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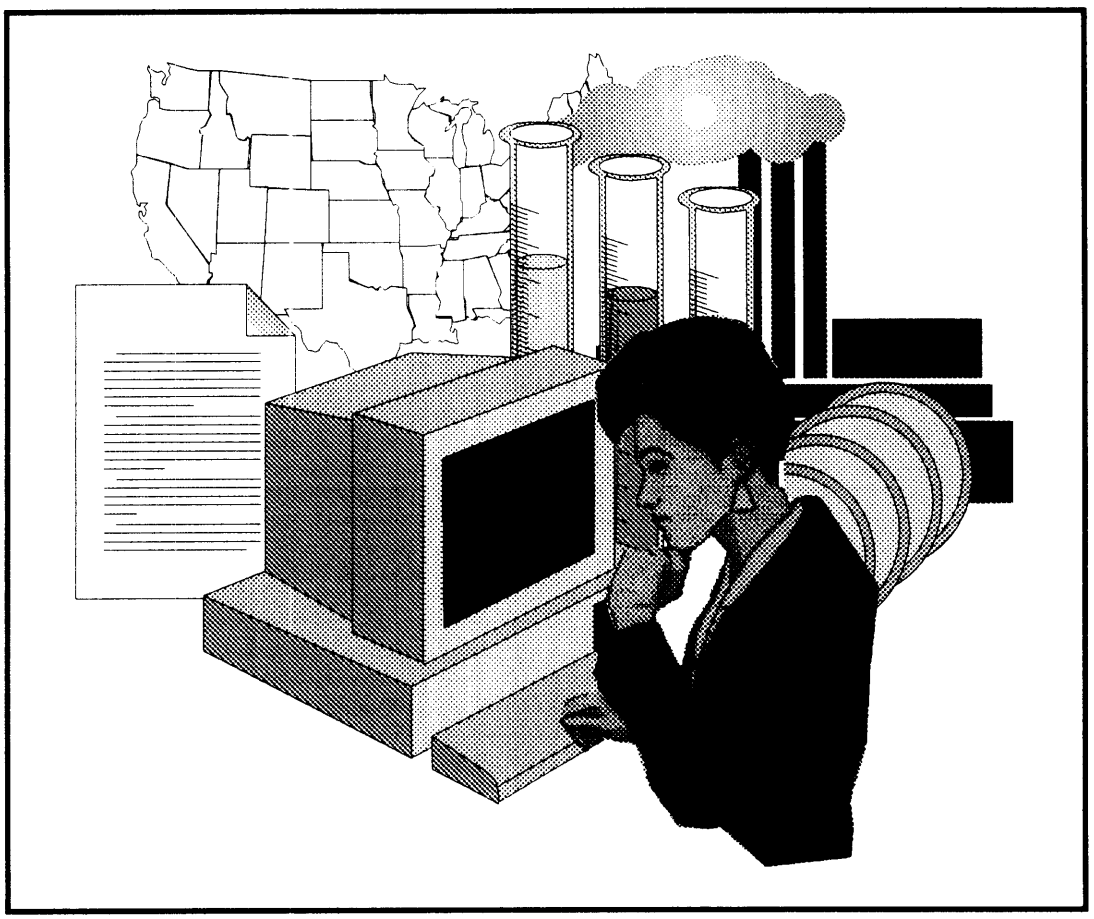
# Ground-Water Modeling Compendium -Second Edition

## Model Fact Sheets,Descriptions, Applications and Cost Guidelines



**OSWER Information Management**

# Purpose of This *Compendium*

The use of this *Compendium* by technical staff and remedial project managers is intended to help promote the appropriate use of models thus effecting sound and defensible modeling in the Agency.

The second edition of the *Ground-Water Modeling Compendium* increases the reader's awareness by describing eight widely-used ground-water models.

It provides summary descriptions of six model applications which illustrate the complexities of the use of models in the Agency's waste management program.

The new section, Cost Guidelines For Ground-Water Model Applications, provides general guidelines and hints for improving cost estimation and cost review of ground-water model applications.

# Who May Benefit From This *Compendium*

This *Compendium* is intended for use by:

- Technical Support Staff
- Remedial Project Managers

This *Compendium* may also help:

- OSWER and Regional Management
- EPA Contractors
- Other Consultants

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# 1.0

# Introduction

## Background

During the past few years, Office of Solid Waste and Emergency Response (OSWER) conducted a pilot project on ground-water modeling with the primary objective of providing useful information on existing modeling practices and models to EPA staff, contractors, and the regulated community.

The first *Ground-Water Modeling Compendium* was prepared as part of the Models Management Initiative conducted by EPA's Office of Solid Waste and Emergency Response (OSWER). OSWER's Resource Management and Information Staff (RMIS) directed this effort in order to promote improved usage of environmental models -- initially focusing on waste management programs, and in the future, supporting Agency-wide efforts.

The second edition of the *Compendium* has been produced for the same purpose; it provides additional information about models and model applications and includes a new section on the cost of ground-water model applications.

The first edition (October 1992) of the *Ground-Water Modeling Compendium* contained the "Assessment Framework for Ground-Water Model Applications". It provides a framework for planning and evaluating ground-water model applications. In 1993, the Science Advisory Board (SAB) was asked to review the Framework in terms of its scientific correctness and its usefulness in improving the use of models. The SAB commented that the "Framework represents a significant advance in OSWER's approach to the management and use of mathematical models" and provided some suggestions for its refinement. The Framework was edited to reflect the SAB's comments and is being distributed separately from the *Compendium*, as suggested by the SAB. For information about the revised Framework, contact OSWER's Resource Management and Information Staff/Information Management Staff.

## Objective and Intended Use

OSWER recognizes that ground-water models are being used in a variety of ways and under different circumstances and constraints. Models can be used to guide and complement field investigations, thereby improving the understanding of the consequences of site-specific hydrogeologic conditions. However, models should not be used in lieu of field investigations and care must be taken to ensure that models are not misused.

The intention of this *Compendium* is to:

- promote the appropriate use of models by increasing users' awareness about the strengths, weaknesses and inherent uncertainties associated with ground-water models and modeling in general; and

- support model users and decision-makers by providing a convenient source of information on how certain models have been applied in the context of waste management programs, the characteristics of eight specific ground-water models, and guidelines on the cost of ground-water modeling applications.

The contents of the *Compendium* have been reviewed extensively by ground-water modeling experts both within and external to EPA. OSWER recommends this document as a reference source for promoting sound and defensible modeling methods and approaches. This document does not, however, constitute official EPA guidance, nor should it be construed as an endorsement of specific models.

## Organization and Structure

The *Compendium* is organized into four distinct sections designed to meet the needs of various audiences, including project/site managers, technical reviewers, and model users. The four sections of the *Compendium* are:

- 1.0, this section, is the **Introduction** describing the *Compendium*'s purpose and organization.

- 2.0, **Cost Guidelines For Ground-Water Model Applications,** provides guidelines for estimating and managing costs for comprehensive numerical ground-water model applications for waste management projects. Historical modeling cost information, derived from private sector firms only, is provided to help plan for resources needed for different elements of a modeling application project and to provide some guidance for estimating overall modeling costs.

- 3.0, **Model Applications,** provides summary descriptions of six model applications, some of which were developed to test the original assessment framework. Each description contains the decision objective, regulatory context, site characteristics (e.g., geology, ground-water contamination), modeling activities and results, interesting features of the application, and the names of EPA staff to contact for more details. This section is intended to help readers understand the variety of modeling applications.

- 4.0, **Model Descriptions,** provides both brief and detailed descriptions for the eight selected models. The brief descriptions are contained on a series of Fact Sheets, which provide important characteristics of the model and sources of additional information. The detailed model information contained in the latter part of the section includes names of the developers, names and addresses of the custodian, technical features, and solution methods. This information has been extracted from a database of ground-water models developed and maintained by the International Ground Water Modeling Center (IGWMC).

## Future Plans

OSWER, with the Office of Research and Development (ORD), requested that the Deputy Administrator establish a temporary Agency Task for Environmental Regulatory Modeling (AFTERM) to address Agency-wide modeling issues. The Task Force has produced a final report which requests a permanent Agency-wide focus for the coordination of information and support concerning modeling. Thus, further editions of any ground-water modeling compendium would come under the direction of this Agency-wide modeling group.

## Acknowledgements

The OSWER Pilot Project has benefited since its inception from input by a team of ground-water modeling experts that included Dr. Mary Anderson, University of Wisconsin, Dr. Paul van der Heijde, International Ground Water Modeling Center, and Dr. Luanne Vanderpool, EPA Region V. These individuals were instrumental in developing the Assessment Framework in the first edition of the *Compendium*, and their insights led to many improvements in the other sections. In addition, staff and managers from the Robert S. Kerr Environmental Research Laboratory, especially David Burden and Joseph Williams, have provided expert review and guidance.

The original Ad hoc committee, representing model users in the EPA Regional offices, in OSWER, and other program offices served as a review group and provided suggestions for the *Compendium*. Its members include:

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# 2.0 Cost Guidelines for Ground-Water Model Applications

## 2.1 Introduction

This section provides guidance for estimating and managing costs for numerical ground-water modeling for projects related to the Comprehensive Environmental Response Compensation and Liability Act (CERCLA)/Superfund Amendment and Reauthorization Act (SARA) and the Resource Conservation and Recovery Act (RCRA). Historical modeling cost information is provided to help managers evaluate the reasonableness of estimated costs. Information on the costs of different elements, or phases, of a modeling project is provided to help managers plan for and allocate resources among those elements. In addition, factors which impact the cost of numerical modeling projects are discussed.

The information in this section is derived from the experiences of hazardous waste investigation and remediation project managers and ground-water modelers. The information is also the result of the collection and analysis of historical cost data from more than fifteen experienced ground-water modelers employed by three environmental restoration firms; thus the data represent project results of private sector firms only.

Thirty-four numerical ground-water model applications were documented using a data collection questionnaire. The majority of these comprehensive numerical ground-water model applications was developed to gain an understanding of the site. A small number of applications was developed for other purposes such as limited design, permitting, and litigation.

It should be noted that, although the cost guidelines and data are based on facts, the following considerations or caveats are important.

- Modeling costs within federal agencies may differ from private sector modeling projects. Likewise, companies regulated by EPA may have in-house modeling staff and thus have lower costs.

- In 1994, the cost of numerical modeling is generally lower than ten years before because of the availability of personal computer versions of the code, decrease in the cost of workstations, reduction in the cost of simulations and presentation of results, and more sophisticated and experienced users.

- The cost data range from 1984 to 1994 and have not been adjusted to 1994 dollar values.

- For a given project, it may be appropriate to analyze the benefit/cost ratios of a modeling project versus data collection and investigation, with respect to the resulting uncertainty factors.

