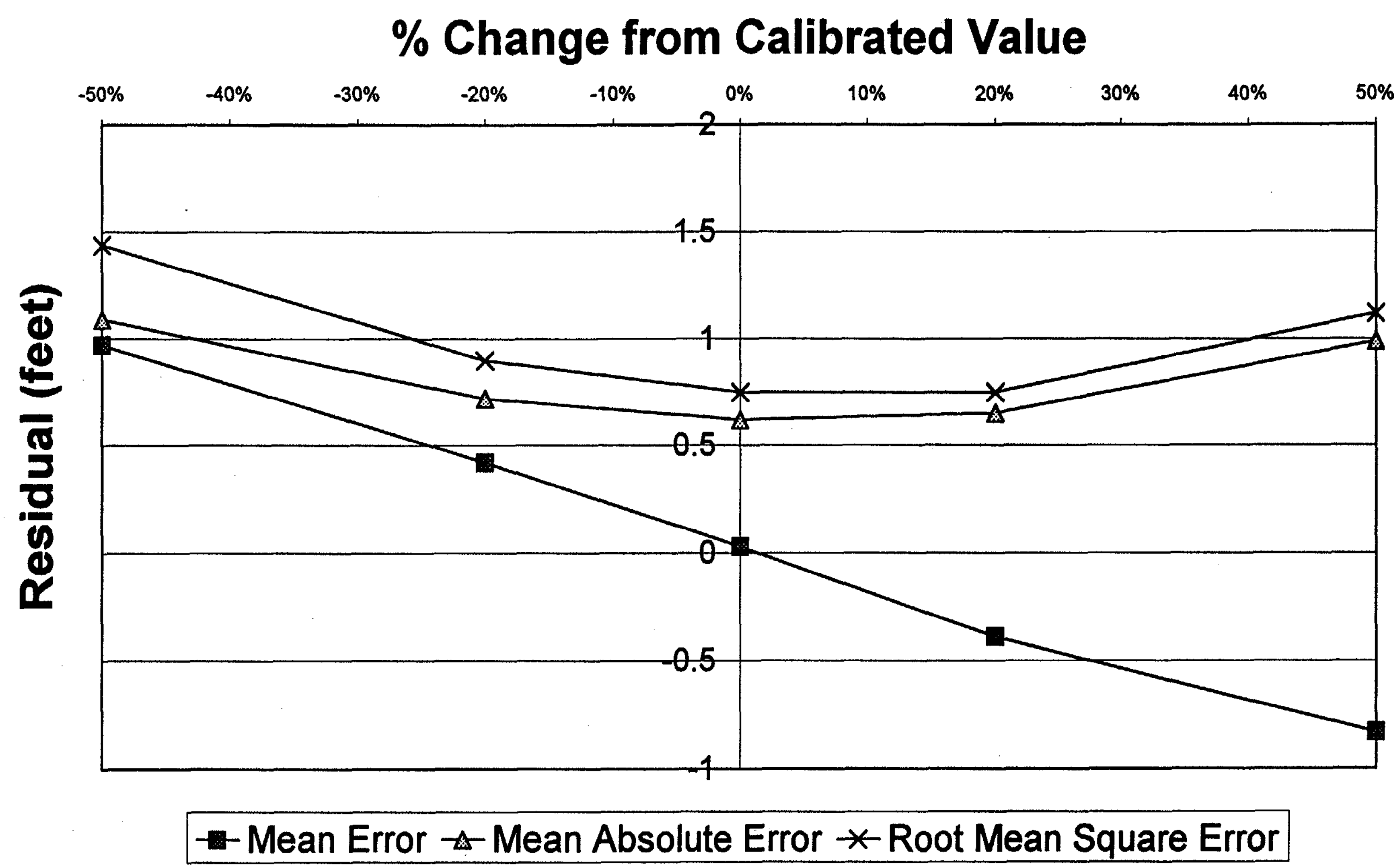


Figure 3-22 Effects of Recharge
% Change from Calibrated Value
-50%
-40%
-30%
-20%
-10%
0%
10%
20%
30%
40%
50%
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Residual (feet)
Mean Error
Mean Absolute Error
Root Mean Square Error

Figure 3-23 Effects of Horizontal K



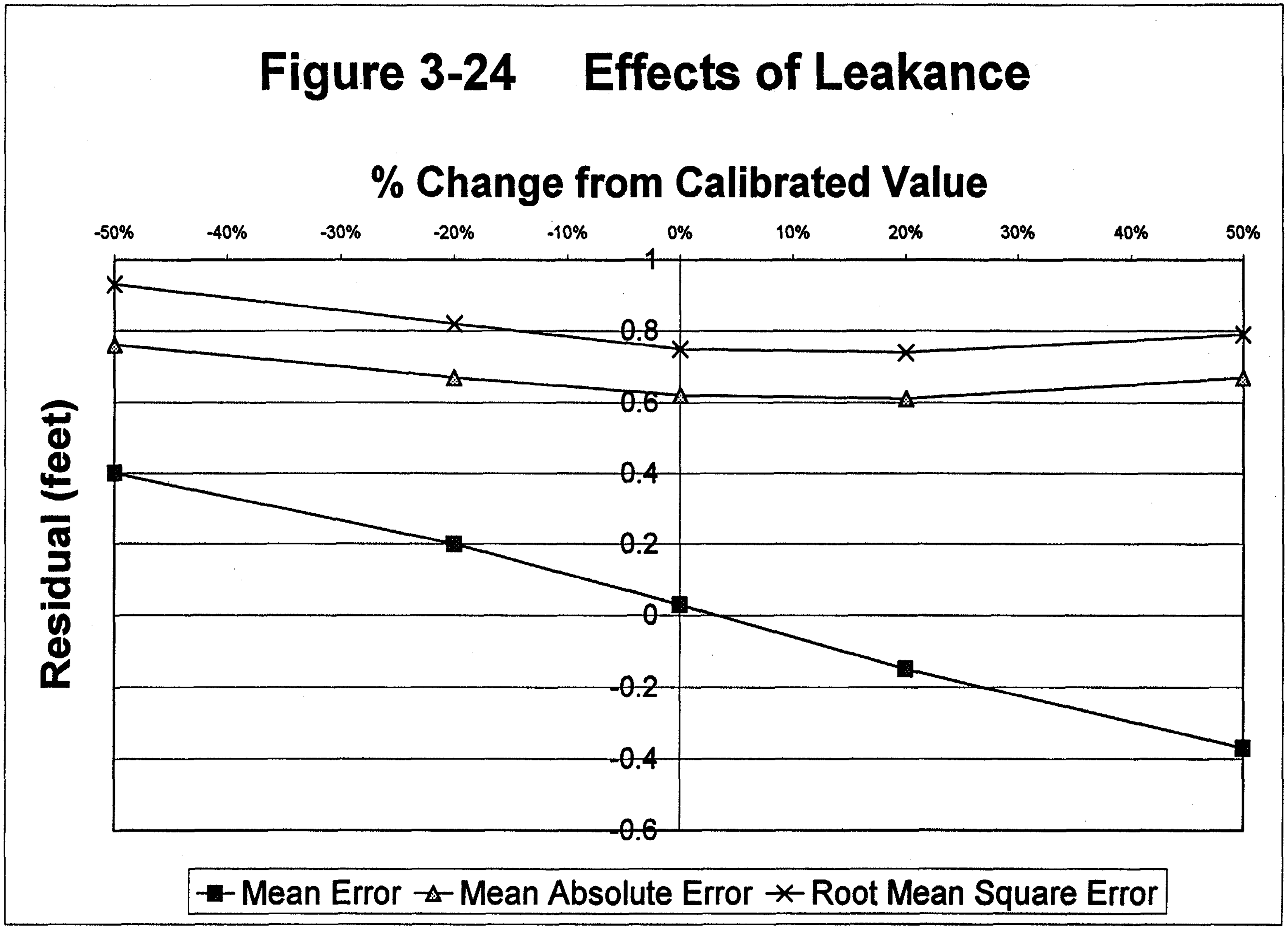


Figure 3-24 Effects of Leakance
% Change from Calibrated Value
-50%
-40%
-30%
-20%
-10%
0%
10%
20%
30%
40%
50%
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Residual (feet)
Mean Error
Mean Absolute Error
Root Mean Square Error

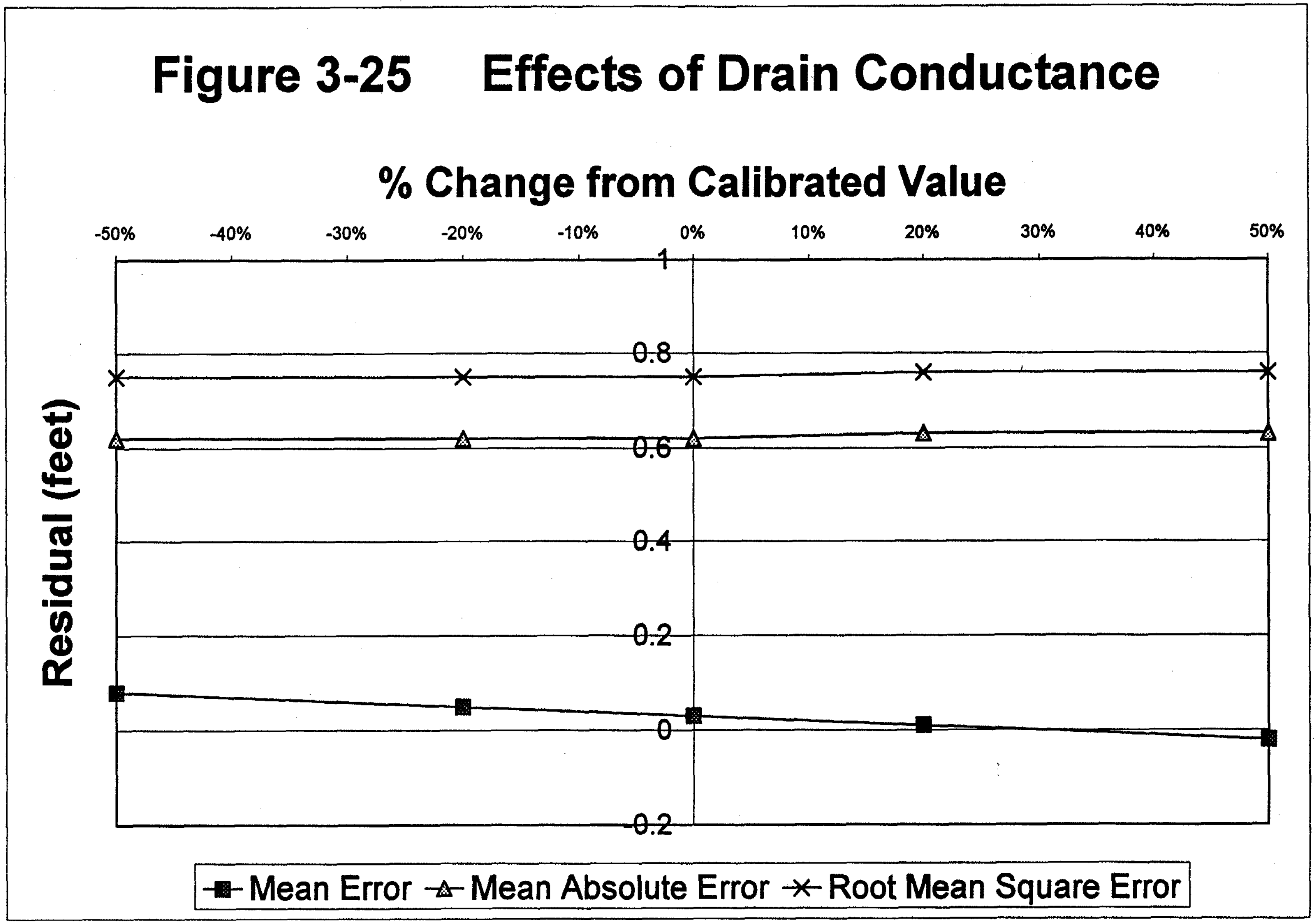


Figure 3-25 Effects of Drain Conductance
% Change from Calibrated Value
-50%
-40%
-30%
-20%
-10%
0%
10%
20%
30%
40%
50%
1
0.8
0.6
0.4
0.2
0
-0.2
Residual (feet)
Mean Error
Mean Absolute Error
Root Mean Square Error

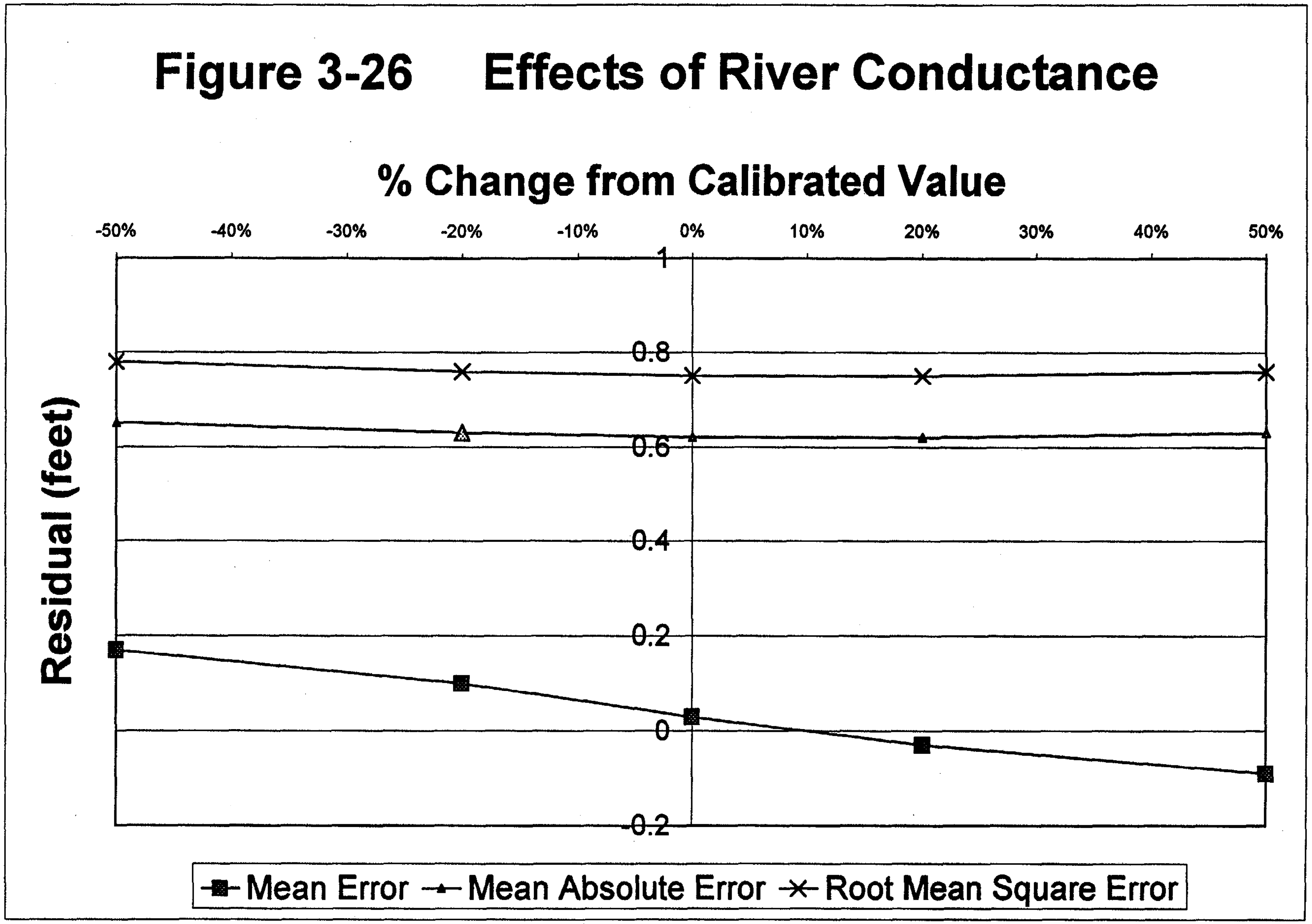
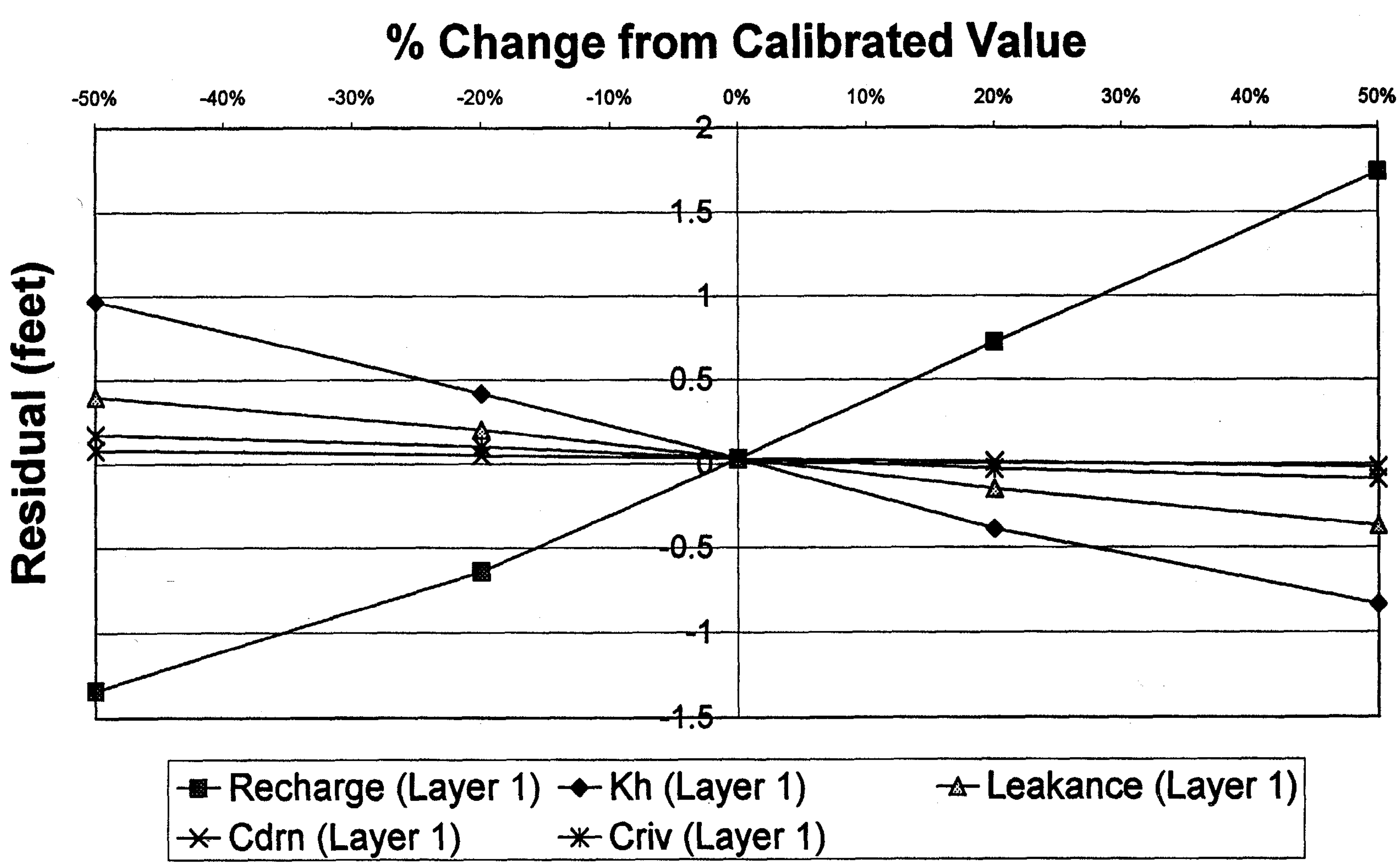


