TECHNICAL UNCERTAINTIES IN AQUIFER RESTORATION, IMPLICATIONS FOR REMEDIAL SYSTEMS DESIGN, AND SUPERFUND POLICY IMPLEMENTATION

by

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ABSTRACT

The present study analyzes technical aspects of the remediation of contaminated groundwater, and describes the implications that these aspects have in the design of extraction systems, and the effects they have had in remediation policy making and implementation.

A case study is presented in which the analysis of pumping schemes for the extraction of the CS-4 plume, at Cape Cod, Massachusetts is performed. Currently, the plume is being contained by a 13-well fence. However, a new plume, termed FS-28 has been recently found, underneath CS-4. This represents an example of the different types of uncertainties encountered in the remediation of groundwater.

A three-dimensional, finite-element groundwater model is constructed to analyze the 13-well system performance. Results indicate that the current well fence is performing as designed, and it is robust and flexible. A seven well fence will be an effective alternative scheme to capture the CS-4 plume. However, in order to capture the recently discovered FS-28 plume, major modifications would be necessary.

General scientific and technical factors determining the remediation of groundwater are described. The relationship with the social components of the Superfund program is discussed, and a policy review is performed. Results indicate that the technical impracticability of the remediation of groundwater at many sites have determined policy actions. These actions are mainly related to the evaluation of risk, the management of risk, and the need to incorporate public input in the remediation process.

Thesis Supervisor: Professor David H. Marks

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I must thank my thesis advisor, Professor David Marks for his help and guidance. Thank you Dave for all your support in many things that I will not itemize because the list would be too long to fit in this page.

I should emphasize that a considerable portion of the engineering sections of this thesis was developed as part of a much larger project, while I was completing the Master of Engineering program. This thesis could never have been completed without the assisstance of my M.Eng. thesis advisor, Professor Lynn Gelhar, and my modeling partner Alberto Lázaro. I am also grateful to Bruce Jacobs for lending his expertise in groundwater modeling, and to Professor Nicholas Ashford from which I learned to intensely enjoy the study of the law and economics behind environmental issues.

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List of Tables

List of Figures

1. INTRODUCTION

1.1 Problem Definition

The Comprehensive Environmental Response Compensation and Liability Act (CERCLA) of 1980, commonly referred as Superfund, has the main purpose of responding to releases of hazardous substances into the environment. The act was substantially amended in 1986 in the Superfund Amendments and Reauthorization Act (SARA), and amended again in 1990, and 1994. The Superfund act, as amended, mandates the Environmental Protection Agency (EPA) to take actions in order to protect public health and welfare and the environment.

The ways in which the EPA has approached the remediation process have changed since the superfund act was passed. During the first years of superfund, the agency showed a tendency to select and implement interim remedial actions based on containment technologies, instead of permanent and definitive remedial actions. This policy was intensely evaluated, studied and questioned by other agencies in the federal government, academics, consulting firms, and citizen groups. As a result of the evaluation of the remedy selection in the first five years of superfund, SARA established the federal policy for the remedy selection process, clearly stating that EPA should give preference to permanent on-site treatment technologies directed to reduce the volume, mobility or toxicity of contaminants.

EPA has tried to align its policy to the statutory directive of promoting permanent cleanups with significant and relevant remedial action decisions. The agency has been very active in the evaluation of the remedial processes at superfund sites. It also has developed new strategies, such as the Superfund Accelerated Cleanup Model, and administrative reforms. Examples of these reforms are the Risk-Sharing initiative, the establishment of a National Remedy Review Board, the updating of remedy decisions at selected sites, and the emission of fact sheets describing “rules of thumb” for remedy selection.

However, the remediation of a contaminated site is not only a matter of policy. The cleanup process of superfund sites, and in particular the remediation of contaminated groundwater, is a very complex technical work. Scientific and technical uncertainties are present that may affect in a great extent the remediation process. In some cases, the remediation of groundwater is technically impracticable, and permanent remediation is not feasible. For this reason, it is very important that strategies, administrative reforms and proposed new policies, focus on risk reduction combined with technical feasibility, and consider technical uncertainties as a central factor involved in the remediation of Superfund sites.

In the Massachusetts Military Reservation (MMR) at Cape Cod, Massachusetts, past releases of contaminants resulted in extensive groundwater contamination. Compounds such as perchloroethylene (PCE), trichloroethylene (TCE), and 1,2-dichloroethylene (DCE) can be found in the different groundwater plumes. Both, carcinogenic and non-carcinogenic health effects are associated with these and other chemicals encountered in the contaminated groundwater underlying western Cape Cod. The MMR was listed in the National Priority List in 1989, becoming a superfund site (E.C. Jordan, 1990).

One of the plumes of contaminants, termed Chemical Spill 4 (CS-4), has currently an interim remedial system (containment system) consisting of a pump and treat scheme, operating at the downgradient edge. The system was designed to extract contaminated water at the toe of the plume, treat it to reduce contaminant concentrations to federal Maximum Contaminant Levels (MCL's) and then return it to the aquifer.

The containment system was designed according to the results of a groundwater flow model of the area, and multiple pumping scheme simulations (E. C. Jordan, 1990). Models are a powerful engineering tool for this kind of designs, the most powerful tool when designing containment based on hydraulic control. The system was designed and constructed with state-of-the-art technology, based on the scientific and technical knowledge available at the time. However, contaminant hydrogeology and remediation technology development are still subject to intense research, since the principles behind the fate and transport of contaminants in the subsurface are still not fully understood. This implies that scientific and technical uncertainties are present in the process of remediation of an aquifer. These uncertainties can produce both, negative and positive unpredicted results during groundwater remediation processes.

A public water supply well for the town of Falmouth is located downgradient of the well fence. In 1996, the Ethylene dibromide (EDB) was detected in the water extracted with this well, and consequently, the well stopped supplying water for the town. As a result, the design, installation and effectiveness of the CS-4 pump and treat system were reviewed. Results indicated that even though the system is installed and performing as designed, it was not possible to determine if the plume was completely contained by the system (IRP, 1996).

The consequences of detecting a contaminant in a monitoring well downgradient from the well fence were many. First, the expansion of the monitoring work to detect the edge of the plume implied increase of costs and public concern. The plume reaching this well caused additional strain on the town's water supply. However, modification of the current system with potential extra costs, and the failure to accomplish the main purpose of the superfund cleanup -reduce the risk to human health and the environment-, could be the principal consequences of the containment system failure.

An intense fieldwork was done to determine the origin of the EDB, and as a result of this new site characterization, a new plume was found. This plume, named FS-28, moves in the same direction of the CS-4 plume, underneath it.

Based on the new information obtained in the field, the current system can be tested to determine the necessity of major changes in it, for the complete containment of the CS-4 plume, and the feasibility of using this same system to capture the newly defined FS-28 plume.

1.2 Objectives

The objective of this work is to analyze the importance of technical uncertainties in the remediation of groundwater at Superfund sites, and the implications they have in the design of remediation systems, and the design and implementation of remediation policies.

Complete comprehension of the natural flow and transport conditions of water and contaminants in the Cape Cod aquifer is the first task. Using hydrologic, geologic and hydrogeologic information of the area, a computer model was established that adequately represents the existing conditions. The model developed was used to analyze the geometry of the capture zones resulting from different pumping scenarios and:

1. Predict an effective pumping scheme for the extraction of the contaminated water, and
2. Analyze the flexibility of the existing well fence, in terms of the way it can be used to respond to different field conditions.

Sources of potential problems in the case of technology failure, are the central point of the cleanup policy review. This review focuses on the cleanup strategy currently followed by EPA, and the way in which it has evolved through the years. The policy review attempts to determine whether the scientific and technical uncertainties, present at any remediation process, have shaped the Superfund remediation policy and its implementation.

1.3 Scope

This study covers the technical aspects of the current situation of the Area of Contamination (AOC) CS-4 at the MMR, and describes effective and robust pump and treat schemes, based on a groundwater model. It also describes the policy and legal framework in which this hazardous waste site remediation is being performed.

The technical sections of this thesis (i.e. the groundwater modeling sections, and the analysis of pumping schemes) were performed as part of a project course in the Master of Engineering program at the Civil and Environmental Engineering Department at MIT. More detailed aspects of the groundwater model and the analysis of the interim remedial action can be found in López-Calva (1996).

It is important to define the type of technical uncertainties that this study considers. This thesis focuses on the remediation aspects of Superfund. The site assessment is out of the scope of this study, and therefore, the scientific uncertainties related to toxicology are not reviewed. The determination of risk is of course central in the Superfund law, and the question how clean is clean is extensively discussed in this thesis. However it is always studied from the point of view of the extent of the remediation. In other words, this study reviews the Superfund program, once it has been decided that a site needs to be remediated.

Uncertainties related to the issue of "waste-in" (i.e. determining the quantities and origin of contaminants, allocating them to particular Potentially Responsible Parties), have also very important effects in transaction costs and complicate settlements. However, these uncertainties are not under the scope of this study.

This work is centered in technical issues and discusses administrative factors only in relation to the technical ones. It is very important to mention that administration of Superfund has been subject to intense debate, and is an issue in which millions of dollars are involved. This study does not ignore the importance of the administrative issues, but does not address them as central objects of study.

The policy review section of this study does not attempt to quantify the importance of the technical factors in policy making, as compared to factors of other nature. The policy analysis is qualitative and pretends to exhibit the effect that the technology side of the Superfund problem has in the social side. This is important, since for some critics of the program, the technical factors are negligible, or not considered, which represents a clear weakness of their analysis.

Another important distinction that needs to be made is that this study focuses on the remediation of groundwater and not soil. The engineering systems to remediate soil and groundwater might be similar in some cases, but there are important differences in the fate and transport of pollutants, as well as in the engineering approach that needs to be taken for remediation.

Finally, this study, in its policy review section, does not attempt to explain what many authors call the "Superfund failure". The study does not present major recommendations for the improvement of the program, either. The only purpose of the analysis is to present evidence of the importance of the technical side of the Superfund program, and to analyze the way in which technical difficulties and uncertainties have motivated and affected political decisions. The case study shows how the remediation of a site may result much more complicated than expected.

Summary

Chapter 2 establishes the political and legal framework of the site remediation. It presents a review of the origin and main objectives of the Superfund law, and briefly introduces the key operational aspects and the central issues of the program.

Chapter 3 describes the site. General geographical background information is provided as well as the history of the activities at MMR. These data are needed to understand the extent of the groundwater contamination.

Section 3.2 covers the site characterization. The presented physical properties of the site are based on the review of reports of previous studies at the area as part of the Installation Restoration Program, and on studies of the site not necessarily related to the contamination problem. This site characterization is needed to develop the conceptual model, assign hydrogeologic properties to the area of the aquifer modeled, and help in the model calibration.

The current situation at the CS-4 site is presented in Section 3.3, including an overview of the plume extent and a description of the existing interim remedial action. A brief review of the newly defined FS-28 plume is also presented.

In Chapter 4, the basis of groundwater modeling is presented. Section 4.1 presents the problem definition of this part of the study, corresponding to the pumping schemes analysis.

In order to develop any groundwater model, a conceptual model is needed. The conceptual model for this study is described in Section 4.2. The approach is discussed and the set of assumptions presented. Delimitation of the modeled area, discretization and hydraulic boundaries are described. Based on the conceptual model, a methodology was designed and followed to assign aquifer properties, calibrate the model, and simulate pumping schemes. This methods are described in detail in Section 4.3. This description is indispensable to fully understand the results from the model and their meaning. In particular, Section 4.3.2, which describes the methods followed for pumping schemes simulations, is important to interpret the results appropriately.

Chapter 5 presents the pumping schemes analysis. General observations are presented about the different geometry of the capture zones, according to different pumping scenarios. This previous analysis is needed as a basis to discuss the flexibility of the well fence, which is important due to the technical uncertainties, and the different ways to obtain effective capture zones. Results of the various simulations are presented and discussed.

Chapter 6 presents a discussion of the main technical aspects controling the remediation of contaminated groundwater. Basic principles of the fate and transport of pollutants in the subsurface are presented, and aspects of the geologic framework in which the water and pollutants move are also shown. In this chapter, a few typical cases of Superfund sites in which technical uncertainties have proved to be important are discussed. The main sources of inaccuracy in the design of the CS-4 remediation system are also described.

Chapter 7 focuses in the specific aspects of the cleanup policy related to technical uncertainties in groundwater remediation. The method followed in the policy review is presented first. The analytic framework is briefly discussed, and the Superfund remedial program explained. The major issues related to technical aspects are described, and the documents from EPA and Congress addressing those issues are identified.

Chapter 8 presents the analysis of the reaction of policy makers and the EPA to the identified issues. Policy decisions are associated with the technical factors and the relationship discussed.

Chapter 9 presents conclusions about the pumping schemes analysis, and the review of the EPA strategies and directives. These conclusions are drawn from the findings of the previous chapters.

1.4 Major Findings

The present study was composed of a technical analysis of a Superfund site, and a policy analysis of the Superfund remedial program, the later motivated by the findings of the technical study. The principal research questions, and the main findings are presented below.

CS-4 Case Study:

The basic questions were: what is an effective pumping scheme to capture the CS-4 plume?, and 2) is the current scheme robust, and flexible enough to respond to the newly found conditions in the field?

The corresponding conclusions were:

The current well fence is performing as designed, and it is robust and flexible. Even a smaller system of seven wells would be an effective scheme to capture the CS-4 plume. However, in order to capture the newly discover FS-28 plume, major modifications would be necessary.

Policy Review:

The research questions were: Have the scientific and technical uncertainties in groundwater remediation determined major policy decisions? Have they shaped the way in which remediation policy is implemented?

And the corresponding conclusions were:

Technical factors influence cleanup costs and time, and define the feasibility or unfeasibility of completely remediating a site. When unfeasibility is a reality, like in the case of groundwater contaminated with DNAPLs, the question of how clean is clean arises, public participation becomes crucial, and the statutory mandate for permanence in cleanup becomes unattainable. Also, in such cases, the need for the development of innovative technologies turns an evident necessity.

Congress policy making process, and EPA's policy implementation have reacted to technical factors such as the unfeasibility of remediating a site, by implementing flexible approaches to evaluate risk and protect communities. The public has been recognized as a key player in cases in which permanent cleanups are not possible, and strategies have been designed accordingly to incorporate the affected communities into the Superfund process.

2. THE POLITICAL AND LEGAL FRAMEWORK: SUPERFUND

CERCLA is the environmental statute which primary purpose is the cleanup of hazardous wastes sites. The statute was substantially amended in 1986 by SARA, and amended again in 1990, and 1994. The term "Superfund" is commonly used to describe these laws, as well as the cleanup program they mandate.

2.1 Hazardous Waste and Superfund Background

The first two primary pieces of legislation regarding toxic substances and hazardous waste were passed in 1976. The Resource Conservation and Recovery Act (RCRA), and the Toxic Substances Control Act (TSCA) address aspects of hazardous waste management. RCRA establishes a significant federal role in the management of hazardous waste. Its primary goal is to control toxic substances when they become a waste (i.e. at the end of the production-consumption process). The primary goal of TSCA is to protect public health and the environment from the risk associated with the production and use of toxic chemical substances (i.e. at the first phases of the production-consumption process). It also refers to the improper disposal of this type of substances.

TSCA imposes requirements on the manufacturers and processors of chemical substances. The most important requirements are the development of data necessary to determine the effect of the substances in the human health and the environment, and the thorough review of chemicals prior to manufacture.

RCRA is the statute that establishes the definition of a hazardous waste, as a sub-category of solid wastes [1]. Under RCRA, section 1004, the term "hazardous waste" means:

> [...] a solid waste or combination of solid wastes, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may:
> (A) cause or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or
> (B) pose a substantial present or potential hazard to human health or the environment, when improperly treated, stored, transported, or disposed of, or otherwise managed (West, 1996).

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[1] It is important to mention that liquids, semi-solids, contained gas and solids can be considered solid waste under the RCRA Section 1004.

The EPA further developed a more specific definition of hazardous waste. Under EPA regulations, a solid waste can be considered hazardous if:

a) The waste is declared hazardous by the generator based on its knowledge of the waste.
b) The waste is specifically listed under EPA regulations.
c) The waste is tested and meets one of the following characteristics: ignitable, corrosive, reactive, toxic.

A very important and well known feature of RCRA is the fact that it establishes responsibilities for the generators of hazardous waste from "cradle to grave". This approach has great implications for liability. Under this concept, generators of hazardous wastes can be held liable, even if they contracted with a third party for their final disposal.

The Hazardous and Solid Waste Amendments of 1984 substantially amended RCRA and gave the EPA the authority to require cleanup of contaminants in soil and groundwater, and more stringent enforcement provisions. This amendments and the RCRA corrective action program of 1988 are important precedents of Superfund, since they require an analysis similar to that conducted at a Superfund site, whenever contamination was suspected (La Grega, et. al. 1994).

RCRA was directed to establish an extensive regulatory program to control current hazardous waste disposal practices (i.e. newly generated hazardous wastes). However, this statute, and the regulations derived from it, did nothing to address the existence of hazardous waste sites resulting from past disposal practices. This was a problem not yet fully recognized, and therefore, a loophole in the nations' regulation of hazardous waste was still open.

The existence of numerous unsound hazardous wastes sites, and its recognition as a major public health problem became a reality in 1978 due to the Love Canal toxic waste scandal, in Niagara Falls, New York[2]. This episode, considered a landmark in

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[2] Love Canal was first used as a hazardous waste disposal site by a chemical company, to be later covered and sold to the School District. An elementary school and many houses were built in the area. Many chemically induced problems were experienced by people, until measures were taken after chemical analysis showed the presence of various chemical substances, including dioxin. A more extensive description can be found in Barnett (1994).

environmental history, was a pivotal event preparing Congress and society to pass the Superfund law.

2.2 What is Superfund?

As mentioned above, Superfund is the term used to describe the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) of 1980, its 1986 amendments (SARA), its 1990 and 1994 amendments, and the cleanup program they mandate.

The origin of this term is the fund that was created in 1980 to take remedial actions at hazardous waste contaminated sites. CERCLA created a five-year, $1.6 billion fund to implement a massive program to handle emergencies at uncontrolled sites, and to clean up the sites, in order to protect public health and welfare and the environment. The fund derived primarily from the chemical and petroleum industry, that were required to pay $1.38 billion into the fund (Barnett, 1994).

The statute was strongly supported by public opinion and many members of Congress that perceived the magnitude of the hazardous waste threat to be extremely large (Barnett, 1994). However, Superfund was controversial and complex. These two factors added to unrealistic expectations about the success of the program, resulted in a slow implementation and poor results in the first five years. This in time resulted in the reauthorization of the program in 1986, to support it in a climate of debate and controversy.

SARA is a very detailed statute, and it is basically a complete rewrite of CERCLA. The statute establishes an $8.5 billion fund for hazardous waste site clean up, derived from a petroleum tax, a chemical feedstock tax, a corporate environment tax, and general revenues (Barnett, 1994). This statute limits EPA discretion, being more specific about schedules, criteria for remedy selection, standards, and settlement policy directives, among other things. However, SARA expands EPA powers, responsibilities and funding.

The Superfund Process

The remediation of a hazardous waste site under the Superfund process consists of a series of phases in which both, technical (scientific and engineering), and non technical (litigation, public participation, etc.) activities are involved. Figure 2.1 presents the different phases of the process.

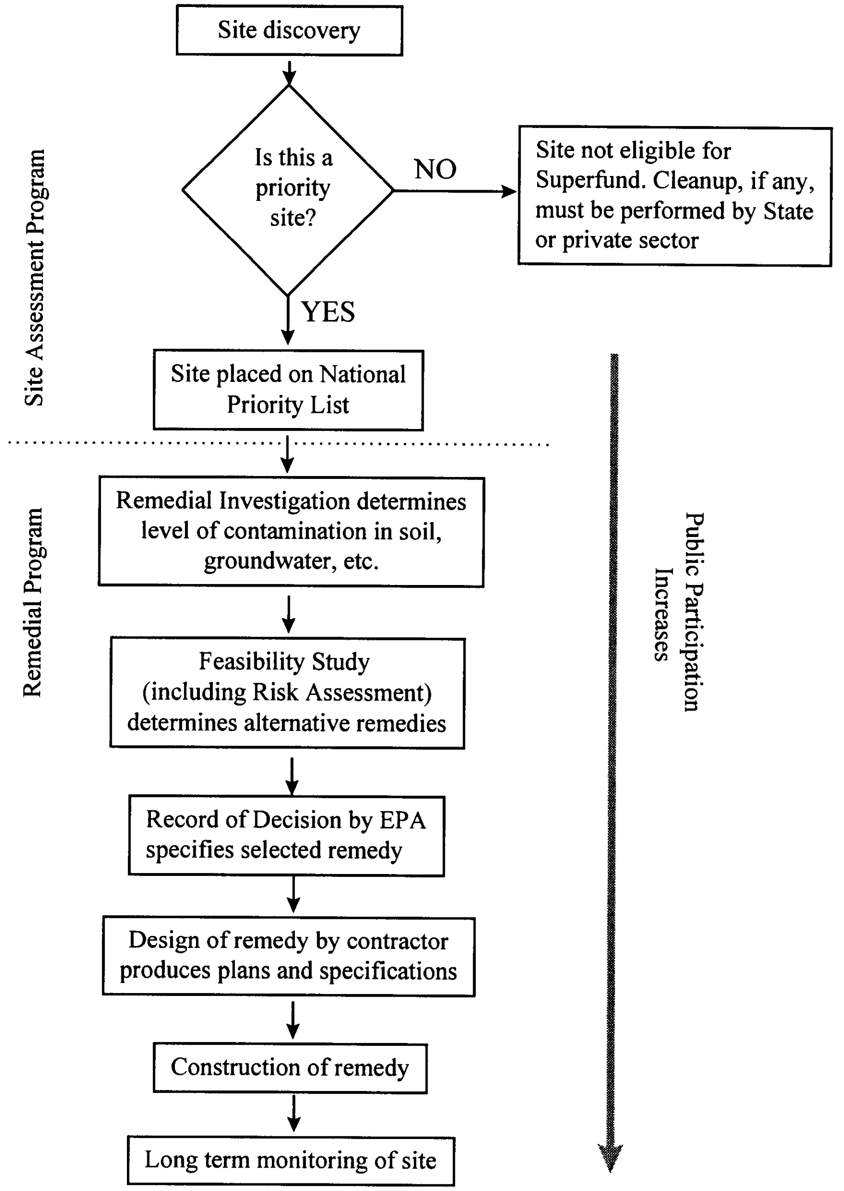

Figure 2-1. The Superfund process

The main two phases of the remediation process are the site assessment program and the remedial program. In the site assessment program, when a site is discovered, a site study is performed, in which the Hazard Ranking System, method developed by the EPA, is used to evaluate the degree of risk that the site poses to human health and the environment. If the Hazard Ranking System score given to a site exceeds a specified threshold value, the site is placed in the National Priority List (NPL), which makes it eligible to Superfund resources.

The remedial program is applied to sites listed on the NPL, and starts with a remedial investigation in which the level of contamination in soil, surface and groundwater, and air is determined. A feasibility study is then performed, in which different remediation alternatives are evaluated under the following criteria (Thompson, 1994):

1) Human health protection
2) Short-term effectiveness
3) Long-term effectiveness
4) Compliance with cleanup standards
5) Implementability
6) Reduction in toxicity, mobility, and volume
7) Cost-effectiveness
8) State concurrence
9) Public (local) acceptance

A public meeting is usually held at this time, before a Record of Decision (ROD) is published by the EPA specifying a specific remedy and summarizing the basis for choosing it, the overall site conditions, and the different alternatives considered.

The selected remedy is designed under the Remedial Design phase (RD), and implemented in the Remedial Action phase (RA), in which monitoring is an essential part. A short-term removal action or an interim remedial action (IRM) may be undertaken at any point on this sequence of remedial steps. IRM are usually implemented when it is necessary to contain migration of contaminants to avoid exposure to a significant health or environmental hazard.

Superfund is one of the most complex and controversial environmental programs ever implemented in United States. The program has had a great impact in different sectors of society, and has been analyzed from many different points of view, by governmental agencies, Congress, academics, industry, and consulting firms. It has also been subject to intense debates within the communities affected by cleanups. Some of the most important issues, such as the liability scheme, the transaction costs, the cleanup costs, cleanup time, and the best way to define risk and set cleanup goals accordingly, will be discussed in Chapter 7 and 8 of this study.

3. SITE DESCRIPTION

3.1 General Description

3.1.1 Location

Cape Cod is located in the southeastern most point of the Commonwealth of Massachusetts (Fig. 3.1). It is surrounded by Cape Cod Bay on the north, Buzzards Bay on the west, Nantucket Sound to the south, and the Atlantic Ocean to the east. Cape Cod, a peninsula, is separated from the rest of Massachusetts by the man-made Cape Cod Canal.

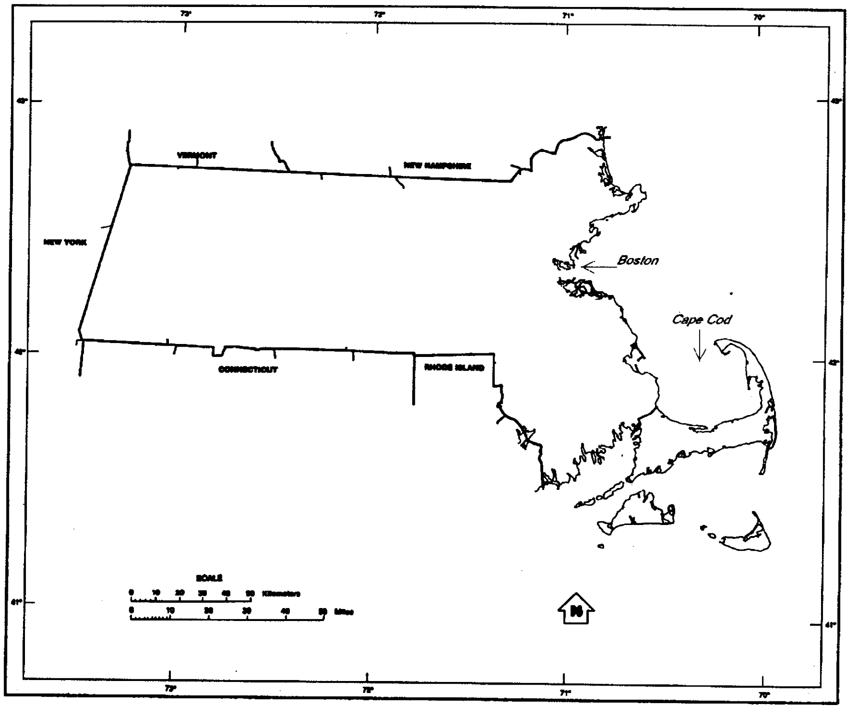

Figure 3-1. Map of the Commonwealth of Massachusetts

The Massachusetts Military Reservation (MMR is situated in the northern part of western Cape Cod (Fig. 3.2). The MMR, previously known as the Otis Air Force Base, occupies an area of approximately 22,000 acres (30 square miles).

