Uncertainty of Risk to Human Health from Groundwater Impacted by the Massachusetts Military Reservation Superfund Site Landfill

by

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B.S., Nuclear Engineering
University of Lowell, 1991

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

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Abstract

The Massachusetts Military Reservation (MMR) site is publicly perceived as having a significant intrinsic risk because the site has received appropriations from the Superfund for remedial clean-up. The MMR stakeholders have repeatedly raised the following question: "What's the risk of just letting the landfill plume go to the ocean untreated?" Although a complete answer to this question is beyond the scope of this thesis, an inspection of the cancer risk from the landfill plume by the groundwater pathway is not.

Since the MMR site has been classified using the Environmental Protection Agency's (EPA's) guidelines which were not specifically developed for the MMR site, the accuracy of the health and environmental risk scores are in question. Unlike the deterministic model which the EPA presently requires to be used for quantifying risk, a probabilistic model was hypothesized to be better able to compensate for a lack of precise information.

By representing distributed variables with point estimates rather than distributed functions reflecting the uncertainty in these quantities, it is hypothesized that the EPA has radically simplified the mathematical representation of a physical phenomenon. A probabilistic model is presented in this thesis to test the hypothesis, and lognormal distributions are used for PDF development. In contrast to a deterministic model, a probabilistic model enables a series of products and quotients of several probability distribution functions (PDFs) to be represented by one PDF. With a single PDF, it is very easy to observe the mean, along with the upper and lower boundary conditions, and the uncertainty is simply represented by the variance of the PDF.

It is found that the EPA's point estimate model results are almost the same as the probabilistic risk model results, in terms of risk magnitude. The mean relative risk predicted by the EPA model and by the probabilistic model are approximately 1.51E-04 and 1.14E-04, respectively. It is also found that this correlation is directly attributable to the statistical variance, otherwise termed uncertainty, associated with the EPA's cancer slope factors (CSFs). The variance of both risk models is almost entirely dominated by the variance of the CSFs. Based on the analysis carried out in this thesis, it is recommended that monitoring programs for the both the drinking water supply and the shellfish supplies which are located near the potential zone of influence of the advancing landfill plume (LF-1) be implemented. Monitoring, along with other probabilistic research, can quantify further potential for both synergistic and systemic health risks. Finally, the EPA's recently proposed changes, published in the Federal Register, to adjust CSFs and reference doses (RfDs) to more accurately approximate their statistical influence upon human health are a good start in the right direction.

Thesis Supervisor: David H. Marks, Ph.D.
Title: James Mason Crafts Professor of Civil and Environmental Engineering

To

the source of all energy that influences all matter and ultimately connects everyone and everything, otherwise and better known as

GOD

Acknowledgments

I would like to first acknowledge my advisor Professor Dave Marks. If it was not for him you would not be reading this. I am grateful he elected to be my mentor and help me craft the potential that was within me; I will always be indebted to him for this. Secondly, I must acknowledge Professor Lynn Gelhar. He gave me the idea to inspect risk by using logarithms. His patience and kindness enabled me to ask all of my questions without embarrassment. His technical suggestions towards the development of this thesis and his inspection of my results are greatly appreciated. He is the finest mathematical mind that I have ever had the opportunity to learn from.

I would also like to thank Shawn Morrissey for the consultations, Bruce Jacobs for his assistance, all Course 1 support staff including, but not limited to, Jackie, Jason, Muriel, Pat, Cynthia, and Jessie, and all other employees at MIT. In addition, I would like to acknowledge the staff and consultants at the MMR, in particular Mr. Ed Pesce and Mr. Dennis LeBlanc of the USGS, along with the many professionals from the private sector, the various representatives of both state and federal agencies, and several Professors at MIT. They helped the M. Eng. Program by making presentations, and by furnishing the M.Eng. group with the documentation and insight which was requisite for the students in the M.Eng. program to adequately research the MMR.

I am very pleased to have this opportunity to thank all of my classmates in my group and in the M.Eng. program for helping me along the way; I had a lot of fun. I would especially like to thank 3rd shift (Enriqué de la Noche, B2 "the print master of disaster", Kashin, Crist, Mitsos, Pete ovah theyah, Communist Bob and Monsieur Christophe) for helping me to forge ahead with respites of torrential laughter during the all-nighters. I also want to thank Ben, Holly and Mike for showing me the MIT ropes.

I am delighted to thank my friends outside of MIT for all of their personal support during this demanding time in my life. These friends include, but are not limited to, my best friend, Jimmy "SUPER Star/Dude/Duper, $^{1}/_{10}$ of 1%" Collins, along with my buddies Sam "Bottom Line, F. King Gill" Thomas, Eric "E, F. King Dubé" Dubé, Mike "The Scourge" Chadwick, and my former mentor Garrett "Garry" Sullivan. I am proud to thank my family: Dad "Beep-beep", Mom "MaMiMa", my sister Mary "Mimi", along with my grandparents, aunts & uncles, and cousins. THANK YOU! I regret that I am incapable to describe how much I love you. Also, I want to thank all the friends of Bill W. and Dr. Bob, especially Rian and Dan; I wouldn't have made it without all of you and my HP.

Finally, and most importantly, I would like to thank my dearest confidant, Danielle. She has given me the most support throughout my entire experience at MIT. Although her personal support has been tremendous, I would be remiss to not acknowledge her professional support in the production of this thesis. She has been an invaluable sounding board for my mathematical ideas and she is a superb editor. Thanks buhby, I love you!

Table of Contents

List of Figures

List of Tables

1.0 INTRODUCTION

This thesis is submitted for partial fulfillment of the course requirements for the Master of Engineering Program in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology (MIT). In addition, this thesis topic was selected because public concern over the Massachusetts Military Reservation (MMR) site as a source of potential risk to human health is varied. It is the opinion of some people that the potential risk imposed by the site upon public health and welfare is low. Conversely, it is the opinion of many others that the MMR site, and more specifically the advancing landfill plume (LF-1), is detrimental to the environment and public health. The MMR was placed on the Superfund National Priorities List (NPL) by the Environmental Protection Agency (EPA) in 1989.

This thesis was performed in conjunction with a research project undertaken to characterize environmental impacts of groundwater contamination leaching from the Main Base Landfill at the MMR, which is located at Cape Cod, Massachusetts. The project report was also submitted for partial fulfillment of the course requirements for the Master of Engineering Program in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology (MIT). The research team consisted of Dan Alden, Kishan Amarasekera, Michael Collins, Karl G. Elias, Benjamin R. Jordan, Robert F. Lee, and myself; all are candidates for the Master of Engineering (M.Eng.) Degree Program at MIT.

An extensive amount of data on contamination at the MMR has been collected, and it is maintained by the MMR Installation Restoration Program (IRP) office, which acts as principal agent for the U.S. government on behalf of the MMR. There are numerous reports which include data observations and professional opinions; these reports are available for public review. These reports, which are cited herein, are the principal sources of information used for analysis in this report. As the MMR LF-1 site is part of an ongoing clean-up, new and updated data from continuous reporting has been included in order to present the most accurate information possible. Investigation of supporting documentation is referenced as appropriate. A general assumption of this project research is that the analytical data which has been collected and included in the publicly available IRP reports are accurate.

The group project report both examined and offered opinions on the potential impacts (*i.e.,* potential danger) of the MMR LF-1 on the public health and welfare and how these effects can be mitigated. The scope of the research project included site characterization, groundwater modeling, risk assessment, management of public interaction, study of source containment, and bioremediation. The underlying objectives of the project research were as follows:

- Characterization of the site through evaluation of subsurface hydraulic conductivity,
- Characterization of the landfill plume chemistry, dimensions, and movement through use of existing data and groundwater modeling,
- Potential protection of the Cape Cod groundwater aquifer from further contamination by source containment with design of a landfill cover system,
- Evaluation of the potential cancer risk which materials identified in the groundwater present to people located near the landfill plume, as well as risks associated with ingestion of potentially contaminated shellfish,
- Design of a bioremediation scheme to remediate contaminated groundwater,
- Characterization of the management of public interaction surrounding base cleanup activities.

1.1 Problem

In general, the MMR site is publicly perceived as having a significant intrinsic risk because the site has been listed on the NPL and has received appropriations from the Superfund for remedial clean-up. Since the MMR site has been classified using EPA guidelines which were not specifically developed for the MMR site, the accuracy of the health and environmental risk scores are hypothesized to be limited by the constraints of the EPA's deterministic risk assessment model. In order to understand better the health and environmental risks associated with the MMR site, a probabilistic model is proposed to test this hypothesis. Unlike the deterministic model which the EPA presently requires to be used for quantifying risk, a probabilistic model should be better able to compensate for a lack of precise information. In addition, specific qualities peculiar to the MMR site could be deliberately incorporated into a probabilistic model. A probabilistic model which is specific to the MMR site can yield a more transparent uncertainty for the overall range of risk. A probabilistic model will continue to underscore the engineering principles which are both implicit in the EPA's deterministic model and explicit in Congress' statutory mandates to the EPA. These engineering principles include the slightly competing goals of showing respect for the well-being of the environment, which includes human health, and having regard for the valuable use of regional site resources. These principles are implemented when decisions are based upon empirical opinions that account for uncertainty when risk control is an issue.

Because of the technical nature of risk control, there are those who consider it to be some sort of witchcraft. Contrary to this belief, risk control is an engineering discipline which is based upon intricate numerical models with uncertainties that may appear overwhelming upon initial inspection. Although risk calculations may seem staggering, risk control models arguably have a reliability which is comparable to other similar systems such as insurance actuarial processes and nuclear engineering dynamics. All three systems are not well understood by the average population, but nearly everyone accepts the facts that insurance companies consistently make money and nuclear systems harness the energy from billions upon billions of atomic collisions to provide reliable power. Like risk calculations, both insurance and nuclear calculations are not specific to a single event. However, these calculations are specific to a collection of random independent events which is large enough to support accurate statistical models. Nonetheless, there will always be those who consider both the insurance and nuclear industries to be black magic of sorts. However, comparable to other industries, it is generally accepted by the majority of the population that risk control can be used to achieve success in balancing the frequently competing goals of social costs and business opportunity costs.

1.2 Objectives

In this thesis, risk, as it pertains to human health as part of the local environment, is defined as the statistical increase in mortality rate for a member of the local community who has been exposed to hazardous materials identified in the MMR LF-1 as compared to the rate for a member of the local community if the MMR LF-1 did not exist.

1.2.1 Identify Hazardous Materials

Hazardous materials are broadly defined as non-carcinogens which are known to have harmful systemic effects upon humans, and carcinogens which have a propensity to initiate and promote cancer. Both terminal and "quality of life" health problems from exposure to hazardous materials are primary human health concerns. Because of these health concerns, human exposure to hazardous materials, especially carcinogens, is a source of risk and is of primary concern for risk control.

1.2.2 Review Existing Reports

Part of this investigation is to conduct a comprehensive review of the available reports which are relevant to risk assessment for the MMR LF-1. This review will include an examination of the methodology used, a discussion on the consistency of the reports with respect to EPA regulatory protocol and standards, and spreadsheet calculations using the equations and numerical values which are cited in the EPA's reports. This three part process will check the accuracy of the reporting which has been used up to now to calculate risk and formulate risk control opinions.

1.2.3 Cranberry Bog Risk

The MMR LF-1 is migrating from its source, otherwise known as the MMR base landfill, towards Buzzards Bay; a cranberry bog is juxtaposed to this general path. This thesis considers cranberry bogs to be potential sensitive receptors. On account of the location of the cranberry bogs, it is important to determine the likelihood of the LF-1 reaching the cranberry bogs and their water supply.

1.2.4 Uncertainty

In all statistically intensive calculations there are uncertainties specific to the numerical model which is being used. Since the EPA's model is the requisite regulatory guideline for Superfund sites, their model is the one which is being scrutinized. In order to understand the level of accuracy which is a function of the uncertainty incorporated into the EPA's model, it is necessary to know how and why the results of a probabilistic model will differ from theirs.

1.3 Scope

Certainly the above discussion is very broad and could provide enough material to offer several publications. However, this project is not being undertaken to achieve that end. At several meetings, members of the community who are interested in ongoing operations at the MMR LF-1, the Massachusetts Department of Environmental Protection (MA DEP), and the EPA have repeatedly raised the following question: "What's the risk of just letting the plume go to the ocean untreated?" Although it is beyond the scope of this thesis to offer an opinion for the purpose of constructing policy, offering an unbiased, empirical opinion as to the potential cancer risk for residents located near the groundwater path of the Massachusetts Military Reservation landfill plume, by offering a probabilistic inspection with transparent uncertainty, is the central purpose of this thesis.

1.3.1 Master of Engineering Thesis

This thesis is being submitted to the Massachusetts Institute of Technology's Department of Civil and Environmental Engineering to satisfy the thesis requirement for a Master of Engineering (M.Eng.) degree. In addition, the professional opinions contained herein are the outcome of an investigation aimed at understanding the direct material risk to human health connected with carcinogens identified in the MMR LF-1. This report is based upon engineering principles, and painstakingly written to remain unbiased towards both government interests and public considerations.

1.3.2 Peer Review

In order to offer scientific opinions regarding risk connected to the MMR LF-1, it is necessary to review air, water and geologic data local to the MMR LF-1 site. For this reason, publicly available documents on the MMR site will be reviewed. In addition, opinions prepared by professionals working on the MMR LF-1 will be examined. The opinions contained in this report are limited to a review of the data available prior to publication of this thesis, including the previously referenced group project report. No invasive site investigation was directed as part of formulating the opinions contained herein; this investigation is limited to interviews and desktop analysis of invasive site investigation reports. It is the intent of this thesis to neither support nor deny the conclusions expressed by many qualified professionals in the MMR reports, but to offer an understanding of risk that incorporates transport modeling to support spatial concentration distributions. Subsequently, this thesis presents a professional opinion for the risk imposed on human health by the MMR LF-1 carcinogens which does not rely solely on the maximum nor on arithmetic means of the detected contaminant concentrations for exposure point concentrations, but on probabilistic modeling with a transparent inspection of uncertainty.

1.3.3 Other Sources of Information

Investigation of supporting documentation will be included as needed. A general assumption of this thesis is that the analytical data which has been collected and reported in publicly available documents are accurate. Additional sources are reviewed and cited to clarify potential discrepancies and uncertainties associated with the risk assessment and risk management processes.

1.3.4 Boundary Conditions

Only the MMR LF-1 materials will be considered in risk calculations. Although it is certainly not the case, in the interest of keeping the calculations manageable, background concentrations in the MMR region are assumed to be equal to zero for this thesis. Ingestion, dermal, and inhalation pathways of household groundwater use are the primary groundwater exposure pathways considered in this thesis. However, cranberries as a potential ingestion pathway are also considered and inhalation exposure is limited to potential volatilization linked to showering.

For the purpose of developing a probabilistic model for comparison to the EPA's deterministic model and new risk opinions, this thesis does not specifically adhere to EPA's risk policy. Nonetheless, the probabilistic model adheres to general EPA guidelines which do not radically alter the accuracy of the model. Briefly, ranges of numerical values which are consistent with probabilities describing observed physical occurrences will be assigned as required. In addition, although an additive model gives a lower bound, additive effects in many cases are not accurate representations of potential synergistic effects. However, identical to the EPA's risk model, the probabilistic risk model developed in this thesis assumes that effects are additive on account of the relatively small values of relative risk (*e.g.* a risk of 1.0E-06 represents an increase of relative risk equal to 1.000001).

Safety factors are matters of policy. In accordance with widely accepted engineering principles, safety factors should be incorporated into engineering decisions. However, when intermediate inclusion of safety factors as part of a calculation will gravely alter the uncertainty of a model, they should be included in the decision making process (risk management) after engineering calculations (risk assessments) have been completed.

2.0 BACKGROUND AND SITE DESCRIPTION

2.1 Upper Cape Cod Geography and Land Use

The Massachusetts Military Reservation (MMR) is located in the northwestern portion of Cape Cod, Massachusetts, covering an area of approximately 30 square miles (ABB, 1992). See Figure 2.1-1 for regional and base maps. Military use of the MMR began circa 1900, and use may generally be categorized as training of mechanized forces along with military aircraft operations. Since commencement of military operations, the base has been used by several branches of the armed services, including the United States Air Force, Army, Navy, Coast Guard, and the Massachusetts Air National Guard. Operations by the Air National Guard and Coast Guard are ongoing.

The area of present study is the Main Base Landfill site, termed LF-1 by the MMR Installation Restoration Program (IRP). The landfill is about 10,000 feet from the western and southern MMR boundaries and occupies approximately 100 acres. The landfill has operated since the early 1940's as the primary waste disposal facility at MMR (CDM, 1995). Unregulated disposal of waste at LF-1 continued until 1984, at which time disposal began to be regulated by the Air National Guard.

Waste disposal operations at LF-1 took place in five distinct disposal cells and a natural kettle hole, as shown in Figure 2.1-2. These are termed the 1947, 1951, 1957, 1970, post-1970, and kettle hole cells. The date designations indicate the year in which disposal operations ceased at that particular cell. Accurate documentation of the wastes deposited at LF-1 does not exist. The wastes may include any or all of the following: general refuse, fuel tank sludge, herbicides, solvents, transformer oils, fire extinguisher fluids, blank small arms ammunition, paints, paint thinners, batteries, DDT powder, hospital wastes, municipal sewage sludge, coal ash, and possibly live ordnance (ABB, 1992).

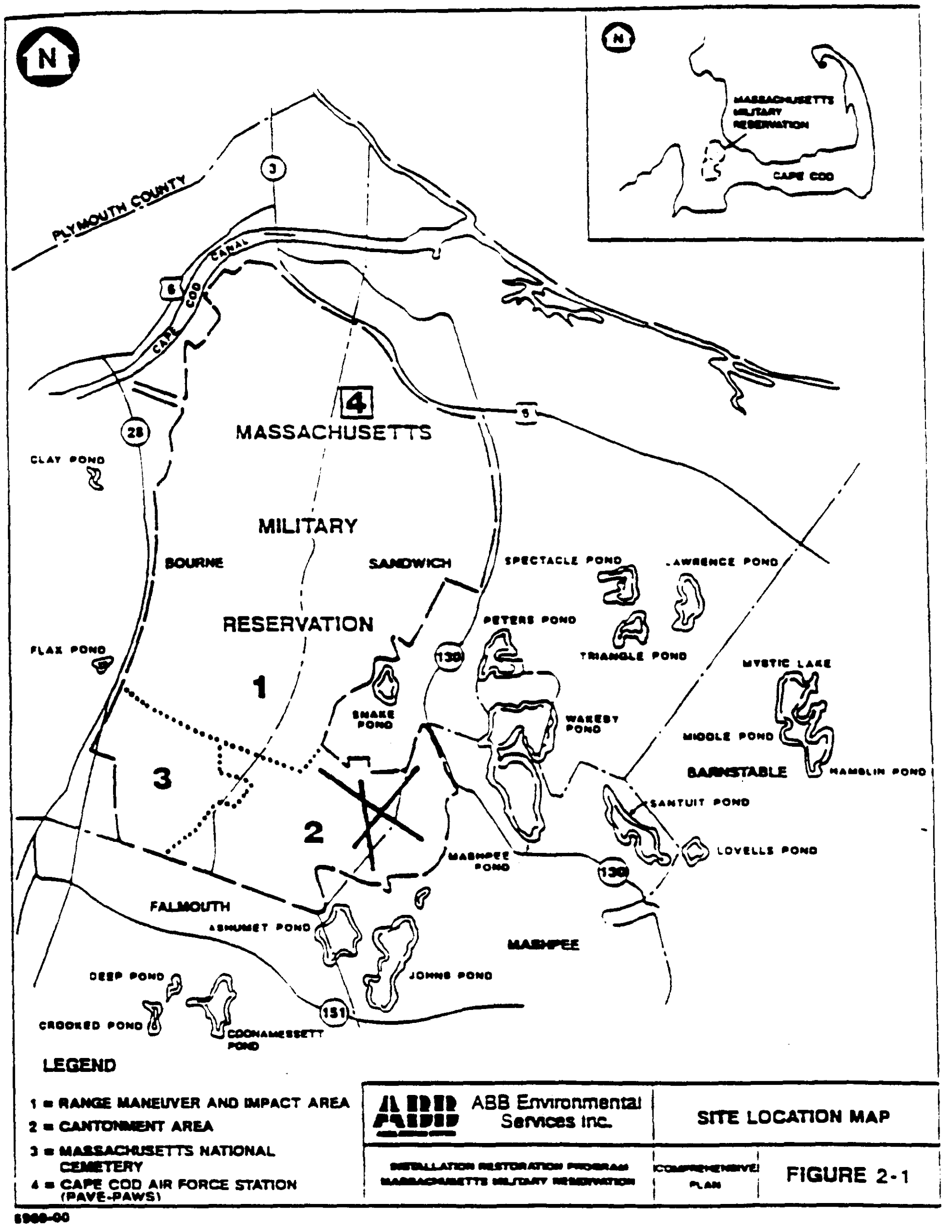


Figure 2.1-1

Site Location Map

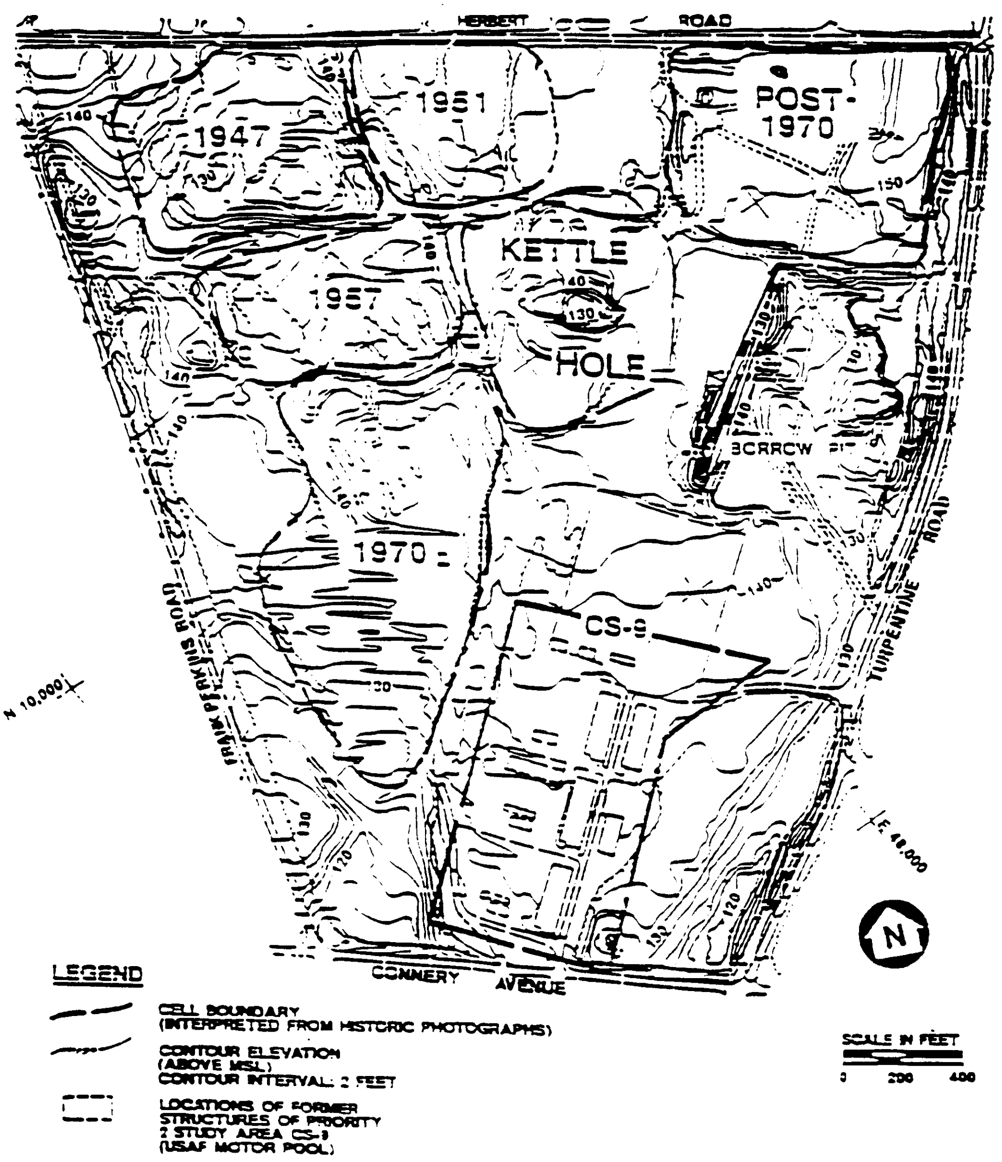


Figure 2.1-2

Map of Landfill Layout

Wastes were deposited in linear trenches, and covered with approximately two feet of native soil. Waste depth is uncertain but estimated to be approximately 20 feet below the ground surface, on average. Waste disposal at the landfill ceased in 1990. A plume of dissolved chlorinated volatile organic compounds, primarily tetrachloroethylene (PCE) and trichloroethylene (TCE), has developed in the aquifer downgradient of the landfill.

The four towns of interest on the western Cape are Bourne, Sandwich, Mashpee, and Falmouth. The total population of this area, according to 1994 census, is 67,400. The area is mostly residential, with some small industry. A significant amount of economic activity is associated with restaurants, shops, and other tourist industries. The total population of Cape Cod is estimated to triple in summer, when summer residents and tourists make up most of the population. The total base population has doubled in the last twenty years. Cape Cod has been one of the fastest growing areas in New England. In 1986, 27% of economic activity was attributed to retirees; tourism accounted for 26%; seasonal residents, 22%; manufacturing, 10%; and business services (fishing, agriculture, and other), 15%. The economy is currently experiencing a shift from seasonal to year-round jobs (Cape Cod Commission, 1996).