Figure 3-26 Effects of River Conductance
% Change from Calibrated Value
-50%
-40%
-30%
-20%
-10%
0%
10%
20%
30%
40%
50%
1
0.8
0.6
0.4
0.2
0
-0.2
Residual (feet)
Mean Error
Mean Absolute Error
Root Mean Square Error

Figure 3-27 Comparison of RM Values



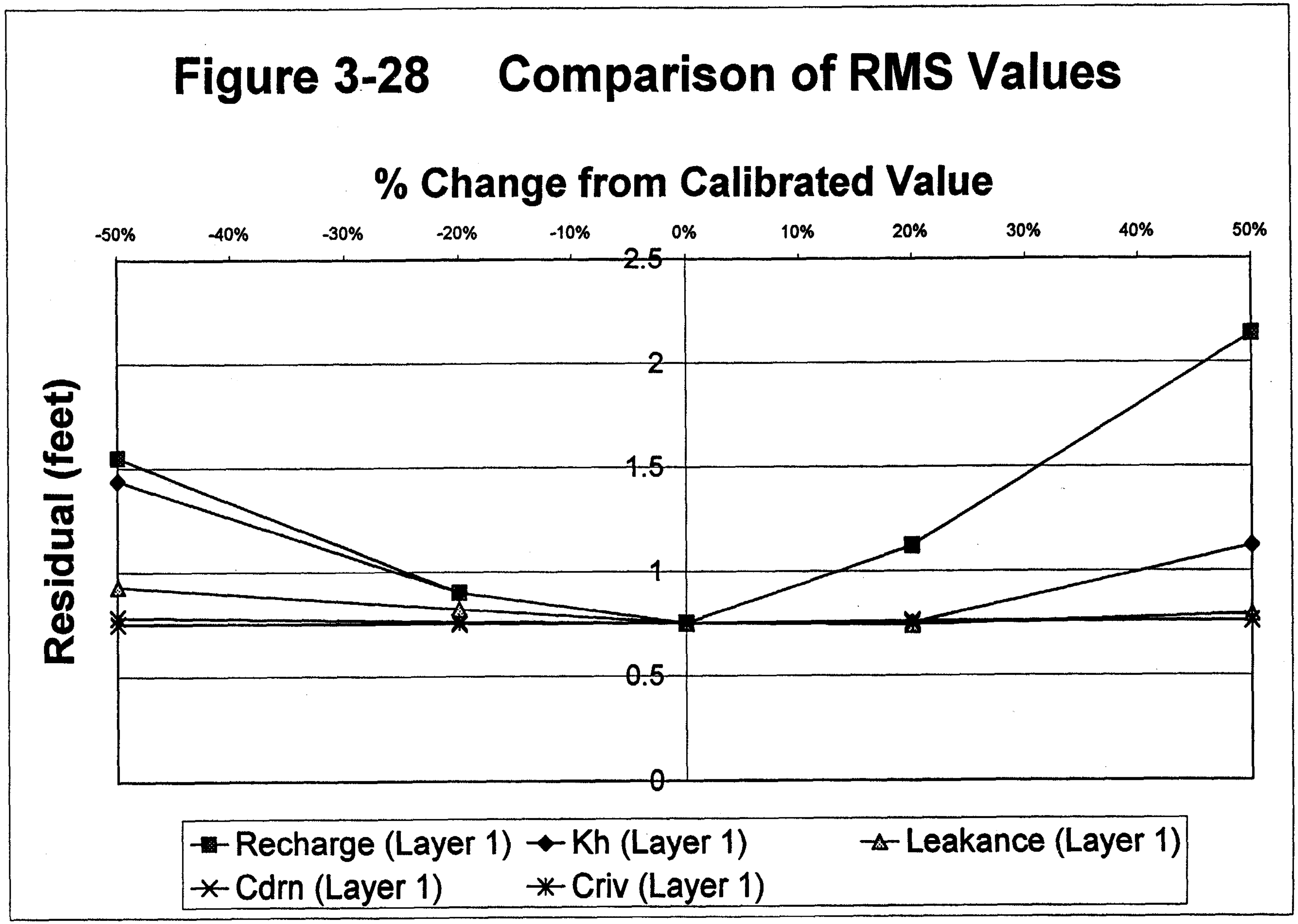


Figure 3-28 Comparison of RMS Values
% Change from Calibrated Value
-50%
-40%
-30%
-20%
-10%
0%
10%
20%
30%
40%
50%
2.5
2
1.5
1
0.5
0
Residual (feet)
Recharge (Layer 1)
Kh (Layer 1)
Leakance (Layer 1)
Cdrn (Layer 1)
Criv (Layer 1)

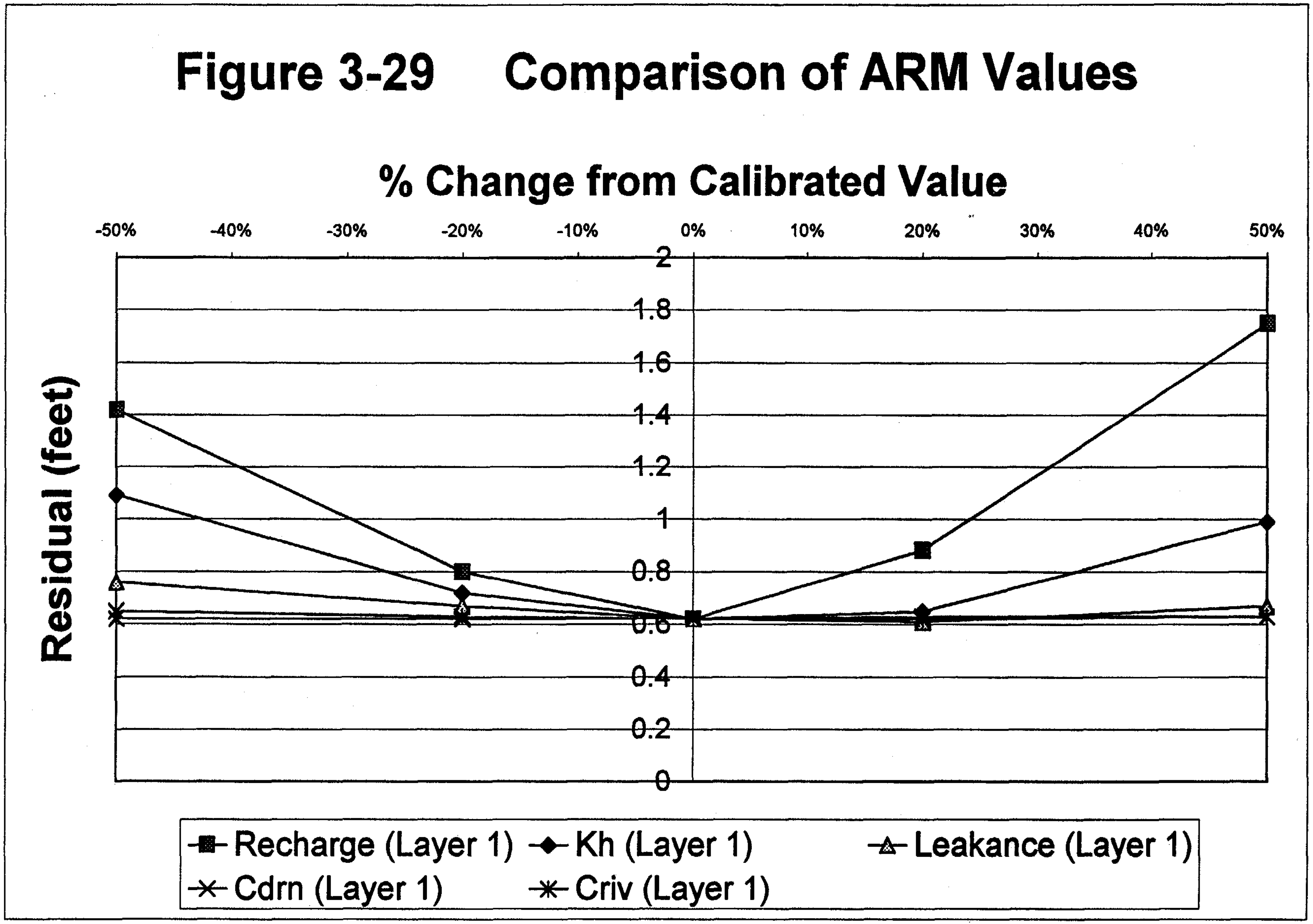


Figure 3-29 Comparison of ARM Values
% Change from Calibrated Value
-50%
-40%
-30%
-20%
-10%
0%
10%
20%
30%
40%
50%
Residual (feet)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Recharge (Layer 1)
Kh (Layer 1)
Leakance (Layer 1)
Cdrn (Layer 1)
Criv (Layer 1)