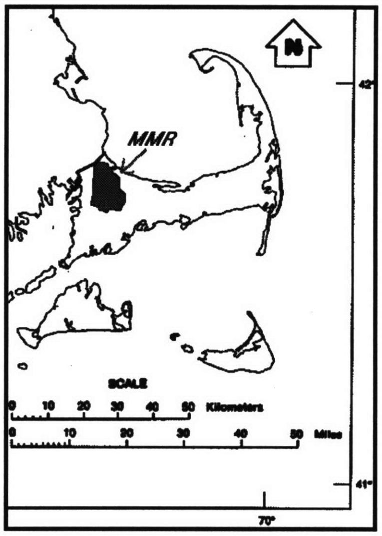

Figure 3-2. Location of MMR

3.1.2 Geopolitics and Demographics

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

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

3.1.3 Natural Resources

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

3.1.4 Land and Water Use

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

Water covers over 4% of the surface area of Cape Cod. This water is distributed among wetlands, kettle hole ponds, cranberry bogs, and rivers. Nevertheless, all 15 communities meet their public supply needs with groundwater. The township of Falmouth is the only municipality that uses some surface water (from the Long Pond Reservoir) as a drinking water source

Water demand in the Cape follows the same seasonal variations as population. Water work agencies are called to supply twice as much water during the summer months (June through August) than during the off-season (September through May). The highest monthly average daily demand (ADD) in 1990 was in July when 34.98 mgd were used. The lowest monthly ADD was in February with 14.03 mgd (Cape Cod Commission, 1996). The towns of Falmouth and Yarmouth have the highest demand for water, with a combined percentage of almost 30% of the Cape's total water demand (Massachusetts Executive Office of Environmental Affairs, 1994).

Agriculture also constitutes a part of the water use in Cape Cod. Cranberry cultivation is an important part of the economy of the Cape and a water intensive activity.

The fishing industry also provides a boost to the Cape's economy. Tourism accounts for a substantial part of the Cape's economy and therefore surface water quality is important for recreational purposes such as boating, swimming, and fishing.

3.1.5 MMR Setting and History

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

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

3.2 Site Geology and Hydrogeology

3.2.1 Geology

The geology of western Cape Cod is composed predominantly by glacial sediments deposited during the Wisconsin Period (7,000 to 85,000 years ago) (E.C. Jordan, 1989b). The three predominant geologic formations of the western Cape are: the

Sandwich Moraine (SM), the Buzzards Bay Moraine (BBM), and the Mashpee Pitted Plain (MPP). The two moraines were deposited by the glacier along the northern and western edges of western Cape Cod. Between the two moraines lies a broad outwash plain, known as MPP, which is composed of well sorted, fine to coarse-grained sands. At the base of unconsolidated sediments (below the MPP), fine grained, glaciolacustrine sediment and basal till are present.

Both the outwash and moraines have relatively uniform characteristics at the regional scale, even though they contain some local variability. The sediments are stratified and thus the hydraulic conductivities are anisotropic. The MPP is more permeable and has a more uniform grain size distribution than the moraines.

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

3.2.2 Hydrology

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

Beneath western Cape Cod lies a single groundwater system (from the Cape Cod Canal to Barnstable and Hyannis) which the U.S. Environmental Protection Agency (EPA) has designated it as a sole source aquifer. This aquifer is unconfined and its only form of natural recharge is by infiltration from precipitation. The highest point of the water table (the top of the groundwater mound) is located beneath the northern portion of the MMR. In general, groundwater flows radially outward from this mound and ultimately discharges to the ocean.

Kettle hole ponds, depressions of the land surface below the water table, are common on the MPP. These ponds influence the groundwater flow on a regional scale. Streams, wetlands and cranberry bogs serve as drainage to some of these ponds and as discharge to the groundwater, and thus comprise the rest of the hydrology of the western cape. Figure 3.3 shows some hydrologic features of western Cape Cod.

3.2.3 Hydrogeology

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

Hydraulic Conductivity

Throughout the western Cape, there appears to be a general trend of decreasing conductivity from north to south and from the surface to the bedrock. The conductivity of the western cape has been studied extensively. Table 3.1 shows a summary of the hydraulic conductivity values reported in the literature. Geologic variability within the outwash suggests that some variability in hydraulic conductivity is likely. Nonetheless, the maximum and minimum values reported are probably biased by the analytical method or exhibit a small-scale geologic heterogeneity. An value of 380 ft/d (obtained from the Ashumet Valley pump tests and corroborated by the tracer test south of the MMR) has been accepted as a representative value of average hydraulic conductivity of the MPP outwash sands (E.C. Jordan, 1989a).

Table 3.1. Estimates of hydraulic conductivity of stratified drift, as determined from analysis of aquifer tests, Cape Cod Basin, Massachusetts. (Adapted from Masterson and Barlow, 1994).

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

Anisotropy Ratio

The ratio of horizontal to vertical hydraulic conductivities (K_h/K_v) has been studied along with some of the hydraulic conductivity tests. Values of anisotropy ratio for different studies are reported in Table 3.1. Typical anisotropy values range from 10:1 to 3:1.

Porosity

Measured values of porosity range from 0.20 to 0.42. Effective porosity of the outwash is estimated from a tracer test (Garabedian et al., 1988; LeBlanc et al., 1991) to be about 0.39.

Hydraulic Gradient

The hydraulic gradient will be affected by the variations in water table elevations. These typically fluctuate about 1 m because of seasonal variations in precipitation and recharge. During the period of a tracer test (22 months), the hydraulic gradient in the study area (Ashumet Valley) varied in magnitude from 0.0014 to 0.0020. Vertical hydraulic gradients measured during this test were negligible except near the ponds (LeBlanc et al., 1991).

Chemistry of the Water

The properties of the chemicals of particular interest for natural attenuation of contaminant plumes (natural bioremediation) are shown Table 3.2 (E.C. Jordan, 1990). The dissolved oxygen values vary with depth. The values reported are for the depths of interest (depth < 100 ft below water table). The concentration of metals is also of particular interest since high concentrations can have a detrimental/toxic effect to microbial growth. The concentration of metals tested for at CS-4 , however, are negligible.

Table 3.2. Groundwater properties

Property	Value
Dissolved oxygen (mg/L)	5.0-10.0
Nitrate (mg/L)	0-1.8
pH	5-7
Temperature	10° C

Equilibrium Sorption

Sorption of contaminants by aquifer solid matrices significantly effects their fate and transport. The bioavailability of contaminants can be reduced considerably because of sorptive uptake. Also, pump and treat times can be prolonged substantially because of a continuous feeding of contaminants to the aquifer by the sorbed species. Another effect of sorption is to alter the dispersive behavior of contaminants. While sorption acts to reduce the hydrodynamic dispersion of any one contaminant, it acts to enhance its longitudinal macrodispersivity.

One way to quantify all of these effects is to use equilibrium sorption distribution coefficients to calculated retardation factors. Laboratory batch tests are setup to determine distribution coefficients. The depth-averaged retardation factors calculated for the contaminants of interest are listed in Table 3.3 (Khachikian, 1996).

Table 3.3. Effective retardation factors

Compound	R_{eff}
DCE	1.04
TCE	1.10
PCE	1.25

3.3 Current Situation

3.3.1 Interim Remedial Action and Objectives for Final Remedy

The existing remedial action was designed as an interim system, with the objective of contain the CS-4 plume against further migration. This is achieved by placing pumping wells at the plume toe and treating the extracted water (see Figure 3.3).

In contrast, the final remedial action will address the overall, long-term objectives for the CS-4 Groundwater Operable Unit which are as follows (ABB Environmental Services, 1992b):

- Reduce the potential risk associated with ingestion of contaminated groundwater to acceptable levels.
- Protect uncontaminated groundwater and surface water for future use by minimizing the migration of contaminants.
- Reduce the time required for aquifer restoration.

In terms of treatment objectives, the target levels for the treatment of the water are defined through the established MCLs. These apply to the contaminants of concern and are summarized in Table 3.4. Maximum measured concentrations, average concentrations within the plume, and an approximate frequency of detection are also given. It is important to realize that these values represent only an approximation, since their determination depends on a definition of the plume borders.

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

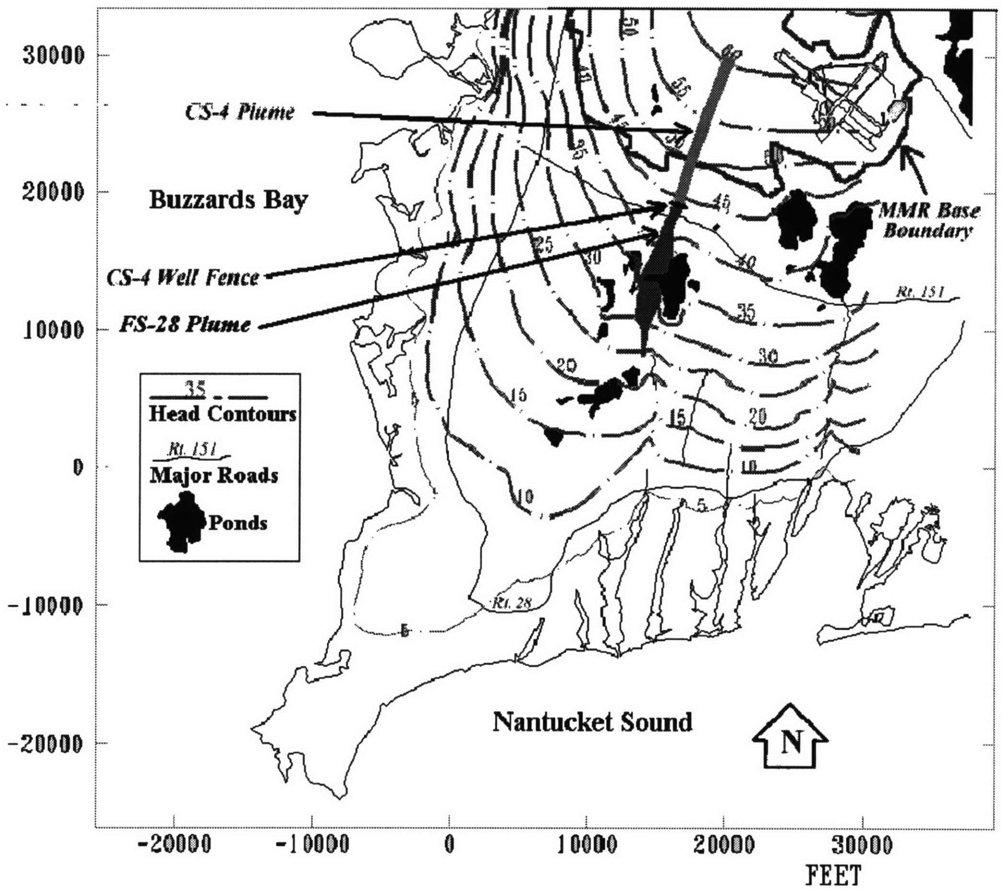

Figure 3-3. CS-4 plume and well-fence location

3.3.2 Existing Remedial Action

The currently operating remediation system consists of the following components:

- Extraction of the contaminated groundwater at the leading edge of the plume by 13 adjacent extraction wells.
- Transport of the extracted water to the treatment facility near the southern boundary of the MMR.
- Treatment of the water with a Granular Activated Carbon (GAC) system.
- Discharge of the treated water back into the aquifer to an infiltration gallery next to the treatment facility.

Table 3.4. Contaminants of concern and treatment target level (Adapted from ABB Environmental Services, 1992b)

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

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

The IRP well fence consist of 13 wells located at the toe of the plume, about 1000 ft north of Route 151. The wells are 60 feet apart, in a straight line (see Figure 3.4), covering a total distance of 720 ft. The well number 11 in the well fence, is not within the straight line defined by the rest of the wells, but located about 20 ft to the north of the line. Each well has a 15 feet screen, 8 inches in diameter. The bottom of the screen is located at a depth of 140 ft. The overall pumping rate is 140 gpm. The wells located at the sides pump 15 gpm and the 11 wells in the middle pump 10 gpm. The water pumped to the treatment facility, treated with GAC, and discharged in an area near the treatment facility.

The treatment facility consists of two adsorber vessel in series filled with granular activated carbon. This system of two downflow, fixed-bed adsorbers in series is the simplest and most widely utilized design for groundwater treatment applications (Stenzel and Merz, 1989). Two vessels in series assures that the carbon in the first vessel is completely exhausted before it is replaced, thus contributing to the overall carbon efficiency. The removed carbon is then transported off-site for reactivation.

3.3.3 Plume Location

CS-4 plume is located in the southern part of MMR moving southward (see Figure 3.3 and 4.1). From field observations, the dimensions of the plume have been defined. According to E. C. Jordan (1990), CS-4 is 11,000 ft long, 800 ft wide and 50 ft thick.

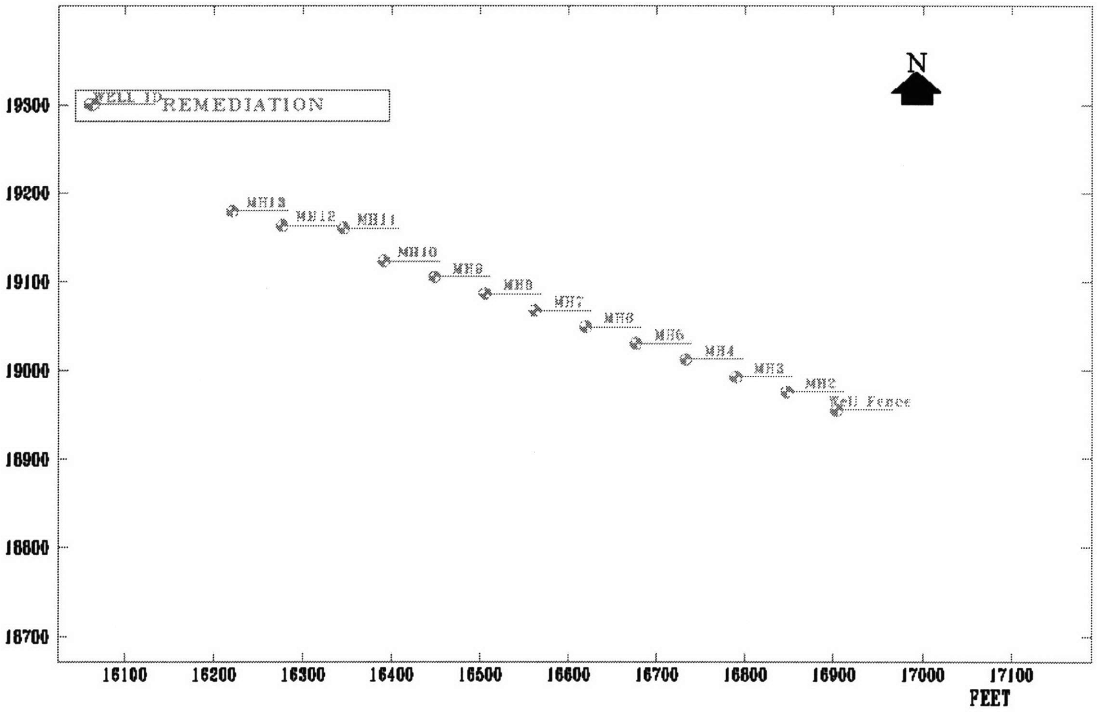

Figure 3-4. Well fence currently in operation at the downgradient edge of the CS-4 plume

3.3.4 Other Technologies Considered

Looking at the technologies that were considered for an interim remedial technology gives a broader understanding of the reason for selecting the current pump and treat system. Of the 13 remedial technologies screened in the Feasibility Study (E.C. Jordan, 1990), five were selected and retained for detailed analysis. For further evaluation, they were compared against the following nine criteria:

- overall protection of human health and the environment
- compliance with ARARs (Applicable or Relevant and Appropriate Requirement)

- long-term effectiveness and permanence
- reduction of mobility, toxicity or volume through treatment
- short-term effectiveness
- implementability
- cost
- state acceptance
- community acceptance

The no action alternative served as a baseline for comparing various strategies (ABB Environmental Services, 1992a; E.C. Jordan, 1990). The selected carbon adsorption technology was evaluated against the following alternatives:

- air stripping followed by activated carbon
- UV oxidation
- spray aeration
- Otis Wastewater Treatment Plant

3.3.5 Performance of Current Remediation Scheme

Since the treatment facility started operating in November 1993, only minimal inflow concentrations (Tillman, 1996) have been detected and treated.

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

In conclusion, the interim CS-4 pump and treat system seems to be an appropriate way to quickly respond to the plume migration. However, in 1996, Ethylene dibromide was detected in the water extracted with this well, and consequently, the well stopped supplying water for the town. As a result, the design, installation and effectiveness of the CS-4 pump and treat system were reviewed. Results indicated that even though the system is installed and performing as designed, it was not possible to determine if the plume was completely contained by the system (IRP, 1996).

An intense fieldwork was done to determine the origin of the EDB, and as a result of this new site characterization, a new plume was defined. This plume, named FS-28, moves in the same direction of the CS-4 plume, underneath it (ABB environmental, 1996. See Figure 3.3).

A more detailed hydraulic performance evaluation test was performed in 1996 (Camp Dresser & McKee, 1997) and preliminary results indicate that the system captures most of the VOC plume "window" that was defined during the feasibility study and design phases. Therefore, the system appears to be working with near-total effectiveness, as designed.

4. GROUNDWATER MODELING

Groundwater flow and contaminant transport modeling can be used to conceptualize and study flow processes, recognize limitations on data, guide collection of new data, design remedial strategies and assist in problem evaluation. Therefore, groundwater modeling is a very important engineering tool to remediate a contaminated aquifer. This chapter describes the basis of the groundwater three-dimensional computer model used to analyze pump and treat system, as part of the technology side of this study.

4.1 Introduction

As mentioned in the previous section, the current remedial system, seems to be appropriate to contain the plume from further migration. Hoffman (1993), refers to pump and treat as the only groundwater cleanup technology that has successfully begun effective remediation of deep widespread groundwater contamination. However, this author also mentions that pump and treat has the disadvantages of being expensive to design, install and operate. Many other authors support this fact but also mention that pump and treat is the most efficient way to prevent contaminated groundwater migration, by providing the required hydraulic control (Hoffman, 1993; Ahlfeld and Sawyer, 1990; Gailey and Gorelik, 1993; Isherwood et al., 1993).

Due to this particular characteristics of pump and treat, it is still widely used but, at the same time, there is a great necessity of more carefully designed and operated systems that consider technical uncertainties and difficulties as a reality in the field, in order to minimize costs. Since pump and treat, as mentioned by Hoffman (1993), in all known cases must be maintained and operated for several years (decades), operation and maintenance cost are one of the most important factors to consider when designing a remedial system. Nyer (1994), mentions that in very long remedial projects, the savings in capital cost, may become insignificant in view of the overall cost of the remedial program. For these reasons, prediction of an alternative capture curve, based in fewer wells or lower pumping rate (aggregated) is one of the objectives of these work.

Cost-effectiveness involves, of course, the pumping schemes and the treatment technologies, as well as monitoring costs. This chapter, and the next one are focused only on the technical aspects of pumping schemes. The different non-technical factors (cost, state and community acceptance), although implicit and important, are mentioned but not emphasized.

Different considerations are needed in the design of pumping schemes for the extraction of contaminated water. The first consideration is related to the main objective: to reduce concentrations of contaminants to an acceptable level (cleanup), or to protect the subsurface from further contamination (containment). Regardless of the main objective, general system components, according to Mercer and Skipp (1990), are:

- A set of goals or objectives
- Engineered components such as wells, pumps and treatment facility
- Operational rules and monitoring
- Termination criteria

Technical considerations are of course very important. Hydraulic conductivity, aquifer heterogeneity, sorption of the contaminants, immobile nonaqueous phase liquids, and many other factors are very important to consider in the pumping system design (Mercer and Skipp 1990).

The design of capture curves for contaminants can be made in a number of ways. Different approaches can be found in the literature. Analytical, semianalytical and numerical flow models are used with or without a particle tracking program to delineate the capture zones of wells. To define zones of hydraulic control and find proper well locations, simulation and optimization techniques have been used by several authors (Gorelick et al., 1993; Gailey and Gorelick, 1993; Ahlfeld and Sawyer, 1990). Groundwater velocity analysis (Heidari et al., 1987), three-dimensional simulations combined with mixed-integer programming (Sawyer et al., 1995), and analytical solutions (Javandel and Tsang, 1987; Yang et al., 1995) have also been developed, to define capture curves and well locations. However, the "industry standard" can be considered the use of three-dimensional numerical models (finite difference or finite element), such as the one used for this study, and the one used to design the well fence currently operating at CS-4.

In this study, a three-dimensional finite-element numerical model, coupled with particle tracking is used to define the capture curves. The opportunity to evaluate a large number of alternatives combining different factors is one of the greatest advantages of the use of a three-dimensional numerical model to help in the design of remedial or containment systems. Some other advantages of this method over the analytical models discussed by Springer and Bair (1993) and Bair and Road (1993), are the ability to account for complicated hydrogeologic settings and nonuniform characteristics, avoiding the conceptual errors due to assumptions common in analytical models.

Flexibility of the existing well fence

The remediation of a site is an active and continuous process. Monitoring contaminant concentrations and head values to determine hydraulic control, using monitoring wells is important in the remedial process. Some details in the remediation schemes can be modified according to monitoring results. In addition, evaluation of the performance of the extraction systems can be very important while remediating a site (Hoffman, 1993).

CS-4 plume is very particular in shape, as can be seen in Figure 3.3 since it is about 11,000 ft long and only 800 ft wide. This means that transverse dispersivity for this plume is extremely low, as explained below. Lázaro (1996), simulates the natural transport of this plume using a value of transverse dispersivity of 0.05 ft, and finds that, after traveling for thirty years and reaching the length of 11,000 ft, the plume would be wider than the plume reported by E. C. Jordan (1990), depicted in Figure 3.3. The value of 0.05 ft for transverse dispersivity used by Lázaro (1996) is among the lowest values presented by Gelhar et al. (1992), in a review of field-scale dispersion in aquifers. This author and Van der Kamp et al. (1994) explain how transverse dispersivity is caused primarily by the temporal variation in hydraulic gradient.

Therefore, the explanation for a plume as narrow as CS-4 would be the existence of an extremely steady flow with minimum variations in the direction of hydraulic gradient, causing almost non transverse dispersivity. However, another reason could be simply that the plume has not been precisely characterized. It is possible in many cases, that the definition of the dimensions of a plume change as we improve site characterization, which reflects the importance of the uncertainties and the need for flexible remedial designs, to the extent possible. For all these reasons one of the purposes of this study is to analyze the flexibility of the current pumping system, and the way it could be modified in response to a wider or deeper plume.

4.2 Conceptual model

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

1) DYNPLOT, which processes all input files (files containing information required to run simulations), and output files (files that can be plotted, presenting the results from simulations).

2) DYNFLOW, which processes all the input files to run flow simulations.

3) DYNTRACK , which uses input files containing information about solutes to simulate transport.

DYNFLOW solves the three-dimensional groundwater flow equation (Freeze and Cherry, 1979):

$$S_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)$$

where S_S is the specific storage coefficient, h is hydraulic head, and K_X, K_y and K_Z are the values of hydraulic conductivity in three dimensions.

4.2.1 Approach

In order to accurately simulate the flow and transport under natural conditions, and qualify the effectiveness of a remedial system, the regional controlling factors must be incorporated into the modeling analysis. Considering the objectives of the project, the model is constructed in an area much greater than the area where CS-4 plume is located. A grid is built with a systematic and well structured refinement. The triangular elements defined by nodes are smaller in the areas of interest to meet numerical constraints and ensure accuracy. In addition, the requirements for vertical discretization are different for stress conditions (pumping) and non-stress conditions (natural flow). Vertical refinement of the grid is used after the model is calibrated, to run capture curve simulations. To run the pump-test simulation, a further modification to increase resolution is done using a regional to local interpolation into a much more discretized grid.

The model is developed according to some assumptions. Steady state conditions were assumed. Recharge due to precipitation is assumed to be uniform throughout the modeled area. Discharge from the aquifer is assumed to be due to natural downgradient flow (into the ocean), discharge into streams, and extraction from pumping wells.

4.2.2 Geometric boundaries

The model includes an area of approximately 51.5 mi^2 on the western Cape (southern part of the western Cape) sowed in Figure 4.1. The horizontal boundaries are defined by two non-flow boundaries and the ocean. The no-flow boundaries (flow lines) are defined by lines perpendicular to the head contours described by Savoie (1995).

The southern end of the model is Nantucket Sound, and Buzzards Bay is at the western end. The eastern boundary is a flow line directed towards Ashumet and Johns Ponds and down along the Childs River to salt water. The western shoreline of these two ponds delimit the modeled area, but the actual body of water is not included in the model. The northern boundary is another flow line originating at the same point of the eastern boundary (the upper-most point in the water table), and extending westward to Buzzards Bay (Figure 4.1).

The thickness of the modeled region is non-uniform, defined by the topographic characteristics of the Cape. As the aquifer is unconfined, the upper limit is the ground surface and the lower limit is the bedrock underlying the Cape Cod Area (Oldale, 1969).

