SIMULATION OF A SOLVENT PLUME IN A SAND AND GRAVEL AQUIFER IN CAPE COD, MASSACHUSETTS USING A 3-D NUMERICAL MODEL

by

ALBERTO M. LÁZARO

B.S., Civil Engineering
Cornell University, 1995

Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING
in Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1996

Signature of the Author Alberto M. Lázaro
Department of Civil and Environmental Engineering
May 10, 1996

Certified by Lynn W. Gelhar
Lynn W. Gelhar
William E. Leonhard Professor of
Civil and Environmental Engineering
Thesis Supervisor

Accepted by Joseph Sussman
Professor Joseph M. Sussman, Chairman
Departmental Committee on Graduate Studies

SIMULATION OF A SOLVENT PLUME IN A SAND AND GRAVEL AQUIFER IN CAPE COD, MASSACHUSETTS USING A 3-D NUMERICAL MODEL

by

ALBERTO M. LÁZARO

Submitted to the Department of Civil and Environmental Engineering
on May 10, 1996 in Partial Fulfillment of the Requirements for the
Degree of Master of Engineering in Civil and Environmental Engineering

ABSTRACT

A groundwater flow model of a portion of the western Cape Cod aquifer is developed using information from previously performed site characterization studies. This groundwater flow model is conceived in order to simulate the Chemical Spill 4 (CS-4) plume emanating from the Massachusetts Military Reservation, and to use this information to execute remediation simulations.

During its development, it is found that the model is very sensitive to subtle changes in both near and far field aquifer properties. The model is first calibrated based on hydraulic head considerations only. The introduction of particles to perform transport simulations demonstrates that the model needs further calibration, since modeled concentrations do not coincide with field observations. Modification of aquifer properties results in similar head distributions and errors, but very different particle pathlines. Calibration based on hydraulic head alone is therefore insufficient for transport simulations in similar heterogeneous aquifers. The development of the model also suggests that simulating the whole western Cape Cod aquifer, instead of only the area of concern, is probably better practice.

The CS-4 plume's source load is determined by comparing field and model observations. The total mass of solvents in the aquifer is estimated to be 288 kg, which is approximately equivalent to one 55 gallon drum. This shows that a small contaminant source can lead to a spatially extensive groundwater contamination problem as reflected in the CS-4 plume.

The model produces a plume with a length of 12,600 ft, an average width of 1,180 ft, and an average height of 40 ft. These measurements are significantly different to the plume interpretation reported by ABB Environmental Services Inc. These differences do not necessarily disprove this model, but does suggest that more field data is needed in order to adequate characterize the CS-4 plume. The use of a similar model during the site investigation could have significantly improved the efficiency of the data gathering phase.

The groundwater flow model is used to simulate two different remediation alternatives. The first simulation, the no treatment alternative, shows that the aquifer below the MMR would be naturally flushed after approximately 80 years after the source is eliminated. The second simulation modeled the well fence currently operating at the MMR. It showed that the pump and treat system would need to run for approximately 70 years in order to reach acceptable concentrations levels. During this simulation, some particles escaped the well fence suggesting, that the migration of a larger plume may not be completely contained by the current system. These simulations indicate that a final remediation scheme should be implemented as a cost and time efficient alternative to a pump and treat system.

Thesis Supervisor: Lynn W. Gelhar
Title: William E. Leonhard Professor of Civil and Environmental Engineering

ACKNOWLEDGMENTS

I would like to thank Professor Lynn Gelhar for being such an instrumental part in the development of this work and in my growth as an engineer. His vast knowledge, care, kindness, and his overall good attitude have supported and guided me throughout the year. Along these same lines, it is also important to mention the help received from Bruce Jacobs. Bruce, the genius behind the DynSystem, always gave more than he was ever asked for.

I would also like to thank Professor David Marks and Shawn Morrissey for helping make the M.Eng. ride a fun and exiting. The support and enthusiasm they have given me have helped me adapt to the shock of graduate school. Special thanks to Mr. Denis LeBlanc of the USGS and Mr. Edward Pesce and his staff at the IRP office in the MMR for generously sharing their time and knowledge.

The team members of the "CS-4 project" must also be acknowledged. Christine Picazo, who always gave me her good humor; Donald Tillman and Pete Skiadas, who entertained me with their discussions; Crist Khachikian, who made me see the light at the end of the tunnel; and specially to Enrique López-Calva, with whom I spent many long hours in the development of the model and learned so much from. I would also like to thank Kishan Amarasekera, fellow modeler and friend. In fact, I would need to mention all the people in the program, who made the long days and nights in the M.Eng. Room seem a little shorter.

My acknowledgments would certainly not be complete without mentioning my family. I would like to thank my mother and my father for all their sacrifices and for giving me the support I have needed throughout my college years. Without them the road would have been much more arduous. Special thanks goes to my uncle and role model, Gerry Sarriera, who has definitively shaped the person I am today.

Last, I would like to thank my girlfriend, Vanessa. She has been there for me through the years and miles. Even when work made my mood and spirits less than what she deserved, she understood and supported me throughout the way.

This thesis is dedicated to the memory of my sister,
Teresa I. Lázaro (1972-1993), who left
engineering to become my guardian angel.

Table of Contents

ABSTRACT **2**

ACKNOWLEDGMENTS **3**

LIST OF FIGURES **6**

LIST OF TABLES **8**

1. INTRODUCTION **9**

1.1. PROBLEM 9
1.2. OBJECTIVES 9
1.3. SCOPE 10

2. SITE DESCRIPTION **12**

2.1. LOCATION 12
2.2. GEOPOLITICS AND DEMOGRAPHICS 13
2.3. GENERAL PHYSICAL SITE DESCRIPTION 14
2.4. NATURAL RESOURCES 14
2.5. LAND AND WATER USE 15
2.6. MMR SETTING AND HISTORY 16
2.7. CURRENT SITUATION 17
  2.7.1. Plume Location *17*
  2.7.2. Current Remedial Action *17*
  2.7.3. Performance of Current Remediation Scheme *18*
  2.7.4. Treatment Levels *19*

3. PHYSICAL CHARACTERIZATION OF THE WESTERN CAPE **20**

3.1 GEOLOGY 20
3.2 HYDROLOGY 21
3.3 HYDROGEOLOGY 23
  3.3.1 Grain Size *23*
  3.3.2 Hydraulic Conductivity *23*
  3.3.3 Anisotropy Ratio *25*
  3.3.4 Porosity *25*
  3.3.5 Hydraulic Gradient *25*
3.4 OTHER PARAMETERS 26

4. HYDROLOGIC FLOW MODEL **27**

4.1 DESCRIPTION OF THE MODEL 27
4.2 APPROACH 27
4.3 GEOMETRIC BOUNDARIES 28
4.4 HYDRAULIC BOUNDARIES 29
4.5 DISCRETIZATION 30
4.6 APPLICATION OF AQUIFER PROPERTIES TO THE MODEL 30
  4.6.1 Hydraulic conductivity *31*
  4.6.2 Recharge *33*
  4.6.3 Hydraulic head *34*
  4.6.4 Aquifer thickness *34*

4.6.5 Dispersivity ... *35*
4.6.6 Sorption ... *36*
4.6.7 Other Parameters ... *37*
4.7 CALIBRATION ... 38
4.7.1 Hydraulic Head Calibration ... *38*
4.7.2 Calibration Using Particle Tracking ... *42*

5. CONTAMINANT TRANSPORT MODEL ... 56

5.1 CS-4 SOURCE ... 56
5.2 PLUME DIMENSIONS AND LOCATION ... 61
5.3 TRANSPORT SIMULATIONS ... 66
5.3.1 Natural Flushing ... *66*
5.3.2 Simulation Using Current Pumping Scheme ... *70*

6. DISCUSSION AND CONCLUSIONS ... 75

REFERENCES ... 77

APPENDIX A ... 83

EXECUTIVE SUMMARY OF THE MASTER OF ENGINEERING GROUP REPORT (CS-4 TEAM) ... 83

APPENDIX B- RESULTS FROM THE MASTER OF ENGINEERING PROJECT REPORT ... 88

B.1 EQUILIBRIUM SORPTION RESULTS ... 88
B.1.1 Effects of Sorption on Contaminant Transport ... *89*
B.2 MODELING PUMPING SCHEMES FOR REMEDIATION ... 92
B.2.1 Pumping Schemes for Remediation ... *92*
B.3 BIOREMEDIATION ... 99
B.3.1 General Considerations ... *99*
B.3.2 Cometabolic Oxidation and Reductive Dechlorination ... *100*
B.3.3 Process Design ... *100*
B.3.4 Phase 1 ... *101*
B.3.5 Phase 2 ... *101*
B.3.6 Phase 3 ... *102*
B.3.7 Discussion ... *103*
B.4 ABOVEGROUND TREATMENT ALTERNATIVE ... 105
B.4.1 Scenarios of inflow concentration ... *106*
B.4.2 Combination of abiotic dehalogenation and GAC ... *107*
B.4.3 Discussion ... *108*
B.5 RISK ... 109
B.5.1 Introduction ... *109*
B.5.2 Results ... *110*
B.5.3 Discussion ... *113*

APPENDIX C ... 115

DYNSYSTEM FILES ... 115

List of Figures

FIGURE 2-1: MAP OF THE COMMONWEALTH OF MASSACHUSETTS 12
FIGURE 2-2:LOCATION OF MMR 13
FIGURE 3-1: HYDROLOGIC FEATURES OF WESTERN CAPE COD 22
FIGURE 4-1: AREA OF THE WESTERN CAPE WHICH WAS MODELED 29
FIGURE 4-2: PLAN VIEW OF THE SURFACE MATERIALS USED IN THE MODEL. 31
FIGURE 4-3: NORTH-SOUTH CROSS SECTION (AA) WHICH SHOWS THE STRATIGRAPHY USED IN THE MODEL 32
FIGURE 4-4: EAST-WEST CROSS SECTION (BB) WHICH SHOWS THE STRATIGRAPHY USED IN THE MODEL. 33
FIGURE 4-5: DISTRIBUTION OF THE DIFFERENCES IN CALCULATED MINUS OBSERVED HEAD AFTER CALIBRATION BASED ON HYDRAULIC HEAD CONSIDERATIONS ONLY. 40
FIGURE 4-6: PLAN VIEW OF INITIAL PATHLINE OF A PARTICLE FROM THE CS-4 SITE USING THE MODEL CALIBRATED BASED ONLY ON HYDRAULIC HEAD CONSIDERATIONS 42
FIGURE 4-7: NORTH-SOUTH CROSS SECTION OF INITIAL PATHLINE OF A PARTICLE FROM THE CS-4 SITE USING THE MODEL CALIBRATED BASED ONLY ON HYDRAULIC HEAD CONSIDERATIONS 43
FIGURE 4-8: SENSITIVITY ANALYSIS ON SOURCE LOCATION 44
FIGURE 4-9: PARTICLE TRACK FROM THE CENTER OF THE CS-4 SOURCE 45
FIGURE 4-10: PATHLINE AFTER HEADS WERE DECREASED IN ASHUMET AND JOHN'S PONDS 46
FIGURE 4-11: PATHLINE AFTER CONDUCTIVITIES WERE DECREASED IN THE BBM 48
FIGURE 4-12: NORTH-SOUTH CROSS SECTION OF PATHLINE AFTER CONDUCTIVITIES WERE DECREASED IN THE BBM 49
FIGURE 4-13: DETAIL OF ORIGINAL GRID 50
FIGURE 4-14: DETAIL OF MODIFIED GRID 50
FIGURE 4-15: PLAN VIEW OF THE PATHLINE AFTER THE FINITE ELEMENT GRID WAS MODIFIED 51
FIGURE 4-16: NORTH-SOUTH CROSS SECTION OF PATHLINE AFTER CONDUCTIVITIES WERE MODIFIED IN THE OUTWASH 52
FIGURE 4-17: FINAL DISTRIBUTION OF THE DIFFERENCES IN CALCULATED MINUS OBSERVED HEAD AFTER PARTICLE TRACKING CALIBRATION 54
FIGURE 5-1: CS-4 SITE (AOC CS-4) AND PLUME AS PRESENTED BY ABB ENVIRONMENTAL SERVICES INC. (1992a). 57
FIGURE 5-2: MAP SHOWING THE AREA THOUGHT TO BE THE SOURCE AREA OF THE CS-4 PLUME (AOC CS-4) FROM ABB ENVIRONMENTAL SERVICES INC. (1992a). 58
FIGURE 5-3: SOURCE LOADINGS FOR THE CS-4 MODEL 60
FIGURE 5-4: DISTRIBUTION OF PARTICLES IN THE CS-4 PLUME SIMULATION 61
FIGURE 5-5: PLAN VIEW OF MAXIMUM CONCENTRATION CONTOURS 62
FIGURE 5-6: NORTH-SOUTH CROSS SECTION OF CS-4 PLUME 63
FIGURE 5-7: EAST-WEST CROSS SECTION OF PLUME THROUGH MW603 WELL CLUSTER 64
FIGURE 5-8: SIMULATION YEAR 1993. NATURAL FLUSHING SIMULATION 67
FIGURE 5-9: SIMULATION YEAR 2008. NATURAL FLUSHING SIMULATION 67
FIGURE 5-10: SIMULATION YEAR 2023. NATURAL FLUSHING SIMULATION 68
FIGURE 5-11: SIMULATION YEAR 2038. NATURAL FLUSHING SIMULATION 68
FIGURE 5-12: SIMULATION YEAR 2063. NATURAL FLUSHING SIMULATION 69
FIGURE 5-13: SIMULATION YEAR 2073. NATURAL FLUSHING SIMULATION 69
FIGURE 5-14: SIMULATION YEAR 1993. CURRENT PUMPING SCHEME SIMULATION 71
FIGURE 5-15: SIMULATION YEAR 1993. CURRENT PUMPING SCHEME SIMULATION 71
FIGURE 5-16: SIMULATION YEAR 2023. CURRENT PUMPING SCHEME SIMULATION 72
FIGURE 5-17: SIMULATION YEAR 2038. CURRENT PUMPING SCHEME SIMULATION 72

FIGURE 5-18: SIMULATION YEAR 2058. CURRENT PUMPING SCHEME SIMULATION...................... 73
FIGURE 5-19: SIMULATION YEAR 2063. CURRENT PUMPING SCHEME SIMULATION...................... 73
FIGURE B-1: LOCATION OF WELL S315 RELATIVE TO THE CENTERLINE OF THE CS-4 PLUME.. 88
FIGURE B-2. RELATIONSHIP BETWEEN f_{om} AND K WITH DEPTH (A). EXPERIMENTALLY DETERMINED RETARDATION FACTORS(B).. 90
FIGURE B-3: CAPTURE CURVE SIMULATION OF THE IRP WELL FENCE. 93
FIGURE B-4: DIAGRAM EXPLAINING THE MEANING OF THE "PLOT STARTING POINTS" FIGURES, ... 94
FIGURE B-5: CROSS-SECTIONAL AREAS OF THE CAPTURE CURVE 1,500 FEET UPGRADIENT OF THE 13-WELL SYSTEM (IRP WELL FENCE).. 95
FIGURE B-6: CROSS-SECTIONAL AREAS OF THE CAPTURE CURVE 1,500 FEET UPGRADIENT OF THE 7-WELL SYSTEM, PUMPING A TOTAL OF 140 GPM... 97
FIGURE B-7: NORTH-SOUTH CROSS-SECTION SHOWING THE CONCEPTUAL BIOREMEDIATION SCHEME.. 102
FIGURE B-8: NORMALIZED CONTAMINANT CONCENTRATIONS AS A FUNCTION OF DISTANCE 103
FIGURE B-9: SCHEMATIC DIAGRAM OF COMBINATION OF ZERO-VALENT IRON WITH GAC SYSTEM 105
FIGURE B-10: CARCINOGENIC RISK... 112
FIGURE B-11: NON-CARCINOGENIC RISK... 112

List of Tables

TABLE 2-1 CONTAMINANTS OF CONCERN AND TREATMENT TARGET LEVEL 19
TABLE 3-1. ESTIMATES OF HYDRAULIC CONDUCTIVITY (ADAPTED FROM MASTERSON AND BARLOW, 1994). 24
TABLE 4-1: DISPERSIVITY VALUES OF THE ASHUMET VALLEY TRACER TEST (FROM GARABEDIAN ET AL., 1988) 35
TABLE 4-2: EFFECTIVE RETARDATION FACTORS 37
TABLE 4-3: HYDROGEOLOGIC PARAMETERS RESULTING FROM THE GROUNDWATER-FLOW MODEL AFTER CALIBRATION BASED ON HYDRAULIC HEAD ONLY. 41
TABLE 4-4: ORIGINAL AND MODIFIED VALUES OF HYDRAULIC CONDUCTIVITY IN THE FOUR LAYERS OF THE BBM 47
TABLE 4-5: ORIGINAL AND MODIFIED VALUES OF HYDRAULIC CONDUCTIVITY AND ANISOTROPY RATIO IN THE UPPER TWO LAYERS OF THE OUTWASH 52
TABLE 4-6: ORIGINAL AND MODIFIED VALUES OF HYDRAULIC CONDUCTIVITY IN THE SOUTHERN OUTWASH 53
TABLE 4-7: HYDROGEOLOGIC PARAMETERS RESULTING FROM THE GROUNDWATER-FLOW MODEL AFTER CALIBRATION BASED ON HYDRAULIC HEAD ONLY. 55
TABLE 5-1: DIMENSIONS OF MODELED PLUME 65
TABLE B-1: SAND IDENTIFICATION INCLUDING LABORATORY MEASURED f_{oc}s AND HYDRAULIC CONDUCTIVITIES, K 89
TABLE B-2:. K_d' VALUES CALCULATED FROM THE LINEAR EQUILIBRIUM SORPTION EQUATION. 89
TABLE B-3:. EFFECTIVE RETARDATION FACTORS 90
TABLE B-4: VALUES OF THE RETARDED LONGITUDINAL MACRODISPERSIVITY, A_{11} 91
TABLE B-5: SIMULATIONS TO PREDICT AN ALTERNATIVE EFFECTIVE CAPTURE ZONE FOR CS-4 PLUME. 96
TABLE B-6: RESULTING NORMALIZED CONCENTRATION OF TCE, DCE, AND VC. 102
TABLE B-7: FOUR SCENARIOS FOR INFLUENT CONCENTRATIONS 107
TABLE B-8: NET SAVINGS OF THE COMBINATION OF GAC AND ZERO-VALENT IRON 107
TABLE B-9: CONTAMINANT LEVELS AFTER CLEANUP THROUGH BIOREMEDIATION 111
TABLE B-10: CONTAMINANT LEVELS AFTER CLEANUP THROUGH BIOREMEDIATION AND PUMP AND TREAT 111
TABLE B-11: RISKS ASSOCIATED WITH REMEDIATION SCHEMES 111

1.Introduction

1.1. Problem

The Cape Cod aquifer is contaminated by various pollutants emanating from the Massachusetts Military Reservation (MMR). One such plume of contaminants, termed Chemical Spill 4 (CS-4), is the only one that so far is being contained. At present, a pump and treat system has been installed to prevent the advancement of the plume. Contaminated water is extracted at the toe of the plume, treated to reduce the contaminant concentrations to federal maximum contaminant levels, and discharged back to the aquifer. However, this pump and treat system is an expensive interim remedial action. A final remedial plan must be formulated to completely clean up the groundwater.

1.2. Objectives

This thesis is submitted in partial fulfillment of the requirements of the Master of Engineering degree of the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technnology. It addresses one aspect of a multi-faceted engineering team project undertaken by a group of six students of the Master of Engineering Program. The team report had as objective to understand the transport mechanisms of the Cape Cod aquifer and to use this information to develop a final remediation scheme. The executive summary of this team's report is included in Appendix A.

This work addresses part of the team's project objective, and itself has three objectives. The first objective of this work is to be able to completly comprehend the natural flow and transport conditions of groundwater and contaminants in the Cape Cod aquifer. To accomplish this, it is necessary to establish a firm understanding of the hydrology, geology, hydrogeology, and geochemistry of the aquifer. Using inferred, calculated and predicted values for the above-mentioned factors, a computer model is established that adequately represents the existing conditions.

The second objective, is to develop a model of the CS-4 solvent plume. Once the flow field is characterized, particles representing contaminants are introduced in increments representing likely contaminant release at the CS-4 site. These contaminants are tracked and a "modeled plume" is obtained.

The third objective is to use the natural flow model model in conjunction with the plume model to perform remediation simulations. Two simulations of interest are the no action option and the simulation of the current pumping scheme at the MMR. These simulations could be useful in the prediction of clean-up times and in the design of a final remedial system.

1.3. Scope

This report covers the technical aspects of the current situation of the CS-4 plume at the MMR Superfund site, and describes the development and use of a groundwater flow model of the area.

First the site is described briefly. General background information is provided as well as the history of the activities at MMR. These data are needed to understand the context and importance of the groundwater contamintation. The current situation at the CS-4 site is presented, including an overview of the plume extent and a description of the existing interim remedial action.

Next, site characterization is addressed. The presented physical properties of the site are based on the review of previous studies of the area as part of the Installation Restoration Program (IRP), and on other studies of the site not necessarily related to the contamination problem. This site assessment is needed to develop the conceptual model, assign hydrogeologic properties to the area of the aquifer modeled, and help in the model calibration. Also included in this chapter are results regarding the sorption behavior of the contaminants, which were found by conducting laboratory studies.

Subsequently, the development of the hydrologic flow model is presented. Descriptions of the model's assumptions and of how it was conceived are covered comprehensively. Groundwater hydrology and theory are not discussed, since it is assumed that the reader will have the proper background. The model calibration process and sensitivity is also described in detail.

The contaminant transport model is presented next, along with the assumptions and information needed for its development. A modeled plume is obtained and its dimensions and location are presented. A comparison is drawn between the model and the current IRP plume interpretations. The model is then used to perform simulations of two remediation alternatives, in order to predict the clean-up times of the two options examined.