02200DDB6Y

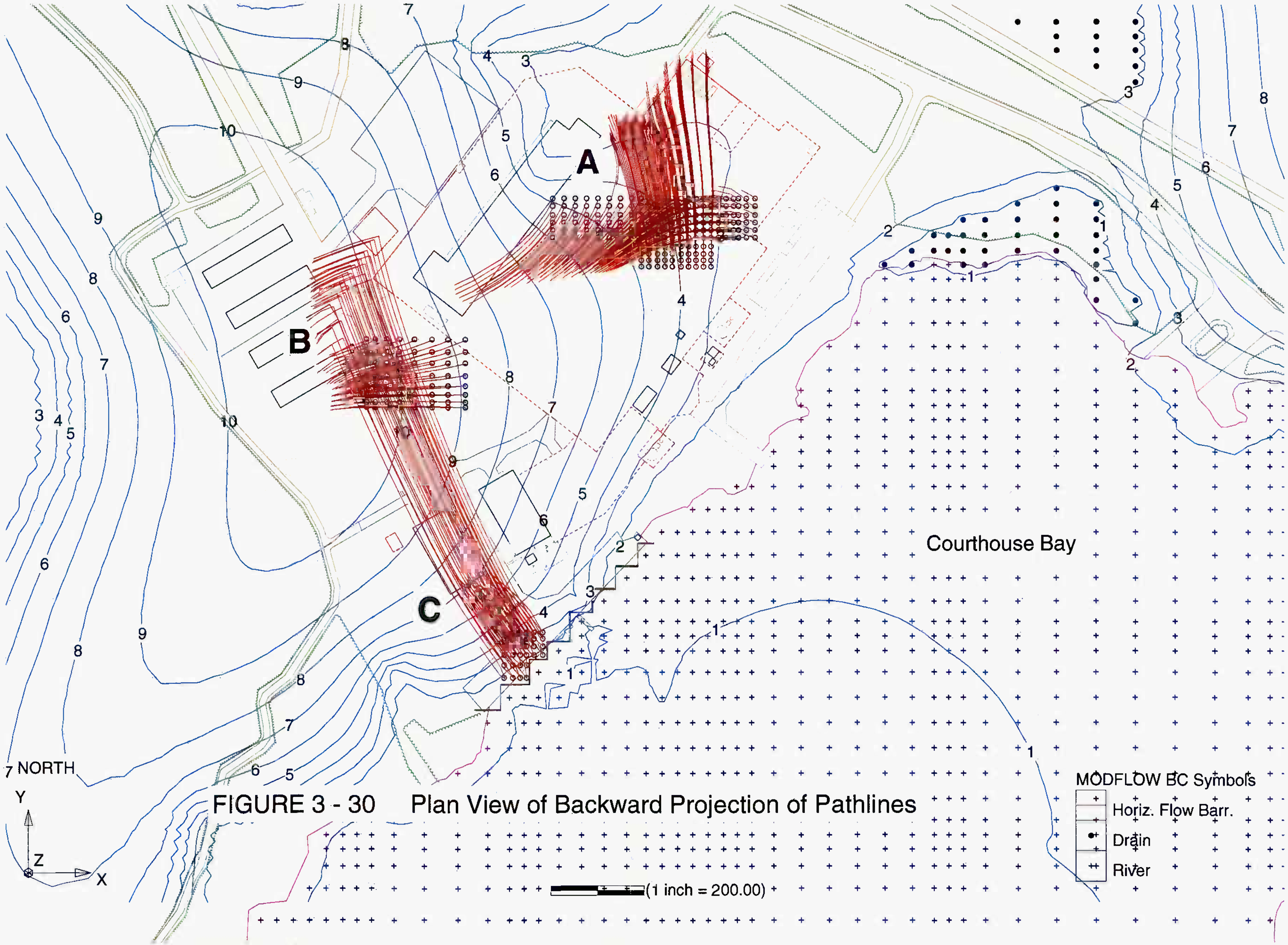


FIGURE 3 - 30 Plan View of Backward Projection of Pathlines

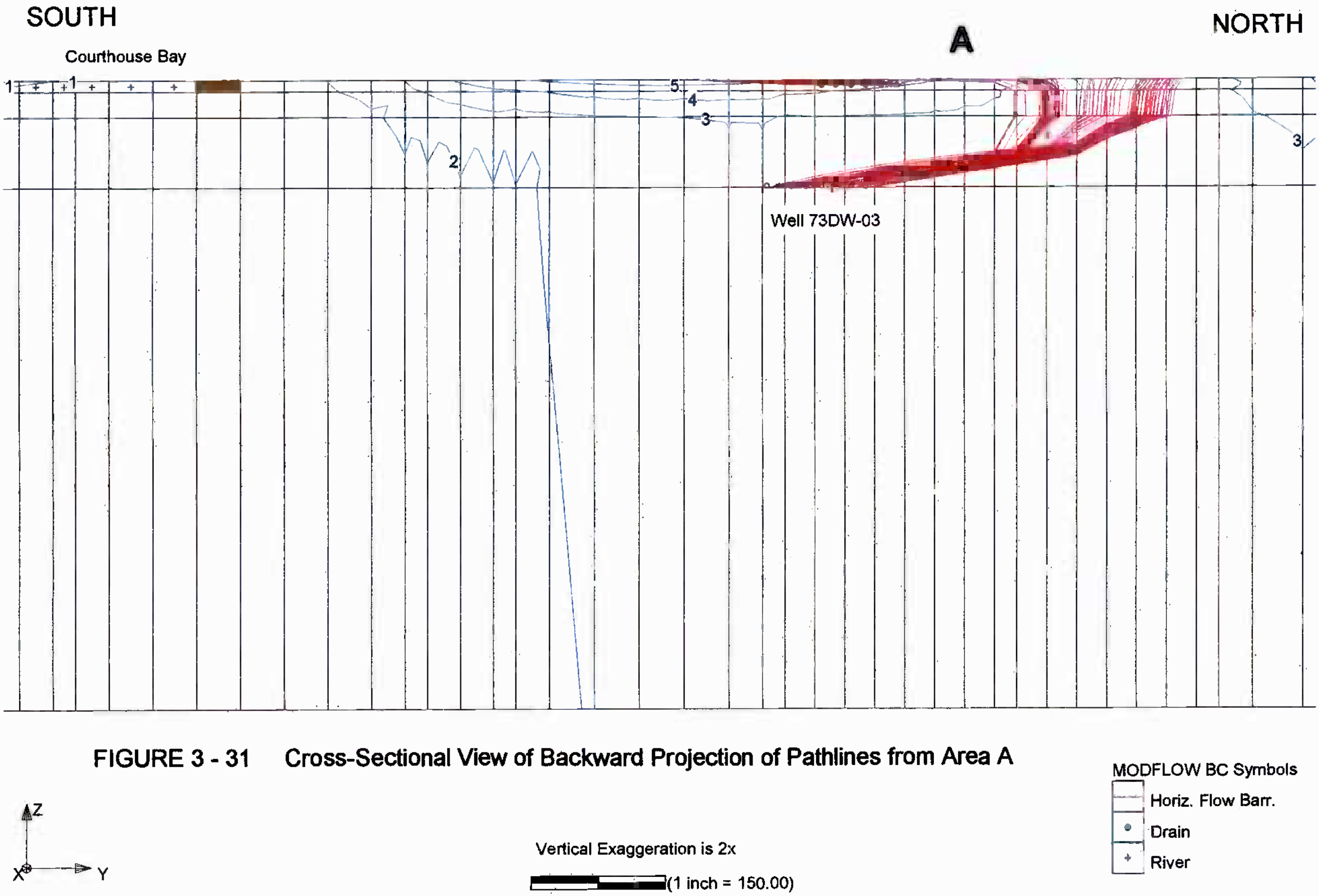


FIGURE 3 - 31 Cross-Sectional View of Backward Projection of Pathlines from Area A

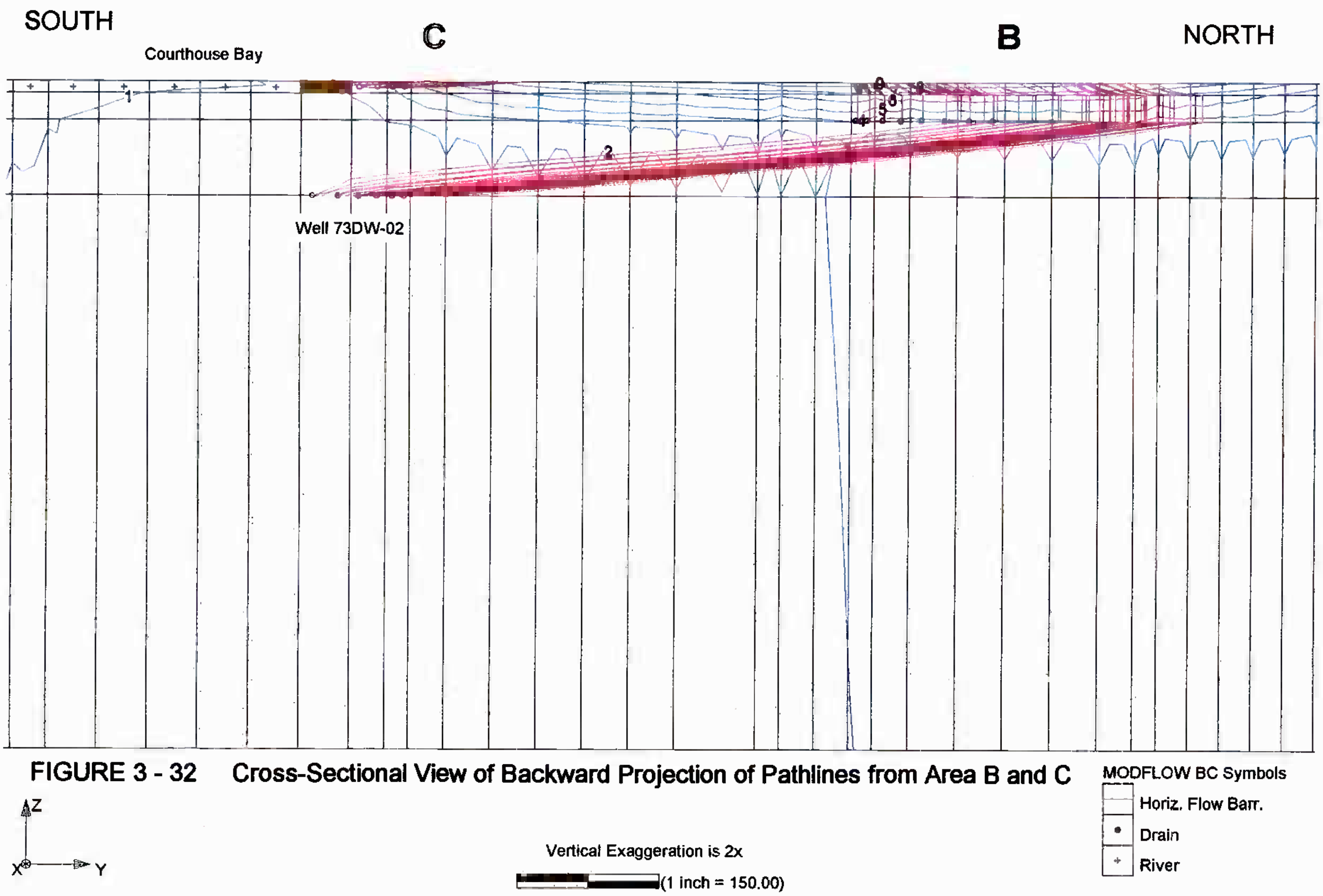


FIGURE 3 - 32 Cross-Sectional View of Backward Projection of Pathlines from Area B and C

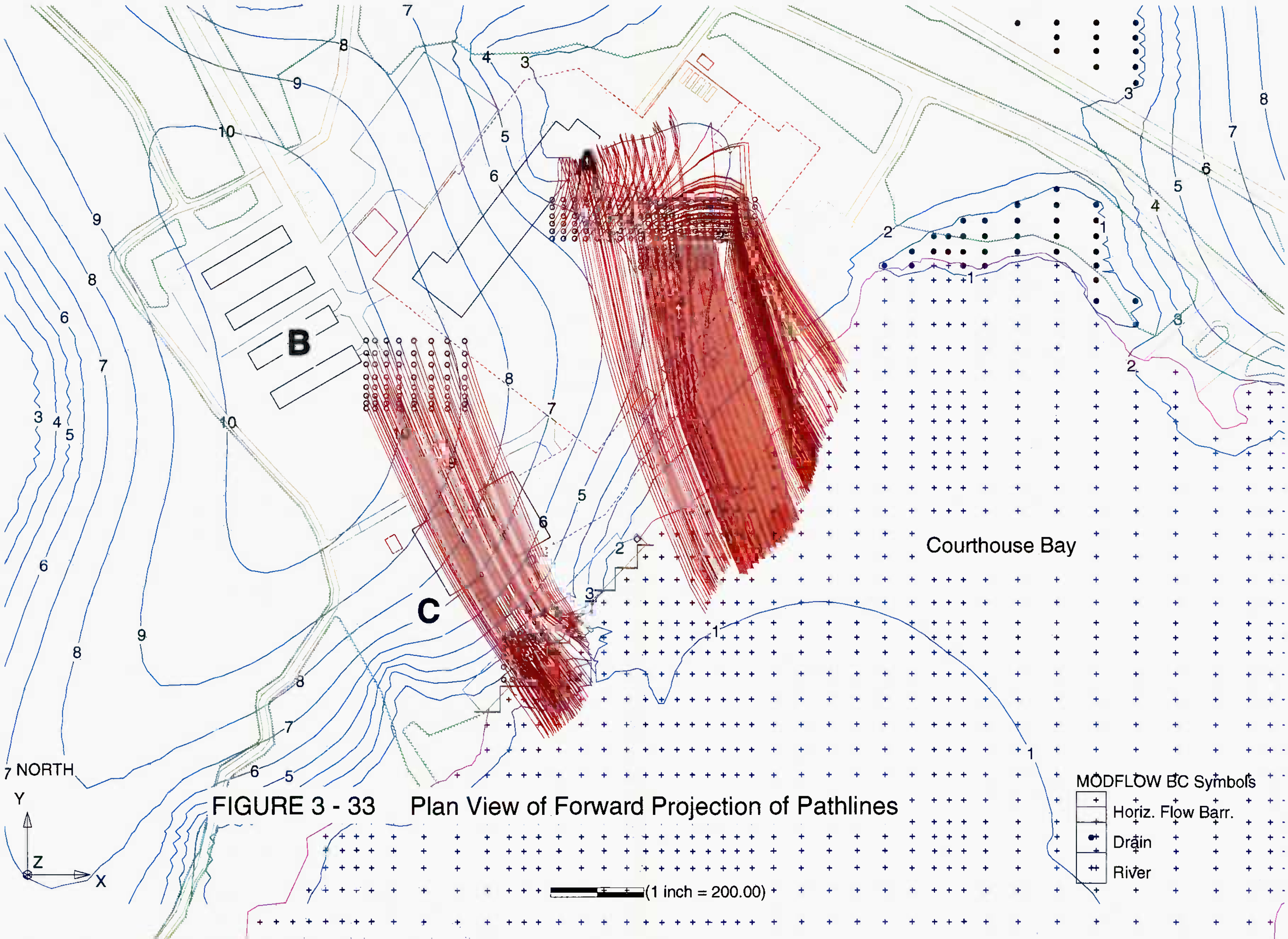


FIGURE 3 - 33 Plan View of Forward Projection of Pathlines

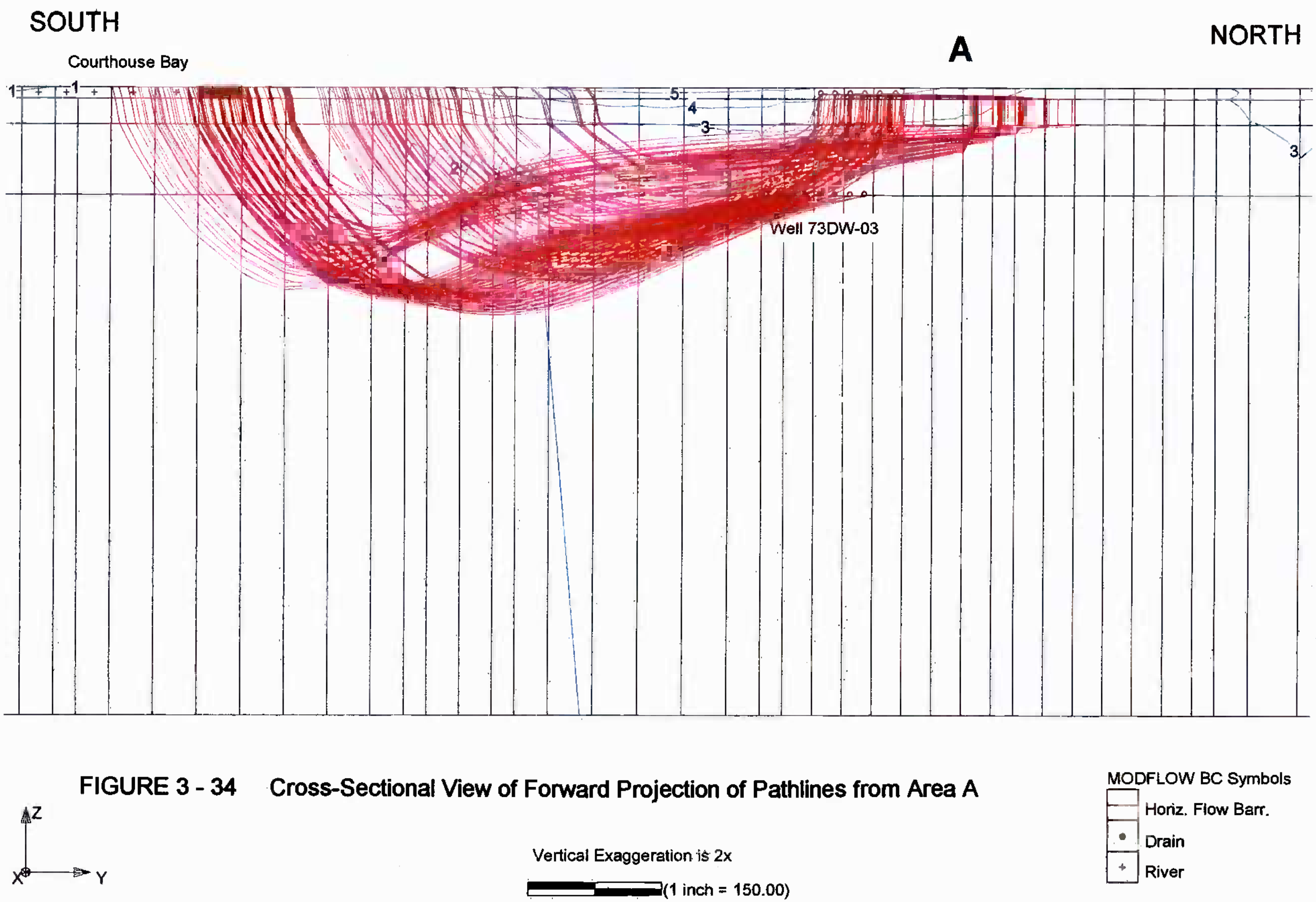


FIGURE 3 - 34 Cross-Sectional View of Forward Projection of Pathlines from Area A