4.2.3 Hydraulic Boundaries

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

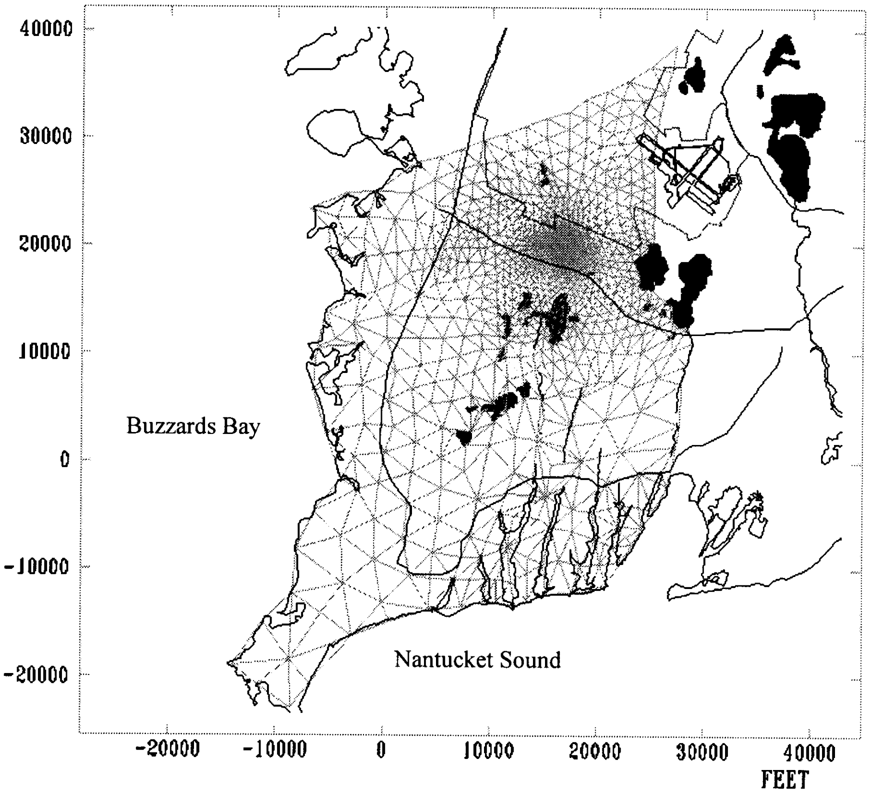

Figure 4-1. Horizontal discretization for the groundwater flow model. The grid includes more than 50 mi^2, divided into 2114 elements. Vertically, the grid is divided in 9 levels. Vertical discretization was increased to 15 levels for pumping simulations

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

The water table is represented by a special type of boundary condition, called rising water boundary condition. This same boundary condition is used at the surface of the ponds and rivers. A node with the rising water condition will have a value of head equal to or less than the elevation of the node.

4.2.4 Discretization

The grid contains 1194 nodes and 2314 elements, distributed horizontally. The vertical discretization consists of 9 levels, dividing the area into 8 different layers. Finer discretization is employed in the area of rapidly changing gradients due to pumping. This grid is used in the simulation of natural flow and transport. For the simulations of the different pumping schemes, however, the grid is modified to analyze hydraulic control due to pumping. Vertical resolution is increased up to 15 levels to better define the three dimensional capture curves (Figure 4.1).

A local grid is constructed from interpolation of the regional grid to run a simulation of the pumping test carried out in the area in April of 1993, by ABB Environmental, Inc. (E. C. Jordan, 1990). This small local grid consists of 2090 elements defined by 1070 nodes, using 15 levels as the vertical discretization. This grid covers an area of about 1,540,000 ft^2.

4.3 METHODS

4.3.1 Natural Flow Model

Aquifer Properties Assignment

The area modeled is divided in two main lithologic entities: the glacial moraine, and the Mashpee Outwash. The Buzzards Bay Moraine is assumed to be composed of four different materials distributed vertically. The area of the outwash forming part of the model is divided into a northern and a southern areas in the horizontal, and in three different materials in the vertical direction, as indicated in Figure 4.2. Within these different facies, different materials are assigned according to the depositional model described by Masterson and Barlow (1994).

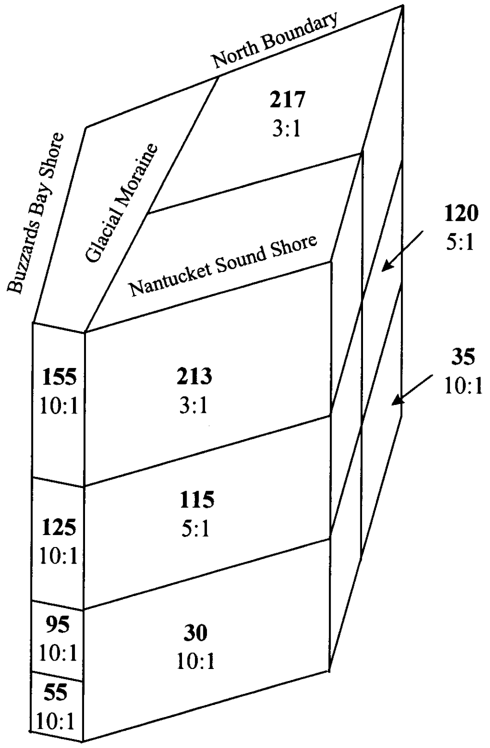

Figure 4-2. Conceptual distribution of horizontal hydraulic conductivity and anisotropy ratio in the western Cape Cod model

a) Hydraulic conductivity

Assignment of hydraulic conductivity is made following the approach of Masterson and Barlow (1994). This authors group the sediments in lithostratigraphic units according to their depositional origin. As described in Section 3.2.1, within the Mashpee Outwash, sediments are coarse in the upper layers and fine in the lower layers. There is also a fining southward tendency. Hydraulic data from different studies in the area (Table 2.1) is used by these authors to determine approximate ranges of hydraulic conductivity for the lithostratigraphic units, based on the relation between lithology and hydraulic conductivity. Table 4.1 summarizes the distribution of the lithostratigraphic units, their lithology and hydraulic characteristics.

Table 4.1. Relation of lithology to hydraulic properties in western Cape Cod

Depositional Origin	Lithostratigraphic unit	Lithology	Horizontal Hydraulic Conductivity (ft/day)	K_h / K_v
Glaciofluvial	Top-set beds			
	Proximal	Coarse sand and gravel	350	3:1
	Mid	Medium sand and gravel	290	3:1
	Distal	Fine sand and gravel	240	3:1
Glaciolacustrine	Fore-set beds			
(nearshore)	Proximal	Medium to coarse sand	280	3:1
	Mid	Fine to medium sand	200	5:1
	Distal	Fine sand	150	10:1
Glaciolacustrine	Bottom-set beds			
(offshore)	Proximal	Fine sand	150	10:1
	Mid	Fine sand and some silt	70	30:1
	Distal	Fine sand and silt	30	100:1
Glacial	Moraine	Sand, silt and clay; unsorted	30-150	10:1

Proximal: Sediments close to the moraines
Mid: Sediments in the central parts of the western Cape
Distal: Sediments away from the moraines

The values of hydraulic conductivity for fine sand and silt, fine sand, fine-medium sand, and medium-coarse sand and gravel (which are the four main materials found in the Mashpee Pitted Plain) shown in Table 4.1 were used as a basis to create the input files of the model.

Anisotropy ratios are also defined, initially, based on the information presented by these authors. As in the case of horizontal hydraulic conductivity, anisotropy ratio is assigned to a particular type of sediment, which is then assumed to be homogeneously distributed along a well defined area in the Cape. The anisotropy ratio is an important calibration parameter for the transport model. Its value, initially based only on a literature review, is slightly modified according to the pumping test simulations and the transport model results presented by Lázaro (1996). Initial anisotropy ratio values used in this model range from 3:1(coarse sands) to 30:1 (glacial moraine).

b) Recharge

Precipitation is the only source of fresh water to the Cape Cod groundwater-flow system. Actual recharge to the groundwater system is less, since some of the water either evaporates or is transpired by plants. LeBlanc et al. (1986) and Barlow and Hess (1993), estimate that 45 to 48 per cent of the total precipitation, about 18 to 23 in/yr, recharges the aquifer. The value used in the flow model is 23 in/yr. During the flow calibration procedure, recharge is not treated as a calibration parameter and is maintained constant.

c) Hydraulic head

Initial values of hydraulic head are obtained from Savoie (1993). Water level data from more than 100 wells, distributed throughout the western Cape were measured in a period of two days. This data is the most representative head data available. Of the total number of well observations reported by this author, 106 wells were used to create the input file of the model. Data from a few wells located within the ponds or very close to them are discarded, since information about screen elevation is not available. These areas near the ponds are under vertical flow conditions and thus head is not constant with depth. Thus, specific screen elevation data is necessary to determine the actual head at that point. The vertical gradient is assumed to be negligible for the rest of the cape (predominantly horizontal flow was assumed). In order to assign a head value to each node in the grid, interpolation of the values is made using the capabilities of the code. This way a initial water table surface is obtained for the entire modeled area. Calibration, however is made with the original discrete points as targets, hence avoiding the possible interpolation bias.

d) Aquifer thickness

The lower limit of the modeled aquifer is considered the bedrock underlying Cape Cod. A thin layer of lacustrine sediments is present overlying bedrock. However, this material is not considered since its thickness becomes appreciable only in marginal portions of our modeled area. A topographic map of the basement surface (bedrock), is presented by Oldale (1969). From the seismic investigations made by this author, elevation contours of the bedrock were digitized and then interpolated to get the surface of the lower limit of the model.

e) Dispersivity

Garabedian et al. (1988) calculated dispersivities using the data obtained during the Ashumet Valley tracer test. The method of moments was used to interpret the data; which was regarded by Gelhar et al. (1992) as having a high degree of reliability. Values of dispersivity are summarized in Table 4.2 below.

Table 4.2. Dispersivity values of the Ashumet Valley Tracer Test (*Garabedian et al.*, 1988)

Dispersivity	Value
Longitudinal (A_L)	3.15 ft
Transverse, horizontal (A_T)	0.59 ft
Transverse, vertical (A_V)	0.005 ft

It must be noted that the values obtained by Garabedian et al. (1988) are for a source with dimensions of 16.4 x 16.4 x 3.3 ft and an overall test scale of 820 ft. In the case of the CS-4 site, the dimensions of the source (about 1050 x 450 x 50 ft) and the test scale (about 11,000 ft) are larger. Rajaram and Gelhar (1995) conclude that dispersivities for transport over large scales are significantly influenced by the source dimensions. Using their methods, the longitudinal dispersivity (A_L) is estimated to be 65.5 ft. Transverse dispersivities are left unchanged, since their variability due to source scale is minimal.

f) Other Parameters

Porosity value of 0.39 was obtained from Garabedian et al., (1988) and LeBlanc et al., (1991), as part of the site characterization (Section 3.2.3).

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

Calibration

For the calibration procedure, the main parameters consider were hydraulic conductivity, recharge, and types of boundary conditions. Anisotropy ratio, was not changed since the natural flow in the area is predominantly horizontal, and porosity was maintained constant, since this property is related only to transport phenomena.

Sensitivity analysis to recharge, boundary conditions and hydraulic conductivity were performed, as a first step. From the results of the sensitivity analyses, a single parameter was selected as a variable.

For the first simulations, the head contours reported by Savoie (1995) were used as targets to make rough adjustments to the model. Head contours are much easier to visualize than discrete points and overall trends can be quickly analyzed. However, for the most part of the calibration, discrete points were used as targets, to avoid the possible bias of the interpolation from which head contours are obtained.

The reduction of error (calculated minus observed head) was focused on the CS-4 area, analyzing results from each simulation and reviewing particularly those points clearly questionable. The thorough review of node elevations and heads for the nodes representing surface water bodies was a standard procedure for the calibration. Verification of the heads in nodes with "invoked rising water" was also a standard step after each model run, since this "invoked rising water" means that the head at those nodes has been fixed by the program as a result of the flux calculations.

The criteria for deciding complete calibration was to have a mean error less than half a foot, with all error differences of less than one foot within the CS-4 area. Results of the calibration are presented in Appendix A.

4.3.2 Pumping Schemes Simulations

Aquifer test simulation

An aquifer test in the CS-4 area was carried out by E. C. Jordan and its results are reported in the feasibility study report (E. C. Jordan, 1990). This aquifer test was simulated using the calibrated natural flow model, in order to analyze the response of the model to pumping conditions and calibrate anisotropy ratios.

To simulate this aquifer test, a new grid was constructed with more discretization and covering a smaller area of the Cape, just the area in which the actual pump test was performed. The new grid was the result of a regional-to-local interpolation, one of the resources of DYNPLOT. The simulation was run in an area of 1,540,000 ft^2. A negative (pumping) flux of 147 gpm was assigned to a node representing the pumping well used in the aquifer test.

Values of specific storage and specific yield were required by the code for transient simulations. A value of 0.35 was used for specific yield, based on the porosity value used for the steady state simulation. A value of 0.001 ft^{-1} for specific storage was considered appropriate to run the first simulation.

Head data from 7 single level monitoring wells and a multi-level well were available for the calibration of the model. The model was calibrated based on drawdown calculated in the simulation and by obtaining the measured drawdown from the log-log drawdown curves found in the feasibility study report (E. C. Jordan, 1990). The main calibration parameter was anisotropy ratio. The criteria for calibration, besides the drawdown values, were the shape of the drawdown vs. time curves and the drawdown distribution (minor to major ellipse axis ratio). Results of the calibration are presented in Appendix A.

Capture Curve Simulations

In order to fulfill the objectives of prediction of the analysis of the performance and flexibility of the existing pumping scheme, the response of the geometry of the capture curves to different pumping scenarios was analyzed. In addition to the simulations for the analysis of the capture of the CS-4 plume, simulations were performed in which the mere analysis of resulting capture zone geometry was the goal.

To study the current well fence, the plume to capture was the CS-4 plume with the dimensions and location described by E.C. Jordan (1990). However assumptions of a bigger plume were made, and the corresponding simulations performed. Also, the existence of the FS-28 plume, underneath CS-4, was considered, and the analysis of the extension of the capture zone to deeper parts of the aquifer was analyzed.

In the process of prediction of an alternative pumping scheme, an important assumption was made. This assumption was that a well fence with fewer wells implies less operation and maintenance costs. Another assumption determining the nature of the simulations was that the increase in pumping rate generates greater costs. For these reasons, all the simulations performed with this objective were carried out decreasing the number of wells, and maintaining the overall pumping rate.

a) Generation of Stress Conditions and Particle Starting Points

The 13 remediation wells of the existing well fence were represented in the grid as nodes. This nodes were different from the rest of the nodes of the grid because of the assignment of one dimensional elements (1-D) to them. A 1-D element is a resource of DYNFLOW, used generally for pumping nodes. A 1-D element connect the nodes of different levels so that the negative flux corresponding to pumping is equally distributed between the nodes representing the well screen.

One-dimensional elements were used in this model to connect the pumping nodes in their levels 6, 7 and 8, which elevation correspond exactly to the elevation of the screen of the remediation wells. Negative fluxes were then assigned to the desired nodes. Fluxes were assigned in cubic feet per day.

The flow model had to be run once the negative fluxes have been assigned. This simulation corresponded to a steady state, since the pumping was assumed to reach steady state in a few days, in contrast with the time of remediation, which is several years.

For the analysis of capture curves, the particle tracking was simulated under the pumping conditions. The flowfield generated in DYNFLOW with the negative fluxes representing pumping was used to run DYNTRACK. Input files to run particle tracking simulations were needed.

The simulated particles were introduced in the aquifer at certain location. Coordinates (x, y, z) were necessary for each particle. For the simulations of capture curves, two different particle tracking approaches were followed: plan view of capture zones and cross-section of the capture zone. A file with particle starting points, time of duration of the simulation and time step of data recording was constructed for both types of particle tracking simulations. This files, once generated, were used for all the different pumping schemes. The only change for each simulation was the flow field.

For the plan view output, a horizontal line of particles was used. The starting point corresponded to a location 1,500 ft upgradient of the well fence. The depth of the line of particles corresponded to the depth of the center of the plume at that location, determined from the cross-sections of the plume presented by E. C. Jordan (1990). The line had a length of 1,500 ft. In other words, the line of particles would represent a plume 700 ft wider than CS-4.

The cross-section of particles was formed by particles which starting points were also 1,500 ft upgradient of the well fence. The cross-section was formed by 286 particles, which covered an area of 183,000 ft^2 (1,500 of width and 122 ft of height). This cross-sectional area was greater then the cross-sectional area of CS-4, which is of about 31,500 ft^2. The objective was to be able to define not only if the plume was captured, but also how greater the capture zone was. The cross-section particle file was used in the "plot starting points" option of DYNPLOT, explained later in this section.

b) Particle Tracking

The particle tracking simulations were run for five years with a time step of 15 days. This means that the model followed the particles for five years, registering the location of each particle every 15 days. The particles that, after traveling the 1,500 ft distance ended at a pumping node were removed from the aquifer. This particle tracking simulations required a fairly considerable amount of computer memory, specially for the cross-section particle tracking, in which 286 particles were used. For this reason, the horizontal line simulation was always run first, and the cross-section simulation was run only in the cases in which it was considered important to gain more precise information.

c) Output Analysis

After each simulation, the flow field was restored in DYNPLOT and the horizontal particle tracking plotted, in plan view. After reviewing the capture curves in plan view, the need of a cross-section particle tracking simulation was decided, in each case.

Whenever more information about the capture curves geometry was needed, the cross-section simulation was run. The cross-section particle tracking was not used to plot trajectories of the particles. It was used to plot only the starting points of the particles with the DYNPLOT option "plot starting points". The plot of the starting points is only a cross-section of the aquifer showing where the particles are at the beginning of a simulation. However, a second plot was made on top of the first one, showing only the starting points of the particles that, as a result of the pumping, were removed from the aquifer. The program compute velocities and construct individual trajectories so that it is possible to know which particles go to a pumping node, and are removed.

5. PUMPING SCHEMES ANALYSIS

The first step in the design of the groundwater treatment system is to determine the quantity of groundwater that will need to be pumped from the aquifer. The required flow rate is directly proportional to the hydraulic conductivity K, the hydraulic gradient J, and the cross-section area of the plume A:

$$Q = AKJ$$

According to data from E.C. Jordan (1990), the cross-sectional area of the plume is 31416 ft^2. From the model results (Appendix A), the hydraulic gradient in the area is 0.0014, and the horizontal hydraulic conductivity, in the area of CS-4 plume is 191 ft/day. The discharge is then:

$$Q = (31416\ \text{ft}^2)\ (0.0014)\ (191\ \text{ft/day}) = 10,500\ \text{ft}^3/\text{day} = 60\ \text{gpm}$$

The minimum overall pumping rate of any remedial system simulated needs to consider this discharge as its minimum pumping rate. As mention in the methodology, in this particular site, the existence of the operating well fence for containment, the Installation Restoration Program well fence, gave a starting point for simulations.

From the analysis of the results of each pumping scenario only in terms of the resulting heads or the horizontal particle tracking it is not possible to fully understand the geometry of the capture curves. For this reason, the cross-section of particles using the "plot starting points" option of the program (Section 4.3.2) was the main tool in the analysis of the pumping schemes. By plotting the starting points of the particles that are removed from the aquifer due to pumping, a cross-section of the capture zone is obtained. This cross-section of the capture zone is perpendicular to the groundwater flow and is located 1,500 ft upgradient of the well fence. In each one of the figures of cross-section of particles presented in the next sections, the larger dots represent the cross-section of the capture zone, 1,500 feet upgradient of the well fence. As shown in Figure 5.1, the CS-4 plume falls within the cross-sectional area defined by the particles.

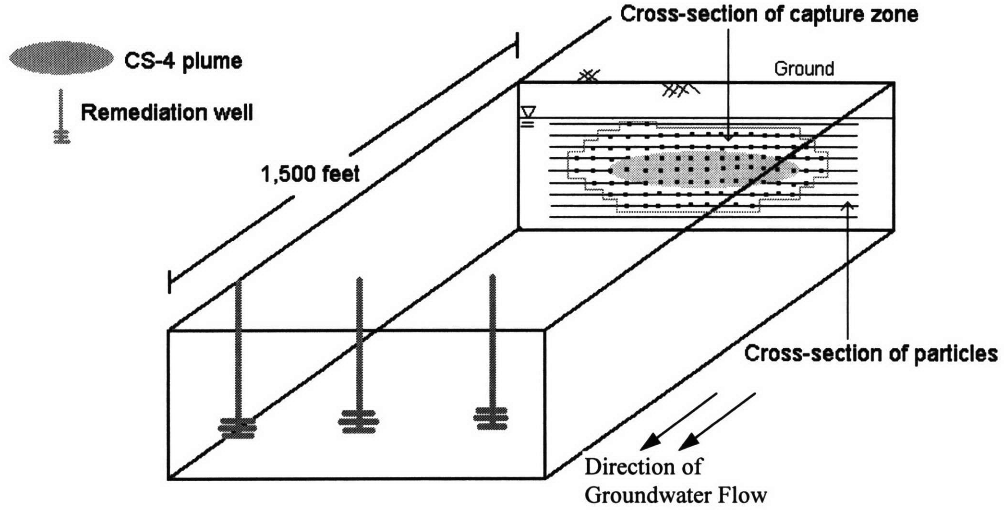

Figure 5-1. Diagram explaining the meaning of the "plot starting points" figures, used to analyze the geometry of the capture curves resulting from the different pumping schemes (Figure shows only three wells for simplicity)

5.1 Analysis of the Capture Zones Under Different Pumping Schemes

To evaluate the effects of well spacing and pumping rates in the geometry of the capture zone, six simulations were run. The first 4 simulations, corresponding to the analysis of the increase in overall pumping rate to compensate well spacing, were run with just three wells. In Table 5.1 the pumping schemes for this simulations are shown.

Table 5.1. Simulations to analyze the response of the capture curve geometry to different pumping rates and well spacing, for a three-well fence. A small theoretical plume (not CS-4 plume) is used for this analysis

Simulation	Wells operating	Pumping rate (gpm)	Individual pumping rate (gpm)	Distance between wells (ft)
1	9, 7, 5	90	30, 30, 30	120
2	10, 7, 4	90	30, 30, 30	180
3	10, 7, 4	135	45, 45, 45	180
4	10, 7, 4	165	55, 55, 55	180
5	11, 7, 3	210	70, 70, 70	240

For the first simulation, a capture zone of about 39,000 ft^2 in cross-sectional area with a width of less than 600 ft was obtained. This pumping scheme was the basis for the changes in pumping and well spacing of the next four simulations.

Moving the wells so that they were 180 ft apart, without increasing the pumping rate gave a clearly inefficient pumping scheme, in which particles escape the well fence passing between the pumping wells. This was observed in the plan view of the capture zone (Figure 5.2).

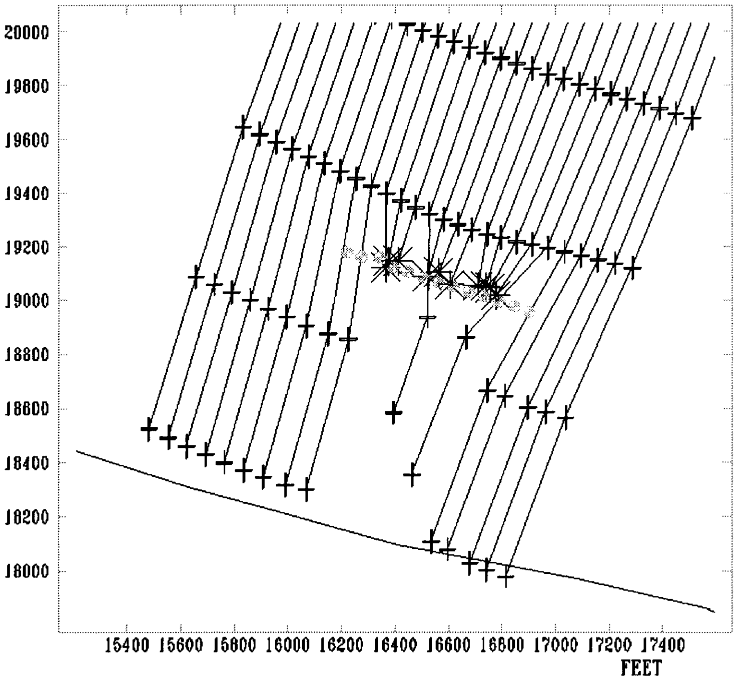

Figure 5-2. Particles escaping a three-well fence due to an inappropriate well spacing of 180 feet, for a total pumping rate of 90 gpm (simulation 2 in Table 5.1.)

The third simulation was run increasing the pumping rate by 50%. In this case, the analysis of the horizontal particle tracking indicated that no particles in the center of the theoretical plume would escape the capture zone. Based on these results, a cross-section of particles was analyzed. In Figure 5.3 it can be observed that the cross-sectional capture zone did not have the elliptical form convenient for the proper removal of contaminants.

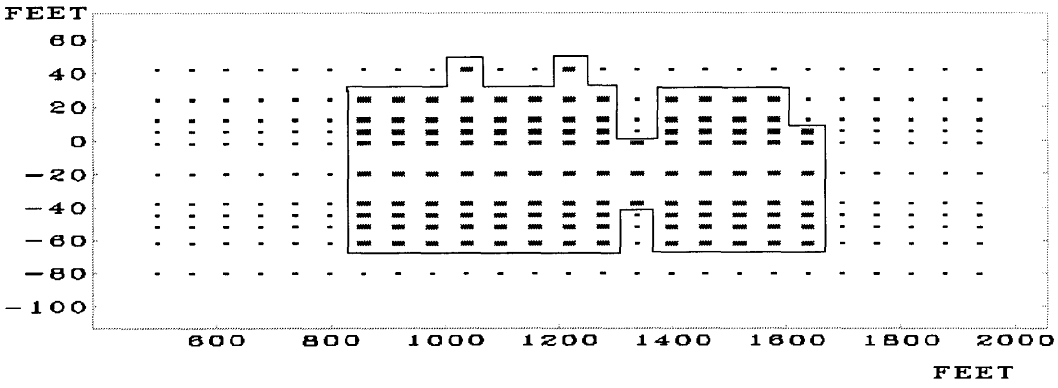

Figure 5-3. Cross-section of the capture zone for 3 wells, 180 feet apart, pumping 45 gpm individually

The particles which reach the well fence in the middle of pumping wells may or may not be captured, depending on the distribution of hydraulic control. In this simulation, particles between the wells 4 and 7 were not captured. They reached the well fence at the midpoint between wells, where zones of greater head value are formed, as seen in Figure 5.4.

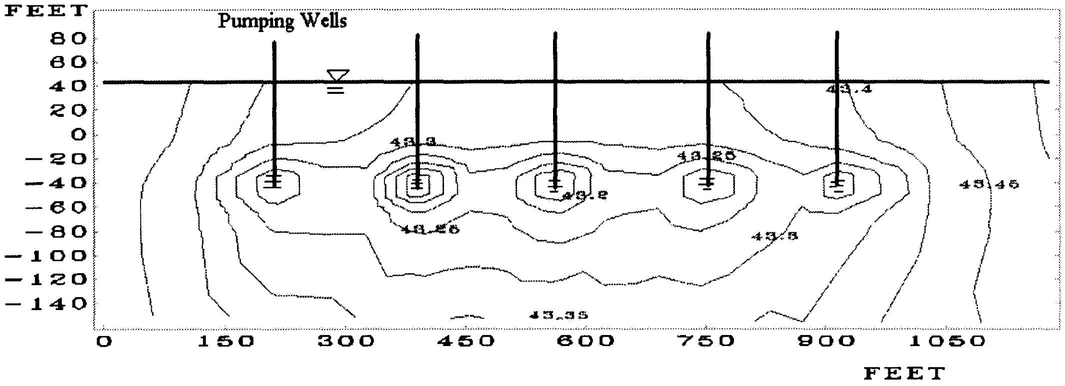

Figure 5-4. Head distribution around pumping wells. Head is lower near the wells and areas of greater values of head are located in the midpoint between wells. Example of five-well system

In the fourth simulation, however, increasing the pumping rate about 80% of the original rate (going from 90 gpm to 210 gpm), it was finally possible to completely extend the hydraulic control, defining an elliptical capture zone (Figure 5.5). A great difference in cross-sectional area of the capture zone was obtained from simulations 1 and 4 (see Table 5.1). This was the result of an increase in well fence length and an increase in pumping rate. The new cross-sectional area was approximately 75,000 ft^2, which is about twice as bigger as the first capture zone. This is easily explained because an increase in the well fence length, as well as an increase in pumping rate were done.