- For a given modeling project, the use of an analytical model may be more appropriate and less costly than the use of a numerical model.

## Effective and Ineffective Usage of Ground-Water Modeling

Properly managed, ground-water models may provide significant cost savings for site investigation and remediation projects. Some project managers responding to the data collection questionnaire had positive things to say about ground-water modeling:

- "By having a comprehensive ground-water model application, over $5 million in data collection costs were saved."

- "The use of the model application saved the agency and the PRP millions of dollars by gaining public acceptance of EPA's program."

- "During the litigation process, the model application helped keep the experts focused on the pertinent issues so that, ultimately, settlement was achieved expeditiously."

- "The model application showed the maximum possible extent of the plume and maximum contaminant concentration, helping to reduce any undue concerns or `alarm' about the site and to minimize site cleanup costs."

All too often, however, managers can expend a great deal of money developing expensive models which never provide useful information. Other managers responding to the questionnaire shared with us some of their frustrations about the use of ground-water models:

- "Modeling was not considered until late in the project, after a great deal of data had been collected. The model application development process identified many gaps in the data, but no funding was available for additional data collection. So the confidence level of the model was

eroded to the point where the model was deemed unusable by site regulators."

- "The model application was originally developed for a feasibility study. Later, the same model was applied for PRP enforcement. The approximate nature of the particle tracking component of the model approach allowed one PRP to `escape' the enforcement process."

- "A complex model application was developed and calibrated on the basis of incorrect survey data. This led to invalidation of the modeling results and a costly re-development of the model application."

The Cost Guidelines for Ground-Water Model Applications have been developed to help increase the number of positive ground-water modeling outcomes.

## Organization of This Section

Sub-section 2.2, Cost Control of Ground-Water Model Applications, presents five guidelines that when followed will improve the management of ground-water modeling application costs. Sub-section 2.3, Overall Cost of Ground-Water Model Applications, presents information and graphs on numerical ground-water model application costs based upon historic cost data. This information may help managers plan for and assess the reasonableness of proposed modeling cost estimates. Sub-section 2.4 provides information on the cost of different components of a modeling application project and when and why the cost of a component might lie outside the typical range of costs. Two examples of the ground-water modeling cost data questionnaires used to solicit the historic cost data are provided in an appendix. Completed questionnaires for the thirty-four model applications are available from the Resource Management and Information Staff in the Office of Solid Waste and Emergency Response. Names of the sites and parties have been removed to protect confidentiality.

## 2.2 Cost Control of Ground-Water Model Applications

Cost control of ground-water model applications is essential to ensure that the benefits of modeling justify modeling costs. The five guidelines presented in Table 2.2-1 and described below will assist in controlling model application costs. These guidelines reflect years of experience by senior ground-water modelers and project managers. The guidelines should help to ensure:

- The efficient use of both ground-water modeling and overall project resources
- The consideration of modeling costs when changes in the modeling objectives or data requirements are proposed.

GUIDELINE #1: INTEGRATE GROUND-WATER MODELS INTO THE OVERALL INVESTIGATION AND REMEDIATION PROCESS

Too often, ground-water modeling is performed as an afterthought, rather than being integrated into the project at its inception. Ground-water modeling's purpose is to provide an improved understanding of the site flow and transport processes and to help predict the future consequences of past or proposed actions. When ground-water modeling is integrated into the overall investigation and remediation process, it can help to minimize investigation and remediation costs and to ensure that the best remediation alternative is selected. Modeling may also correctly indicate the need for additional investigation.

Bringing ground-water modelers into a project during the initial planning phase will help to ensure that ground-water modeling is integrated into the overall process. The modeler can assist in comprehensively organizing the available data and can help in the determination of new field data collection needs. Conducting the project in this integrated manner enables investigators to minimize the cost of collecting the data needed to support any necessary modeling.

The integrated approach also helps to ensure that the type and timing of the modeling will meet management's decision objective (see Guideline #3 below). For example, the use of a less sophisticated model during the remedial investigation phase of a project may help determine the potential off-site impact of the contamination. The use of a more sophisticated model during the remediation design phase of a project may help to ensure more effective and less costly site remediation. An example, a paraphrase of an actual project, which demonstrates the cost of failing to integrate ground-water models into the overall project planning is provided below.

**Table 2.2-1**

**Five Guidelines for Cost Control of Ground-Water Modeling**

| | |
|---|---|
| #1 | Integrate Ground-Water Models into the Overall Investigation and Remediation Process |
| #2 | Plan for the Iterative Nature of Ground-Water Model Applications |
| #3 | Match the Modeling Objectives to Management's Decision Objectives |
| #4 | Use Modeling to Guide and Optimize Data Collection |
| #5 | Perform a Cost Review at Major Decision Points in the Model Process |

*Example #1:* On a site in the Northeast, a major water supply wellfield was shut down because of volatile organic compounds (VOCs). Underlying the site were a sand and gravel aquifer and a thin layer of the fractured bedrock. The general presumption was that the wells were being contaminated by a plume in the sand and gravel aquifer. Instead of investigating this assumption through the use of a relatively simple ground-water model early in the investigative process, an extensive design of a large pump-and-treat system for the sand and gravel aquifer was initiated. A third-party review uncovered inconsistencies in the ground-water data being used for the design. The project managers then decided to use a model to verify the location of the plume. The results of the modeling demonstrated that the plume lay in the fractured bedrock, and thus, initial design efforts were wasted at some cost to the project. These costs could have been avoided if there had been a careful integration of modeling throughout the overall investigation and remediation process.

GUIDELINE #2: PLAN FOR THE ITERATIVE NATURE OF GROUND-WATER MODEL APPLICATIONS

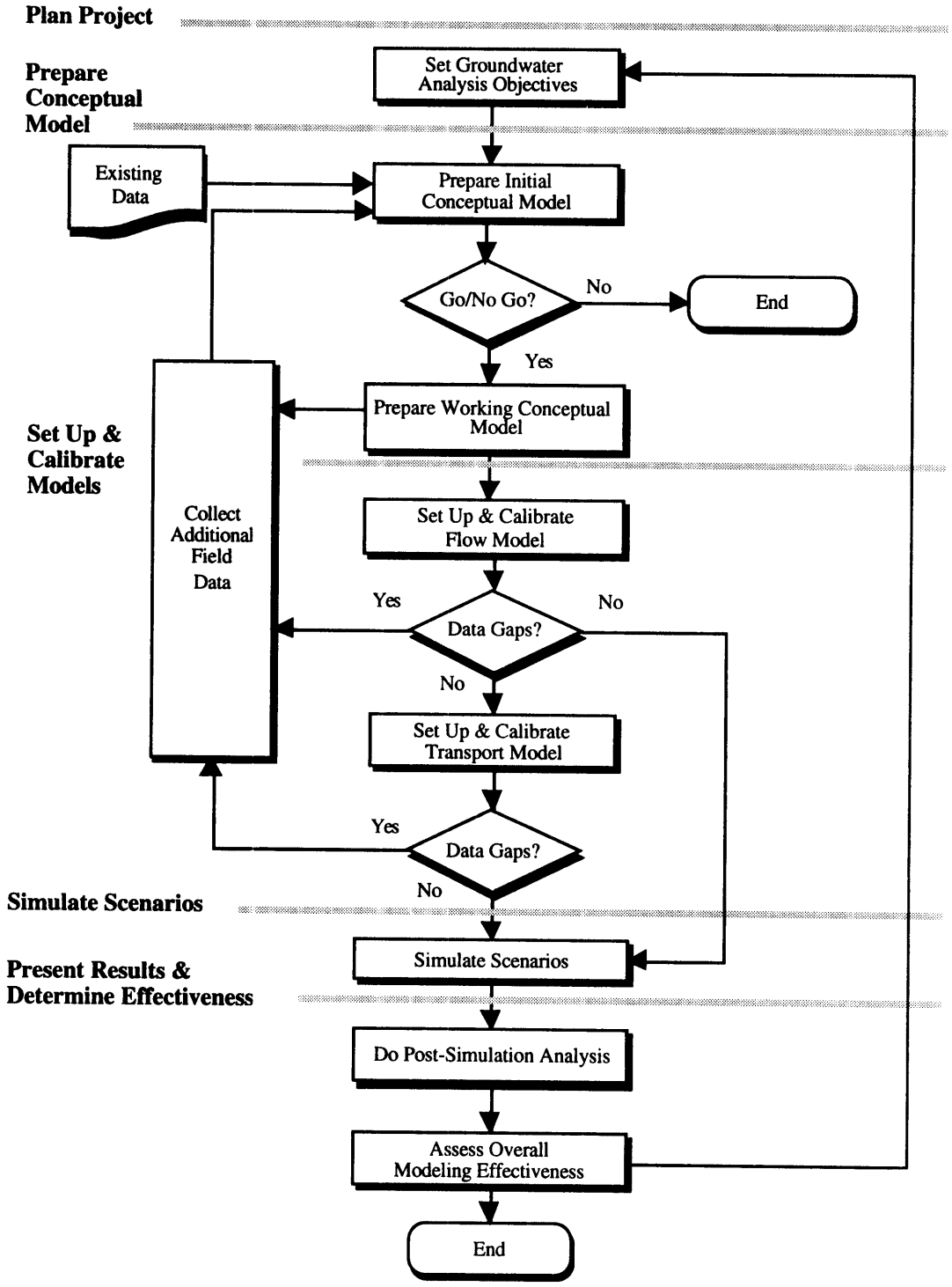
Ground-water modeling is usually most effective when performed as a series of phases, with iterations between the phases, as shown in Figure 2.2-1. Flexibility must be incorporated into the initial project plan. The second phase in Figure 2.2-1 is the development of an initial conceptual model, with subsequent phases leading to the development of an improved conceptual model and, if necessary, the application of a computer model. The result of each phase may be a decision that the results of a prior phase of the modeling process must be amended. Such results are common because modeling is a deductive reasoning process that focuses upon verifying assumptions about hydrogeologic conditions and flow and transport systems. The disproof of an assumption will often require the review of prior assumptions and a fundamental change in the characterization of the ground-water system. This iterative process continues until the characterization of the ground-water system and its response to past or proposed actions is sufficiently accurate and detailed to support management's decision objectives.

Approaching modeling this way helps to eliminate unnecessarily complex modeling and best reflects the practical aspects of the modeling process. An example which demonstrates the benefit of planning for the iterative nature of ground-water model applications is provided below.

*Example #2:* On a large project, failure to plan for the iterative nature of ground-water modeling caused serious difficulties for one of the interested parties. This party chose to begin a large and complex modeling effort at the onset of the RI/FS, when there was a limited understanding of the site. After the installation of

## Figure 2.2-1

## The Ground-Water Modeling Process



numerous wells and many rounds of data collection, the party reviewed the modeling effort and realized that the entire effort was based upon a fundamental misunderstanding of the site hydrogeology. Consequently, much of their prior data collection and modeling efforts were wasted.