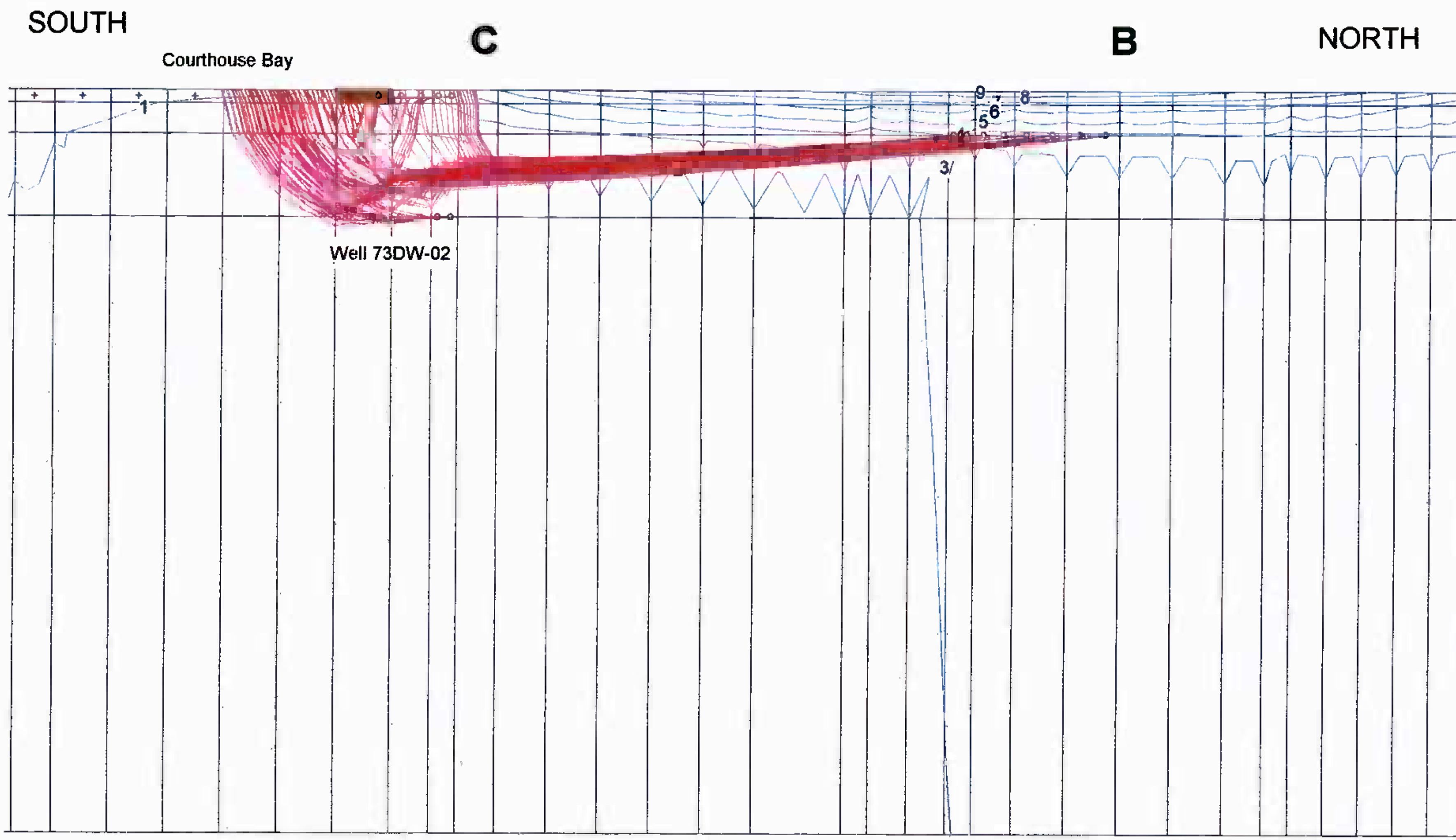
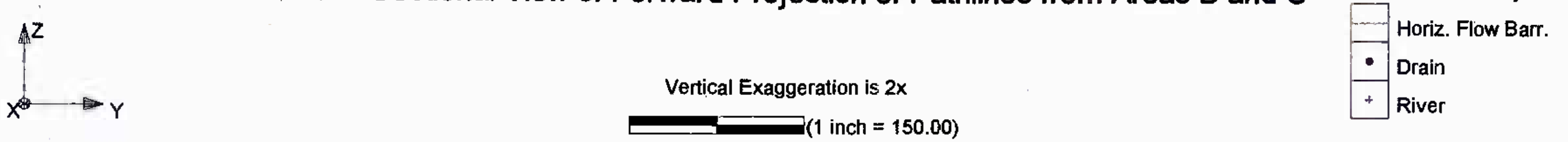


FIGURE 3 - 35 Cross-Sectional View of Forward Projection of Pathlines from Areas B and C



4.0 ALTERNATIVES TO THE SITE 73 SOLUTE TRANSPORT MODEL

The ultimate objective of the proposed transport modeling was to evaluate the risk to Courthouse Bay by predicting the concentration of TCE that would be discharged into the surface water. Although it was not explicitly stated, the use of a groundwater flow/transport model to estimate chemical risk to a surface water body presumes that no dilution would occur when groundwater discharges to surface water. This was a conservative assumption and seemed acceptable when it was assumed that there was only one dissolved contaminant (or species) present in groundwater.

Because the RI data was only just becoming available at the start of this project, it was assumed that TCE was the only contaminant of concern. TCE was the focus of the modeling effort mainly because of its relatively high concentrations in the Castle Hayne Aquifer. The original intent was to simulate the fate of a single dissolved species (TCE) as it flowed through the subsurface and discharged to Courthouse Bay. However, upon a detailed review of the RI data and the associated report (Baker, 1997), it appears that the degradation products of TCE (specifically VC) present more risk to Courthouse Bay receptors than the TCE.

4.1 <u>Single-Species Solute Transport Calibration</u>

As anticipated (and as clearly stated in the IP), the lack of chemical data over time precluded a proper calibration of transient transport of TCE at Site 73. Without a transient calibration, the temporal predictions (e.g., predictions of cleanup times or projected TCE concentrations in X years at distance Y) would have been non-unique and of very limited use because the input values would not have been "calibrated" to match reality. For example, input parameters such as degradation rates would have been assumed from laboratory or other literature-based (non-site-specific) data with no tailoring to site conditions. This limitation would render the transport model to be very limited in capabilities until more data were collected and a calibration performed. Even so, if TCE had been the only groundwater contaminant, these limitations would have been acceptable to construct a solute transport model. As stated above, the presence of degradation products found during the RI changed the nature of this effort. The strategy of evaluating the selective chemical risk of TCE alone was necessarily adjusted to include a comprehensive risk evaluation of TCE and its degradation products.

The recent advent of new dechlorination reaction models (e.g., RT3D and Bioplume III) have made possible the simulation of multi-species conditions such as are found at Site 73. It would be feasible to model this site in the future after the proper data have been collected with which to calibrate the dechlorination model.

Attempts were made to calibrate the solute transport model (using MT3D) to two rounds of TCE values measured in the monitoring wells at Site 73. Several model runs were completed in an attempt to reconstruct the history of where (and when) the TCE originated. Several scenarios were run depicting the future migration and degradation of TCE over time. But it was soon realized that this would not address the risk posed by the degradation products because DCE and VC were being "created" and degraded over time as the TCE was being degraded. Rather than calibrating another transport model using MT3D separately for each of the degradation products (DCE and VC), it was thought prudent to choose an alternative approach to evaluating the comprehensive risk to Courthouse Bay. Two alternatives for evaluating the risk posed by TCE and its degradation products were pursued and are discussed below.

Even though the effort to finish the transport model calibration was judged to be not cost-effective, the existing flow model (described in the previous section) will serve as a baseline which can be updated to include multi-species transport as monitoring at the site increases the database.

4.2 North Carolina Risk Framework Document

Recently, the NC DENR released the Draft Risk Analysis Framework Document (NC DENR, 1996). This document describes a simple approach for calculating the risk of groundwater contamination discharging to Courthouse Bay. The method described in the document uses one of three approaches to limiting groundwater concentrations that discharge to surface water bodies (Category G-3 of several risk scenarios). According to the draft document, the groundwater concentration of a given contaminant may remain in the groundwater at concentrations equal to (or less than) the highest of the following three values:

1. The quantitation limit for the contaminant, or

2. The background groundwater concentration, or

3. Another value determined to be the lowest of the following three values:

   a. 50% of the solubility limit of the contaminant; this is a ceiling concentration limit (CCL #1), or

   b. 1,000 times the groundwater quality (drinking water) standard; this is also a ceiling concentration limit (CCL #2), or

   c. Modeled source concentrations calculated by one of three methods:

      Method I — concentrations from Table 3.2 in the document that were calculated by the G-3 Contaminant Transport Model (G3CTM) using very conservative input values, or

      Method II — concentrations calculated by G3CTM using site-specific input values, or

      Method III — concentrations calculated by another groundwater-to-surface water discharge model (assuming the data are available to adequately run the model) with approval of the NC DENR

Though the above description (summarized from the NC DENR document) may seem confusing, the logic behind the proposed limits of groundwater discharge to surface water is very simple: no contaminant concentrations will be allowed to remain in the groundwater if the model predicts that they will discharge to surface water above the applicable surface water limits.

This proposed approach would be used as the preferred alternative over the comprehensive risk assessment as described in the Risk Assessment Guidance for Superfund (RAGS, USEPA, 1989). The document states that the RAGS should be used under certain circumstances and that this proposed approach should not be used in conjunction with RAGS.

Using the proposed NC DENR methods, the results of Methods I and II turned out to be identical for Site 73 because the calculated source concentrations were much higher than the ceiling concentration limits (CCLs) for both TCE and VC. These results were calculated using very conservative values for 7Q10 (0.001 or 0.002 cfd), which means that an assumption of little to no dilution with surface water was used. Therefore, according to the proposed NC DENR Risk Analysis Framework Document, the groundwater may contain as much as the following table presents.

ALLOWABLE GROUNDWATER CONCENTRATIONS (ug/L)

	TCE	DCE	VC
Surficial Unit	818	16,200	15
Castle Hayne	994	5.53×10^6	15

Appendix C contains the worksheets used to calculate these groundwater concentration limits for scenario G-3 (groundwater discharge to surface water).

With respect to required remediation under this strategy, only those areas with greater than 15 ppb VC in the shallow (surficial unit) would need remediation. The concentrations of contaminants in groundwater in the other areas of the site do not exceed the acceptable risk, according to the draft methods of risk evaluation proposed by NC DENR.

4.3 Natural Bioattenuation of TCE

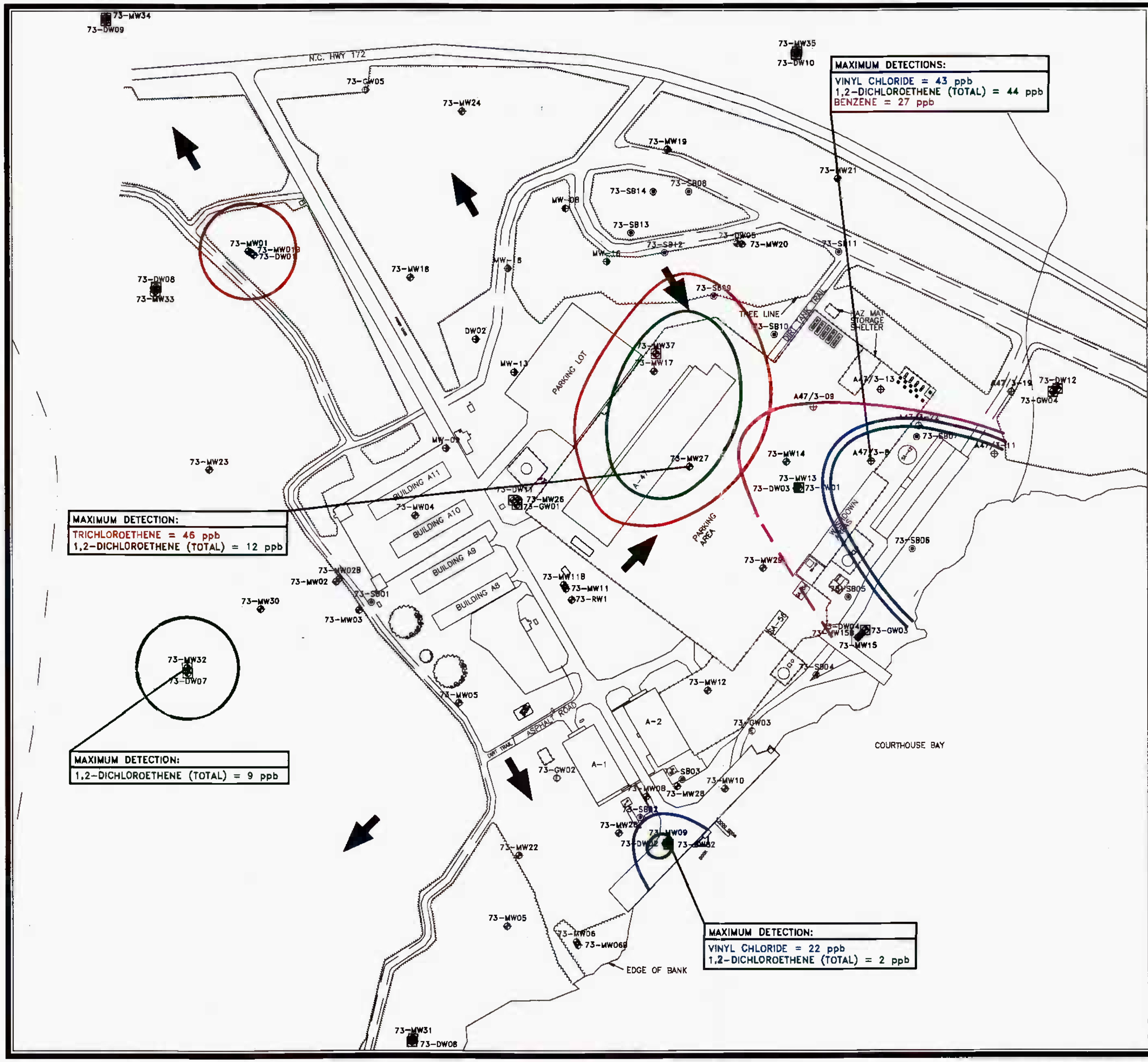
The chemical groundwater data collected during the RI indicates very strongly that TCE may be degrading to DCE and VC beneath Site 73. Figure 4-1 shows the volatile organic contaminants in the surficial unit superimposed on the water table contours. This figure shows that groundwater containing TCE originating near well 73-MW27 flows almost due east past wells 73-MW13 and A47/3-8 on its way toward Courthouse Bay. Figure 4-2 is a graph of contaminant concentrations versus distance; it is a simple, graphical representation of the best available chemical indication for the potential occurrence of natural attenuation at this site. The lines connecting the dots are meant to show the apparent trends over distance: degradation from TCE to cis-1,2-DCE to VC along a groundwater flow path in the surficial unit. The lines show an apparent pattern that typifies the changes in concentration over distance that take place during degradation: the decrease in TCE, the increase and subsequent decrease of DCE, and the increase of VC. Additional data will be needed to confirm this apparent trend.

Two types of VC degradation are possible. Complete reductive degradation of the VC would result in the production of ethene and ethane. This reductive (anaerobic) degradation takes place rather slowly and VC concentrations tend to accumulate because it is being produced faster than it can be degraded. Under aerobic conditions, the VC can be "mineralized" into CO_2, Cl^-, and water. VC does not accumulate under these conditions because of the faster kinetics of the reactions. No data currently exist to prove or disprove either of these hypotheses. However, an environment conducive to VC mineralization may exist downgradient of A47/3-8 in a zone where tidal influence is measurable within about 56 feet from Courthouse Bay (Baker, 1997). The tidal action may serve to oxygenate the groundwater within the tidally-influenced zone and increase the likelihood of complete VC mineralization.

In order to implement a natural bioattenuation remediation alternative, additional wells would be necessary to collect data on the parameters associated with the degradation of chlorinated organic compounds. Data would have to be collected inside and outside the contaminant plume(s), analyzed and reported on a regular basis to document the natural bioattenuation occurring at Site 73. An existing protocol to document such degradation was developed by the Air Force Center for Environmental Excellence (AFCEE, 1996) and is applicable to Site 73.

After more data are collected, additional modeling with RT3D will be possible to help understand the mechanics of the degradation processes.