In order to provide a better picture of the applicability of the model and of the overall problem, Appendix A and B are included. In them, the executive summary of the Master of Engineering group project and its results are included. Details of these results can be found in Khachikian (1996), López-Calva (1996), Picazo (1996), Skiadas (1996), and Tillman (1996).

2. Site Description

2.1. Location

Cape Cod is located in the southeastern most point of the Commonwealth of Massachusetts (Fig. 3-1). It is surrounded by Cape Cod Bay on the north, Buzzards Bay on the west, Nantucket Sound to the south, and the Atlantic Ocean to the east. Cape Cod, a peninsula, is separated from the rest of Massachusetts by the man-made Cape Cod Canal.

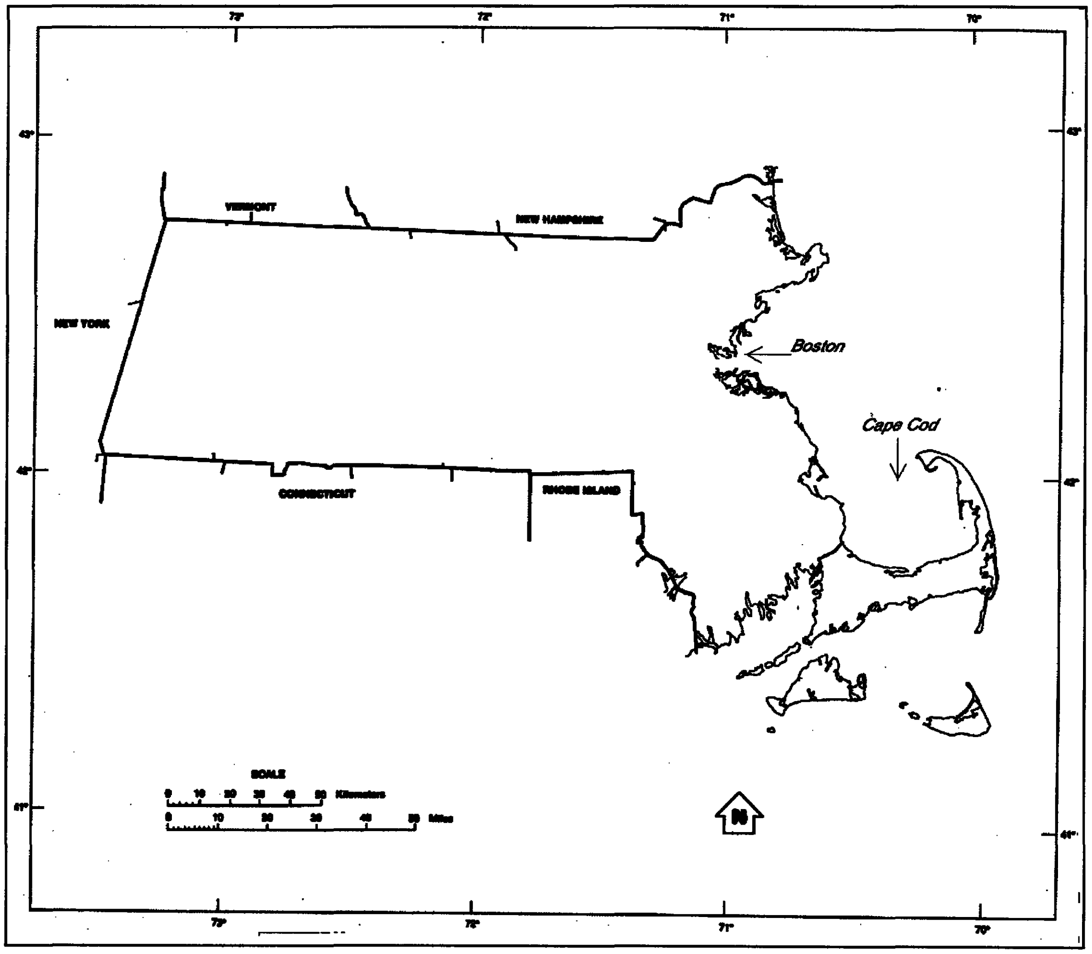

Figure 2-1: Map of the Commonwealth of Massachusetts

The MMR is situated in the northern part of western Cape Cod (Fig. 3-2). Previously known as the Otis Air Force Base, the MMR occupies an area of approximately 22,000 acres (30 square miles).

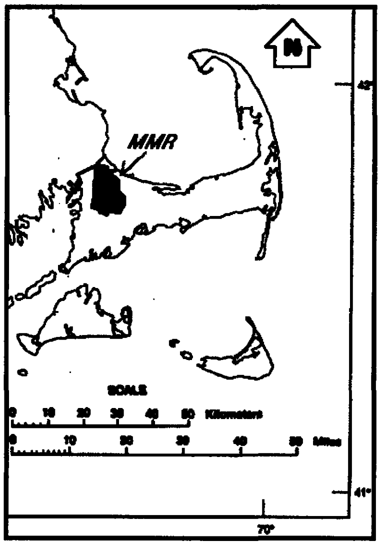

Figure 2-2:Location of MMR

2.2. Geopolitics and Demographics

Geopolitically, Cape Cod is located in Barnstable County, and is divided into 15 distinct municipalities (towns): all of these municipalities have their own individual form of government and community organizations. The MMR is bordered by four towns: Bourne to the west, Sandwich to the east, Falmouth to the south, and Mashpee to the southeast.

The population of Cape Cod fluctuates with the season. In 1990, the U.S. Census Bureau (USCB) determined the number of year-round residents to be 186,605 (Massachusetts Excecutive Office of Environmental Affairs, 1994). It is estimated that the number of Cape residents triples from winter to summer, topping a half million with the influx of summer residents and visitors (Cape Cod Commission, 1996). The county's median age in 1990 was 39.5 years (Cape Cod Commission, 1996). Age distribution studies conducted by the USCB conclude that 22% of the Cape's residents are aged 65 and over, the highest percentage of this age group in any county in Massachusetts (Cape Cod Commission, 1996). Population growth studies estimate the year-round population of Cape Cod to increase 23% by the year 2020 (Massachusetts Excecutive Office of Environmental Affairs, 1994).

2.3. General Physical Site Description

Cape Cod sediments are predominantly sands and gravel with a low percentage of silt. Left behind by the advancement of a glacier thousands of years ago, these deposits are generally well-sorted, but layered, and therefore heterogeneous in character. These sandy deposits allow a large portion of precipitation to seep beneath the surface into groundwater aquifers. This is the only form of recharge these aquifers receive. The groundwater system of Cape Cod serves as the only source of drinking water for most residents.

2.4. Natural Resources

Cape Cod is characterized by its richness of natural resources. Ponds, rivers, wetlands and forests provide habitat to various species of flora and fauna. Many of the Cape's ponds and coastal streams serve as spawning and feeding grounds for a variety of fish. The Crane Wildlife Management Area, located south of the MMR in western Cape Cod, is home to many species of birds and animals. In addition, throughout the Cape there are seven Areas of Critical Environmental Concern (ACEC) as defined by the Commonwealth of Massachusetts. These were established as areas of highly significant environmental resources and protected because of their central importance to the welfare, safety, and pleasure of all citizens.

2.5. Land and Water Use

The majority of the land in Cape Cod is covered by forests or is “open land”. Twenty-five percent of the land is residential, and less than 1% of the land is used for agriculture or pasture (Cape Cod Commition, 1996).

Water covers over 4% of the surface area of Cape Cod. This water is distributed among wetlands, kettle hole ponds, cranberry bogs, and rivers. Nevertheless, all 15 communities meet their public supply needs with groundwater. Individual towns develop and maintain separate municipal water supply systems. Falmouth is the only municipality that uses some surface water (from the Long Pond Reservoir) as a source of drinking water. Approximately 75% of the Cape’s residents use water supplied through public works, while the remaining use private wells within their property.

Water demand in the Cape follows the same seasonal variation as population. Water work agencies are called to supply twice as much water during the summer months than during the off-season (September through May). The highest monthly average daily demand (ADD) in 1990 was in July when 34.98 mgd were used. The lowest monthly ADD was in February with 14.03 mgd (Massachusetts Excecutive Office of Environmental Affairs, 1994). The towns of Falmouth and Yarmouth have the highest demand for water, with a combined percentage of almost 30% of the Cape’s total water demand (Massachusetts Excecutive Office of Environmental Affairs, 1994).

Agriculture also constitutes a part of the water use in Cape Cod. Cranberry cultivation is an important part of the economy of the Cape and is a water intensive activity. The fishing industry also provides a boost to the Cape's economy. Tourism accounts for a substantial part of the Cape's economy, and therefore the surface water quality is also important.

2.6. MMR Setting and History

The MMR has been used for military purposes since 1911. From 1911 to 1935, the Massachusetts National Guard periodically camped, conducted maneuvers, and pursued weapons training in the Shawme Crowell State Forest. In 1935, the Commonwealth of Massachusetts purchased the area and established permanent training facilities. Most of the activity at the MMR occurred after 1935, including operations by the U.S. Army, U.S. Navy, U.S. Air Force, U.S. Coast Guard, Massachusetts Army National Guard, Air National Guard, and the Veterans Administration.

The majority of the activities consisted of mechanized army training and maneuvers as well as military aircraft operations. These operations inevitably included the maintenance and support of military vehicles and aircraft. The level of activity has greatly varied over the MMR operational years. The onset of World War II and the demobilization period following the war (1940-1946) were the periods of most intensive army activity. The period from 1955 to 1973 saw the most intensive aircraft operations. Today, both army training and aircraft activity continue at the MMR, along with U.S. Coast Guard activities. However, the greatest potential for the release of contaminants into the environment was between 1940 and 1973 (E.C. Jordan, 1989a). Wastes generated from these activities may include oils, solvents, antifreeze, battery electrolytes, paint, waste fuels, and metals and dielectric fuels from transformers and electrical equipment (E.C. Jordan, 1989b).

2.7. Current Situation

2.7.1. Plume Location

From field observations, E.C. Jordan (1990) has determined the CS-4 plume to be located in the southern part of MMR moving southward (see Figure 2.3). The dimensions of the plume have been estunated. According to the *Groundwater Feasibility Study, Study Area CS-4* (E.C. Jordan, 1990), the plume is 11,000 ft long, 800 ft wide and 50 ft thick. A map of the MMR and the groundwater plumes emanating from (including CS-4) is shown in Figure 2-3.

2.7.2. Current Remedial Action

The existing remedial action was designed as an interim solution. The purpose of its implementation was to contain the plume against further migration. This is achieved by placing pumping wells at the toe of the plume and treating the extracted water.

The currently operating system consists of the following components:

- Extraction of the contaminated groundwater at the leading edge of the plume using a well fence;
- Transport of the extracted water to the treatment facility at the edge of the MMR;
- Treatment of the water with a granular activated carbon (GAC) system;
- Discharge of the treated water back into the aquifer to an infiltration gallery next to the treatment facility.

The well fence consists of thirteen wells located at the toe of the plume, about 1000 ft north of Route 151. The wells are 60 feet apart, covering a total distance of 720 feet. All but ane of the wells are arranged in a straight line. Each well is 8 inches in diameter and has a 15 feet screen. The bottom of the screen is located at a depth of 140 ft. The overall pumping rate is 140 gpm. The wells located at the sides pump at 15 gpm while the 11 wells in the middle pump at 10 gpm. The water pumped to the treatment facility, treated with granular activated carbon a, and discharged in a gravel infiltration gallery.

2.7.3. Performance of Current Remediation Scheme

Since the treatment facility started operating in November 1993, only minimal inflow concentrations of 0.5 ppb (ABB Environmental Services Inc., 1996) have been detected and treated.

Numerous authors have raised serious concerns about the ability of existing pump and treat to restore contaminated groundwater to sound environmental and health-based sound standards (Mackay and Cherry, 1989; Travis and Doty 1990; MacDonald and Kavanaugh, 1994). Other studies have shown that pump and treat in conjunction with other treatment technologies can restore aquifers effectively (Ahlfeld and Sawyer, 1990; Bartow and Davenport, 1995; Hoffman, 1993). However, there is a consensus that pump and treat is an effective means of *controlling* the plume migration.

In conclusion, the interim CS-4 pump and treat system seems to be appropriate way to quickly respond to the plume migration. However, for the final CS-4 remedial system new methods of remediating the aquifer must be addressed. To this end, portions of Appendix B examines the feasibility of applying bioremediation and combining the existing carbon treatment with zero-valent iron technology. This is further developed in Tillman (1996).

2.7.4. Treatment Levels

In terms of treatment objectives, the target levels for the treatment of the water are defined through the established Maximum Contaminant Levels (MCL). These apply to the contaminants of concern and are summarized in Table 2.1. Maximum measured concentrations, average concentrations within the plume, and an approximate frequency of detection are also given. It is important to realize that these values represent only an approximation, since their determination depends on a definition of the plume borders.

Contaminant of concern	Maximum Concentration (ppb)	Average Concentration (ppb)	Frequency of detection	Target level (MCL) (ppb)
Tetrachloroethylene (PCE)	62	18	14/20	5
Trichloroethylene (TCE)	32	9.1	14/20	5
1,2-Dichloroethylene (DCE)	26	1.1	11/20	70
1,1,2,2- Tetrachloroethane (TeCA)	24	6.8	1/20	2*

***Table 2-1** Contaminants of concern and treatment target level (Adapted from ABB Environmental Services Inc. (1992b))*

** No Federal or Massachusetts limits existent. Therefore, a risk-based treatment level was proposed. This was calculated assuming a $1x10^5$ risk level and using the USEPA risk guidance for human health exposure scenarios.*

Although the existing remedial action is interim, its clean-up goals have to be consistent with the long-term goals. Therefore, the above target levels are applicable to the existing interim action.

3. Physical Characterization of the Western Cape

A detailed area evaluation is essential for achieving a thorough understanding of the site and its characteristics. Meticulous study of already perfomed site characterizations was conducted. This data is critical for the development of a flow model. Parameters of interest for this study are discussed below.

3.1 Geology

The geology of western Cape Cod is predominantly composed of glacial sediments deposited during the Wisconsin Period (7,000 to 85,000 years ago) (E.C. Jordan (1989b)). As a result of glacial activity during this period, two moraines, the Sandwich Moraine (SM) and the Buzzards Bay Moraine (BBM), were deposited along the northern and western edges of western Cape Cod, respectively. Between the two moraines lies a broad outwash plain, known as the Mashpee Pitted Plain (MPP), which is composed of poorly sorted, fine to coarse-grained sands. At the base of uncosolidated sediments (below the MPP), fine grained, glaciolacustrine sediment and basal till are present.

At the regional scale, both the outwash and moraines have relatively uniform characteristics even though they contain some local variability. The way the sediments were deposited, made the sands stratify and thus made the deposits anisotropic. The MPP is more permeable and has a more uniform grain size distribution than the moraines. Nonetheless, both the SM and the BBM have a relatively low fraction of silt and clay, making it more permeable than similar geologic formations.

The total thickness of the unconsolidated sediments (i.e., moraine, outwash, lacustrine, and basal till) is estimated to increase from approximately 175 feet near the Cape Cod Canal in the northwest to approximately 325 feet in its thickest portion in the BBM; it then decreases to 250 feet near Nantucket Sound in south. The thickness of the MPP outwash sediments ranges from approximately 225 feet near the moraines, to approximately 100 feet near shore of Nantucket Sound (E.C. Jordan, 1989b).

3.2 Hydrology

Cape Cod's temperate climate produces an average annual precipitation of about 48 inches, widely distributed throughout the year (Masterson and Barlow, 1994). High permeability sands and low topographic gradient, minimize the potential for runoff and erosion, and thus recharge values have been reported in the range of 17 to 23 inches/year (LeBlanc, 1986). Consequently, approximately half the water that precipitates migrates to the subsurface. This creates a high probability of contaminant transport from the surface to the groundwater.

Beneath the western part of Cape Cod lies a single groundwater system (from the Cape Cod Canal to Barnstable and Hyannis). The U.S. Environmental Protection Agency (EPA) has designated it as a sole source aquifer. This aquifer is unconfined and its only source of recharge is infiltration from precipitation. The highest point of the water table (the top of the groundwater mound) is located beneath the northern portion of the MMR. In general, groundwater flows radially outward from this mound. The aquifer is bounded by the ocean in three sides, with groundwater discharging to Cape Cod Bay on the north, to Nantucket Sound on the south, and to Buzzards Bay on the west. The eastern lateral boundary is comprised by the Bass River in Yarmouth.

Kettle hole ponds, depressions of the land surface below the water table, are common on the MPP. These ponds influence the groundwater flow on a local scale. The larger and deeper the pond, the greater its effect on horizontal groundwater flow. Strong changes in hydraulic gradient are evidenced near some of these ponds, particullarly at Johns and Ashumet Ponds (the deepest and largest kettle hole ponds). Streams and cranberry bogs, serve as drainage for some of these ponds and as areas of groundwater discharge, and thus comprise the rest of the hydrology of the western Cape. Figure 3-1 is a map that shows the major hydrologic features of western Cape Cod.

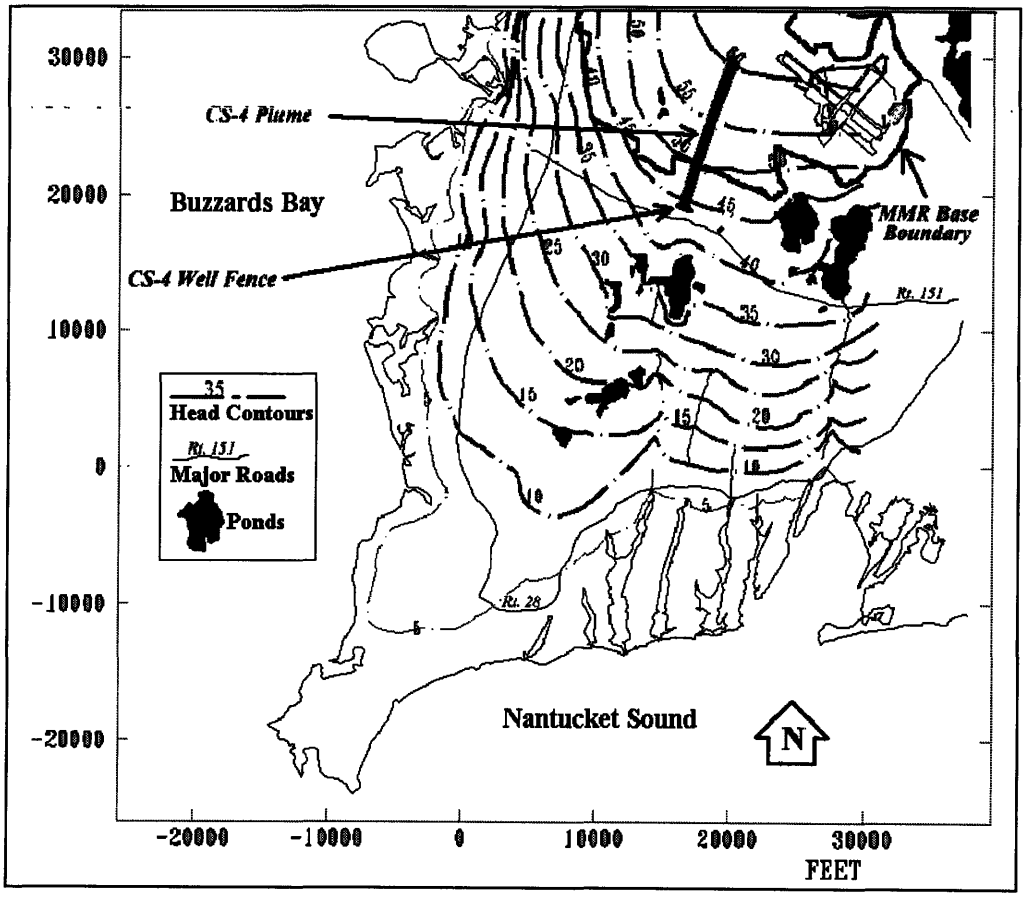

Figure 3-1: Hydrologic features of western Cape Cod

3.3 Hydrogeology

The geology and hydrology of western Cape Cod define the hydrogeologic characteristics of the aquifer. General information on the geology and hydrology of Cape Cod can be found in the works by Oldale (1982), Guswa and LeBlanc (1985), LeBlanc et al. (1986), and Oldale and Barlow (1987). This section summarizes the data on the major aquifer properties measured throughout the area. Variability of these values may be due not only to natural heterogeneities of the soil, but also to differences in mearuring techniques and data analysis (E.C. Jordan, 1989b).

3.3.1 Grain Size

The MPP is characterized by generally well-sorted sand and gravel with minor amounts (about 1%) of silt and clay. The grains of the MPP have an average diameter of 0.5 mm and in general are coarser in the north and finer towards the south (LeBlanc, 1984). The same trend is present in the Cape's stratigraphy: grains are distributed from coarse grains at the ground surface to silty fine grains above the bedrock.

3.3.2 Hydraulic Conductivity

Because of their direct relationship, the hydraulic conductivity (K) of western Cape Cod is distributed in the same way as the grain size. There appears to be a general trend of decreasing conductivity from north to south and from surface to bedrock.

The hydraulic conductivity of the western Cape has been studyed extensively. Values have been estimated by the use of various different methods including slug tests, aquifer tests, laboratory permeameter tests, and grain size analyses. Table 3-1 is a summary of the hydraulic conductivity values.