By contrast, at this same site, another interested party utilized an iterative modeling approach in which the party began with a relatively simple model of the site. The results of this model were compared with newly acquired field data and adjustments in the modeling were made. With these adjustments, this party was able to rapidly identify the fundamental components of the ground-water system and to focus the remedial alternatives analysis. By planning for the iterative nature of ground-water modeling, this party was able to significantly reduce both modeling and project costs as compared to the first interested party.

GUIDELINE #3: MATCH THE MODELING OBJECTIVES TO MANAGEMENT'S DECISION OBJECTIVES

Often, modeling is initiated without a clear understanding of management's decision objectives. When this is the case, the results of the modeling, regardless of the technical quality of the modeling, will often fail to support management's decision objectives. This is the most common modeling pitfall and the cause of most modeling "horror stories." For example, a typical management decision objective is to identify all potentially responsible parties (PRPs). A modeling objective that matches this decision objective would be to assist in the identification of the spatial location, timing and/or quantities of source based upon the contaminant ground-water plume and the underlying site hydrogeology.

Modeling, used as a tool, may support many different objectives. For example, a modeling project may identify the best locations for monitoring and pumping wells. It may produce estimates of concentrations at receptors. It may test alternative cleanup scenarios. Or it may support several different objectives concurrently. Because modeling is a often multi-purpose exercise, defining the particular set of objectives in each case is critical to the ultimate success of the effort.

Modeling is most successful when its objectives are tied to management's decision objectives. The link between these two should be clearly defined in the project plan. It should also be reflected in the project controls. A strong link, set at the beginning and built into the project controls will keep modeling focused on the right objectives. It aids in the shaping of all future aspects of the process, from developing the initial conceptual model to presenting the findings and conclusions.

Management must accept the responsibility for clearly communicating their decision objectives. The modeling team must accept the responsibility for translating management's objectives into modeling objectives. Regular review of the compatibility between the modeling objectives and management's decision objectives is the most important component of the modeling quality assurance program. Management's decision objectives and the role that modeling is to play in meeting their objectives must be clearly defined at the onset of the project and must be reviewed regularly. An example of what can happen when this guideline is not followed is described below.

*Example #3:* In this case, a municipal well was contaminated by nearby VOC spills. Three of the regulatory decision objectives were: 1) to quantify the nature and the extent of the contamination, 2) to identify potential remedial technologies, and 3) to identify the PRPs. However, because the regulators were confident that they could easily identify the PRPs, they did not explain to the modeling team that they would need to use the model results to support the PRP identification. The modeling team therefore focused upon supporting the first two decision objectives and consequently developed a relatively simple ground-water model application. This application was well suited to these two decision objectives and was implemented at very little cost.

Difficulties, however, were encountered when the regulators tried to utilize the modeling application to support their enforcement recovery against the PRPs. Because the application had not been designed to support this use, the assumptions, level of detail, and documentation of the application could not withstand legal challenges. The regulatory agencies were thus unable to recover costs from several of the PRPs. The modeling team noted that if they had been advised that the application was to be used to support enforcement recovery, they would have insisted on enough resources to enable them to develop a much more sophisticated modeling application. They were confident that the results of the more sophisticated application would have mirrored the results of the simpler application, but the more sophisticated application would have better withstood the legal challenges.

GUIDELINE #4: USE MODELING TO GUIDE AND OPTIMIZE DATA COLLECTION

Site ground-water data collection efforts are often inefficient and costly because critical data needs are not identified early in the project planning process. While iterative data collection plans are often very appropriate, incorporating ground-water modeling expertise at the conceptualization of the project can significantly improve the efficiency and completeness of each round of data collection. For example, a preliminary conceptual model of the site can help to identify the type, location, and frequency of data required to characterize the site's ground-water

system. As additional data are collected, the assumptions of the conceptual model can be reviewed, adjustments made, and additional data needs for numerical modeling identified and incorporated into the regular site data collection activities. By using the modeling activities to optimize this data collection process, it is more probable that the "right" data will be collected from the beginning and the subsequent field data collection stages can be more focused. This process typically results in better cost control. Figure 2.2-1 illustrates the phasing of data collection efforts. An example of the benefit of using modeling to guide and optimize data collection is presented below.

*Example #4*: At a site involving an active landfill, a nearby water supply well was contaminated with VOCs. The landfill was the only apparent source, but was situated downgradient of the well. One hypothesis to explain the upgradient presence of VOCs was that landfill gas migration could have caused the VOCs to move from the landfill into the capture zone of the water supply well. To verify this hypothesis subsurface vapor and ground-water sampling data were required. A ground-water model was used to identify the most appropriate locations for collection of these data. The use of the model significantly reduced the number of wells needed to collect data. Thus, significant cost savings were achieved by using the model to guide and optimize data collection for verification of the landfill gas hypothesis.

GUIDELINE #5: PERFORM A COST REVIEW AT MAJOR DECISION POINTS IN THE MODEL PROCESS

The iterative nature of ground-water modeling often requires frequent adjustments to the modeling process. These adjustments can result in changes to the cost of the modeling project. These cost changes must be regularly reviewed to ensure that the benefits of the modeling results continue to justify the incurred and projected costs and that the costs remain within the project budget.

Cost reviews should be performed at the completion of the conceptual model, at the completion of the flow model, at the completion of the transport model, and whenever another iteration of the modeling process is proposed. The cost reviews are performed in conjunction with regular technical reviews of the project (see *Assessment Framework for Ground-Water Modeling*, OSWER Draft Directive, April 1994). For example, if calibration targets cannot be met during the preparation of a flow model, the conceptual model may have to be revised, and therefore, additional data may need to be collected. At this point, the cost of collecting the additional data, revising the conceptual model, and recalibrating the model should be reviewed to determine whether the benefit of the modeling results justifies the additional costs.

Example 5 illustrates what can happen when this guideline is not followed.

*Example #5:* Near a large federal facility, ground-water modeling was proposed to support both the screening of remediation alternatives and the conceptual design of the selected alternative. Supporting the conceptual design required a more sophisticated model application than was needed to support the screening of the remedial alternatives. During the formulation of the initial conceptual model, it was discovered that the existing field data did not meet the data requirements of a sophisticated ground-water model. Without first performing a cost review, an extensive data collection effort was initiated. The costs of the data collection effort were significant and, at the completion of the additional data collection, there were insufficient funds remaining to proceed with a sophisticated model application.

Consequently, attempts to use modeling to support the conceptual design of the selected alternative were abandoned and a simpler model application was developed to assist only in the screening of remedial alternatives. The simpler model application, however, could have been developed without the additional data collection. Thus a large part of the cost of the data collection effort was wasted. If a cost review had been performed as part of the conceptual model development, the impact of the data collection costs on the overall project budget and the modeling objectives could have been identified prior to initiating the additional data collection and adjustments could have been made.

## 2.3 Overall Cost of Ground-Water Modeling Applications

The purpose of this sub-section is to provide information that can be used to evaluate the reasonableness of the overall cost of numerical ground-water modeling applications. This information is based on historical ground-water modeling costs for hazardous waste investigation and remediation projects.

Engineering and modeling cost data were collected for numerical saturated flow and contaminant transport model applications at CERCLA and RCRA facilities. The modeling cost data were compared to the total engineering costs.

**Engineering costs include data collection, modeling, and drilling supervision costs. They do not include analytical laboratory or drilling costs.**

**The modeling costs include project planning, preparing a conceptual model, setting up and calibrating a flow model, setting up and calibrating a transport model, simulating scenarios, and presenting results and determining the overall effectiveness of the modeling project. The modeling costs do not include data collection costs.**

The cost data were collected through questionnaires and follow-up telephone conversations with over 15 experienced ground-water modelers and project managers at three environmental restoration firms. Sufficient data to meet the analysis objectives were obtained for 34 projects. For a number of the projects, it was impossible to obtain precise cost breakdowns. In such cases, estimates were used only if provided by individuals with first-hand knowledge of the model applications.

NOTE: Cost data are not all expressed in 1994 dollars. Table 2.3-1 shows that costs are associated with projects ranging in time from 1984 to 1994.

BASIC CONCLUSIONS

- The historical cost information shows that ground-water modeling costs increase as the total engineering costs increase (See Figure 2.3-1).

- The percent of modeling costs to engineering costs decreases as the engineering costs increase (see Figure 2.3-2).

  For example, the modeling costs of smaller projects tend to be approximately 20 percent of the engineering costs, while the modeling costs of very large projects ($10 million and over) tend to be approximately