SECTION 4.0 FIGURES



LEGEND

73-SB01 — SOIL BORINGS ADVANCED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE I (APRIL-MAY, 1995)

73-MW01 — MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE I (APRIL-MAY, 1995)

73-MW31 — MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE II (FEBRUARY-MARCH, 1996)

A47/3-8 — MONITORING WELLS INSTALLED DURING UST INVESTIGATION BY GSI AND LAW-CATLIN AND ASSOCIATES (1993)

MW-18 — MONITORING WELLS INSTALLED BY BAKER DURING UST INVESTIGATION (1992 AND 1993)

MW-08 — MONITORING WELLS INSTALLED DURING A UST INVESTIGATION BY ATEC AND ASSOCIATES (1991)

73GW-02 — MONITORING WELLS INSTALLED BY ESE DURING CONFIRMATORY SAMPLING (1990)

APPROXIMATE DIRECTION OF GROUNDWATER FLOW

NOTES:

THE FOLLOWING ISOCONCENTRATION LINES DEFINE THE AREAS OF CONCERN:

TRICHLOROETHENE = 1.0 PARTS PER BILLION (ppb)

CIS-1,2-DICHLOROETHENE (TOTAL) = 1.0 ppb

VINYL CHLORIDE = 1.0 ppb

BENZENE = 1.0 ppb

PHASE II DATA FROM THE UPPER PORTION OF THE SURFICAL AQUIFER WAS USED TO DEVELOP ISOCONCENTRATION LINES.

SOURCE: LANIER SURVEYING CO., APRIL 4, 1996.

250 0 125 250

1 inch = 250 ft.

Baker

Baker Environmental, Inc.

FIGURE 4-1
VOCs IN SURFICIAL GROUNDWATER
SITE 73 - AMPHIBIOUS VEHICLE MAINTENANCE FACILITY
GROUNDWATER MODELING REPORT, CTO-0312

MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA

02200DD02Y

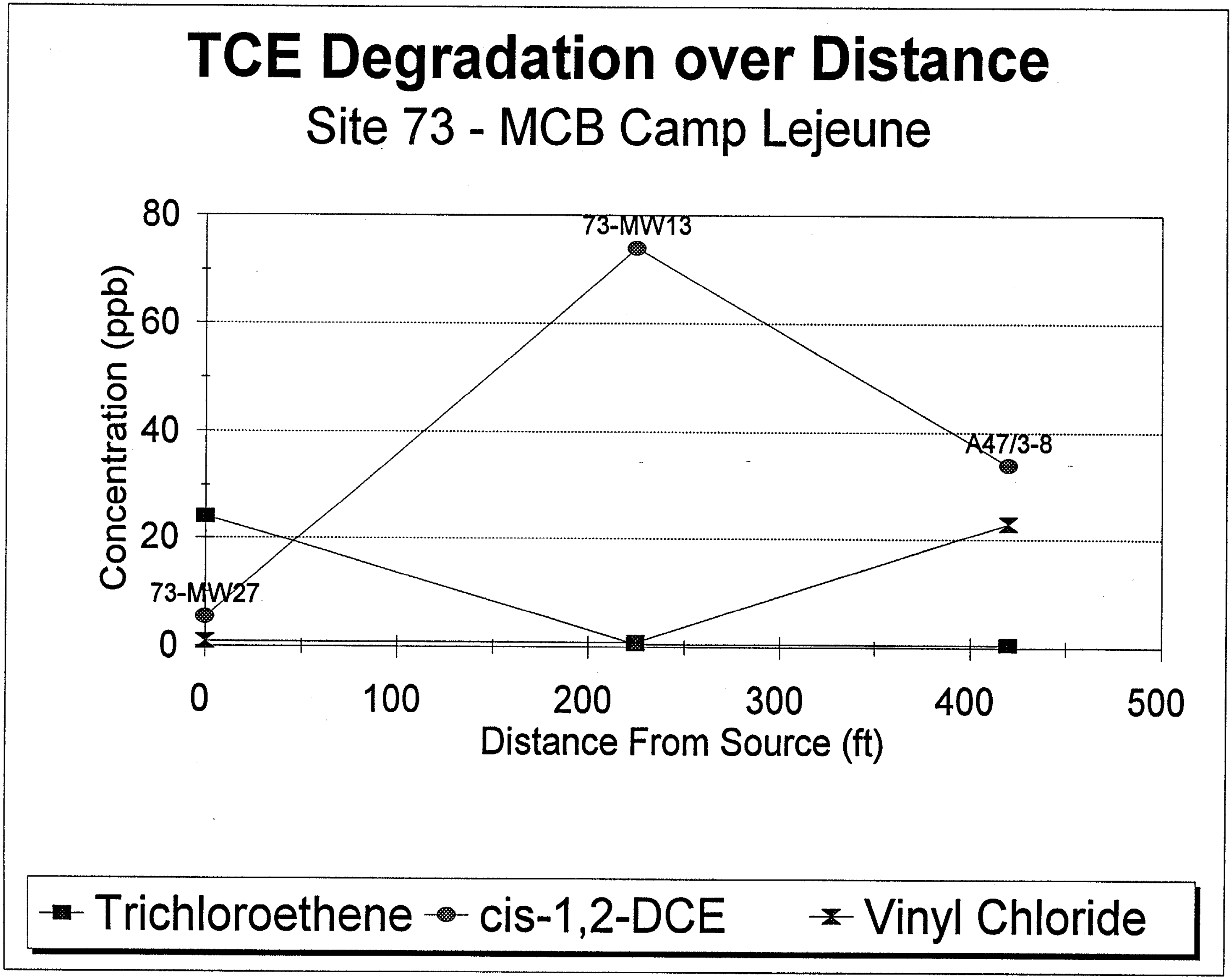


Figure 4-2 TCE Degradation over Distance in Surficial Groundwater

5.0 REMEDIATION SCENARIO SIMULATIONS

Three chlorinated aliphatic compounds (TCE, cis-1,2-DCE, and VC) and one aromatic compound (benzene) have been identified as contaminants of concern in the surficial and Castle Hayne groundwater at Site 73. Several remedial scenarios emerged from the modeling process as providing protection to groundwater, but the choice of which is best will depend heavily on the strategy used at the next stage (corrective action)of the RI/FS/CA process. Three major strategies may be justified at Site 73:

1. Containment (by extraction and *ex-situ* treatment) of surficial and Castle Hayne groundwater containing concentrations of VOCs above the groundwater quality (GWQ) standards.

2. Containment (by extraction and *ex-situ* treatment) only of surficial groundwater containing concentrations of VOCs above the "source concentrations" calculated by the methods in the NC DENR Risk Framework Document (i.e., > 15 ppb VC).

3. Additional data collection and long-term monitoring to support the theory that natural bioattenuation of TCE, DCE, VC and benzene are occurring and will continue until the concentrations are below both the "source" concentrations and the GWQ standards.

The final strategic decision should be made with regard to the effectiveness of each strategy to: 1) reduce actual risk; 2) maintain low risk and intrusiveness to operations during implementation; and, 3) provide a premium cost-to-benefit ratio. The following discussion details each of the scenarios and may provide some guidance as to the benefits that each would provide.

Capture zone analyses were performed to illustrate the comparative virtues of each remedial alternative and to demonstrate whether the well(s) and/or trench could contain the contaminant plume(s).

5.1 <u>Surficial Unit Remedial Scenarios</u>

After the Site 73 groundwater flow model was calibrated to existing conditions and the pathline analyses of existing conditions were run, two types of remedial measures were superimposed on the model to accomplish the objective in Scenario 1. Scenario 1A used seven wells to contain the contamination within the areas of highest concentration while Scenario 1B used one well and an extraction trench to contain the groundwater at the facility boundary before discharge to Courthouse Bay.

5.1.1 Scenario 1A in Layer 1 - Surficial Unit

The objective in Scenario 1 is to contain all of the surficial groundwater exceeding the GWQ standards by pumping and *ex-situ* treatment. If accepted as the applicable limits for Site 73, the GWQ standards would limit the contaminants to the following maximum concentrations: TCE - 0.0028 mg/L; DCE (total of *cis* and *trans* isomers) - 0.070 mg/L; VC - 0.000015 mg/L; and benzene - 0.001 mg/L. The areas of contaminant concentrations exceeding the GWQ standards in the surficial unit are shown in Figures 5-1.

In Scenario 1A, the model indicated that seven shallow extraction wells would be necessary to contain the TCE, DCE, VC, and benzene above groundwater quality standards. The steady-state (constant) sustainable pumping rates of these were estimated by the model to yield between 0.25 and 2 gpm. At higher rates, the model indicated that the wells would go dry. The locations of the seven wells were optimized to contain the surficial groundwater contamination. Simulated remedial scenarios with fewer wells were tried unsuccessfully to contain the existing contaminant plumes.

Figure 5-2 shows the simulated water table response in a close-up plan view of the Site 73 area with the surficial extraction wells activated. Four shallow (10 to 20 feet bgs) wells pumping 2 gpm each were sufficient to contain the bulk of the contamination east of Building A47. Three other isolated areas of contamination required an extraction well near surficial wells 73-MW19, 73-MW-23, and 73-MW09 pumping 2, 1, and 0.5 gpm, respectively. This figure shows the capture zones of each well superimposed on the resulting water table contours. The steady-state simulation shows that the proposed wells are able to contain the surficial contamination and prevent further off-site migration toward Courthouse Bay.

5.1.2 Scenario 1B in Layer 1 - Surficial Unit

Scenario 1B used one trench and one well to contain the groundwater exceeding the GWQ standards at the facility boundary before it discharged to Courthouse Bay. The extraction well near 73-MW09 is pumping 0.5 gpm and the trench is pumping approximately 20 gpm. Figure 5-3 shows the capture zones of the well and trench superimposed upon the resulting water table contours. The steady-state simulation shows that the proposed well and trench are able to contain the surficial contamination and prevent further off-site migration toward Courthouse Bay.

5.1.3 Scenario 2 in Layer 1 - Surficial Unit

Scenario 2 entails remediating only those areas exceeding the "source" concentrations calculated by Method II under the G-3 (groundwater discharge to surface water) classification as described in the Draft NC DENR Risk Framework Document. Under this scenario, the applicable limits to protect the quality of surface water in Courthouse Bay (SA classification - protective of commercial shell fishing) is the lowest of three values: the calculated "source" concentrations; 1,000 times the GWQ standard; or half the solubility limit (the latter two being Ceiling Concentration Limits or CCLs). For TCE, the CCLs are 2.8 mg/L and 550 mg/L; and for VC the CCLs are 0.015 mg/L and 550 mg/L. Appendix C shows the worksheet used during the calculation of the G-3 limits.

According to the model G3CTM, the allowable "source" concentration for TCE in the surficial unit would be 0.818 mg/L, for DCE the allowable "source" concentration in the surficial unit would be 16.2 mg/L, and for VC the allowable "source" concentration would be 1.21 mg/L. For VC, however, the lower CCL value of 0.015 mg/L (1,000x the GWQ standard) had to be used in the comparison. As shown in the worksheet, the only limit exceeded was that for VC (CCL = 0.015 mg/L) in wells A47/3-8 (0.023 and 0.043 mg/L in two rounds) and 73-MW09 (0.011 and 0.022 mg/L in two rounds). Caution should be exercised in making a decision to remediate the area near 73-MW09 based on only two rounds of data when its concentration did not exceed the "source" concentration limit in both sampling events.

Figure 5-4 shows the capture zone of each well superimposed upon the resulting water table contours. The extraction well near 73-MW09 is pumping 0.5 gpm and the well near A47/3-8 is pumping 2 gpm.

The steady-state simulation shows that the proposed well and trench are able to contain the surficial contamination and prevent further off-site migration toward Courthouse Bay.

5.1.4 Scenario 3 in Layer 1 - Surficial Unit

Under Scenario 3, additional data collection would be necessary to provide sufficient evidence that natural bioattenuation is occurring. This modeling effort makes a case based on available data that TCE may currently be degrading naturally (see Figure 4-2). The spatial distribution of TCE and its degradation products (cis-1,2-DCE, and VC) indicate very strongly that natural bioattenuation of TCE may actually be occurring. The degree to which VC is being degraded remains the key issue in evaluating the risk to Courthouse Bay. If it can be established that conditions conducive to VC degradation (oxygen-rich, aerobic environment) exists, actual degradation products (e.g., ethene and/or ethane) are present downgradient of A47/3-8, or if VC concentrations decline downgradient of A47/3-8, it may be reasonably concluded that VC is being degraded before reaching Courthouse Bay.

Additional monitoring wells would be necessary inside and outside of the plume(s) to monitor the conditions that are conducive to natural bioattenuation (AFCEE, 1996). Long-term quarterly monitoring of the appropriate parameters would also be necessary to account for seasonal variations and to track the "progress" of the attenuation.

5.2 Castle Hayne Aquifer Remedial Scenarios

5.2.1 Scenario 1 in Layer 3 - Castle Hayne Aquifer

In the first round of sampling, all five of the DW-series wells and two of the six B-series wells contained concentrations of TCE above the GWQ standard. In the second round, only one DW-series well (73-DW03) and two B-series wells (73-MW01B and 73-MW11B) contained levels of TCE above the GWQ standard. Again, caution should be exercised in making the decision to remediate the levels of contaminants that have not been confirmed by at least two rounds of sampling. Figure 5-5 shows three areas in which TCE is most likely present. Although this excludes some of the DW-series wells, it is a reasonable assumption until more data can confirm the actual concentration of TCE in the DW-series and B-series wells in the upper Castle Hayne Aquifer.

Figure 5-6 shows three deep (35 to 70 feet bgs) extraction wells that would be necessary to contain the Castle Hayne groundwater containing contaminants in excess of the GWQ standards (as shown in Figure 5-5). The figure shows steady-state potentiometric surface contours in the upper Castle Hayne at Site 73 with all three deep extraction wells activated. On this figure the capture zones around each well show that the contaminants in the upper Castle Hayne Aquifer can be contained before discharge to Courthouse Bay. Figure 5-7 shows that the capture zones are not limited to the upper Castle Hayne, but extend into every layer at quite some distance when projected backwards over a very large time frame.

5.2.2 Scenario 2 in Layer 3 - Castle Hayne Aquifer

Scenario 2 entails remediating only those areas exceeding the "source" concentrations calculated by Method II under the G-3 (groundwater discharge to surface water) classification as described in the Draft NC DENR Risk Framework Document. Under this scenario, the applicable limits to protect the quality of surface water in Courthouse Bay (SA classification - protective of commercial shell fishing) is the lowest of three values: the calculated "source" concentrations; 1,000 times the GWQ standard;

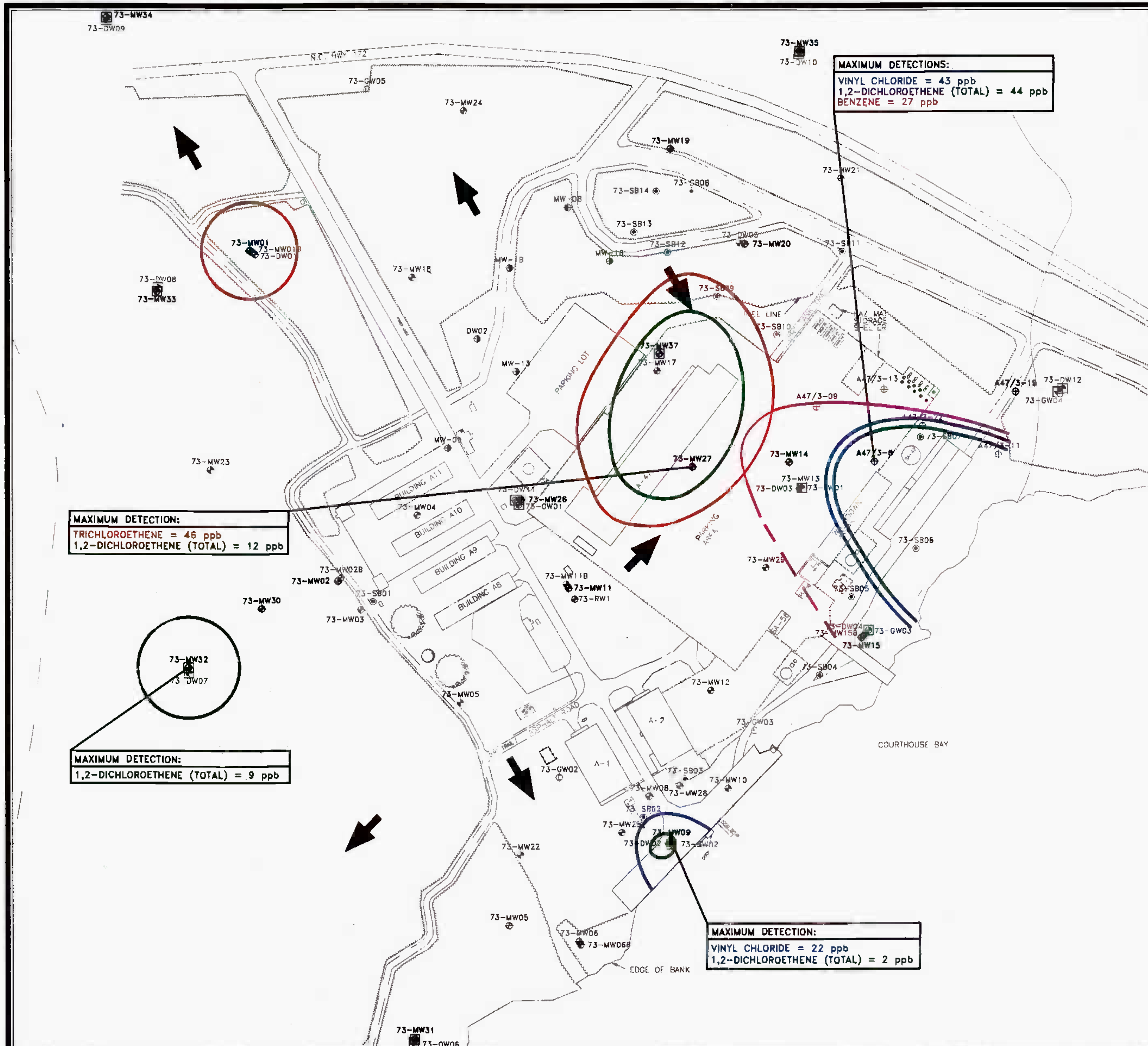
or half the solubility limit (the latter two being Ceiling Concentration Limits or CCLs). For TCE, the CCLs are 2.8 mg/L and 550 mg/L; and for VC the CCLs are 0.015 mg/L and 550 mg/L. Appendix C shows the worksheet and questionnaire used during the calculation of the G-3 limits.