2.2 Climate

The Cape Cod climate is categorized as a humid, continental climate. Average wind speeds range from 9 mph from July through September to 12 mph from October through March. Precipitation is fairly evenly distributed, with an average of approximately 4 inches per month. Average annual precipitation is approximately 47 inches. There is very little surface runoff. Approximately 40% of the precipitation infiltrates the ground and enters the groundwater system (CDM, 1995).

2.3 Geology

The Cape Cod Basin consists of material deposited as a result of glacial action during the Wisconsinian stage between 7,000 and 80,000 years ago. Advancing glaciers from the north transported rock debris gouged from the underlying bedrock until they reached their southernmost point of advance at Martha's Vineyard and Nantucket Island. The glacial action also resulted in a thin layer of basal till being deposited over the bedrock. The entire sedimentation process occurred as a sequence of glacial deposition, erosion and re-deposition. In later periods, the glaciers melted, receded, and reached a stagnation point near the western and northern shores of Cape Cod. The remaining glacial till was deposited there and formed the Buzzards Bay and Sandwich moraines. The present day Sandwich moraine is thought to be of glacio-tectonic origin, due to pro-glacial sediments being thrusted over older morainal deposits during a readvance of the Cape Cod Bay glacier (Oldale, 1984).

The regional geology in the LF-1 study area can be classified into three main sedimentary types. These are the Buzzards Bay and Sandwich moraines (BBM and SM), the Mashpee Pitted Plain (MPP) and the Buzzards Bay Outwash (BBO). The geographic distribution of these materials is depicted in Figure 2.3-1 (E.C. Jordan, 1989). The MPP consists of stratified coarse to fine grained sands that were transported from the melting Buzzards Bay and Cape Cod Bay ice sheets and deposited over a bed of fine-grained glacio-lacustrine sediments and basal till. The general trends in the glacial outwash deposits in terms of grain size are coarsening upwards and fining north to south. The thickness of the coarse material decreases north to south, as the distance from the outwash source increases.

The morainal sediments were deposited directly as the ice-sheets melted. Thus, these deposits are not stratified like the MPP glacial outwash and are thought to occur in layers of poorly sorted sediment-flow deposits and finer till material. These sandy sediments overlie a fining sequence of sand, silt, clay and basal till. The unsorted glacial till that comprise the BBM ranges in size from boulders to fine clays. This complex heterogeneity leads to wide variations in observed hydrogeological parameters in the moraine. A general trend of fining in material size results in lower hydraulic conductivities (LeBlanc, 1986).

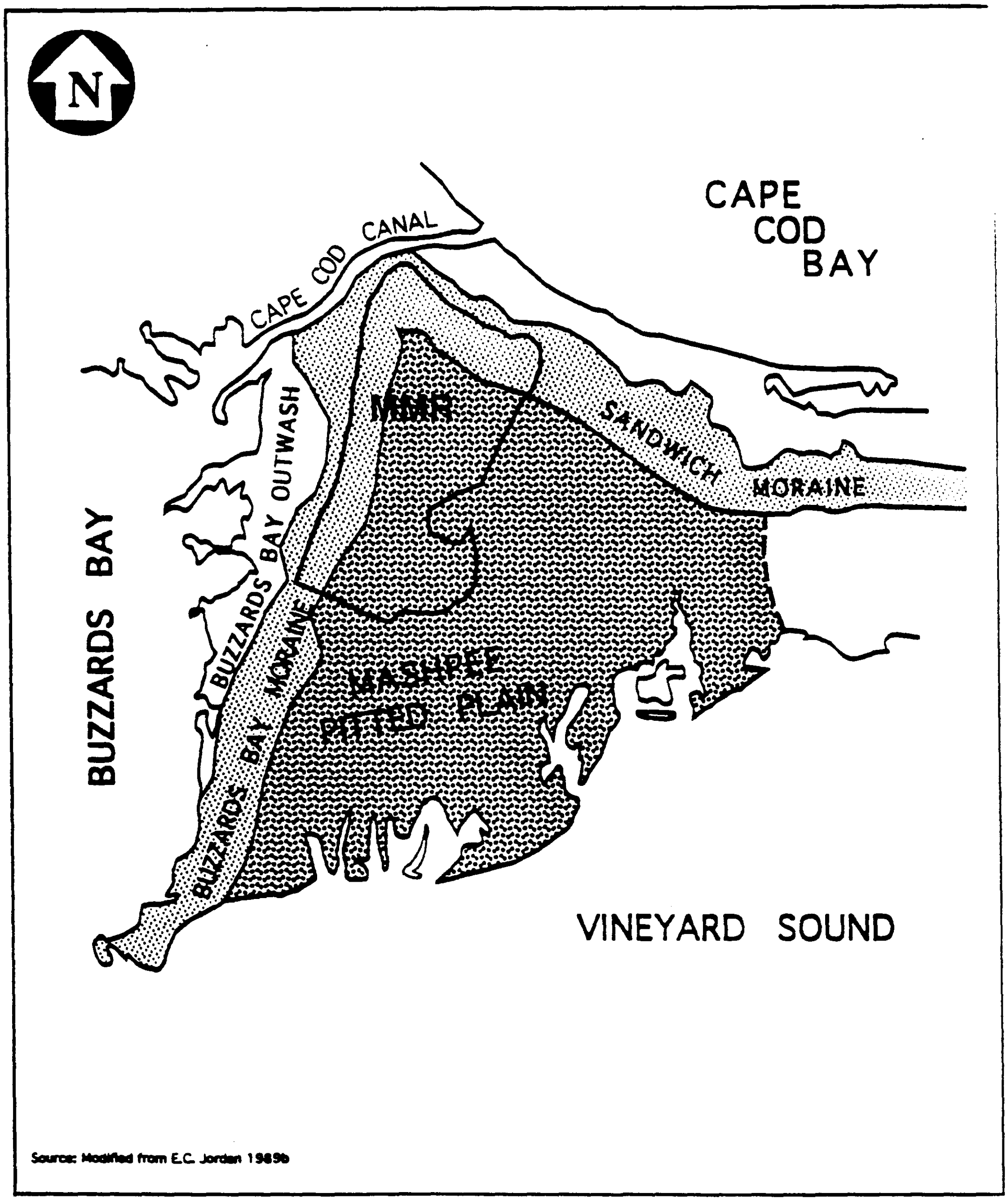
The Buzzards Bay Outwash (BBO) was deposited as a result of sedimentation between the retreating ice sheets and the newly deposited Buzzards Bay Moraine. BBO sediments are generally sand and gravel, and are considered to be stratified in the same manner as the MMP outwash, with a general trend of fining downwards.

The geologic structure described above lies atop a Paleozoic crystalline bedrock. The bedrock contours range in depth from 70 to 500 feet below sea level (Oldale, 1984). The bedrock is of a much lower hydraulic conductivity than the surrounding sediments, and therefore acts as an impermeable barrier to groundwater flow and thus forms the bottom boundary of the Cape Cod aquifer.

2.4 Groundwater System

Cape Cod is underlain by a large, unconfined groundwater flow system. This phreatic aquifer has been designated a sole source aquifer by the United States Environmental Protection Agency (EPA). The aquifer is divided into six flow cells according to the hydraulic boundaries of the flow system. The MMR and LF-1 are located in the west Cape flow cell, the largest of the six flow cells. The aquifer system and water table contours in the west Cape region are depicted in Figure 2.4-1 (CDM, 1995).

The water table in this region occurs at a depth of 40-80 feet below the ground surface. Surface water is also present in the study area as intermittent streams in drainage swales and more importantly as ponds in kettle holes on the Mashpee Pitted Plain. In addition, there are a few large kettle ponds that can significantly influence the flow regime near the LF-1 site and plume. Cranberry bogs are present near surface discharges of groundwater, but it is thought that the cranberry bogs west of the LF-1 site are underlain by localized perched water tables, and are thus hydrologically disconnected from the larger aquifer system (CDM, 1995). This fact, and the depth of the contaminant plume near these cranberry bogs makes it unlikely that contaminants from LF-1 will discharge into these important agricultural areas.



Source: Modified from E.C. Jordan 1989b

Figure 2.3-1

West Cape Cod Glacial Deposits

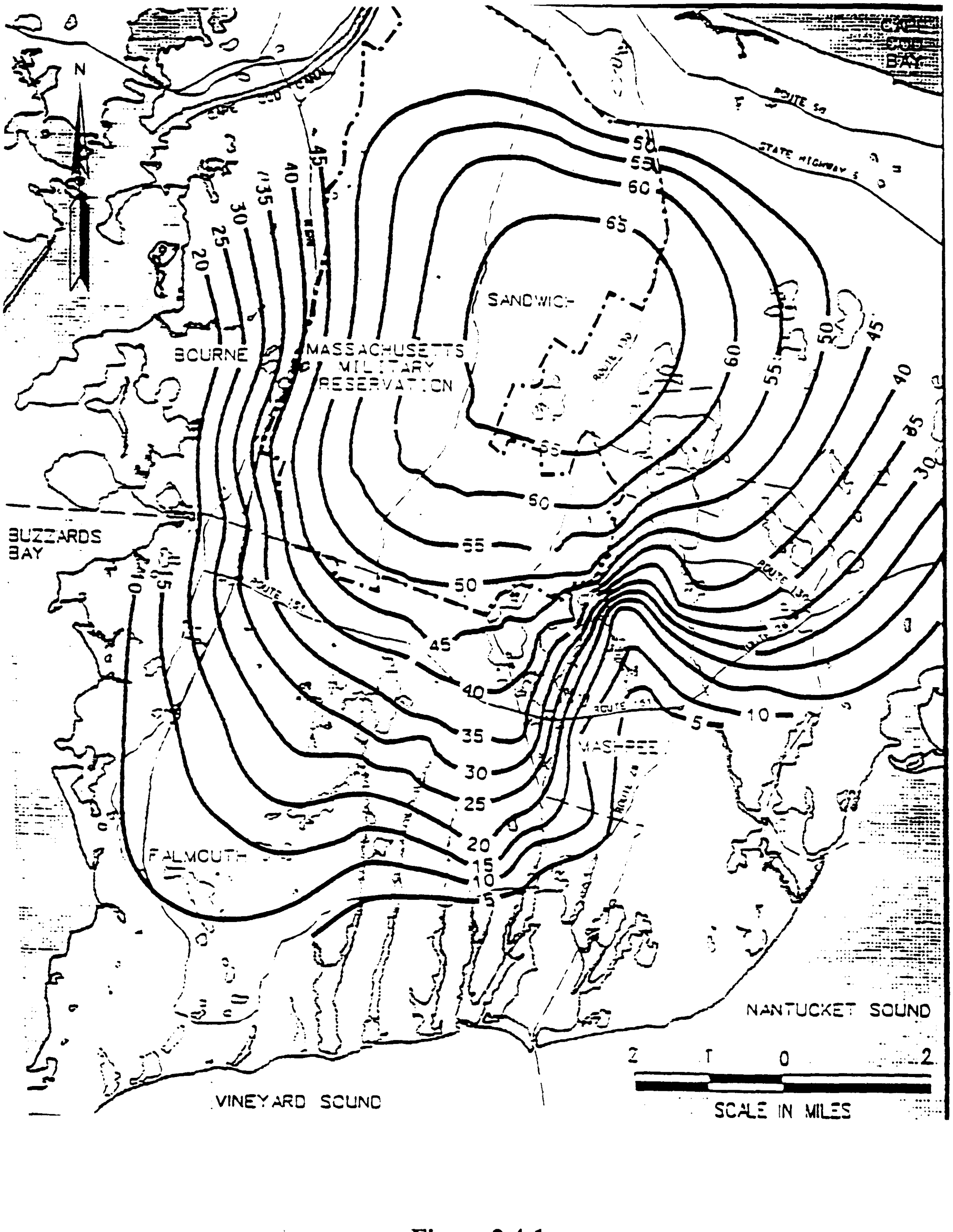


Figure 2.4-1

MMR Groundwater Contour Map

2.4.1 Vertical Hydraulic Gradients

Vertical gradients that have been calculated for the LF-1 site are very small. Most gradients calculated in the IRP hydrologic investigations were below the survey accuracy threshold. Significant upward vertical gradients exist where groundwater discharges into large ponds and near coastal areas where the aquifer discharges into the ocean. Small downward gradients of about 10^{-3} to 10^{-4} ft_{head}/ft_z are observed throughout the rest of the study area (CDM, 1995). Such vertical gradients generally indicate upward flow near the shoreline and surface water bodies, and downward flow elsewhere.

2.4.2 Horizontal Hydraulic Gradients

Groundwater flow in the region is driven mostly by horizontal gradients. These can be measured by dividing a groundwater elevation contour interval by the horizontal distance between the contours. The latter value can be estimated from a contour map similar to Figure 2.4-1. Horizontal gradients calculated for the LF-1 study area using February 1994 water levels range from $1.3\text{x}10^{-3}$ to $6.8\text{x}10^{-3}$ $ft_{head}/ft_{x\text{-}y}$ (CDM Federal, 1995). These gradients are observed to steepen from the LF-1 source area westwards.

2.4.3 Seepage Velocity

Calculated seepage velocities in the LF-1 study area indicate that advective contaminant transport takes place at velocities ranging from 0.10 ft/day to over 3 ft/day. Since seepage velocity is a function of hydraulic conductivity, the differential permeabilities of the various sediment types strongly influence calculation of seepage velocities at this site. An estimate of seepage velocity of contaminants made using observed LF-1 migration distance and time yielded an average seepage velocity of 0.9 ft/day (CDM, 1995).

2.5 The MMR's Listing on the National Priorities List

The MMR is one of 1,236 sites that have been placed on the National Priority List (NPL) by the U. S. Environmental Protection Agency (EPA). NPL sites are those which the EPA has assigned relatively high human health and environmental risk rankings, as compared to other sites. Rankings are determined from an evaluation of the risk to public health and the environment from hazardous substances identified in the air, water and geologic surroundings local to a site. Once placed on the NPL, sites are targeted for remedial clean-up financed by the Superfund, which is the federal government's fiduciary and political device for remediating hazardous waste sites. Additional funding for cleanup is provided by potentially responsible parties (PRPs), those individuals and organizations whose activities have resulted in potential responsibility for contamination at the site.

2.6 Present Activity

Due to the health and environmental risks which have been attributed to activities at the MMR, federal activity is underway to quantify further and reduce, to the extent required, the risk imposed upon human health and the environment. As part of remediation operations at MMR, several of the landfill cells have recently been secured with a final cover system. These cells include the 1970 cell, the post-1970 cell, and the kettle hole. The remaining cells (1947, 1951, and 1957) have collectively been termed the Northwest Operable Unit (NOU). Remedial investigations as to the necessity of a final closure system for these cells is ongoing. Other IRP activities associated with the LF-1 site include design of a plume containment system and further plume delineation and groundwater modeling. Figures 2.6-1 (CDM, 1995) and 2.6-2 (OpTech, 1996) illustrate the MMR's historical understanding of the location of LF-1 during April, 1994 and April, 1996.

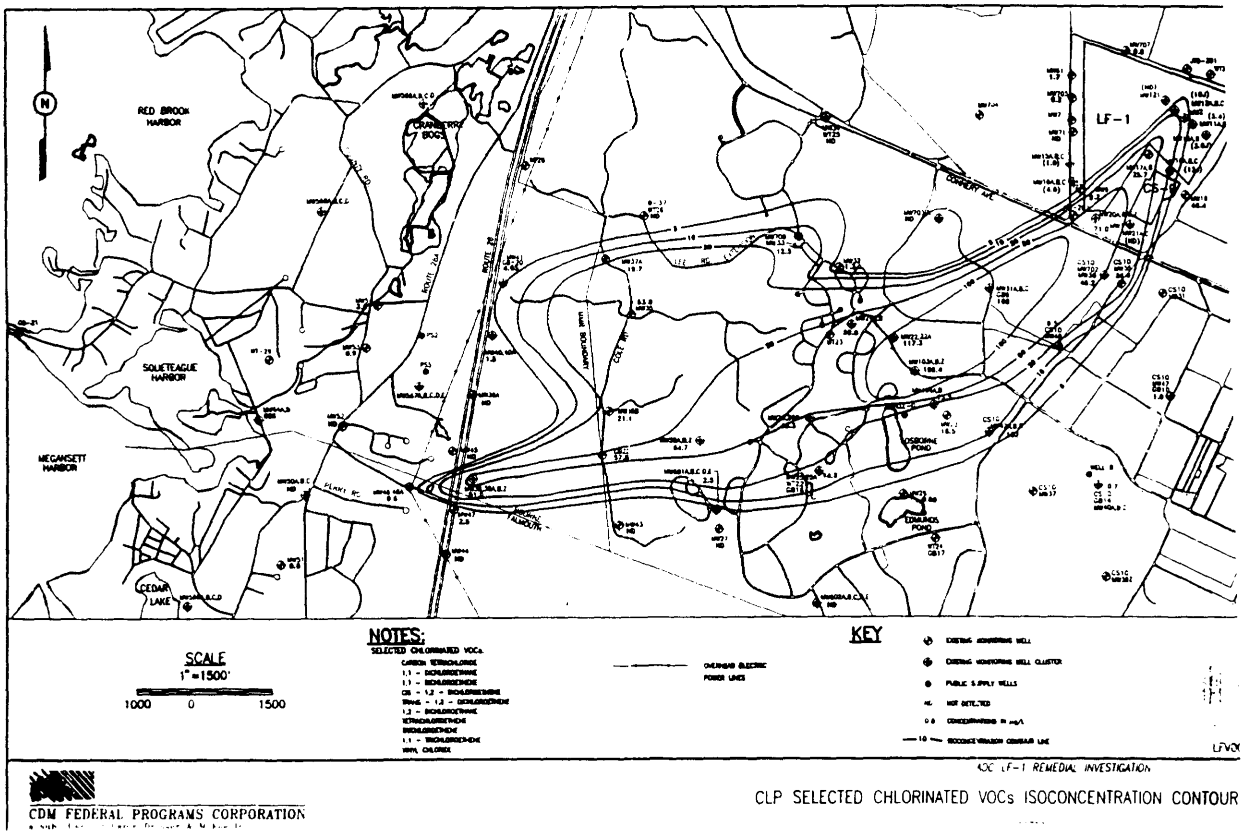


Figure 2.6-1
April, 1994, LF-1 Location

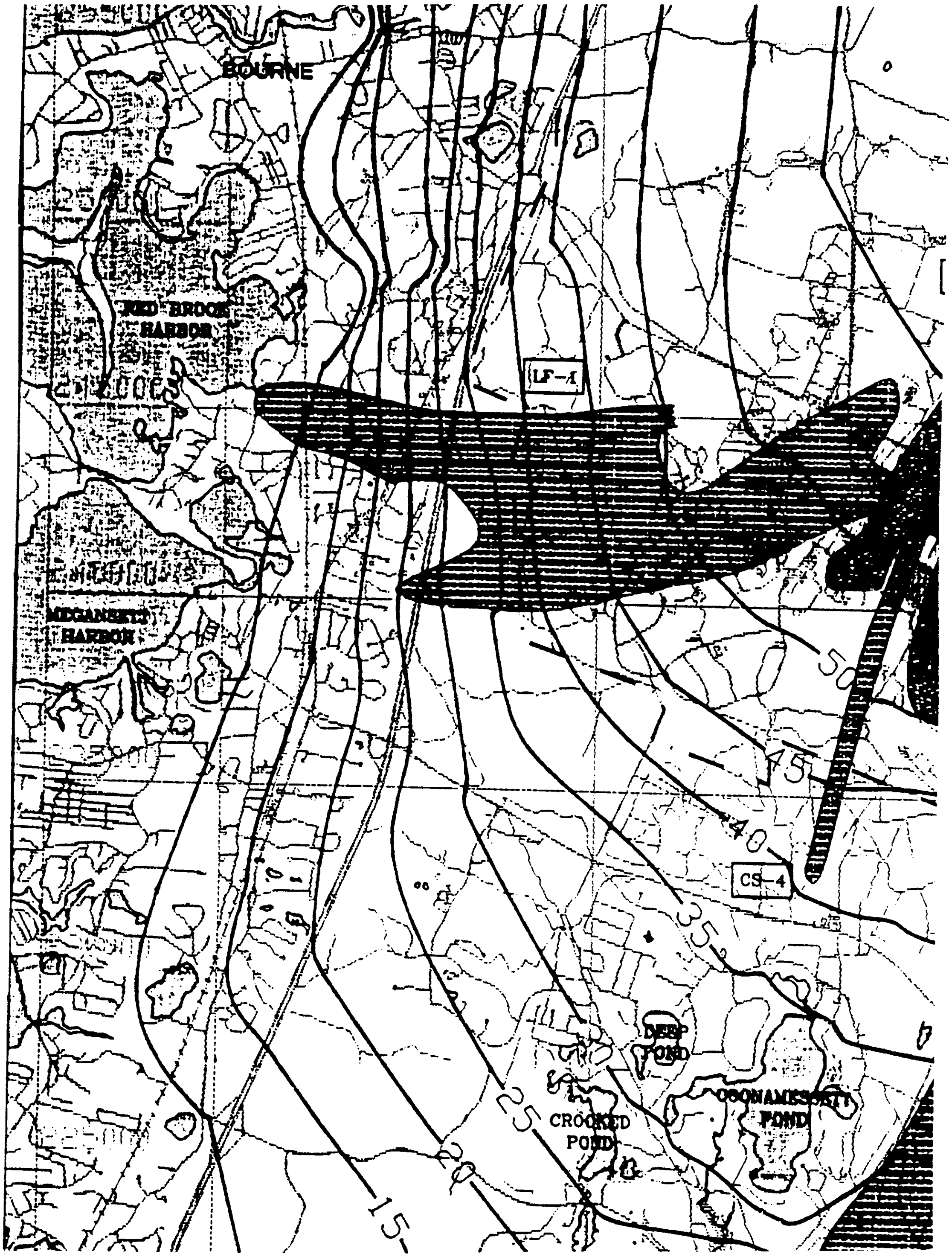


Figure 2.6-2

April, 1996, LF-1 Location

3.0 Results of the MMR LF-1 Group Project Report

The results of the MMR LF-1 group project report are presented here because they are requisite to understanding the development and significance of the probabilistic risk model which is presented in section 4.0. All results contained in section 3.0 can be researched in greater detail by reviewing the individual theses prepared by Dan Alden, Kishan Amarasekera, Michael Collins, Karl G. Elias, Benjamin R. Jordan, and Robert F. Lee, the members of my project group. Their publications are cited after their respective sections of the group project report and in the references section of this thesis.

3.1 Site Characterization

Site characterization investigations followed two main topics. The first involved describing the nature and extent of the chemical contamination in the groundwater. The second involved analyzing tests for hydraulic conductivity to determine parameters that could be used for modeling contaminant migration.

3.1.1 Groundwater Contamination

As part of the Superfund Remedial Investigation process, 73 wells at different locations and different depths were tested for 34 of the most likely compounds. The EPA standard for drinking water sets individual maximum contamination levels (MCLs) for most of these compounds. Twenty eight out of the 73 wells had at least one contaminant which exceeded the MCL. Seven out of the 34 possible contaminants were at levels which exceeded the MCL. These contaminants are vinyl chloride (VC), carbon tetrachloride (CT), trichloroethene (TCE), tetrachloroethene (PCE), 1,4 dichlorobenzene (1,4 DCB), benzene (B), and chloroform (CF). All of these compounds have an MCL of 5 parts per billion (ppb), except for vinyl chloride which has an MCL of 2 ppb. The highest total of all 7 of these contaminants at any one well was 168 ppb (CDM, 1995).

The highest total of all contaminants sampled at any one well was 236 ppb. (Some of these contaminants have an MCL much higher than 5 ppb.) The highest three individual contaminant readings were CT at 60 ppb, TCE at 64 ppb, and PCE at 65 ppb. One ppb by volume is equivalent to one drop in 15,000 gallons. One hundred sixty eight ppb is equivalent to about 1/3 of an ounce per 15,000 gallons. At 60 gallons per day of individual water use, 15,000 gallons would be used in 250 days. At 236 ppb, the highest total concentration sampled, this works out to about 1 drop of exposure per person per day. The risk assessment section of this report discusses the danger to humans from potential exposure.

Using the two dimensional log-linear contours of the contamination data points and vertical section filtered contours (see Figure 3.1-1), a very rough estimate of the total volume of contamination can be made. This is estimated to be about 103 cubic feet or fourteen 55 gallon drums. This mass is distributed over approximately 4.5 square miles. The area where any single MCL level is exceeded is approximately 2 square miles.

Contamination contours show that little degradation of PCE is occurring. TCE is the degraded product of PCE. The contours show the center of PCE concentration to be downgradient from the center of TCE concentration, therefore the upgradient TCE could not be the result of PCE degradation. Instead, this relationship indicates that TCE must have been one of the original contaminants released at the site.

A comparison can be made between possible contaminant discharge to the ocean through groundwater migration versus an equivalent discharge through a pipe from a hypothetical industrial source. If the contaminant front is considered to be 50 feet thick by 5000 feet wide and moving at a rate of 1 foot per day, the equivalent outfall pipe is 2 feet in diameter with a flow rate of 1 foot per second. (A one mile per 8 minute pace is exactly 11 feet per second.) In addition to drinking water standards, the EPA publishes guidelines for allowable contaminant marine discharge beyond the mean low water mark. The concentration limits of these standards are considerably higher than those for drinking water. If the landfill plume were being discharged from a single pipe, the EPA would have to decide whether to permit such a discharge. Although the hypothetical pipe concentrations are below maximum marine levels, it is uncertain if a permit would be granted because the plume discharges in a region harvests shellfish and other seafood for human consumption. However, the plume discharge is, in effect, put through a diffuser over an area 2,500 times as large as the hypothetical pipe.