## Table 2.3-1

## Ground-Water Modeling Historical Costs

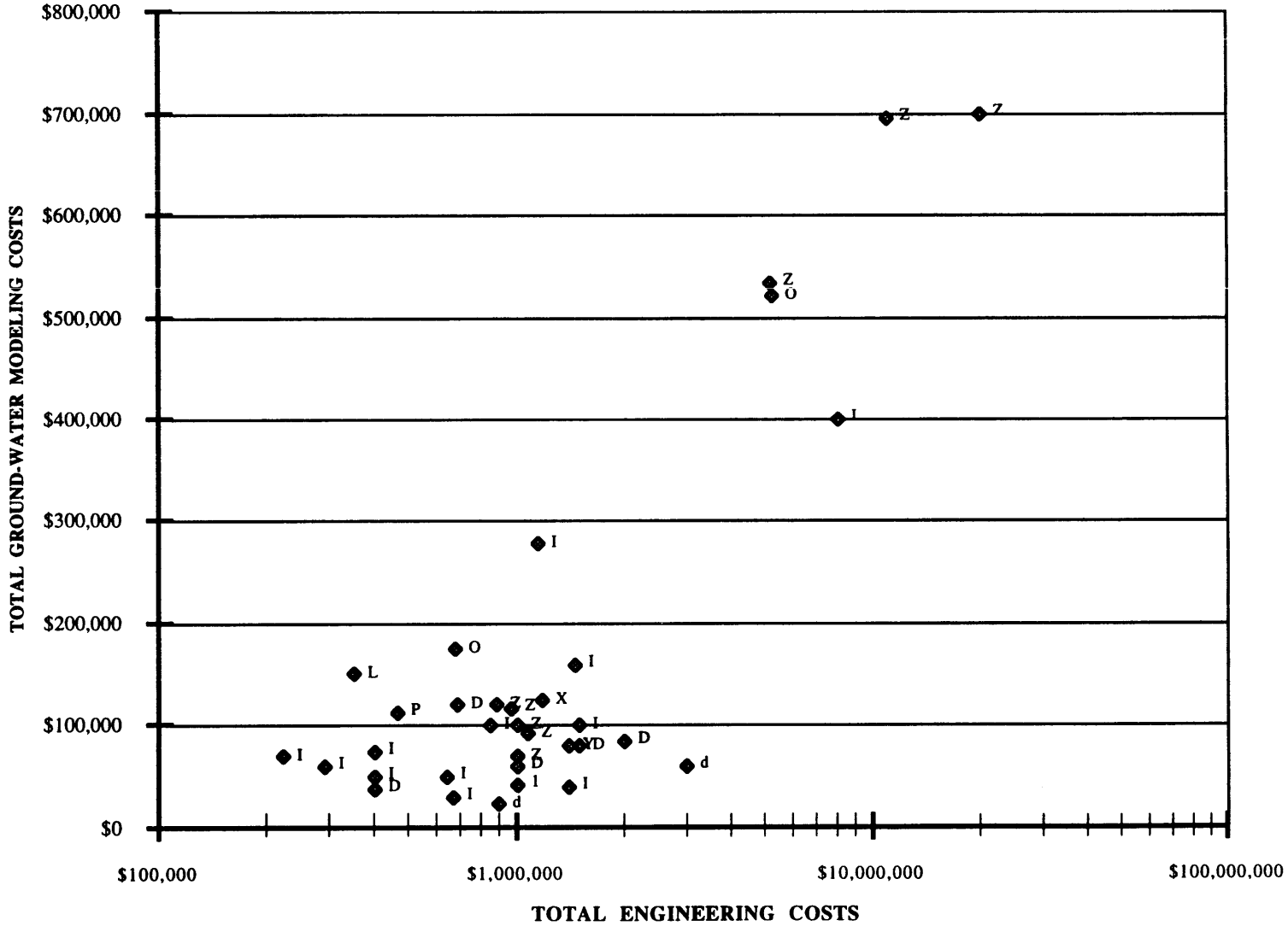
| NUMBER | TYPE | PHASE | MODEL $ | $ | /ENG $ | PERIOD |
|---|---|---|---|---|---|---|
| 1 | I | RFI | $42,000 | $1,000,000 | 4.2% | 92 |
| 2 | Y | OTHER | $80,000 | $1,400,000 | 5.7% | 92 |
| 3 | Z | RI/FS/RD | $700,000 | $20,000,000 | 3.5% | 93-94 |
| 4 | d | RD | $23,400 | $883,600 | 2.6% | 87-present |
| 5 | I | RI/FS | $30,000 | $656,800 | 4.6% | 87 |
| 6 | O | RI/FS | $521,000 | $5,250,000 | 9.9% | 87-present |
| 7 | I | RI/FS | $160,000 | $1,455,300 | 11.0% | 87-89 |
| 8 | P | OTHER | $112,800 | $460,000 | 24.5% | 86-87 |
| 9 | I | RI/FS | $100,000 | $838,000 | 11.9% | 86-88 |
| 10 | Z | RI/FS/RD | $120,000 | $875,000 | 13.7% | 87-94 |
| 11 | Z | RI/FS/RD | $117,600 | $958,000 | 12.3% | 91-94 |
| 12 | I | RI/FS | $100,000 | $1,500,000 | 6.7% | 92 |
| 13 | L | OTHER | $150,000 | $350,000 | 42.9% | 90-92 |
| 14 | Z | RI/FS/RD | $100,000 | $1,000,000 | 10.0% | 86-88 |
| 15 | I | RI/FS | $40,000 | $1,400,000 | 2.9% | 89-90 |
| 16 | I | RI/FS | $50,000 | $637,000 | 7.8% | 85-86 |
| 17 | Z | RI/FS/RD | $92,300 | $1,075,000 | 8.6% | 86-88 |
| 18 | I | RI/FS | $70,000 | $220,000 | 31.8% | 90-93 |
| 19 | O | RI/FS | $175,000 | $667,200 | 26.2% | NK |
| 20 | X | RI/FS | $124,600 | $1,173,700 | 10.6% | 84-87 |
| 21 | I | RI/FS | $75,000 | $400,000 | 18.8% | 85-86 |
| 22 | I | RI/FS | $60,000 | $288,000 | 20.8% | 85-86 |
| 23 | Z | RI/FS/RD | $696,000 | $11,000,000 | 6.3% | 89-94 |
| 24 | D | RD | $85,000 | $2,000,000 | 4.3% | NK |
| 25 | I | RI | $50,000 | $400,000 | 12.5% | NK |
| 26 | Z | RI/FS/RD | $534,000 | $5,149,500 | 10.4% | 93-94 |
| 27 | I | RI/FS | $278,500 | $1,149,500 | 24.2% | 84-94 |
| 28 | D | RD | $60,000 | $1,000,000 | 6.0% | 90-91 |
| 29 | D | RD | $37,700 | $400,000 | 9.4% | 93-94 |
| 30 | D | RD | $80,000 | $1,500,000 | 5.3% | 88-90 |
| 31 | Z | RI/FS/RD | $70,000 | $1,000,000 | 7.0% | 88-90 |
| 32 | I | RFI | $400,000 | $8,000,000 | 5.0% | 89-92 |
| 33 | D | RD | $120,000 | $680,000 | 17.6% | NK |
| 34 | d | RD | $60,000 | $3,000,000 | 2.0% | 93 |

**LEGEND**

D = Design
d = Limited Design
I = Site Investigation (typically RI/FS)
L = Litigation
O = Oversight
P = Permitting
X = Site Investigation & Litigation
Y = Permitting & Design
Z = Investigation & Design (typically part of RI/FS/RD)
NK = Not Known

Figure 2.3-1

Ground-Water Modeling Costs Versus Engineering Costs




| Legend: | | | | | |
|---|---|---|---|---|---|
| D | = | Design (RD) | O | = | Oversight |
| d | = | Limited Design | P | = | Permitting |
| I | = | Site Investigation (Typically RI/FS) | X | = | Site Investigation & Litigation (I/L) |
| L | = | Litigation | Y | = | Permitting & Design (P/D) |
| | | | Z | = | Investigation & Design (Typically RI/FS & RD) |

5 percent of the engineering costs. The distribution of case studies when modeling costs are expressed as a percent of engineering costs, versus total engineering costs is depicted in Figure 2.3-2.

Looking at this figure it is reasonable to assume a decreasing trend in the ratio of modeling costs to total engineering costs. Total engineering costs may increase dramatically as a project moves from site investigation to remedial design and remedial action. The incremental costs of updating a site investigation ground-water model, however, to support remedial design or action activities are relatively low. Thus the modeling costs as a percentage of the engineering costs can be expected to decrease.

- The historical costs data also show that, regardless of the project size, there was a start-up or basic cost of $40,000 to $60,000 to use a numerical ground-water model. This start-up cost can be seen in Figure 2.3-1, where very little of the data lies below $40,000 and much of the data on even the smallest projects lies above $50,000. In 1994 dollars, however, it is safe to conclude that start-up costs range from $50,000 to $75,000. However, it should be noted that basic costs may be less depending on such factors as availability of in-house modeling staff and user-friendly, highly functional software.

- The data suggest that total engineering costs may be used to reasonably estimate modeling costs.

- There are factors that may cause modeling costs to exceed the normal cost ratios. These factors include very complex geology, modeling transient situations, or modeling multiple contaminants. These factors are summarized in Figure 2.4-2 in Sub-section 2.4.

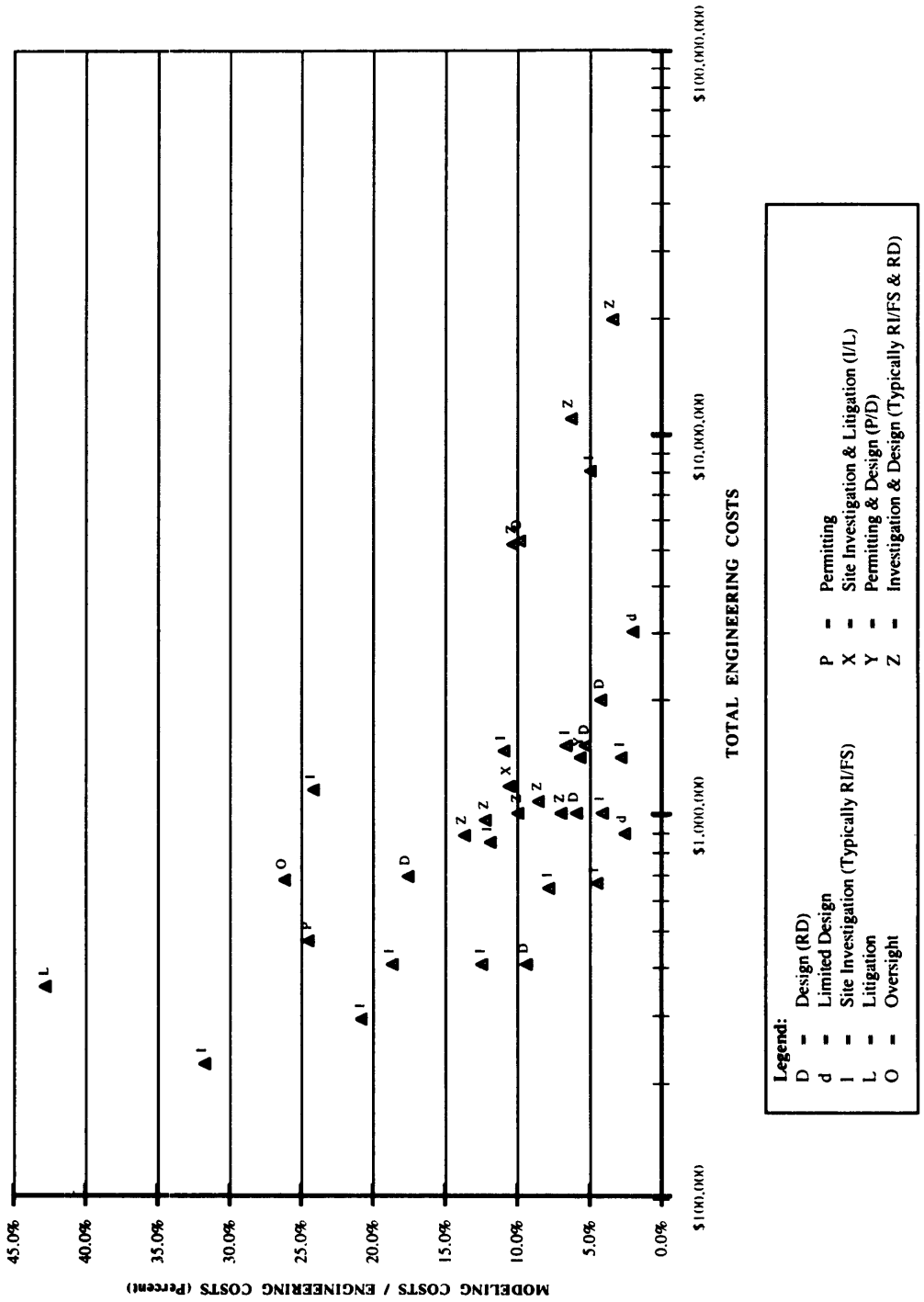
DISCUSSION OF GROUND-WATER MODELING COSTS

To better explore the variance in the cost data, the case studies listed in Table 2.3-1 were segregated into nine modeling types, based on the purpose of the modeling. A description of each type, the number of case studies under each type, and the ranges in modeling costs and engineering costs are discussed below. Engineering costs include data collection and drilling supervision costs. They do not include analytical laboratory or drilling costs. The modeling costs do not include data collection costs. The cost data are also plotted by type in Figure 2.3-1.