According to the model G3CTM, the allowable "source" concentration for TCE in the Castle Hayne would be 0.994 mg/L, for DCE the allowable "source" concentration in the Castle Hayne would be 5.53×10^6 mg/L, and for VC the allowable "source" concentration would be 6.7 mg/L. For VC, however, the lower CCL value of 0.015 mg/L (1,000 x the GWQ standard) had to be used in the comparison. As shown in the worksheet, neither the calculated "source" concentrations nor the applicable CCL limits were exceeded in the upper Castle Hayne Aquifer. Therefore, under Scenario 2, no remediation would be necessary in the upper Castle Hayne Aquifer.

5.2.3 Scenario 3 in Layer 3 - Castle Hayne Aquifer

Under Scenario 3, additional data collection would be necessary to provide sufficient evidence that natural bioattenuation is occurring. This modeling effort makes a case based on available data that TCE is currently being degraded in the surficial unit before groundwater discharges to Courthouse Bay. Additional monitoring wells would be necessary inside and outside of the plume(s) to monitor the conditions that are conducive to natural bioattenuation. Long-term quarterly monitoring of the appropriate parameters would also be necessary to account for seasonal variations and to track the "progress" of the attenuation.

SECTION 5.0 FIGURES



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LEGEND

73-SB01	SOIL BORINGS ADVANCED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE I (APRIL-MAY, 1995)
73-MW01	MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE I (APRIL-MAY, 1995)
73-MW31	MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE II (FEBRUARY-MARCH, 1996)
A47/3-8	MONITORING WELLS INSTALLED DURING UST INVESTIGATION BY GSI AND LAW-CATLIN AND ASSOCIATES (1993)
MW-18	MONITORING WELLS INSTALLED BY BAKER DURING UST INVESTIGATION (1992 AND 1993)
MW-08	MONITORING WELLS INSTALLED DURING A UST INVESTIGATION BY ATEC AND ASSOCIATES (1991)
73GW-02	MONITORING WELLS INSTALLED BY ESE DURING CONFIRMATORY SAMPLING (1990)
	APPROXIMATE DIRECTION OF GROUNDWATER FLOW

NOTES:

THE FOLLOWING ISOCONCENTRATION LINES DEFINE THE AREAS OF CONCERN:

- TRICHLOROETHENE = 1.0 PARTS PER BILLION (ppb)
- CIS-1,2-DICHLOROETHENE (TOTAL) = 1.0 ppb
- VINYL CHLORIDE = 1.0 ppb
- BENZENE = 1.0 ppb

PHASE II DATA FROM THE UPPER PORTION OF THE SURFICAL AQUIFER WAS USED TO DEVELOP ISOCONCENTRATION LINES.

SOURCE: LANIER SURVEYING CO., APRIL 4, 1996.

250 0 125 250

1 inch = 250 ft.

Baker

Baker Environmental, Inc.

FIGURE 5-1
VOCs EXCEEDING GWQ STANDARDS
IN SURFICIAL AQUIFER
SITE 73 - AMPHIBIOUS VEHICLE MAINTENANCE FACILITY
GROUNDWATER MODELING REPORT, CTO-0312

MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA

02200DDB7Y

Figure 5-2 Capture Zone Pathline Map -- Simulated Remediation of Water Table - Scenario 1A

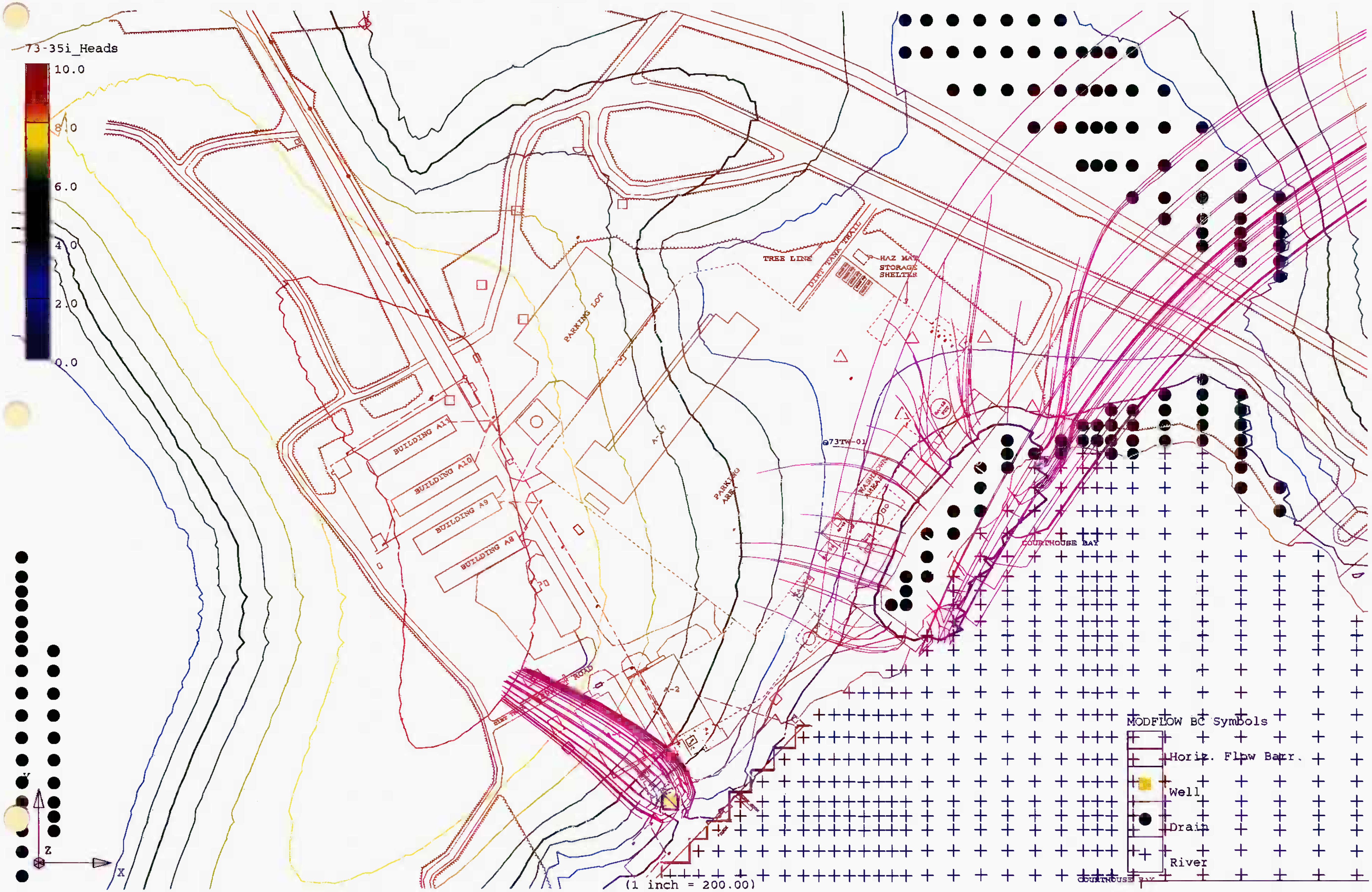
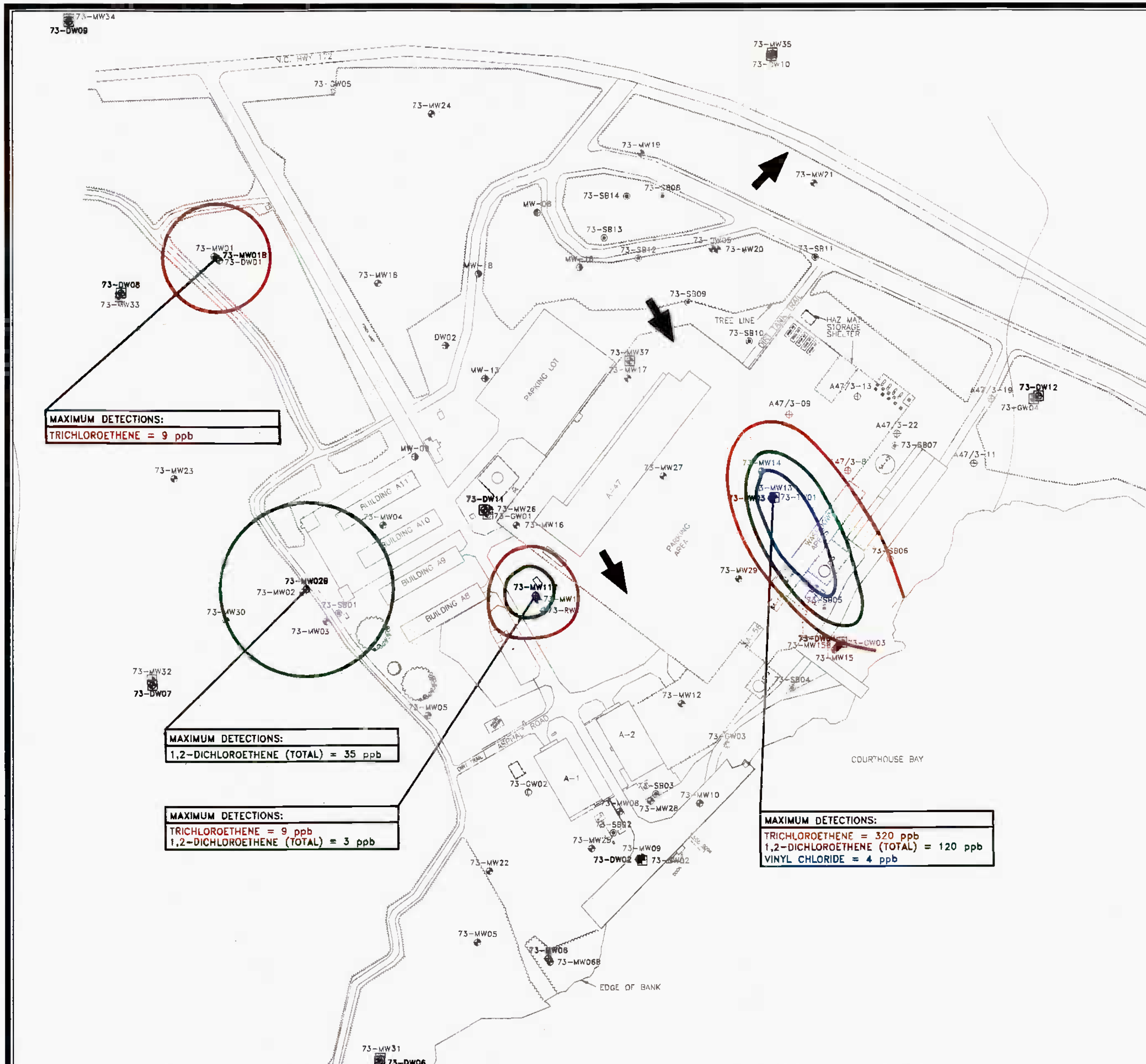


Figure 5-3 Capture Zone Pathline Map -- Simulated Remediation of Water Table - Scenario 1B

Figure 5-4 Capture Zone Pathline Map -- Simulated Remediation of Water Table - Scenario 2



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LEGEND

73-SB01 — SOIL BORINGS ADVANCED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE I (APRIL-MAY, 1995)

73-MW01 — MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE I (APRIL-MAY, 1995)

73-MW31 — MONITORING WELLS INSTALLED BY BAKER DURING REMEDIAL INVESTIGATION, PHASE II (FEBRUARY-MARCH, 1996)

A47/3-8 — MONITORING WELLS INSTALLED DURING UST INVESTIGATION BY GSI AND LAW-CATLIN AND ASSOCIATES (1993)

MW-18 — MONITORING WELLS INSTALLED BY BAKER DURING UST INVESTIGATION (1992 AND 1993)

MW-08 — MONITORING WELLS INSTALLED DURING A UST INVESTIGATION BY ATEC AND ASSOCIATES (1991)

73GW-02 — MONITORING WELLS INSTALLED BY ESE DURING CONFIRMATORY SAMPLING (1990)

APPROXIMATE DIRECTION OF GROUNDWATER FLOW

NOTES:

THE FOLLOWING ISOCONCENTRATION LINES DEFINE THE AREAS OF CONCERN:

TRICHLOROETHENE = 1.0 PARTS PER BILLION (ppb)

1,2-DICHLOROETHENE (TOTAL) = 1.0 ppb

VINYL CHLORIDE = 1.0 ppb

PHASE II DATA FROM THE UPPER PORTION OF THE CASTLE HAYNE AQUIFER AND LOWER PORTION OF THE SURFICIAL AQUIFER, WAS USED TO DEVELOP THE ISOCONCENTRATION LINES.

SOURCE: LANIER SURVEYING CO., APRIL 4, 1996.

250 0 125 250
1 inch = 250 ft.

Baker
Baker Environmental, Inc.