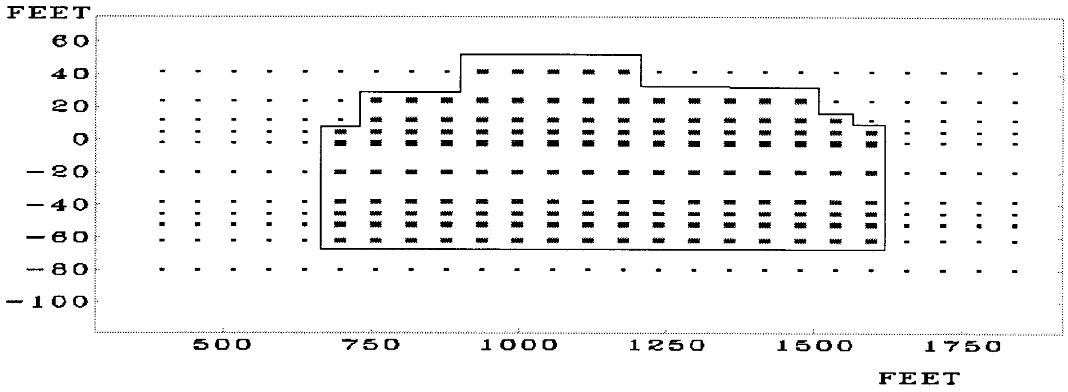

Figure 5-5. Cross-section of the capture curve generated by pumping 165 gpm with 3 wells (see Table 5.1). The larger dots represent the capture zone cross-sectional area

Well spacing is one of the decision variables for a remedial or containment system. As mentioned in Section 4.1, different approaches have been used to define proper well locations. Use of simulation and optimization to control hydraulic gradients (Gorelick et al., 1993), constraining groundwater velocities (Heidari et al., 1987), and use of three-dimensional simulations combined with mixed-integer programming (Sawyer et al., 1995) are some of the examples given.

Analytical solutions have also been developed (Javandel and Tsang, 1987; Yang et al., 1995). Javandel and Tsang (1987) explain that in general, when the distance between two wells is too large for a given discharge rate, a stagnation point will be formed behind each pumping well, and some particles are able to escape from the interval between the two wells. When the distance between the two wells is reduced while keeping the discharge rate constant, eventually a position will be reached where only one stagnation point will appear. In this case, no particles can escape from the space between the two wells. Similarly, increasing the discharge rate, as shown in the previous results, can compensate the well spacing, up to a certain point. These authors develop analytical solutions useful to calculate well spacing. However, the solutions are based on fully penetrating wells in homogeneous and isotropic aquifers of uniform thickness.

The advantage of a the three-dimensional numerical model, as the one used in this study, is that the location of wells can be planned according to the results of simulations and much more complex scenarios can be modeled and evaluated.

An interesting result came from the simulation of three wells, 240 ft apart, pumping at 70 gpm each. In Figure 5.6, a plan view showing particle tracking and head contours is presented. It can be seen that one of the particles simulated escaped the well fence . This particle passed between the wells 7 and 3, represented as black dots in the figure. However, in the other side of the well fence all particles were captured.

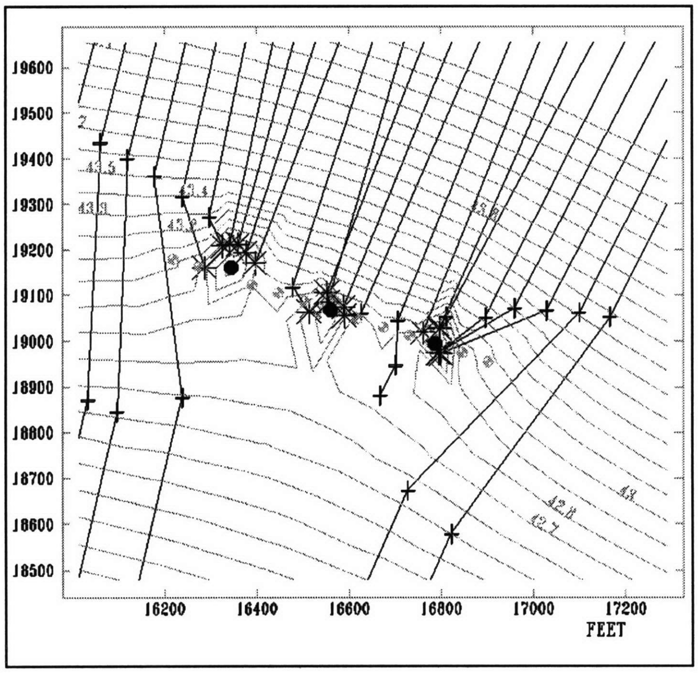

Figure 5-6. Capture curve resulting from a three-well option (simulation 5 in Table 5.1). The head distribution and the hydraulic control are asymmetric result of the well fence asymmetry

As described in Section 3.3.3, the well number 11 of the well fence, which is the one used for pumping in this simulation, is not aligned as the rest of the wells. This can be the reason for the asymmetry of the capture curve, in terms of drawdown and stagnation points distribution. The stagnation points generated while pumping to remediate a site are important parameters of hydraulic control and can cause inefficient performance of the system. Stagnation points may cause particles to escape (Javandel and Tsang, 1987), and can also be the reason of increasing the time for cleanup, since it is in this stagnation points where the water does not move or move really slowly (Hoffman, 1993). In general, different well location will cause a different location of the stagnation points and then a different performance of the remedial system.

However, in this case, a single simulation is not enough to conclude that the different location of the well number 11 is beneficial in terms of capturing the contaminants for the given pumping scheme. Irregularities in the model discretization may also affect this result. In Figure 5.6, the head contours shown are not smooth and are formed by straight lines. This is the result of the interpolation from the elements forming the grid. Discretization might slightly affect results. Regardless of these possible discretization problems, it is interesting to review this simulation and mention the fact that well location is a very important parameter to consider while designing a remedial or containment system. Locating the wells not necessarily in a straight line may result in different hydraulic control.

All previous results come from equally-spaced wells. Different ways to achieve hydraulic control were also evaluated having non-equally-spaced wells.

The results from the simulation of six non-equally-spaced wells indicate that this option is less effective than the equally-spaced option. However, a solid capture curve could be achieved with a proper combination of pumping rates (Figure 5.7). Pumping rates are presented in Table 5.2 for two different simulations. For the first one, with an overall discharge of 220 gpm, some of the particles escaped the well fence. In the second case, increasing the pumping and redistributing it, the capture zone was attained.

Table 5.2. Simulations to analyze the response of the capture curve geometry to different pumping rates with non-uniform well spacing. A small theoretical plume (not CS-4 plume) is used for this analysis

Simulation	Wells operating	Pumping rate (gpm)	Individual pumping rate (gpm)	Distance between wells (ft)
1	13, 10, 8, 6, 4, 1	220	50, 30, 30, 30, 30, 50	180, 120, 120, 120, 180
2	13, 10, 8, 6, 4, 1	240	50, 40, 30, 30, 40, 50	180, 120, 120, 120, 180

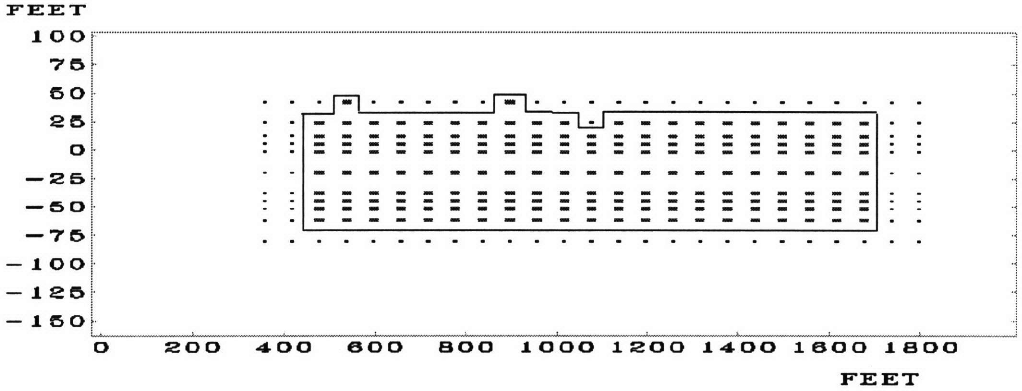

Figure 5-7. Cross-section of the capture curve generated by six wells, pumping 240 gpm, as indicated in Table 5.2 (simulation number 2)

5.2 Flexibility of the Current Well Fence

The Installation Restoration Program well fence was simulated. A particle tracking simulation using 13 wells pumping 140 gpm, located 60 ft apart as in the IRP well fence, was run (Section 3.3.3). According to Figure 5.8, the pumping rate and the number and spacing of wells can be considered adequate. In this horizontal view, a capture curve approximately 1100 ft wide is observed. From the analysis of the cross-section of particles and the "plot starting points" output, the vertical and horizontal effects of the pumping scheme can be considered sufficient for the capture of the plume (Figure 5.9). The capture zone is approximately 250 ft wider and 25 ft thicker than CS-4. The area of the ellipse formed by the plume was of 31,400 ft^2. The area of the ellipse formed by the capture zone was about 64,800 ft^2. The cross-section of the capture zone is then two times bigger than the cross-section area of the plume. This guarantee the removal of all contaminated water.

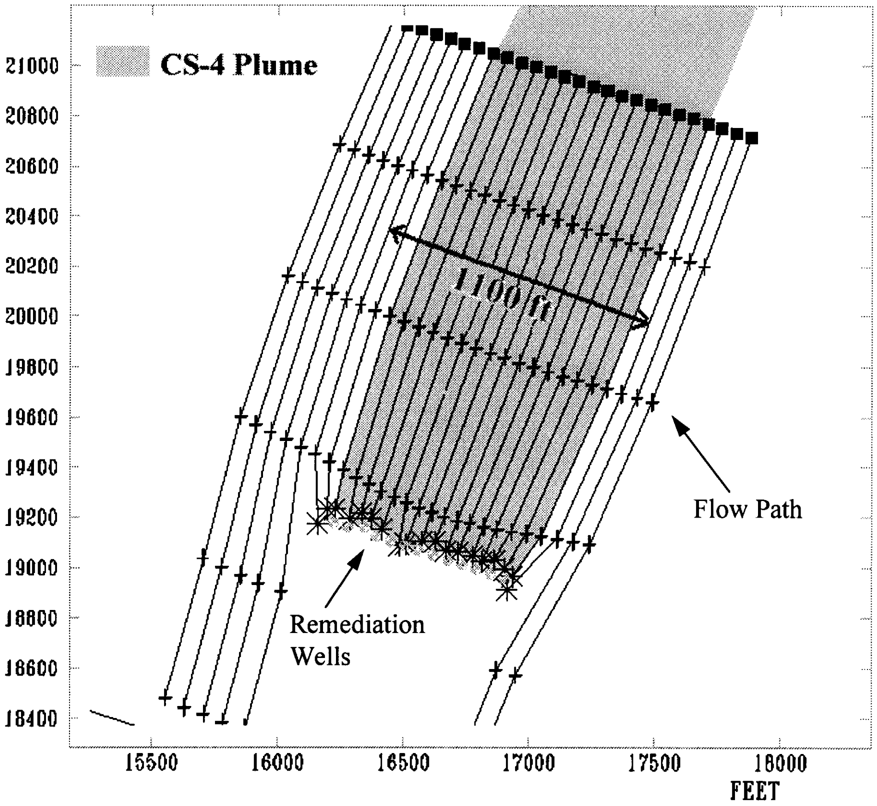

Figure 5-8. Two-dimensional horizontal capture curve resulting from the simulation of the existing pumping scheme at MMR

To analyze what could be done with the existing containment system, in response to a bigger or deeper plume, simulations using the current well fence but increasing the pumping rate were made and the extent of the resulting capture zones analyzed. Results are presented in Table 5.3.

Results shown in this table indicate that the increase in the vertical extent of the capture zone was apparently due to water coming from the upper side (i.e., the water table side) of the capture zone. No change in the lower limit of the capture zone was registered in any of the simulations run, while the upper limit significantly changed.

Table 5.3. Enlargement of the capture curve using 13 wells, in response to the increase of pumping rates, distributing the stress equally throughout the well fence

Pumping Rate (gpm)	Width (ft)	Thickness (ft)	Cross-sectional Area (ft^2)	% increase in cross-sectional area	Elevation of lower limit (ft msl)
140*	1100	75	64, 800	-	-65
182	1100	85	73, 400	13	-65
200	1100	85	73, 400	13	-65
220	1220	85	81, 400	26	-65
250	1220	105	100, 600	55	-65

* IRP well fence

A factor that can contribute to this response is the lower conductivity of the deepest layer of the aquifer. This layer has a conductivity of 35 ft/day, whereas the layer in the middle and the upper-most layer have values of 120 ft/day and 217 ft/day respectively. Another very important factor contributing to this effect is the anisotropy ratio, which is about three times bigger in the lower part of the aquifer (Figure 4.3). It is easier for the water to flow to the well from the upper layer. It is also important to have in mind the degree of resolution of the cross-section used for particle tracking. The lower-most line of particles is located 20 ft below the lower line of particles captured. Any increase in the thickness of the capture zone of less than 20 ft in the bottom part of the aquifer could not be detected because there were no particles in that area that could indicate the enlargement of the capture curves. Nevertheless, it was clear that the increase in thickness was in general due to the capture of more water from the water table side.

In the horizontal, the capture zone increased in less proportion than it did in the vertical. With an increase of 110 gpm (from 140 to 250 gpm), the capture zone increased approximately 30 ft in the vertical, corresponding to more than 3 ft per unit of pumping (gpm). In the horizontal, the capture zone increased about 120 ft, which corresponded to less than 1 ft per unit of pumping. These proportions, however, are mentioned merely to illustrate the main results, and can not be considered as design parameters.

According to the results presented in Table 5.3, pumping 220 gpm, the well fence will capture a plume about 50% bigger than CS-4 plume. However, to contain the FS-28 plume, located deeper in the aquifer, the sole increase in pumping rate will not be effective, since the lower limit of the capture zone do not go deeper even for a pump rate 75% larger than the original pump rate of 140 gpm. Placing the well screens deeper into the aquifer could be a more effective way to contain FS-28, than increasing the pumping rate. Faybishenko, et al. (1995) analyze the hydrodynamics of the capture zone of a partially penetrating well, and conclude, as one would expect, that the maximum vertical extent of the capture surface increases as the degree of penetration increases. Although this analysis is for a confined aquifer, very similar results are expected in the Cape Cod aquifer, since the amount of drawdown relative to the total saturated thickness of the aquifer is very small, and therefore transmisivity can be assumed constant.

After the analysis of the different ways in which the pumping scheme currently in operation can be modified to respond to a different plume, or to capture FS-28, an analysis of the response to technical problems related to the well fence itself was performed.

The assumption of one of the wells out of operation was made. The simulations to determine the different pumping strategies necessaries to achieve a similar capture curve were performed, changing the location of the non-operating well. The results indicate that such a situation can be easily solved by increasing the pumping rate of the wells adjacent to the well out of operation. The capture curves obtained from the normal situation and the 12-well operation are very similar (Figure 5.9 a and b).

Figure 5.9 shows how the capture zones of both pumping schemes were effective, and in fact, they were practically the same. In the case of the 12-well situation, the well number 10 have been turned off, and wells 11 and 9 are pumping 15 gpm, instead of 10 gpm, which is the rate of pumping in the normal situation. The increase in pumping rate easily offset the negative effect (i.e., loss in hydraulic control) of a non-operating well.

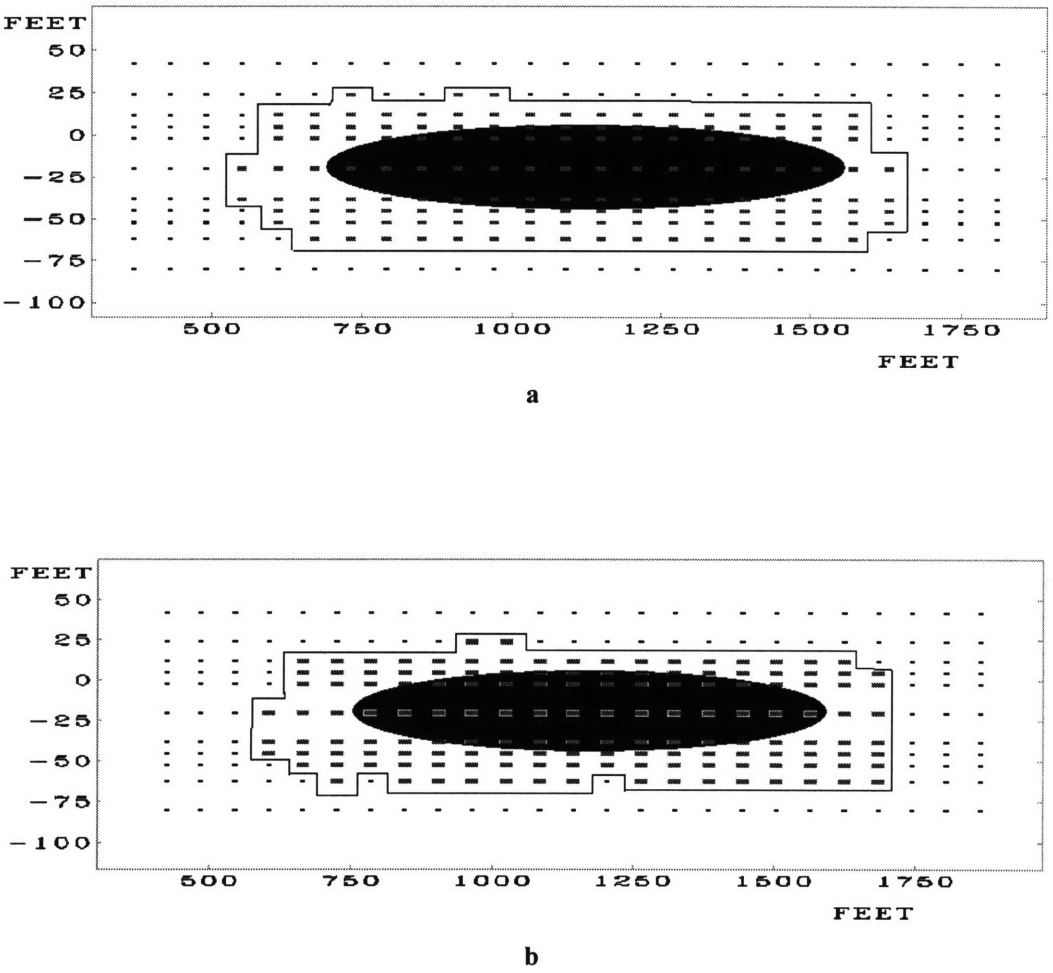

Figure 5-9. Comparison of capture curves obtained from the current pumping scheme (a), and the well fence with one of the wells out of operation with a different pumping rate distribution, but maintaining the overall pumping rate of 140 gpm (b)

5.3 Prediction of an Alternative Pumping Scheme

After the analysis of the current well fence of 13 wells, and the response of the aquifer to different pumping scenarios, the option of an alternative containment system, based on the one already in place, was addressed. The different simulations run for this purpose are presented in Table 5.4.

Table 5.4. Simulations to predict an alternative effective capture zone for CS-4 plume. Simulations were run according to the dimensions of the plume reported by E. C. Jordan (1990)

Number of wells	Wells operating	Pumping rate (gpm)	Individual pumping rate (gpm)	Distance between wells (ft)
8	13, 11, 10, 8, 7, 5, 3, 1	140	20 in the outside wells and 16.7 at the rest of the wells	102
8	13, 11, 10, 8, 7, 5, 3, 1	140	17.5	102
7	13, 11, 9, 7, 5, 3, 1	140	20	120
5	13, 10, 7, 4, 1	140	28	180

All simulations were run with schemes of equally-spaced wells, based in the results of the six well simulation, described above. In the six-well simulation, it was clear that an option of non-equally spaced wells presents disadvantages with respect to the uniformly-spaced options. At the same time, a system of six wells could not be considered a feasible option, since replacement of wells would be needed. In addition to this negative factor, although a combination of pumping rates can be found that satisfies the requirements for capturing the plume, these pumping rates may be too high with respect to the ones from equally-spaced options.

As indicated in the Table 5.4, the first simulation of eight wells was run with a non-uniform pumping, based on the fact that the IRP well fence works with more pumping in the wells located at the sides (Section 3.3.3). However, the second simulation was run pumping equally from each well. The results in the cross-section capture zone were very similar in terms of the shape of the capture zone and almost identical in terms of cross-sectional area, which was about 64,800 ft^2.

Since fewer wells for a fixed pumping rate (140 gpm) presumably implies reduction in the operation and maintenance costs, a simulation of seven wells was performed.

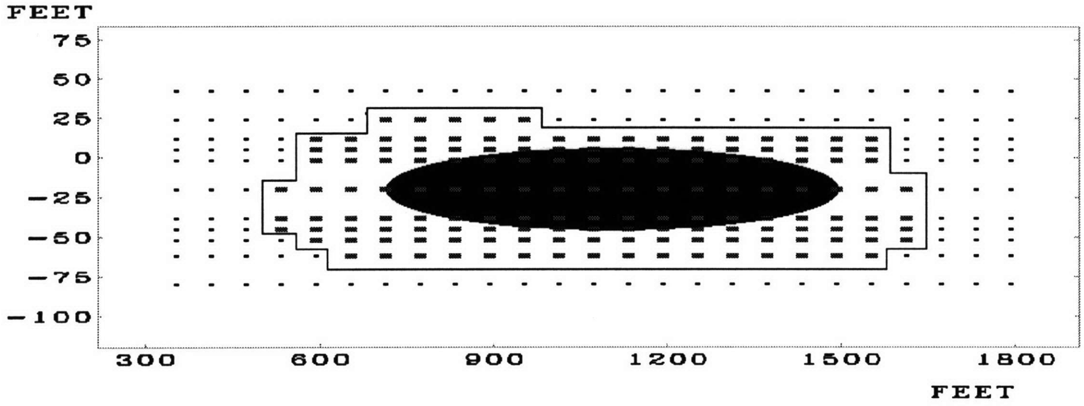

Figure 5-10. Cross-section of the capture curve resulting from seven-well option, in which the overall pumping rate is 140 gpm

The area of the seven-well pumping strategy was approximately 64,800 ft^2, as in the eight well simulations (Figure 5.10). Interestingly, the existing pumping scheme of 13 wells resulted in a very similar cross-sectional area.

The seven-well option is preferred over the eight-well option because both produced the same results, and in the eight-well system the wells had to be relocated. This relocation of wells would imply costs, not needed for the seven-well option.

The next simulation was done with five wells using 140 gpm overall discharge. As expected, that pumping rate was not enough to capture the CS-4 plume, since well spacing becomes fairly important. The objective then, was to increase the pumping rate until the proper capture zone were achieved.

An increase of more than 40% was necessary to obtain a horizontal capture curve output without particles passing between wells. A cross-sectional particle tracking was run and it was observed that this pumping rate resulted in a capture zone of approximately 79,000 ft^2, which was greater than the one obtained from 13, 8 and 7 wells. The greater capture zone from the five well simulation implies the capture of a larger proportion of clean water, which makes this option less effective. This, however, was not the only disadvantage of the five-well option, since when the cross-section was analyzed, it could be seen that the cross-section of the capture zone did not show the uniform ellipsoidal shape observed for seven, eight or 13 wells (Figures 5.9 and 5.10). The cross-sectional shape of the capture zone was very similar to the one obtained for three wells pumping a total rate 135 gpm, shown in Figure 5.3 as an example of inefficient pumping scheme.

It is important to mention, as a first consideration, that all calculations of area and observations of cross-sectional shape of the capture zones, are based on the particle tracking of 286 particles (procedure described in Section 4.3). The degree of resolution limits the exact definition of the cross-sectional shape. It is of course likely that the three different pumping schemes considered effective (7, 8 and 13 wells) derive in different cross-section area of the capture zones. However, from the results of this study, no significant changes were observed, which implies great flexibility.

The explanation for the fact that 13, and 7 wells gave as a result practically the same capture curve geometry, must be based on the well spacing to pumping rate relationship. The seven-well alternative consisted of wells located at 120 ft apart, which is twice the distance of the wells in the current well fence. The pumping rate for each individual well was increased, although the overall pumping rate was maintained constant. The results showed that the negative effect of increasing distance between wells was offset by the positive effect of increasing individual pumping rates.

After analyzing the results from these candidate alternative pumping scenarios, the seven well option seems to be a good alternative pumping scheme. The operation and maintenance cost would presumably be reduced and the capture of CS-4 plume would still be attained. However, other factors, technical and non-technical have to be considered to make decision about changing the existing pumping scheme.

Technical uncertainties need to be considered in the design of a containment system. One of the most important factors that may influence the geometry of a capture zone for a given pumping condition is aquifer heterogeneity. As mentioned in Section 5.2, differences in hydraulic conductivity lead to different amounts of water drawn from distinct lithologic units. The effect discussed in Section 5.2 is due to the existence of a low conductivity layer at the bottom of the aquifer. However, heterogeneity may also exist within layers, and this is not represented in the model. For this model the layers are assumed to be homogeneous (see Figure 3.3), and effects of changes in hydraulic conductivity due to the presence of lenses of different materials, can not be observed in the results of this study. Heterogeneity is present in the Mashpee Pitted Plain, as indicated by Foster-Reid (1994) and Springer (1991). The large-scale heterogeneity, characterized by Springer (1991), as well as small scale heterogeneity may have effects on the geometry of the capture zones, once a well fence is operating. The hydraulic performance evaluation developed by Camp Dresser & McKee in 1996 (Camp Dresser & McKee, 1997) addresses issues related to hydraulic conductivity in a thorough manner.