Predominant grain size of tested interval	Latitude ° “ ‘	Longitude ° “ ‘	Horizontal hydraulic conductivity (ft/day)	Anisotropy ratio	Source
Fine sand and silt	41 36 06	70 30 29	40	50:1	Barlow and Hess (1993)
Fine sand	41 40 00	70 14 72	160	30:1	Barlow (1994)
Fine to medium sand	41 37 03	70 33 00	380	5:1-3:1	LeBlanc, et. al. (1988)
Fine to coarse sand and gravel	41 40 10	70 13 53	220	10:1	Barlow (1994)
Medium to coarse sand and gravel	41 45 16	69 59 39	300	> 10:1	Guswa and LeBlanc (1985)

Table 3-1*. Estimates of hydraulic conductivity of stratified drift, as determined from analysis of aquifer tests, Cape Cod Basin, Massachusetts. (Adapted from Masterson and Barlow, 1994).*

Geologic variability within the outwash suggests that some variability in hydraulic conductivity is likely. Nonetheless, the maximum and minimum values reported in the literature are probably biased by the analytical method or exhibit a small-scale geologic heterogeneity. An value of 380 ft/d (obtained from the Ashumet Valley pump tests and corroborated by the tracer test south of the MMR) has been accepted as a representative value of average hydraulic conductivity of the MPP outwash sands (E.C. Jordan, 1989b).

3.3.3 Anisotropy Ratio

The ratio of horizontal to vertical hydraulic conductivities (K_h/K_v) has been studied along with some of the hydraulic conductivity tests. Values of anisotropy ratio for different studies are reported in Table 3-1.

3.3.4 Porosity

There have been several tracer experiments performed in the western Cape in which porosity has been measured. The effective porosity is similar to the total porosity in coarse grained sediments, such as the sand and gravel outwash of the MPP (E.C. Jordan, 1989b). Greater values of porosity are typical of well-sorted, coarse sediments; while lower values are associated with poorly-sorted deposits having various grain sizes. Measured values of porosity reported in the literature range from 0.20 to 0.42. Effective porosity of the outwash is estimated from various tracer studies (Garabedian et al., 1988; LeBlanc et al., 1991) to be about 0.39.

3.3.5 Hydraulic Gradient

The hydraulic gradient is affected by variations in water table elevations. These typically fluctuate in the Cape about 1 m because of seasonal variations in precipitation and recharge. During the period of a tracer test (22 months), the hydraulic gradient in the study area (Ashumet Valley) varied in magnitude from 0.0014 to 0.0020 and in direction from 173° to 156° east of magnetic north. This directional variation is influenced by the Ashumet Pond water level; as water table levels increase, the gradient tends to steepen and shift eastward (LeBlanc et al., 1991).

An attempt to measure vertical hydraulic gradients was also performed during the period of the Ashumet Valley tracer test. LeBlanc and others concluded that the vertical gradient must be smaller than the 0.3 cm (accuracy of water level measurements) per 25 m (vertical separation of wells). Consequently, groundwater flow is mostly horizontal. Vertical flow is most notably present near the ponds (LeBlanc et al., 1991).

3.4 Other Parameters

Dispersivity and sorption are two parameters that are location dependent and are discussed in Section 4.

4. Hydrologic Flow Model

4.1 Description of the model

A three-dimensional model is constructed using the finite-element modeling code DynSystem (Camp, Dresser & McKee, Inc, 1992). This numerical-modeling code has the flexibility to evaluate various extraction systems and the ability to simulate most natural conditions observed in the area, in three dimensions. DynSystem is composed of various components of which three were used in this study:

- DYNPLOT- a graphical interface code which processes all input and output
- DYNFLOW- processes input files and runs flow simulations
- DYNTRACK- simulate transport

More than 320 wells are located in the area of concern. A text files containing well ID, coordinates and hydraulic head data from wells used recently as monitoring wells is constructed, and used as input file (Appendix C).

4.2 Approach

In order to accurately simulate the flow and transport under natural conditions, the regional controlling factors must be incorporated into the modeling analysis. Considering the objectives of the model, it is constructed in an area much greater than the area where CS-4 plume is located. A grid is built with a systematic and structured refinement. The triangular elements defined by nodes are smaller in the areas of interest to meet numerical constraints and ensure accuracy. This is also taken into account in the vertical, in the elevation where the plume is thought to be.

The model is developed according to some assumptions. These are the following:

- Steady state conditions
- Recharge due to precipitation is assumed to be uniform throughout the modeled area
- Discharge from the aquifer is assumed to be due to natural downgradient flow (into the ocean), discharge into streams, and extraction from pumping wells

4.3 Geometric boundaries

The model includes an area of approximately 50 mi^2 on the western Cape (Figure 4-1). The thickness of the modeled region is non-uniform, defined by the topographic characteristics of the Cape. As the aquifer is unconfined, the upper limit is the ground surface and the lower limit is the underlying bedrock (Oldale, 1969). The horizontal boundaries are defined by two flow lines and the ocean. The southern end of the model is Nantucket Sound, and Buzzards Bay is at the western end. The eastern boundary follows a flow line south towards Ashumet Pond, along the western shores of Ashumet and Johns Ponds, and down along the Child's River to saltwater. The northern boundary is another flow line originating at the same point of the eastern boundary (the upper-most point in the water table), and extending westward to Buzzards Bay (Figure 4-1).

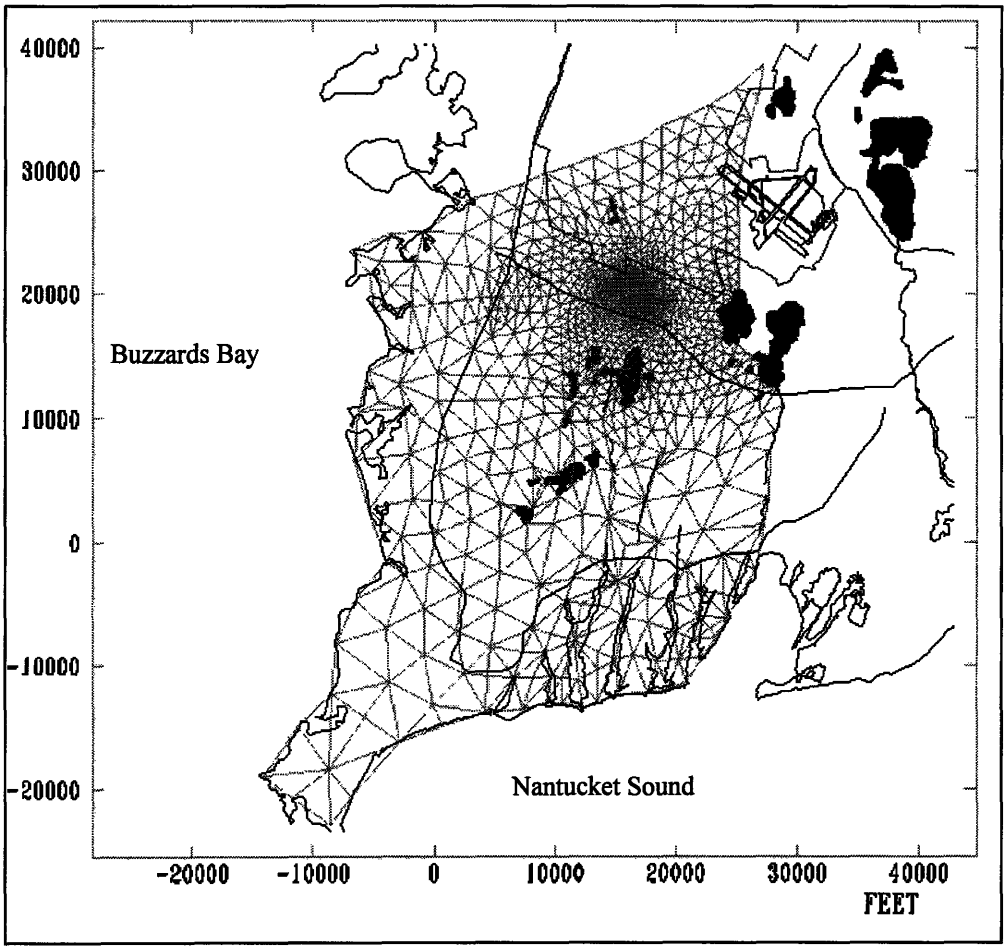

***Figure 4-1**: Area of the western Cape which was modeled*

4.4 Hydraulic Boundaries

Johns Pond, Ashumet Pond and Childs River are included in the model as fixed head boundary conditions. Coonamessett Pond is the most important surface water body within the modeled area because of its vicinity to the end of the CS-4 plume region. Since most of the pumping activity is going to occur in this region, this area is one of major interest. Other ponds included in the area of the model are Osborne, Deep, Edmonds, Crooked, Shallow, Round, Jenkins, Mares and Deer. The ponds are represented in the model as areas of very high hydraulic conductivity, and effective porosity equal to one. This is done to get negligible horizontal hydraulic gradients and to correctly represent the flat surfaces of these water bodies.

The saltwater-freshwater interface at the western and southern boundaries is constructed assuming hydrostatic conditions for the salt water, and defining an increase in hydraulic head with depth according to the density differences. Head is fixed at sea level in these boundaries. Fixed head is also used in the nodes corresponding to the boundaries of Johns and Ashumet ponds. The rivers are represented by nodes with a specified and well defined elevation.

4.5 Discretization

The grid contains 1194 nodes and 2314 elements, distributed horizontally. The vertical discretization consists of 9 levels, dividing the area into 8 different layers. Finer discretization is employed in the area near the well fence where rapidly changing gradients are expected due to pumping. This grid is used in both the simulations of natural flow and transport.

4.6 Application of Aquifer Properties to the Model

The area modeled is divided in two main lithologic entities: the glacial moraine, and the Mashpee Outwash. Within these two different facies, different materials are assigned according to the depositional model described by Masterson and Barlow (1994). The Buzzards Bay Moraine is assumed to be composed of four different materials distributed vertically. The area of the outwash forming part of the model is divided into a northern and a southern areas in the horizontal, and in three different materials in the vertical direction. All these assumptions were made based on the depositional model, which was in turn based on different geologic and geophysical studies conducted in the area (Masterson and Barlow, 1994). Figure 4-2 shows a plan view of the different surface materials used in the model.

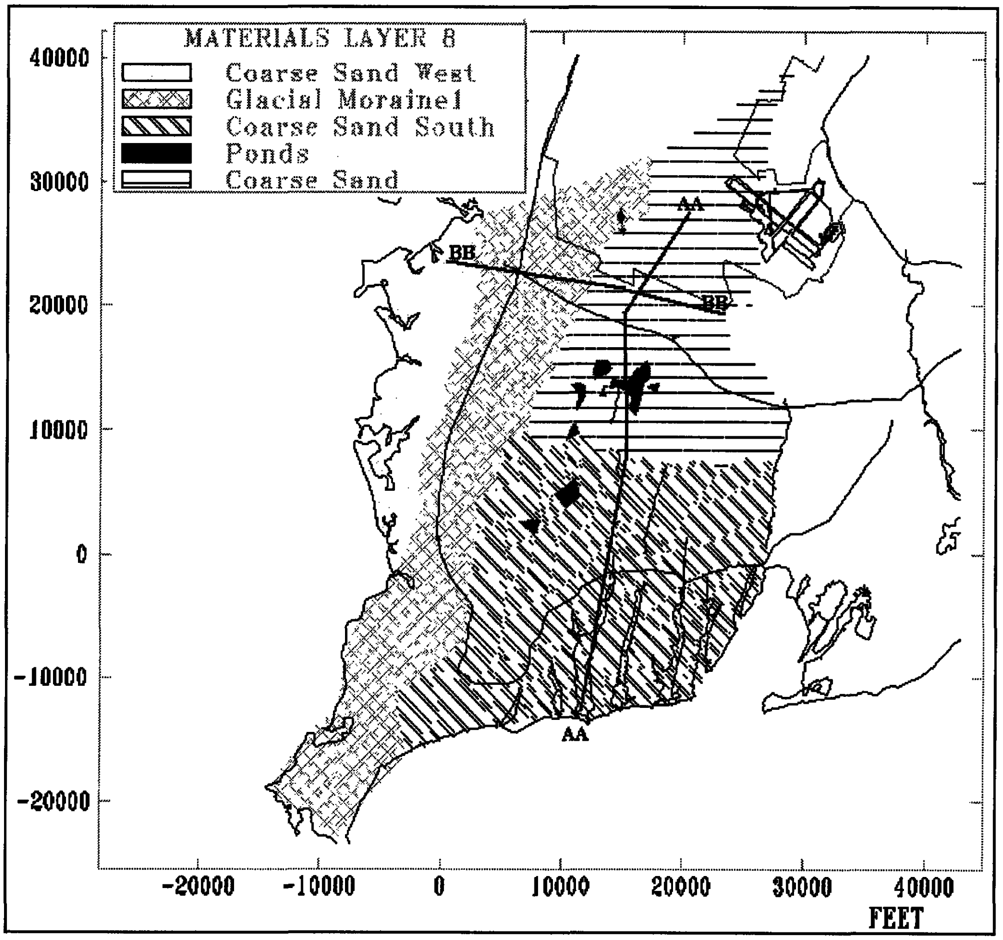

Figure 4-2: Plan view of the surface materials used in the model.

4.6.1 Hydraulic conductivity

Assignment of hydraulic conductivity is made following the approach of Masterson and Barlow (1994). These authors base the definition of hydraulic conductivity on their depositional model. Different aquifer-test analyses have been made in the area. From the results of these aquifer tests, values of hydraulic conductivities have been assigned to different sediments, grouping these sediments according to grain size. Comparing lithologic boundaries to these values of hydraulic conductivity, this property is distributed throughout the modeled area. A hydrogeologic section showing the lithology are presented in Figure 4-3 and Figure 4-4. In Table 3-1, different estimates of hydraulic conductivity determined from aquifer-test in the area were shown. These estimates are used by Masterson and Barlow (1994) to define a generalized value of hydraulic conductivity for fine sand and silt, fine sand, fine-medium sand, and medium-coarse sand and gravel, which are the four main materials found in the Mashpee Pitted Plain.

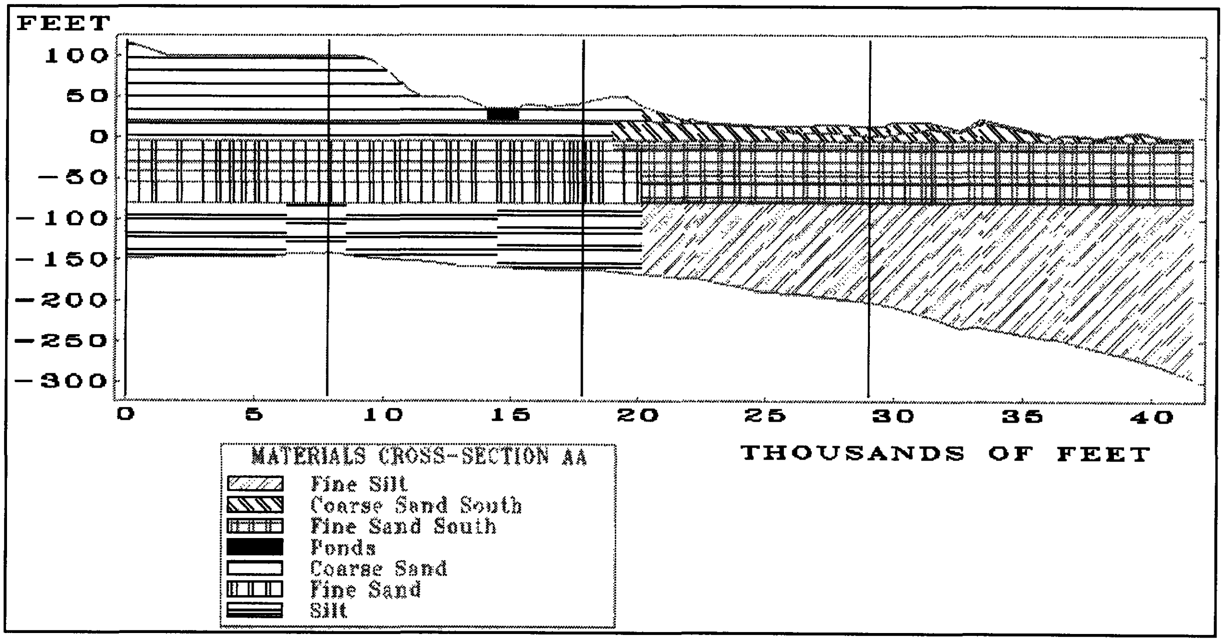

Figure 4-3: *North-south cross section (AA) which shows the stratigraphy used in the model. Refer to Figure 4-3 for the cross section location.*

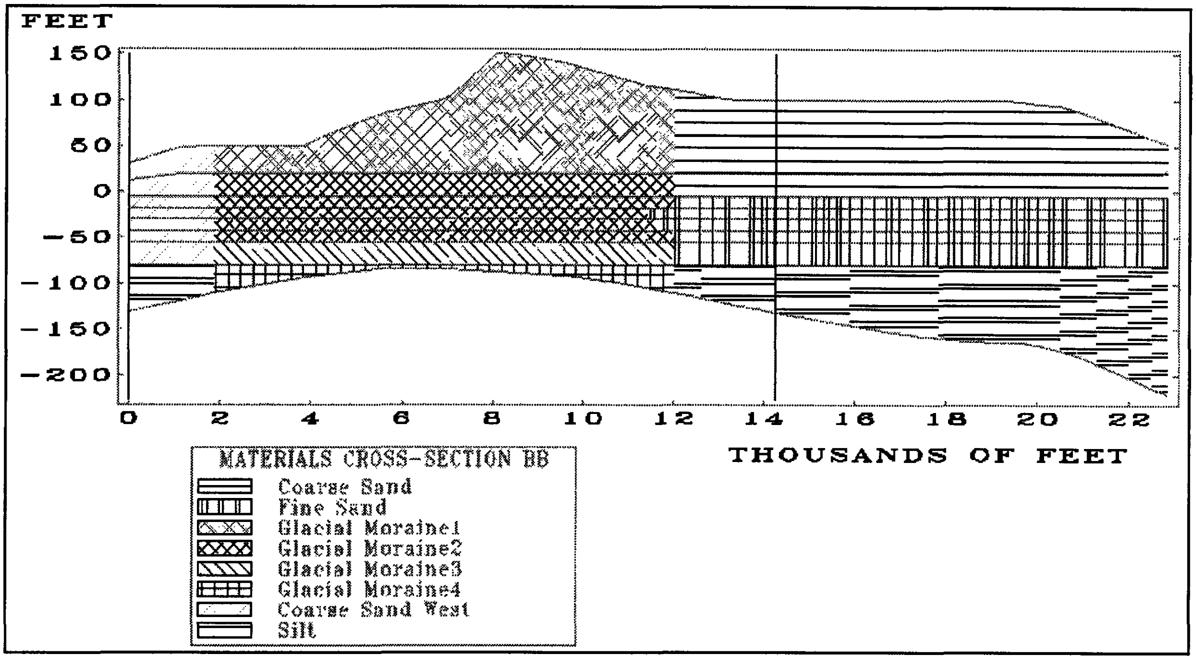

***Figure 4-4**: East-west cross section (BB) which shows the stratigraphy used in the model. Refer to Figure 4-3 for the cross section location.*

Anisotropy ratios are also defined, initially, based on the information presented by these authors. As in the case of horizontal hydraulic conductivity, anisotropy ratio is assigned to a particular type of sediment, which is then assumed to be homogeneously distributed along a well defined area in the Cape. The anisotropy ratio is an important calibration parameter for the transport model. Its value, initially based only on a literature review, is slightly modified according to the transport model results (Section 4.7.2). Initial anisotropy ratio values used in this model range from 3:1(coarse sands) to 30:1 (glacial moraine).

4.6.2 Recharge

Precipitation is the only source of fresh water to the Cape Cod groundwater-flow system. Actual recharge to the groundwater system is less, since some of the water either evaporates, is transpired by plants, or runs-off. LeBlanc et al. (1986) and Barlow and Hess

(1993), estimate that 45 to 48 per cent of the total precipitation, about 18 to 23 in/yr., recharges the aquifer. The value used in the flow model is 23 in/yr. During the flow calibration procedure, recharge is not treated as a calibration parameter and is maintained constant.

4.6.3 Hydraulic head

Initial values of hydraulic head are obtained from Savoie (1995). Water level data from 106 wells, distributed throughout the western Cape were measured in a period of two days. One hundred and six of those wells lie within the modeled area and were used as calibration points. This data is the most representative head data available. Data from a few wells located within the ponds or very close to them are discarded, since information about screen elevation is not available. Specific screen elevation data is necessary to determine the actual head at that point since these areas are under vertical flow conditions and thus head is not constant with depth. The vertical gradient is assumed to be negligible for the rest of the Cape. In order to assign a head value to each node in the grid, interpolation of the values is made using the capabilities of the code. This way a initial water table surface is obtained for the entire modeled area. Calibration, however is made with the original discrete points as targets, hence avoiding the possible interpolation bias.

4.6.4 Aquifer thickness

The lower limit of the modeled aquifer is considered the bedrock underlying Cape Cod. A thin layer of lacustrine sediments is present overlying bedrock. However, this material is not considered since its thickness becomes appreciable only in marginal portions of our modeled area. A topographic map of the basement surface (bedrock), is presented by

Oldale (1969). From these seismic investigations, elevation contours of the bedrock were digitized and then interpolated to get the surface of the lower limit of the model.

4.6.5 Dispersivity

Garabedian et al. (1988) calculated dispersivities using the data obtained during the Ashumet Valley tracer test. The method of spatial moments was used to interpret the data; which was regarded by Gelhar et al. (1992) as having a high degree of reliability. Values of dispersivity obtained by Garabedian et al. (1988) are summarized in Table 4-1 below.