FIGURE 5-5
VOCs EXCEEDING GWQ STANDARDS
IN CASTLE HAYNE GROUNDWATER
SITE 73 – AMPHIBIOUS VEHICLE MAINTENANCE FACILITY
GROUNDWATER MODELING REPORT, CTO-0312

MARINE CORPS BASE, CAMP LEJEUNE
NORTH CAROLINA

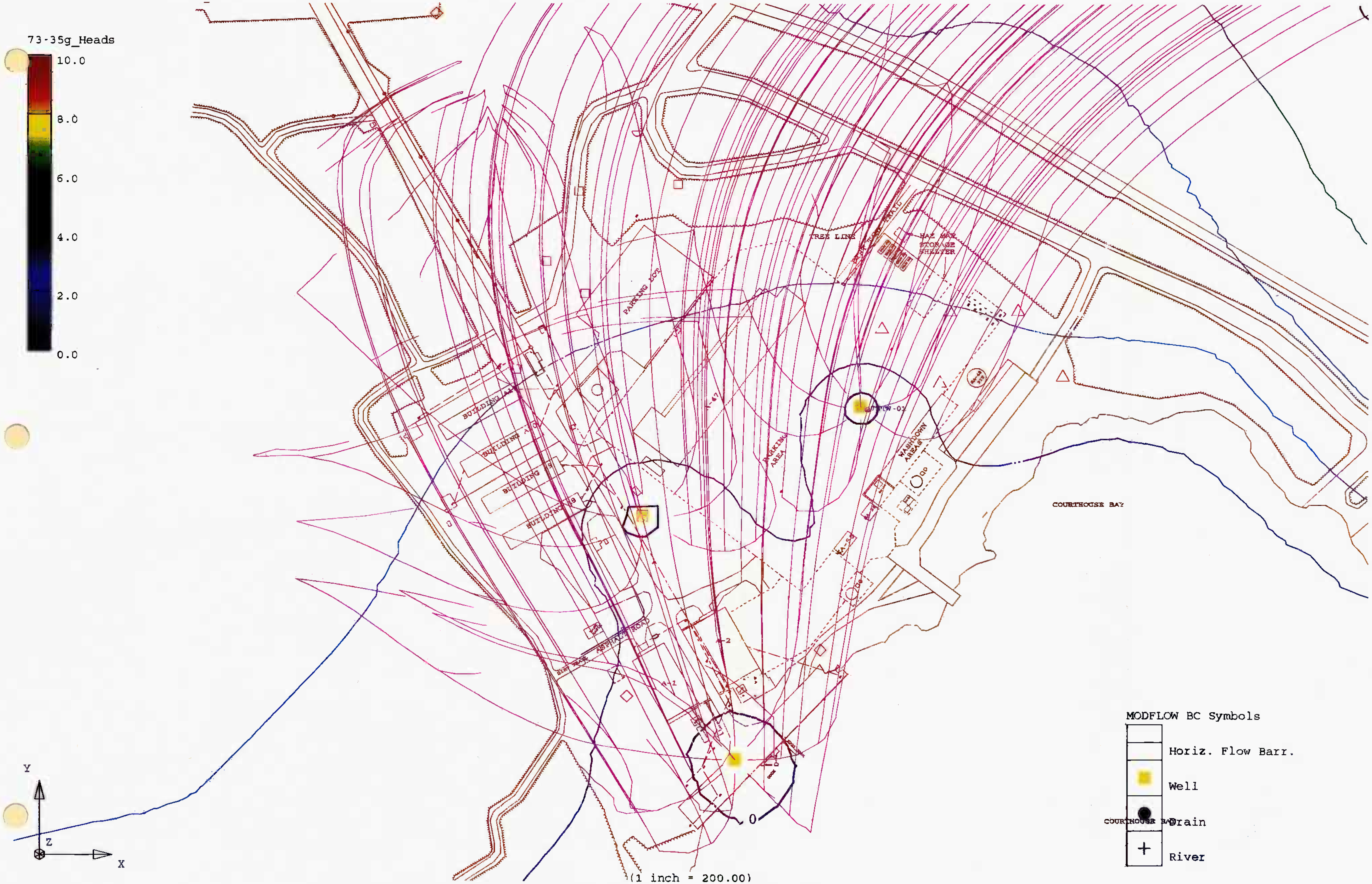


Figure 5-6 Capture Zone Pathline Map -- Simulated Remediation of Castle Hayne Groundwater - Scenario 1

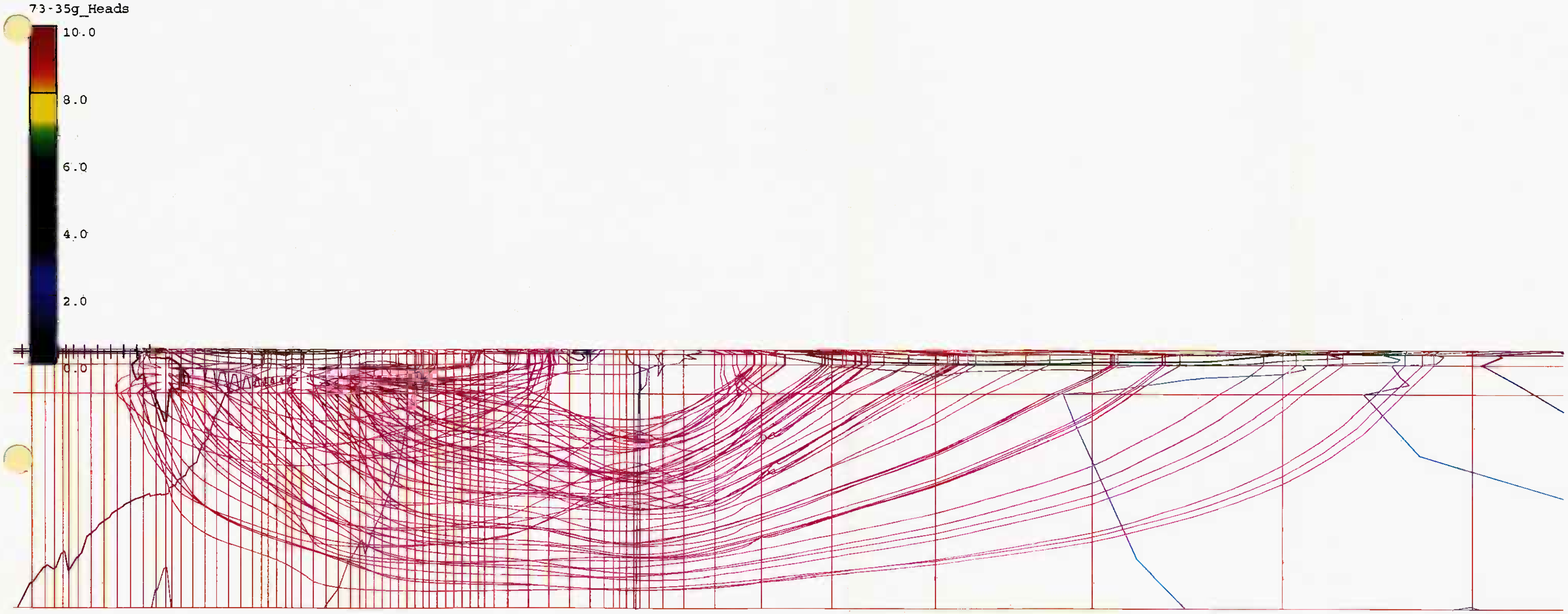
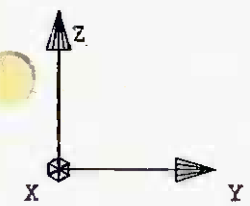
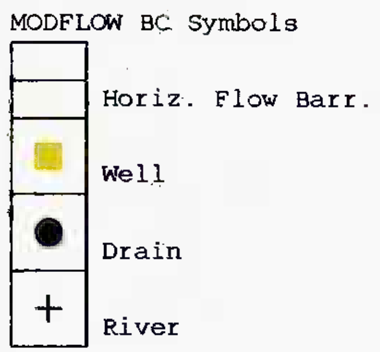


Figure 5-7 Capture Zone Pathline Map -- Simulated Remediation of Castle Hayne Groundwater - Scenario 1 - Cross-Section View





(1 inch = 400.00)

6.0 SUMMARY AND CONCLUSIONS

This Groundwater Modeling Report was prepared to support the evaluation of remedial alternatives in the Feasibility Study (FS) for Operable Unit No. 9, Amphibious Vehicle Maintenance Facility at Marine Corps Base (MCB) Camp Lejeune, North Carolina. Specifically, the modeling effort provided data interpretation to assist in evaluating the impact on groundwater contaminants of various remedial options and the risk mitigating effects of those options on adjoining Courthouse Bay.

6.1 Accomplishment of Objectives

This report describes the several steps taken to:

1. Define the three-dimensional groundwater flow directions beneath the site (using MODFLOW).

2. Determine the fate of the identified dissolved contaminants (by advection using MODPATH).

3. Estimate concentration in surface water after discharge into Courthouse Bay (using G3CTM).

4. Assess the need for remediation based on appropriate objectives in three different scenarios.

5. Optimize the remedial measures (using MODFLOW and MODPATH).

6. Compare the efficacy of the various remedial scenarios (e.g., wells versus trench using MODFLOW and MODPATH).

Groundwater flow modeling played a major role in accomplishing the above objectives. The combination of numerical (MODFLOW) and analytical (G3CTM) models was used to conceptualize and illustrate the exposure pathway of a contaminant from groundwater to surface water. There were several specific objectives and two major objectives of the modeling effort. The first major objective was to develop a site-specific, steady-state, three-dimensional, calibrated groundwater flow model (using MODFLOW and MODPATH) that would be used to:

- Predict the fate (and perhaps suggest source area locations) of the groundwater contaminants at Site 73 by simulating the existing three-dimensional patterns of groundwater flow at Site 73 in the surficial hydrologic unit and the Castle Hayne Aquifer including the interaction of groundwater and surface water (Courthouse Bay).

- Assess the potential for contaminant migration toward water supply wells across Courthouse Bay toward BB-44 or other Courthouse Bay area wells.

- Compare the efficacy of various remediation schemes for Site 73 in order to protect potential human and/or ecological receptors from groundwater contaminants (particularly trichloroethene and its degradation products: cis-1,2-dichloroethene and vinyl chloride).

- Evaluate the potential hydrologic effects of the remedial scenarios on the groundwater regime.

- Support the design of the selected remedial alternative.

The groundwater flow model has proved useful in helping to predict the ultimate fate of the groundwater contaminants and also helped in answering many questions regarding the associated risk. Based on the conceptual model (as described in Section 2.3) and within the limitations of its calibration, the Site 73 model describes how groundwater flows beneath the Amphibious Vehicle Maintenance Facility (Objective 1). It also demonstrated that the groundwater contaminants at Site 73 are not likely the source of trace contamination in water supply well BB-44 (Objective 2). The Site 73 model demonstrates the effects of remedial groundwater withdrawals on the surficial water table and the Castle Hayne Aquifer (Objective 3). The model demonstrates that the relatively low-volume withdrawal rates of the extraction wells will have an extremely localized effect on the water levels in the surficial unit and the Castle Hayne Aquifer (Objective 4). The model can also be used to help design and optimize the remediation system(s) if necessary (Objective 5).

The second major objective was to develop a steady-state, single-species contaminant transport model (using MT3D with the results from MODFLOW) that would be used to predict the fate of trichloroethene (TCE) in the subsurface beneath Site 73 and to evaluate the risk to Courthouse Bay (the only receptor) associated with the TCE concentrations under several remedial scenarios. However, the risk associated with the degradation products of TCE [especially vinyl chloride (VC)] in groundwater is actually greater than that posed by the TCE. This meant that the concentrations of the single-species (TCE) predicted by MT3D would not provide adequate information to evaluate the risks posed by vinyl chloride (VC) and cis-1,2-dichloroethene (DCE).

Therefore, instead of completing the MT3D calibration, the proposed Draft Risk Analysis Framework (NC DENR, 1996) was used to estimate the surface water concentrations of TCE, DCE and VC from groundwater discharge (class G-3, Method II). Using site-specific input values and conservative assumptions it was determined that the allowable "source" concentrations in the surficial unit were 0.818 mg/L TCE, 16,200 mg/L DCE and 1.21 mg/L VC. In the Castle Hayne Aquifer, the values were 0.994 mg/L TCE, 5.53×10^6 mg/L DCE and 6.7 mg/L VC in 73-DW03. These "source" concentrations are considered protective of the applicable surface water quality standards (0.0924 mg/L TCE, 7.0 mg/L DCE and 0.525 mg/L VC). However, according to the "Draft Risk Analysis Framework Document", the allowable "source" concentrations may not be higher than the Ceiling Concentration Limits (CCLs). The CCLs for VC are defined as either 1,000 times the groundwater quality standard (1,000 x 0.000015 mg/L = 0.015 mg/L) or half of the solubility limit (½ x 1,100 mg/L = 550 mg/L). The lowest of the three types of values for VC is 0.015 mg/L. The calculated "source" values for TCE and DCE did not exceed either of their CCLs.

Finally, the data from the RI (Baker, 1997) indicate that TCE may be degrading to DCE and VC and that the VC may be further degrading to harmless compounds before it reaches Courthouse Bay. In this case, the actual risk to Courthouse Bay would be zero. Additional data collection would be necessary over a period of years to prove that such natural bioattenuation is actually occurring. The parameters and monitoring locations necessary for this are beyond the scope of this effort, but have been documented (AFCEE, 1996).

6.2 Recommendations

There are three possible strategies to remediate the affected areas beneath Site 73:

1. Use groundwater quality (GWQ) standards as cleanup levels protective of drinking water and actively remediate those areas that exceed them.

2. Use the "source" concentrations (as calculated by the model G3CTM) as clean-up levels protective of SA surface water quality and actively remediate those areas that exceed them.

3. Passively remediate the affected areas on-site by gathering data to support the natural bioattenuation option to reach one or both of the above clean up levels.

Baker believes that the best alternative to remediate the risk at Site 73 is to collect additional data that will support the hypothesis that the VC is being completely naturally bioattenuated before it reaches Courthouse Bay.

6.3 Impact of Site 73 Model on the BRAGS Model

The BRAGS basewide groundwater flow model was intended to be a "working" model, that is, it was meant to be transferred into the hands of base personnel (or their representatives) to update and modify to site-level work or as new information becomes available. The updated BRAGS model will be effective decision-making tools for optimal groundwater resource management, protection, and restoration. The models can be used to determine the relative effectiveness of various remedial scenarios at individual sites around the base.

The BRAGS groundwater flow model was designed to simulate the three-dimensional pattern of groundwater flow within the surficial units and the Castle Hayne Aquifer. The model reasonably predicts the elevation and flow direction of the surficial and Castle Hayne groundwater in many areas around the base where no data currently exist. The BRAGS model also demonstrates that discharge to the New River and its tributaries is the controlling factor on flow directions in the Castle Hayne Aquifer in the vicinity of Camp Lejeune. The BRAGS model output indicates that the relatively high-volume withdrawal rates of the supply wells have only a localized effect on the water levels in the Castle Hayne (Baker, 1996). If kept updated, the BRAGS groundwater flow model will be useful in managing the future RI activities at the base. Future groundwater flow and/or contaminant transport modeling done at the site level should be coordinated with the BRAGS groundwater flow model so that the "big picture" of the groundwater flow is consistent across the Base.

The Site 73 groundwater model is consistent with the Basewide Remediation Assessment Groundwater Study (BRAGS) numerical groundwater model. In fact, the Site 73 model was first constructed using the same assumptions as in the BRAGS model. With the addition of site-specific data, the Site 73 model became more detailed than the BRAGS model was designed to be. That is, the denser finite-difference grid of the site model yields better detail around the site area of interest.

Because the BRAGS model will be updated periodically as part of a separate project, the update to the BRAGS basewide model was not included in this effort. However, the details used in the Site 73 model (e.g., the breached clay and the groundwater flow directions) will be included as much as possible in the BRAGS model.

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APPENDIX A
MODFLOW INPUT AND OUTPUT FILES FOR CALIBRATED STEADY-STATE GROUNDWATER FLOW MODEL (CD-ROM)

APPENDIX B
MODPATH INPUT AND OUTPUT FILES FOR CALIBRATED STEADY-STATE GROUNDWATER FLOW MODEL (CD-ROM)

APPENDIX C
NC DENR GROUNDWATER DISCHARGE TO SURFACE WATER MODEL CALCULATIONS (G3CTM)

TABLE A1.1. WORK TABLE FOR DETERMINING GROUNDWATER TARGET CONCENTRATIONS.

See Worksheet A1.1 For Instructions On Completing This Work Table.

DATE: March 17, 1998
SITE: Site 73, MCB Camp Lejeune
COUNTY: Onslow
MAILING ADDRESS: ____________________

INCIDENT NUMBER: ____________________
RESPONSIBLE PARTY: ____________________
PHONE NUMBER: ____________________

All concentrations are in mg/L.

I	II	III	IV	V	VI	VII
Contaminants Found in Groundwater	Maximum Groundwater Concentration at Site	Target Concentrations by Groundwater Category			Required Groundwater Target Concentration*	Groundwater Category and Method
		G-1	G-2	G-3		
TCE (surficial)	46 ug/L			818	818 ug/L	G-3 II
DCE (surficial)	72 ug/L			16,200	16,200 ug/L	G-3 II
VC (surficial)	43 ug/L			15	15 ug/L	G-3 II
TCE (deep)	320 ug/L			994	994 ug/L	G-3 II
DCE (deep)	120 ug/L			5.53e+6	5.53e+6 ug/L	G-3 II
VC (deep)	4 ug/L			15	15 ug/L	G-3 II

* Lowest of the three target concentrations in Columns III through V unless none of the categories applied. If none of the categories apply, then enter the concentration for CCL where: CCL = the lower of 1000 times Groundwater quality standard (or interim groundwater quality standard) and 50% of the aqueous solubility of the contaminant.