As mentioned in Section 3.1, the opportunity to evaluate a large number of alternatives combining different factors is one of the greatest advantages of the use of a three-dimensional numerical model to help in the design of remedial or containment systems. The natural flow model developed in this study can be used to evaluate a great number of capture zone options. This can be done not only to design or evaluate a containment system, which was the objective of this study, but also to design a remediation scheme, by moving some of the wells to the points of maximum concentration of contaminants.

6. LIMITING TECHNICAL FACTORS IN GROUNDWATER REMEDIATION

Since 1980, when the Superfund program started, scientific and technical knowledge about the transport and transformation of contaminants in the subsurface has increased, and many important lessons have been learned regarding the feasibility of the restoration of groundwater. Both, the state-of-the-science and the state-of-practice technology have improved, giving policy makers the possibility to modify directives and make more informed decisions, particularly with respect to the "How clean is clean?" issue.

This chapter describes the limiting factors and the technical uncertainties in groundwater remediation. It is divided in three sections. The first one analyzes the current situation at the CS-4 site, explaining the technical uncertainties that have been present in its remediation. The second section presents a brief description of technical problems encountered at other Superfund sites. The third section describes general concepts of the fate and transport of pollutants in the subsurface, its implications in groundwater restoration, and the way they have influenced the Superfund remediation policy.

6.1 Uncertainties in the Remediation of the CS-4 Plume

The previous three chapters have presented technical aspects in the remediation of the CS-4 plume, at the Massachusetts Military Reservation. This remediation process is still in the interim remedial action phase, which means that the plume is being contained but no remediation process has started. This phase has presented challenges, due to the existence of uncertainties that have resulted in modification of the original system, and under-utilization of the treatment facilities. In addition, while monitoring the containment of this plume, the presence of another plume of contaminants has been detected, many years after the initial site assessment program was finished. Some of the problems originating these negative outcomes are analyzed below.

The main technical issues that have been present at CS-4 are related to site characterization, and the inherent uncertainties present in groundwater modeling. A groundwater model is a representation of the actual conditions encountered in an aquifer, and many limitations are present in its construction. The model incorporates the three main aspects of an aquifer: geologic, hydrologic and hydraulic aspects. Some hydrologic information, such as precipitation, is easy to measure with reasonable accuracy. In the case of Western Cape Cod precipitation is about 48 in/yr (LeBlanc et al., 1986), as indicated in section 3.2.2. However, the actual recharge to the aquifer is much more difficult to determine, and authors report values ranging from 17-23 in/yr (LeBlanc et al., 1986). This reflects a first type of uncertainty encountered in the construction of a groundwater model.

Regarding geological information, uncertainties are even bigger, since any global geologic description will include subjective interpretation of very limited -and expensive to obtain- data. Western Cape Cod, and in particular the area in which the CS-4 plume moves, can be considered fairly homogeneous. This area has not a complex geologic configuration (see section 3.2). However, the possibility of some localized heterogeneity is always present, and should not be neglected.

To model the groundwater flow, hydraulic properties of the geologic framework are necessary, in addition to the geologic description. Many different methods to estimate hydraulic conductivity exist, all of them based on empirical relations and bearing a significant margin of error. All of this determinations, except for the pump test, are realized for a discrete point of the aquifer, and interpretation of trends are needed in order to define global characteristics of an area. In Table 3.1, the different determinations of K are presented. Values in the table vary for all the different sites and by method, as well.

The groundwater model constructed in this study is based on a set of assumptions, described in the conceptual model (section 4.2), and uncertainty is necessarily involved in it. The same is true for the model developed during the remedial design phase of CS-4 (E. C. Jordan, 1990). These are important reasons to design remedial systems with flexibility and implement monitoring and performance evaluations, once the system is in place.

At the CS-4 site, not only uncertainties related to hydrogeology have been present. Discovery of the FS-28 plume is an example of another type of uncertainty: it is often difficult to determine what kind of waste has been dumped, how much, for how long, and where. This is an inherent uncertainty in the Superfund site assessment program, since Superfund cleanups deal mainly with sites contaminated in the past, for which precise records are not available.

6.2 Superfund Cleanup at Other Sites

During the first ten years of the Superfund program, many sites were found to be very complex in terms of hydrogeology, and contaminant behavior. With the purpose of providing the reader with some clear examples of the technical difficulties and uncertainties likely to be present in the remediation of groundwater, three complex site cleanups are briefly described below. Many other examples can be found in the literature (OTA, 1985; OTA, 1989; Mackay and Cherry, 1989; Gupta and Van Houtven, 1995). In these examples, technical limitations regarding site characterization and contaminant fate and transport can be identified.

6.2.1 The Stringfellow Site

The Stringfellow Acid Pits site near Glen Avon, California, has a long history of investigations and actions regarding environmental restoration. The following description is based on the report found in the document *Superfund Strategy* (OTA , 1985).

According to OTA's description, most of the work, and many of the misinterpretations of the site hydrogeology, occurred before Superfund was even passed. Original geological studies concluded that the site was on impermeable bedrock and that, with the installation of a downstream concrete barrier, there would be no damage of groundwater contamination. The canyon site was therefore declared a hazardous waste facility. Subsequent information and events revealed that the site was quite unsuitable for such a facility, and there have been substantial amount of surface and groundwater contamination over a period of years. In fact, underlying the site is the Chino Basin aquifer, supplying potable water to 500,000 people (1985 data). In 1985, the State estimated the permanent cleanup cost in $65 million, while containment attempts were being made, unsuccessfully due to the complex site hydrogeology, including fracture bedrock and underground springs.

6.2.2 The Sylvester site

Located in Nashua, New Hampshire, this site was a former sand and gravel pit where hazardous wastes were dumped illegally, along with solid wastes for five to ten years. The first important uncertainty about this site was the total weight of hazardous materials dumped. Various consultants who worked on the site used a figure of about 240,000 pounds, and State officials supported this estimation based on affidavits submitted by several PRPs, records of inspections at the dump, and exploratory test pits and borings. However, as OTA (1985) indicates, based on a number of solid samples, and what they contained, considerable amounts of waste could be present but undetected, in the volume above the water level; that is, the possibility of a much higher figure for total hazardous wastes deposited could not be rejected with confidence, on the basis of the sampling of solid material at the site. This problem of determining the amount and nature of hazardous wastes, and the location in which they were dumped, is similar to the problem encountered at MMR. At the MMR site, no knowledge about the presence of EDB, the contaminant that now constitutes the FS-28 plume, was present until the chemical was detected.

At the Sylvester site, the two main actions constituting the strategy for cleanup were: 1) minimize the amount of water entering and leaving the site through use of a slurry wall around the area, and a cap over it, and 2) cleanup of contaminated groundwater with a pump and treat system. It is relevant to mention that OTA (1985) in its description, refers to this strategy as "bold and innovative", and mentions that there were several uncertainties with that cleanup approach (OTA, 1985).

In fact, cleanup resulted ineffective due to two main factors: 1) greater than expected flow off the site after the installment of the slurry walls, and 2) uncertainties about the quantity and the nature of the contaminants remaining in the soil and sitting at the water table. In particular, the slurry walls were not enough to reduce the flow off the site due to the existence of underflow because of highly fractured bedrock.

In 1985, after five years of work, OTA concluded:

> [...] it is not yet possible to evaluate the effectiveness of the cleanup strategy. If the State officials are correct in their estimate of the nature and quantity of the hazardous wastes disposed at Sylvester, the cleanup will be permanent. If not,

future costs could rise the total cleanup costs significantly above the currently estimated $13 million (OTA, 1985).

6.2.3 Conservation Chemical Company Site

This site located at Kansas City, Missouri, is located on top of an aquifer supplying drinking water to private residents and public water supply companies. Approximately 93,000 cubic yards of hazardous material were buried on the site. Severe groundwater contamination resulted, by toxic and/or carcinogenic, inorganic and organic compounds. The remedy chosen in the 1987 ROD included: 1) use of a permeable cap to allow water intrusion to assist groundwater cleanup, 2) a pump and treat system, and 3) an off-site monitoring system.

In 1988, one year after the signing of the ROD, OTA reported about great uncertainties regarding the total time for cleanup, the rate of mass of contaminants removal, the protectiveness of the cap on the site, and the ability of the hydraulic containment to prevent contaminants from moving off site in the groundwater (OTA, 1988). In particular, OTA declared that total time for cleanup was “unpredicted but probably a very long time -decades”. All these uncertainties were related to the different characteristics of the contaminants present in groundwater, and their unpredictable behavior in the subsurface.

6.3 Lessons Learned

Groundwater contamination problems are ubiquitous in the Superfund program. Over 85% of Superfund National Priority List have some degree of groundwater contamination (EPA, 1993). As described in section 2.2.2, restoration cleanup levels in the Superfund program are established by ARARs, such as the Federal or State standards for drinking water quality (see also section 7.2). However, one of the most important lessons learned during the implementation of the Superfund program is that restoration to drinking water quality (or more stringent levels where required), may not be possible at many complex sites, using currently available technology. An equally important lesson is that complex site conditions -in terms of hydrogeologic characteristics, source and type of contaminants- are more common than anticipated. This has obviously consequences in the remediation process policy, particularly regarding the how clean is clean issue. The following section presents factors limiting remediation. It is important to mention that the following discussion is a generalization. The particular factor or combination of factors that may critically limit restoration potential will be site specific.

Factors limiting remediation potential

In general, the different factors affecting the remediation potential of ground water may be grouped under three general categories (EPA, 1993):

- Hydrogeologic factors
- Contaminant-related factors
- Remediation system design inadequacies

The last category, remediation system design inadequacies, is highly related to the complexity of the site conditions. Engineering solutions to the contaminant extraction, in situ treatment or immobilization, are based on the interpretation of observed conditions, and analytical models (i.e. mathematical expressions). The techniques used for engineering estimations of groundwater restoration potential are still evolving. As discussed in sections 4.1 and 6.1, modeling of groundwater flow, and contaminants fate and transport have uncertainties implicit. Models are sensitive to values of hydraulic conductivity, retardation factors and leachability, and source locations, as well as initial general assumptions. Estimations of contaminant mass removal have also great uncertainties involved, mainly related to the initial mass released, and the total mass remaining in the site. As presented in the CS-4/FS-28 case, and the Sylvester and Conservation Chemical Company sites, these uncertainties are the result of the lack or inaccuracy of historical site waste management records, and the difficulty in defining the magnitude and extent of subsurface contamination.

One way to show the kind of assumptions and the type of parameters that are needed to make estimations about contaminant concentrations in the aquifer, is by examining the differential equation for the three dimensional solute transport through porous media[3].

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[3] Khachikian (1996) presents a description of this equation, with actual parameter and concentration values for the CS-4 plume site.

$$\frac{\partial C}{\partial t} + \frac{u}{R}\frac{\partial C}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{1}{R}D_{ij}\frac{\partial C}{\partial x_j}\right] - kC$$

C = aqueous concentration of solute (moles/L)
D_{ij} = dispersivity tensor (m^2/day)
k = first order degradation constant (day^{-1})
u = advection velocity (m/day)
R = retardation factor

In this equation, three important assumptions have already been done: 1) constant porosity, 2) constant bulk density, and 3) linear sorption. In order to make estimations about contaminant distributions using this equation, the advection velocity, dispersivity in three dimensions, degradation constant, and retardation factor need to be measured. This is a very complex task, and complete accuracy in the determination of all these parameters in the field is not an achievable goal. Therefore, judgments about the relative importance of each of these parameters are needed, and assumptions will accordingly be done. These parameters are determined after different field and laboratory procedures -in which sources of error are not absent-, and after extrapolating data from discrete samples.

The purpose of this discussion is not to disregard the value of analytical models and engineering solutions. This discussion is directed to state, as clearly as possible, that the remediation of the subsurface is not an easy and straightforward task, but a complicated and technically challenging one.

With respect to contaminant-related factors limiting the remediation of groundwater, some chemical characteristics, as well as the contaminant phase, are very important to consider. Figure 6.1 presents a generalization of the conditions related to difficulty of remediation. Retardation potential and decay potential (represented by R and k, respectively in the equation above), and volatility, greatly affect restoration processes, negatively or positively. The retardation factor is contaminant specific, and represents the advection reduction of solutes due to sorption. It is directly correlated to a partition coefficient that relates the aqueous concentration of a solute, with its sorbed concentration (Schwarzenbach, et. al, 1993). Solutes with higher affinity to the soil matrix of the aquifer will suffer sorption, and therefore their retardation factors will be high, which implies difficulties in extracting those compounds from the aquifer. This is of particular importance in pump and treat systems, in which the total time for remediating a site can increase.

Contaminant phase has been found to be crucial in the remediation of a site (EPA, 1993). Non aqueous phase liquids (NAPLs) and in particular those denser than water (DNAPLs), are examples of contaminants that may pose technical limitations to aquifer restoration efforts. DNAPLs are difficult to locate and remove from the subsurface; their ability to sink through the water table and penetrate deeper portions of aquifers is one of the properties that makes them very difficult to remediate (EPA, 1993).

Hydrogeologic factors limiting the restoration of groundwater have been already discussed in Chapter 5. Stratigraphy, grain size, heterogeneity, differences in hydraulic conductivity -horizontal and vertical-, changes in the direction of hydraulic gradient, etc. are factors that may complicate the remedial design and the remedial action in Superfund sites.

These are all lessons learned from remediation efforts since the Superfund was passed. The EPA has reacted to this continuous learning process and has issued many technical guidances, addressing the main issues (EPA, 1989; EPA 1991; EPA, 1993; EPA, 1996). In particular, the documents *Guidance for Evaluating the Technical Impracticability of Ground-Water Restoration* (EPA, 1993), and *Final Guidance: Presumptive Response Strategy and Ex-situ Treatment Technologies for Contaminated Ground Water at CERCLA Sites* (EPA, 1996), contain specific directions to address the How clean is clean issue, suggesting the requirement of ARAR waivers when technical impracticability is determined. This two documents, are important because they present the phased approach that may be followed in order to characterize the site and determine the technical feasibility of the remediation to ARAR levels.

Generalized Remediation Difficulty Scale

Increasing Difficulty →

Contaminant Characteristics

Site Use

Nature of Release	Small Volume Short Duration Slug Release	→	Large Volume Long Duration Continual release

Chemical Properties

Biotic/Abiotic Decay Potential	High	→	Low
Volatility	High	→	Low
Contaminant Retardation (Sorption) Potential	Low	→	High

Contaminant Distribution

Contaminant Phase	Aqueous, Gaseous → Sorbed → LNAPLs	→	DNAPLs
Volume of Contaminated Media	Small	→	Large
Contaminant Retardation (Sorption) Potential	Shallow	→	Deep

Hydrogeologic Characteristics

Geology

Stratigraphy	Simple Geology, e.g. Planar Bedding	→	Complex Geology, e.g. Interbedded Strata
Texture of Unconsolidated Deposits	Sand	→	Clay
Degree of Heterogeneity	Homogeneous	→	Heterogeneous

Hydraulics/Flow

Hydraulic Conductivity	High ($>10^{-2}$cm/sec)	→	Low ($<10^{-4}$cm/sec)
Temporal Variation	Little/None	→	High
Vertical Flow	Little	→	Large Downward Flow Component

Figure 6-1. Examples of factors affecting groundwater restoration. The particular factor or combination of factors that may critically limit restoration potential will be site specific. Taken from EPA (1993) with minor modifications.

The state-of-the-science and the state-of-the-art have also advanced giving the opportunity to reduce the number of sites with remediation system design inadequacies. Better strategies are followed today to characterize sites, and improvements in field technology allow faster and more effective site characterizations. Lessons have also been learned in the actual design of remediation schemes, and the possibility of obtaining good results simple sites have increased considerably. However, complex sites are still a big challenge.

It is not rare to find studies about Superfund and its different dimensions (toxicology, law, economics, politics), in which the technical complexity of the remediation of groundwater is ignored. This chapter has intended to demonstrate the great importance of the technological aspects of aquifer remediation, and how they need to be considered when policy decisions are made.

7. SUPERFUND REMEDIATION STRATEGY: RELATIONSHIP WITH TECHNICAL UNCERTAINTIES

The purpose of the next two chapters is to present arguments to show that, in the remediation process, there are technical aspects determining policy decision making. This is a chapter in "political technology" of Superfund, an approach emphasizing the technological factors underlying political decisions.

7.1 Method of Analysis

Superfund is one of the most complex and controversial environmental programs ever implemented in United States. The program has had a great impact in different sectors of society, such as communities affected by contaminated site cleanups, Potentially Responsible Parties (PRPs), and the industry taxed to create the fund, as well as the EPA and some other sectors of the Federal government. Due to this impact, Superfund has been analyzed from many different points of view, by governmental agencies, Congress, academics, industry, and consulting firms. It is also subject to intense debates within the communities affected by cleanups. Therefore, the existing literature regarding the Superfund program is abundant.

The methodology used for the analysis of the importance of technical aspects in the performance and implementation of the program, is composed by three steps described below, which are based on an extensive literature review:

1) Identification of the most important Superfund issues discussed over the years, intrinsically related to, or likely to be affected by technical difficulties and/or uncertainties.
2) Identification of the main Congress and EPA documents regarding the remedial program of Superfund[4].
3) Analysis of the policy directives included in the documents identified in step 2, designed to address the issues identified in step 1.

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[4] Remedial program as defined in section 2.2, in which the overall Superfund program was described as composed by two phases, the site assessment program and the remedial program.

When a specific document addresses a particular issue through a policy directive, this policy directive was analyzed in terms of its observed and/or prospective results. The literature review included documents from governmental entities (i.e. Congress, Office of Technology Assessment, Environmental Protection Agency), academics, and the environmental consulting industry.

The literature review as a method for the identification of the main issues and the most important documents in the Superfund policy and its implementation, provided the possibility to observe different criteria of evaluation of the program. Later, this combination of criteria obtained from the literature review was used in the analysis of the observed or prospective results of the different policy directives, providing consistency in the study.

The use of multiple criteria is crucial in public discourse. McRae and Whittington (1997), mention that in public debate, the analyst must usually consider more than one criterion in order to form a full and balanced judgment among a set of alternatives.

Criteria guide the entire process of policy analysis. When a policy analyst measure social conditions -such as employment, crime or disease- these conditions are of concern because they are valued or disvalued. The values that underlie these concerns, when expressed more precisely, constitute a basis for the analyst's criteria. Those values implicitly guide any exploration of the causes of the conditions that signal a problem, and they can also be used later in the analysis of policies for improving the conditions (McRae and Whittington, 1997).

7.1.1 Identification of Issues

The first step in the analysis presented in this chapter (number 1 above), constitutes the problem formulation. The literature review is a method to become acquainted with the questions or issues by examining the valuative concerns of the public involved. The justification of the use of documents issued by different sectors of society (i.e. industry, governmental agencies, academics) is that their position is distinct, and so are their views. The interpretation of the Superfund program problems and issues from different points of view not only implies different criteria, but also the attribution of the situation to different causal processes.

In the selection of sources for the literature review, the reasons mentioned above were not the only factor that was taken into account. The sources were selected to contain criteria based on three different types of analysis: first, quantitative measures of the effects of policy implementation strategies, such as the analysis in documents from governmental offices (OTA, 1985); second, analysis of how a specific implementation strategy addresses key factors as identified by the authors, such as the study in political economy of Superfund by Barnett (1994); and third, analysis of how an implementation strategy affects causal relations of different aspects of the problem, such as the analysis in the document of Clean Sites (1994).

7.1.2 Selection of Congress and EPA Documents

In the second step of the analysis presented in this chapter (number 2 above), the importance of the documents to be analyzed was defined in terms of its relevance to the overall Superfund program, as found in the public debate.

The model of policy implementation by Thomas Smith (Nachmias and Nachmias, 1981) was used, as a framework for the identification of the characteristics of the documents to be selected. This model presents the complexity that policy implementation implies, and the interactions of the many different parties and forces in society. Once the policy making process finishes (i.e. a policy has been made), implementation will not usually proceed orderly to achieve the goals desired by policy makers. On the contrary, interest groups, affected individuals and organizations, as well as public officials, often attempt to force changes in policy during the implementation process.

Smith conceptualizes the policy implementation process as composed by four main elements:

1. The idealized policy, that is, the idealized patterns of interaction that policy makers are attempting to induce.

2. The target group, defined as those who are required to adopt new patterns of interaction by the policy. They are the individuals who must change to meet the policy demands, and therefore who are most directly affected by it.
3. The implementing organization, usually a government agency.
4. The environmental factors, those elements in the environment that are influenced by the policy implementation. Smith includes the general public and various special interest groups in this component of the process.

This four elements interact after the policy making process has been finished, and a specific policy has emerged from it. This public policy serves as a tension generating force in society: while policies are implemented, *tensions*, strains and conflicts are experienced by those who are implementing the policy, and by those affected by it (Nachmias and Nachmias,1981). The response to tensions and conflicts among the components of the policy implementation context in Smith's model, are *transactions*. Transactions and the existing *institutions* in the social environment generate feedback for both, the policy implementation process itself, and for new policy making processes.

Superfund is a unique piece of policy in the sense that the EPA is both, the implementing organization and a key target group. Under CERCLA, the EPA is the agency designated to implement the policy, but at the same time, this act mandates the EPA to take action to achieve the cleanup task. This generates a very particular situation in the policy implementation, and creates needs for the EPA, in terms of financial and human resources, that cannot be satisfied in reality and become important constraints in the agency regulatory environment. These constraints will be discussed further under section 7.2.

7.1.3 Review of the Policy Implementation

The third step in the policy review (number 3 above), was based on the same criteria used by different authors in the literature review, as described before. Also, the relevance of the policy directives, and policy implementation directives was based on the description of Church and Nakamura (1993), about the elements that an implementation strategy must include:

- A defining characteristic that can be easily described and understood
- A theory about why a particular approach will produce the desired result
- A notion of the series of tasks that must be performed, and how the agency should apportion its efforts
- Guidance on how governmental actors should behave toward other participants, how they should present themselves by words and deeds to communicate how they may be expected to behave and how they expect others to behave

As mentioned in the scope of work, the review of the cleanup policy and its implementation, and their relationship with technical aspects of the remediation of groundwater, did not attempt to design new strategies, nor to state formal recommendations as to how the EPA and Congress should proceed to improve Superfund performance. In other words, the purpose of the analysis presented in this chapter and the next one is not to establish policy recommendations, but rather to show how technical factors affect the policy process.

7.2 Identification of Issues Related to Unsuccessful Remediation

The remedial program of Superfund contains two dimensions closely interrelated, which are the technical dimension and the social dimension (Figure 7.1). Superfund is a good example of technology policy: a response to a scientifically identified problem related to human health and the environment, by policy makers facing social demands. The problem is originated mainly by technology utilization, and its solution is ultimately technical, yet solutions need to be implemented taking into account the social context. Figure 7.1 attempts to represent the main structure of the Superfund remedial program relationships, among the different entities and factors within the two principal dimensions. This graphic representation is an oversimplification, and its purpose is not to define a new approach to the analysis of Superfund interaction of factors, nor to set a frame to quantify the relative importance of the different components. The mere objective of this figure is to show the existence of two dimensions, one technical and one social, interrelated and composed of many factors. It will be used as a guide in the discussion of the issues found in the Superfund remedial program, once it has been decided that a particular site needs to be remediated.

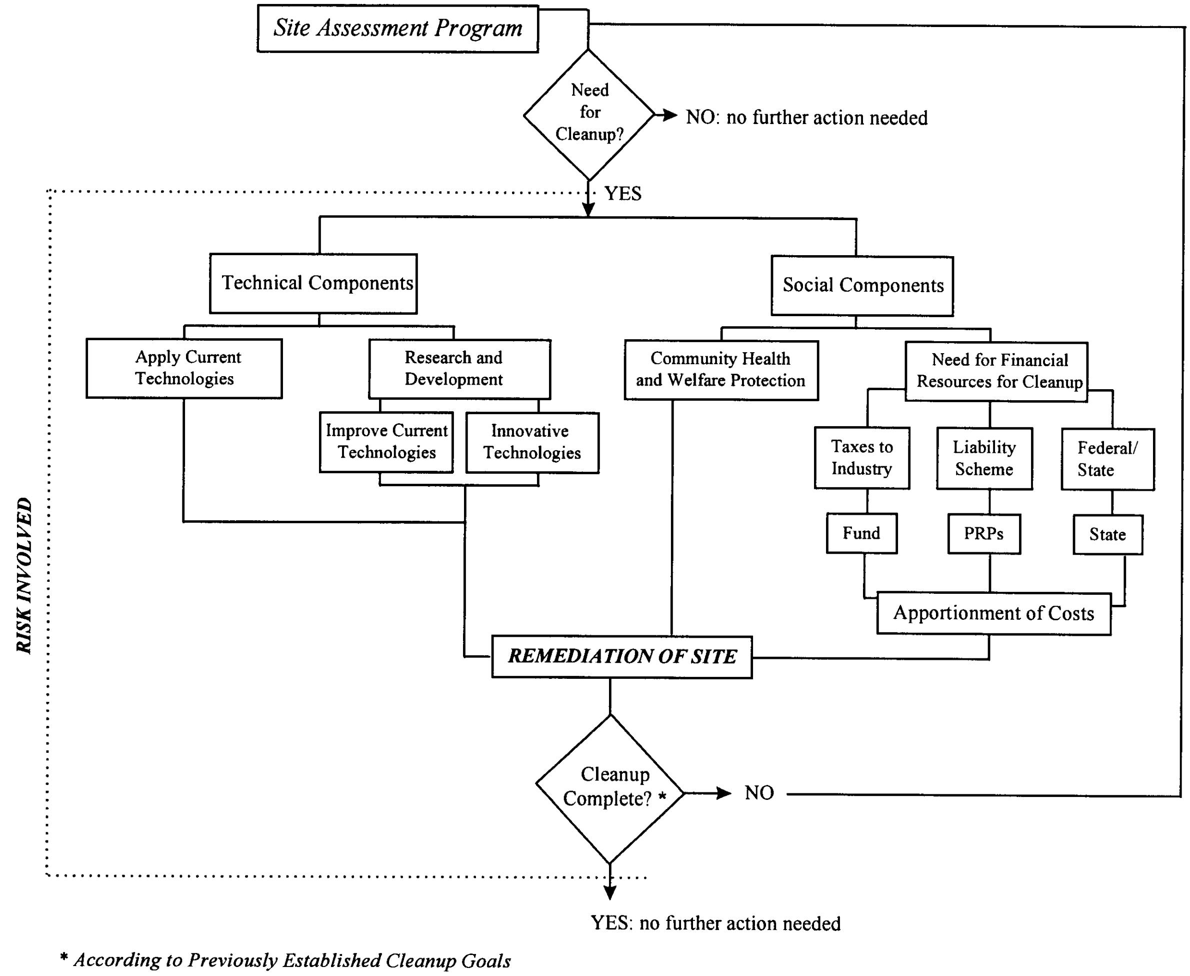

Figure 7-1. Main components and interactions in the Superfund remedial program. There are two clear dimensions: social and technical, both interrelated. During the remediation process, risk to human health and the environment is present, as defined by the agency. Financial risk is also present during the process due to uncertainties in the remedial action

Not all aspects generating inefficiency or controversy are directly related to the technical factors of the remediation. Many are related to administrative structures and procedures, enforcement strategies, and legal factors limiting the implementation of the program. This factors (included in the "social components" side of Figure 7.1), were consider out of the scope of this study, which is directed to determine the importance of technical issues in the remediation of groundwater at Superfund sites. However, the administrative core of the Superfund program is crucial for its success, and has been subject to profound analyses and reforms in an attempt to make it more efficient.