Dispersivity	Value (ft)
Longitudinal (A_0)	3.15
Transverse, horizontal (A_{22})	0.59
Transverse, vertical (A_{33})	0.005

***Table 4-1**: Dispersivity values of the Ashumet Valley Tracer Test (from* Garabedian et al., *1988)*

It must be noted that these values, which are generally well accepted in the literature for the site, were obtained for a source with different dimensions as the CS-4 site. The displacement of the CS-4 plume is larger than that of the bromide used in the tracer experiment. Consequently, the overall test scale of the CS-4 site is larger, and the macrodispersivity should be adapted (Gelhar, 1993). In addition, Rajaram and Gelhar (1995) conclude that dispersivities for transport over large scales are significantly influenced by the source dimensions. The authors define a relative dispersivity which are is appropriate for characterizing the dilution and spreading at individual heterogeneous aquifers. Using their two scale exponential model, the relative longitudinal dispersivity (A_0^r) is estimated to be 66 ft (Gelhar, 1996).

Transverse dispersivities are not modified, since their variability is not due to this effect but to temporal variations of the hydraulic gradient's direction (Rehfeldt and Gelhar, 1992). Van der Kamp *et al.* (1992) conducted a field study of a very long and narrow plume in a similar aquifer. The authors concluded the narrowness of the plume was possibly due to the unusual steadiness of aquifer flow. The narrowness of the CS-4 plume might also be caused by this phenomenon. This is a topic that is undergoing current research, and thus is beyond the scope of this work.

4.6.6 Sorption

Equilibrium sorption is the only site characterization parameter for which new analyses were performed. Cape Cod outwash sand samples were taken at different depths and their equilibrium sorption was determined from laboratory analyses. Appendix B contains a short description on the background, theory and a summary of the laboratory procedure and analyses.

Sorption of contaminants by aquifer solid matrices may significantly affects their fate and transport. The bioavailability of contaminants can be reduced considerably because of sorptive uptake. Also, pump and treat times can be prolonged substantially because of a continuous feeding of contaminants to the aquifer by the sorbed species. Another effect of sorption is that it may alter the dispersive behavior of contaminants.

Sorption coefficients were determined through laboratory analyses and used to calculate retardation factors for the contaminants of interests (Table 4-2).

Compound	R_{eff}
DCE	1.04
TCE	1.10
PCE	1.25

***Table 4-2**: Effective retardation factors*

Values in Table 4-2 were calculated by averaging the different values for the samples obtained at different depths. These include samples from the vadose zone, where there is no flow of groundwater. Depth averaging the effective retardation factors over the saturated zone yield significantly smaller values. Furthermore, since the model simulates the sum of PCE, TCE and DCE, the effective retardation factor for the sum of the compounds is very close to one. Barber et al. (1988) report a retardation factor of one for TCE and PCE in another plume in the same aquifer. Thus, this work assumes retardation to be negligible.

4.6.7 Other Parameters

Storativity properties such as specific yield and specific storage are not considered in the regional flow model, since these are properties related to transient simulations, and the model is simulated under the steady state assumption.

4.7 Calibration

The groundwater flow model was created as the basis of the modeling of transport of particles. A flow model that approximates real conditions as best possible will produce the most accurate particle tracks and the most useful results.

4.7.1 Hydraulic Head Calibration

The model was first calibrated taking into account hydraulic heads only. A good calibrating procedure is to vary only one parameter of the model and while keeping the others constant. A preliminary sensitivity analysis was performed and it was apparent that the modeled heads were not too sensitive to recharge variations within the 18-23 in/yr range. The recharge was then set constant at 23 in/yr. The anisotropy ratio was also kept constant for the flow model calibration, since flow in the aquifer is assumed to be predominantly horizontal. The elevation of the boundaries of the different lithographic units were also kept constant.

Hydraulic conductivity is the main parameter varied during the calibration procedure of the flow model, but the trends and ranges described in Masterson and Barlow (1994) were always maintained. Calculated values of hydraulic heads were thus approximated to the target heads by modifying horizontal hydraulic conductivities.

As an initial calibration procedure, the target head values (Savoie, 1995) were interpolated using the capabilities of the code and a water table was created. The water table was then contoured. These contours proved to be useful as initial, since it is easier to visualize and therefore calibrate to head contours than it is to heads at specific points. Nevertheless, for the most part of the calibration process head values at specific points were used as targets. The final calibration criteria was also based on point values.

From the modeled head contour one of the most notable features were the effects of ponds and streams on the groundwater flow. The ponds were incorporated into the model by approximating them with as a material of very high hydraulic conductivity that corresponds to each pond's elements. Thus for a specified flow, since the conductivity is so high, the horizontal gradients are essentially zero (and hence the water table has a slope of zero). Refinement of the grid was necessary in the pond areas to accurately represent them and thus have the desired effect. The streams were included into the model by aligning nodes along the stream path. Ground surface elevations at the nodes representing surface water bodies were revised so that they would coincide with the stream or pond elevations. This was necessary because the ground surface interpolation, in most of the cases, does not assign the proper river elevation at these points. These were required for an accurate representation of the field conditions.

The sensitivity of the model to the fixed head boundary condition at Ashumet and Johns Pond was tested. The flow pattern near the ponds shows some sensitivity, but the effect of the change in the boundary condition seemed negligible in the head values in the area of the CS-4 plume.

After these adjustments and further variation of the hydraulic conductivity, the model approximated the target values fairly well throughout the outwash plain. However, in the moraine, values did not converge to the target values as well. A definitive effect of the moraine properties on the overall head pattern was evident. Further discussion of this effect is discussed Section 4.7.2.

As discussed previously in the approach, the size of the modeled area was much greater than the area of concern. This gave us freedom with respect to the boundary conditions, since these were far away from the region in which the plume is thought to be. During the calibration process, this factor was considered so that the main effort was to reduce the error within the CS-4 area. The model was considered calibrated after reaching a mean difference of -0.295 ft (calculated minus observed head) and a standard deviation of 1.271 ft for the entire region. In Figure 4-5 the distribution of the differences in calculated and observed head is presented.

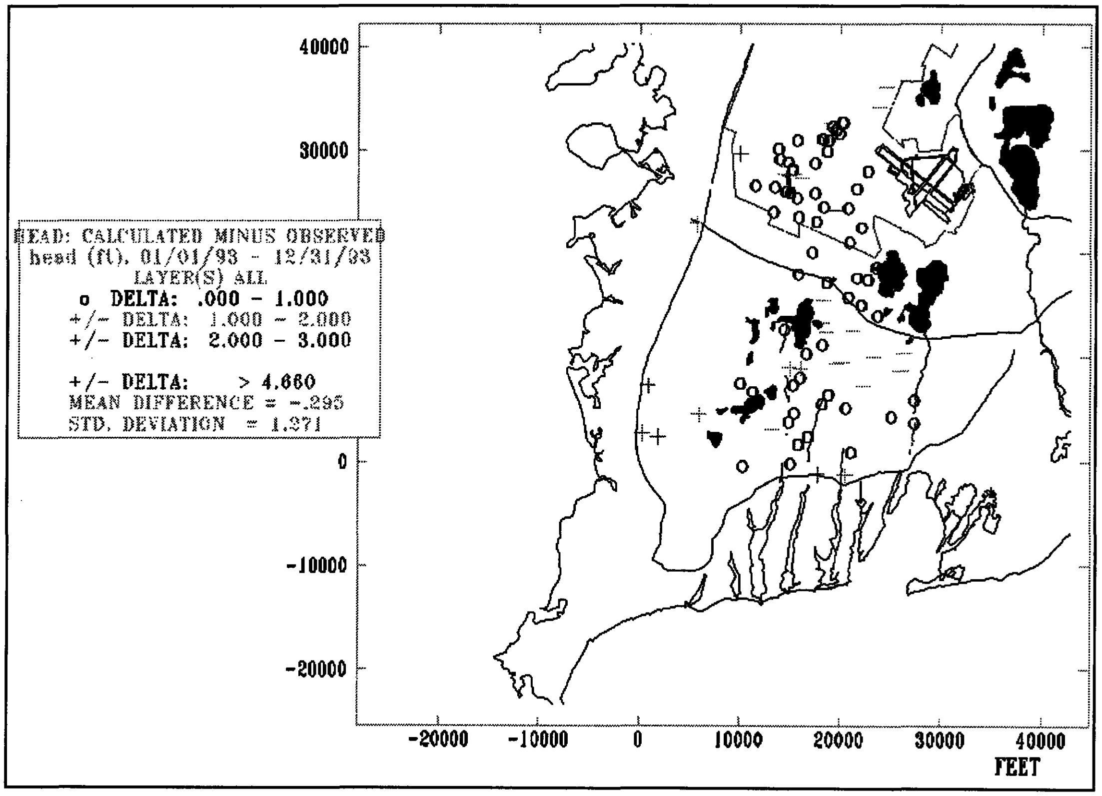

***Figure 4-5**: Distribution of the differences in calculated minus observed head after calibration based on hydraulic head considerations only.*

It can be seen from Figure 4-5 that heads in the BBM were higher than the observed value; and in Ashumet Valley lower. In a well calibrated model, positive and negative errors should be equally distributed over the entire area. In the CS-4 area however, the error is minimal and well distributed. Thus, the overall error in the model was considered unimportant for the modeling purposes in CS-4. Table 4-3 presents a summary of the values used for and obtained after the final hydraulic head calibration.

Parameter	Value
Maximum Hydraulic Conductivity (coarse sands in the north- top layer)	290 ft/day
Minimum Hydraulic Conductivity (silty soils in the north- bottom layer)	30 ft/day
Arithmetic Mean Hydraulic Conductivity (north section of model)	173.3 ft/day
Hydraulic Gradient (CS-4 area)	0.0014
Seepage Velocity (CS-4 area) *	0.62 ft/day
Anisotropy Ratio	3:1, 5:1 and 10:1

***Table 4-3**: Hydrogeologic parameters resulting from the groundwater-flow model after calibration based on hydraulic head only.*

Groundwater velocity is calculated using the following form of the Darcy Equation:

$$v = \frac{K}{n_e} J$$

where,

v = average groundwater pore velocity

K = average hydraulic conductivity

n_e = effective porosity

J = hydraulic gradient

Effective porosity was assumed at 0.39 (Section 3.3.4). The arithmetic mean of hydraulic conductivity was calculated by taking averages of the upper-most and lower-most layer thickness (since these are not constant).

4.7.2 Calibration Using Particle Tracking

The objective of creating a steady-state groundwater flow model was to be able to use it as the basis for transport simulations of the CS-4 plume. Using the calibrated model described in the previous section, simulated fluid particles were tracked starting from the CS-4 source (see Section 5.1 for source definition). After pathlines were developed for the first run, it was evident that the particles were not coinciding with the known extent of the CS-4 plume, which in general extends from north to south (E.C. Jordan, 1990). The simulated pathline curved towards the west and went too deep into the aquifer (Figure 4-6 and 4-7).

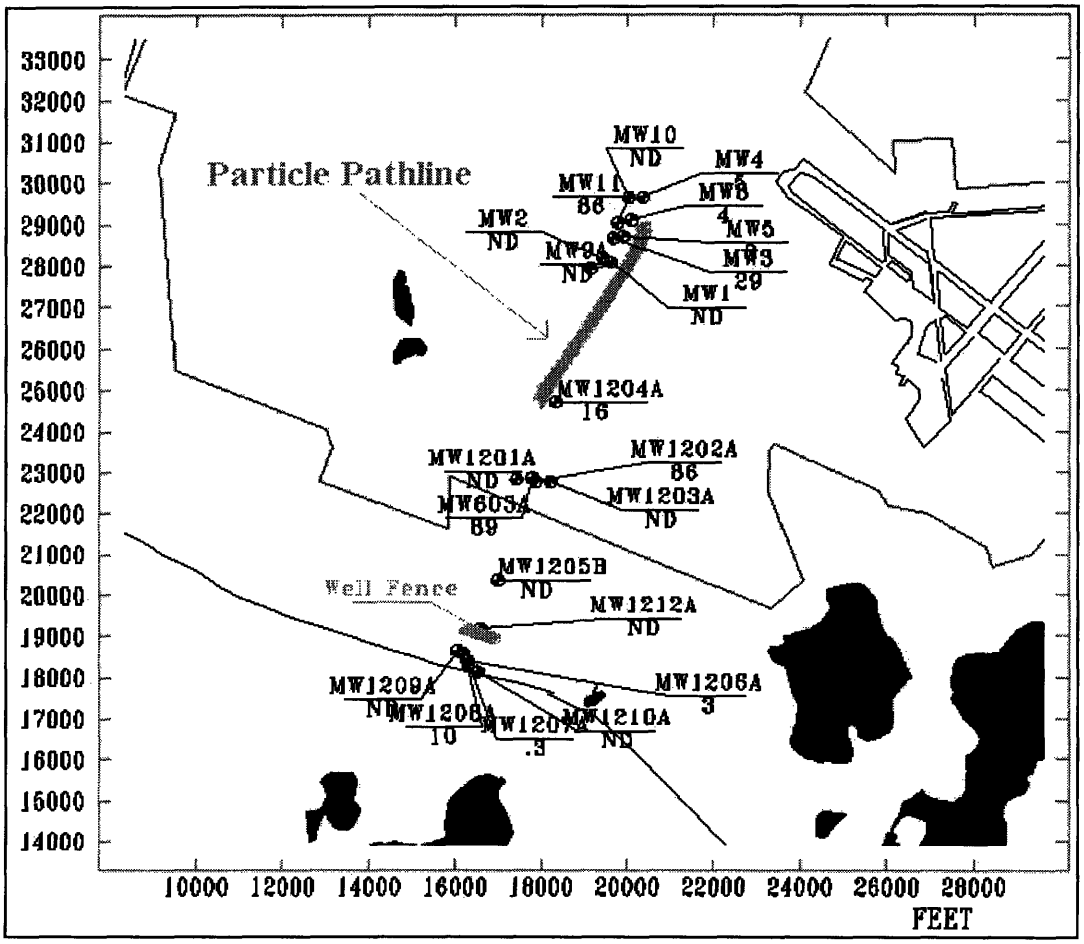

Figure 4-6: Plan view of initial pathline of a particle from the CS-4 site using the model calibrated based only on hydraulic head considerations

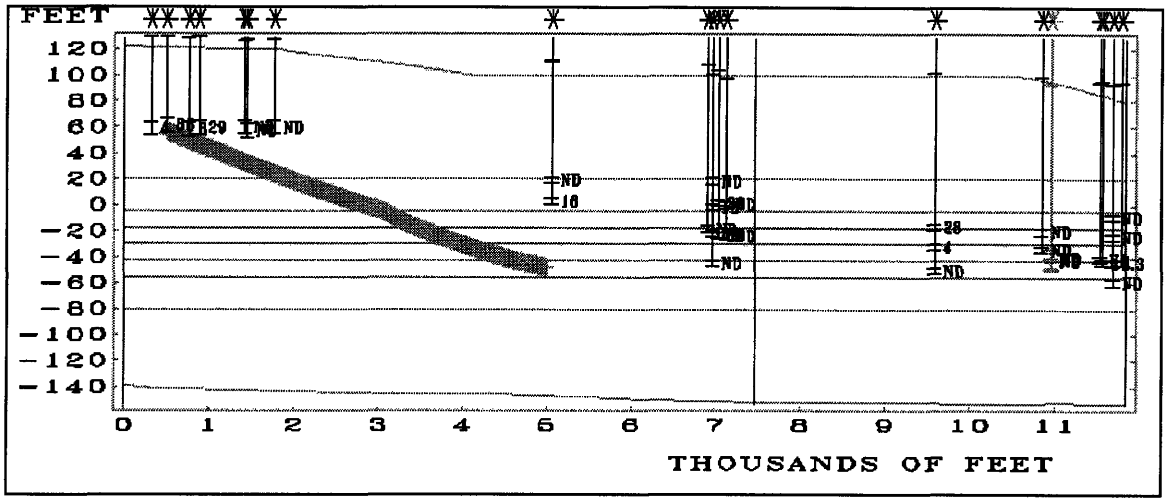

Figure 4-7: North-south cross section of initial pathline of a particle from the CS-4 site using the model calibrated based only on hydraulic head considerations

Field observations suggest that the plume travels south-southwest towards the well fence and passes between wells MW1201 and MW1203. The particle in Figure 4-6 was not moving in this fashion. The model, once considered to be calibrated based on hydraulic head, had to be re-calibrated tacking into account the transport analysis. Masterson and Walter (1993), who developed a model of the Ashumet Valley sewage plume, also encountered this problem in their simulation. The authors concluded that an accurate calibration might require the incorporation of contaminant information if groundwater flow models were to be used as accurate predictors of plume migration.

The first step taken was to decrease the hydraulic conductivity in the lower layer sediments so that the pathline would not migrate so deep into the aquifer. The conductivity was changed from 35 to 10 ft/day and the particle did not go into the lower layers of the model. The simulation time was also increased, since it was evident that the pathline was shorter than expected. Next, a sensitivity analysis on the source location was performed. Two more particles were seeded 50 ft on each side of the original particle. Figure 4-8 shows the pathlines of the three particles, and indicates the sensitivity of the location of the source.

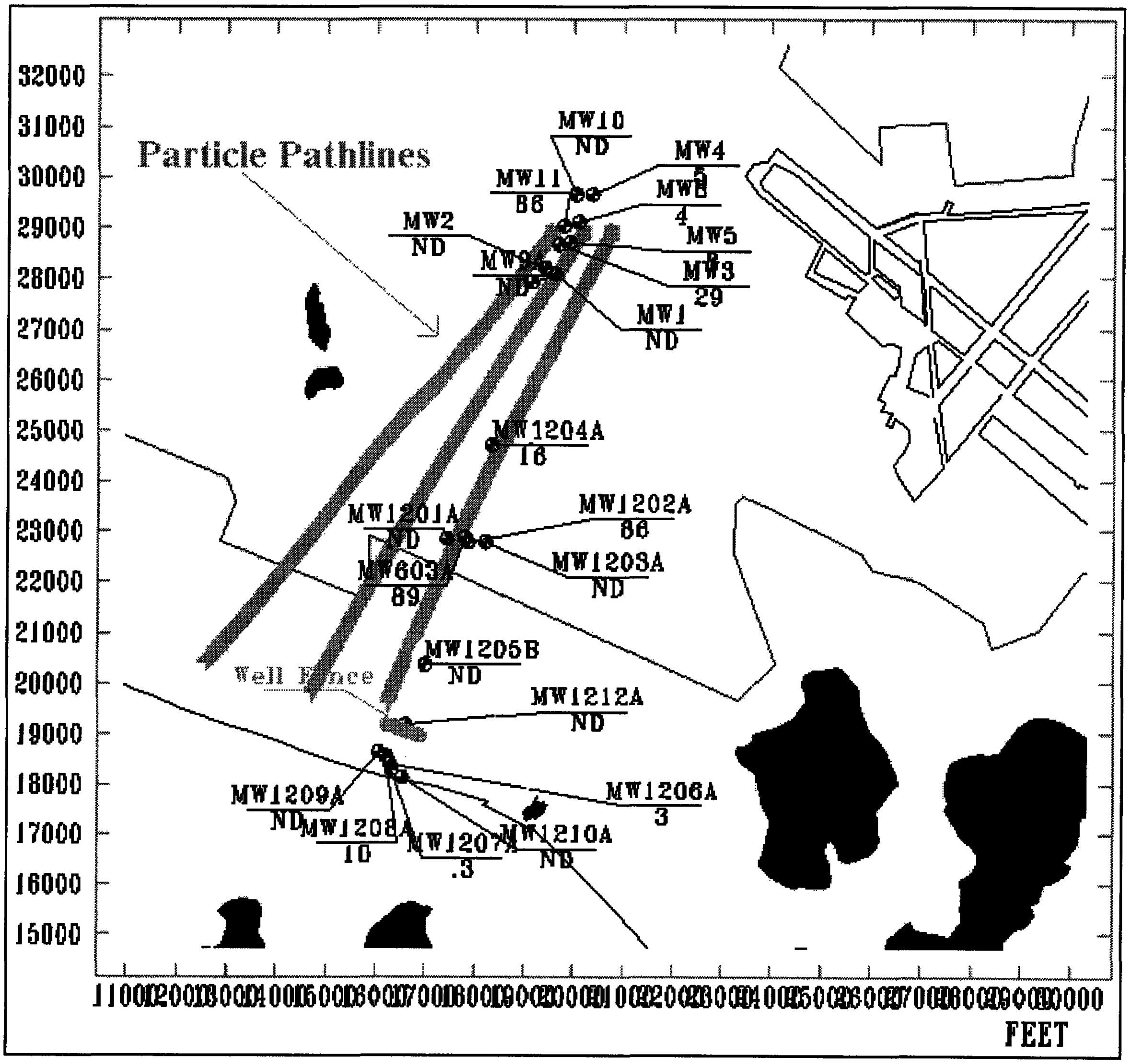

Figure 4-8: Sensitivity analysis on source location

This confirmed that is was critical for the transport model to have the source location well defined. A map of the CS-4 area presented in E.C. Jordan, 1990) was used to locate the source. The center of the source was determined by measuring the distance from the MMR airfield, a location well defined in both the model and the E.C. Jordan maps. This turned out to be between the middle and rightmost particle in Figure 4-8. Figure 4-9 shows the pathline a particle starting from the new modified location.