- **Site Investigation (I):** This type of model is used for Remedial Investigations/Feasibility Studies (RI/FS) and RCRA projects. This model application is used to: (1) support site characterization, (2) evaluate

Figure 2.3-2

Percent of Ground-Water Modeling Costs to Engineering Costs Versus Engineering Costs



different remediation alternatives, and (3) develop a conceptual design of the selected alternative. Thirteen of the 34 case studies are of this type. In general, the ground-water modeling costs ranged from $30,000 to $278,500 and the total engineering costs ranged from $220,000 to $1.5 million. Case Study No. 32 was the one exception to these general ranges; this was a large RI/FS project with ground-water modeling application costs of $400,000, and total engineering costs of $8 million (see Figure 2.3-1). The ratio of the modeling costs to the engineering costs range from 2.9 percent to 31.8 percent, with half of the model applications having ratios that lie between 5 percent and 19 percent (see Figure 2.3-3).

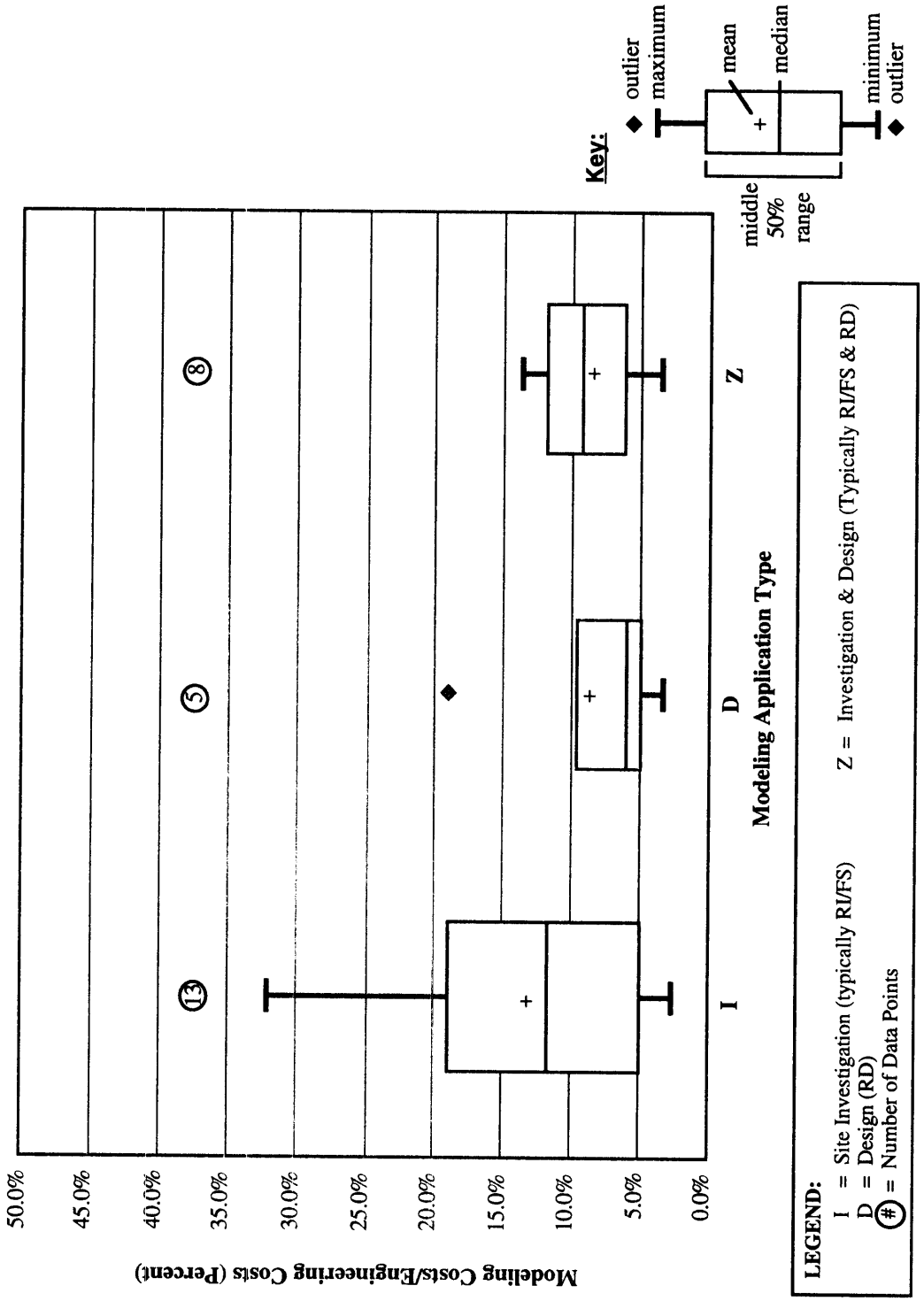
- **Design (D):** This type of model application is used for Remedial Design Action (RD) projects. Five of the 34 case studies are of this application type. Ground-water modeling costs ranged from $37,700 to $120,000, while engineering costs ranged from $400,000 to $2 million. The ratio of the modeling costs to the engineering costs range from 4.3 percent to 17.6 percent, with half of the model applications having ratios that lie between 5.3 percent and 9 percent (see Figure 2.3-3).

- **Investigation and Design (Z):** This type of model is a combination of the Investigation and Design and Implementation models. The Investigation and Design model is generally initiated at the beginning of a site characterization and refined and updated as a project proceeds through various phases. Typically, the model is used for the detailed design (RD) of a remediation system, and to support the RA. Eight of the 34 case studies are of this type. The ground-water modeling costs ranged from $70,000 to $700,000, while engineering costs ranged from $875,000 to $20 million. The ratio of the modeling costs to the engineering costs ranged from 3.5 percent to 13.7 percent, with half of the model applications having ratios that lay between 7 percent and 12 percent (see Figure 2.3-3).

- **Limited Design Analysis (d):** This type of model is used to support limited design objectives such as the design of a ground-water capture/well-point system. Generally, this type of modeling only requires the use of a flow model, and the conceptual model may be relatively simple. The ratio of modeling costs to engineering costs is generally very low as compared to other types. Two of the 34 case studies are this type. The ground-water modeling costs ranged from $23,400 to $60,000, while engineering costs ranged from $883,600 to $3 million. The ratio of the modeling costs to the engineering costs ranged from 2.0 percent to 2.6 percent.

Figure 2.3-3

Variation In The Ratio Of Ground-Water Modeling Cost To Engineering Costs By Model Type



- **Permitting of Facilities (P):** This type of model is used to support the permitting of landfill facilities and is very similar to the Investigation (I) type described above. However, the P-type model typically involves less feasibility study work and more preliminary design efforts. Only one of the 34 case studies fell within this type. The total ground-water modeling costs were $112,800, while engineering costs for this case were $460,000 for a ratio of 24.5 percent.

- **Oversight (O):** This type of model is used to support technical oversight. Modeling is used to evaluate or verify the results of another model application. In the two case studies presented here, the ratios of modeling costs to engineering costs are 9.9 percent and 26.2 percent, with actual ground-water modeling costs of $521,000 and $175,000 respectively.

- **Litigation (L):** This type of model is used to support litigation or enforcement actions. In general, the ratio of modeling costs to engineering costs is high because the modeling results may be subject to legal challenge. In the single case study, the ground-water modeling cost was $150,000, with a total engineering cost of $350,000, with a ratio of 42.9 percent.

## 2.4 Cost Elements of a Project Management Plan for a Ground-Water Modeling Application

A typical ground-water modeling project may be divided into cost elements for planning and allocating resources. Described below are those cost elements and general ranges of the ratio of the costs of the elements compared with the engineering cost. The cost elements correspond to the activities described in the Assessment Framework for Ground-Water Model Applications (OSWER Draft Directive, April 1994).

In addition, a base case ground-water modeling application is described and the factors which impact the costs are identified.

The following findings and conclusions are the result of analyzing questionnaires completed by modeling application project managers. Two completed questionnaires are in Appendix A. Completed questionnaires for the thirty-four model applications are available from the Resource Management and Information Staff in the Office of Solid Waste and Emergency Response. Names of the sites and parties have been removed to protect confidentiality.

COST DATA COLLECTION METHODOLOGY

Most ground-water modeling applications may be divided into six cost elements. Each of these cost elements accounts for a percentage of the total cost of a given modeling effort. Figure 2.4-1 shows the range of estimated percentages of total cost for each of the six cost elements, based on responses to the modeling study questionnaires.