Examining cross sectional contours of contamination (see Figure 3.1-2), an observation is that a contamination level exceeding the MCL comes within 10 feet of the top of the aquifer. It is estimated that the withdrawal depth of a hypothetical private well pulling 1000 gallons per day would be 13 feet, given conservative figures for the average hydraulic conductivity (50 ft/day) and the hydraulic gradient (1/100). Therefore, it is possible that private wells located directly over the uppermost levels of contamination could draw in water exceeding the MCL levels for drinking water.

3.1.2 Hydraulic Conductivity

Hydraulic conductivity (K) was determined using 140 grain size samples from 21 well locations and 79 slug test well locations. A comparison of values from these two different tests generally shows very poor correlation. However, a good correlation was seen between the Alyamani/Sen (Alyamani, et al., 1993) and Bedinger (Bradbury, et al., 1990) grain size methods. This is due to the fact that both depend on the grain size fraction d_{50}. Both grain size and slug test data were put through a 3-D gauss filtering process. The resulting data and corresponding contours exhibit a significant correlation between the Hazen and slug methods. However, the Hazen values are much lower.

The filtered slug contours match the general geology of the area, showing a decline in conductivity from north to south and with increasing depth. In addition, the Buzzard's Bay Moraine is clearly seen (see Figure 3.1-3). The contours also show a zone of lower conductivity in a region where the contaminant plume appears to be dividing. This finding may provide part of the explanation for the observed migration path. The arithmetic mean of the unfiltered slug test data was 75 feet/day, ranging from less than 1 ft/day to 316 feet/day. The calculated horizontal conductivity from the filtered slug test data had a mean of 85 feet/day and a maximum of 272 feet/day. In addition to hydraulic conductivity, a determination of overall hydraulic anisotropy was made using the filtered slug K values. The number was approximately 3.4. This value is very similar to the value of 3.2 determined by Springer for the Mashpee Pitted Plain (Springer, 1991).

3.1.2.1 Groundwater Summary

In summary, a large area of groundwater has been contaminated by the MMR LF-1 with halogenated volatile organic compounds. The contaminant plume is heading west through the Buzzards Bay Moraine. Public and private drinking water supply wells are in danger of drawing up water with contaminants at concentration levels that exceed EPA drinking water standards. Hydraulic conductivity trends can be ascertained using gaussian filtered slug test data. Values for horizontal and vertical hydraulic conductivity may be calculated from the filtered data. These values may be used to model migration of the plume. The next section describes the groundwater modeling process (Alden, 1996).

3.1.2.2 Groundwater Modeling and Particle Tracking Simulation

This section of the report describes a three dimensional groundwater model and particle tracking simulation of the portion of the aquifer that is deemed to affect the spatial characteristics and migration pathlines of LF-1. The DYNSYSTEM modeling package developed by CDM, Inc. is utilized for this purpose. The goals of the modeling effort are as follows:

- Develop a steady state flow model for the study area,
- Track particles released from a continuous source area and observe migration patterns,

- Determine flushing time and plume migration with source removed,
- Determine sensitivity of model results (plume migration) to the Buzzards Bay Moraine and other geologic features and characteristics of the region,
- Explore the possibility that the deep plume observed in advance of the main plume is caused by a pool of dense leachate from the landfill sinking below the source area.

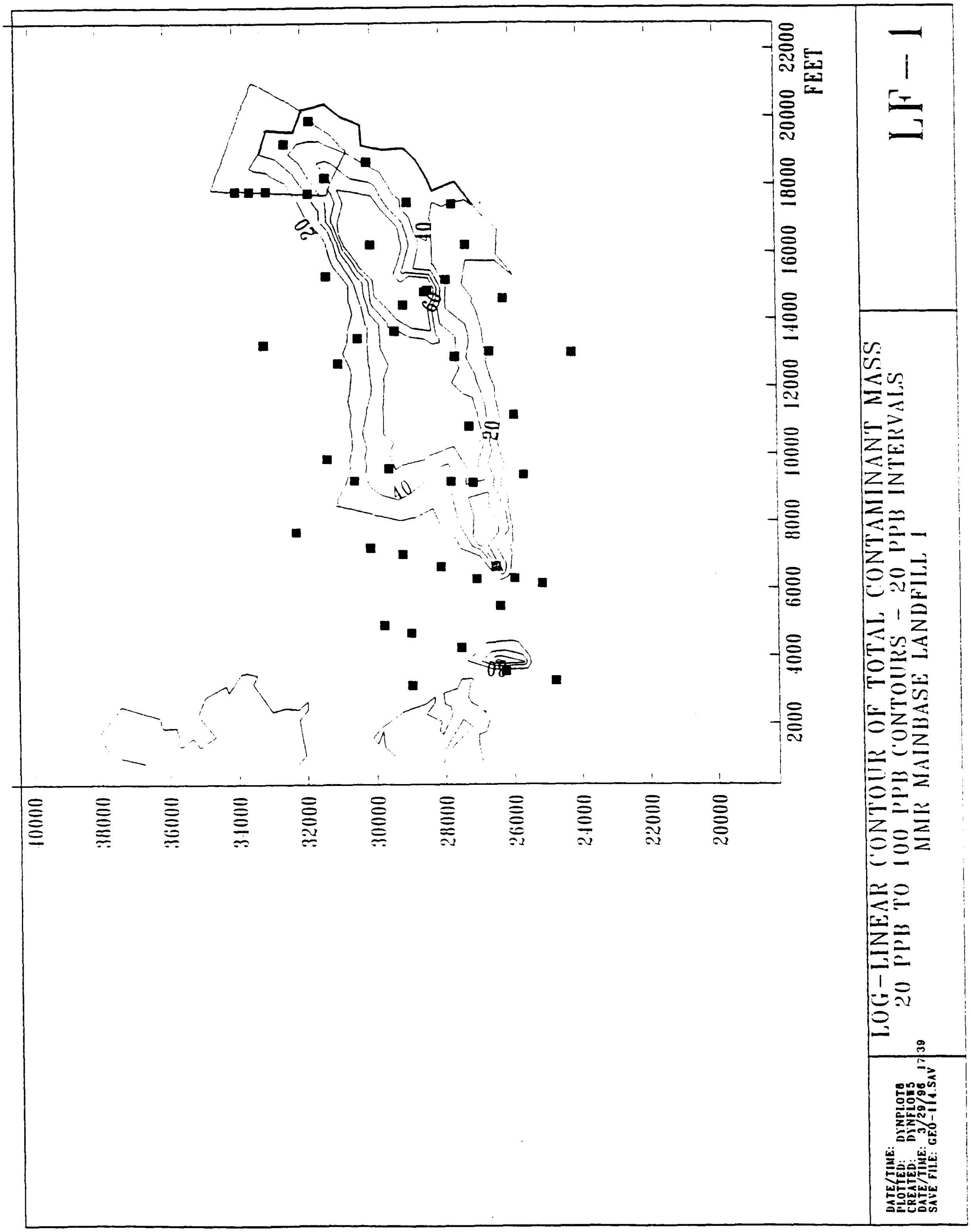


Figure 3.1-1

Log-linear Contour of Total Contaminant Mass

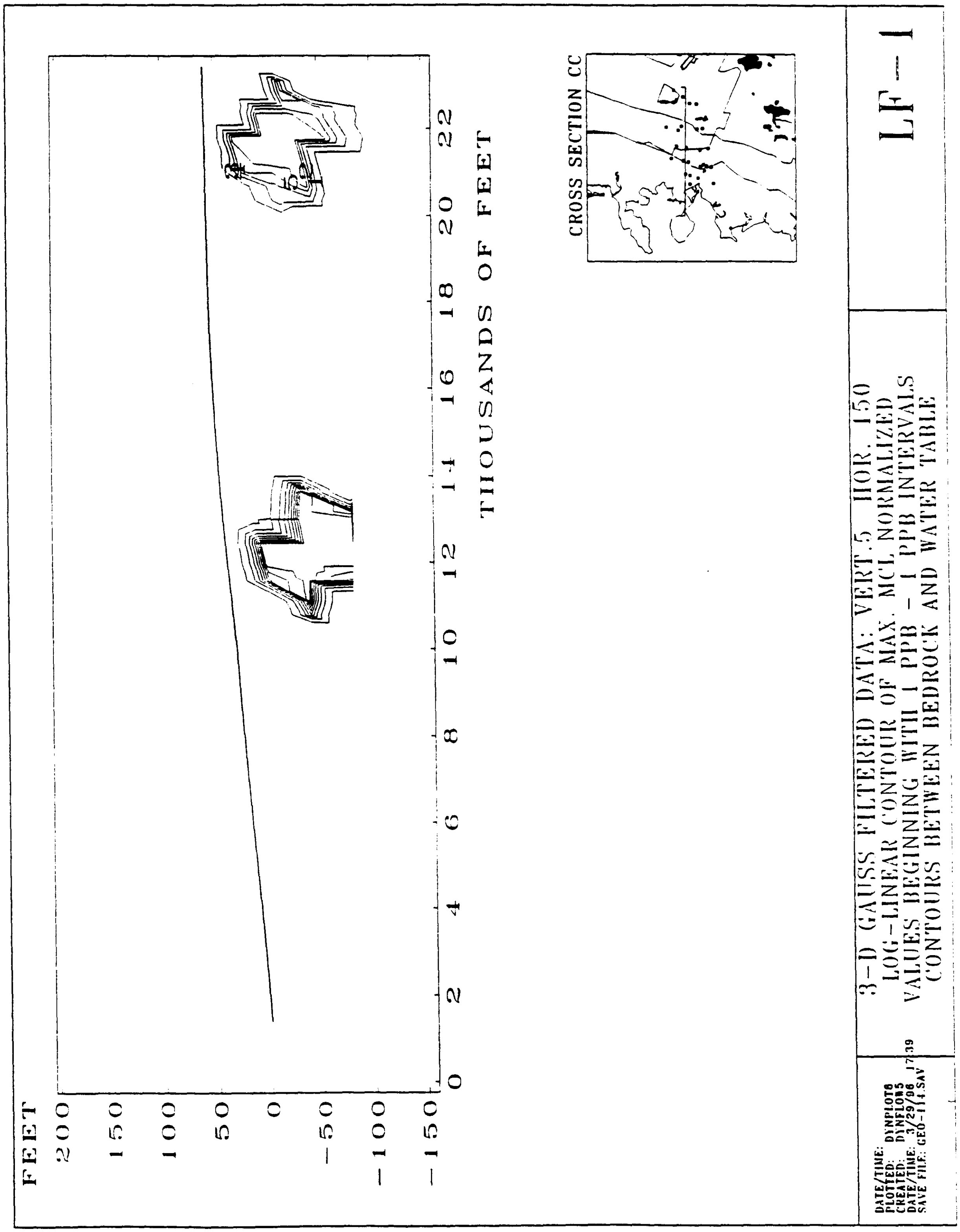


Figure 3.1-2

Log-linear Contour of Maximum MCL

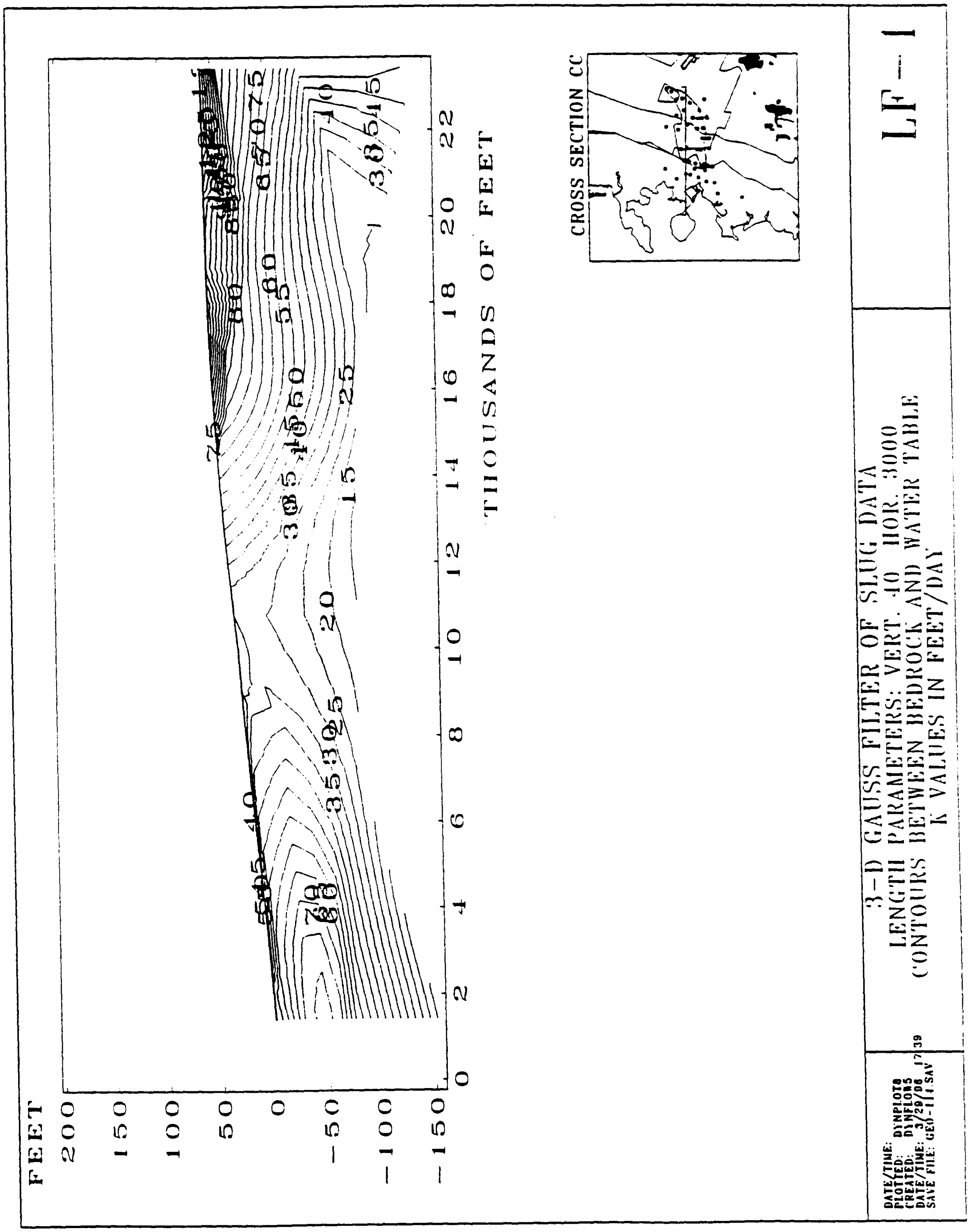


Figure 3.1-3

3-D Gauss Filter of Slug Data

3.2 DYNFLOW, DYNTRACK and DYNPLOT Systems

The groundwater flow system of the western Cape is modeled with the DYNFLOW groundwater modeling package. DYNFLOW is a FORTRAN based program that simulates three-dimensional flow using a finite element formulation. A distinct advantage of the finite element based model over a finite difference model like MODFLOW is that the former allows the user the flexibility to use variable sized grid elements. Thus, in regions of interest, the user can obtain higher resolution without having to implement the same degree of resolution throughout the model and obtain significant advantages in terms of computational time and complexity.

DYNTRACK simulates three-dimensional contaminant mass transport and uses the same finite element grid, flow field and aquifer properties that were used in and derived from DYNFLOW. DYNTRACK models either single particle tracking or 3-D transport of conservative or first-order decay contaminants with or without adsorption and dispersion. DYNPLOT is both a graphical pre-processor and post-processor that can create full color displays (in plan view or cross-sectional view) of observed data, DYN system calculated data, and simulated results. DYNPLOT is also capable of generating the finite element grid used by the flow and tracking models.

3.2.1 Study Area and Grid

The roughly triangular study area of the model was chosen to be large enough to ensure that boundary effects did not unduly influence the calculated flow and head values in the area of concern. The study area, approximately 58 square miles in extent, is depicted in Figure 3.2-1. The northern and eastern boundaries of the model are streamlines (no-flux boundaries). The western part of the grid area is bounded by the ocean. The ocean-aquifer interface is of particular interest because it determines how far out at sea LF-1 will discharge if it is not completely contained.

The grid covering the LF-1 study area was generated in DYNPLOT, with smaller grid elements in the source area and presently observed plume locations. Progressively coarser grid elements move away from these locations. The study grid is composed of 3156 triangular elements and 1652 nodes. The grid discretizes the vertical dimension of the study area in 8 layers (9 levels). The bottom (1st) level follows the bedrock contours, while the top (9th) level approximates the surface topography.

3.2.2 Model Formulation

3.2.2.1 Assigned Geologic Materials

The geologic structure of the LF-1 study area was represented as depicted in Figures 3.2-2, 3.2-3, 3.2-4 and 3.2-5. The geographic locations of the material were assigned according to United States Geological Survey (USGS) maps of the region. The Mashpee Pitted Plain (MPP) was represented vertically as two material types and two horizontal sections. This was done to accurately represent the upward coarsening and north-south fining that is observed (LeBlanc, 1986). The Buzzards Bay Moraine (BBM) was defined vertically as four different materials of increasing permeability upwards and two horizontal divisions. The Buzzards Bay Outwash (BBO) was depicted by two vertical materials, coarsening upwards. All three deposit types were underlain by a layer of Glacio-Lacustrine deposits (GLS) of varying thickness and bedrock.

3.2.2.2 Source

The LF-1 source was represented by six distinct cells within the source area. In the particle tracking simulation, three cells were defined as being non-sources after 1994. This was done to simulate a successful capping of part of the landfill in 1994 by the IRP.

3.2.2.3 Ponds

Ponds were modeled as a layer of material that was almost infinitely permeable horizontally and with a high vertical conductivity on the order of 500 ft/day. The pond material layer was extended to the observed depth of each pond. These pond nodes were then assigned a rising head boundary condition. With this method, the material defined as the pond displays a consistent horizontal head, acts as a sink for groundwater upgradient of the pond, and as a source of groundwater for sections of the grid that are relatively downgradient. This formulation was considered to most closely approximate the behavior of ponds in the Cape Cod region.

3.2.3 Hydraulic Properties

3.2.3.1 Anisotropy Ratio

The anisotropy ratio, K_H/K_V, assumed for Cape Cod sediments usually ranges from 1:1 to 50:1 (Masterson and Barlow, 1994). An anisotropy value of 3:1 was initially assumed for all material types in this model. This particular parameter is important in determining the flow regime and vertical migration of the simulated particles in the mass transport model.

3.2.3.2 Retardation

Sorption driven retardation factors ranging from 1.82 (TCE) to 4.19 (CCL_4) were considered to apply for western Cape Cod soils in the IRP analysis of a containment system for LF-1 (Op-Tech, 1996). However, laboratory analysis of sorption of volatile organic compounds onto the soils in this region indicated retardation factors ranging from 1 to 1.25 (Kachikian, 1996). Thus, retardation of contaminant particles in the Cape Cod aquifer due to sorption onto soils was considered negligible in formulating the transport model. Therefore, the particle tracking procedure was run assuming a retardation value of 1.0.

3.2.2.3 Hydraulic Conductivity

Estimates of hydraulic conductivity for the LF-1 region have been made through field investigations. Many slug tests and laboratory tests of soil samples have been carried out for the sediments found in the Cape Cod region. The previous section on site characterization includes a full discussion of these empirical findings. For the purposes of the groundwater model, hydraulic conductivities proved to be the parameter to which the flow model was most sensitive. Hydraulic conductivity values of each sediment type were considered a variable input, and were assigned values within an empirically determined range during calibration of the flow model. The final values of hydraulic conductivities assigned to each geologic material are included in Table 3.2-1.

Material	K_x, K_y (ft/day)	K_z (ft/day)	Long. Disp. (feet)	Trans. Disp. (feet)	Disp. Ratio (vert./horiz.)
Lacustrine	15	5	90.0	3.3	0.03
Fine Sand West	80	27	90.0	3.3	0.03
Coarse Sand West	180	60	90.0	3.3	0.03
Fine Sand South	135	45	90.0	3.3	0.03
Coarse Sand South	210	70	90.0	3.3	0.03
BBM Low -North	30	10	90.0	3.3	0.03
BBM Med Low-North	110	33	90.0	3.3	0.03
BBM Med High-North	150	50	90.0	3.3	0.03
BBM High-North	170	57	90.0	3.3	0.03
BBM Low -South	15	5	90.0	3.3	0.03
BBM Med Low-South	60	20	90.0	3.3	0.03
BBM Med High-South	100	33	90.0	3.3	0.03
BBM High-South	135	45	90.0	3.3	0.03
Nant. Ice Deposits	190	63	90.0	3.3	0.03
Pond Material	10^{-5}	10	90.0	3.3	0.03
Fine Sand North	140	47	90.0	3.3	0.03
Coarse Sand North	270	90	90.0	3.3	0.03
Fine Lacustrine	10	3	90.0	3.3	0.03

Table 3.2-1

Hydraulic Conductivities and Dispersivities for Flow and Mass Transport Models

3.2.3.4 Dispersivity

DYNTRACK mass transport software simulates the dispersion process by adding random dispersive displacements to each particle. The input requirements to account for dispersion in the particle tracking procedure program are the longitudinal dispersivity (α_L, ft), the transverse dispersivity (α_T, ft), and the dimensionless vertical dispersion anisotropy ratio (S_a) for each soil type.

Accurately characterizing the dispersivity at a field site is essential in predicting the transport and spreading of a contaminant plume. Due to natural heterogeneities in the field that cause irregular flow patterns, field-scale dispersivities are several orders of magnitude larger than laboratory scale values (Gelhar et al., 1992). Therefore, the fact that the LF-1 site is a large one, on the scale of about a kilometer, must be taken into account when assuming values of dispersivities to use in the particle tracking procedure. Ideally, dispersivity values obtained from a site similar in geology to the western Cape and with a source similar in scale to the LF-1 site should be used. In this model, a tabulation of field-scale dispersivity data is used to obtain suitable values of the dispersivity coefficients while taking into account the scale of the LF-1 source (Gelhar et. al., 1992). The dispersivity values adopted in the model are included in Table 3.2-1.

3.2.3.5 Effective Porosity

Porosity estimates for the outwash in the LF-1 study area range from less than 1% to over 30% (CDM Federal, 1995). These values are somewhat lower than expected from tracer tests of Cape Cod, which range from 38-42% (Garabedian et. al, 1988; LeBlanc et al., 1988; Barlow, 1989). It was decided to use an effective porosity value of 39% throughout the model.

3.2.4 Boundary Conditions

3.2.4.1 Saltwater-Freshwater Interface

The saltwater-freshwater interface determines where the landfill plume, if not fully contained, will discharge into Megansett, Red Brook and Squeteague harbors. The steepness and the distance from the shore of the interface depends on the aquifer discharge and geologic characteristics of the coastal region. Available geologic information does not indicate the existence of low permeability layers above the aquifer near the shore that will force the saltwater-freshwater interface further into the ocean. Therefore, for the purposes of this report, it is assumed that the location and shape of the saltwater-freshwater interface along the western Cape Cod shore are determined entirely by the discharge and hydraulic conductivity of the aquifer. The distance from the shore to the saltwater-freshwater interface was calculated to be approximately 500 ft.

3.2.4.2 No-Flux Boundaries

No-flux boundaries are modeled in DYNFLOW by assigning all nodes on streamlines at the edge of the study area a "free head" boundary condition. It is assumed that the no-flux boundaries are far enough from the observation areas of the model that they do not influence the calculated values of head and velocity.

3.2.4.3 Recharge

Natural recharge is the largest source of replenishment of the west Cape aquifer system. This natural recharge is composed entirely of rainfall infiltrate through the surface layer. Cape Cod on average receives 47 inches of rainfall annually. Nearly half of this precipitation, or 46-50%, infiltrates to the groundwater system through the highly permeable top soil (LeBlanc et al., 1986). There is little or no surface runoff due to the permeable nature of the soils and the small topographic gradients present in this region. Artificial recharge and pumping is considered to be negligible in this region in comparison with the natural recharge.

3.2.5 Groundwater Modeling Results

The calibrated flow model agreed with observed water table measurements at 106 wells within 0.044 ft mean difference and 2.159 ft standard deviation. Figure 3.2-6 shows the calibrated model results and calculated water table contours. The calculated contours are also consistent with observed water table contours in the region.

The flow model was found to be very sensitive to the difference in permeability between the moraine and surrounding deposits. This sensitivity is highlighted by the curvature of the model calculated head contours, which in turn significantly influence the migration pathlines of a contaminant released at the LF-1 site. The sensitivity of the particle paths to head contours is enhanced by the fact that the LF-1 source area is located close to the point where north-south head contours change to an east-west orientation.

The first particles released at the LF-1 site will migrate to the ocean in 50 years. Figure 3.2-7 shows a 51 year mass transport simulation in plan view, with particles reaching the ocean interface. Figure 3.2-8 is a cross-section of the simulated plume. Thus, assuming that the volatile organic compounds of concern at this site were released in 1945, the predicted extent of the plume reaches the ocean discharge face by 1996. The initial discharge point is at Red Brook Harbor. This finding is in agreement with the Op-Tech Data Gap Report which concludes that the LF-1 has now reached Red Brook Harbor (Op-Tech, 1996).