DATAFILE NAME: TCE-MW27.DAT
North Caroline Department of Environment and Natural Resources
Risk Assessment, Category G-3, Method II
G-3 Groundwater Contaminant Transport model

INPUT PARAMETERS:

CONTAMINANT CHEMICAL NAME		Trichloroethene
SURFACE WATER CHEMICAL STANDARD	(mg/l)	0.0924
DISTANCE FROM P.L.E. TO SURFACE WATER BODY (P.L.E. = PLUME LEADING EDGE)	(Feet)	660
AQUIFER HYDRAULIC CONDUCTIVITY	(Feet/Day)	3
AQUIFER GROUNDWATER GRADIENT	(Feet/Feet)	0.01
AQUIFER EFFECTIVE POROSITY	(unitless)	0.2
AQUIFER DISPERSION COEFFICIENT	(Feet^2/Day)	66
CHEMICAL RETARDATION FACTOR	(unitless)	1.0
CHEMICAL BIODEGRADATION DECAY RATE	(1/Day)	0.0
LENGTH OF CONTAMINANT PLUME	(Feet)	300
THICKNESS OF SURFICIAL AQUIFER	(Feet)	15
WIDTH OF CONTAMINANT PLUME	(Feet)	300
7Q10 OF RIVER OR STREAM	(Feet^3/Second)	0.002
UP-STREAM CHEMICAL CONCENTRATION	(mg/l)	0

MODELING RESULTS:
Maximum Groundwater Contaminant Concentration at Surface Water Boundary
occurs at Time = 0.8674E+01 years
with Groundwater Concentration C/Csource = 0.2576E+00
where Csource = Maximum Source Concentration

Maximum Groundwater Source Concentration = 0.8178E+00 mg/l
for the chemical Trichloroethene

DATAFILE NAME: TCE-DW03.DAT
North Caroline Department of Environment and Natural Resources
Risk Assessment, Category G-3, Method II
G-3 Groundwater Contaminant Transport model

INPUT PARAMETERS:

CONTAMINANT CHEMICAL NAME		Trichloroethene
SURFACE WATER CHEMICAL STANDARD	(mg/l)	0.0924
DISTANCE FROM P.L.E. TO SURFACE WATER BODY (P.L.E. = PLUME LEADING EDGE)	(Feet)	380
AQUIFER HYDRAULIC CONDUCTIVITY	(Feet/Day)	3
AQUIFER GROUNDWATER GRADIENT	(Feet/Feet)	0.001
AQUIFER EFFECTIVE POROSITY	(unitless)	0.2
AQUIFER DISPERSION COEFFICIENT	(Feet^2/Day)	38
CHEMICAL RETARDATION FACTOR	(unitless)	1.0
CHEMICAL BIODEGRADATION DECAY RATE	(1/Day)	0.0
LENGTH OF CONTAMINANT PLUME	(Feet)	300
THICKNESS OF SURFICIAL AQUIFER	(Feet)	60
WIDTH OF CONTAMINANT PLUME	(Feet)	300
7Q10 OF RIVER OR STREAM	(Feet^3/Second)	0.001
UP-STREAM CHEMICAL CONCENTRATION	(mg/l)	0

MODELING RESULTS:
Maximum Groundwater Contaminant Concentration at Surface Water Boundary
occurs at Time = 0.5618E+02 years
with Groundwater Concentration C/Csource = 0.2418E+00
where Csource = Maximum Source Concentration

Maximum Groundwater Source Concentration = 0.9937E+00 mg/l
for the chemical Trichloroethene

DATAFILE NAME: DCE-MW09.DAT
North Caroline Department of Environment and Natural Resources
Risk Assessment, Category G-3, Method II
G-3 Groundwater Contaminant Transport model

INPUT PARAMETERS:

CONTAMINANT CHEMICAL NAME		cis-1,2-DCE
SURFACE WATER CHEMICAL STANDARD	(mg/l)	7.0
DISTANCE FROM P.L.E. TO SURFACE WATER BODY (P.L.E. = PLUME LEADING EDGE)	(Feet)	50
AQUIFER HYDRAULIC CONDUCTIVITY	(Feet/Day)	3
AQUIFER GROUNDWATER GRADIENT	(Feet/Feet)	0.032
AQUIFER EFFECTIVE POROSITY	(unitless)	0.2
AQUIFER DISPERSION COEFFICIENT	(Feet^2/Day)	5
CHEMICAL RETARDATION FACTOR	(unitless)	1.0
CHEMICAL BIODEGRADATION DECAY RATE	(1/Day)	0.0
LENGTH OF CONTAMINANT PLUME	(Feet)	125
THICKNESS OF SURFICIAL AQUIFER	(Feet)	15
WIDTH OF CONTAMINANT PLUME	(Feet)	100
7Q10 OF RIVER OR STREAM	(Feet^3/Second)	0.002
UP-STREAM CHEMICAL CONCENTRATION	(mg/l)	0

MODELING RESULTS:
Maximum Groundwater Contaminant Concentration at Surface Water Boundary
occurs at Time = 0.7757E+00 years
with Groundwater Concentration C/Csource = 0.9524E+00
where Csource = Maximum Source Concentration

Maximum Groundwater Source Concentration = 0.1617E+02 mg/l
for the chemical cis-1,2-DCE

DATAFILE NAME: DCE-A3-8.DAT
North Caroline Department of Environment and Natural Resources
Risk Assessment, Category G-3, Method II
G-3 Groundwater Contaminant Transport model

INPUT PARAMETERS:

CONTAMINANT CHEMICAL NAME		cis-1,2-DCE
SURFACE WATER CHEMICAL STANDARD	(mg/l)	7.0
DISTANCE FROM P.L.E. TO SURFACE WATER BODY (P.L.E. = PLUME LEADING EDGE)	(Feet)	290
AQUIFER HYDRAULIC CONDUCTIVITY	(Feet/Day)	3
AQUIFER GROUNDWATER GRADIENT	(Feet/Feet)	0.01
AQUIFER EFFECTIVE POROSITY	(unitless)	0.2
AQUIFER DISPERSION COEFFICIENT	(Feet^2/Day)	29
CHEMICAL RETARDATION FACTOR	(unitless)	1.0
CHEMICAL BIODEGRADATION DECAY RATE	(1/Day)	0.0
LENGTH OF CONTAMINANT PLUME	(Feet)	200
THICKNESS OF SURFICIAL AQUIFER	(Feet)	15
WIDTH OF CONTAMINANT PLUME	(Feet)	200
7Q10 OF RIVER OR STREAM	(Feet^3/Second)	0.002
UP-STREAM CHEMICAL CONCENTRATION	(mg/l)	0

MODELING RESULTS:
Maximum Groundwater Contaminant Concentration at Surface Water Boundary
occurs at Time = 0.4817E+01 years
with Groundwater Concentration C/Csource = 0.3703E+00
where Csource = Maximum Source Concentration

Maximum Groundwater Source Concentration = 0.5520E+02 mg/l
for the chemical cis-1,2-DCE

DATAFILE NAME: DCE-DW03.DAT
North Caroline Department of Environment and Natural Resources
Risk Assessment, Category G-3, Method II
G-3 Groundwater Contaminant Transport model

INPUT PARAMETERS:

CONTAMINANT CHEMICAL NAME		cis-1,2-DCE
SURFACE WATER CHEMICAL STANDARD	(mg/l)	7.0
DISTANCE FROM P.L.E. TO SURFACE WATER BODY (P.L.E. = PLUME LEADING EDGE)	(Feet)	500
AQUIFER HYDRAULIC CONDUCTIVITY	(Feet/Day)	3
AQUIFER GROUNDWATER GRADIENT	(Feet/Feet)	0.001
AQUIFER EFFECTIVE POROSITY	(unitless)	0.2
AQUIFER DISPERSION COEFFICIENT	(Feet^2/Day)	50
CHEMICAL RETARDATION FACTOR	(unitless)	1.0
CHEMICAL BIODEGRADATION DECAY RATE	(1/Day)	0.0
LENGTH OF CONTAMINANT PLUME	(Feet)	300
THICKNESS OF SURFICIAL AQUIFER	(Feet)	60
WIDTH OF CONTAMINANT PLUME	(Feet)	300
7Q10 OF RIVER OR STREAM	(Feet^3/Second)	1.0
UP-STREAM CHEMICAL CONCENTRATION	(mg/l)	0

MODELING RESULTS:
Maximum Groundwater Contaminant Concentration at Surface Water Boundary occurs at Time = 0.5658E+02 years
with Groundwater Concentration C/Csource = 0.2025E+00
where Csource = Maximum Source Concentration

Maximum Groundwater Source Concentration = 0.5535E+05 mg/l
for the chemical cis-1,2-DCE

DATAFILE NAME: VC-A3-8.DAT
North Caroline Department of Environment and Natural Resources
Risk Assessment, Category G-3, Method II
G-3 Groundwater Contaminant Transport model

INPUT PARAMETERS:

CONTAMINANT CHEMICAL NAME		Vinyl Chloride
SURFACE WATER CHEMICAL STANDARD	(mg/l)	0.525
DISTANCE FROM P.L.E. TO SURFACE WATER BODY (P.L.E. = PLUME LEADING EDGE)	(Feet)	290
AQUIFER HYDRAULIC CONDUCTIVITY	(Feet/Day)	3
AQUIFER GROUNDWATER GRADIENT	(Feet/Feet)	0.01
AQUIFER EFFECTIVE POROSITY	(unitless)	0.2
AQUIFER DISPERSION COEFFICIENT	(Feet^2/Day)	29
CHEMICAL RETARDATION FACTOR	(unitless)	1.0
CHEMICAL BIODEGRADATION DECAY RATE	(1/Day)	0.0
LENGTH OF CONTAMINANT PLUME	(Feet)	200
THICKNESS OF SURFICIAL AQUIFER	(Feet)	15
WIDTH OF CONTAMINANT PLUME	(Feet)	200
7Q10 OF RIVER OR STREAM	(Feet^3/Second)	0.002
UP-STREAM CHEMICAL CONCENTRATION	(mg/l)	0

MODELING RESULTS:
Maximum Groundwater Contaminant Concentration at Surface Water Boundary
occurs at Time = 0.4817E+01 years
with Groundwater Concentration C/Csource = 0.3703E+00
where Csource = Maximum Source Concentration

Maximum Groundwater Source Concentration = 0.4140E+01 mg/l
for the chemical Vinyl Chloride

DATAFILE NAME: VC-MW09.DAT
North Caroline Department of Environment and Natural Resources
Risk Assessment, Category G-3, Method II
G-3 Groundwater Contaminant Transport model

INPUT PARAMETERS:

CONTAMINANT CHEMICAL NAME		Vinyl Chloride
SURFACE WATER CHEMICAL STANDARD	(mg/l)	0.525
DISTANCE FROM P.L.E. TO SURFACE WATER BODY (P.L.E. = PLUME LEADING EDGE)	(Feet)	50
AQUIFER HYDRAULIC CONDUCTIVITY	(Feet/Day)	3
AQUIFER GROUNDWATER GRADIENT	(Feet/Feet)	0.032
AQUIFER EFFECTIVE POROSITY	(unitless)	0.2
AQUIFER DISPERSION COEFFICIENT	(Feet^2/Day)	5
CHEMICAL RETARDATION FACTOR	(unitless)	1.0
CHEMICAL BIODEGRADATION DECAY RATE	(1/Day)	0.0
LENGTH OF CONTAMINANT PLUME	(Feet)	125
THICKNESS OF SURFICIAL AQUIFER	(Feet)	15
WIDTH OF CONTAMINANT PLUME	(Feet)	100
7Q10 OF RIVER OR STREAM	(Feet^3/Second)	0.002
UP-STREAM CHEMICAL CONCENTRATION	(mg/l)	0

MODELING RESULTS:
Maximum Groundwater Contaminant Concentration at Surface Water Boundary
occurs at Time = 0.7757E+00 years
with Groundwater Concentration C/Csource = 0.9524E+00
where Csource = Maximum Source Concentration

Maximum Groundwater Source Concentration = 0.1213E+01 mg/l
for the chemical Vinyl Chloride

DATAFILE NAME: VC-DW03.DAT
North Caroline Department of Environment and Natural Resources
Risk Assessment, Category G-3, Method II
G-3 Groundwater Contaminant Transport model

INPUT PARAMETERS:

CONTAMINANT CHEMICAL NAME		Vinyl Chloride
SURFACE WATER CHEMICAL STANDARD	(mg/l)	0.525
DISTANCE FROM P.L.E. TO SURFACE WATER BODY (P.L.E. = PLUME LEADING EDGE)	(Feet)	500
AQUIFER HYDRAULIC CONDUCTIVITY	(Feet/Day)	3
AQUIFER GROUNDWATER GRADIENT	(Feet/Feet)	0.001
AQUIFER EFFECTIVE POROSITY	(unitless)	0.2
AQUIFER DISPERSION COEFFICIENT	(Feet^2/Day)	50
CHEMICAL RETARDATION FACTOR	(unitless)	1.0
CHEMICAL BIODEGRADATION DECAY RATE	(1/Day)	0.0
LENGTH OF CONTAMINANT PLUME	(Feet)	300
THICKNESS OF SURFICIAL AQUIFER	(Feet)	60
WIDTH OF CONTAMINANT PLUME	(Feet)	300
7Q10 OF RIVER OR STREAM	(Feet^3/Second)	0.001
UP-STREAM CHEMICAL CONCENTRATION	(mg/l)	0

MODELING RESULTS:
Maximum Groundwater Contaminant Concentration at Surface Water Boundary
occurs at Time = 0.5658E+02 years
with Groundwater Concentration C/Csource = 0.2025E+00
where Csource = Maximum Source Concentration

Maximum Groundwater Source Concentration = 0.6741E+01 mg/l
for the chemical Vinyl Chloride

From: "Dianne Reid" <dianne_reid@h2o.enr.state.nc.us>
To: Dan Fisher <DFISHER@mbakercorp.com>
Date: 3/10/98 4:14pm
Subject: Re: SW standard for DCE in the New River

Use 7000 ug/l. This is based on EPA's AQUIRE database, a 96hr LC50 for bluegill of 140,000 ug/l and a safety factor of 0.05 per 15A NCAC 2B .0208.

I reviewed available EPA data on both cis & trans 1,2-dichloroethene and found very little information available. EPA does have a criteria for trans 1,2-dichloroethene of 140,000 ug/l for organism consumption. However, due to the small dataset available for cis 1,2-DCE no national criteria have been promulgated.

Let me know if you have further questions, e-mail or 919.733.5083 x 568.

Dan Fisher wrote:

> Ms. Reid,
>
> I'm sorry if you get this message twice but I saw two addresses on the
> internet listing...
>
> I was referred to you by Dave Lown of the Superfund Groundwater
> Section to obtain a site-specific surface water quality standard for
> cis-1,2-dichloroethene (DCE) for the Amphibious Vehicle Maintenance
> Area (Site 73) along Courthouse Bay at MCB, Camp Lejeune. I will use
> the SW standard in the G3CTM model to calculate the allowable
> groundwater concentrations of DCE at the site.
>
> The final report is due at the end of this month. I apologize because I
> know that doesn't give you much time, but I just started my work on this,
> too.
>
> Feel free to call me directly at the number below or email.
>
> Thanks.
>
> Daniel S. Fisher, P.G.   Senior Hydrogeologist
> +++
> Baker Environmental, Inc./ Michael Baker Corporation
> 420 Rouser Road - Airport Office Park Building 3
> Coraopolis, PA 15108 e-mail: dfisher@mbakercorp.com
> Tel. (412) 269-6018   Fax. (412) 269-6057
> Corporate Home Page: http://www.mbakercorp.com
> +++
> "Only two things make government work in America
> and that is religion and morality. You could never
> call yourself a patriot if you tried to separate
> religion and morality from politics."
>   - George Washington
> +++