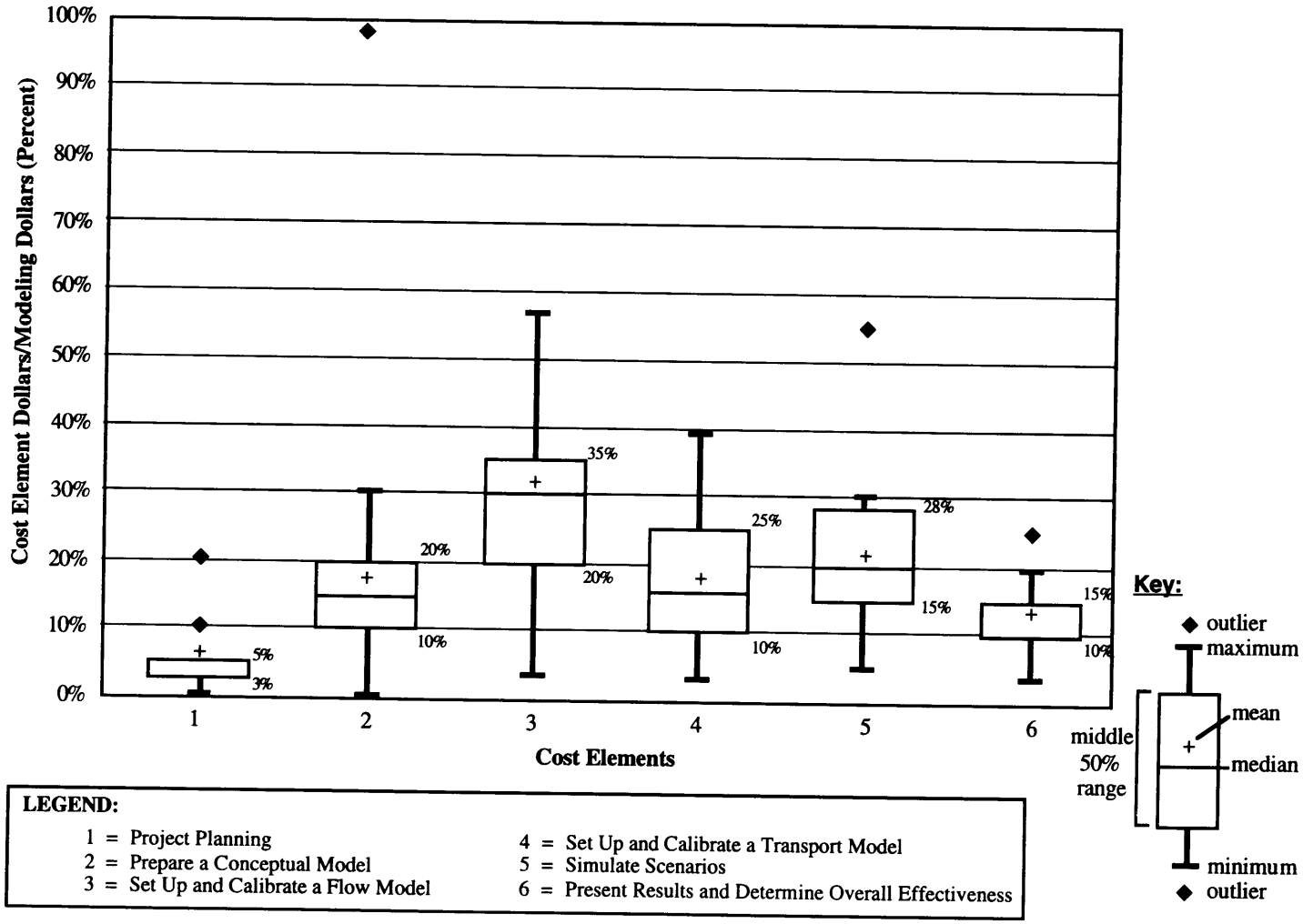
Cost Element 1 - Project Planning

The first cost element is probably the most important part of a modeling project; however, in many cases it is de-emphasized. In these cases, not enough time is spent on an initial review of the available data and finalizing the modeling objectives with project management. As a result of this poor planning, additional costs may be incurred at a later date. As shown on Figure 2.2-1 in Sub-section 2.2, time needs to be spent up-front to develop and incorporate the modeling objectives into a work plan. A start-up meeting should be held with project management at this stage. Flexibility should be built into the work plan to anticipate the iterative nature of a ground-water modeling project.

Despite the importance of Cost Element 1, the historical cost data generally encompasses only about 3 to 5 percent of a modeling budget (see Figure 2.4-1), a small investment that can yield important benefits when made wisely. However,

Figure 2.4-1

Variation In Ground-Water Modeling Cost Element Data



on more complex projects, especially those with lower total modeling budgets, this element can consume up to 20 percent of the budget.

Cost Element 2 - Prepare a Conceptual Model

The second cost element involves development of a sound conceptual model to provide a foundation upon which to build a flow and transport model. Existing site and regional data are organized into an initial conceptual model which forms the basis for deciding whether or not to develop a numerical model for a particular site. If the decision is made to move forward, data gaps should be identified and used to help guide the preparation of a field data collection plan for the site. (Cost of data collection is not included as part of model costs.) Additional data are condensed, organized, and used to prepare a working conceptual model.

Although the statistically determined middle range to prepare a conceptual model is somewhat small (10 to 20 percent, as shown in Figure 2.4-1), there is large range of deviation: values of up to 30 percent were common and one extreme case had a value of 98 percent. In that particular case, the only objective was to provide an understanding of the hydrogeologic conditions for site characterization.

Cost Element 3 - Set Up and Calibrate a Flow Model

The third cost element includes activities such as selecting a suitable mathematical model, building a grid, estimating input, selecting suitable calibration targets, and calibrating the model. Figure 2.2-1 shows that if the original calibration targets cannot be met, it may be necessary to collect additional data, update the working conceptual model, and re-calibrate the flow model.

Although a flow model can be set up rather easily due to the sophisticated modeling software now available, calibration of a flow model is still a costly and time-consuming step. Cost Element 3 is generally the costliest portion of modeling efforts, because the calibrated flow model is essential for both the "understanding" aspects of the modeling project and for being able to simulate and predict future conditions. As shown in Figure 2.4-1, calibration costs typically consume 20 to 35 of the modeling budget, and may be as high as 58 percent of the total modeling cost.

Cost Element 4 - Set Up and Calibrate a Transport Model

The fourth cost element includes the selection of representative indicator compounds, input estimation, adjustment to the model grid and layering, selection of suitable transport model calibration targets, and calibration.

Although it is a recommended step, calibration of the transport model is not incorporated in some modeling projects. This is either because the available calibration data are too limited or due to the scope of the modeling project. When calibration targets are used, often it becomes apparent that the working conceptual model needs to be updated, and more data may need to be collected (as shown on Figure 2.2-1).

Figure 2.4-1 shows that Cost Element 4 typically requires 10 to 25 percent of the total budget, with possible costs ranging up to 40 percent. Note that, once the calibration is completed, it is likely that over 60 percent of the budget, and perhaps more than 75 percent, will have been expended.

Cost Element 5 - Simulate Scenarios

The fifth cost element includes the selection of the scenarios to be modeled, modeling the scenarios, making predictions, and summarizing the results for oral presentations. Cost Element 5 usually consumes 15 to 28 percent of the modeling budget, with costs rarely exceeding 30 percent (see Figure 2.4-1).

Cost Element 6 - Present Results and Determine Overall Effectiveness

The sixth cost element includes the preparation of a modeling report, meeting with client to discuss the report, and evaluation of how the modeling results satisfied management's objectives.

Follow-up work may be required, such as providing negotiation support, performing a post audit of the model results based on any new data collected, or ongoing usage of the model for predictions or fine-tuning the remediation system. If these follow-up costs can be anticipated, they should be included as a part of this cost element within the ground-water modeling plan. Otherwise, they should be set up under a separate budget.

Figure 2.4-1 shows that Cost Element 6 typically requires 10 to 15 percent of the total budget, with possible costs ranging up to 20 percent.

TYPICAL COSTING APPROACH

When estimating costs for modeling, the professionals in charge of the modeling have stated that they typically work from a "base case." The "base case" method utilizes the simplest possible situation, in terms of the hydrogeologic and contaminant source/transport factors. Then, the modelers add or subtract costs (and corresponding scope elements) to handle the additional complexities that go beyond the "base case."

The modeling base case has the following characteristics:

- Single-layer aquifer
- Unconsolidated sediments (i.e., not fractured bedrock)
- RI/FS-type investigation, with some testing of alternative remediation plans
- Single contaminant plume from a single source
- Conservative contaminant
- No resource-significant peer review or technical oversight, and no litigation-level modeling.

The table below provides the range of percentages for each of the base case cost components based on analysis of the 34 completed questionnaires.

**Table 2.4-1**

**Range of Costs in Percent of Base Cost, by Element**

| Element Number | Element Name | Range |
|---|---|---|
| 1 | Project Planning | 3 - 5% |
| 2 | Prepare Conceptual Model | 10 - 20% |
| 3 | Set Up & Calibrate Flow Model | 20 - 35% |
| 4 | Set Up & Calibrate Transport Model | 10 - 25% |
| 5 | Simulate Scenarios | 15 - 28% |
| 6 | Present Results & Determine Overall Effectiveness | 10 - 15% |

Once the base case is established, then factors that may increase or diminish the costs of a modeling exercise in relation to the base case are identified. These factors are described below and summarized in Figure 2.4-2. Figure 2.4-2 represents the results of analyses of data from the subset of questionnaires which contained information on the percentage of model cost element to model application cost (Part III of the questionnaires in the Appendix). Further analyses of the questionnaires resulted in the classification of those model applications according to the factors which impact the cost of the base case. The determination of the cost impact, whether an increase or a decrease, was straightforward. The relative amount of increase or decrease (small, medium, large), as displayed, is not strictly quantitative. The analyses were performed by an experienced ground-water modeler.

**Flow Model Only**: If only a flow model is prepared, generally the cost of the modeling project will be less than the base case, since the base case includes transport modeling.

**Large Model Area**: A large model area can significantly impact the cost of preparing a conceptual model, since additional data need to be organized. In addition, the cost of the flow model setup may be more than the base case since a larger grid is required. Also, computational costs may be higher due the higher number of input arrays.