If the entire landfill is successfully capped by the year 2000, and the contaminated groundwater is allowed to flush unmitigated into the ocean, a DYNTRACK simulation expects that 110 additional years is required for all LF-1 derived contaminants in the aquifer to travel beyond the Buzzards Bay Moraine. In addition, 55 more years are required for all the contaminant particles to be discharged from the aquifer.

The predicted plume exhibits the same differential North and South Lobe travel times observed in the field. In the model, the presence of a low-permeability layer in the moraine causes the southern part of the plume to be retarded. The northern section, by virtue of having to travel a shorter distance to the moraine, is at a higher elevation than the southern part of the plume and thus travels through a higher permeability layer of the moraine. These differential travel velocities through the moraine cause the distinct northern and southern lobes observed in the simulated plume. Figure 3.2-9 is a north-south cross-section of the plume at the point of entry into the moraine, showing the differential elevations of the particles from north to south.

The previous finding that the portion of the plume at a lower elevation is retarded by the presence of a lower conductivity layer of moraine deposits indicates that the deep plume observed near the shoreline cannot be simulated by a sinking source of contaminant in this model formulation. A tenable explanation for the observed deep northern plume is that the down-sloping bedrock surface near the shoreline causes the faster moving simulated northern lobe to sink further due to infiltration as it traverses the Buzzards Bay Outwash towards the shoreline. Since the slower moving southern lobe is still in the moraine, the leading edges of the northern lobe near Red Brook Harbor now appear to be a northern plume lobe at a lower elevation.

If an extraction well system is constructed along Route 28, and it is assumed that the extraction pumping and infiltration are carried out so that the hydraulic system is relatively unchanged, the uncaptured section of the LF-1 will take an additional 12 years to completely discharge into the ocean. This result was obtained assuming that the portion of the plume upgradient of the extraction well fence is fully captured.

In summary, the groundwater flow and particle transport model provides results that are similar to field observations. The Buzzards Bay Moraine exerts a great deal of influence on the regional hydrologic system. The geologic characteristics assigned in the flow model to the BBM defines the shape of the regional head contours and thus the travel path and velocity of the simulated plume. Therefore, it is essential that the geology of this moraine be properly identified if a flow and particle tracking model that can accurately represent the region is to be formulated. In the absence of such data, any groundwater flow model of the LF-1 region will contain a significant degree of uncertainty. The models developed in this study can be used to determine the effects of an extraction system to contain or capture the LF-1 and also as a means of designing an efficient capture system for this contaminated site. The following section addresses the risks associated with the LF-1 and how these risks can be managed (Amarasekera, 1996).

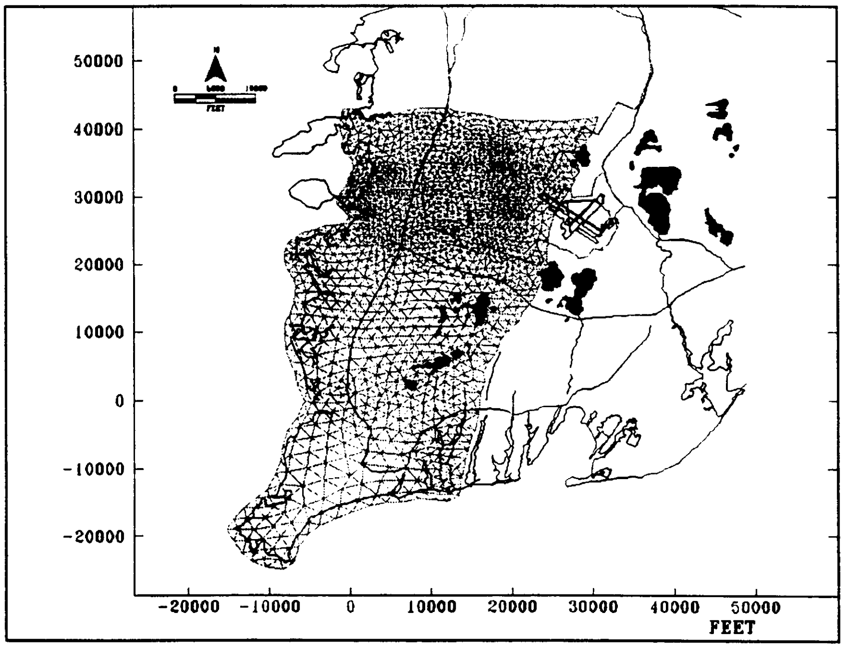


Figure 3.2-1

LF-1 Study Area and Finite Element Grid

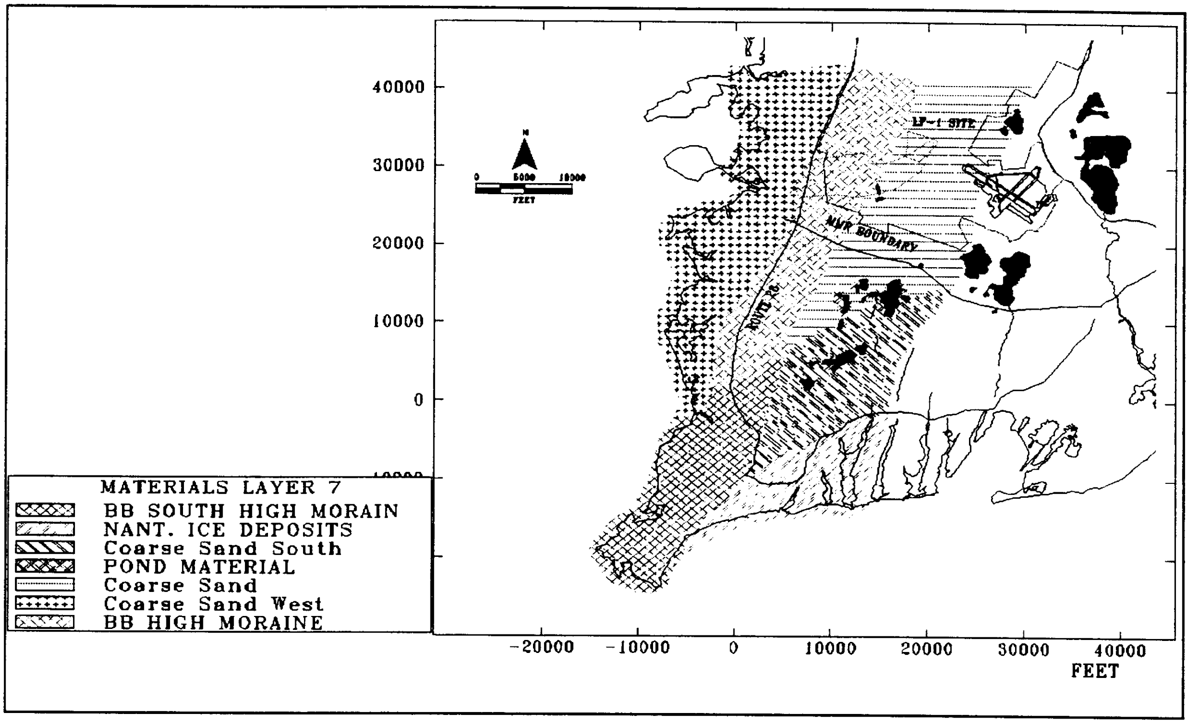


Figure 3.2-2: Plan view of LF-1 Study Area with Assigned Geologic Materials

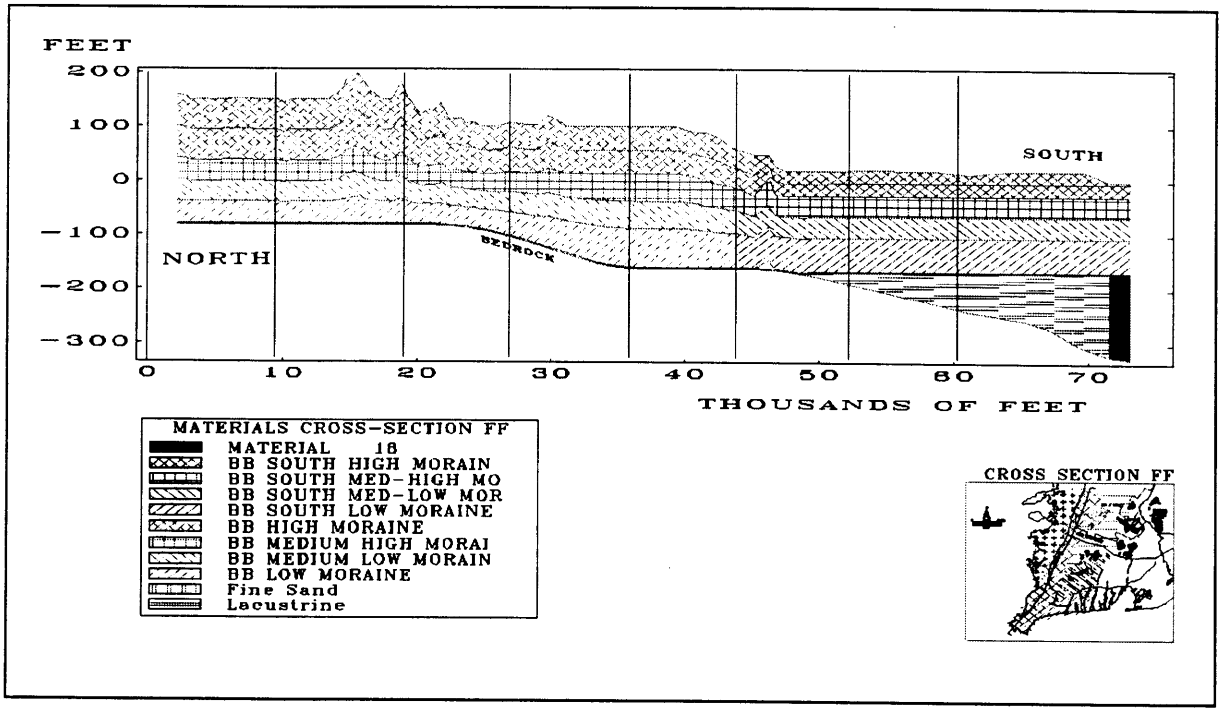


Figure 3.2-3:Cross-sectional View of Buzzards Bay Moraine Deposits

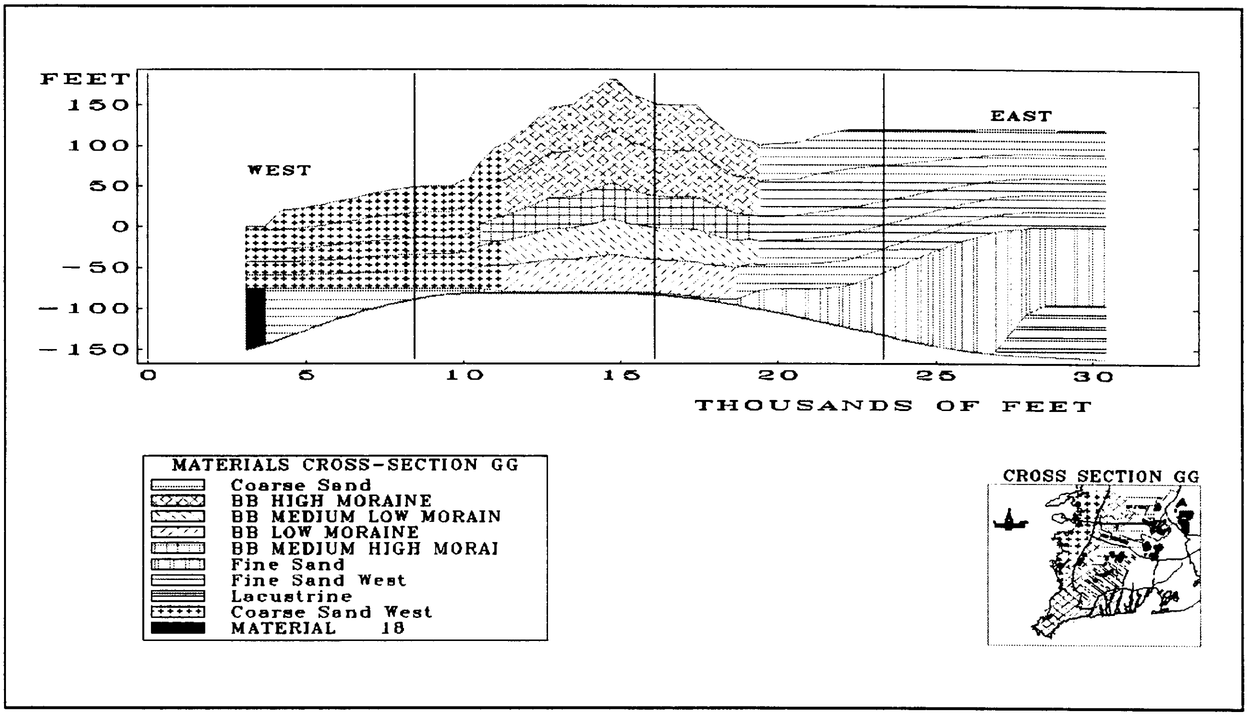


Figure 3.2-4: East-West Cross-section of Study Area near Buzzards Bay

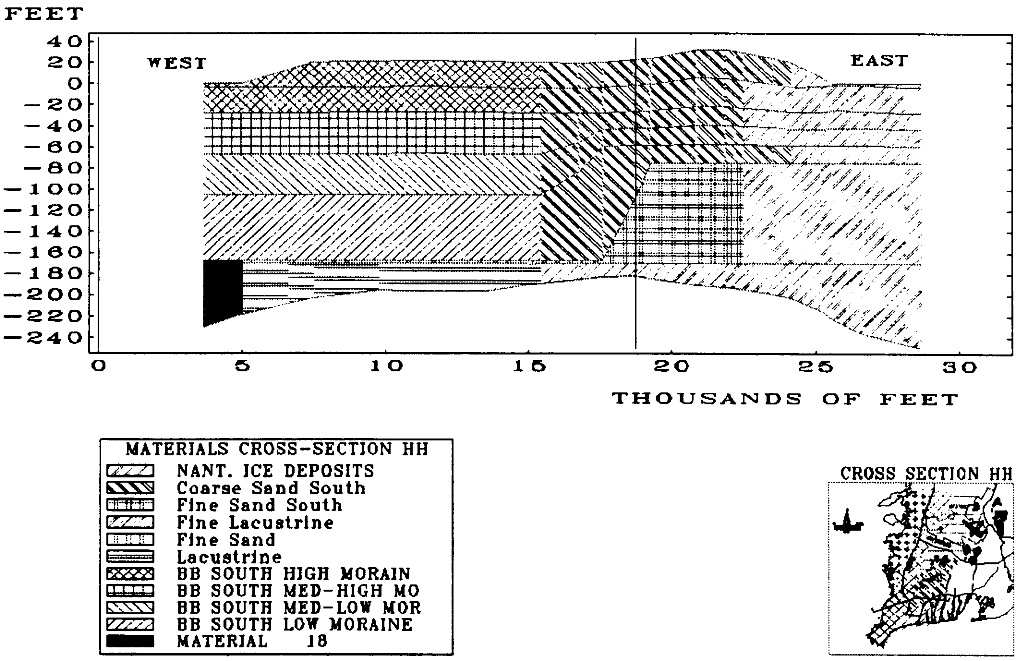


Figure 3.2-5: East-West Cross-section of Study Area near Nantucket Sound

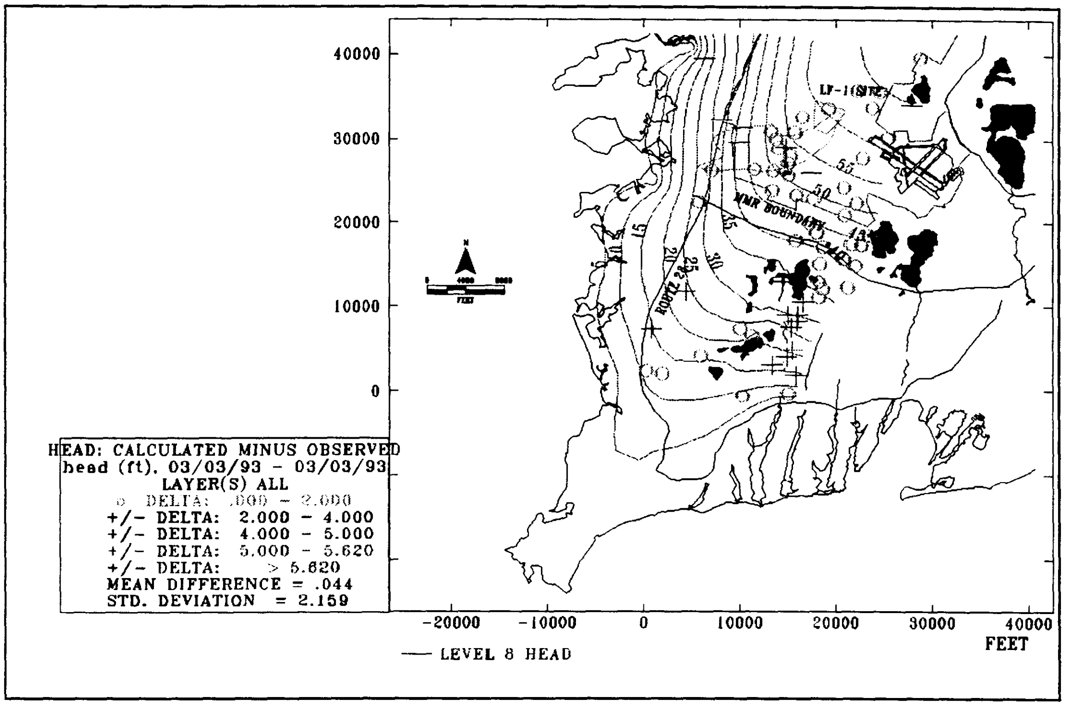


Figure 3.2-6: Calculated Water Table Elevation Contours and Flow Model Calibration Results

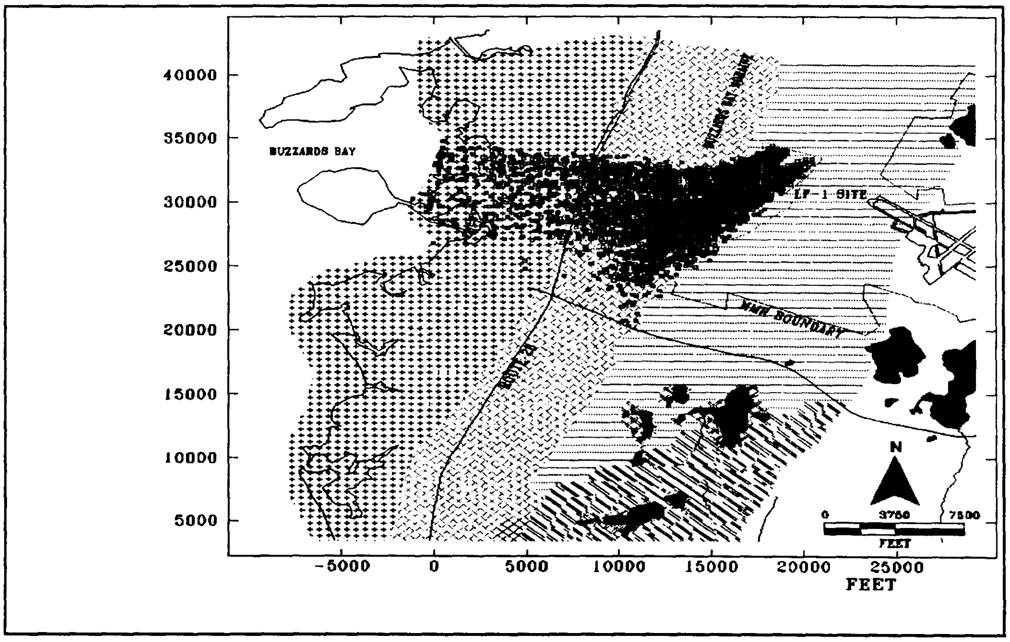


Figure 3.2-7: Plan view of Simulated LF-1, Buzzards Bay Moraine is also in View

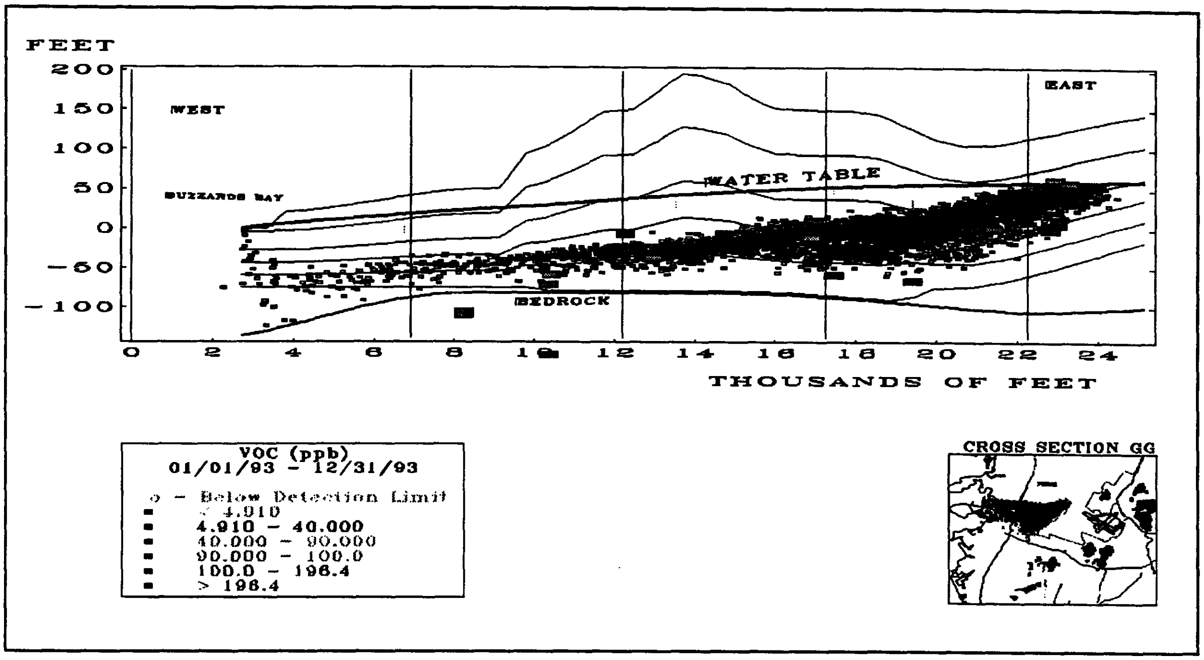


Figure 3.2-8: Cross-Section of Simulated LF-1 and Observed Contamination Locations

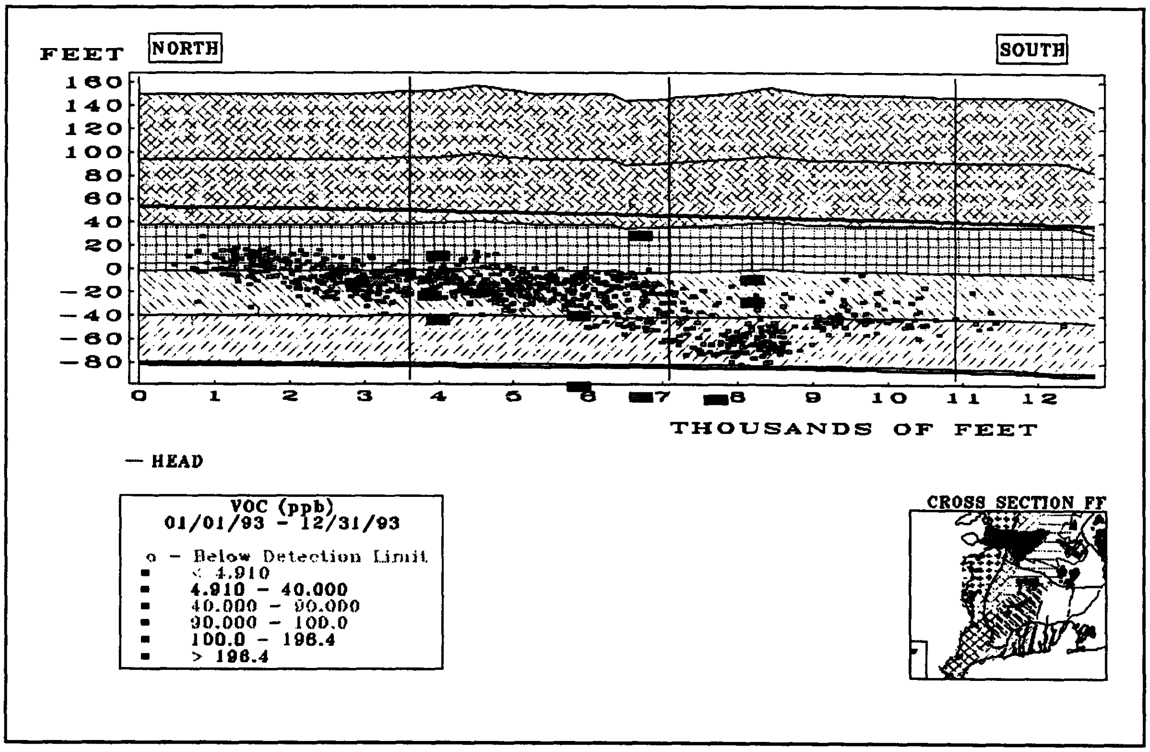


Figure 3.2-9: Cross sectional View of LF-1 as it enters the Buzzards Bay Moraine

3.3 Risk Assessment & Management of Risks

The IRP's Remedial Investigation Report, (CDM, 1995) and their Final Risk Assessment Handbook (Automated Sciences Group, Inc., 1994) present an evaluation of potential adverse effects to human health from materials identified in the MMR LF-1. The MMR site has been classified using EPA guidelines which were not specifically developed for the MMR site. The accuracy of the health and environmental risk scores are hypothesized to be limited by the constraints of the EPA's deterministic risk assessment model.