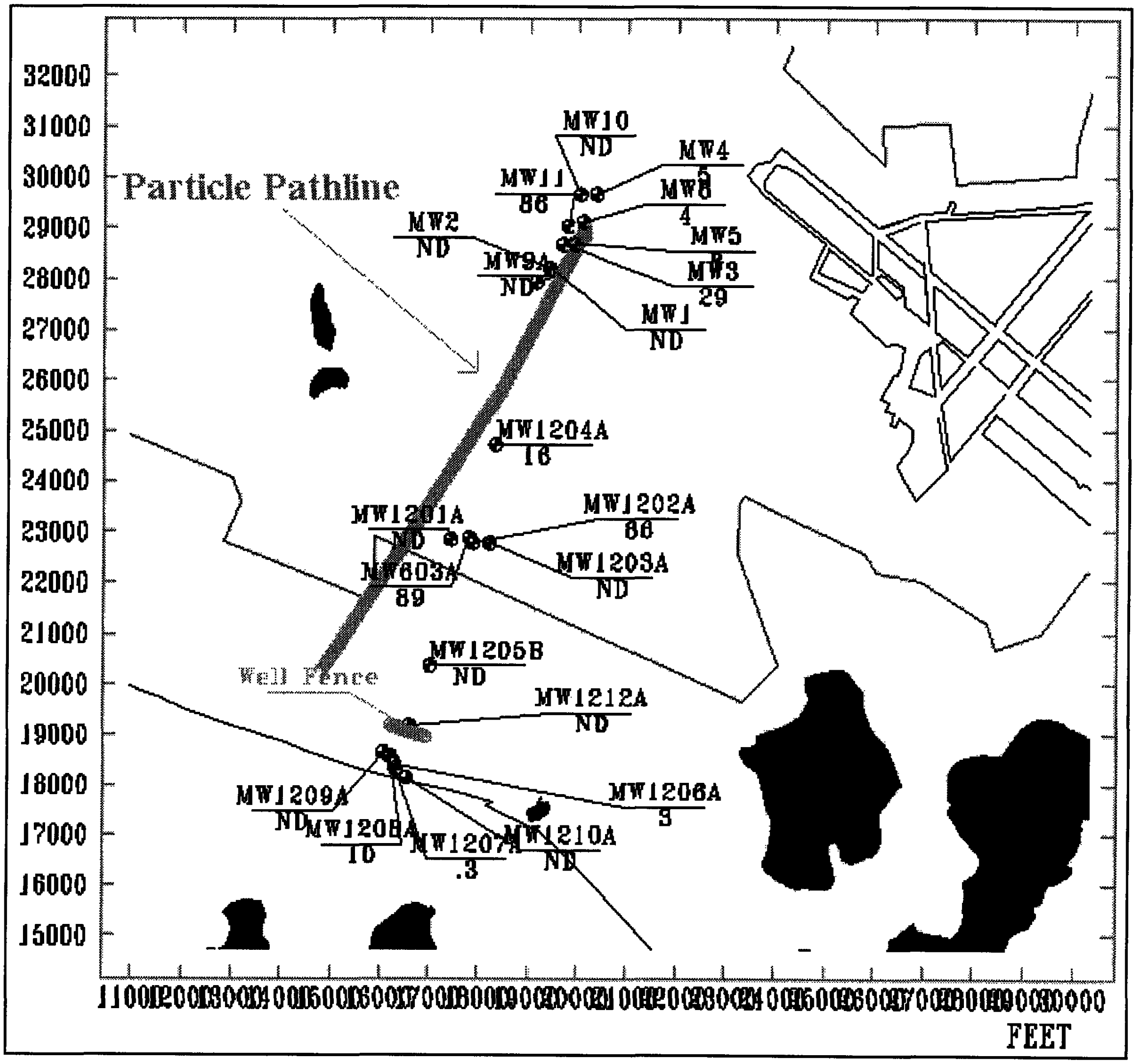

Figure 4-9: Particle track from the center of the CS-4 source

From the pathline in Figure 4-9, it was evident that heads were lower on the west than in the south. Upon examining pond levels, it was found that Coonamessett and other ponds around it had a lower head than it was initially assigned (about one to two feet lower). On the other hand, Ashumet and John's Ponds water levels had not decreased since they had a fixed head boundary condition. Thus, the head in all ponds in the area had decreased by one or two feet, but not the one in Ashumet or John's Pond. With this in mind, and the idea that the particle had to go from north to south, heads in Ashumet and John's Ponds were decreased by 1.5 ft (to 43 ft). This is probably justified, since pond levels fluctuate seasonally throughout the year with changes well within this range of elevations. The effect of changing the pond level elevation on the particle pathline can be seen in Figure 4-10.

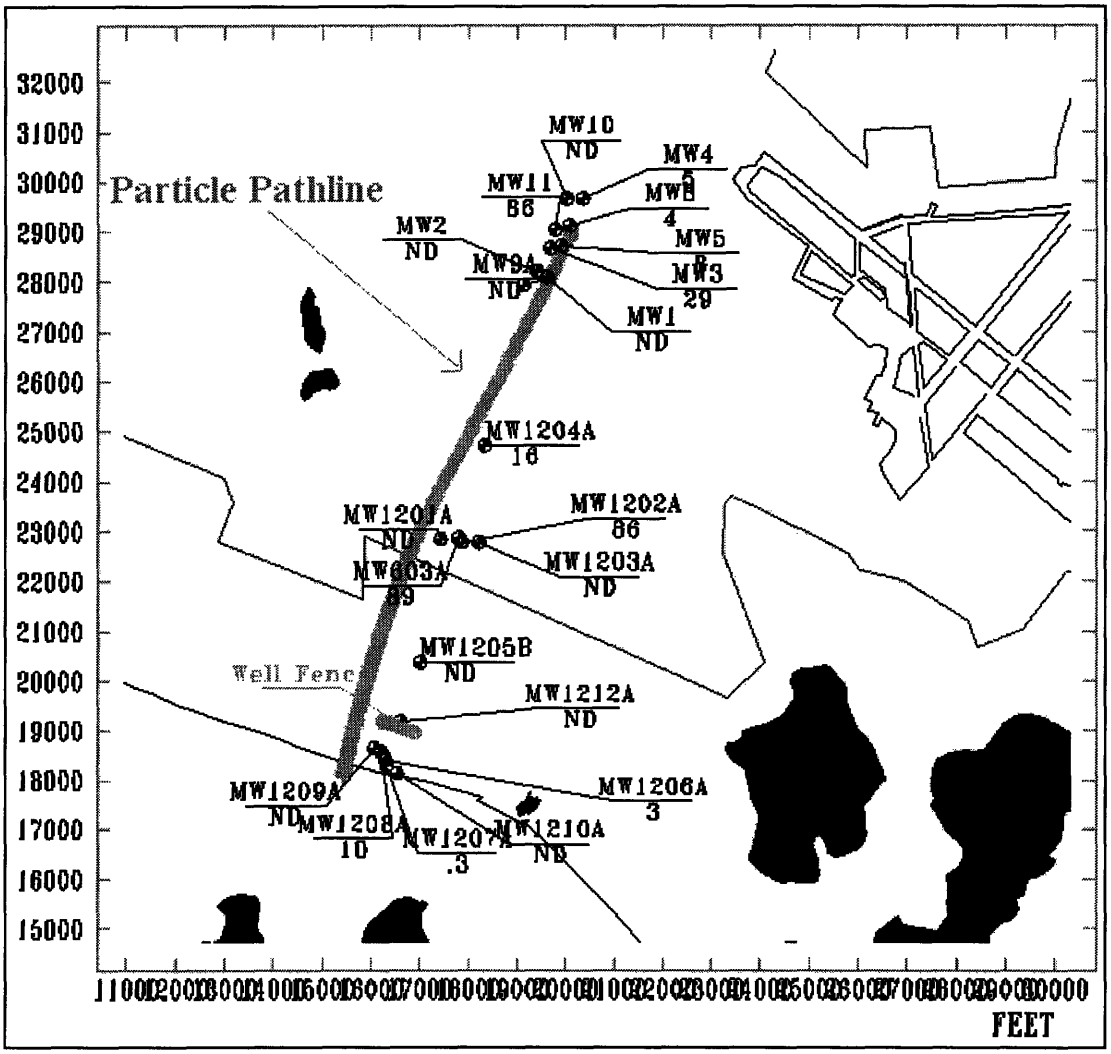

Figure 4-10: Pathline after heads were decreased in Ashumet and John's Ponds

A definite change in the particle's path can be seen in the figure above. Ashumet and John's Pond's head have a visible influence on the particle track and most probably on the CS-4 plume also. Nevertheless, the pathline did not meet the well fence or pass between wells MW1201 and MW1203. Something else needed to be done in order to correct the path of the particles.

Since the particles had the tendency to go towards the west, the hydraulic conductivity in the BBM was reduced. Table 4-4 shows the original and modified values of hydraulic conductivity in the four layers of the BBM.

Layer in BBM	Original K_h (ft/day)	Modified K_h (ft/day)
Top	155	120
Top-middle	125	80
Lower-middle	95	50
Lower	55	5

***Table 4-4**: Original and modified values of hydraulic conductivity in the four layers of the BBM*

The model showed to be particularly sensitive to the conductivity values in the Buzzards Bay Moraine. This is shown in Figure 4-11.

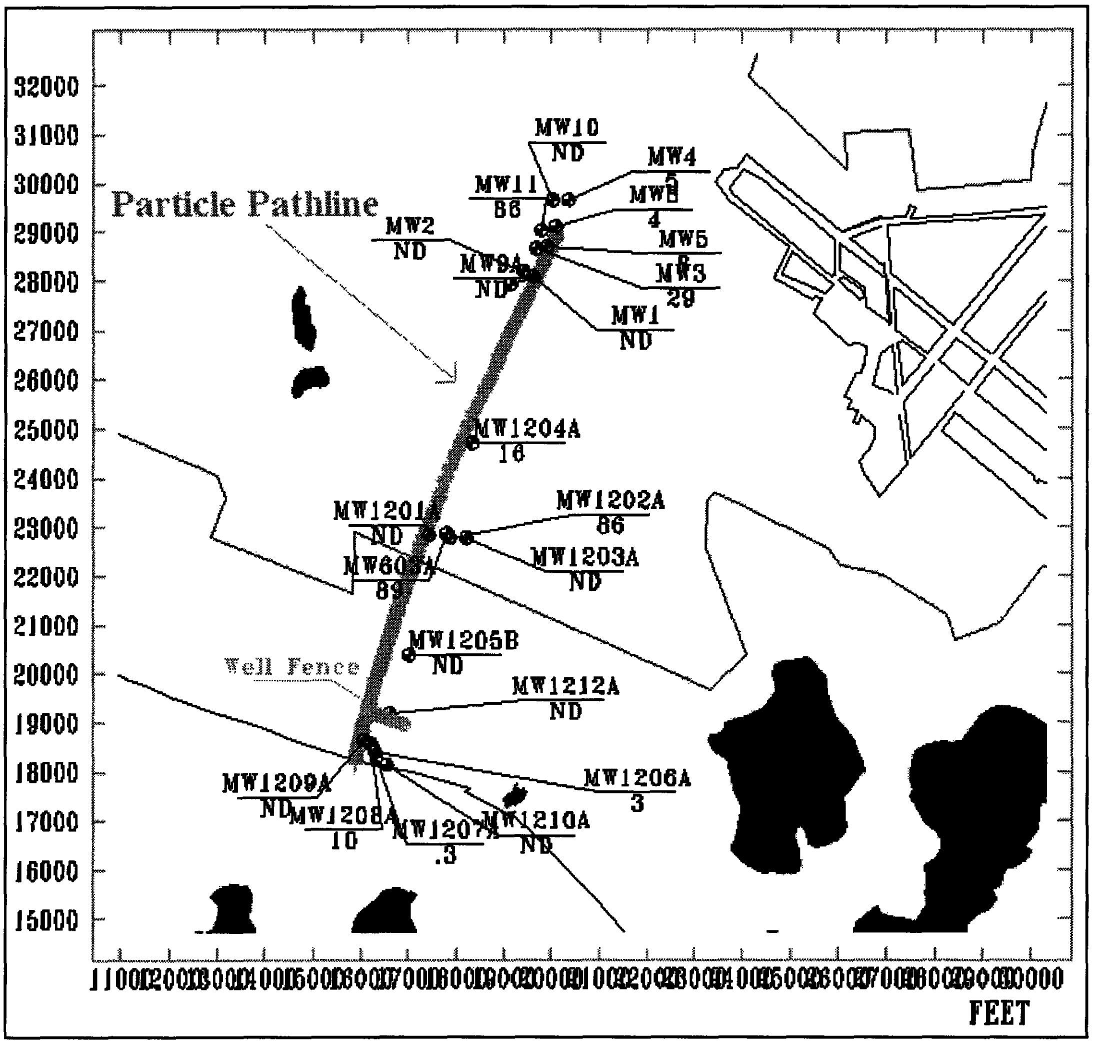

Figure 4-11: Pathline after conductivities were decreased in the BBM

Hydraulic conductivity in the lower layers was reduced considerably more than at the top, because these layers correspond to the outwash layer where the particles mostly travel. A lower conductivity in this layers not only changed the particle's path as shown in the figure above, but it also made the particle stay higher in the aquifer. In Figure 4-12 a north-south cross section shows the particle's path is higher than that of Figure 4-7.

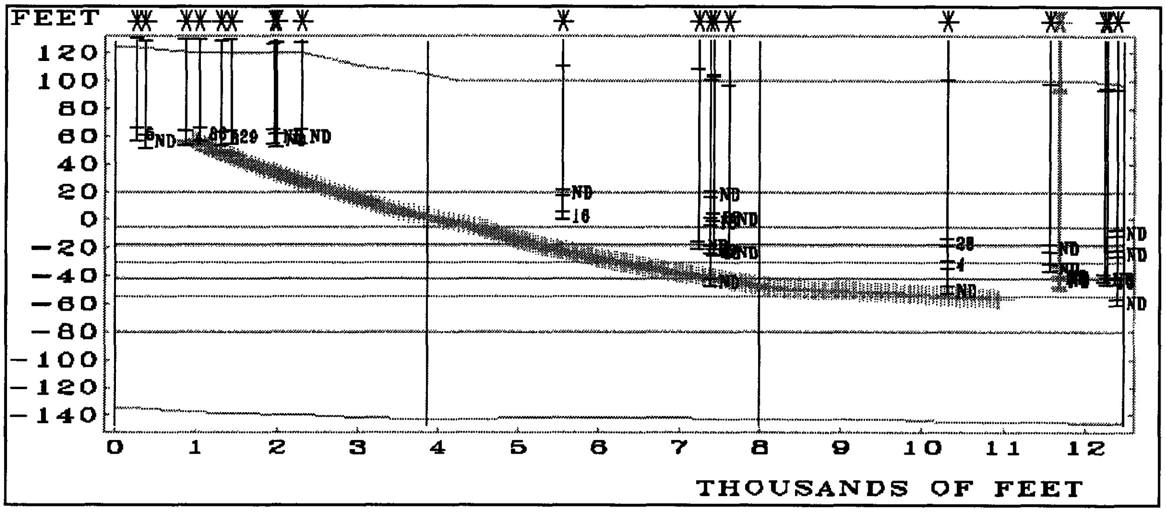

Figure 4-12*: North-south cross section of pathline after conductivities were decreased in the BBM*

This decrease in the moraine conductivity makes a notable difference in the path the particle takes. However, decreasing the hydraulic conductivity in the moraine increased the error of the head observations within the moraine and thus increased the overall model error. Furthermore, the decrease in conductivity in the moraine shown above, does not completely correct the pathline trajectory.

As a final effort to make the particle's trajectory travel towards the well fence and pass between wells MW1201 and MW1203, the grid was modified. This was done as a refining step, since the pathline in Figure 4-12 is already very close to what is expected. By modifying the grid (Figure 4-14), from what it was previously (Figures 4-13), the hydraulic gradient's direction is adjusted so that it points slightly more towards the south.

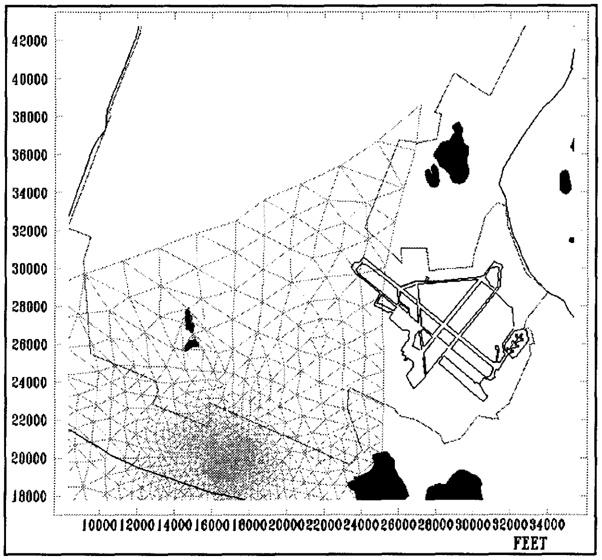

Figure 4-13: *Detail of original grid*

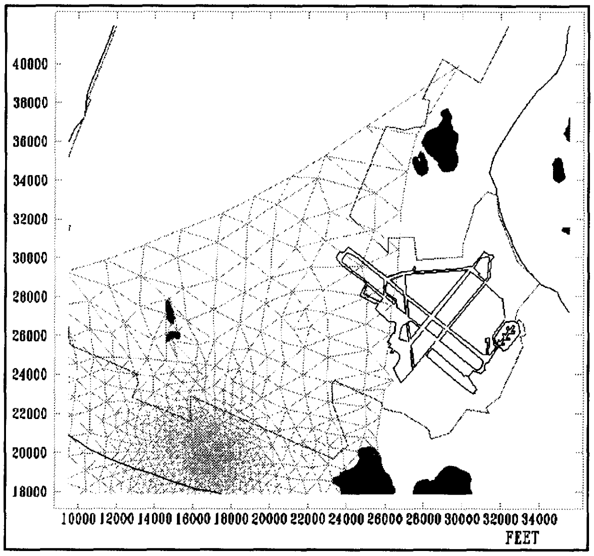

Figure 4-14: *Detail of modified grid*

Notice the difference in the upper right hand most part of the grids

Doing this adjustment to the grid is justified, since what essentially is being done is moving the water table divide and the water table mound. These are not very well defined in the literature or any hydrologic map. Nevertheless, this suggests that modeling portions of aquifers is not the best practice. Amarasekera (1996) and Riva (1996), who also modeled other portions of the western Cape, also reached the same conclusion. Using the entire western Cape Cod aquifer would have probably been a better model, and yielded more credible results. By modifying the grid, the particle's pathline passes between wells MW1201 and MW1203. This is shown in Figure 4-15.

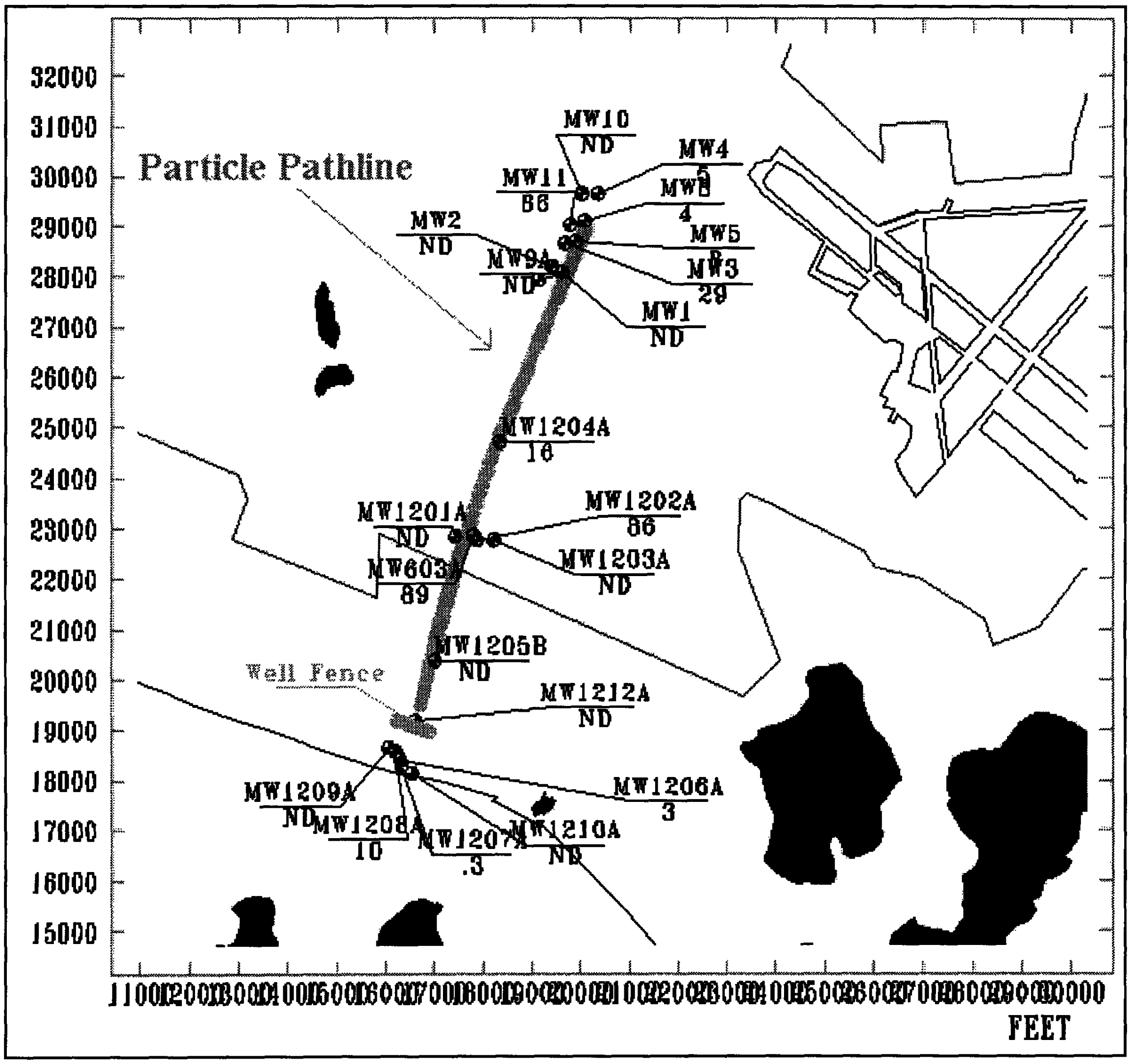

__Figure 4-15__: Plan view of the pathline after the finite element grid was modified

The pathline was now traveling in the expected direction. Table 4-5 shows the original and modified values of hydraulic conductivity in the upper two layers of the outwash. This re-calibration process shows the high sensitivity to subtle changes in hydrogeologic conditions. It also suggests that if other remediation wells are installed near the area, the path of the plume might be affected and the well fence may become useless. Furthermore, the CS-

4 plume might reach Coonamessett or Deep Pond and affect surface waters. Engineers and hydrologist who work with the other MMR plumes should pay close attention to this matter.