At the same time, one needs to keep in mind that technical aspects of the remediation will become important as long as the social context reacts to them, and gives them a place in the social agenda. Figure 7.1 shows how the technical components of the remedial program are one of the inputs into the remediation of a site. The inefficient or inappropriate technical input in the remediation, will hamper the elimination of the need for cleanup, retaining the need for protection of human health, and the need for financial resources.

Although this study focuses in the technical aspects of Superfund, and its relation to social components, it is necessary to describe some legal/administrative aspects that are characteristic of the program and have generated enormous debate, controversy and analysis. The first of these is the liability scheme, and the second one is the existence of very high transaction costs.

The liability scheme is established in the statute, and it is therefore a mandatory element in any Superfund implementation strategy. Under CERCLA, liability is: 1) *strict*, meaning that it is not required to demonstrate negligence on the part of the PRP, 2) *retroactive*, in the sense that past releases of waste that occurred before the Superfund enactment can form the basis for liability for remedial costs after its enactment, 3) *joint and several*, which implies that, each of the PRPs, can be potentially singled out to bear all of the cleanup costs. This liability scheme requires individuals, business, and other government units to absorb many of the cleanup costs and administrative expenses at sites where they are responsible parties, and it is ultimately enforced in court.

This strong liability scheme generates high transaction costs. This costs constitute a separate category, because they are not related to actual cleanup activities. As defined by Church and Nakamura (1993) "transaction costs consist of those expenses that are directly related to determining issues of liability, and in forcing the private parties to live up to their obligations under the statutes". The high transaction costs preceding actual cleanups, have been strongly and persistently criticized.

In his analysis of EPA strategies followed at different sites, Church and Nakamura (1993) provide an explanation to the origin of both, the strong liability scheme, and the high transaction costs it generates. The first element to consider is that the Superfund trust fund, is not enough to finance all the necessary cleanups, since Superfund sites are numerous and the costs of cleanup very high. Also, the administrative personnel available to the EPA are limited in number, experience and capacity. Therefore, the agency cannot assume all the administrative and managerial tasks required to achieve expeditious cleanups of the sites. These are two very important resource constraints in the EPA strategic environment, and the solution to both is the strong liability scheme, explicitly stated in the statutes.

Technical uncertainties in the remediation of groundwater under the Superfund program have an *ex ante* effect on transaction costs, since PRPs will want to negotiate settlements in which the future obligations are explicitly and very specifically stated. This *ex ante* effect is discussed in more detail below, under the section of cleanup costs.

With this view of the Superfund remedial program, the literature review resulted in the identification of six main issues, relating the technical components and the social components of the program:

1. Need to comply with the statutory mandate for permanent cleanups
2. The question "How clean is clean?"
3. Cleanup costs and their apportionment
4. Overall cleanup time
5. Public involvement
6. Need for innovative technologies

This six issues and the way in which they are linked to technical limitations and uncertainties are described below in detail. These six issues are not isolated, but in close relation. Despite the fact that the following sections try to explain each one of the issues separately, significant overlap will be found. This overlap arises because in some of the cases it is necessary to bring into discussion different factors, in order to better understand the importance of the issue being described.

7.2.1 Need to Comply With the Statutory Mandate for Permanent Cleanups

The mandate for permanent cleanups was the congressional response to the need for protection of human health and the environment, which was perceived as unattended during the first years of Superfund. The approach for the selection of remedies that will ultimately protect human health and the environment has changed over the years. Thus, this issue of remedy selection is an example of the dynamic character of the program. The evolution of the selection of permanent or non-permanent remedies has taken place mainly because the expectations from available technologies for groundwater remediation, and the approaches to evaluate risk have changed.

Before continuing the presentation of this aspect of Superfund and its relation to technical limitations and uncertainties, it is necessary to define what a containment remedy and a permanent treatment technology are:

> *Containment remedies* are intended to seal hazardous wastes on site of off site, restrict the movement of contaminants and prevent further groundwater contamination, and reduce community and environmental exposure. They do not address the sources of contamination. They generally involve relatively low capital costs and require substantial operation and maintenance costs which are borne by the states for as long as thirty years. *Permanent treatment technologies*, in contrast are intended to permanently change or destroy the hazardous composition of waste by chemical, biological, thermal, or physical means and to reduce toxicity, mobility or volume. They generally involve high capital costs and low or no long term operation and maintenance costs (Barnett, 1994).

As mentioned before, the selection of remedies for Superfund sites have evolved since the act was passed in 1980. Figure 7.2 shows the proportion of containment, treatment and innovative treatment cleanup remedies at Superfund sites , from 1982 to 1994.

In the first years of Superfund, a preference for containment or disposal technologies was clear. After SARA, in 1986, the proportion of these options was lower as compared to the option of treatment.

After 1988 the proportion of treatment and containment options has been stable, with a predominance in treatment options, and with an increase in the use of innovative technologies. However, after 1992, the proportion of the containment as an option of action for Superfund sites has started to slightly increase again.

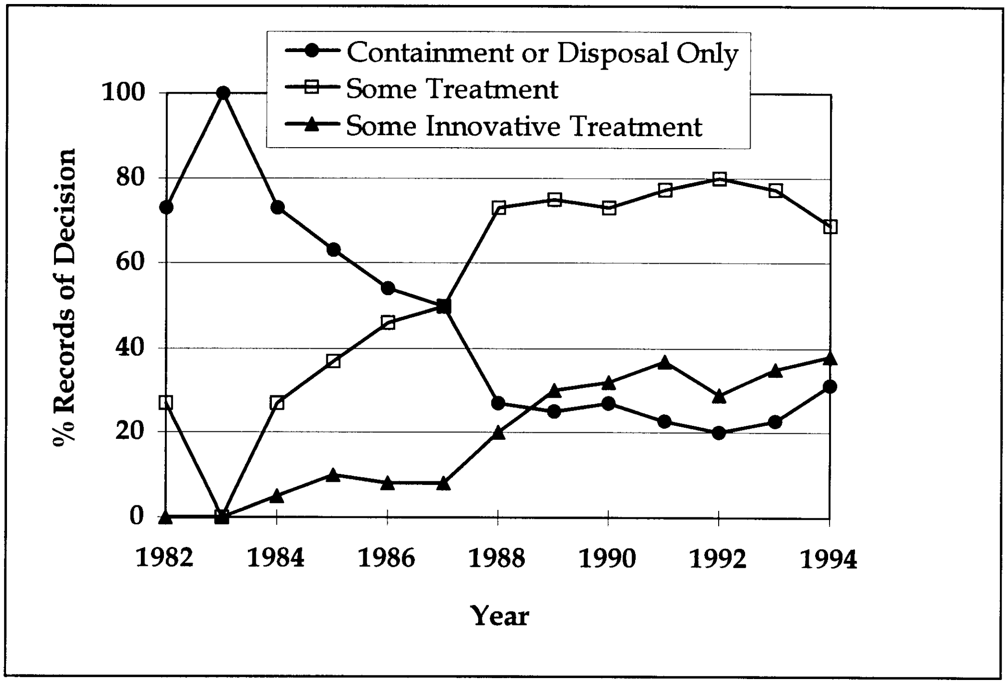

Figure 7-2. Remedial options selected from 1982 to 1994, according to data reported in records of decision (from Rubin et. al. 1996)

The preference for containment and disposal options during the first years of Superfund was greatly questioned by policy analysts. The Office of Technology Assessment (OTA, 1985) in its document *Superfund Strategy*, commented on the disadvantages associated with non-permanent options. This critique is based mainly on two factors derived from the results of the analysis: 1) no risk reduction is accomplished by containment or land disposal options, which represents failure to comply with the statutory mandate of protection of human health, welfare and the environment; 2) inefficiency of temporary solutions (e.g. high operation and maintenance costs, system failure), which was common in the first five years of Superfund. The OTA explains that containment was preferred by EPA because it was seen as a cost-effective remedy. However, the containment systems failure eventually resulted in higher costs. Barnett (1994) mentions that if long-term operation and maintenance costs and the likelihood of containment failure were included in cost-effectiveness comparisons, treatment technologies might be found to be relatively more cost-effective. This author also analyzes the lateral effects of the selection of non-permanent remedies on research and development of new technologies. From an economic perspective, being Superfund the market for treatment technologies, the selection of the "no treatment" option discouraged the investment on research and development for innovative technologies, since the likelihood of the selection of these technologies as an option for cleanup was perceived as very low. In its *Superfund Strategy* document (OTA, 1985), the OTA recommended to follow a two part strategy. Part I would consist on early identifications, initial responses, development of institutional capabilities for a long term program and "permanent remedial cleanups for some specially threatening sites". Part II would have a long-term character, with more extensive site studies and "focus on permanent cleanups, when they are technically feasible, at all sites that pose significant threat to human health and the environment".

The 1986 amendments strongly considered these recommendations and explicitly included the mandate for preference of permanent solutions. In Section 121 of SARA, dedicated to cleanup standards, Congress included the following statements establishing the policy directive regarding selection of remedies:

> §121(b)General Rules-(1) Remedial actions in which treatment which permanently and significantly reduces the volume, toxicity or mobility of the hazardous substances, pollutants and contaminants is a principal element, are to be preferred over remedial actions not involving such treatment [...]. The President shall select a remedial action that is protective to human health and the environment, that is cost effective, and that utilizes permanent solutions [...] to the maximum extent practicable (West, 1996).

However, in this same section, the statute gives the EPA discretion in this respect by stating: "if the President selects a remedial action not appropriate for a preference under this subsection, the President shall publish an explanation as to why a remedial action involving such reductions was not selected (West, 1996)". This last sentences acknowledge the existence of technical limitations in the remediation of some sites, particularly sites with contaminated groundwater, which at that time were starting to be recognized as very complex sites to remediate.

SARA had a clear impact in the decision making process of the EPA regarding the selection of remedy (Figure 7.2, after 1986). Treatment options became predominant generating greater costs, since treatment technologies are more capital intensive than land disposal or containment. Gupta et. al. (1995), in a study about the costs and benefits of Superfund cleanups, present some examples of the difference in costs of permanent and non-permanent remedial actions. At a wood preserving site the cost of capping contaminated soil was $400,000 (1987 US dollars), while the cost of excavation and incineration, which was the option selected by the EPA, was $11.8 million. For PCB sites, the implicit value of incineration over the cost of capping was $12 million at small sites (10,000 cubic yards), and $40 million at large sites (greater than 15,000 cubic yards). These authors present these figures as examples after an intense review of the costs of the program. The implicit value attached to permanence in selection of cleanup option is considered too high for these authors. They question the policy defined by Congress and suggest reconsideration of disposal alternatives:

> What must be asked is whether the benefits of more permanent cleanups [...] are worth the amount EPA is willing to pay for them. To answer this question it will be necessary first to define and then value the benefits of alternative waste disposal technologies (Gupta, et. al, 1995).

This clearly presents a different perception of the way in which the EPA makes decisions, from the perception of OTA (1985) and Barnett (1994), discussed above. This exemplifies the controversial character of the program, and in particular, the controversy surrounding the preference for permanence. More recently, debate about this issue was still part of the agenda. Rubin, et. al (1996) state that critics of the program consider the elimination of preference for permanence, and the approach of tailoring cleanups to actual health risks and future land use, as an injection of needed reality into the cleanup process.

Technical limitations in the remediation of groundwater are intrinsically related to the issue of preference for permanent cleanups. As presented above, during the first years of Superfund the selection of containment and disposal was criticized, and the possibility of failure of these non-permanent options was regarded as an important factor to consider. Nonetheless, the same argument became evident also for treatment options: the possibility of failure was also present when selecting them, and the health and financial risk associated were high.

After a decade of cleaning up Superfund sites, technical limitations were recognized, and the unfeasibility of the remediation of groundwater at some sites was acknowledged.

7.2.2 "How Clean is Clean?" Question

This issue is central in the Superfund program, and it has been and remains controversial. It is closely related to the issue of remedy selection, discussed in the previous section. The common element in both issues is the statutory mandate for protection of human health, welfare and the environment. This mandate requires the definition of risk, and the estimation of protection that derive in the selection of cleanup goals and the most appropriate remedy for an specific site. The key legislative aspects of this two issues are found in the same section of the statute, Section 121, dedicated to cleanup standards.

Determination of how clean is clean is crucial in the site assessment program and the risk assessment process. The definition of risk is based on a set of assumptions and determinations for which values of concentration of contaminants are needed. This values of concentration, acting as inputs in the risk assessment process are values used to define cleanup goals -with the consideration of other factors, as well. This process is immersed in uncertainty due to the difficulties in reliably measuring risk, and defining "acceptable" risk. The how clean is clean issue is therefore resolved most often based on political and not technical criteria.

The scientific uncertainties present in the risk assessment process are out of the scope of this work, which central object of study is the remedial process. However, the existence of these uncertainties are key in the Superfund program and need to be considered when analyzing or designing a policy.

Although defining the degree of cleanup is in great extent related to the process previous to the actual remediation of a site, the definition of cleanup goals is also a fundamental part of the remedial program of Superfund. Cleanup goals define the extension of the remedial process. In Figure 7.1, cleanup goals are implicit in the determination of completeness of the cleanup process (final box in the figure). As long as the cleanup goals are not accomplished, the cycle represented in Figure 7.1 will continue, with the risks and time associated.

After more than a decade of Superfund sites cleanup, this fundamental issue remains controversial. It is hence important to present the statutory language, to better understand the problem facing policy makers. In Section 121, CERCLA states:

> §121(d) Degree of cleanup: (1) Remedial actions [...] shall attain a degree of cleanup of hazardous substances, pollutants and contaminants released into the environment and of control of further release at a minimum which assures protection of human health and the environment (West, 1996).

For the case of hazardous substances, pollutants or contaminants that will remain on site, the statute mentions: "the remedial action selected shall require [...], a level or standard of control [...] which at least attains [a] legally applicable or relevant and appropriate standard, requirement, criteria or limitation". The applicable or relevant and appropriate requirement is known as ARAR. The statute proposes the use of ARARs established in any Federal environmental law, including but not limited to, the Toxic Substances Control Act, The Safe Drinking Water Act, The Clean Air Act, the Clean Water Act. It also gives the administrator the authority to require more stringent State standards.

The statute, therefore, do not establish a clear goal or set of goals for cleanup. It only gives broad directives to define these goals in a site specific basis. At the same time, in section 7.2.1. of this work it can be seen that the statute requires "protective", "cost-effective" and "permanent" remedial actions. The problem policy makers have to face at each site is to define these three terms -protective, cost-effective and permanent- and select a concrete cleanup goal according to them, from the possible sources of ARARs.

The OTA recognizes the difficulty of setting the level of cleanup, mentioning that it is not inconsistent to say that enough information exists to know that a site presents significant risk to warrant action, but not enough to know *precisely* (emphasis added) what a level of cleanup should be (OTA, 1985). They acknowledged the need for a detailed framework for determining cleanup goals nationally consistent in themselves or in the process used to reach them. The office stated the importance of explicitly attend this issue at the highest policy levels, in order to appropriately select the cleanup technologies and evaluate the performance of the program.

The assignment of cleanup goals in a site-specific-conditions basis, gives discretion to the EPA but at the same time requires the use of congruent decision-making criteria, in order to avoid an ad hoc approach to the problem. This is the intention of Congress establishing the use of ARARs in the statute. However, the wide margin of action results in a highly demanding policy process requiring participation of stakeholders (see section 7.2.5. below). Powers (1996) shows how land use and community preferences are key to selection of cleanup goals and remedy, and gives an example on how one community may settle for lower levels of cleanup to avoid incineration, while other might want a higher degree of destruction.

Steubner (1996), in a description of the situation of the Bunker Hill Superfund Site in north Idaho, explains how the conjugation of the great extent of the contamination, the technical limitations involved, and the high costs associated with the existing technologies for cleanup, make the cleanup to pre-contamination conditions practically impossible. Groundwater and soil contamination will remain at the site after the cleanup ends, bringing up the question of how clean is clean.

It is this link of the technical -and/or financial- impracticability of remediation, with the definition of cleanup goals, what makes the issue important in the analysis of the remedial process of the program. Ultimately, failure of a remedial system means failure to meet established cleanup objectives.

7.2.3 Cleanup Costs and Their Apportionment

The economic component of the Superfund program is one of the main ones. As mentioned in section 7.2.1, the cleanup costs are very high and the Superfund trust fund is limited with respect to the overall financial resources needed to cleanup all Superfund sites. The policy response to this budgetary constraint is the strong liability scheme, generating legal processes in which the apportionment of costs is ultimately defined in court. At the same time, this pre-cleanup process of enforcement generates high transaction costs that have resulted in a whole new, and very important issue. This section will focus on the actual cleanup costs, and the way in which the technical factors of the remediation affect them. However, as previously discussed, the high actual cleanup cost in many cases is one of the main factors originating long, expensive settlement processes. Thus, one should keep in mind the *ex ante* effect of the cleanup costs in the transaction costs, and the long administrative and legal processes preceding actual cleanup activities, and generating inefficiency.

In Figure 7.1, representing the remedial program of Superfund, once the need for cleanup has been established, the need for financial resources derives in three branches involving the federal government, the States and industry (through PRPs and the trust fund). The interaction among these three sectors of society are a central factor of the Superfund law. Church and Nakamura (1993) explain how the multibillion dollar Superfund embodied a substantial commitment of public funds to the national cleanup enterprise, but this was expected to be a revolving fund, used primarily in emergencies or when no viable PRPs could be located. Congress intended to accomplish the cleanup of all Superfund sites at the minimum cost to tax payers. The result is what Barnett (1994) sees as the driven factor of the Superfund operational inefficiency: "the conflict over who will pay the toxic debt". In his book *Toxic Debts and the Superfund Dilemma* (Barnett, 1994), this author studies the political economy of Superfund, and concludes that the root cause of the Superfund "dilemma" is "the fact that all program decisions impact on the distribution of cleanup costs and benefits either by specifying who will pay and who will gain or by determining the amount of these expenditures and benefits".

Congress policy, as reflected in the act, is to assume that the benefits of cleanup are large enough -or too difficult to determine, but substantial- to mandate cost-effectiveness as a criterion for selection of remedial actions, without explicitly mandating a cost-benefit analysis. This can be found in Section 121 of the act:

> §121(b)General Rules-(1) [...]. The President shall select a remedial action that is protective to human health and the environment, that is cost effective, and that utilizes permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable (West, 1996).

However, as discussed in section 7.2, the term cost-effective can be subjective, and context dependent. It has been previously mentioned that the effectiveness of the different systems is difficult to determine, since different criteria may be used to evaluate it. Nevertheless, the costs are also very difficult to predict in many cases.

Daniels (1996), mentions that professional managers are often unable to estimate what is the most a cleanup project could cost, the least, or even the average. This author reviews a model developed by professor James Diekmann, at the University of Colorado, connecting uncertainties present in remedial processes, and costs. The model categorizes risks as internal (e.g. excavation costs, placement costs, cover costs) and external. Until now external risks, related to regulatory changes, waste quantity, and technical factors forcing design changes, have been very difficult to factor into costs equations. According to Diekmann, these external risk factors do not show up as project line items, but have profound effect on remediation costs. This difficulties in predicting future risks implying potential costs that may be borne by the PRPs, the State or the Superfund, or some combination of the three, generate one of the main contentious issues in Superfund negotiations, which is the allocation of these risks. Church and Nakamura (1993) review the Superfund implementation approaches in many sites, and concludes that "the desire of corporate PRPs to obtain some degree of closure on as many aspects of the future risk as possible was present in nearly all the cases examined". The statutory response to this issue was the enactment of a number of provisions designed to ease the way to settlement. These devices will be discussed in detail later under the section of the policy response.

Cleanup costs are also associated to the establishment of cleanup goals, discussed in the previous section. It is generally very difficult to define cleanup objectives (i.e. negotiate them) at early stages of the site characterization process, when little is known about the magnitude of the contamination at the site. This is due to the fact that the different parties involved in the cleanup have much at stake in where the levels are set, since these levels will have an impact in the overall costs.

The relationship between the technical uncertainties and the cleanup costs is one of the most intuitive ones and easy to undestand. It is also, as we have seen, one of the most important factors determining the course of the Superfund program, and the way in which it is implemented.

7.2.4 Cleanup Time

This an important issue of Superfund, related to all other issues discussed in this chapter. To reduce cleanup time has been an implicit and explicit goal during the Superfund program, and significant discussion has been present in this regard. The policy mandate for cleanup in SARA does not include a specific and explicit directive with respect to the reduction of cleanup time. However, other directives in the statute are linked to cleanup time, such as the mandate for taking in to account the long term of maintenance costs while assessing the treatment technologies available, found in Section 121(b)(E) of the act. In the implementation of the policy, the response to this statutory mandate is found in the criteria to select cleanup options during the FS, established in the NCP (see section 2.2.1). However, the NCP do not explicitly mention cleanup time as a criterion. Long-term effectiveness, reduction of toxicity, mobility and volume, and cost-effectivenes are three criteria related to clenup time found in the NCP.

All different factors involved in the Superfund remediation process (Figure 7.1) are related to time. As long as there is a need for cleanup, the risk is considered to be present, financial resources are required, communities are being in some way affected, and the entire cycle is in place. Thus, the issue of time has been present in the Superfund discussion along the years, and some examples of the different perceptions are presented below.

In the OTA review of Superfund after its first five years (OTA, 1985), the office showed great concern about the length of the many different steps of the program, and the fact that only a few sites had been removed from the NPL. In a document presenting recommendations for cleanup policy improvement, Clean Sites (1994) mentions that the Superfund process is extremely slow, and that the delay often frustrates the different parties involved. PRPs may experience significant costs increases, people living near the sites may be left exposed to real risks, and the regulatory agencies receives substantial criticism for inefficiency. Curch (1993) shows that RI/FS process at major sites even when optimally efficient, can last one to three years, RD can take almost as long, and the actual remediation can consume a decade or more.

In the discussion of the time for cleanup, the links to other issues of the Superfund process is commonly present. Clean Sites (1994) mentions that in some cases, in which the process becomes too long, the parties are discouraged and in some cases prevented from taking quick action to reduce the risk at the site, or keep the problem from getting worse. In this case, the long process results in the failure to comply with the statutory mandate for prevention of human health and the environment.

There is also a link of cleanup time and the establishment of cleanup goals. Clean Sites (1994) presents that at some sites, the major cause of delay is that there are some specific problems for which there is no final remedy that meets the national risks reduction goal as stipulated in the NCP. It is important to appreciate that this factor is not determined by the implementation of the policy, and it is not either a result of administrative deficiencies. This is a problem related to the limitations of available technologies that exposes the need for the promotion of innovative ones.

There has been a slow recognition of the technical limitations as an important factor strongly related to the overall cleanup time. The comment of Clean Sites presented above is a good example. Church and Nakamura (1993) mention that relatively prompt cleanups can take place at simpler sites, regardless of the implementation strategy chosen. However, at complex sites, remediation decision making concerning technical issues is unavoidable lengthy, independently of how the governmental agency chooses to proceed. These authors recognize that at complex sites, the technical and engineering questions that must be solved before remediation can begin, make the process long. Also, the actual physical cleanup is frequently a time consuming process. The issue at complex sites is then not which of the different approaches to Superfund implementation promises speedy cleanup, but rather which is least likely to add delay.

Lately, cleanup time has become particularly important in a new approach to Superfund cleanup in some sites called brownfields. A brownfield is a Superfund site in which private money (not from PRPs) is invested for remediation and redevelopment. In this approach, a whole set of new issues is present, and the cleanup time is of course one of the must important factors from the point of view of the private investors. The sooner the site is remediated, the sooner the expected payoff can be realized.

7.2.5 Public Involvement

Public involvement is an essential part of the Superfund program. Public opinion was in fact a crucial factor in the enactment of CERCLA, in 1980. Barnett (1994) described how the bill passed due to a conjugation of political and economic forces and regulatory ideology at the close of the environmental decade (70's). At that time, a large segment of the public and many members of Congress perceived the magnitude of the hazardous waste threat to be extremely large. After more than fifteen years of Superfund cleanups, the public remains as a key player in the program.

In the first years of Superfund , the OTA recognized that more emphasis was needed to address the legitimate concerns of the public, improve public confidence in the program, and promote effective public participation in site identification, site assessment, initial responses, cleanup and long-term monitoring (OTA, 1985). The office recommended the inclusion of the public in the decision making process, and the provision of Federal support to aid communities in obtaining technical assistance. In the statute, Congress establishes a notice and comment decision making procedure and grants for technical assistance. The proposed plan in the statute is established in Section 117(a):

> Before adoption of any plan for remedial action to be undertaken by the President, [or] by the State [...], the President or State, as appropriate, shall take one of the following actions:
> (1) Publish a notice and brief analysis of the proposed plan, and make such plan available to the public.
> (2) Provide a reasonable opportunity for submission of written and oral comments, and opportunity for a public meeting at or near the facility at issue (West, 1996).

Public participation is in some cases crucial in the selection of remedial actions , and the definition of cleanup goals. As mentioned in section 7.2.2, for some communities less stringent cleanup goals are preferred, as long as incineration, which is a permanent cleanup option, is not carried out. Only through the public involvement and the consideration of other factors, such as future land use, is this kind of definition of cleanup objectives and remedial actions possible.