Relative cancer risk can be defined as the ratio of increased mortality rate for a member of the local community who develops cancer on account of exposure to carcinogenic materials identified in the MMR LF-1, to the mortality rate for a member of the local community if the MMR LF-1 did not exist. Normalized, it is the product of the probability of an event occurring and the magnitude of the effect which an event will likely produce. An increase in relative cancer risk is the product of the probability of an increase in exposure to carcinogens and the probability of dying from cancer because of exposure to carcinogens.

3.3.1 Toxicology

According to the EPA guidelines (cited in both Automated Sciences Group, Inc., 1994 and LaGrega et. al., 1994), toxicology and dose are to be calculated by following specific protocols. In terms of toxicology, carcinogens are considered to vary greatly in their potency. "When considering lifetime cancer risk to humans, it is widely accepted that carcinogenesis works in a manner such that it is possible, however remote, that exposure to a single molecule of a genotoxic carcinogen could result in one of the two mutations necessary to initiate cancer" (LaGrega et al., 1994, p. 277). Therefore, the calculation of carcinogenic risk from toxicology involves the use of cancer potency factors which are basically the slopes of the dose-response curves for carcinogens which are extrapolated to zero for extremely small doses. These extrapolated slopes are commonly referred to as cancer slope factors (CSFs) and they are used for the toxicological component of the EPA's acceptable risk calculations. CSFs are maintained in the EPA's Integrated Risk

Information System (IRIS) database. Many papers have been published which comment upon the uncertainty of the EPA's CSFs. In addition, "the EPA is well aware of the problems associated with overly conservative risk estimates and has repeatedly stressed that the unit cancer risk estimate only provides a plausible upper limit for a risk that can very well be much lower. The problem is that, in reality, official EPA unit risk estimates are widely used, more or less, as absolute standards." (LaGrega et al., 1994, p.280).

3.3.2 Dose

In terms of dose calculations, it is important to understand the environmental pathway. Therefore, for this cancer risk evaluation it is important to identify the following:

- carcinogens,
- source of carcinogens,
- release mechanisms,
- transport mechanisms,
- transfer mechanisms,
- transformation mechanisms,
- exposure paths,
- exposure point concentrations,
- receptors.

However, it is interesting to note that in performing an EPA risk assessment, only the carcinogens and the exposure point concentrations are used to calculate risk. Although the other seven above-referenced factors are essential for developing spatially distributed exposure point concentrations, EPA protocol requires maximum detect concentrations for maximum or upper bound risk calculations. In addition, EPA protocol requires arithmetic averaging of detect concentrations for mean risk calculations. That is to say, two sites with hazardous materials at similar concentrations with entirely different hydrogeologic conditions would have the same risk according to EPA model results. However, at their discretion, EPA will review risk assessments which incorporate site-specific conditions into their calculations. The probabilistic model presented in section 4.0 incorporates site-specific conditions for the MMR LF-1 into the risk calculations.

3.3.3 Identification of Hazardous Materials

Hazardous materials are broadly defined as non-carcinogens which are known to have harmful systemic effects upon humans, and carcinogens which have a propensity to initiate and promote cancer. Both terminal and "quality of life" health problems from exposure to hazardous materials are primary human health concerns. Because of these health concerns, human exposure to hazardous materials, especially carcinogens as a source of risk, is of primary concern for risk assessment and management. However, for this report, only the carcinogenic materials identified in the MMR LF-1 are being evaluated for potential risk; they are identified in the risk spreadsheets, Tables 3.3-1 to 3.3-5.

According to Boston University's School of Public Health Upper Cape Cancer Incidence Study which was prepared under contract to the Massachusetts Department of Public Health, cancer incidence rates between 1982 and 1990 for the MMR regional area have increased by approximately fifty six (56) percent, 5.56% annually (Aschengrau et al., 1992). In addition, according to the Journal of the American Medical Association, cancer incident rates are increasing steadily for the United States; the total relative rate increase from 1973 to 1987 is approximately fifty (50) percent, 2.90% annually (Davis et al., 1994). Furthermore, it is generally accepted that approximately twenty five (25) percent of all annual deaths in the US are caused by cancer. When the uncertainties presented in the above-referenced reports are taken into account, both the MMR cancer rate and the US cancer rate overlap. Since these cancer rates are within statistical proximity to each other, further research is required to discern if the cancer rate increase in the MMR region is attributable to the background national cancer rate increase, or if the cancer rate increase near the MMR is tied to the release of carcinogenic materials at the MMR site.

3.3.4 Review of Existing Reports

Part of this investigation was a comprehensive review of the previously referenced Remedial Investigation (RI), and the Risk Assessment Handbook (RAH) which are relevant to risk assessment for the MMR LF-1. An examination of the methodology used, the consistency of the reports with respect to the EPA's regulatory guidelines, and independent spreadsheet calculations using the equations and numerical values which are cited in the above-referenced reports supplied similar results. This three part process confirmed the consistency of the reporting which has been provided to MIT to calculate risk and formulate risk opinions. Independent spreadsheet calculations are included in Tables 3.3-1 to 3.3-5.

3.3.5 Uncertainty

In all statistically intensive calculations there are uncertainties specific to the numerical model which is being used. Since the EPA's model is the requisite regulatory guideline for Superfund sites, their model is the one which is being scrutinized. The EPA's deterministic model does not distribute uncertainty uniformly. When combined, concentration uncertainty and cancer slope factor (CSF) uncertainty account for approximately 97% of total risk uncertainty. Approximately 80% - 95% of the total risk uncertainty is CSF uncertainty. The EPA understands that their methods are statistically conservative and consequently will tend to overestimate risk, because the EPA incorporates policy constructs into risk quantification calculations. Basically, the EPA uses regulated risk assessment as opposed to probabilistic risk assessment coupled with regulations for risk management. Ultimately, risk regulated by the EPA is as uncertain as the EPA's CSFs. Recently, according to several major journals including the April 17, 1996 issue of the Wall Street Journal, the EPA has proposed policy changes, published in the Federal Register, for their assignment of CSFs. This should decrease the overwhelming unbalanced uncertainty that is inherent within EPA regulated risk assessment calculations. Uncertainty calculations and conclusions are included in sections 4.0 and 5.0 of this thesis, respectively.

MEAN RISK	Risk	C_{mean} (RI)	Inhalation	Inh. Risk	Dermal	Derm. Risk	Ingestion	Ing. Risk
Parameters	**Net Increase**	**ppb**	**Risk/ppm exp.**	**Net Increase**	**Risk/ppm exp.**	**Net Increase**	**Risk/ppm exp.**	**Net Increase**
Volatile Organic Compounds								
1,1-Dichloroethene	4.7573E-05	0.79	0.0528	4.1742E-05	3.3701E-04	2.6624E-07	7.0450E-03	5.5656E-06
Trichloroethene	1.9583E-06	4.87	0.0003	1.2866E-06	8.7696E-06	4.2708E-08	1.2916E-04	6.2900E-07
Benzene	1.3233E-06	0.81	0.0013	1.0343E-06	1.6289E-05	1.3194E-08	3.4051E-04	2.7581E-07
Chloroform	4.0778E-06	1.12	0.0036	3.9945E-06	2.7631E-06	3.0947E-09	7.1624E-05	8.0219E-08
1,2-Dichloroethane	3.4139E-06	0.67	0.0040	2.6846E-06	1.9971E-05	1.3381E-08	1.0685E-03	7.1589E-07
Carbon Tetrachloride	1.4292E-05	3.56	0.0023	8.3078E-06	1.5458E-04	5.5030E-07	1.5264E-03	5.4341E-06
Dibromochloromethane	6.1611E-07	0.62	0.0000	0.0000E+00	7.4197E-06	4.6002E-09	9.8630E-04	6.1151E-07
1,1,2,2-Tetrachlorethane	9.5255E-06	0.84	0.0088	7.3973E-06	1.8527E-04	1.5562E-07	2.3483E-03	1.9726E-06
Vinyl Chloride	3.0843E-05	0.86	0.0132	1.1360E-05	3.4555E-04	2.9717E-07	2.2309E-02	1.9186E-05
1,4-Dichlorobenzene	6.0904E-07	1.89	0.0000	0.0000E+00	4.0442E-05	7.6434E-08	2.8180E-04	5.3260E-07
Chloroethane	1.9709E-08	0.57	0.0000	0.0000E+00	5.2545E-07	2.9951E-10	3.4051E-05	1.9409E-08
Inorganic Carcinogens								
Beryllium	3.6352E-05	0.72	0.0000	0.0000E+00	0.0000E+00	0.0000E+00	5.0489E-02	3.6352E-05
Mean Additive Cancer Risk	***1.5060E-04***			***7.7807E-05***		***1.4230E-06***		***7.1375E-05***
TOTAL $RISK_{mean} = \Sigma$ (Concentration x [(Inhalation Risk/Exposure) + (Dermal Risk/Exposure) + (Ingestion Risk/Exposure)])								

Table 3.3-1
Mean Risk Calculations According to EPA Guidelines

INHALATION RISK/EXPOSURE	Inhalation	Inh. CSF	Exp. Dur.	Exp. Freq.	Volatil. Fact.	Air Inh. Rate	Body Wt.	Avg. Time	Unit Adj.
Parameters	Risk/ppm exp.	mg/kg/day	years	days/yr.	l/m^3	m^3/day	kilograms	years	days/yr
Volatile Organic Compounds									
1,1-Dichloroethene	0.0528	1.2000	30	350	0.5	15	70	70	365
Trichloroethene	0.0003	0.0060	30	350	0.5	15	70	70	365
Benzene	0.0013	0.0290	30	350	0.5	15	70	70	365
Chloroform	0.0036	0.0810	30	350	0.5	15	70	70	365
1,2-Dichloroethane	0.0040	0.0910	30	350	0.5	15	70	70	365
Carbon Tetrachloride	0.0023	0.0530	30	350	0.5	15	70	70	365
Dibromochloromethane	0.0000	0.0000	30	350	0.5	15	70	70	365
1,1,2,2-Tetrachlorethane	0.0088	0.2000	30	350	0.5	15	70	70	365
Vinyl Chloride	0.0132	0.3000	30	350	0.5	15	70	70	365
1,4-Dichlorobenzene	0.0000	0.0000	30	350	0.5	15	70	70	365
Chloroethane	0.0000	0.0000	30	350	0.5	15	70	70	365
Inorganic Carcinogens									
Beryllium	0.0000	8.4000	30	350	0	15	70	70	365

INHALATION RISK/EXPOSURE = (Exposure Duration x Exposure Frequency x Inhalation CSF x Volatilization Factor x Indoor Air Inhalation)

(Body Weight x Averaging Time) x (Unit Adjustments)

Table 3.3-2
Inhalation Risk Calculations According to EPA Guidelines

DERMAL RISK/EXPOSURE	Dermal	Dermal CSF	Exp. Dur.	Exp. Freq.	Surface Area	Dermal Perm.	Unit Adj.	Unit Adj.	Body Wt.	Avg. Time	Unit Adj.
Parameters	**Risk/ppm exp.**	**mg/kg/day**	**years**	**days/yr.**	**cm^2**	**cm/hour**	**l/cm^3**	**hours/day**	**kilograms**	**years**	**days/yr**
Volatile Organic Compounds											
1,1-Dichloroethene	3.3701E-04	0.6000	30	2.9	19,400	0.0248	0.001	24	70	70	365
Trichloroethene	8.7696E-06	0.0110	30	2.9	19,400	0.0352	0.001	24	70	70	365
Benzene	1.6289E-05	0.0290	30	2.9	19,400	0.0248	0.001	24	70	70	365
Chloroform	2.7631E-06	0.0061	30	2.9	19,400	0.0200	0.001	24	70	70	365
1,2-Dichloroethane	1.9971E-05	0.0910	30	2.9	19,400	0.0097	0.001	24	70	70	365
Carbon Tetrachloride	1.5458E-04	0.1300	30	2.9	19,400	0.0525	0.001	24	70	70	365
Dibromochloromethane	7.4197E-06	0.0840	30	2.9	19,400	0.0039	0.001	24	70	70	365
1,1,2,2-Tetrachlorethane	1.8527E-04	0.2000	30	2.9	19,400	0.0409	0.001	24	70	70	365
Vinyl Chloride	3.4555E-04	1.9000	30	2.9	19,400	0.0080	0.001	24	70	70	365
1,4-Dichlorobenzene	4.0442E-05	0.0240	30	2.9	19,400	0.0744	0.001	24	70	70	365
Chloroethane	5.2545E-07	0.0029	30	2.9	19,400	0.0080	0.001	24	70	70	365
Inorganic Carcinogens											
Beryllium	0.0000E+00	4.3000	30	2.9	19,400	0.0000	0.001	24	70	70	365
DERMAL RISK/EXPOSURE = (Exposure Duration x Exposure Frequency x Dermal CSF x Surface Area x Dermal Permeation)											
(Body Weight x Averaging Time) x (Unit Adjustments)											

Table 3.3-3
Dermal Risk Calculations According to EPA Guidelines

INGESTION RISK/EXPOSURE	Ing. Exp.	Ingestion CSF	Exp. Dur.	Exp. Freq.	H_2O Ing. Rate	Body Wt.	Avg. Time	Unit Adj.
Parameter	**Risk/ppm exp.**	**mg/kg/day**	**years**	**days/year**	**liters/day**	**kilograms**	**years**	**days/year**
Volatile Organic Compounds								
1,1-Dichloroethene	0.0070	0.6000	30	350	2	70	70	365
Trichloroethene	0.0001	0.0110	30	350	2	70	70	365
Benzene	0.0003	0.0290	30	350	2	70	70	365
Chloroform	0.0001	0.0061	30	350	2	70	70	365
1,2-Dichloroethane	0.0011	0.0910	30	350	2	70	70	365
Carbon Tetrachloride	0.0015	0.1300	30	350	2	70	70	365
Dibromochloromethane	0.0010	0.0840	30	350	2	70	70	365
1,1,2,2-Tetrachlorethane	0.0023	0.2000	30	350	2	70	70	365
Vinyl Chloride	0.0223	1.9000	30	350	2	70	70	365
1,4-Dichlorobenzene	0.0003	0.0240	30	350	2	70	70	365
Chloroethane	0.0000	0.0029	30	350	2	70	70	365
Inorganic Carcinogens								
Beryllium	0.0505	4.3000	30	350	2	70	70	365

INGESTION RISK/EXPOSURE = $\dfrac{\text{(Exposure Duration x Exposure Frequency x Ingestion CSF x Water Ingestion Rate)}}{\text{(Body Weight x Averaging Time) x (Unit Adjustments)}}$

Table 3.3-4
Ingestion Risk Calculations According to EPA Guidelines

MAXIMUM RISK	Risk	C_{max} in μg/l	Inh. Exp.	Inh. Risk	Dermal Exp.	Derm. Risk	Ing. Exp.	Ing. Risk
Parameters	**Net Increase**	**ppb**	**Risk/ppm exp.**	**Net Increase**	**Risk/ppm exp.**	**Net Increase**	**Risk/ppm exp.**	**Net Increase**
Volatile Organic Compounds								
1,1-Dichloroethene	3.5530E-04	5.90	0.0528	3.1174E-04	3.3701E-04	1.9884E-06	7.0450E-03	4.15656E-05
Trichloroethene	2.5735E-05	64.00	0.0003	1.6908E-05	8.7696E-06	5.6125E-07	1.2916E-04	8.26614E-06
Benzene	2.2872E-05	14.00	0.0013	1.7877E-05	1.6289E-05	2.2805E-07	3.4051E-04	4.76712E-06
Chloroform	3.2768E-05	9.00	0.0036	3.2099E-05	2.7631E-06	2.4868E-08	7.1624E-05	6.44618E-07
1,2-Dichloroethane	1.2738E-05	2.50	0.0040	1.0017E-05	1.9971E-05	4.9928E-08	1.0685E-03	2.67123E-06
Carbon Tetrachloride	2.4088E-04	60.00	0.0023	1.4002E-04	1.5458E-04	9.2746E-06	1.5264E-03	9.15851E-05
Dibromochloromethane	4.9686E-07	0.50	0.0000	0.0000E+00	7.4197E-06	3.7099E-09	9.8630E-04	4.93151E-07
1,1,2,2-Tetrachlorethane	1.2474E-04	11.00	0.0088	9.6869E-05	1.8527E-04	2.0379E-06	2.3483E-03	2.58317E-05
Vinyl Chloride	3.0485E-04	8.50	0.0132	1.1228E-04	3.4555E-04	2.9372E-06	2.2309E-02	0.000189628
1,4-Dichlorobenzene	4.5114E-06	14.00	0.0000	0.0000E+00	4.0442E-05	5.6618E-07	2.8180E-04	3.94521E-06
Chloroethane	1.7288E-08	0.50	0.0000	0.0000E+00	5.2545E-07	2.6272E-10	3.4051E-05	1.70254E-08
Inorganic Carcinogens								
Beryllium	1.8176E-04	3.60	0.0000	0.0000E+00	0.0000E+00	0.0000E+00	5.0489E-02	1.8176E-04
Max. Additive Cancer Risk	***1.3067E-03***			***7.3781E-04***		***1.7672E-05***		***5.5118E-04***
TOTAL $RISK_{max} = \Sigma$ (Concentration x [(Inhalation Risk/Exposure) + (Ingestion Risk/Exposure) + (Dermal Risk/Exposure)])								

Table 3.3-5

Maximum Risk Calculations According to EPA Guidelines

3.4 Assessment of Risk from Ingestion of Contaminated Shellfish

From the current LF-1 data, the contaminants are projected to discharge into Red Brook, Squeteague, and Megansett harbors of Buzzards Bay (OpTech, 1996 and CDM, 1995). The shallow tidal flats of these harbors support a rich population of local shellfish species. Soft-shell clams, quahogs (hard-shell clams), oysters, bay scallops, surf clams, mussels, and conch are harvested by local commercial and recreational fishermen. Since metals are part of LF-1 contaminants and shellfish have been shown to bioaccumulate metals in their body tissue, the potential discharge of the plume into the harbors along the shoreline presents a risk to the coastal marine shellfish population as well as to human health from the consumption of potentially contaminated shellfish. The results of maximum cancer and non-cancer risk assessment of consuming contaminated quahogs over a life time are calculated for each metal in Table 3.4-1.

	Max. C$^{@,1}$ (ug/l)	Max. C$^{@,2}$ (ug/l)	Oral SF	Oral RfD	Cancer Risk^{1}	Cancer Risk^{2}	Hazard Index^{1}	Hazard Index^{2}
Aluminum	20,900.0	10,200.0	NA	1	NA	NA	3.18217	1.55302
Antimony		2.6	NA	0.0004	NA	NA	0	0.98967
Arsenic	3.5	8.4	1.75	0.0003	0.00093	0.00224	1.77633	4.2632
Barium	400.0	107.0	NA	0.07	NA	NA	0.87004	0.23274
Beryllium	3.6	1.1	4.3	0.005	0.00236	0.00072	0.10963	0.0335
Cadmium	2.0	2.0	NA	0.001	NA	NA	0.30451	0.30451
Chromium$^{\#}$	54.2	66.3	NA	0.005	NA	NA	1.65047	2.01893
Copper	48.7	28.2	NA	NA	NA	NA	NA	NA
Cyanide	16.4		NA	0.02	NA	NA	0.12485	0
Iron	134,000.0	24,000	NA	0.5	NA	NA	40.8049	7.30834
Lead	27.8	9.8	NA	NA	NA	NA	NA	NA
Manganese	5,040.0	824.0	NA	0.14	NA	NA	5.48126	0.89614
Mercury	0.3*	0.3*	NA	0.0003	NA	NA	0.15226	0.15226
Nickel	24.4	184.0	NA	0.02	NA	NA	0.18575	1.40077
Vanadium	33.0	41.0	NA	0.007	NA	NA	0.71778	0.89179
Zinc	262.0	184.0	NA	0.3	NA	NA	0.13297	0.09338

Notes:

1 Derived from CDM Federal (1995)
2 Derived from OpTech (1996)
@ Maximum total concentration
# Chromium (VI) values are used

CSF = Cancer slope factor
RfD = Non-cancer reference dose
NA = Not Available
* Maximum dissolved concentration

Table 3.4-1
Maximum Cancer and Non-cancer Risk for each Metal

The maximum concentration of metals detected in well samples from LF-1 are derived from the reports of CDM, 1995 and OpTech, 1996. The oral cancer slope factors (CSFs) and non-cancer reference doses (RfDs) of the metals are obtained from the Risk Assessment Handbook for MMR published by Automated Sciences Group, 1994. Using the CDM, 1995 data, the maximum cancer risk from consumption of potentially contaminated quahogs is 3.3E-03, according to EPA maximum risk model results. This risk is interpreted as the incremental increase in probability of developing cancer above the background level for each exposed resident. The United States Environmental Protection Agency (EPA) acceptable risk standard ranges from 1.0E-06 to 1.0E-04. The standard is set independently for each site and case. The increased risk of 3.3E-03 for each exposed resident is above the highest acceptable EPA standard. A maximum cancer risk of 3.0E-03 is also calculated when maximum concentration of metals from OpTech, 1996 data is used in the assessment. The cancer risk for humans from consumption of tainted quahogs is derived from only two metals - arsenic and beryllium - since these are the only metals with published cancer slope factors.

The overall maximum hazard index (HI) for non-cancer risk from potential exposure to the contaminated quahogs are 55.5 and 20.1, when CDM, 1995 and OpTech, 1996 data are used in the assessment, respectively. The EPA's acceptable HI standard for non-cancer risk is 1.0. Calculated HIs that are above the EPA standard pose possible non-cancer deleterious health effects to the exposed population. The maximum cancer and non-cancer risks from contaminated quahogs are summarized below in Table 3.4-2.

	Maximum Cancer Risk	Maximum Hazard Index
CDM Federal Data	3.3E-03	55.5
OpTech Data	3.0E-03	20.1

Table 3.4-2

Total maximum cancer and non-cancer risks from consumption of tainted quahogs

The maximum risk assessment results show that both cancer and non-cancer risks are above the EPA standards. The EPA risk standards are set at levels which should adequately protect human health and the natural environment. The calculated risk results indicate that tainted quahogs from the coastal harbors where LF-1 is predicted to discharge present a significant risk to consumers of shellfish from these harbors. The calculated risk estimations are based on worst case assumptions. Thus, the risk is a conservative estimate and indicates a maximum risk to human health from these results, it is recommended that a monitoring program for shellfish harvested from Red Brook, Squeteague, and Megansett harbors be implemented (Lee, 1996).

3.4.1 Qualitative Assessment of Potential Ecological Risk

Since quahogs are predicted to bioaccumulate metals, the discharge of the LF-1 groundwater plume into Red Brook and Megansett harbors is likely to have detrimental effects on the coastal ecological system. Since quahogs are not at the top of the shoreline ecosystem food web, they are consumed by higher order food chain species. In this process of nutrient transfer up the food chain, contaminants accumulated within lower food chain organisms are transferred up the food web. Thus, tainted quahogs can potentially transfer toxic metals to higher food chain species. The bioaccumulation of metals in the higher order organisms can lead to the decline of a particular population of species and the ecosystem as a whole (Lee, 1996).

3.5 Public Perception

3.5.1 Management of Public Interaction at the MMR

An analysis of the approaches used to manage public interaction at the Massachusetts Military Reservation was undertaken to characterize the evolution of public perception of risk posed by past activities at the MMR. Several public meetings held at the MMR between January 15, 1996 and March 31, 1996 were attended. In addition, a comparison of management approaches at other federal bases was carried out. This included interviewing personnel at military bases in California and Arizona. As part of the analysis, suggested future approaches at IRPs were explored. This included the design of public opinion surveys to be carried out early in the IRP process. Other suggestions for future approaches are also presented.

3.5.2 Public Perception in Superfund Cleanup

In any scenario where pollution is an issue, there is frequently a gap between the perceived risk to human health and the actual risk posed by contamination. Because of scientific uncertainty in risk assessment, often times, the actual risks are not known, and so the perceived level of risk results from speculation by many parties. In the siting of hazardous waste facilities, the potential threat to human health results in the "Not in my backyard" (NIMBY) syndrome. Often times this "potential threat" is a perceived one. Public interest groups have fought many a facility siting and won, not due to actual risk, but because of a perceived one. In Superfund cases, unlike potential hazardous waste facility sitings, contamination has already occurred, but there is still a question of whether the contamination poses a real threat to public health. The gap between actual and perceived risks in this case results in the answer to the question "how clean is clean?" becoming a policy, rather than a scientific, issue. Groundwater contamination at the Massachusetts Military Reservation Superfund site is perceived to be a problem, and steps are being taken to remediate this problem to the greatest extent feasible. Public opinion has defined "the greatest extent feasible" as treating the groundwater to "non-detect" levels for contaminants that pose a threat to human health. In private sector cases, economics would figure into the calculation of feasibility of cleanup, but in the case of the MMR, where an entity as large as the federal government is funding the cleanup, the public believes that "anything is affordable" and therefore feasible.

3.5.3 History of Public Involvement at the MMR

The initial approach to management of public interaction surrounding the IRP at the MMR was similar to the "compliance-based" approach many companies take towards environmental regulation; the National Guard Bureau met only the minimum requirements necessary. Actions taken by the NGB were reactive rather than proactive. The NGB promulgated press releases and sent reports to local libraries, as well as holding news conferences after technical meetings, but any actions beyond that were minimal. Technical meetings concerning IRP activities were closed to the public and media, and virtually no public information meetings were held.