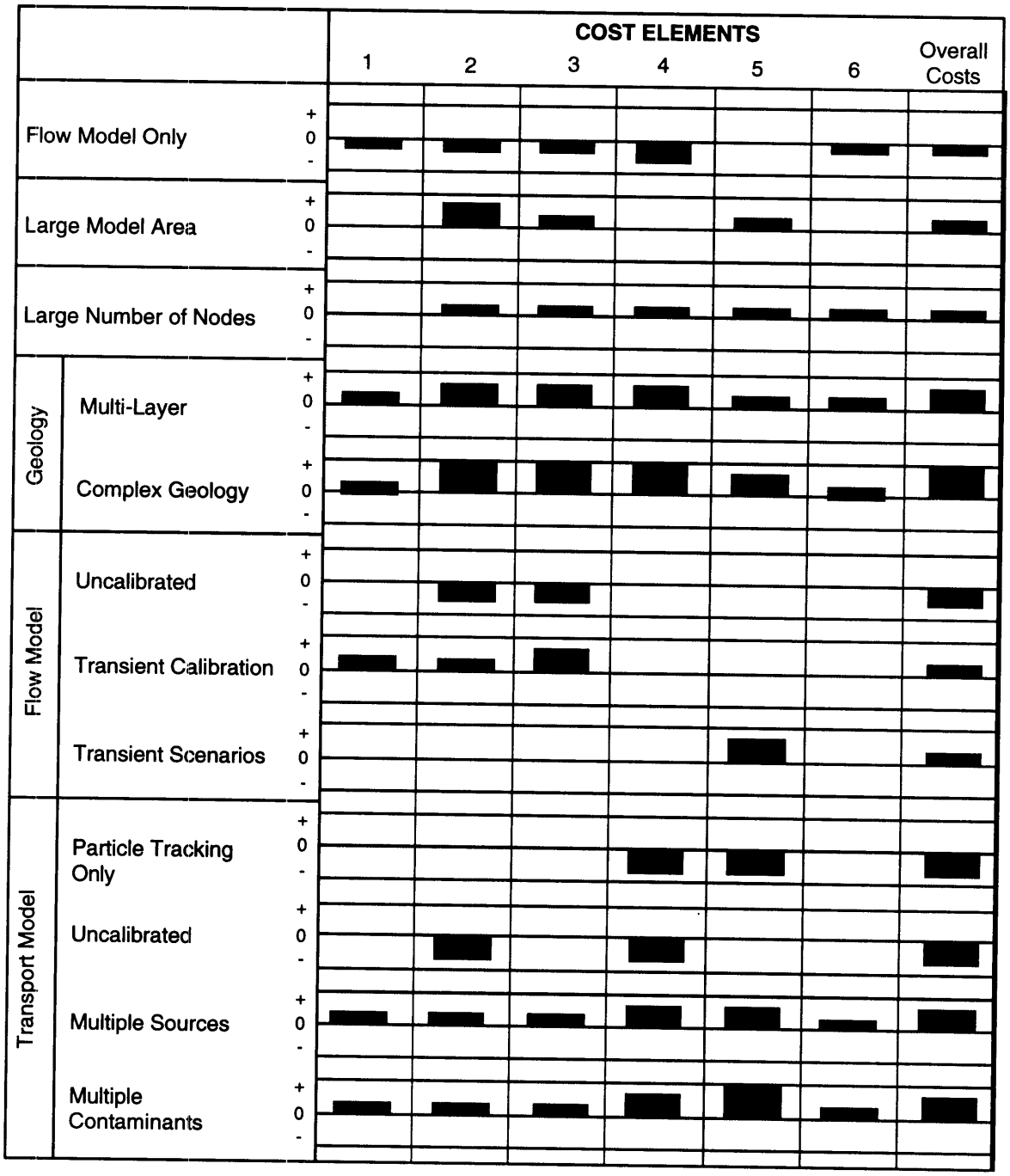
**Large Number of Nodes**: Even though the model may cover a small area, it can still have a larger number of nodes depending upon the specific problem and modeling objectives. More nodes add to the overall cost, particularly in the model setup and computational phases. (Some models have a local grid refining capability which reduces the overall number of nodes.)

**Geology**: Geologic conditions may greatly impact the ground-water modeling application costs. Multi-layer or three-dimensional models are more difficult to set up and more data are required. This also applies for sites which have complex geology. At many sites, the geology may vary greatly over both horizontal and vertical distances. Contaminants will be transported more quickly in zones of higher hydraulic conductivity; therefore, clear delineation of these zones is important.

**Flow Model**: The type of flow model affects cost. In general, uncalibrated modeling is not appropriate. However, if, in exceptional cases, an uncalibrated model is used that is not based on actual site data, the ground-water modeling costs may be slightly less than the base case. If transient calibration of the model is performed, there will a higher cost, especially in the flow-model-calibration step (Cost Element No. 3).

## Figure 2.4-2

## Factors Which Impact Cost Of Base Case




Base Case Definition: Calibrated Flow and Calibrated Transport Modeling; Single Layer Aquifer; unconsolidated; RI/FS investigation and alternatives Identification only; no litigation or oversight or peer review; single plume, single source; single contaminant, conservative.

When transient scenarios are performed, this will lead to a higher cost in the simulation-of-scenarios step (Cost Element No. 5).

**Transport Model**: Likewise, the type of transport model also affects cost. For limited modeling objectives, simple particle tracking to identify contaminant pathways or to outline capture zones of extraction systems can be used, resulting in a slightly lower modeling cost. This is also the case if the transport model is uncalibrated. Modeling of multiple sources or multiple contaminants can lead to a significantly higher cost, especially in the transport-model step (Cost Element No. 4) and in the simulation-of-scenarios step (Cost Element No. 5).

In addition, although not represented in Figure 2.4-2, the purpose for which a model application is developed impacts its cost. Model applications used for enforcement purposes may have a significantly higher cost. Model applications used for projects which require the applications to be externally peer reviewed may have a higher cost.

## 2.5 Summary

The execution of a properly calibrated numerical model may support a greater understanding of site conditions, lead to the selection of the best remediation alternative, and in the long run, decrease total costs by contributing to a more effective remediation design. Such proper use of a model may also help EPA in cost recovery efforts by enabling investigators to properly identify PRPs.

To support cost management of ground-water modeling applications, five guidelines for cost control have been described. The guidelines are:

- Integrate ground-water models into the overall investigation and remediation process.
- Plan for the iterative nature of ground-water model applications.
- Match the modeling objectives to management's decision objectives.
- Use modeling to guide and optimize data collection.
- Perform a cost review at major decision points in the model process.

To support the estimation of costs of numerical ground-water model applications, the historical data presented in Table 2.3-1 may be referenced. There usually is a relatively constant start-up cost and the ratio of modeling costs to total engineering costs decreases as the engineering costs increase. The purpose of a model application, of course, directly affects the cost. It should also be noted that the cost of numerical modeling is generally lower than ten years ago due to the availability of personal computer versions of the code, the decrease in the cost of modeling software, and the increased capability of software to present modeling results.

To support estimation of the various elements or phases of a numerical ground-water model application, general ranges of percents of those elements are provided. In addition, a "base case" model is described and the cost impact of factors such as geology and large model area is provided.

The intention of this Section on Cost Guidelines for Ground-Water Model Application is to promote not only the appropriate use of models within the Agency's waste management programs, but also to provide references and suggestions for better management of the costs of numerical ground-water modeling.

# APPENDIX A

## TWO EXAMPLES OF COMPLETED GROUND-WATER MODELING COST DATA QUESTIONNAIRES

GROUND-WATER MODELING COST DATA
PROJECT I - CASE STUDY 30 IN TABLE 2.3-1

I. TOTAL ENGINEERING COST

A. Total Cost of Project for All Phases of a Site (in which the model application was used). *$1.5 million*

B. Total Cost of Project by Phase. *N/A*

II. MODEL APPLICATION COST

A. Total Cost of the Model Application (for all phases in which the model was used). *$80,000*

B. Total Cost of the Model Application by Phase. *N/A*

III. PERCENTAGE OF MODEL COST ELEMENT TO MODEL APPLICATION COST

A. Cost Element No. 1: Establish Modeling Objectives and Prepare a Project Management Plan. *5%*

B. Cost Element No. 2: Collect Existing Data and Set Up a Conceptual Model. *15%*

C. Cost Element No. 3: Select, Set Up, and Calibrate a Flow Model. *45%*

D. Cost Element No. 4: Select, Set Up, and Calibrate a Transport Model.

*No transport model was used for this project.*

E. Cost Element No. 5: Simulate Scenarios. *25%*

F. Cost Element No. 6: Present Results and Determine Overall Effectiveness. *10%*

## IV. ADDITIONAL DATA

### A. Type of Project and Purpose of the Model Application.

*The project supported (1) the collection of site characterization information and (2) the design and construction of a groundwater extraction/hydraulic barrier system for the remediation of groundwater at a site located at a harbor. Involvement by the modeling contractor began in December 1988 and continued through May 1990. Following the development of a preliminary ground-water flow model for the site, the modeling results guided the collection of additional hydrogeologic data. The additional information led to the refinement of the flow model calibration. Predictive scenarios simulated with the model evaluated the effectiveness of remedial design alternatives involving combinations of ground-water extraction wells, drains and hydraulic barriers.*

### B. Brief Description of Groundwater Contamination Problem at the Site.

*The contaminant of concern at the site was hexavalent chromium.*

### C. Major Geologic Conditions at the Site Affecting the Model Application Cost.

*The model simulated groundwater flow in a multiaquifer system consisting of unconsolidated sediment and bedrock material. Discretization of these geologic materials required six model layers. The flow model was calibrated in two steps. Following a preliminary calibration of the model using available data, the model guided the collection of additional hydraulic conductivity and water-level data in the field. The results from the field testing provided new information for the refinement of the model calibration.*

### D. Type of Model Used on the Project.

*The U.S. Geological Survey (USGS) three-dimensional modular flow model (MODFLOW) was used for the flow modeling. Particle-tracking simulations were performed with MODPATH, also developed by the USGS, for the purpose of evaluating groundwater flow directions.*

E. Start Dates and Completion Dates of Both the Model Application and the Project.

*The modeling began in December 1988 and continued through May 1990.*

F. Benefits of the Model Application - Economic/Environmental

*The modeling results provided the client with a quantitative decision-making tool that evaluated the effectiveness of various remedial alternatives costing millions of dollars. The model predicted that a suitable hydraulic barrier system placed around the perimeter of the site would require very low pumping rates to maintain a specified inward hydraulic gradient across the barrier. The pumping rate significantly affected long-term treatment costs for the system.*

G. Technical Information about the Model.

1. Modeled Area (in square miles). *0.18 square miles*

2. Number of Nodes and Layers. *3456 nodes and 6 layers*

3. Flow Model.

   a. Calibrated - yes/no? *Yes*
   b. Steady-state and/or transient calibration? *Steady-state*
   c. Steady-state and/or transient scenarios? *Steady-state*

4. Transport Model. *N/A*

H. Other Miscellaneous Information

1. Area of the Country (e.g., midwestern, northeastern, etc.).

   *Mid-Atlantic*

2. Shortcomings and Limitations of the Model Application.

   *None. The modeling met the objectives of the study.*

3. Peer Review.

   *The EPA reviewed the model application.*

4. Tandem Model.

*No tandem modeling of the site was performed. That is, the PRP did not conduct an independent modeling exercise concurrently ("in tandem") with EPA's modeling as a means of checking the agency's conclusions.*

GROUNDWATER MODELING COST DATA
PROJECT II - CASE STUDY 28 IN TABLE 2.3-1

I. TOTAL ENGINEERING COST

A. Total Cost of Project for All Phases of a Site (in which the model application was used). *$1 million*

B. Total Cost of Project by Phase. *N/A*

II. MODEL APPLICATION COST

A. Total Cost of the Model Application (for all phases in which the model was used). *$60,000*

B. Total Cost of the Model Application by Phase. *N/A*

III. PERCENTAGE OF MODEL COST ELEMENT TO MODEL APPLICATION COST

A. Cost Element No. 1: Establish Modeling Objectives and Prepare a Project Management Plan. *Modeling objectives and management plan developed during scoping.*

B. Cost Element No. 2: Collect Existing Data and Set Up a Conceptual Model. *10%*

C. Cost Element No. 3: Select, Set Up, and Calibrate a Flow Model. *25%*

D. Cost Element No. 4: Select, Set Up, and Calibrate a Transport Model. *15%*

E. Cost Element No. 5: Simulate Scenarios. *25%*

F. Cost Element No. 6: Present Results and Determine Overall Effectiveness. *25%*

IV. ADDITIONAL DATA

A. Type of Project and Purpose of the Model Application.

*The project was performed to assess the performance of an asphalt cap to control leaching through stabilized contaminated material.*