In residential areas, the public input and the management of the public opinion are counted among the most important factors in the remedial process. Rubin and Steubner

(1996) describe the importance of public involvement in Superfund remediations in this type of areas. In some cases, the biggest project challenge for the remediation of these areas is community relations, since in most of these sites the technical aspects are not specially complicated. These authors also comment about the fact that cleanups are not always appreciated, the reason being that the remediation process imply a great environment disturbance. Remedial actions in most Superfund sites involve the presence of a great number of people in the area, some kind of demolition, noise, and soil removal that usually takes place at the expense of the elimination of public or private gardens, trees, and recreational areas. The cleanup time, which is an issue discussed above, is an important factor that residents consider due to the environment disturbance linked to the remedial action.

Public involvement in the establishment of cleanup goals, and the remedy selection is an element necessary in complicated sites in which technical limitations and uncertainties are present. To promote community's basic understanding of the technical issues facilitates community relations.

7.2.6 Need for Innovative Technologies

In the discussion of the previous issues, the need for innovative technologies have been mentioned repeatedly. In the presentation of the case of the CS-4 plume in the MMR, the pump and treat system was mentioned to be useful only as a containment scheme, and its limitations were broadly discussed (see Chapters 5 and 6). However, the pump and treat alternative was extensively used during the first years of Superfund, and it is still very common. In chapter 6 the scientific and technical aspects constraining the remediation of groundwater were presented. These same principles of the fate and transport of pollutants in the subsurface are the ones used to develop new technologies for aquifer restoration.

New technologies will contribute to lower the cost of the remediations, and reduce the time for cleanup. In particular, in situ treatment technologies will reduce the risk to human health and the environment, without exposing people to the additional risk that is usually involved in ex situ schemes.

Great concern exist about the high costs of remediation of sites, mainly because the aggregated cost of remediating all sites would be extremely high. Clean sites (1994) mention that if new, less expensive technologies are not forthcoming, the effort to remediate the tens of thousands of contaminated sites could costs the nation hundreds of billions of dollars. They comment on the impact of this great expenditure that would have serious implications for government budget, corporate viability and economic growth. This high costs are associated to both cleanup time, and risk reduction. Existing technologies, in many cases cannot satisfy the objectives and preferences established in the Superfund law. The permanent risk reduction desired, at many sites, can only be achieved after decades of treatment and/or at a very high cost.

The risk associated to some of the existing technologies is also a concern, particularly for ex situ technologies involving incineration and large-scale removal of contaminated materials. This technology-associated risk partially offset any risk reduction at the site (Clean Sites, 1994).

Regardless off the great need for more efficient -less risk associated, less cleanup time involved- and less expensive technologies, their development and use have proceed slowly (Figure 7.2). According to Wagner (1991), three of the main obstacles for the incorporation of innovative technologies in Superfund remediations are: "1) public reticence with respect to the use of new technologies and the TISE (take it somewhere else) syndrome, 2) liability issues regarding response contractors and responsible parties, and 3) cost recovery for possible higher costs of new technologies". This author and Clean Sites (1994) also mention that market uncertainties are a key factor slowing the development of new technologies. The remediation market is a legislation-driven market, in the sense that the regulations determine the need for remediation and the degree of it. It has been mentioned previously that Superfund is a dynamic program: regulations and laws are constantly evolving. This is perceived as regulatory uncertainty, which in this case directly translates into market uncertainty -"the inability to gauge market size, potential and/or duration (Wagner, 1991)".

The strong liability scheme and its relation to technical uncertainties also affect the development and use of innovative technologies. Although PRPs are concerned about cost reduction, they may prefer not to use an innovative technology because they are aware of the risk of a technology failure, and they perceive the costs associated with this failure to be too high. On the other hand, when PRPs have been identified and EPA officials are less concerned about costs, they are more likely to select a proved technology based on the assumption of its success and the achievement of risk reduction, even if the technology selected is expensive (Clean Sites, 1994).

The unambiguous statutory response to this last obstacle for the development and use of innovative technologies is found in Section 121 of the amended act:

> § 121(b)(2) The President may select an alternative remedial action [...] whether or not such action has been achieved in practice at any other facility or site that has similar characteristics. In making such as selection, the President may take into account the degree of support for such remedial action by parties interested in such site (West, 1996).

The OTA recommended the promotion of innovative technologies (OTA, 1985), and stated the advantages they might represent, including the reduction of cost and time, and the reduction of treatment-associated risks, as the main ones.

Innovative technologies present the disadvantage of the increase in the degree of uncertainty regarding the possibilities of success at a particular site. The main response to this problem, as discussed later in this study, has been the implementation of pilot studies at different sites.

Chapter 8 presents the analysis of the reaction of Congress and the EPA to the issues identified in this chapter. Policy decisions are associated with the technical factors and the relationship discussed.

8. THE POLICY RESPONSE

Once the main issues concerning the remedial program of Superfund have been identified and presented, and their relation to technical uncertainties discussed, it is possible to focus on the governmental response by means of policy directives, and policy implementation.

The objective of the policy review of this study is to determine whether the scientific and technical uncertainties, present at any remediation process, have shaped the Superfund remediation policy and its implementation. Therefore, among the dozens of documents issued by the EPA and the statutes written by Congress, the attention was centered in documents addressing technical issues of the remediation process.

8.1 Governmental Documents Used for the Analysis

Four documents were identified as the main ones addressing the issues identified in the section 7.2:

1. The Superfund Amendments and Reauthorization Act of 1986
2. The Superfund Innovative Technologies Evaluation Program (SITE)
3. The Superfund Accelerated Cleanup Model (SACM)
4. The latest EPA administrative reforms (1996) for the Superfund program.

SARA is a key document in the analysis of remediation policy, since it was the first governmental response to the problems encoutered during the first five years of the program. These problems were administrative, financial, legal and technical. During these first five years, technical uncertainties and limitations were encountered to be much more important than predicted, and combined with administrative inefficiency, they generated an impresion of complete failure of the Superfund program.

The need for innovative technologies, as discussed in section 7.2.6, has been evident through the years of the Superfund law, and the response to this need was the implementation of the SITE program. This document is mainly concerned with technical issues, and its purpose is to directly address one of the main needs of Superfund, regarding the limitations of the current state-of-the-art remediation technologies.

The SACM was designed as a new approach to the remediation program. The model incorporates many administrative changes regarding the implementation of the remediation policy, and directives that pressumibly reduce the sources of delay in the cleanup process. Many technology-related directives are included, which makes this model necessary to analyze in order to adequately conduct the policy review presented in this chapter.

The EPA carried out administrative reforms in 1996, directed to optimize the cleanup program. Some of these reforms are directly related to the remedial systems selection, the incorporation of public opinion in the remedy process, and the review of RODs from previous years to actualize remedies selected in the past. All of these reforms with technical components need to be analyzed to determine the effect that technical aspects have on policy making and policy implementation.

Other EPA, more specific documents, were also reviewed. These documents were directly concerned with technical issues present in the remediation of groundwater.

8.1.1 SARA

Many aspects of SARA have been discussed already in the previous sections. In Chapter 2, the origin of the amendments and the political context in which they were enacted were described. It is important to bear in mind that the amendments were enacted after the first five years of Superfund, in which the perception about the toxic threat did not change, and the knowledge of the technical limitations for remediating complex sites were slowly been recognized.

As discussed in section 7.2.1, the preference for permanent treatment options was introduced by SARA due to two main aspects recognized during the first five years of Superfund: the fact that disposal and containment options did not reduce the risk at the sites, and the perceived inefficiency of this temporary alternatives (e.g. high operation and maintenance long-term costs, and the possibility of failure). Therefore, SARA in its Section 121(b) introduced the mandate for preference for permanent technologies, and this mandate had an important effect in the remedy selection process (see Figure 7.2).

The mandate for preference for permanent options in the selection of remediation systems was the policy response to the need for protection of human health and the environment. The effectiveness of this policy solution is highly questionable, particularly because it was based on the assumption of successful implementation of treatment systems. The technical limitations in the remediation of groundwater became evident during the first decade of the Superfund program, and therefore, the preference for permanent solutions is now deemed unrealistic in many cases. The EPA has used the discretion provided in the act, and has promoted different approaches to the risk assessment and remedy selection process. This new approaches will be discussed later in more detail, under the presentation of the SACM and the latest administrative reforms of Superfund.

Protection of human health and the environment is in practical terms defined by the answer to the question "how clean is clean?". SARA stated broad directives to define cleanup goals, and established the use of ARARs as a national standard rational for the definition of the extent of cleanup. However, SARA did not established specific cleanup objectives for categories of sites, but rather left the assignment of cleanup goals in site-specific-conditions basis. This site-specific policy has allowed the EPA to exercise its discretion and creativity, and the how clean is clean issue is now a process solved in a regional/local basis, in many cases with an intense public participation process. This will be discussed later in more detail.

The economic aspects of the program, crucial in its development, implementation and performance, are attended in SARA, also. The 1986 amendments incorporate a number of very important provision directed to ease settlements, and reduce transaction costs. These provisions include settlement devices in which the agency assumes some of the costs, such as mixed funding, *de minimis* settlements, and releases from future liability. Church and Nakamura (1993) analyzed this provisions and concluded that they have two characteristics in common: they embody departures from pure joint and several liability toward some notion of what the authors call "distributive justice and fairness", and they involve governmental assumption of some elements of the cleanup and transaction costs at a site. In general, this devices involve the assumption of costs in its three dimensions: cleanup, administrative, and future risk. This last type of costs, as discussed in section 7.2.3, generally rise the total cleanup costs in a considerable way, particularly in complex sites including groundwater remediation, and have a great *ex ante* effect on transaction costs.

In addition to this provisions, which are more directly related to the reduction of transaction costs, SARA stated again the cost-effectiveness as a criterion for selection of remedies. We have discussed already the ambiguity of this term, and the advantages and disadvantages that this ambiguity have for policy implementation: the little guidance that it provides for specific sites (disadvantage), and the discretion that the agency can make use of, to comply with the cost-effectiveness criterion (advantage).

The cleanup time issue is not directly address in the 1986 amendments. It is, however implied in some of the directives provided in the statue, as discussed in section 7.2.4, particularly in the use of long-term costs as a criterion for selection of remedies. The NCP, did not include time for reduction of risk in its criteria for remedy selection. As a result of this lack of a nonambiguous directive for reduction of cleanup time, the Superfund process commonly resulted a very slow one. The resulting consequences of this very long time to take significant action, were that the program was strongly criticized for inefficiency, the communities surrounding sites were left in many cases exposed to significant risks, and the different parties involved were generally frustrated (Clean Sites, 1994). The negative associated effects of the long time taking to remediate sites have been already discussed in section 7.2.4. The most important response to this issue by the EPA is the SACM, that will be presented later.

Regarding the issue of public involvement in the Superfund process, SARA responded with significant provisions, mainly in Section 117 of the act. This section ratifies the notice and comment structure of the process, but also, establishes the grants for technical assistance. These grants are intended to provide communities affected by a Superfund cleanup, with technical assistance regarding the nature of the contamination problem, and any of the steps of the NCP. The establishment of these grants is the first step in the recognition of the importance of the public involvement in the process.

With regard to the promotion of innovative technologies, Congress addressed the issue adding Section 311(b) in SARA, with provisions for the establishment of a research and demonstration program. The act defined alternative or innovative treatment technologies as:

> technologies, including proprietary or patented methods, which permanently alter the composition of hazardous waste through chemical, biological or physical means so as to significantly reduce the toxicity, mobility or volume (or any combination thereof) of the hazardous waste or contaminated materials being treated (West, 1996).

In Section 311(b), the act contains very specific directives for the establishment of the program, its administration, management of contracts and grants, use of sites, demonstration assistance, field demonstrations, criteria of evaluation, technology transfer and training.

Also, SARA included Section 121(b)(2), in which provided discretion for taking remedial actions not achieved previously in other sites, given the support of the parties involved in the remedy selection.

An indirect measure facilitating the research and development of innovative technologies was the inclusion of the preference for permanent remedial actions. As discussed in section 7.2.6, the selection of treatment options, instead of containment or disposal options, was a positive market signal for the development of treatment technologies. However, the perceived regulatory uncertainty, translating to market uncertainty, and the poor public acceptance of new non-proved technologies, obscured the signal and slowed the process of development of technologies.

According to the model of policy implementation presented in section 7.1, CERCLA, the original act of 1990, represents the idealized policy, product of a policy making process. We have discussed in this and previous sections, the way in which some environmental factors (e.g. technical limitations and uncertainties), and the response of the target groups (PRPs, States, and the EPA itself), and the implementing organization (the EPA), interacted and transacted during the first five years of Superfund, generating the feedback that resulted in the enactment of SARA. This act of 1986, represents just as CERCLA, the idealized policy generating tensions experienced by the target group and the implementing agency. In the next sections, the strategies for the implementation of SARA followed by the EPA will be presented.

8.1.2 The SITE Program

The introduction in SARA of the mandate for preference of treatment technologies, the use of ARARs requiring very low levels of contamination as cleanup goals, and the provisions for the implementation of a research and demonstration program, created the appropriate political and legislative conditions for the creation of SITE. However, the limitations of existing technologies to remediate the subsurface had been already recognized by the agency (i.e. the technological environment was already appropriate for the creation of SITE). In fact, a program for research, development and demonstration of innovative technologies was already in the planning phase when SARA was enacted. This program was first advertised in February 13 of 1986 in the *Commerce Business Daily* (Wagner, 1991).

The purpose of SITE is to create a framework for research, develop and test remedial technologies (EPA, 1989b). The approach followed to accomplish this objective is the use of funding and technology transfer mechanisms. The program is composed of five divisions: demonstration program, emerging technologies program, measurement and monitoring technologies development program, innovative technologies program, and technology transfer program.

It is interesting to analyze the results of the program, after many years of its creation. Wagner (1991), in a study of the program and its results, concludes that SITE appears to be managed by the EPA in a competent manner. However, this author maintains that it is not clear if the program is an important funding alternative for remedial technology developers. According to EPA data presented in Figure 7.2, the use of innovative technologies have been increasing. The increase was particularly important between 1987 and 1991.

The creation and implementation of this program is the response to the need to promote innovative technologies, discussed in section 7.2.6. It is probably the clearest example of policy response to technology limitations in the remediation of Superfund sites.

8.1.3 SACM

This program was created in response to the necessity of speeding up cleanups, in order to better deal with budgetary constraints and meet the high expectations of the public. The program is characterized for an emphasis in reduction of the time for cleanup, and the associated reduction in costs.

The main objective of the program as defined by the agency is to make Superfund work better, and deliver results the public value, such as the reduction of the acute risk, and the restoration of the environment on the long term.

The program is composed of three main components: 1) a one step site screening and risk assessment, 2) give regional management teams discretion to take early action to reduce immediate risk to people, and perform long term cleanup to restore the environment, and 3) combine enforcement, community relations and public involvement throughout the process.

The main aspects deriving from this three components of the program are the distinction of short term and long term actions, and the emphasis in the regional management approach and public involvement.

The agency called the program the “new Superfund paradigm”, and it actually represents a significant transformation in the strategy for cleanup of Superfund sites, in which the how clean is clean question becomes central. In the description of the program as a new approach to the remediation problem, the agency mentions that the “new” Superfund must be realistically achievable (i.e. realistic cleanup commitments), and focused on rapid protection of people and the environment. In the SACM document (EPA, 1992) the EPA mentions that the Superfund program must be “disconnected from the single and unattainable goal of returning all groundwater to pristine condition”.

Under the SACM, the remediation process is divided in short (less than 5 years) and long (more than 5 years) term phases. The regional approach is encouraged through the formation of the Regional Decision Teams (RDT), and public participation if favored.

The RDT institutes short term activities, including cleanup (in many cases almost all the risk is reduced in this phase), and determines the need for long term remediation. If the long term remediation is deemed necessary, the RDT lists the site in the Long Term Remediation List, and the agency here mentions that this list is in fact the NPL.

In this separation of short and long term, in which significant action is taken in the first five years and the site is listed on the NPL *after* the short term action is completed, a fundamental administrative problem arises. Under CERCLA, and the NCP, only sites listed in the NPL are eligible for financial resources from the fund, therefore all short term actions would be financed by PRPs. The complication exists due to the fact that settlements are uncommon in the first years of a Superfund cleanup. Thus, the original SACM document emphasized immediate response, but did not provided an answer as to where the money needed for that action would come from. SACM however, did encouraged enforcement, as one of the main objectives of the program, and in fact issued a document in this respect (EPA, 1992b).

Due to this and other apparent contradictions in the Superfund implementation suggested by SACM, and the mandated implementation strategy in CERCLA and the NCP, the agency issued a series of guidances, one of which directly address the issue of compliance with the act (EPA, 1992c). The importance of ensuring compliance is that this strengthen the agency's ability to recover its costs, "defend the selected response actions on a site-specific basis, and to retain full support for the SACM initiative from Congress and the public (EPA, 1992c)".

In this document presenting the strategies for implementing SACM under CERCLA and the NCP, the agency accentuate the discretion and flexibility provided by Congress in the act and the plan. Also, the guidance describes specifically the effect of SACM implementation on the NPL, and establishes a strategy for maintaining sites eligible for Superfund money, even if substantial reduction is accomplished during early actions, and the site is consider not eligible for long term remediation.

This series of administrative specifications were needed on account of the fact that the SACM was designed to operate relying on the discretion and flexibility provided by Congress. The agency reacted to the impracticability of remediating groundwater in many cases, designing a new approach for the remediation of sites almost in conflict with the statutory mandate. The EPA recognized this and mentioned that “experience from the SACM pilot projects may also prompt changes in national policies (EPA, 1992c)”.

The single site assessment characteristic of the SACM responds to the necessity of reducing time and costs in the program. The most important step taken by EPA in this regard is the elimination of the difference in remedial and removal actions, eradicating the redundancies in the assessment of a site.

SACM considered innovative technologies as a viable option, offering opportunities for cost efficiencies. However, this model for cleanup did not established concrete directives to incorporate this technologies as a significant factor in the reduction of time and cost. About existing technologies, SACM introduced the concept of standardized cleanups for similar sites, suggesting their use to expedite cleanups generating cost efficiencies. This concept of standardized cleanups would be developed later in more detail and incorporated in the administrative reforms of 1996, as presumptive remedies. This aspect will be discussed later in the description of the new reforms.

The previous discussion has concentrated mainly in the short term response. However, groundwater restoration falls in most of the cases in the domain of long term restoration. For long term actions, the approach proposed by SACM is also significantly different from the one practiced during the first decade of the program. According to SACM, sites will be listed in the long term remediation list after “clearly” establishing the need in the site assessment.

The question of how clean is clean is central in this issue, and to facilitate the implementation of this idea, public participation is fostered. Regarding the long term remediation under SACM, and the importance of community relations in this respect, the agency mentions that “of greatest benefit, the public would understand that the actions placed on the [long term remediation] list would require many years, if not decades, to cleanup, but would pose no immediate threat at all to existing populations (EPA, 1992)”.

The main characteristic of the SACM, for the purpose of this study, is the fact that this model of Superfund implementation removes the groundwater restoration question to a separate part of the decision making process. By doing this, it gives the RDTs the opportunity to decide the feasibility of groundwater restoration given limited funding. This, in principle, is inconsistent with the statutory mandate for permanently cleaning up Superfund sites. The SACM clearly relies in the flexibility and discretion provided by Congress in the act. This is a policy decision motivated by technical factors (i.e. impracticability of groundwater remediation in some sites) needed to deliver results appreciated by the public.

In the conclusions of the document presenting the SACM, the EPA mentioned: “A program [...] having as a separate activity, the long and difficult job of environmental media restoration, has a better chance of being understood, appreciated, and, therefore, publicly supported (EPA, 1992)”.

8.1.4 Latest Superfuind Administrative Reforms

Since the SACM was established providing institutional support for regional decision making, and the implementation of pilot projects, some changes to the program had place within the existing statutory framework. Since 1993, the EPA launched three rounds of administrative reforms, based mainly on the pilot projects. This study presents the latest reforms, described in the *Superfund Administrative Reforms Annual Report* (EPA, 1997), which are significant in terms of volume, depth and prospective results. Also, the analysis of these reforms provides a vision of the current situation of Superfund implementation, after more than 15 years of the program.

The key aspects of the reforms are:

1) The prospective reduction of cleanup costs, achieved through the establishment of a Remedy Review Board, updating remedy decisions, and implementing remedies selected with community participation.
2) Reducing litigation and increasing fairness
3) Increasing public involvement, and maintaining the regional decision making approach.

One of the primary components of the new reforms is the change in the risk evaluation approach, and the enormous emphasis in this step of the Superfund process.

There are reforms directed to many aspects of the risk evaluation. These include the establishment of national criteria on Superfund risk assessment, the standardization of the process, the promotion of risk assessment performed by PRPs and with community participation, the encouragement of risk-based priority for NPL sites, and the consideration of land use in remedy selection. All this reforms have the principal objective of accelerating settlements (reducing transaction costs), setting realistic cleanup goals, and reducing the costs of cleanup. The emphasis in the evaluation of risk is congruent with the SACM, in which immediate reduction of risk is a priority, and is also the main criterion of the evaluation of the success of the program. The chief factors behind the emphasis in risk assessment in the SACM and the new reforms, are the budgetary constraints, the need for reducing transaction costs, and the impracticability of remediating sites with extensive groundwater contamination.

Regarding the costs of cleanup, many reforms are proposed. Some of them are clearly directed to the mere correction of administrative inefficiencies detected through the years, and therefore are out of the scope of this policy review. However, there are three important technology-related reforms related to the reduction of cleanup costs, which are:

1) the establishment of a National Remedy Review Board, which is in charge of the review of high-cost cleanup plans, prior to final remedy selection.
2) the update of remedy decisions made in the past, consisting in the review of past RODs, many of which have not yet been implemented. The long and slow process that characterized the first years of the program, as well as budgetary constraints, have resulted in the delay of the implementation of some of the RODs. With many more years of experience in the remediation of sites, the update of decisions may result in important cost savings.
3) issuing "rules of thumb" for remedy selection, or remedy selection management flags. This are basically key principles and expectations in the Superfund remedy selection process.

All these three reforms are related to the selection of remedies. EPA encourages the selection of what it calls "presumptive remedies". These presumptive remedies are basically the same concept first outlined in SACM, in which the EPA selects a type of remedy that has proved to be effective. In the annual report, agency states "where EPA has accumulated a body of experience in addressing a particular type of site, it has identified standardized remedies known as 'presumptive remedies' to eliminate the need for costly studies and processes that are likely to yield the same process (EPA, 1997)".

The common element in these reforms is the confidence on the part of the agency, to select some type of remedies with a high degree of certainty about their successful performance, all based on more than a decade of experience. Powers (1996) mentions that the most important aspect of the use of presumptive remedies is that there is an element of "no fault" in their use. The liability is released in great extent in sites where presumptive remedies are used. This author also explains that the concept of pre-approving remedies (presumptive remedies) began to emerge in the early 90's, as EPA gained experience and began to see patterns. It became clear that "the same conclusions were being reached at 80 to 90% of similar Superfund sites". It is interesting to compare this statements with the comments of the OTA in 1985, in its analysis of the first five years of the program. In this analysis, the office wrote: "there is too little information in most sites to decide about permanent cleanup, particularly when there are no national cleanup goals. Furthermore, there are not enough people with experience in this area to implement a large, permanent cleanup effort (OTA, 1985)". Clearly, the experience gained by the EPA and contractors working on the field have changed the perception of some technical aspects of the Superfund program.

As opposed to SACM, the administrative reforms of 1996 do not emphasize the reduction of cleanup time. This, however, underlies most of the reforms directed to increase efficiency of the cleanup process.

The fact that the use of presumptive remedies is animated does not mean that innovative technologies are ignored. It is important to keep in mind that presumptive remedies are "available" for only some of the types of Superfund sites. The reforms address the need for the promotion of the development of innovative technologies by including a very important proposal. This is the Risk Sharing Initiative implementing innovative technologies. In this initiative, the EPA agrees to borne a considerable percentage of the cost of the innovative technology, if this one does not fulfill expectations and additional remedial action is necessary. This is a clear response of the EPA to the technical uncertainty involved in the use of new technologies in field scale.

An indirect positive effect for the promotion of innovative technologies is the standardization of the remedy selection process mentioned above, which reduces market uncertainty.

Changes in the risk evaluation approach due to technical impracticability and limited budget, need to be accompanied by the promotion of public participation. Public involvement is fostered in this reforms through the promotion of community advisory groups, involvement in the enforcement and in the remedy selection processes, and the establishment of a Superfund Ombudsman in every region. The promotion of this last directive has very good prospective results, since the Ombudsman will provide a good vehicle for negotiation and conflict resolution. The importance of the public involvement and community relations are incorporated in these reforms regarding the public.

In summary, the Superfund reforms of 1996 reflect a very important element in the technical side: the greater degree of certainty in the remediation of sites. After more that a decade of cleanup efforts, the EPA (and other parties involved) faces less technical uncertainties, and understands and accepts the technical limitations in the remediation of groundwater, so that it is possible to provide standard guidance for remedy selection. Public involvement is recognized to be crucial, particularly with regard to the risk evaluation, from which the extent of the remedy is determined. Public input is therefore promoted.

8.1.5 Other Documents

Since this study focuses on the technical limitations and uncertainties in the remediation of groundwater, two documents issued by the EPA were reviewed as part of the policy implementation analysis. This two documents provide technical guidance related to groundwater restoration.

The first document, issued by the Office of Solid Waste and Emergency Response, is the *Guidance for Evaluating the Technical Impracticability of Ground-*

Water Restoration (EPA, 1993). This document is mainly technical, and addresses most of the issues discussed in Chapter 6, regarding technical factors limiting the restoration of groundwater. Emphasis is made on sites with DNAPL contamination, due to the difficulties present in their characterization and remediation (see Chapter 6).

Despite the strong technical character of this document, its purpose is not only related to technical issues, but also concerned with the proposal of alternative strategies to comply with the central statutory mandate of CERCLA. As defined in this guidance, its purpose is "[to] clarify how EPA will determine whether groundwater restoration is technically impracticable, and what alternative measures or actions must be undertaken to ensure that the final remedy is protective of human health and the environment (EPA, 1993)". An explicit acknowledgment of the impossibility of restoring groundwater to pristine conditions (i.e. unfeasibility of permanent remedy instrumentation) is present in this important technical document.

The alternative remedies suggested by this technical guidance are remedies based on exposure control, source control, and aqueous plume remediation. The exposure control consists mainly in the use of institutional notifications and restrictions on water supply. The source control requires the location and treatment or removal of the source of contamination, where feasible and where significant risk reduction is expected, regardless of the agency's previous determination of the technical impracticability of groundwater. The aqueous plume remediation is not a clearly achievable goal, and the EPA provides guidance for situations in which the plume will not be remediated.