During 1990 and 1991, there was a modest effort to increase public involvement in the cleanup at Otis, as the IRP office at the MMR was created to manage the program locally rather than from far away. The "Joint Public Involvement Community Relations Plan" was presented, bi-monthly public information meetings were initiated, site tours/briefings were made possible, a site mailing list was created, and the IRP office began to print quarterly fact sheets that described the IRP activities. Although these fact sheets were limited in scope, they, along with the public information meetings, represented the first real effort to inform the public about specific activities associated with the IRP.

Late 1991 marked a major change in the way public interaction was managed at the MMR. The IRP office began updating technical reports much more frequently, and progress reports were made available to all interested parties. The local IRP office began educating the public by participating in local radio/cable TV programs as well as taking part in neighborhood association meetings. An educational display was created to be used at these meetings and at libraries, and detailed bi-monthly fact sheets were developed. In addition, all technical meetings were opened to the public and media.

The post-1991 period also has included the creation of many committees that assist the cleanup activities at the MMR. These committees, called "process action teams", are made up of personnel from the MMR, the relevant regulatory agencies, and the public. These process action teams (or "PATs") report to the senior management board, which was created to oversee the restoration. Presently, a total of eight community working groups hold regular meetings (Jordan, 1996). Although the public is highly involved in the IRP process at this point, how much influence the public actually has in the decision-making process is still a question.

3.5.4 Design Of Future Approaches At The MMR And Elsewhere

There are several things that should be considered before an Installation Restoration Program is initiated at a particular base or military reservation. Not the least of these is the management of public interaction surrounding the restoration. Government and public interest group opinions are very likely to polarize as soon as contamination and threat to public health are made known. Public distrust of government, especially on the federal level, compounds the fear that public health is in danger and contributes to the belief that any cleanup activities will be inadequate to alleviate the problem of contamination.

There are steps that can be taken to minimize the potential for adversarial relationships developing between all interested parties in base cleanup. Since the public has been involved in the restoration process at the MMR, the relationships between all interested parties have become less of a barrier to cleanup as all parties are seen to have input into the process. However, analysis of the approach used to manage public interaction at the MMR shows that, even though outwardly it appears that all the "right" approaches were taken, public concern is still an issue. This is due to the fact that early in the MMR IRP process the public was not included and was seen more as a "problem" than a potential source of solutions (Jordan, 1996).

3.6 Source Containment

As part of remediation operations at MMR, several of the cells at the Main Base Landfill have recently been secured with a final cover system. These cells include the 1970 cell, the post-1970 cell, and the kettle hole. The remaining cells (1947, 1951, and 1957) have collectively been termed the Northwest Operable Unit (NOU). Remedial investigation as to the necessity of a final closure system for these cells is ongoing. This proposal is focused on the design of a final closure system for the 1951 cell. The landfill final closure requirements of the Resource Conservation and Recovery Act (RCRA) and Massachusetts Solid Waste Management Regulations will be examined and adapted to site specific conditions. Material and design options for the components of the cover system will be examined and choices will be made according to performance, availability, and relative cost, as applicable to site-specific conditions. A cross-section of the proposed cover system is provided in Figure 3.6-1.

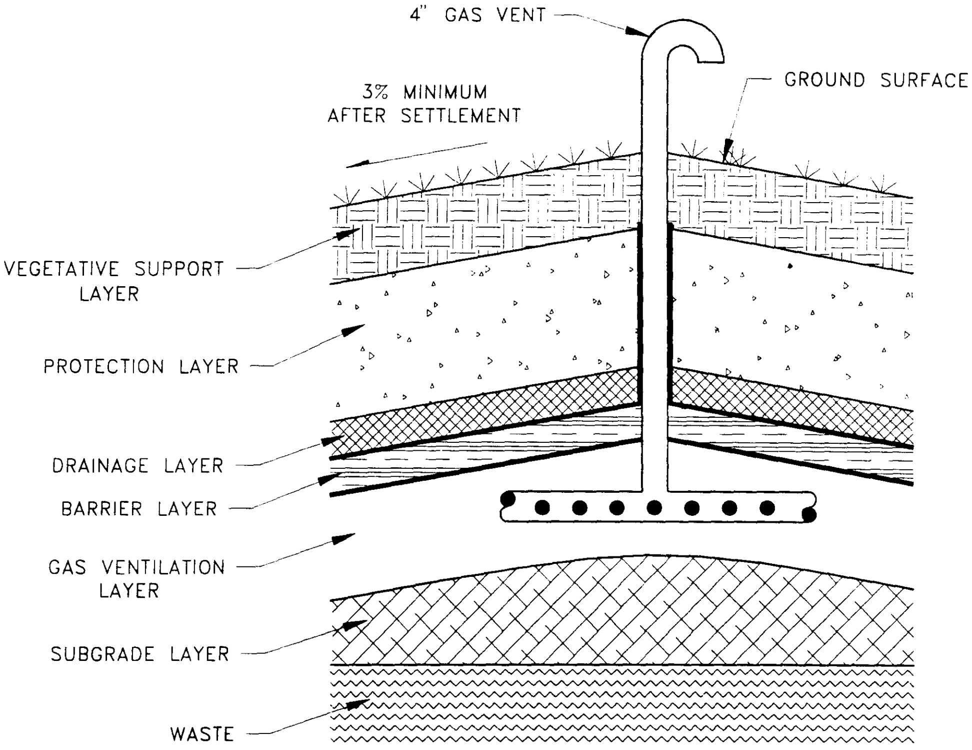
3.6.1 Regulatory Review

Massachusetts Solid Waste Management regulations specify the following as minimum design requirements for a landfill final closure system (MA DEP, 1993):

- Subgrade layer,
- Venting layer with minimum hydraulic conductivity of 1×10^{-3} cm/sec,
- Low conductivity layer with minimum thickness of 18 inches and maximum hydraulic conductivity of 1×10^{-7} cm/sec, or an approved flexible membrane liner (geomembrane),
- Drainage layer with minimum thickness of 6 inches and minimum hydraulic conductivity of 1×10^{-3} cm/sec, or a synthetic drainage net (geonet),
- Combined vegetative support / protection layer of minimum thickness 18 inches, with at least 12 inches of soil capable of supporting vegetation.

Subparts G, K, and N of the Resource Conservation and Recovery Act (RCRA) Subtitle C (Hazardous Waste Management) regulations dictate the requirements for hazardous and mixed waste landfill cover systems (US EPA, 1988). The EPA recommends that a final cover system consist of the following (US EPA, 1988):

- A low hydraulic conductivity geomembrane / soil layer consisting of a 24 inch layer of compacted natural or amended soil with a hydraulic conductivity of 1×10^{-7} cm/sec in intimate contact with a geomembrane liner of minimum thickness 0.5 mm (20 mil),
- A drainage layer of 12 inch minimum thickness having a minimum hydraulic conductivity of 1×10^{-2} cm/sec, or a geosynthetic material of equal transmissivity,



NOT TO SCALE

LAYER	MATERIAL	SPECIFICATIONS
Vegetative Support	Loam	6" thickness
Protection	Borrow Soil	18" thickness
Drainage	Geonet	Transmissivity $> 3 \times 10^{-5}$ m^2/sec
Barrier	Geomembrane over Geosynthetic Clay Liner	Geomembrane: 60mil VLDPE Geosynthetic Clay Liner: Gundseal with 40mil VLDPE Substrate
Gas Ventilation	Screened Borrow Soil	12" thickness Hydraulic conductivity $> 1 \times 10^{-3}$ cm/sec

Figure 3.6-1

Cross-section of Proposed Cover Design

- A top vegetative support / soil layer consisting of a top layer with vegetation or an armored surface, and a minimum of 24 inches of soil graded at a slope between 3 and 5 %.

The EPA does encourage design innovation, and will accept an alternative design upon a showing of equivalency.

3.6.2 Subgrade Layer

The subgrade layer acts as a foundation for the overlying layers of the cap, and it is also used as a contouring layer to create the appropriate final slope of the cover system. It is recommended that the foundation layer be placed to provide a final grade (after settlement) no greater than 5% and no less than 3%. This slope range provides sufficient grade to promote some surface water runoff while not being so steep as to produce erosion of the surficial soils. Allowance must be made for waste settlement that will occur as a result of the vertical stresses imposed by the weight of the cover materials.

Materials typically utilized for foundation layers include a variety of soils and some acceptable wastes. At sites such as MMR where soil borrow volumes are relatively plentiful, soil is the obvious choice for the foundation layer. Results of on-site borrow characterization tests (ABB, 1992) have revealed that this material is acceptable for use in the foundation layer. The material is classified as a fine-to-medium sand with trace-to-some fine-to-coarse gravel (ABB, 1992). This material has a relatively low fines content and has acceptable compressibility characteristics; therefore, it is recommended for use in this layer. The subgrade should be placed in lifts of approximately 8 inches and compacted by 4 to 6 passes of a typical sheepsfoot roller. This placement procedure should result in compaction to approximately 90% of the maximum dry density.

3.6.3 Gas Ventilation Layer

The gas venting layer is a permeable layer containing piping for the collection and venting or recovery of gases produced from waste degradation. Based on the cell composition (predominantly burn-fill), the moist, aerobic conditions provided by the intermediate cover, and the time since placement (over 40 years), it is concluded that gas generation rates at the 1951 cell will be low. Consequently, a passive gas venting system is recommended. It is recommended that material from the "lower layer" of the borrow area be utilized for the ventilation layer. The soil must be screened on a 3/8 inch sieve prior to placement, and then placed with a light machine in a single lift with no further compaction efforts. To collect the gas, PVC collector pipe is imbedded in the sand and run laterally along the slope. To vent the gas to atmosphere, it is recommended that a total of ten ventilation risers be installed and spaced equidistantly. Flexible (to accommodate loading and settlement) 4 inch perforated PVC is recommended for the collector pipe, and 4 inch non-perforated rigid PVC is recommended for the risers.

3.6.4 Hydraulic Barrier Layer

The barrier layer is designed to minimize the percolation of water through the cover system directly by impeding infiltration and indirectly by promoting storage and drainage of water in the overlying layers. Water is eventually removed by runoff, evapotranspiration, and internal storage processes (Geosyntec, 1994). This design proposal recommends a composite geomembrane over a geonsynthetic clay liner (GCL) as the hydraulic barrier layer. The specified geomembrane is a 60 mil (1.5 mm) textured very low density polyethylene (VLDPE), and the specified GCL is a Gundseal® GCL with a 40 mil (1.0 mm) textured VLDPE substrate placed bentonite-side up.

3.6.5 Drainage Layer

The drainage layer functions to remove water which infiltrates the vegetative support/protection layer. It should be designed to minimize the standing head and residence time of water on the barrier layer in order to minimize leachate production (EPA, 1989). The recommended drainage layer for this design is an extruded solid rib geonet with factory bonded nonwoven, heat-bonded geotextile on both faces. The composite drainage layer must have a minimum transmissivity of $3x10^{-5}$ m^2/sec.

3.6.6 Surface Layer

The top layer of the cover system is actually comprised of two separate layers. The lower layer is a protection layer and the upper layer is the surface layer. On-site or local soil is the most commonly used and typically the most suitable material for the protection layer. Suitable on-site materials are available for use in the protection layer. The on-site borrow materials have been classified as a fine-to-medium sand with trace-to-some fine-to-coarse gravel (ABB, 1992). This material has a relatively low fines content and a low organic content; therefore, it is acceptable for use in the protection layer. The borrow material should be placed to a thickness of 18 inches using a small dozer with low ground-pressure to protect the underlying cover components. Compaction beyond that which occurs during placement is not necessary.

Vegetation is specified as the surface layer cover; consequently, the surface layer will be designed for vegetative support. The on-site borrow material is not well suited to supporting vegetation; therefore, it is recommended that loam be imported from an off-base supplier and placed to a thickness of 6 inches. A warm season grass mix is specified as the vegetative cover. Periodic mowing and inspection of the vegetative cover are recommended as part of a post-closure program.

3.6.7 Landfill Cover Conclusions

It is concluded that this cover system, if constructed with appropriate construction quality assurance / quality control, will satisfy the primary objective of minimizing the source of leachate, thus mitigating further contamination of groundwater by the waste fill. The composite geomembrane / geosynthetic clay liner barrier layer is theoretically nearly impermeable. Estimates of the hydraulic conductivity of VLDPE geomembranes are on the order of $1x10^{-10}$ cm/sec (Koerner, 1994), and estimates of the hydraulic conductivity of Gundseal® GCLs are on the order of $1x10^{-12}$ cm/sec (Eith et al., 1991). Essentially all infiltration that does occur through such a composite barrier is the result of defects from manufacturing and / or construction processes. Theoretical performance of the cover was evaluated using the Hydrologic Evaluation of Landfill Performance (HELP) computer model (Schroeder et al., 1994). HELP is a quasi-two-dimensional, deterministic, water-routing model for determining water balances (Schroeder et al., 1994). HELP predicted zero inches of annual percolation through the barrier layer. Clearly, this prediction is unrealistic as no cover is absolutely impermeable. Because the performance of the cover system is so closely linked to construction QA/QC, it is very difficult to make an accurate estimate of anticipated infiltration through the barrier layer. It is accurate to state, however, that if this proposed cover system is constructed with appropriate QA/QC, it will meet and exceed the regulatory performance specifications. To accurately monitor the performance of the cover system, it is recommended that the downgradient groundwater quality be closely monitored before and after cover construction to identify contaminant concentration trends indicative of cover system effectiveness.

While the primary objective of the cover system is to minimize infiltration into the waste fill, there are several other significant performance criteria which must be satisfied. Given the site-specific conditions, the cover system must also:

- isolate the waste from humans, animals, and other components of the surrounding ecosystem,
- control gases generated within the waste fill,
- be resistant to erosion by wind and water,
- be resistant to static and seismic slope failures,
- be durable, maintaining its design performance level for 30 years (regulatory) or the life of the waste fill (prudent),
- control surface water runoff and lateral drainage flow in a manner which does not promote erosion and does not adversely impact the surrounding environment.

The waste is well isolated from the surrounding ecosystem by a total of over 5 feet of soil. Any gases produced by the waste will be vented to the atmosphere to prevent explosive conditions from occurring within the waste layer. Additionally, atmospheric monitoring is included as part of the post-closure program to ensure that vented gases do not violate Clean Air Act standards and to ensure that no gas migrates off-site. The cover is designed to be erosion-resistant. The surface is graded to a moderate slope, seeded with an appropriate grass mixture, and covered with straw mulch. Surface water runoff and lateral drainage flow are handled by a network of open channels and culverts which divert flow to specified recharge areas in a controlled manner which also assists in erosion control. The cover system is also resistant to static and seismic slope failure. The minimum static factor of safety of the proposed cover system is 3.1, and the minimum seismic factor of safety is 1.0. The recommended minimum factors of safety are 1.5 and 1.0 respectively.

Relatively little research on the long-term durability of geosynthetics in landfill covers has been performed, and since the history of geosynthetics in cover systems is fairly short, there are few, if any, case studies of sufficient length (e.g., over 30 years) to fill the data gap. However, the research that has been performed indicates that a cover system is an environment which is relatively conducive to geosynthetic survivability (Koerner et al., 1991). In a cover, the geosynthetics are not exposed to toxic chemicals, they are isolated from ultraviolet radiation, and they are fairly well protected from the effects of freeze/thaw cycles. Thus, it seems likely that the cover system will maintain its integrity well into the future. If constructed with appropriate construction QA/QC, the proposed cover system design will provide a potentially excellent barrier while also controlling lateral drainage flow, surface runoff, and decomposition gases with a stable, durable design that should maintain its integrity for a relatively long time (Elias, 1996).

3.7 Bioremediation

Bioremediation of the LF-1 has been considered as a potential remedial action for the site, but a comprehensive plan has yet to be proposed (ABB Environmental, 1992).

Conventional enhanced bioremediation systems stimulate microbial degradation by amending groundwater from the aquifer with oxygen and nutrients and recirculating it through the contaminated area (O'Brien & Gere Engineers Inc., 1995). The immense size of the LF-1 would necessitate the pumping and recirculation of hundreds of millions of gallons of water in order to ensure the removal of all of the chlorinated solvents. This plan would not only be prohibitively costly, it would also be ineffective because the plume contains PCE which cannot be aerobically degraded (Pavlostathis and Zhuang, 1993).

In order to solve the technical problems associated with a traditional enhanced bioremediation action, a passive anaerobic/aerobic system can be used. This system would consist of two groups of horizontal injection wells which are driven into the aquifer at a depth just below that of the plume (see Figure 3.7-1). The wells would be driven across the width of the plume and have thousands of small injection ports along the top of each one. The ports are used to inject gases into the aquifer in order to stimulate the microbes which will degrade the plume contaminants. Each set of wells will form a distinct biozone above it. The first biozone will be anaerobic and will treat the PCE in the plume, while the second biozone will be an aerobic treatment phase which will remove the remaining chlorinated solvents. This system has a significant advantage over traditional systems because it is a flow-through system; the gas is injected below the plume where it can rise up into the contaminated water and stimulate microbial activity as the plume flows over the gas injection wells. This significantly reduces the pumping costs associated with a more traditional bioremediation system.

The LF-1 contains significant quantities of PCE which can only be degraded anaerobically because methanotrophic bacteria possess a monooxygenase enzyme which cannot oxidize a fully chlorinated ethene molecule (Semprini, 1995). Therefore, the first stage of the system must be designed to turn the system anaerobic so that anaerobic bacteria can utilize the PCE in the plume in the process of reductive dechlorination. PCE is an oxidized chemical species, while organic matter is relatively reduced. Reductive dechlorinating bacteria use the PCE as a chemical oxidant in a redox reaction with organic matter in order to obtain energy to function and grow (Hollinger et al, 1993). In the process, one or more chlorines are removed from the PCE and replaced with hydrogen. This renders the PCE susceptible to aerobic attack.

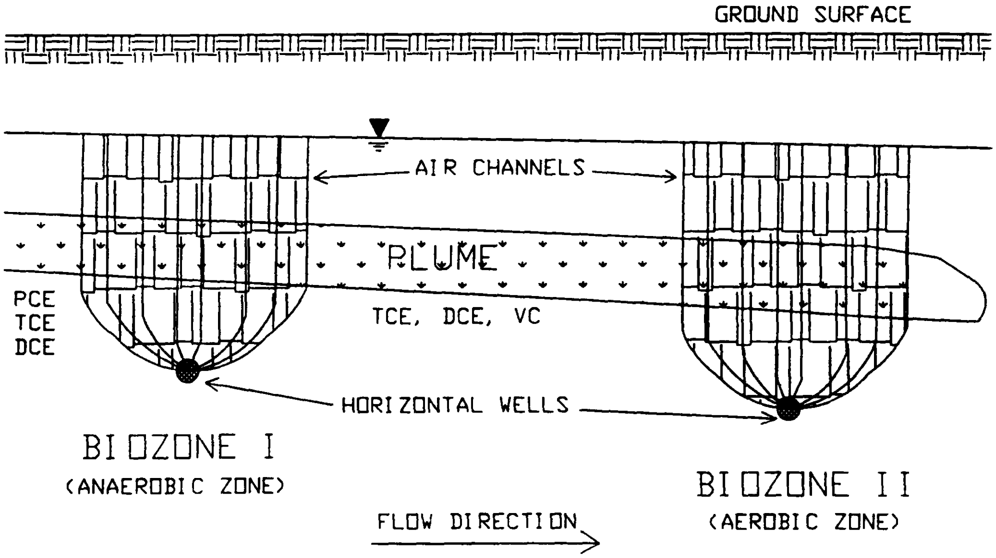


Figure 3.7-1

Horizontal Injection Well System

In order to turn the aquifer anaerobic, methane and air are injected at the first biozone. This injection serves a threefold purpose. Methanotrophs utilize the methane for growth and deplete the oxygen in the plume as it flows past the well. In addition, the methanotrophs will also degrade some of the TCE and DCE in the plume since their monooxygenase enzymes can degrade the solvents as well as methane (Semprini, 1995). Finally, as methane is utilized by the methanotrophs for growth, biomass will be accumulated in the region above the treatment well. This biomass will then be used by methanogenic bacteria to fuel the process of reductive dechlorination of PCE within the plume.

Once the oxygen is depleted from the plume, the first biozone will be anaerobic. It will remain anaerobic since there will be little or no vertical mixing with oxygenated recharge water (Domenico and Schwartz, 1990). Furthermore, oxygen will be depleted from the plume as it flows into the biozone by periodic injections of methane. Bacteria in this anaerobic zone will utilize the dead biomass and reductively dechlorinate the solvents in the plume. This is a slow biological process; based on laboratory batch studies and the temperature and pH of the aquifer, the biozone needs to produce at least five milligrams per liter of biomass and it should take about 540 days to achieve extensive removal (greater than 99 percent) of the PCE in the plume (Collins, 1996). Given a PCE migration rate within the plume of 0.9 ft per day and a treatment zone of two hundred feet associated with each horizontal well, three six-thousand foot horizontal wells will need to be installed to create the first biozone. Some of the TCE and DCE in the plume will also be dechlorinated within this area, rendering all of the chlorinated solvents in the LF-1 more susceptible to treatment by aerobic degradation.

The second biozone will be an aerobic zone that will be used to degrade the bulk of the chlorinated solvents in the plume. Gaseous methane, air, nitrous oxide, and triethyl phosphate will be injected into the aquifer (Skiadas, 1996). Methanotrophs will feed on this and will also degrade the solvents in a process termed cometabolic oxidation. One horizontal well must be used to produce the aerobic biozone which will achieve a ninety-five percent reduction in the concentration of TCE and ensure total remediation of DCE and VC (Collins, 1996). This level of remediation is more than sufficient to ensure that federal MCLs for the pollutants in the LF-1 are not exceeded in private drinking wells in the path of the plume.

It is apparent that the enhanced bioremediation system proposed above has the potential to effectively remediate the chlorinated solvent plume emanating from the main base landfill at the MMR on Cape Cod. The system would be difficult to manage and expensive to emplace, but it does offer many cost advantages over other remediation or containment schemes because it does not involve pumping large volumes of water or treating contaminated groundwater with granular activated carbon to remove the chlorinated organics. However, this type of system has never been used in the field, so a pilot-scale study should be conducted at a smaller site to ensure that the concept works and is cost-effective. If this test produces positive results, then a sequential anaerobic/aerobic enhanced bioremediation system of this nature could be used to mitigate LF-1 (Collins, 1996).

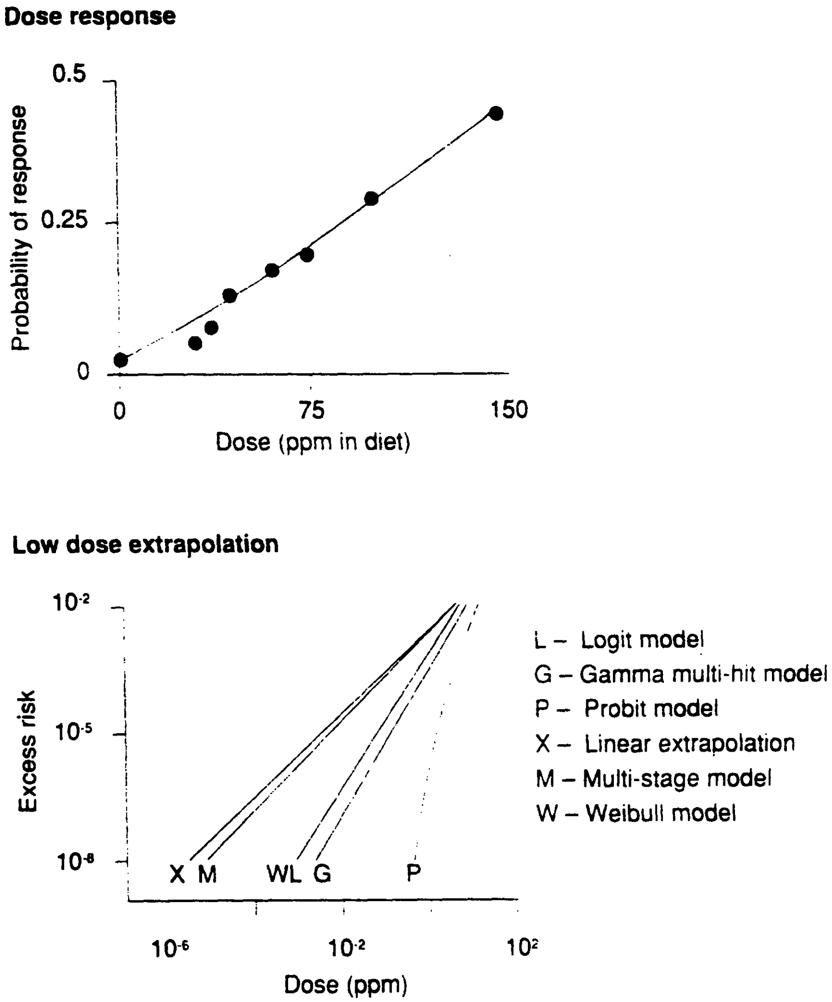
4.0 Probabilistic Risk to Human Health from LF-1

4.1 Probabilistic Model

The risk calculations which are illustrated in Tables 3.3-1 through 3.3-5 in section 3.3 are deterministic because all of the variables are treated as known constants, or point estimates. The above-referenced tables were generated by methods which are consistent with the EPA's guidelines. In addition, the risk results presented therein are calculated values based upon independent spreadsheet calculations using the RI data. The results in this thesis numbers are equal to the RI's point estimate calculations for risk.