Material Layer in Outwash	Original K_h (ft/day)	Original K_h:K_v	Modified K_h (ft/day)	Modified K_h:K_v
Top	217	5:1	265	10:1
Middle	120	10:1	100	12.5:1

***Table 4-5**: Original and modified values of hydraulic conductivity and anisotropy ratio in the upper two layers of the outwash*

The pathline in Figure 4-15 had the anticipated direction, but was still going too deep into the aquifer. To increase the pathline's elevation, horizontal hydraulic conductivities and anisotropy ratios in the outwash were modified. By changing the hydraulic conductivities in this way, most of the flow in the aquifer is confined to the top portion of the aquifer, and thus the particle pathline rises as shown in Figure 4-16. It is interesting to note that Masterson and Walter (1993) had to modify the outwash's hydraulic conductivity in the same way as it was done for this model; by increasing the upper material's conductivity and decreasing the middle and lower one.

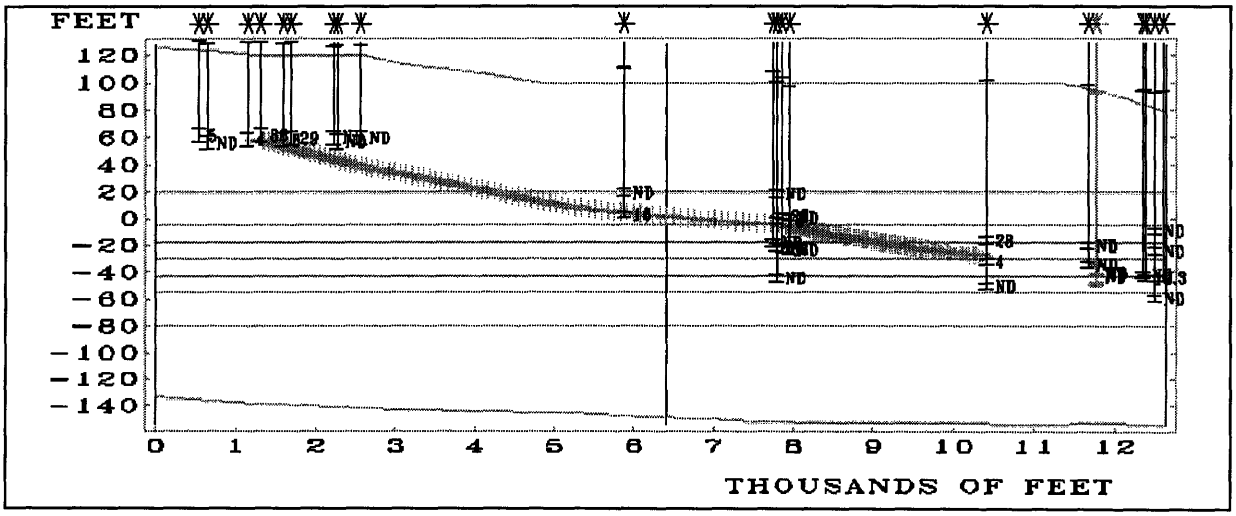

***Figure 4-16**: North-south cross section of pathline after conductivities were modified in the outwash*

As a final calibration procedure, the distribution of the differences in calculated and observed head was examined. This showed that the error here was about 6 times larger than when the model was calibrated considering hydraulic head only. However, since hydraulic conductivities were adjusted in the northern part of the model, they also had to be adjusted in the southern part to maintain the trends and ranges described in Masterson and Barlow (1994). The southern portion of the model had mostly negative errors in the observation points. Therefore, hydraulic conductivities were adjusted keeping this and the geological trends in mind. Final values of hydraulic conductivity in the southern area of the outwash are shown in Table 4-6.

Layer in Outwash	Original K_h (ft/day)	Modified K_h (ft/day)
Top	213	200
Middle	115	95
Lower	30	10

***Table 4-6**: Original and modified values of hydraulic conductivity in the southern outwash*

In addition, recharge was lowered to 19 in/yr in order to decrease the overall error of the model. This amount of recharge is still well within the range of that reported in the literature (Section 4.6.2). A map showing the final distribution of the differences in calculated and observed head is presented in Figure 4-17.

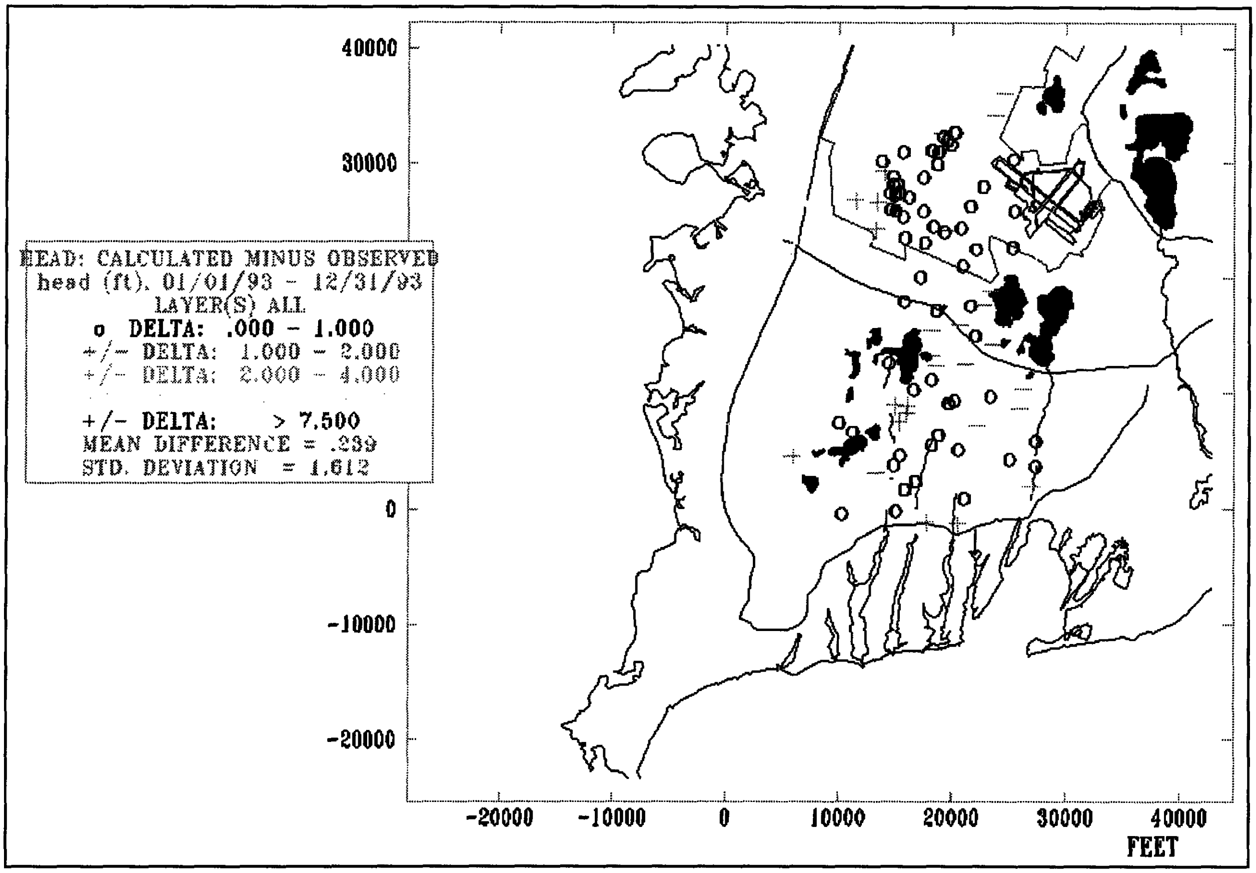

***Figure 4-17**: Final distribution of the differences in calculated minus observed head after particle tracking calibration*

The absolute mean head differences and the head standard deviations in both models are fairly close, even though significant modifications were made to the aquifer properties of the calibrated flow model,. The two models produced very different particle pathlines, although both models could be considered calibrated in terms of hydraulic heads. Furthermore, the models high sensitivity to subtle changes in hydrogeologic conditions suggests that if other remediation wells are installed near the area, the path the plume takes might be affected and the well fence may render useless. The next chapter explores the application of the calibrated contaminant transport model to the MMR.

Table 4-7 presents a summary of the values used for and obtained after the final hydraulic head calibration.

Parameter	Value
Maximum Hydraulic Conductivity (coarse sands in the north- top layer)	265 ft/day
Minimum Hydraulic Conductivity (silty soils in the north- bottom layer)	10 ft/day
Arithmetic Mean Hydraulic Conductivity (north section of model)	223 ft/day
Hydraulic Gradient (CS-4 area)	0.0014
Seepage Velocity (CS-4 area) *	0.8 ft/day
Anisotropy Ratio	5:1, 10:1, and 12.5:1

***Table 4-7**: Hydrogeologic parameters resulting from the groundwater-flow model after calibration taking particle tracks into account.*

**Seepage velocity calculated in same way as Section 4.7.1.*

The value of velocity in the area of CS-4 plume is lower than values reported in the literature (LeBlanc et al., 1991). The reason for this may be that in the presented model, the northern part of the western Cape is not included, which has predominantly very high values of hydraulic conductivity (LeBlanc, 1986) associated with the proximal sedimentary facies which are characterized by coarser grain size. The thickness of the coarse sand and gravel material corresponding to the shallow sediments increases as we go north. This makes the overall hydraulic conductivity increase as well. Since our modeled area is located in the southern part, we miss the higher conductivity values, obtaining a lower groundwater velocity.

5. Contaminant Transport Model

The calibrated hydrologic flow model is used as the basis for the simulations of contaminant transport in the aquifer. The movement of particles generated from the source is simulated using DYNTRACK. Concentrations are calculated based on the particles weight and distribution throughout the area. The source is calibrated by comparing the model concentrations to the field observations. Transport simulations are useful as characterization and remediation tools.

5.1 CS-4 Source

A thorough description of the source, its location, dimensions, and input loadings are essential for a reliable model. E.C. Jordan (1989b) provides a complete description of what is believed to be the CS-4 plume source. Figure 5-1 shows the CS-4 site and plume as presented in the Installation Restoration Program's *Groundwater Focused Feasibility Study, West Truck Motor Pool* (ABB Environmental Services Inc., 1992a).

The source of the CS-4 plume is believed to be located on the former Defense Property Disposal Office (DPDO) storage yard (1965-1983). Prior to this, the area was a military vehicle maintenance area for the U.S. Army (1940-1946) and the U.S. Air Force (1955-1973). This historical information suggests that the greatest potential for the release of contaminants into the environment was between 1940 and 1973.

Due to limitations in the program code, the solvents PCE, TCE and DCE were modeled as one contaminant. TeCA was neglected, since it was only dectected in one well.

As part of the process, the source loading has to be calibrated to match, as best possible, the field values. Consequently, the calculated concentrations are compared to the sum of the observed values at different well locations.

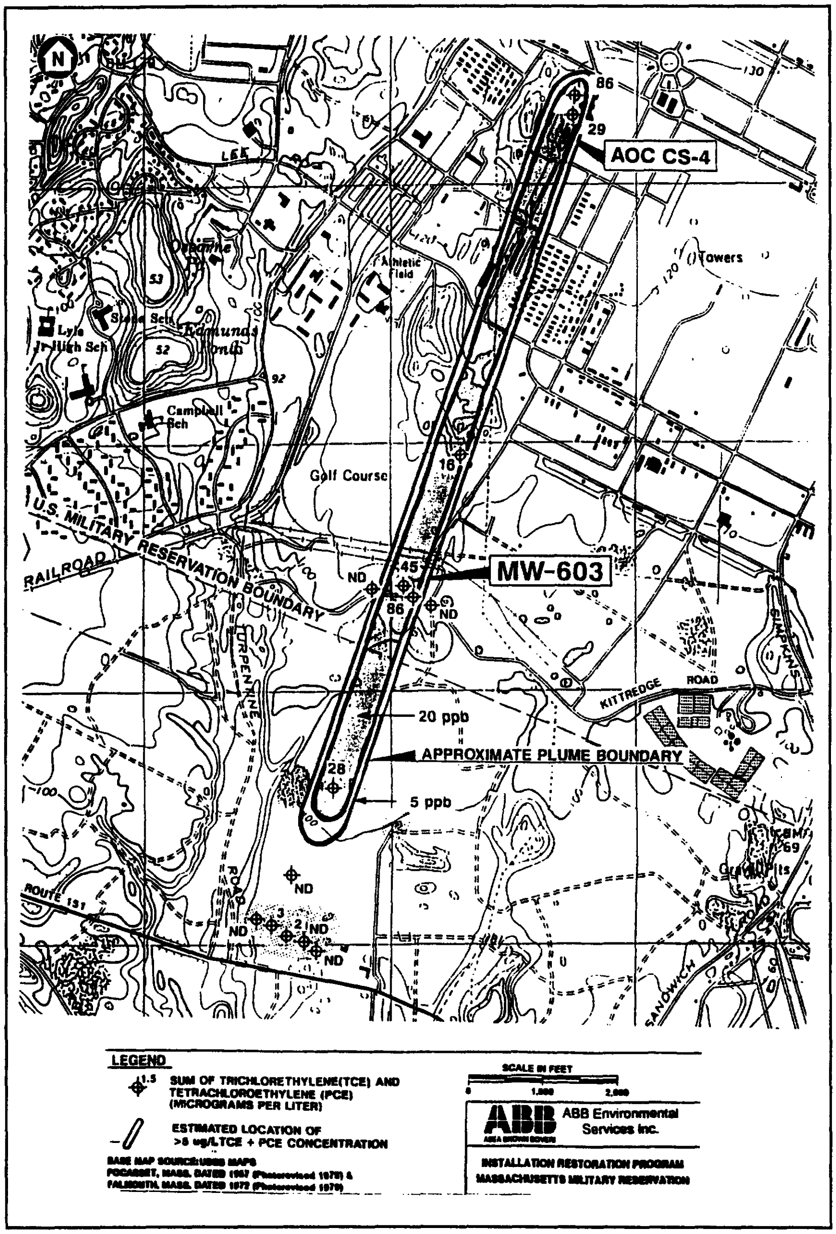

Figure 5-1: *CS-4 site (AOC CS-4) and plume as presented by ABB Environmental Services Inc. (1992a).*

The AOC CS-4 was simulated as a continuos source with variable input. Since there are recorded observations in wells in the toe, middle and source of the plume, the source was assumed have discharged continuously for the period it was contaminating. However, it is important to note that the field data is very limited and thus interpretation of the observations have a high probability of containing errors.

Figure 5-2 shows a map of the AOC CS-4. Using this information by ABB Environmental Services Inc (1992a), the source was interpreted to be a rectangular area of 1000 ft in length and 500 ft wide. The source's center was located at the same coordinates as the particle that generated the final pathline in Section 4.7.2. In addition,

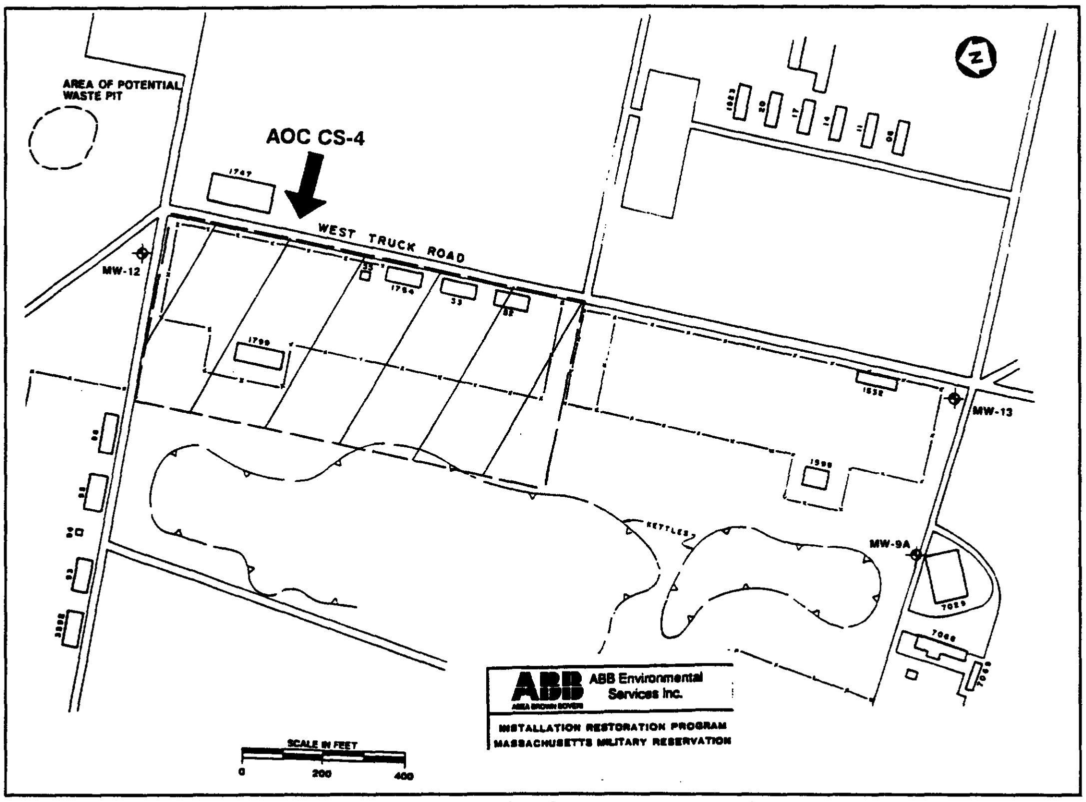

***Figure 5-2**: Map showing the area thought to be the source area of the CS-4 plume (AOC CS-4) from ABB Environmental Services Inc. (1992a).*

DYNTRACK requires that the angle that the source makes with the horizontal be included in the source's description. This angle was determined to be 62 degrees north-northeast (interpreted from the ABB Environmental Services Inc, 1992a). DYNTRACK distributes seeded particles evenly over the entire source area prior to their release.

From groundwater velocity data, it can be determined that the CS-4 contamination must have started at least 15 years ago. The source loading was then modeled as seven 5 year intervals (from 1958 to 1993). This was done for two reasons:

1. In order to introduce variability in the source load if it was needed during the concentration calibration process.
2. To make the loading process more manageable. It is probably easier to calibrate the concentrations with seven 5 year loads, than with one 35 year interval.

The seven 5 year intervals were calibrated by comparing the modeled concentrations, obtained at the end of each simulation, with the observed field data. Calibration of the source refers to comparing the modeled concentrations to the field observations, and adjusting the source load as needed in order to approximate to the field values as best possible. The procedure was performed by initially releasing only the first interval (1958-1963) and letting the model run until the end of the simulation (1993). The other interval loads were set to zero, and thus adjustment of the source load calibrated this interval's concentrations only. When the concentrations were acceptably close, the second interval of particles (1963-1968) was introduced along with the first. These two were calibrated together, and then the third interval was introduced and so on. In general, concentrations were considered calibrated when they were within 30 ppb (or closer) to the field observations. Final source loadings for the CS-4 model are shown in Figure 5-3 below.

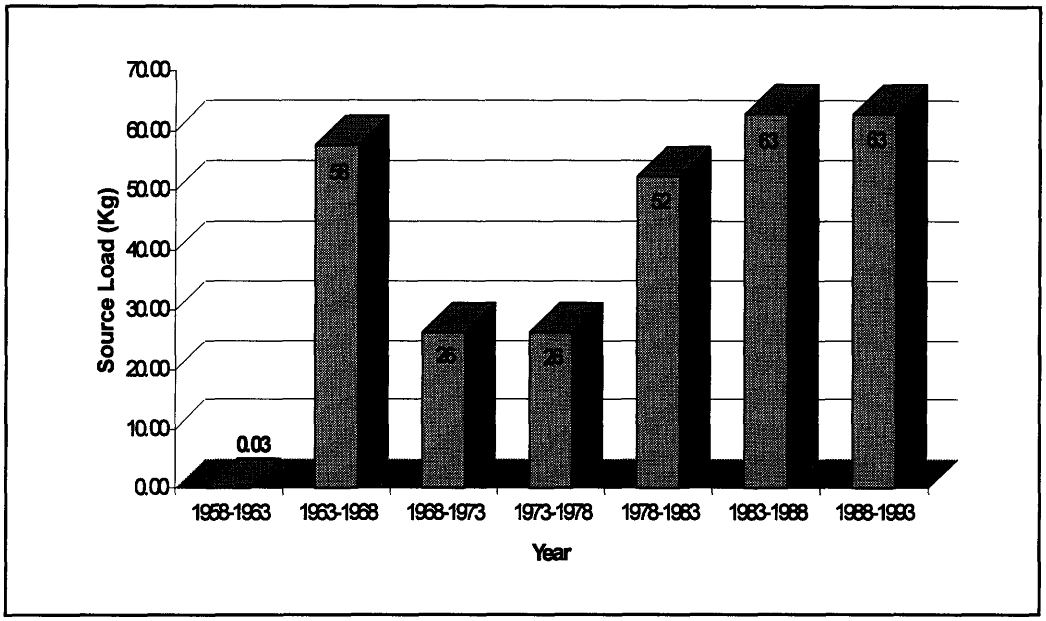

Figure 5-3: Source loadings for the CS-4 model

The total source load was 288 kg over the 35 year interval. Assuming a density of 1.5 kg/L for the compound mixture (mean density between PCE, TCE and DCE), then the total source load in a volume basis is 192 L, which is equivalent to about 50 gallons. Considering that most wastes of this type are stored in 55 gallon drums, then it is simple to visualize the minuscule amounts of solvents that are in the aquifer. This does not mean that only a drum of solvent was spilled, since there was contamination in the soil above the water table.