As discussed in Chapter 6, the remediation of the aqueous plume will not be possible if the source is not treated, removed, or controlled. In many DNAPL-contaminated sites, this will be the case, and the EPA guidance proposes alternative solutions. These solutions consist on hydraulic containment of the leading edge of the plume, establishment of less stringent cleanup levels, and natural attenuation or natural gradient flushing of the plume.

It is important to note that these three alternative remedies proposed by the EPA in this document, for the case of impracticability of groundwater restoration, are non-permanent solutions, and in fact the last two are "no action" alternatives. EPA, in these cases requires the presentation of sufficient and strong evidence of the impracticability of the remediation, and assurance of institutional controls for water supply, reliable and enforceable, to prevent exposure. It also requires the consideration of State and community acceptance of the alternative remedy.

The second document reviewed as part of the policy implementation analysis is the *Presumptive Response Strategy and Ex-Situ Treatment Technologies for Contaminated Groundwater at CERCLA Sites* (EPA,1996). This is also a technical guidance, containing most of the information presented in the first guidance (EPA, 1993), but focusing on the use of presumptive technologies for ex-situ treatment of the groundwater. Presumptive response strategy, as defined in the previous section, is an approach emphasizing better integration of site activities and more frequent use of early actions, in a phased fashion.

This guidance developed more concise directives for DNAPL sites, defining early actions such as containment of the plume, containment of the hot spots of the plume, controlling the source, and removing or treating the source to the extent practicable. The hot spots in a plume are associated to sources, therefore, the second and third actions are essentially the same.

This document also describes the strategy to follow for long-term actions. The guidance refers to DNAPL sources as principal threats, but at the same time, acknowledges the impracticability of the sources remediation in most of the cases. For this reason, the guidance provides directives to request ARAR waivers after a RI has been completed and *before* the final remedy decision is made. An ARAR waiver is the agency's permission for remedial actions at a site in which compliance with an ARAR is not expected, due to technical impracticability of attaining such a goal. The guidance emphasizes the fact that "data from remedy performance are not always necessary to justify an ARAR waiver due to technical impracticability (EPA, 1996)".

The two documents discussed also address some administrative issues, such as the technical impracticability review and the decision process, specifying all steps that should be taken by the agency and other parties involved.

8.2 Concluding Remarks

Technical factors influence cleanup costs and time, and define the feasibility or unfeasibility of completely remediating a site. When unfeasibility is a reality, like in the case of groundwater contaminated with DNAPLs, the question of how clean is clean arises, public participation becomes crucial, and the statutory mandate for permanence in cleanup becomes unattainable. Also, in such cases, the need for the development of innovative technologies turns an evident necessity.

Congress policy making process, and EPA's policy implementation have reacted to technical factors such as the unfeasibility of remediating a site, by implementing flexible approaches to evaluate risk and protect communities. The public has been recognized as a key player in cases in which permanent cleanups are not possible, and strategies have been designed accordingly to incorporate the affected communities into the Superfund process.

9. CONCLUSIONS

The first objective of this study was to develop a groundwater flow model to get a comprehensive understanding of the groundwater system at Cape Cod, Massachusetts. Using the model as a tool, different pumping schemes for the extraction of contaminated groundwater were analyzed. The final purpose of this work was to study different characteristics of the containment pumping system existing at the site, to predict an effective pumping scheme, and to analyze the possibilities of using this system to contain a deeper plume.

From the findings of this study, the following conclusions can be made:

Well fences of seven and eight equally-spaced wells, pumping a total of 140 gpm uniformly distributed, resulted in very similar capture zone geometry. These geometry are also very similar to the capture curve resulting from the pumping scheme currently operating at the MMR.

Since the seven well simulations corresponded to wells that are part of the existing well fence, this seven well system would be an effective alternative pumping scheme for the containment of CS-4. The operation and maintenance costs would presumably be reduced and the capture of the plume would still be attained.

The 13-well pumping scheme currently operating at the MMR showed interesting features regarding the different ways in which can be operated to respond to different field conditions. The 13-well system showed great flexibility in terms of achieving the same capture curves geometry when one of the wells can not be operated. The increase in pumping rate in the adjacent wells clearly offsets the loss in hydraulic control due to the missing well.

Supporting the conclusion stated above, the seven-well system proposed as an alternative proves that the redistribution of pumping rates is very effective to generate adequate capture zones. However, other results showed that as well spacing increases considerably, the increase in pumping rates may not be the best option to achieve an effective capture zone. In such cases, relocation of wells should be considered.

If as a result of monitoring and an improved site characterization, the CS-4 plume were redefined as a bigger plume, the existing well fence could be modified in its operation and still capture the contaminants. Increasing pumping rates with the 13-well, results in an increase of the capture curve dimensions.

An increase in pumping rate resulted in an expansion of the height of the capture zone. The amount of water drawn from the lower portion of the aquifer remained approximately constant, and thus the effect of this increase in pumping rate is more noticeable in the upper section of the aquifer. This might be result of the lower conductivities (horizontal and vertical) of the lower part of the aquifer. Therefore, to capture the FS-28 plume, the increase in pumping rates may not be the most effective alternative. A better option would be to place the wells deeper in the aquifer, incurring, of course, in greater costs.

Aquifer heterogeneity is a factor that may influence the geometry of capture zones for a given pumping condition. Simulations to explore the influence of heterogeneity are recommended.

As a general conclusion, to provide the necessary hydraulic control for the containment of the CS-4 plume, the 13-well fence currently operating at the MMR proved to be effective and flexible. Modifications to this pumping scheme will need to consider well spacing, well screen depth and pumping rate distribution. The system is not appropriate to contain the newly characterized FS-28 plume.

The study of the CS-4 plume site, complicated now by the discover of the FS-28 plume, and the history of some other Superfund sites showed that the existence of technical uncertainties and their associated risk is a common reality. A review of the Superfund remediation policy was performed in order to determine how these technical uncertainties have affected the policy making process, and the policy implementation. Conclusions from the policy review are presented below.

Policy review

Superfund is a complex policy in itself, and unique in the sense that it is implemented by an agency that, at the same time, is also one of the main target groups, responsible for the cleanup program that the policy mandates. The EPA operates under budget and management-capability constraints, due to the fact that the cleanup of the subsurface is a technical task characterized by high complexity and high costs. The policy solution to this implementation problem, was the establishment of a strong liability scheme, that generated long processes of enforcement, ultimately attained in court. This enforcement action was usually complicated even more by the fact that there is no accurate method to measure risk to human health derived from the contamination of the sites. Even after establishment of "acceptable risk" levels as cleanup goals, the remediation of many sites, particularly those with groundwater contamination, proved to be much more complex than presumed by Congress, generating unpredictable future costs.

The main issues identified in this study, related to technical uncertainties in the remediation of groundwater, are interrelated and essential in Superfund policy implementation. These issues are the cleanup costs and time, the extent of cleanup, public involvement, development of new cost-efficient technologies, and the need to comply with the statutory mandate for permanently clean up sites.

Technological factors of the remediation are related to each one of these issues. There are some clear and intuitive relations for some of the issues (e.g. if the use of existing technologies implies extremely high costs, then there is a need for less expensive technologies), but there are also less conspicuous effects that technical uncertainties have on the issues discussed. These relationships have been analyzed, and the policy response has been reviewed.

Superfund policy, and its implementation have changed through the years. The principal two driving forces have been the economic and the technical factors, and the relation between them. The scope of this work did not include a political economy analysis of Superfund, but only a review of the policy decisions based on technical factors.

The results of the policy review indicate that the EPA, and Congress, have modified their strategy according to the changes in the state-of-the-science and the state-of-the-art of the remediation of soil and groundwater. Interestingly, this program has motivated the scientists and engineers in this field. Technical uncertainties have decreased in the past 15 years, and the EPA is now in a better position to concentrate in administrative reforms in order to reduce costs and accelerate positive results. The technological constraints have been released to some extent, giving the agency a greater "feasible region" to operate in the implementation of the program. Notwithstanding, the need for new technologies is still a reality, and the EPA has also taken steps to foster their development.

Where the limitations of current technologies are evident, like in many cases of extensive groundwater contamination, policy response has focused on different strategies to accommodate an appropriate definition of risk, and reduce it accordingly. The use of different approaches to define risk is possible, since CERCLA provides flexibility and discretion to the agency in this respect. Strategies to reduce risk in cases in which groundwater remediation is unfeasible, are generally contrary to the statutory mandate for permanence in cleanup, and rely in the discretion granted in the act.

In these cases of impracticability of groundwater remediation, the agency has recognized that public participation is crucial, and has designed mechanisms to incorporate their input.

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APPENDIX A

Natural Flow Model Calibration

A. Sensitivity Analyses

For the sensitivity analyses of the model, in which sensibility to recharge and boundary conditions and hydraulic conductivity were changed, the results showed an important influence of the hydraulic conductivity in the head distribution throughout the aquifer. The influences of recharge changes or the release of the heads at the shorelines of Ashumet and Johns ponds, were not important in the overall flow in the aquifer. The variations in the error and standard deviation due to changes in recharge and type of boundary conditions are presented in Table A1.

In the case of the recharge, the distribution of error in the modeled area remained the same. The general flow was not disturbed when recharge was varied. When the type of boundary condition was changed from fixed head to free head at Ashumet and Johns pond shorelines, the flow experimented a slight change near the ponds. The different error and standard deviation due to these changes was, in general, due to the changes in heads near these ponds. However, as can be seen in Table A1, the variation in the error was minimum, and the flow in the CS-4 area was not perceivably modified.

Table A1. Mean error and standard deviation for the sensitivity analysis. Recharge in the modeled area, and boundary conditions at Ashumet and Johns ponds were tested.

Simulation	Model Conditions	Mean Error	Standard Deviation
Calibrated Model	Recharge = 23 in/yr, and Heads fixed at Ashumet and Johns Ponds	-0.214 ft	1.255 ft
Recharge Sensitivity	26 in/yr	-0.235 ft	1.304 ft
	19 in/yr	-0.219 ft	1.278 ft
Boundary Conditions Sensitivity	Free heads at Ashumet and Johns Ponds	-0.296 ft	1.075 ft

According to these results, heads in Ashumet and Johns Ponds were maintained fixed during the calibration and simulation procedures. Recharge, in turn, was set to 23 inches per year and maintained at that value. Hydraulic conductivity was the parameter to vary for the calibration procedure. The anisotropy ratio was also kept constant for the regional, no-stress flow model calibration, since flow in the aquifer is predominantly horizontal.

B. Calibration

The calibrating parameter was the horizontal hydraulic conductivity. Values of this parameter were changed in many different ways, maintaining always the trends described in Masterson and Barlow (1994) discussed in Section 3.3.1. Head contours interpolated as described in the methodology proved to be useful as initial targets for rough calibration, since it was easier to visualize and therefore calibrate to head contours than it is to heads at specific points. The final calibration criteria, however, were based on point values. From the head contour comparison, the most notable differences were the effects of ponds and streams on the groundwater flow. Refinement of the grid was necessary in the pond areas to accurately represent them using the high hydraulic conductivity values and, thus, have the desired effect.

After these adjustments and further variation of the hydraulic conductivity, the model approximated the target values fairly well throughout the outwash plain. The model was considered calibrated after reaching a mean difference of -0.214 ft in head and a standard deviation of 1.255 ft. for the entire region. Also, positive and negative errors should be equally distributed in the area of interest. However, in the moraine, values do not converged to the target values as well. A definitive effect of the moraine properties on the overall head pattern was evident and hydraulic conductivities in the moraine had to be revised to adjust the head as best as possible.

In the moraine region, the calculated heads seem to be higher than the observed head. In the CS-4 area, however, the error was minimal and well distributed. In order to decrease the error in the moraine, hydraulic conductivity was changed in many different ways making use of the vertical distribution of materials assigned to this region.

However, as mentioned above, changes in the moraine clearly affected the flow pattern in the CS-4 area. In Ashumet Valley, calculated heads tended to be lower than the observed ones. As in the case of the moraine, this error was corrected as much as possible and the remaining error was considered not important for the modeling purposes in CS-4.

In Figure 3.2, the distribution of hydraulic conductivity is presented. The average groundwater pore velocity can be calculated using the Darcy Equation

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

where, v= average groundwater pore velocity

K= hydraulic conductivity

J= hydraulic gradient

n_e= effective porosity

To compute velocity, the value of 0.39 for effective porosity is used. For hydraulic conductivity it is convenient to consider only the area of CS-4 plume and take the arithmetic mean of hydraulic conductivity of the lithologic facies in which the plume moves. It is necessary to calculate the average of the upper-most layer thickness since this is not constant. The calculated arithmetic mean for the area in which the plume is located is:

$$K_h = \frac{(120 ft/day)(50 ft)+(217 ft/day)(140 ft)}{50 ft+140 ft}$$

$$K_h = 191 ft / day$$

The hydraulic gradient resulting from the model, was 0.0014. Using the values for K, n_e, and J mentioned above, the average groundwater pore velocity is 0.67 ft/day.

The final hydraulic conductivity, anisotropy ratios, gradient, and velocity for the area of the CS-4 plume are presented in Table A2.

The value of velocity in the area of CS-4 plume is lower than values reported in the literature (LeBlanc et al., 1991; Garabedian et al., 1991) of 0.4 m/d (1.3 ft/day). The reason for this may be that in the presented model, the northern part of the western cape is not included, which has predominantly very high values of hydraulic conductivity (Masterson and Barlow, 1994) associated with the proximal sedimentary facies which are characterized by coarser grain size. Besides, the thickness of the coarse sand and gravel material corresponding to the shallow sediments increases as we go north. This makes the overall hydraulic conductivity increase as well. Since our modeled area is located in the southern part, we miss the higher conductivity values, obtaining a lower groundwater velocity.

Table A2. Hydrogeologic parameters resulting from the groundwater flow model. Values correspond only to the CS-4 plume area.

Parameter	Value
Average Hydraulic Conductivity	191 ft/day
Gradient	0.0014
Velocity	0.67 ft/day
Anisotropy Ratio	3:1, 5:1 and 10:1

Aquifer Test Simulation

As mentioned in the methodology, head data from 7 single level monitoring wells and a multi-level well were available for the calibration of the model. In Figure B-2 we can see a plan view of the drawdown distribution and the location of the six nearest monitoring wells. In Figure B-3 the differences between the measured and the simulated drawdown are shown, in a cross-section. The final mean difference is -0.153 ft and the standard deviation is 0.185 ft.

This differences are important to decide if the model is calibrated in its anisotropy ratio. However, the shape of the ellipse formed by the drawdown contours, and the shape of the time drawdown curves, were consider just as important.

As described by Freeze and Cherry (1979), drawdown at any point at a given time is directly proportional to the pumping rate and inversely proportional to the aquifer transmisivity *T* and aquifer storativity *S*. For an ideal confined aquifer, the time-drawdown curve would be the ideal Theis curve, but the response of a real aquifer to pumping often deviates from it, according to its geologic configuration. Thus, obtaining from the model a similar curve to the actual test curve, showing the same trends in different periods of time, was important to confirm the proper representation of the aquifer.

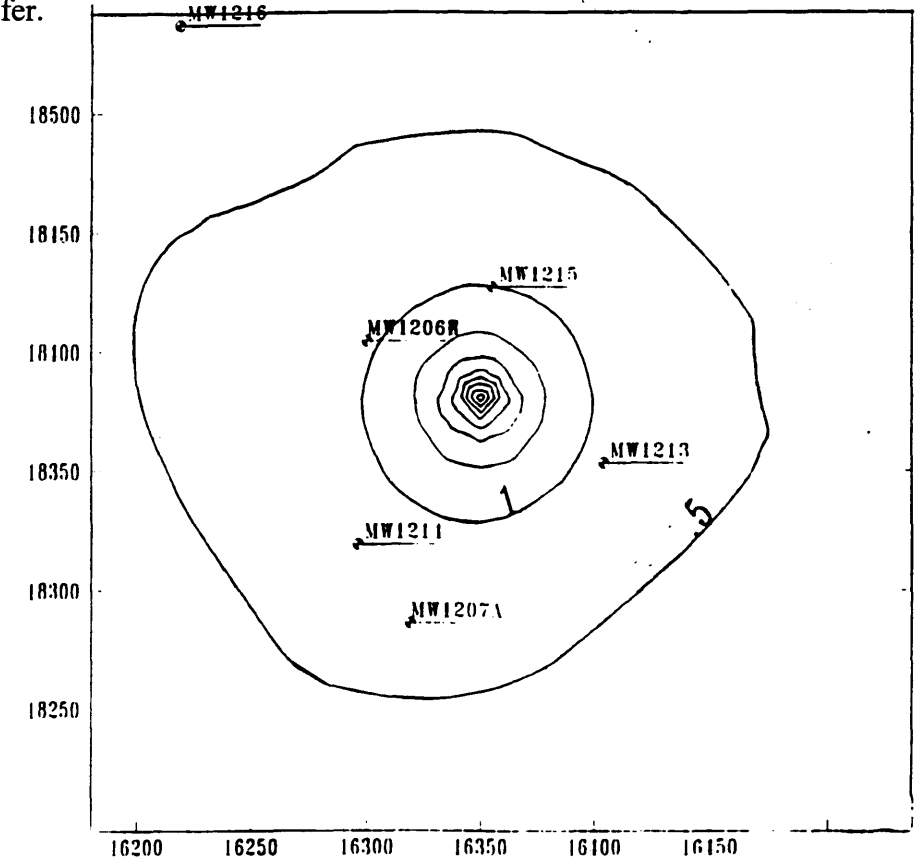

Figure A2. Plan view of the drawdown distribution and location of monitoring wells.

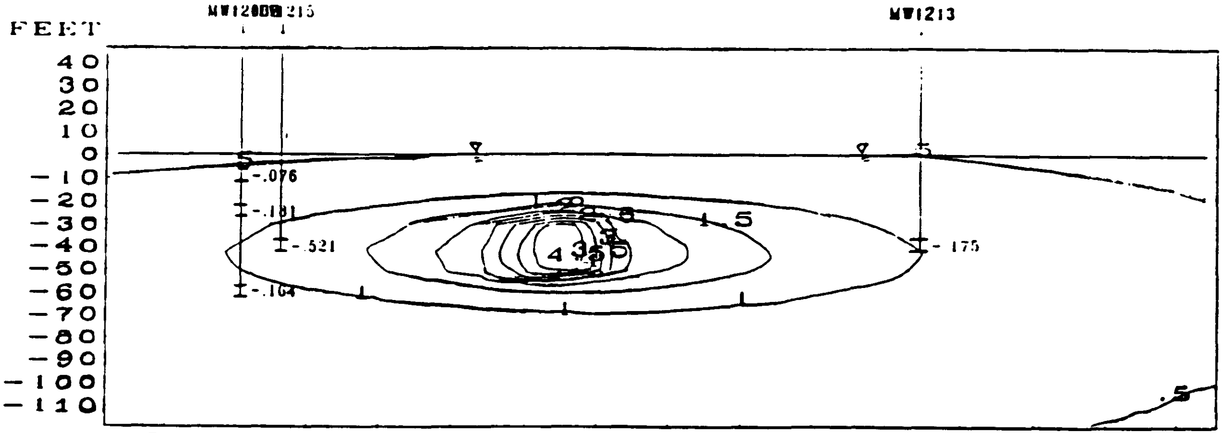

Figure A3. Cross-section at the pumping well showing the drawdown distribution for the aquifer test simulation. The elliptical shape of the contours is due to the anisotropy.

The shape of the drawdown curves obtained from the simulations were similar to the shape obtained by real measurements in the field. An example of the drawdown obtained in the simulation is shown in Figure A4. Figure A5 shows the drawdown curve obtained in the actual pump test for the same well.

Based on the cross-section of drawdown presented in E. C. Jordan (1989), the ratio of minor and major axis of the ellipses were calculated giving a result of 0.41, while the simulated pumping test gives a ratio of ellipse-axis of 0.38 (calculated from the cross-section showed in Figure B-3). The anisotropy ratios giving the best results are 3:1 for the upper layers of medium-coarse sand and gravel, 5:1 to the middle layers of fine-medium sand, and 10:1 for the find sand and silt layers at the bottom of the aquifer. Specific storage was maintained at the value of 0.001 ft^{-1}.

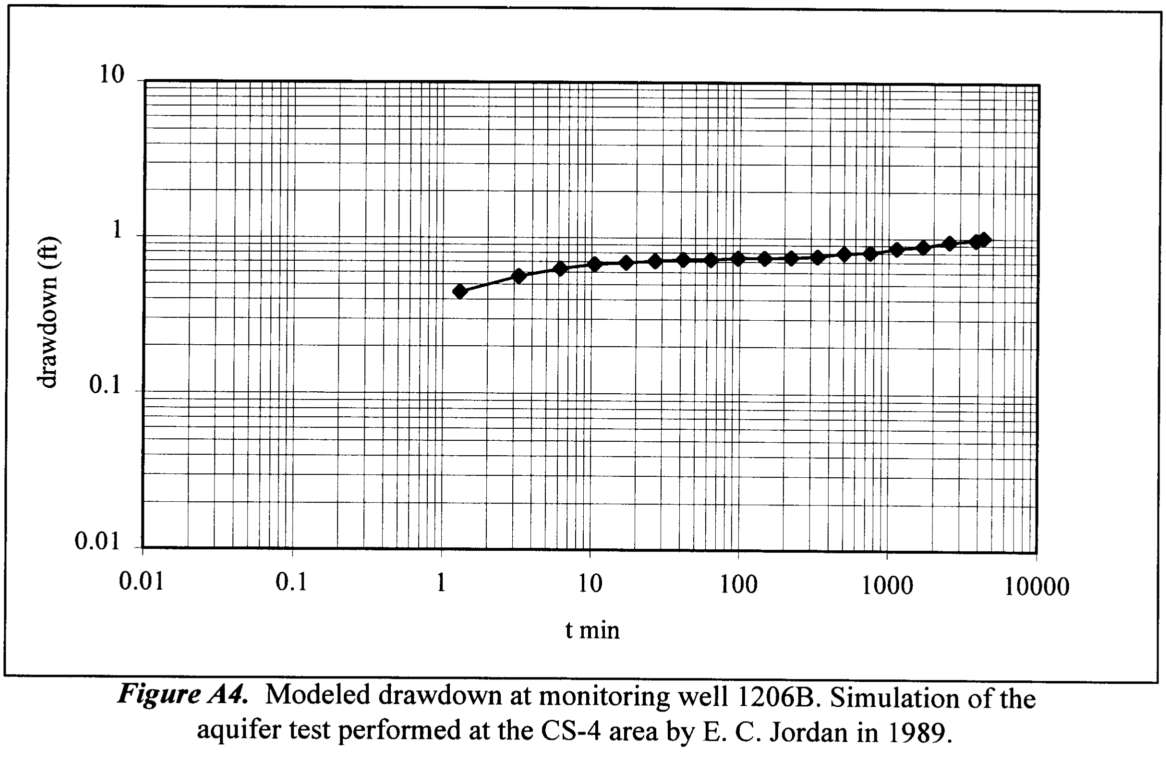

Figure A4. Modeled drawdown at monitoring well 1206B. Simulation of the aquifer test performed at the CS-4 area by E. C. Jordan in 1989.

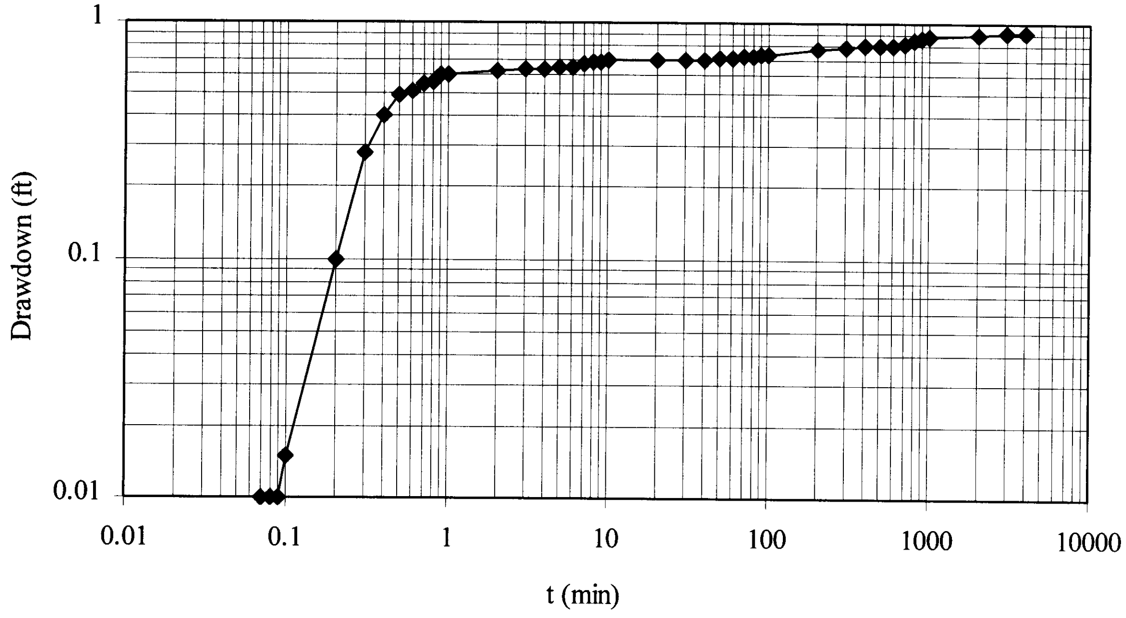

Figure A5. Measured drawdown at monitoring well 1206B.
Aquifer test performed at the CS-4 area by E. C. Jordan in 1989.

APPENDIX B

Acronyms

ARAR	Applicable or Relevant and Appropriate Requirement
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CS-4	Chemical Spill Number 4
DCE	Dichloroethylene
DNAPL	Dense Non Aqueous Phase Liquids
EPA	U. S. Environmental Protection Agency
FS	Feasibility Study
FS-28	Fuel Spill Number 28
IRP	Installation Restoration Program
MCL	Maximum Contaminant Levels
MMR	Massachusetts Military Reservation
NAPL	Non Aqueous Phase Liquids
NCP	National Contingency Plan
NPL	National Priority List
OTA	U. S. Congress, Office of technology Assessment
PCE	Perchloroethylene
PRP	Potential Responsible Party
RA	Remedial Action
RCRA	Resource Conservation and Recovery Act
RD	Remedial Design
RDT	Regional Decision Teams
RI	Remedial Investigation
ROD	Record of Decision
SACM	Superfund Accelerated Cleanup Model
SARA	Superfund Amendments and Reauthorization Act
SITE	Superfund Innovative Technologies Evaluation Program
TCE	Trychloroethelene
TSCA	Toxic Substances Control Act