The EPA's point estimate model furnishes a number for maximum relative risk and a number for mean relative risk which is based upon a model which is not site specific. The EPA's model does not explicitly define a control volume and their point estimates are selected according to specific policies in order to make simple representations of probability distribution functions (PDFs). Although many point estimates are quite reasonable estimates of the mean for certain PDFs, other point estimates are typically upper boundary conditions. For example, for the above-referenced EPA risk assessment, the air inhalation rate, the average adult body weight, and the body surface area are all very reasonable point estimate approximations of the mean of these independent PDFs. However, it is my opinion that the values for exposure duration and CSFs are clearly upper boundary point estimates.

In addition to being an upper boundary condition, the CSFs are represented by an uncertain value which has been augmented, often by orders of magnitude, by the EPA. It is very possible that the extrapolation of data from the 10-90% carcinogenisis range of test animal to 0.0001% carcinogenisis yields results which are conservative by several orders of magnitude for carcinogenic initiators and are incorrect for carcinogenic promoters and immunosuppressors. The range of error in experimental dose-response extrapolation for low carcinogenic frequencies in a potentially exposed human population is indicated in Figure 4.1-1, which shows the results from an experiment with 2-acetylaminofluorene (LaGrega et al., p.280).


Dose response

Low dose extrapolation

Figure 4.1-1

Extrapolation of Dose-Response Relationship for Liver Tumors Induced by 2-acetylaminofluorene in the Low-Dose Range

The EPA model represents the products and quotients of several independently distributed variables by multiple point estimate products and quotients. By representing the independently distributed variables with point estimates rather than random variables reflecting the uncertainty in these quantities, it is hypothesized that the EPA has simplified the mathematical representation of a physical phenomenon. Although the EPA's point estimate model parameters are generally a good representation of some potential risk parameters (*i.e.* exposure duration, concentration, exposure frequency, etc.), the point estimates which are used to represent the independently distributed variables are not adequate to quantitatively include the uncertainty in these values.

4.2 Methodology

The contribution to risk, R_j, is a combination of products and quotients of uncertain input variables as illustrated by the equation below:

$$R_j = \frac{x_1 \cdot x_2 \cdot x_3 \cdot x_4}{x_5 \cdot x_6}$$

By taking the natural logarithm (ln) of both sides, the logarithm of risk, Y_j, is

$$Y_j = \ln(R_j) = \ln(x_1)+\ln(x_2)+\ln(x_3)+\ln(x_4)-\ln(x_5)-\ln(x_6)$$

and the uncertainty of the risk, termed the variance, would be expressed as follows:

$$\sigma^2_{\ln(R_j)} = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 + \sigma_5^2 + \sigma_6^2 \quad .$$

Let X_g be the maximum value of the gaussian probability distribution functions (PDFs), both skewed and non-skewed random variable distributions, which are in the X domain. Tables 4.3-1 to 4.3-7, were then constructed by following the steps below:

1. Assume X_i are *independent* lognormal random variables,

2. Therefore, the mean is the expected value of Y, E(Y), and can be defined as follows:

$$\overline{Y_j} = E[\ln x_1] + \cdots - E[\ln x_6] = \ln(R_{g_j}),$$

and the variance is defined, $\sigma_{Y_j}^2 = E\left[\left(Y_j - \overline{Y_j}\right)^2\right] = \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_6^2$,

where R_g is the geometric mean risk and $\sigma_i^2 = \sigma_{\ln X_i}^2$.

3. E[lnX$_i$] can be defined because $\ln X_{g_i}$ is the mean of $\ln X_i$ which is normally distributed. For a normal distribution the interval ± 2 standard deviations around the mean corresponds to 95% probability. To estimate X_{g_i} and σ_i, the natural logarithms of the estimated upper and lower bounds of the variable X_i are assumed to be separated by $4\sigma_i$, *i.e.* $\sigma_i = \frac{\ln(x_{i_{\max}}) - \ln(x_{i_{\min}})}{4}$.

4. In addition, the mean is simply the average of the natural logarithms of the two bounds, *i.e.* $\ln X_{g_i} = \frac{\ln(x_{i_{\max}}) + \ln(x_{i_{\min}})}{2}$.

5. $Y_j = \ln R_j$, is a sum of normal random variables and therefore is normal or R_j is lognormal.

6. Total risk from several compounds is the sum of the contributions of each compound.

The following equations are the basis of the calculations for Total Cumulative Risk:

Let us define $Y_i = \ln R_j$, R$_T$= $\sum_{j=1}^{N} R_j$, and $\overline{Y_j} = \ln(R_{g_j})$. In addition,

$\overline{R_j} = R_{g_j} e^{\sigma_j^2/2}$ and $\sigma_{R_j}^2 = \overline{R_j}^2\left(e^{\sigma_j^2} - 1\right)$ are properties of the distributions, and σ_j^2 can be defined as $\sigma_{Y_j}^2$. Furthermore, because I have assumed independence, $\overline{R_T}$ is now defined as the Expected Value of R$_T$ such that $\overline{R_T} = \sum_{j=1}^{N} \overline{R_j}$, and $\sigma_{R_T}^2$ is now defined as $E\left[\left(R_T - \overline{R_T}\right)^2\right]$, which is equal to $\sum_{i=1}^{N}\sigma_{R_i}^{2} = \sum_{i=1}^{N}\left(R_{g_i}^{2} e^{\sigma_i^2}\left(e^{\sigma_i^2}-1\right)\right)$, and $= \sum_{i=1}^{N}\overline{R_i}^{2}\left(e^{\sigma_i^2}-1\right)$.

However, normal distributions can yields negative numbers which are not possible. Therefore, a plausible approach is to assume a lognormal distribution.

$$\sigma_{\ln R_T}^{2} = \ln\left(1+\frac{\sigma_{R_T}^{2}}{\overline{R_T}^{2}}\right) \text{, and } E(\ln R_T) = \ln\overline{R_T} - \frac{\sigma_{\ln R_T}^{2}}{2}.$$

Therefore,

$$\text{Risk}_{\text{mean}} = e^{[\ln(\overline{R_T})]} \quad ,$$

$$\text{Risk}_{\text{upper boundary}} = e^{[E(\ln R_T)+2\sigma \ln R_T]} \quad \text{, and}$$

$$\text{Risk}_{\text{lower boundary}} = e^{[E(\ln R_T)-2\sigma \ln R_T]} .$$

A probabilistic model will enable a series of PDF products and quotients to be represented by one PDF. This composite PDF is sufficient to provide an overall mean, variance and other subsequent information (*e.g.* standard deviation). With a single PDF, it is very easy to observe the mean along with the upper and lower boundary conditions. In addition, the uncertainty is simply represented by the variance for the PDF. Furthermore, the probabilistic model's composite PDF is sufficiently transparent to observe uncertainty distributions by parameter. Therefore, the uncertainty distribution of the probabilistic model will illustrate the extent to which the EPA's point estimate model mathematically characterizes risk phenomenon.

4.2.1 Lognormal Distributions

While the normal distribution arises from the sum of many small effects, it is desirable also to consider the distribution of a phenomenon which arises as the result of a multiplicative mechanism acting on a number of factors. If the logarithms of a random variable are normally distributed, then their distribution is lognormal. The lognormal distribution is an excellent statistical model of products used in many civil engineering applications, especially for hydrological events (Benjamin et al., 1970). For the probabilistic model presented in this thesis, lognormal distributions are used. An illustration of both normal and lognormal distributions for a single variable is included in Figure 4.2-1 (Gelhar, 1993).

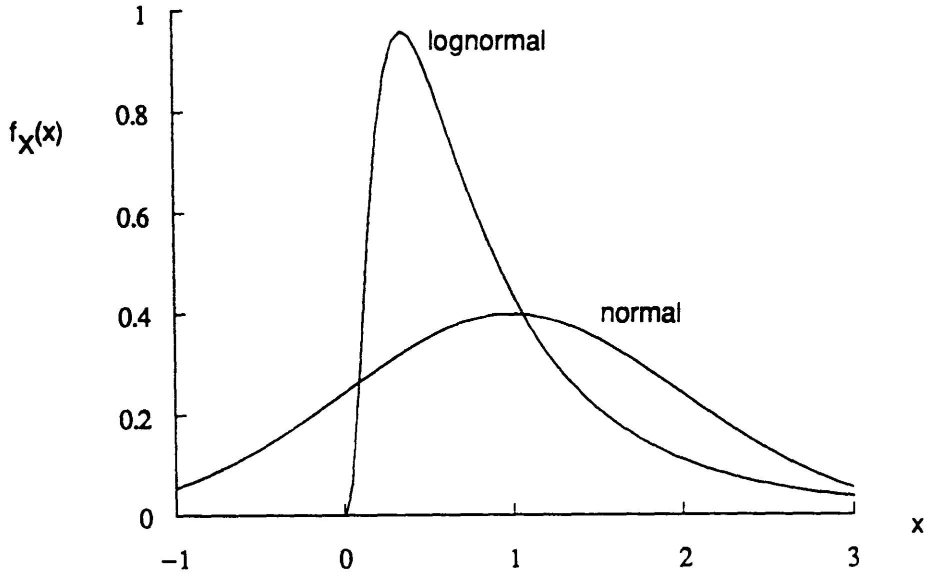


Figure 4.2-1

Comparison of Normal and Lognormal Distributions for a Random Variable

4.2.2 Ninety Five Percent (95%) Confidence Intervals

In order to develop lognormal distributions for the probabilistic model, it was necessary to make assumptions for 95% confidence intervals. The 95% confidence interval is two standard deviations on both the left and right sides of the mean of a normal distribution, or four standard deviations (4σ) total. For example, in the case of trichlorethene, the 95% confidence interval was assumed to be between the maximum detected concentration of 64.0 parts per billion (ppb) and one-half the detection limit, which is equal to 0.5 ppb. The 95% confidence level in this example is equal to ln(64.0) - ln(0.5) which is also equal to 4σ. Furthermore, the mean is equal to $e^{(\ln(64.0) - 2\sigma)}$, which is also equal to $e^{(\ln(0.5) + 2\sigma)}$, and the variance, which characterizes the uncertainty, is equal to σ^2. Tables 4.3-6 and 4.3-

7 enclosed at the end of section 4.3 labeled "95% Confidence Intervals" and "CSF 95% Confidence Range: (CSF/1 to CSF/100)" contain the assumptions which were selected for all subsequent spreadsheet calculations. These spreadsheet calculations are electronically linked to the calculations in the remaining tables.

4.3 Comparison to the EPA's Model

Not all of the parameters were calculated using 95% confidence intervals with lognormal distributions. Some of the parameters were kept as constants. The reason that some parameters were kept as constants is that this is not a complete probabilistic model analysis, but a transparent study of a probabilistic model to examine the variance (σ^2), or uncertainty, of the information presented in the EPA's point estimate model.

4.3.1 Inhalation, Dermal and Ingestion Risk

According to the probabilistic model and the EPA's point estimate model, the following was observed:

Risk	Probabilistic (mean)	EPA (mean)
Inhalation	6.18E-05	7.78E-05
Dermal	1.85E-06	1.42E-06
Ingestion	5.04E-05	7.14E-05
Total	1.14E-04	1.51E-04

Table 4.2-1

Mean Risk for Probabilistic and Point Estimate Models

The close agreement of the EPA's point estimate model and the probabilistic model is significant. Although there are no minimum values given for the EPA model, the maximum risk for the EPA model and both the upper and lower bounds for the probabilistic model are presented below.

Risk	Probabilistic (upper)	EPA (max)
Inhalation	3.79E-04	7.38E-04
Dermal	1.26E-05	1.77E-05
Ingestion	3.03E-04	7.38E-04
Total	3.94E-04	1.31E-03

Table 4.2-2

Upper Boundary of Risk Calculation for Probabilistic and Point Estimate Models

Risk	Probabilistic (lower)	EPA (minimum)
Inhalation	1.49E-06	not calculated
Dermal	2.12E-08	not calculated
Ingestion	1.37E-06	not calculated
Total	1.83E-05	not calculated

Table 4.2-3

Lower Boundary of Risk Calculation for Probabilistic and Point Estimate Models

These values are transposed from the spreadsheet calculations which are presented as tables in sections 3 and 4 of this thesis. The EPA point estimate model calculations are those included in section 3 and the probabilistic model calculations are those included at the end of section 4.

4.3.2 Uncertainty

The variance (σ^2), otherwise termed the uncertainty, is included in Tables 4.3-1 to 4.3-7 presented at the end of this section. In addition, it is the uncertainty which provides the most information about the probabilistic model. Specifically, inspection of the Lognormal

Inhalation Risk, Lognormal Dermal Risk, and Lognormal Ingestion Risk tables illustrate that the CSF variance and the concentration variance together account for approximately 95% of the total uncertainty. Furthermore, if the 95% confidence level of the CSF were altered to range over four orders of magnitude, CSF/1 to CSF/10,000, then, continuing with this relatively transparent inspection of the probabilistic model to examine the uncertainty, the CSF uncertainty alone would account for approximately 90% of the total uncertainty.

4.4 Calculations

The risk numbers presented are not intended to challenge the numerical risk conclusions which have been presented by many qualified consultants working on the MMR. The numbers presented herein do not account for synergistic risk affects, potential risk from shellfish ingestion, non-cancer risks, risk from swimming exposure, etc. The numerical results included in Tables 4.3-1 to 4.3-7 and Figure 4.3-1 illustrate the relative importance of the individual input uncertainties in calculating distributed relative risks.

4.5 Cranberry Bog Risk

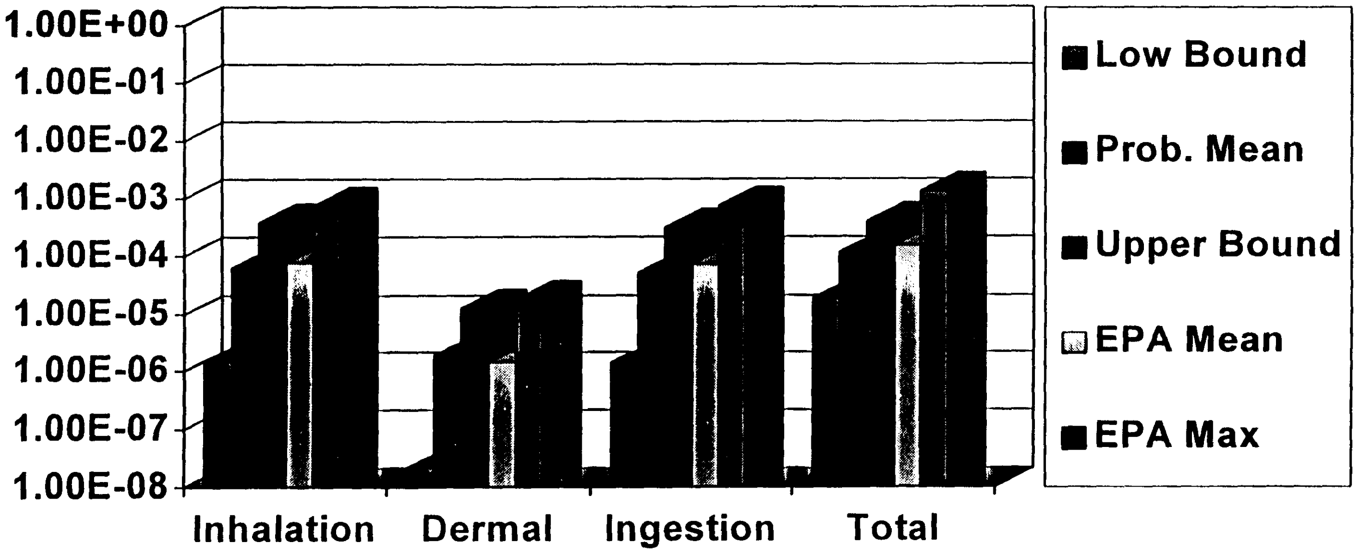
On account of the proximity of cranberry bogs to the MMR LF-1, they were examined as potential sensitive ingestion receptors. Upon an inspection of the cranberry bogs in the area near the MMR LF-1 path, the following was observed:

- Ponds are typically created by dams in the area near the cranberry bogs because the water is required for irrigation and to flood the bogs for cranberry harvesting;
- The dammed ponds alter the local hydraulic conditions because they are elevated sources of water and ultimately, groundwater recharge areas;
- Water is pumped from the ponds through sprinklers approximately six feet above the bogs for irrigation;
- Cranberry roots are located in the top 5 inches of soil;
- Cranberries are harvested annually.

On account of the hydraulic conditions, the dammed ponds represent hydraulic recharge areas, so the likelihood of part of the plume discharging into the dammed ponds from the subsurface is extremely small. In addition, if any groundwater were to enter parts of a cranberry bog recharge pond and also contained part of the landfill plume, the concentration of contaminant would be diluted proportionally to the volume of the pond. Furthermore, at this point any of the volatile organic compounds which had potentially entered the pond would be required to travel through a sprinkler system elevated above the bog which delivers approximately five inches of water to the bog annually. Therefore, in consideration of the hydraulic conditions, the size of the ponds, and the sprinkler system, it is my opinion that the cranberries cannot take up MMR LF-1 constituents due to an absence of potential exposure.

Comparison of EPA and Probabilistic Model Results

Figure 4.3-1



TOTAL RISK	Inhalation Risk	Dermal Risk	Ingestion Risk	Carcinogen Risk
Parameter				
Volatile Organic Compounds				
1,1-Dichloroethene	1.2575E-05	1.0288E-07	1.6767E-06	1.44E-05
Trichloroethene	2.0709E-07	8.8168E-09	1.0124E-07	3.17E-07
Benzene	4.6814E-07	7.6595E-09	1.2484E-07	6.01E-07
Chloroform	1.0484E-06	1.0418E-09	2.1054E-08	1.07E-06
1,2-Dichloroethane	6.2076E-07	3.9684E-09	1.6554E-07	7.90E-07
Carbon Tetrachloride	1.7712E-06	1.5047E-07	1.1585E-06	3.08E-06
Dibromochloromethane	0.0000	6.5935E-10	6.8336E-08	6.90E-08
1,1,2,2-Tetrachlorethane	2.8618E-06	7.7221E-08	7.6315E-07	3.70E-06
Vinyl Chloride	3.7735E-06	1.2661E-07	6.3730E-06	1.03E-05
1,4-Dichlorobenzene	0.0000	1.9017E-08	1.0331E-07	1.22E-07
Chloroethane	0.0000	4.6694E-11	2.3592E-09	2.41E-09
Inorganic Carcinogens				
Beryllium	0.0000	0.0000	9.3865E-06	9.39E-06
Upper Risk Boundary				3.94E-04
Totals	**6.18E-05**	**1.85E-06**	**5.04E-05**	**1.14E-04**
Lower Risk Boundary				1.83E-05
Uncertainty (Variance)			σ^2 =	***1.04E-08***

Table 4.3-1
Total Risk Summary

INHALATION	$\exp(\Sigma \text{Ln Xg})$	ΣLn Xg	$\Sigma\sigma^2$	Ln Xg	σ^2	Ln Xg	σ^2	Ln Xg	σ^2	Ln Xg	σ^2
Parameter	**Inhalation Risk**	**Sum of Ln Xg**	**Uncertainty**	**Conc.(ppb)**	**Conc.(ppb)**	**Inh. CSF**	**Inh. CSF**	**Exp. Dur.**	**Exp. Dur.**	**Exp. Freq.**	**Exp. Freq.**
Volatile Organic Compounds											
1,1-Dichloroethene	1.2575E-05	-11.28	1.7806	0.5409	0.3807	-2.1203	1.3255	9.3237	0.0300	-0.2027	0.0103
Trichloroethene	2.0709E-07	-15.39	2.8713	1.7329	1.4714	-7.4186	1.3255	9.3237	0.0300	-0.2027	0.0103
Benzene	4.6814E-07	-14.57	2.0939	0.9730	0.6940	-5.8430	1.3255	9.3237	0.0300	-0.2027	0.0103
Chloroform	1.0484E-06	-13.77	1.9220	0.7520	0.5221	-4.8159	1.3255	9.3237	0.0300	-0.2027	0.0103
1,2-Dichloroethane	6.2076E-07	-14.29	1.5618	0.1116	0.1619	-4.6995	1.3255	9.3237	0.0300	-0.2027	0.0103
Carbon Tetrachloride	1.7712E-06	-13.24	2.8324	1.7006	1.4325	-5.2400	1.3255	9.3237	0.0300	-0.2027	0.0103
Dibromochloromethane	0.0000	N/A	N/A	-0.6931	0.0000	0.0000	N/A	9.3237	0.0300	-0.2027	0.0103
1,1,2,2-Tetrachlorethane	2.8618E-06	-12.76	1.9971	0.8524	0.5972	-3.9120	1.3255	9.3237	0.0300	-0.2027	0.0103
Vinyl Chloride	3.7735E-06	-12.49	1.9016	0.7235	0.5017	-3.5066	1.3255	9.3237	0.0300	-0.2027	0.0103
1,4-Dichlorobenzene	0.0000	N/A	N/A	0.9730	0.6940	0.0000	N/A	9.3237	0.0300	-0.2027	0.0103
Chloroethane	0.0000	N/A	N/A	-0.6931	0.0000	0.0000	N/A	9.3237	0.0300	-0.2027	0.0103
Inorganic Carcinogens											
Beryllium	0.0000	N/A	N/A	0.2939	0.2436	-0.1744	1.3255	9.3237	0.0300	-0.2027	0.0103
Ln(INHALATION RISK) = Ln(Concentration) + Ln(Exposure Duration) + Ln(Exposure Frequency) + Ln(Inhalation CSF)											
+ Ln(Volatile Factor) + LN(Indoor Air Inhalation) - LN(Body Weight) - LN(Averaging Time) + LN(Unit Adjustments)											
Sum Totals	2.3326E-05										

Table 4.3-2
Lognormal Inhalation Risk

Constant	Ln(Const.)	Constant	Ln(Const.)	Ln Xg	σ^2	Constant	Ln(Const.)	Constant	Ln(Const.)
Volatil. Fact.	**Volatil. Fact.**	**Air Inh. Rate**	**Air Inh. Rate**	**Weight**	**Weight**	**Avg. Time**	**Avg. Time**	**Unit Adj.**	**Unit Adj.**
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.5000	-0.6931	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078
0.0000	N/A	15.00	2.7081	3.7835	0.0341	25,567.50	10.1491	1.00E-03	-6.9078

Table 4.3-2
Lognormal Inhalation Risk

DERMAL	exp(ΣLn Xg)	ΣLn Xg	$\Sigma\sigma^2$	Ln Xg	σ^2	Ln Xg	σ^2	Ln Xg	σ^2	Ln Xg	σ^2
Parameter	**Dermal Risk**	**Sum of Ln Xg**	**Uncertainty**	**Conc.(ppb)**	**Conc.(ppb)**	**Dermal CSF**	**Dermal CSF**	**Exp. Dur.**	**Exp. Dur.**	**Exp. Freq.**	**Exp. Freq.**
Volatile Organic Compounds											
1,1-Dichloroethene	1.0288E-07	-16.09	2.1519	0.5409	0.3807	-2.8134	1.3255	9.3237	0.0300	-4.42051	0.385927
Trichloroethene	8.8168E-09	-18.55	3.2425	1.7329	1.4714	-6.8124	1.3255	9.3237	0.0300	-4.42051	0.385927
Benzene	7.6595E-09	-18.69	2.4651	0.9730	0.6940	-5.8430	1.3255	9.3237	0.0300	-4.42051	0.385927
Chloroform	1.0418E-09	-20.68	2.2933	0.7520	0.5221	-7.4021	1.3255	9.3237	0.0300	-4.42051	0.385927
1,2-Dichloroethane	3.9684E-09	-19.34	1.9330	0.1116	0.1619	-4.6995	1.3255	9.3237	0.0300	-4.42051	0.385927
Carbon Tetrachloride	1.5047E-07	-15.71	3.2037	1.7006	1.4325	-4.3428	1.3255	9.3237	0.0300	-4.42051	0.385927
Dibromochloromethane	6.5935E-10	-21.14	1.7712	-0.6931	0.0000	-4.7795	1.3255	9.3237	0.0300	-4.42051	0.385927
1,1,2,2-Tetrachlorethane	7.7221E-08	-16.38	2.3683	0.8524	0.5972	-3.9120	1.3255	9.3237	0.0300	-4.42051	0.385927
Vinyl Chloride	1.2661E-07	-15.88	2.2728	0.7235	0.5017	-1.6607	1.3255	9.3237	0.0300	-4.42051	0.385927
1,4-Dichlorobenzene	1.9017E-08	-17.78	2.4651	0.9730	0.6940	-6.0323	1.3255	9.3237	0.0300	-4.42051	0.385927
Chloroethane	4.6694E-11	-23.79	1.7712	-0.6931	0.0000	-8.1456	1.3255	9.3237	0.0300	-4.42051	0.385927
Inorganic Carcinogens											
Beryllium	0.0000	N/A	N/A	0.2939	0.2436	-0.8440	1.3255	9.3237	0.0300	-4.42051	0.385927
Ln(DERMAL RISK) = Ln(Concentration) + Ln(Exposure Duration) + Ln(Exposure Frequency) + Ln(Dermal CSF)											
+ Ln(Dermal Permeation) + Ln(Surface Area/Body Weight) - Ln(Averaging Time) + Ln(Unit Adjustments)											
Sum Totals	4.9839E-07										