5.2 Plume Dimensions and Location

DYNPLOT capabilities allow concentration data to be contoured and delineated. From this information the general size and shape of the contaminant plume can be evaluated. The figures below (Figures 5-4 to 5-7) show the graphical output of the model.

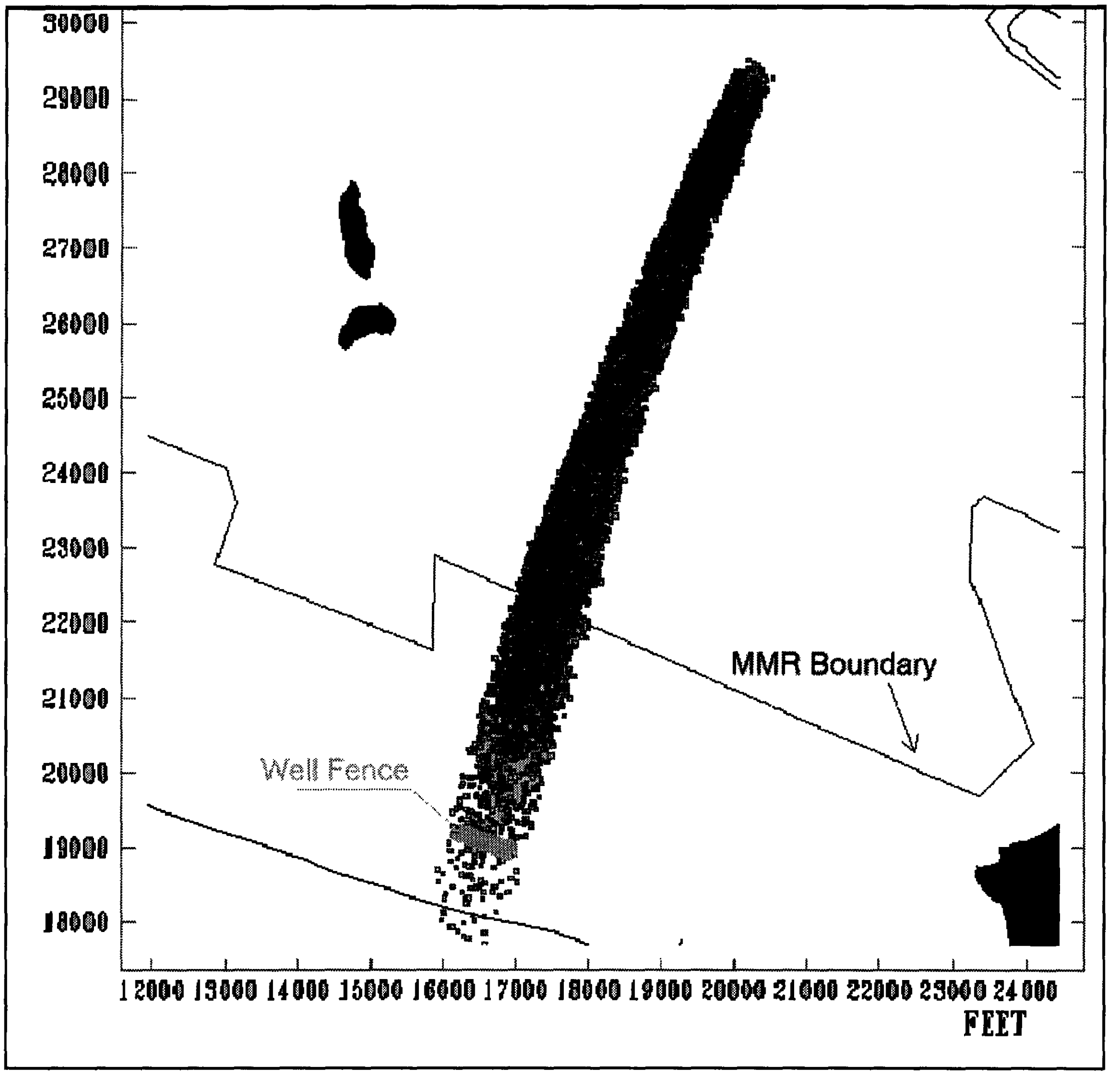

***Figure 5-4**: Distribution of particles in the CS-4 plume simulation*

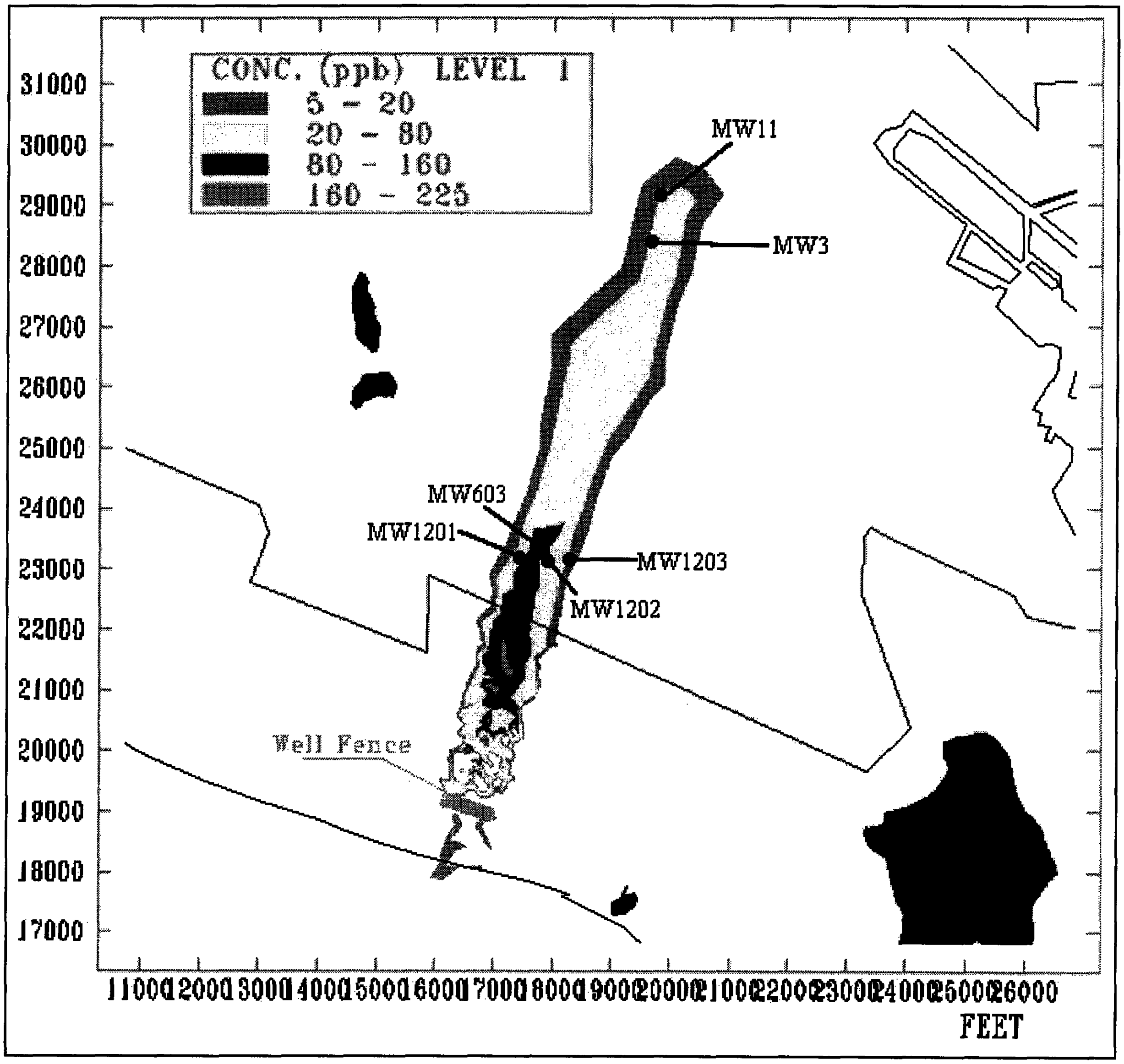

Figure 5-5: Plan view of maximum concentration contours

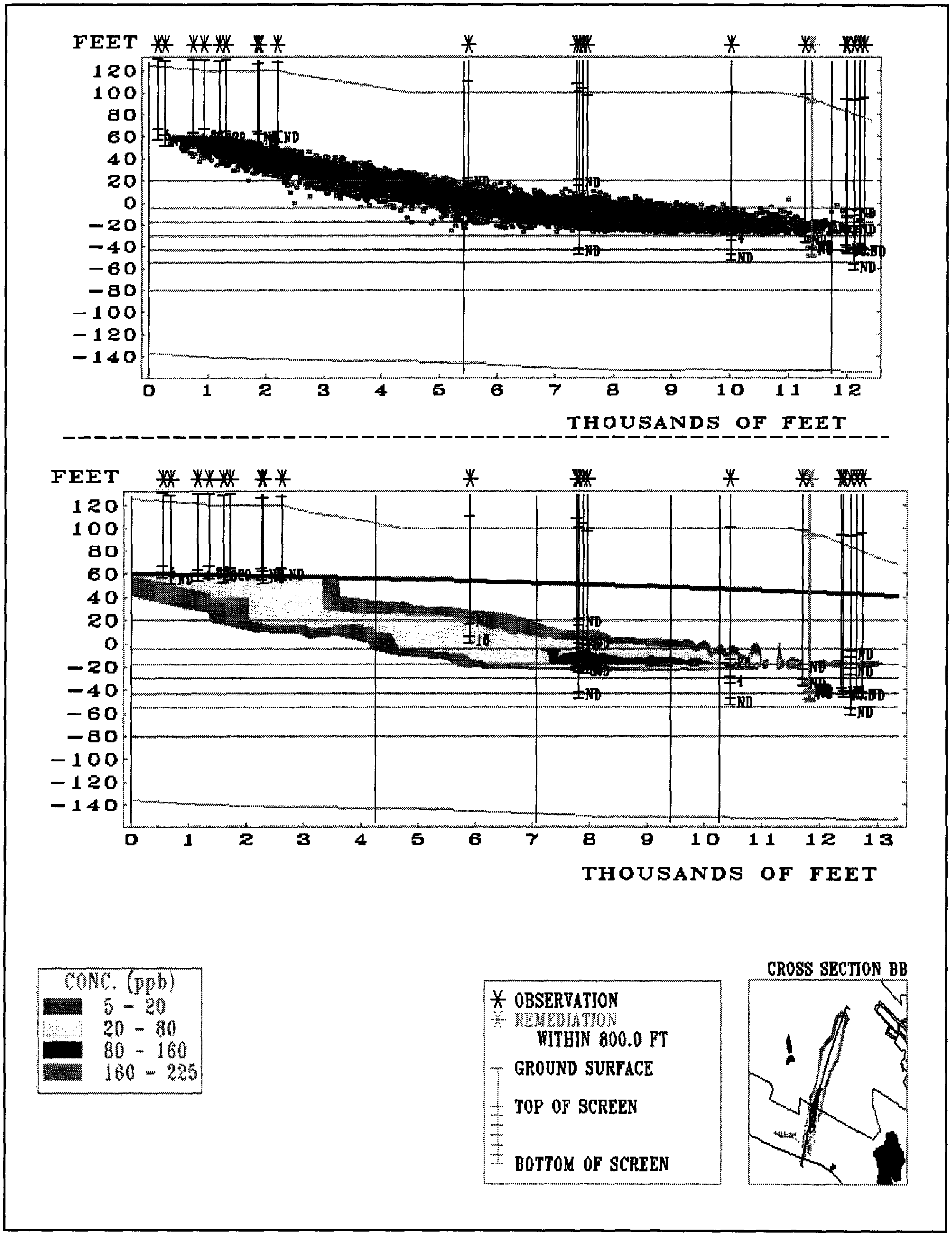

Figure 5-6: North-south cross section of CS-4 plume showing particle distribution (top), concentration contours (bottom)

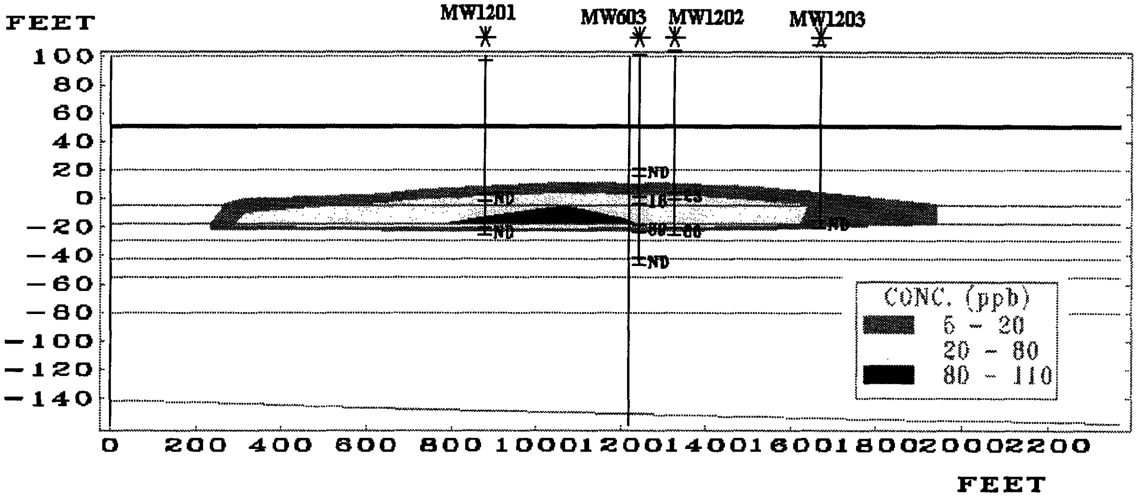

Figure 5-7: East-west cross section of plume through MW603 well cluster

Figure 5-5 shows the plan view of maximum concentration contours of the modeled plume. This can be compared with Figure 5-1 to show that the modeled plume is much wider. This can be attributed not only to transverse dispersion, but also to the discretization of the grid. Discretization problems can be seen especially where the plume has its maximum width. However, there are no field observations in this area that can disprove the model's result. In fact, there are no observation wells between MW1204 and wells at the source(a distance of about 4,400 ft). Since this was a high uncertainty area, concentration was assumed to be continuous in order to "fit" to the observations in MW1204 and wells at the source. Figure 5-5 and its respective north-south cross section (Figure 5-6) show a constant range of concentration (from 5 to 80 ppb) in this area.

Figure 5-5 also shows concentrations of 5 to 20 ppb past the well fence. In Figure 5-2 concentrations are reported for those wells past the fence (MW1208, MW1207 and MW1206), but the plume does not demonstrate this. Even though these are low concentrations, most probably due to longitudinal dispersion, they may still be part of the CS-4 plume.

A wider plume is also evident in Figure 5-7, the east-west cross section through the MW603 well cluster. Field observations suggest that the plume passes between wells MW1201 and MW1203, since there was a "No Detect" reported on these wells while high concentration values were reported for the two wells in between (MW603 and MW 1202). Nevertheless, these are the only wells that define the width of the ABB Environmental Services Inc. (1992a) plume.

The larger width of the simulated plume may also be due to the actual area of the source. As discussed earlier, the source dimensions were assumed to be 1000 by 500 ft. The model may suggests a more localized source, since the distance between MW1201 and MW1203 in only about 800 ft, and transverse dispersion is already very low. At the same time, this might also support the rationale that the contaminants that leached into the groundwater were stored in drums.

From the DYNPLOT graphical output files one can quantify the different dimensions that describe the size of the plume. Table 5-1 summarizes the dimensions of the modeled plume.

Dimension	Measurement (ft)
Length	12,600
Maximum Width	2,100 *
Average Width	1,180
Maximum Height	55
Average Height	40

***Table 5-1**: Dimensions of modeled plume*
**Maximum width is may be overestimated due to grid resolution*

In general, the dimensions of the modeled plume are greater than the ones reported by ABB Environmental Services Inc. (1992a). This result does not necessarily invalidate either plume interpretation. The ABB Environmental Services Inc. (1992a) plume was developed from interpretation of the field observations. This simulation used field observations and site characterization data, applied to a calibrated natural conditions model of the Cape Cod aquifer, and thus probably produces a more appropriate representation of the real plume. Nevertheless, there are many assumptions that are made and factors that come in when a computer model is constructed. Some of these, such as source dimensions and location, hydraulic conductivity distribution, amount of data available; may ultimately be the sources of discrepancy between the modeled solution and the real plume.

5.3 Transport Simulations

The CS-4 plume model described above was used to simulate two different remediation alternatives. Both simulations were started with the particles as shown in Figure 5-4. Therefore it was assumed that no contaminants were emanating from the source after the simulation year 1993. These simulations attempted to forecast the clean-up times for the alternatives examined.

5.3.1 Natural Flushing

The first remediation alternative simulated was the no action alternative. It consequently modeled the natural flushing of contaminants. It was assumed that the system would be naturally flushed when all the particles that make up the simulated plume passed the well fence and reached Coonamessett Pond. Figures 5-8 through 5-13 show a sequence of the maximum concentrations for the natural flushing simulation.

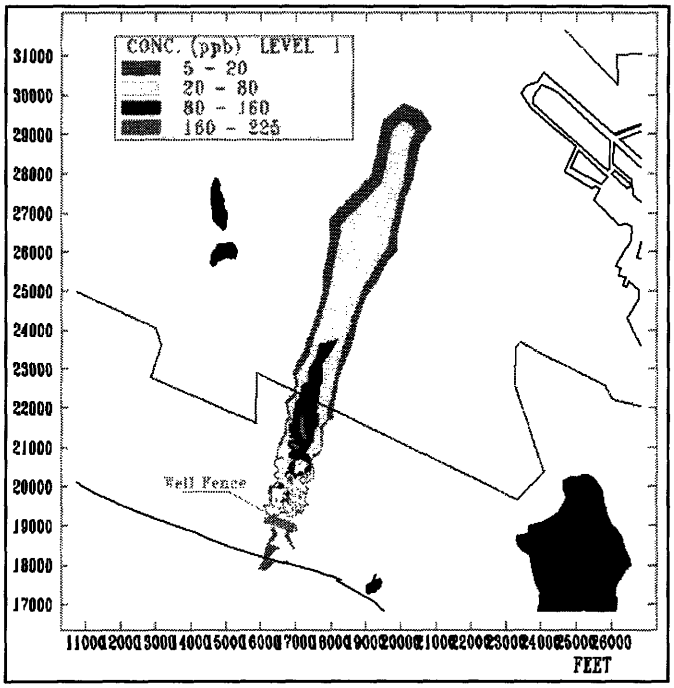

Figure 5-8: Simulation year 1993. Natural flushing simulation.

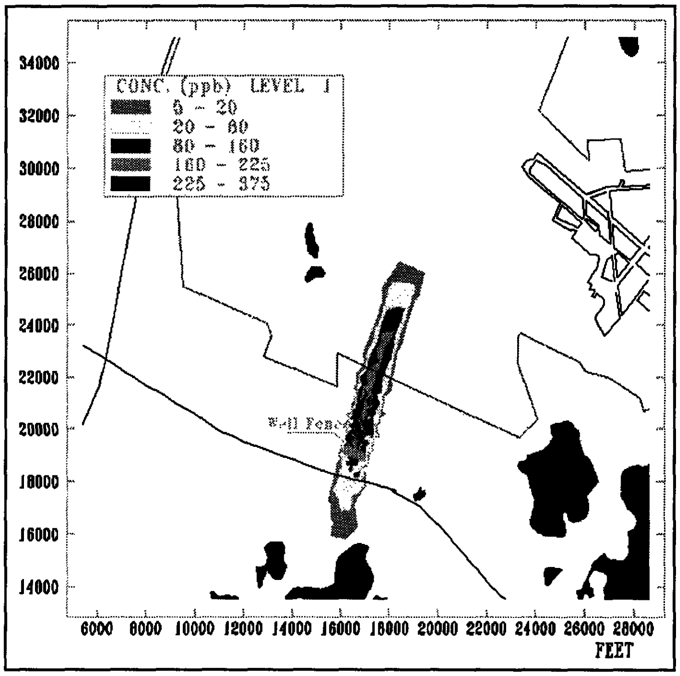

Figure 5-9: Simulation year 2008. Natural flushing simulation.

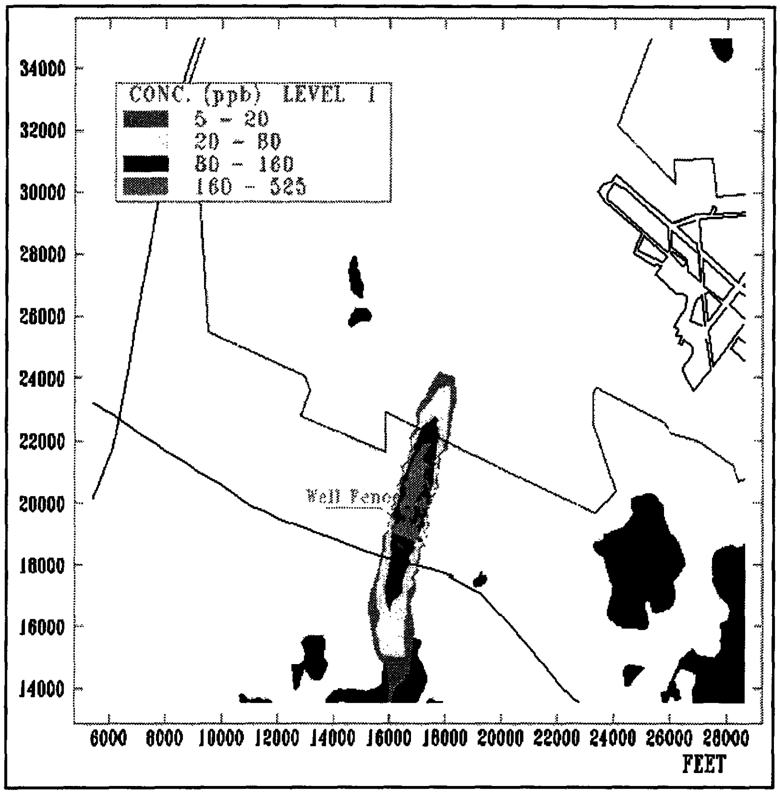

Figure 5-10: *Simulation year 2023. Natural flushing simulation.*

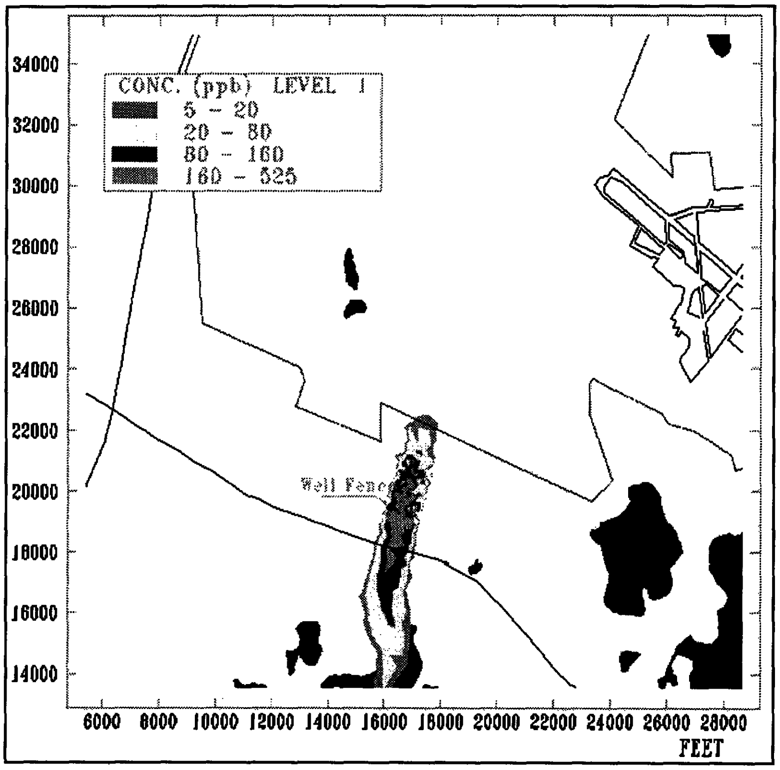

Figure 5-11: *Simulation year 2038. Natural flushing simulation.*

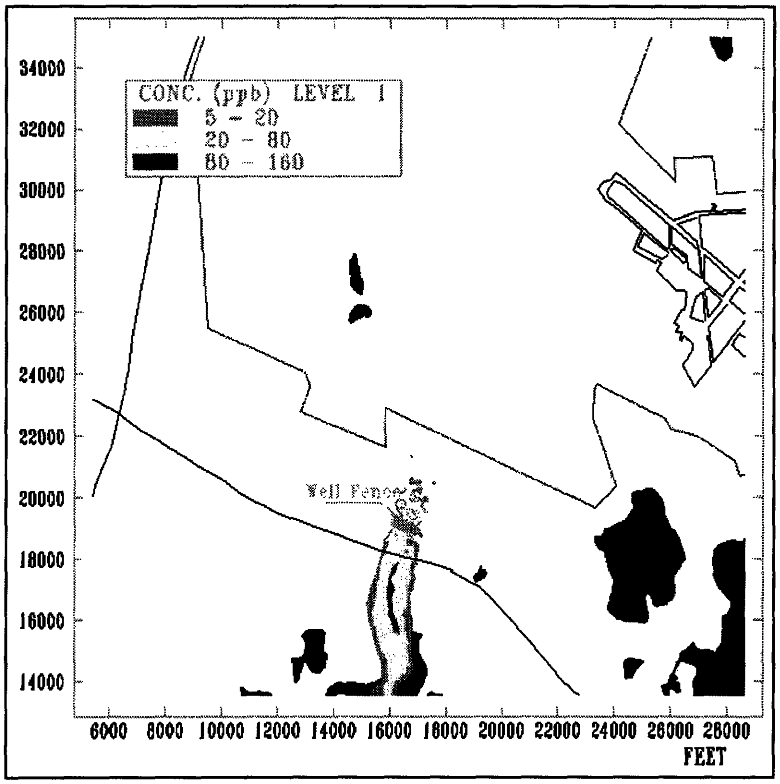

Figure 5-12: Simulation year 2063. Natural flushing simulation.

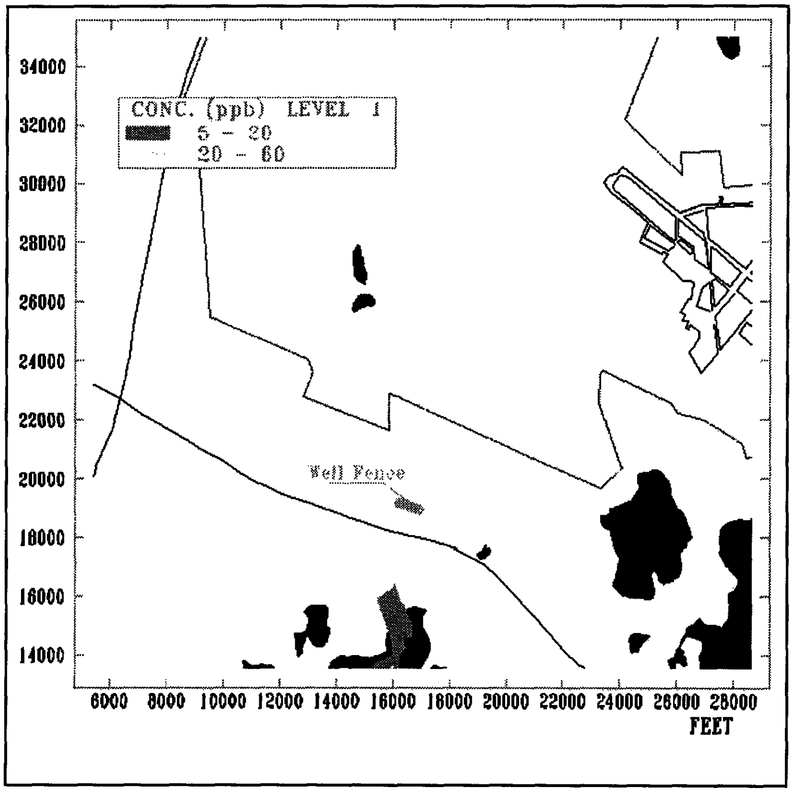

Figure 5-13: Simulation year 2073. Natural flushing simulation.

Figures 5-9 through 5-11 show an increase of concentration within the plume. This is because the code calculates concentrations based on particle location density. This does not interfere with the objective of the figure sequence since its intentions is to demonstrate the plum's transport and not the modeled concentrations.

The total time it took for all the particles to enter Coonamessett Pond was between 80 to 85 years. Thus, the model suggests that if the well fence had not been operating, the aquifer under the MMR would be "clean" approximately by the year 2075. Once the particles reached the pond, concentrations dropped notably, possibly due to dilution effects. The model indicates that concentrations in Coonamessett Pond and beyond would still exceed maximum contamination levels; but, of course, the model, which represents the pond as a very high conductivity porous medium, does not realistically represent mixing, degradation and volatilization in the pond. The model results in terms of mass influx to the pond, could be used as the basis for further studies on surface water impacts.

5.3.2 Simulation Using Current Pumping Scheme

A second simulation attempted to replicate the current pump and treat scheme used at the MMR. The purpose of this simulation was to observe the time it would take to run the pump and treat system until concentrations in the aquifer reached acceptable levels. A file was created that would defined the pumping wells as nodes in the grid with negative flux. This file was used to modify the flow field. As in the existing well fence, the two wells at the extremes pumped at 15 gpm and the 11 wells in between at 10 gpm.. Particles were introduced in the same location as in Figure 5-4 (simulation year 1993). The simulated pumping began in the simulation year 1994. Figures 5-14 through 5-19 show a sequence of the maximum concentrations for this simulation.

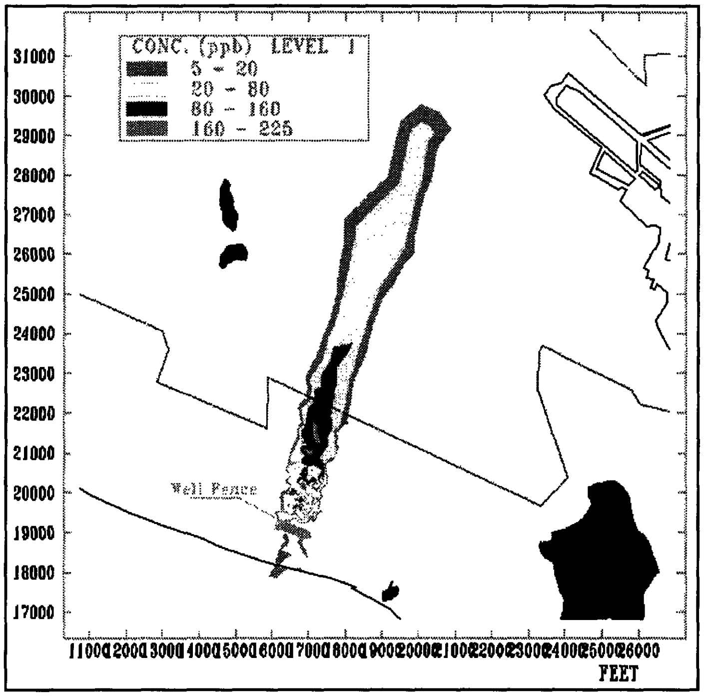

Figure 5-14: Simulation year 1993. Current pumping scheme simulation.

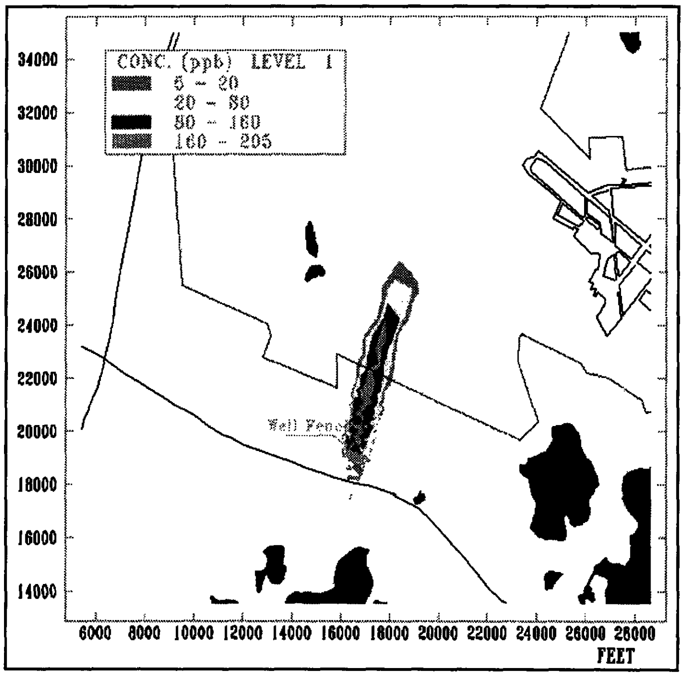

Figure 5-15: Simulation year 1993. Current pumping scheme simulation.

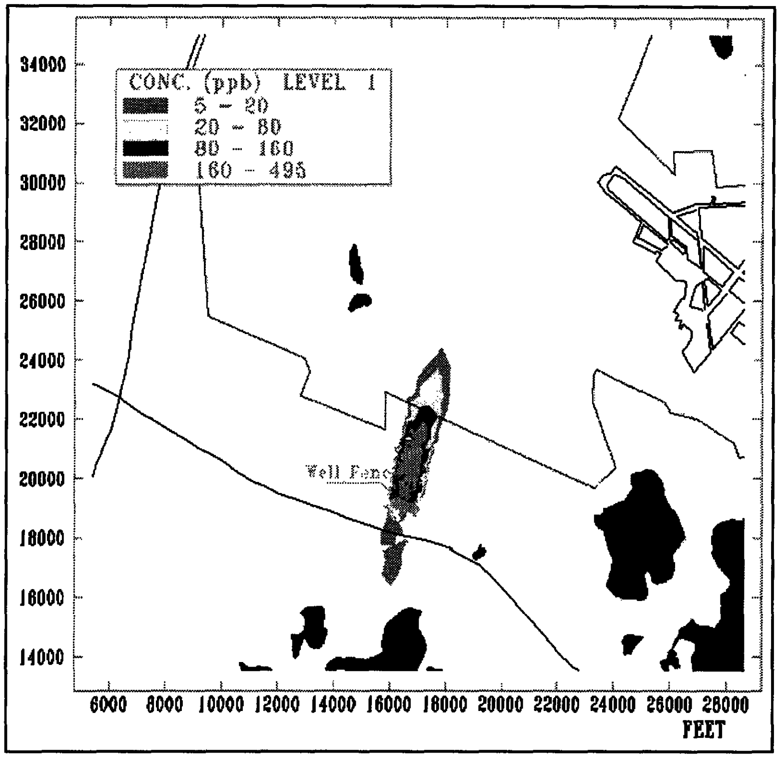

***Figure 5-16:** Simulation year 2023. Current pumping scheme simulation.*

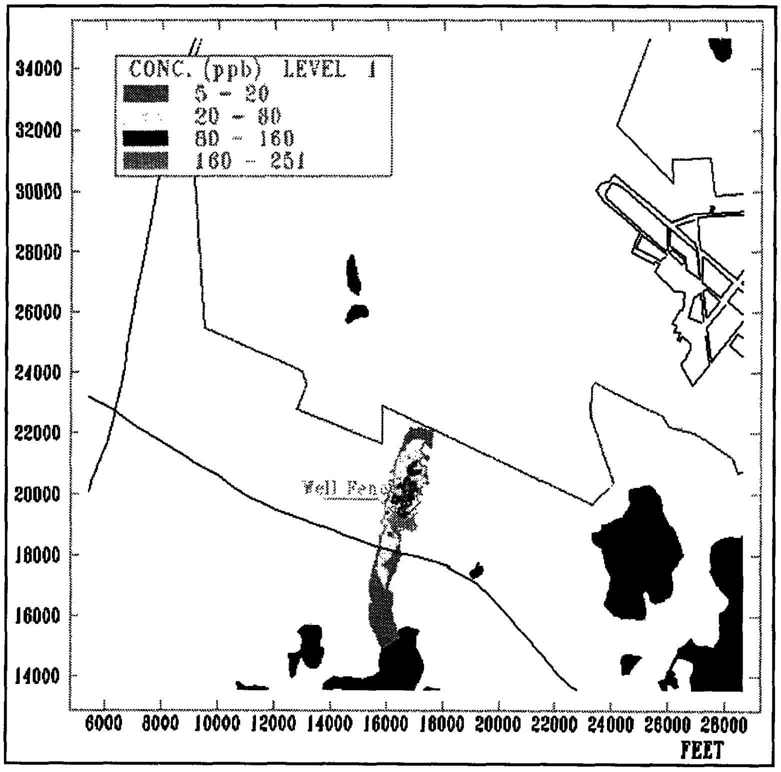

***Figure 5-17:** Simulation year 2038. Current pumping scheme simulation.*

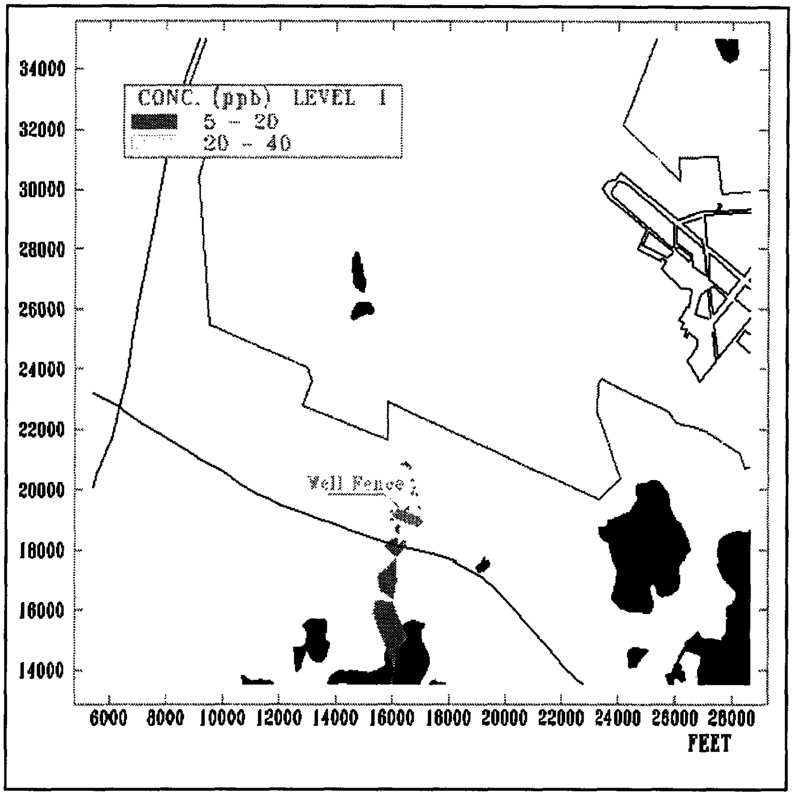

Figure 5-18: Simulation year 2058. Current pumping scheme simulation.

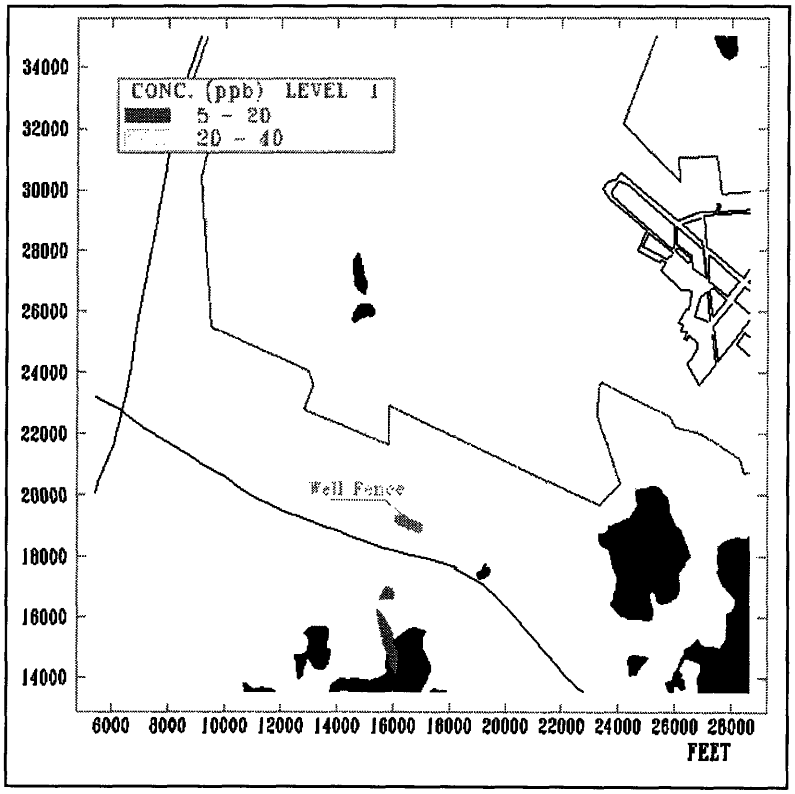

Figure 5-19: Simulation year 2063. Current pumping scheme simulation.

The model simulation showed that the pump and treat system would have to run for 70 to 75 years (after the source is eliminated) in order to remediate the site. A pump and treat system running continuously for this amount of time would probably have very high operation and maintenance costs (MacDonald and Kavanaugh, 1994; Mackay and Cherry, 1989). This strongly suggests that a final remedial system where clean-up times are less would probably more time and cost efficient. The CS-4 site should continue to be used to contain the plume, but an effective final remedial scheme should be installed promptly.

It is important to note however, that some particles escaped the well fence and ultimately ended up in Coonamessett Pond. This might be due to the fact the well fence is designed for an 800 ft wide plume, and the modeled plume is much wider. Capturing a wider plume with the current well fence might still be possible if higher flow rates are used, although this would depend the system's capacity. Appendix B, gives a summary of the findings of López-Calva (1996) who explored alternate pumping schemes for the well fence in question.

6. Discussion and Conclusions

Site characterization information was used to create a hydrogeologic model of a portion of the western Cape Cod aquifer. This model was first calibrated using the latest and most complete hydraulic head data available. Initially, the model was assumed calibrated under hydraulic head considerations only. However, particle tracking demonstrated that the model needed further calibration. Particle pathlines were used in conjunction with field data to recalibrate the model. The modeled plume demonstrated to be very sensitive to subtle changes in hydrogeologic conditions. This also suggests that if other remediation wells are installed near the area, the path the plume takes might be affected and the well fence may render useless.

After the final calibration, both models (the one calibrated based on hydraulic head only and the one calibrated based on particle tracks) had similar errors, despite their significantly different particle pathlines. This suggests that particle tracking is an essential calibrating procedure for transport models in heterogeneous aquifers similar to the one of Cape Cod. The calibration procedure also suggests that a model of the whole western Cape aquifer would probably be more appropriate.

This calibrated flow model was used to simulate the CS-4 plume of the MMR. The source load was determined by comparing well observations to the modeled concentrations. The total mass of solvents in the aquifer was determined to be 288 kg, approximately equivalent to one 55 gallon drum. This suggests that wastes were stored in barrels, and shows