Table 4.3-3
Lognormal Dermal Risk

Ln Xg	σ^2	Constant	Ln(Const.)	Constant	Ln(Const.)	Constant	Ln(Const.)
S.A./Wt.	S.A./Wt.	Derm. Perm.	Derm. Perm.	Unit Adj.	Unit Adj.	Avg. Time	Avg. Time
5.7630	0.0297	0.5952	-0.5189	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.8448	-0.1687	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.5952	-0.5189	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.4800	-0.7340	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.2326	-1.4586	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	1.2600	0.2311	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.0936	-2.3687	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.9816	-0.0186	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.1927	-1.6465	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	1.7856	0.5798	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.1920	-1.6503	1.00E-06	-1.38E+01	25,567.50	10.1491
5.7630	0.0297	0.0000	N/A	1.00E-06	-1.38E+01	25,567.50	10.1491

Table 4.3-3
Lognormal Dermal Risk

INGESTION	exp(ΣLn Xg)	ΣLn Xg	$\Sigma\sigma^2$	Ln Xg	σ^2	Ln Xg	σ^2	Ln Xg	σ^2	Ln Xg
Parameter	**Ingestion Risk**	**Sum of Ln Xg**	**Uncertainty**	**Conc.(ppb)**	**Conc.(ppb)**	**Ingestion CSF**	**Ingestion CSF**	**Exp. Dur.**	**Exp. Dur.**	**Exp. Freq.**
Volatile Organic Compounds										
1,1-Dichloroethene	1.6767E-06	-13.30	1.7806	0.5409	0.3807	-2.8134	1.3255	9.3237	0.0300	-0.2027
Trichloroethene	1.0124E-07	-16.11	2.8713	1.7329	1.4714	-6.8124	1.3255	9.3237	0.0300	-0.2027
Benzene	1.2484E-07	-15.90	2.0939	0.9730	0.6940	-5.8430	1.3255	9.3237	0.0300	-0.2027
Chloroform	2.1054E-08	-17.68	1.9220	0.7520	0.5221	-7.4021	1.3255	9.3237	0.0300	-0.2027
1,2-Dichloroethane	1.6554E-07	-15.61	1.5618	0.1116	0.1619	-4.6995	1.3255	9.3237	0.0300	-0.2027
Carbon Tetrachloride	1.1585E-06	-13.67	2.8324	1.7006	1.4325	-4.3428	1.3255	9.3237	0.0300	-0.2027
Dibromochloromethane	6.8336E-08	-16.50	1.3999	-0.6931	0.0000	-4.7795	1.3255	9.3237	0.0300	-0.2027
1,1,2,2-Tetrachlorethane	7.6315E-07	-14.09	1.9971	0.8524	0.5972	-3.9120	1.3255	9.3237	0.0300	-0.2027
Vinyl Chloride	6.3730E-06	-11.96	1.9016	0.7235	0.5017	-1.6607	1.3255	9.3237	0.0300	-0.2027
1,4-Dichlorobenzene	1.0331E-07	-16.09	2.0939	0.9730	0.6940	-6.0323	1.3255	9.3237	0.0300	-0.2027
Chloroethane	2.3592E-09	-19.86	1.3999	-0.6931	0.0000	-8.1456	1.3255	9.3237	0.0300	-0.2027
Inorganic Carcinogens										
Beryllium	9.3865E-06	-11.58	1.6435	0.2939	0.2436	-0.8440	1.3255	9.3237	0.0300	-0.2027
Ln(INGESTION RISK) = Ln(Concentration) + Ln(Exposure Duration) + Ln(Exposure Frequency) + Ln(Ingestion CSF)										
+ Ln(Water Ingestion Rate) - Ln(Body Weight) - Ln(Averaging Time) + Ln(Unit Adjustments)										
Sum Totals	1.9945E-05									

Table 4.3-4
Lognormal Ingestion Risk

σ^2	Ln Xg	σ^2	Constant	Ln(Const.)	Constant	Ln(Const.)	Constant	Ln(Const.)
Exp. Freq.	Weight	Weight	H_2O Ing. Rate	H_2O Ing. Rate	Unit Adj.	Unit Adj.	Avg. Time	Avg. Time
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491
0.0103	3.7835	0.0341	2.0000	0.6931	1.00E-03	-6.9078	25,567.50	10.1491

Table 4.3-4
Lognormal Ingestion Risk

TOTAL RISK	R_{gi}	σ_i^2	$R_{¥} = R_{gi}(e^{(\sigma_i^2/2)})$	$\sigma_{Yi}^2 = R_i^2(e^{(\sigma_i)^2}-1)$	$\sigma_Y^2/¥^2$	$\sigma_{\ln Y}^2 = \ln(1+(\sigma_Y^2/¥^2))$	$\sigma_{\ln Y}$	$\ln(¥)$	$\sigma_{\ln Y}^2/2$
Parameter	**Inhalation Risk$_i$**	**Uncertainty**							
Volatile Organic Compounds									
1,1-Dichloroethene	1.2575E-05	1.7806	3.0632E-05	4.6293E-09	4.9335	1.7806	1.3344	-10.3935	0.8903
Trichloroethene	2.0709E-07	2.8713	8.7026E-07	1.2617E-11	16.6598	2.8713	1.6945	-13.9545	1.4356
Benzene	4.6814E-07	2.0939	1.3337E-06	1.2658E-11	7.1163	2.0939	1.4470	-13.5276	1.0469
Chloroform	1.0484E-06	1.9220	2.7409E-06	4.3834E-11	5.8349	1.9220	1.3864	-12.8072	0.9610
1,2-Dichloroethane	6.2076E-07	1.5618	1.3554E-06	6.9210E-12	3.7674	1.5618	1.2497	-13.5114	0.7809
Carbon Tetrachloride	1.7712E-06	2.8324	7.2999E-06	8.5188E-10	15.9863	2.8324	1.6830	-11.8277	1.4162
Dibromochloromethane	0.0000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1,1,2,2-Tetrachlorethane	2.8618E-06	1.9971	7.7678E-06	3.8420E-10	6.3674	1.9971	1.4132	-11.7655	0.9985
Vinyl Chloride	3.7735E-06	1.9016	9.7650E-06	5.4319E-10	5.6966	1.9016	1.3790	-11.5367	0.9508
1,4-Dichlorobenzene	0.0000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Chloroethane	0.0000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Inorganic Carcinogens									
Beryllium	0.0000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Values	**ΣRg_i**		**$¥ = \Sigma R_{¥}$**	$\sigma_Y^2 = \Sigma\sigma_{Yi}^2$					
Cumulative Totals	2.3326E-05		6.1765E-05	6.4846E-09					
		Total							**Total**
TOTAL RISK CALCULATIONS		$\Sigma ¥ =$	6.18E-05 +	1.85E-06 +	5.04E-05 =	1.1402E-04			$\Sigma\sigma_Y^2 =$

Table 4.3-5
Calculations for Total Probabilistic Risk

$E(\ln Y)=\mathrm{Ln}(¥) - \sigma_{\ln Y}^2/2$	$E(\ln Y) - 2\sigma_{\ln Y}$	$E(\ln Y) + 2\sigma_{\ln Y}$	Lower Bound	Mean (¥)	Upper Bound		R_{gi}	σ_i^2	$R_i = R_{gi}\,(e^{(\sigma_i^2/2)})$	$\sigma_{Yi}^2 = R_i^2(e^{(\sigma_i)^2}-1)$
			Inhalation Risk	**Inhalation Risk**	**Inhalation Risk**		**Dermal Risk$_i$**	**Uncertainty**		
-11.2838	-13.9526	-8.6150	8.72E-07	3.06E-05	1.81E-04		1.0288E-07	2.1519	3.0171E-07	6.9189E-13
-15.3901	-18.7791	-12.0011	6.99E-09	8.70E-07	6.14E-06		8.8168E-09	3.2425	4.4608E-08	4.8949E-14
-14.5745	-17.4685	-11.6805	2.59E-08	1.33E-06	8.46E-06		7.6595E-09	2.4651	2.6272E-08	7.4302E-15
-13.7683	-16.5410	-10.9955	6.55E-08	2.74E-06	1.68E-05		1.0418E-09	2.2933	3.2790E-09	9.5774E-17
-14.2923	-16.7918	-11.7929	5.10E-08	1.36E-06	7.56E-06		3.9684E-09	1.9330	1.0432E-08	6.4324E-16
-13.2439	-16.6098	-9.8779	6.12E-08	7.30E-06	5.13E-05		1.5047E-07	3.2037	7.4667E-07	1.3170E-11
N/A	N/A	N/A	N/A	N/A	N/A		6.5935E-10	1.7712	1.5985E-09	1.2463E-17
-12.7641	-15.5904	-9.9377	1.70E-07	7.77E-06	4.83E-05		7.7221E-08	2.3683	2.5235E-07	6.1639E-13
-12.4875	-15.2455	-9.7295	2.39E-07	9.76E-06	5.95E-05		1.2661E-07	2.2728	3.9446E-07	1.3548E-12
N/A	N/A	N/A	N/A	N/A	N/A		1.9017E-08	2.4651	6.5227E-08	4.5800E-14
N/A	N/A	N/A	N/A	N/A	N/A		4.6694E-11	1.7712	1.1320E-10	6.2506E-20
N/A	N/A	N/A	N/A	N/A	N/A		0.0000	N/A	N/A	N/A
							ΣRg_i		$¥ = \Sigma R_i$	$\sigma_Y^2 = \Sigma\sigma_{Yi}^2$
			1.49E-06	***6.18E-05***	*3.79E-04*		4.9839E-07		1.8467E-06	1.5936E-11
							Total			**Total**
6.48E-09 +	1.59E-11 +	3.93E-09 =	1.0431E-08				$\Sigma\sigma_Y^2/\Sigma ¥^2 =$	0.8024		$\sigma_{\ln Y}^2 =$

Table 4.3-5
Calculations for Total Probabilistic Risk

$\sigma_Y^2/\bar{Y}^2$	$\sigma_{\ln Y}^2 = \ln(1+(\sigma_Y^2/\bar{Y}^2))$	$\sigma_{\ln Y}$	$\ln(\bar{Y})$	$\sigma_{\ln Y}^2/2$	$E(\ln Y) = \ln(\bar{Y}) - \sigma_{\ln Y}^2/2$	$E(\ln Y) - 2\sigma_{\ln Y}$	$E(\ln Y) + 2\sigma_{\ln Y}$	Lower Bound	Mean ($\bar{Y}$)	Upper Bound	
								Dermal Risk	Dermal Risk	Dermal Risk	
7.6009	2.1519	1.4669	-15.0138	1.0759	-16.0897	-19.0236	-13.1559	5.47E-09	3.02E-07	1.93E-06	
24.5986	3.2425	1.8007	-16.9253	1.6213	-18.5466	-22.1480	-14.9452	2.41E-10	4.46E-08	3.23E-07	
10.7649	2.4651	1.5701	-17.4548	1.2326	-18.6873	-21.8275	-15.5472	3.31E-10	2.63E-08	1.77E-07	
8.9075	2.2933	1.5144	-19.5357	1.1466	-20.6824	-23.7111	-17.6536	5.04E-11	3.28E-09	2.15E-08	
5.9105	1.9330	1.3903	-18.3784	0.9665	-19.3449	-22.1256	-16.5642	2.46E-10	1.04E-08	6.40E-08	
23.6224	3.2037	1.7899	-14.1076	1.6018	-15.7095	-19.2892	-12.1297	4.20E-09	7.47E-07	5.40E-06	
4.8776	1.7712	1.3308	-20.2542	0.8856	-21.1398	-23.8015	-18.4781	4.60E-11	1.60E-09	9.44E-09	
9.6793	2.3683	1.5389	-15.1924	1.1842	-16.3766	-19.4545	-13.2987	3.56E-09	2.52E-07	1.68E-06	
8.7070	2.2728	1.5076	-14.7457	1.1364	-15.8822	-18.8974	-12.8670	6.21E-09	3.94E-07	2.58E-06	
10.7649	2.4651	1.5701	-16.5454	1.2326	-17.7780	-20.9181	-14.6378	8.23E-10	6.52E-08	4.39E-07	
4.8776	1.7712	1.3308	-22.9018	0.8856	-23.7874	-26.4491	-21.1257	3.26E-12	1.13E-10	6.69E-10	
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
								2.12E-08	***1.85E-06***	*1.26E-05*	
		Total	**Total**	**Total**	**Total**	**Total**	**Total**	**Total**	**Total**	**Total**	
		$\sigma_{\ln Y}$	$\ln(\bar{Y})$	$\sigma_{\ln Y}^2/2$	$E(\ln Y) = \ln(\bar{Y}) - \sigma_{\ln Y}^2/2$	$E(\ln Y) - 2\sigma_{\ln Y}$	$E(\ln Y) + 2\sigma_{\ln Y}$	Lower Bound	Mean ($\bar{Y}$)	Upper Bound	
0.5891		0.7675	-9.0792	0.2946	-9.3737	-10.9088	-7.8386	***1.83E-05***	***1.14E-04***	***3.94E-04***	

Table 4.3-5
Calculations for Total Probabilistic Risk

R_{gi}	σ_i^2	$R_i = R_{gi}(e^{(\sigma_i^2/2)})$	$\sigma_{Yi}^2 = R_i^2(e^{(\sigma_i)^2}-1)$	σ_Y^2/¥^{2}	σ_{lnY}^2	σ_{lnY}	Ln(¥)	$\sigma_{lnY}^2/2$	E(lnY)	E(lnY) - $2\sigma_{lnY}$	E(lnY) + $2\sigma_{lnY}$
Ingestion Risk$_i$	**Uncertainty**										
1.6767E-06	1.7806	4.0843E-06	8.2299E-11	4.9335	1.7806	1.3344	-12.4084	0.8903	-13.2987	-15.9675	-10.6299
1.0124E-07	2.8713	4.2546E-07	3.0157E-12	16.6598	2.8713	1.6945	-14.6701	1.4356	-16.1057	-19.4947	-12.7168
1.2484E-07	2.0939	3.5565E-07	9.0013E-13	7.1163	2.0939	1.4470	-14.8493	1.0469	-15.8963	-18.7903	-13.0022
2.1054E-08	1.9220	5.5043E-08	1.7678E-14	5.8349	1.9220	1.3864	-16.7152	0.9610	-17.6762	-20.4489	-14.9034
1.6554E-07	1.5618	3.6144E-07	4.9216E-13	3.7674	1.5618	1.2497	-14.8332	0.7809	-15.6141	-18.1135	-13.1146
1.1585E-06	2.8324	4.7747E-06	3.6446E-10	15.9863	2.8324	1.6830	-12.2522	1.4162	-13.6684	-17.0343	-10.3024
6.8336E-08	1.3999	1.3760E-07	5.7842E-14	3.0548	1.3999	1.1832	-15.7989	0.7000	-16.4988	-18.8652	-14.1325
7.6315E-07	1.9971	2.0714E-06	2.7321E-11	6.3674	1.9971	1.4132	-13.0873	0.9985	-14.0858	-16.9122	-11.2595
6.3730E-06	1.9016	1.6492E-05	1.5494E-09	5.6966	1.9016	1.3790	-11.0126	0.9508	-11.9634	-14.7214	-9.2055
1.0331E-07	2.0939	2.9433E-07	6.1649E-13	7.1163	2.0939	1.4470	-15.0386	1.0469	-16.0855	-18.9795	-13.1915
2.3592E-09	1.3999	4.7506E-09	6.8942E-17	3.0548	1.3999	1.1832	-19.1650	0.7000	-19.8649	-22.2313	-17.4986
9.3865E-06	1.6435	2.1349E-05	1.9020E-09	4.1731	1.6435	1.2820	-10.7545	0.8217	-11.5762	-14.1402	-9.0123
ΣRg_i		¥ $=\Sigma R_i$	$\sigma_Y^2 = \Sigma\sigma_{Yi}^2$								
1.9945E-05		5.0406E-05	3.9305E-09								

Table 4.3-5
Calculations for Total Probabilistic Risk

	Lower Bound	Mean (¥)	Upper Bound
	Ingestion Risk	Ingestion Risk	Ingestion Risk
	1.16E-07	4.08E-06	2.42E-05
	3.42E-09	4.25E-07	3.00E-06
	6.91E-09	3.56E-07	2.26E-06
	1.32E-09	5.50E-08	3.37E-07
	1.36E-08	3.61E-07	2.02E-06
	4.00E-08	4.77E-06	3.36E-05
	6.41E-09	1.38E-07	7.28E-07
	4.52E-08	2.07E-06	1.29E-05
	4.04E-07	1.65E-05	1.00E-04
	5.72E-09	2.94E-07	1.87E-06
	2.21E-10	4.75E-09	2.51E-08
	7.23E-07	2.13E-05	1.22E-04
	1.37E-06	***5.04E-05***	*3.03E-04*

Table 4.3-5
Calculations for Total Probabilistic Risk

Parameter	Maximum	Minimum	Ln Max.	Ln Min.	Std Dev (σ)	σ^2	Ln Xg	Xg
Concentration								
1,1-Dichloroethene	5.90	0.5	1.7750	-0.6931	0.6170	0.3807	0.5409	1.7176
Trichloroethene	64.00	0.5	4.1589	-0.6931	1.2130	1.4714	1.7329	5.6569
Benzene	14.00	0.5	2.6391	-0.6931	0.8331	0.6940	0.9730	2.6458
Chloroform	9.00	0.5	2.1972	-0.6931	0.7226	0.5221	0.7520	2.1213
1,2-Dichloroethane	2.50	0.5	0.9163	-0.6931	0.4024	0.1619	0.1116	1.1180
Carbon Tetrachloride	60.00	0.5	4.0943	-0.6931	1.1969	1.4325	1.7006	5.4772
Dibromochloromethane	0.50	0.5	-0.6931	-0.6931	0.0000	0.0000	-0.6931	0.5000
1,1,2,2-Tetrachlorethane	11.00	0.5	2.3979	-0.6931	0.7728	0.5972	0.8524	2.3452
Vinyl Chloride	8.50	0.5	2.1401	-0.6931	0.7083	0.5017	0.7235	2.0616
1,4-Dichlorobenzene	14.00	0.5	2.6391	-0.6931	0.8331	0.6940	0.9730	2.6458
Chloroethane	0.50	0.5	-0.6931	-0.6931	0.0000	0.0000	-0.6931	0.5000
Beryllium	3.60	0.5	1.2809	-0.6931	0.4935	0.2436	0.2939	1.3416
Ingestion Exposure Frequency	1.00E+00	6.67E-01	0.0000	-0.4055	0.1014	0.0103	-0.2027	0.8165
Body Weight	63.60	30.40	4.1526	3.4144	0.1845	0.0341	3.7835	43.9709
Exposure Duration	15,840.00	7,920.00	9.6703	8.9771	0.1733	0.0300	9.3237	11,200.57
Dermal Exposure Frequency	4.17E-02	3.47E-03	-3.1780	-5.6630	0.6212	0.3859	-4.4205	0.0120
Surface Area/Weight	449.342	225.472	6.1078	5.4182	0.1724	0.0297	5.7630	318.2987

Table 4.3-6
95% Confidence Intervals

Parameter	Maximum	Minimum	Ln Max.	Ln Min.	Std Dev (σ)	σ^2	Ln Xg	Xg
Dermal & Ingestion (CSFs)								
1,1-Dichloroethene	0.6000	0.0060	-0.5108	-5.1160	1.1513	1.3255	-2.8134	6.00E-02
Trichloroethene	0.0110	0.0001	-4.5099	-9.1150	1.1513	1.3255	-6.8124	1.10E-03
Benzene	0.0290	0.0003	-3.5405	-8.1456	1.1513	1.3255	-5.8430	2.90E-03
Chloroform	0.0061	0.0001	-5.0995	-9.7046	1.1513	1.3255	-7.4021	6.10E-04
1,2-Dichloroethane	0.0910	0.0009	-2.3969	-7.0021	1.1513	1.3255	-4.6995	9.10E-03
Carbon Tetrachloride	0.1300	0.0013	-2.0402	-6.6454	1.1513	1.3255	-4.3428	1.30E-02
Dibromochloromethane	0.0840	0.0008	-2.4769	-7.0821	1.1513	1.3255	-4.7795	8.40E-03
1,1,2,2-Tetrachlorethane	0.2000	0.0020	-1.6094	-6.2146	1.1513	1.3255	-3.9120	2.00E-02
Vinyl Chloride	1.9000	0.0190	0.6419	-3.9633	1.1513	1.3255	-1.6607	1.90E-01
1,4-Dichlorobenzene	0.0240	0.0002	-3.7297	-8.3349	1.1513	1.3255	-6.0323	2.40E-03
Chloroethane	0.0029	0.0000	-5.8430	-10.4482	1.1513	1.3255	-8.1456	2.90E-04
Beryllium	4.3000	0.0430	1.4586	-3.1466	1.1513	1.3255	-0.8440	4.30E-01

Parameter	Maximum	Minimum	Ln Max.	Ln Min.	Std Dev (σ)	σ^2	Ln Xg	Xg
Inhalation Cancer Slope Factors (CSFs)								
1,1-Dichloroethene	1.2000	0.0120	0.1823	-4.4228	1.1513	1.3255	-2.1203	1.20E-01
Trichloroethene	0.0060	0.0001	-5.1160	-9.7212	1.1513	1.3255	-7.4186	6.00E-04
Benzene	0.0290	0.0003	-3.5405	-8.1456	1.1513	1.3255	-5.8430	2.90E-03
Chloroform	0.0810	0.0008	-2.5133	-7.1185	1.1513	1.3255	-4.8159	8.10E-03
1,2-Dichloroethane	0.0910	0.0009	-2.3969	-7.0021	1.1513	1.3255	-4.6995	9.10E-03
Carbon Tetrachloride	0.0530	0.0005	-2.9375	-7.5426	1.1513	1.3255	-5.2400	5.30E-03
Dibromochloromethane	0.0000	0.0000	N/A	N/A	N/A	N/A	N/A	N/A
1,1,2,2-Tetrachlorethane	0.2000	0.0020	-1.6094	-6.2146	1.1513	1.3255	-3.9120	2.00E-02
Vinyl Chloride	0.3000	0.0030	-1.2040	-5.8091	1.1513	1.3255	-3.5066	3.00E-02
1,4-Dichlorobenzene	0.0000	0.0000	N/A	N/A	N/A	N/A	N/A	N/A
Chloroethane	0.0000	0.0000	N/A	N/A	N/A	N/A	N/A	N/A
Beryllium	8.4000	0.0840	2.1282	-2.4769	1.1513	1.3255	-0.1744	8.40E-01

Table 4.3-7
CSF 95% Confidence Range: (CSF/1 to CSF/100)

5.0 CONCLUSIONS

Ultimately, the Environmental Protection Agency (EPA) is approximating probability distribution functions (PDFs) with delta functions (*i.e.* gaussian distributions with variances equal to zero) located at means of their choice and based upon their policies. These delta functions are otherwise referred to as point estimates. The probabilistic model expands the EPA's zero-order model to a first-order model which represents the uncertainties in the input parameters by using lognormal distributions. The total risk is the product and quotient of several lognormal independent random variables and, as a result, the PDF for risk is generally a skewed PDF.

The risk spreadsheets presented as Tables 3.3-1 to 3.3-5 and 4.3-1 to 4.3-7, and Figure 4.3-1, illustrate that the EPA's point estimate model results are not significantly different from the probabilistic risk model results, in terms of risk magnitude. The mean risk predicted by the EPA model and the mean risk predicted by the probabilistic model are approximately 1.51E-04 and 1.14E-04, respectively.

The probabilistic model is not a comprehensive statistical model of the risk, but it is a relatively simple and transparent method for working with potentially hidden information and, in this case, for examining uncertainty. In consideration of the statistical variance, otherwise termed uncertainty, associated with the EPA's cancer slope factors (CSFs), it is concluded that the certainty of the risk is predominantly, *if not almost entirely*, dominated by the certainty of the CSFs.

The total potential risk to human health from the Massachusetts Military Reservation's (MMR's) advancing landfill plume (LF-1) cannot be accurately quantified unless all potential effects including, but not limited to, shellfish ingestion, synergistic chemical effects and groundwater transport phenomenon, are taken into account along with overall uncertainty. Shellfish ingestion and chemical synergy could potentially increase overall risk. However, groundwater transport modeling indicates that plume migration by the groundwater pathway (unless LF-1 is captured by the town wells) could potentially reduce risk.

Although this thesis research has solely applied the probabilistic model to the inspection of potential cancer effects of the chemicals listed in the spreadsheets by direct exposure, the finding that the EPA mean risk model is similar to a probabilistic risk model should not radically alter. This is on account of the fact that the EPA requires all risk calculations to use EPA mandated toxicological input parameters.

This thesis contends that the calculations in Tables 4.3-1 through 4.3-7 support the argument that a conservative estimate of the annual increase in relative cancer risk (not accounting for any potential shellfish risk) is approximately 1E-04, if the LF-1 continues to migrate to Buzzards Bay without further treatment. In addition, the uncertainty of an estimate of approximately 1E-04 is predominantly attributable to CSF variance. Furthermore, because the EPA toxicological input parameters are conservatively extrapolated to zero, this thesis supports the opinion that the estimated annual cancer risk of 1E-04 is a maximum conservative value for the MMR's LF-1.

Based on the analysis carried out in this thesis, the extent to which the LF-1 will present any adverse health risks is uncertain. Thus it is recommended that a monitoring program for both the drinking water supply and the shellfish supplies which are located near the potential zone of influence of LF-1 be implemented to quantify further potential adverse health risks. The EPA's recently proposed changes, published in the Federal Register, to adjust cancer slope factors and reference doses to more accurately approximate their statistical influence upon human health are a good start in the right direction.

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