B. Brief Description of Groundwater Contamination Problem at the Site.

*Groundwater contaminated with PAHs, PCBs, lead and benzene.*

C. Major Geologic Conditions at the Site Affecting the Model Application Cost.

*Site has surficial aquifer controlled by local waterbodies. Some contact with underlying regional aquifer.*

D. Type of Model Used on the Project.

*The Corps model, HELP, was used to estimate infiltration rates through the asphalt cap. The USGS groundwater flow model, MODFLOW, was used to develop steady-state flows in the aquifer systems underlying the site. The USGS model, MOC, was used to simulate contaminant transport and to estimate solute diffusion at the site boundary.*

E. Start Dates and Completion Dates of Both the Model Application and the Project.

*12/90 to 4/91.*

F. Benefits of the Model Application - Economic/Environmental

*The model study demonstrated that a properly designed cap would contain the underlying contaminated material within the site boundaries. The study was used to help establish cap performance criteria.*

G. Technical Information about the Model.

1. Modeled Area (in square miles). *0.4 square miles*

2. Number of Nodes and Layers. *700 nodes and 3 layers*

3. Flow Model

   a. Calibrated - yes/no? *Yes*
   b. Steady-state and/or transient calibration? *Steady-state*
   c. Steady-state and/or transient scenarios? *Steady-state*

4. Transport Model.

   a. Practice Tracking or Advection/Dispersion Model? *MOC*
   b. Fate Model? *None*
   c. Calibrated Transport - yes/no? *Yes*

H. Other Miscellaneous Information

1. Area of the Country (e.g., midwestern, northeastern, etc.).

   *Northwest*

2. Shortcomings and Limitations of the Model Application.

   *Poor linkage between flow and transport models.*

3. Peer Review.

   *Internal by client.*

4. Tandem Model.

   *None. The PRP did not conduct an independent modeling exercise concurrently ("in tandem") with EPA's modeling as a means of checking the agency's conclusions.*

# 3.0

# Model Applications

## Introduction

This section provides summary descriptions of the model applications, some of which were developed to test the original Assessment Framework. These descriptions are presented to help the reader understand the variety of model applications that the Framework was tested against. These descriptions are not intended to be examples of the application of the Framework but simply summaries of the test cases. Each description discusses the:

- Decision objective;
- Regulatory context;
- Site characteristics (e.g., geology, ground-water contamination);
- Modeling activities and results;
- Interesting features of the application; and
- Names of EPA staff to contact for more details about the test case.

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## 3.1 - Summary Description #1

# 3.1

# Model Applications
# Summary Description #1

Decision Objective:

This RCRA site was modeled to determine if the effects of a hydraulic barrier and hydraulic head maintenance system would meet hydraulic gradient performance standards set forth in a Consent Decree. This was an enforcement lead site where contractors for the responsible party performed the modeling. The Region reviewed the modeling effort and results to ensure that the site was modeled as accurately as possible and that the model results indicated that the proposed corrective action would meet the Consent Decree performance standards.

Background:

The site is located in an area of industrial, commercial and warehousing operations on a peninsula in Baltimore Harbor. A significant portion of the perimeter of the site abuts the harbor. Chromium ore was processed at the site from 1845 to 1985. This was a waste intensive operation that generated large quantities of process residuals containing soluble chromium. Historically, these process residuals were used as fill material at the plant site and in other areas around Baltimore Harbor. (See Figure 3.1-1.)

The contamination of soil and ground water with elevated levels of chromium creates the potential for human and environmental exposure. The risk of such exposure, although small, will potentially exist as long as the site remains uncontrolled. To minimize this risk of exposure, a combination of a low permeability cap, a hydraulic barrier and ground-water extraction wells was proposed as a containment strategy.

Remedial investigation and subsequent ground-water modeling of this site began in October 1985, with further site investigations occurring through 1989 as potential remedial actions were evaluated and the ground-water model was refined. The ground-water modeling that is the focus of this case study began with the refinement of the prior model to increase modeling accuracy. This work was performed in 1989 and 1990.

Geologic Summary:

The site is located within the Coastal Plain Physiographic Province, an area that is characterized by an unconsolidated sediment wedge that thickens toward the Atlantic coast. In the vicinity of the site, coastal plain sediments are on the order of 70 ft thick. This site is underlain by artificial fills, recent organic silty clay deposited in the harbor, Pleistocene sediments, lower Cretaceous sediments and bedrock.

The deepest geologic unit investigated consists of gneiss bedrock which is composed of three distinct strata. The lowest stratum is weathered rock composed of fine to medium grained gneiss that is often broken and fractured. Overlaying this lowest stratum is a second stratum with an average thickness of eighteen feet. This stratum consists of fine to coarse sand within a white clay-silt matrix that includes a high feldspar content and a fine to coarse sand containing trace to some silt with a high biotite content. The upper bedrock stratum consists of clayey fine to coarse sand and has an average thickness of ten feet.

Overlaying the bedrock are Lower Cretaceous sediments which vary in thickness from 12 to 40 feet. These sediments range from a silty white sand to white sand and gravel to a white clayey silt. Blanketing the Lower Cretaceous sediments are Pleistocene deposits composed of silty clay, sand, gravel and cobbles which range from 5 to 15 feet in thickness. Above the Pleistocene deposits black organic silty clays and silty fine sand are found along the bulkhead margins of the site. The organic silty clays have an average thickness of 20 feet and the silty fine sand varies between 5 and 10 feet in thickness.

The fill materials, which created the level surface on which the site facilities were built, consist of silty sands, micaceous sandy silts and poorly to well graded sands as well as construction debris, bricks and wood fragments. The fill material occurs at every location across the site and can be as much as 30 feet thick.

Ground-Water Contamination Summary:

The chromium contamination at the site was found to be present in two ground-water yielding layers, one shallow, a water table aquifer, and one deep, a regional aquifer system. The shallow ground water, which lies principally above the low permeability silts near the site perimeter, flows radially off the site through the bulkheads to the north, west and south. The shallow ground-water contamination, which occurs chiefly near major source areas was found to have chromium levels from 0.01 mg/L to 14,500 mg/L.

Deep ground-water contamination within the Cretaceous sands was also highest near the source areas. Regionally, flow in the deep ground water originates from the northwest of the site and flows towards the southeast. Locally, the deep ground water flows radially away from the central portion of the site, with localized small upward and downward flow gradients between the deep and shallow ground water.

Modeling Summary:

The U. S. Geological Survey's three dimensional flow code, MODFLOW, was used to model this site in a steady state. Six model layers, each of which was constructed with variable thicknesses and bottom elevations, were used to simulate the flow of ground water under the site. A 24 row by 24 column finite-difference grid was constructed. (See Figure 3.1-2.) Grid cell dimensions varied between 75 and

150 feet with the smallest cells located directly over the study site. Boundary conditions modeled included the flow directions and gradients of the water table and regional aquifer systems, leakage from the harbor and precipitation recharge. Horizontal hydraulic conductivity was determined for each layer by averaging hydraulic conductivities from field tests. Vertical hydraulic conductivities were initially assumed to equal the horizontal hydraulic conductivities and were adjusted during calibration of the model.

During the calibration of the model, water levels in the observation wells were used as targets and compared to simulated water levels. The hydraulic parameters were adjusted to provide the best possible match between measured and calculated heads at the calibration targets. Residual analysis was used to measure the effectiveness of the calibration. The residual sum of squares was equal to 32.6 $ft^2$ and the residual mean was 0.0053 ft.

Additional field testing was performed to refine the calibration of the model. Aquifer tests were used to improve hydraulic conductivity estimates. Additional piezometers were also installed to better understand hydraulic gradients. The model was then recalibrated with these new data.

Three hydraulic barrier scenarios were evaluated through model simulations. All scenarios assumed site closure with the emplacement of a low-permeability cap over the entire site. The first scenario simulated a "deep soil mixing" wall that extended one foot into the uppermost stratum of the bedrock, a clayey fine to coarse sand. This scenario was modeled in combination with ground-water extraction wells and with perimeter trench drains placed at different depths.

The second scenario simulated a shallow slurry wall that extended two feet into the clayey silt stratum of the Lower Cretaceous sediments. This scenario was modeled in combination with alternative configurations of ground-water extraction wells and with perimeter trench drains placed at different depths.

The third scenario simulated only ground-water extraction wells on the site.

Modeling Results Summary:

Model simulations of the first scenario indicated that the use of a deep hydraulic barrier without pumping or trench drains would not meet the head difference performance standards of the Consent Decree. However, the use of 12 extraction wells pumping a total of 2100 gal/day in combination with the wall would meet these performance standards. The model simulations also indicated that perimeter drains in combination with the deep hydraulic barrier would meet the performance standards. When drains were placed at -0.5 ft msl. and 0.0 ft msl. the model simulations indicated that 13,500 gal/day and 3,500 gal/day of ground-water extraction would occur respectively.

Model simulations of the second scenario indicated that the shallow hydraulic barrier without pumping or drains would not meet the head difference performance standards of the Consent Decree. Moreover, the modeling indicated that the use of the shallow hydraulic barrier instead of the deep hydraulic barrier would require significantly increased ground-water extraction. If twelve extraction wells were used a total pumpage of 27,500 gal/day would be needed. If only eight wells were used, the pumpage requirements would increase to 28,000 gal/day. If perimeter trench drains were used in lieu of wells the ground-water extraction rate would vary between 17,440 and 13,500 gal/day depending on the elevation of the drains.

Model simulations of the third scenario indicated that the head difference performance standards of the Consent Decree could be met by pumping alone with no hydraulic barrier. The total pumpage, however, required to meet the performance standard would be 92,580 gal/day distributed over twelve extraction wells.

In summary, model simulations indicated that the Consent Decree hydraulic head difference performance standards could be met by each of the three modeling scenarios. The first scenario, a deep wall and pumping resulted in minimum extraction rates. Pumping wells alone were able to meet the performance standards; however, in the absence of a hydraulic barrier, the amount of pumpage necessary to maintain the performance standards was more than an order of magnitude greater than that of the first scenario.

Strengths And Interesting Features Of This Application:

In this case study, an existing model of a site was refined and recalibrated. The refinement of the model reflected the need for increased simulation accuracy as the regulatory process moved from site characterization, to technology screening, to the design of a specific containment technology and management strategy.

This modeling application was used to predict the performance of alternative corrective actions and the impact of those alternatives upon the hydrogeologic system. It should be noted that the quantity and quality of site field data in this case study are atypical of most sites. These data allowed the development of a model with considerable hydrogeologic specificity.

This application provided the information necessary to justify the need for both a slurry wall and ground-water pumping inside the wall. Originally the responsible party had proposed just a slurry wall with no pumping. This study demonstrated the problems with such an approach and the effectiveness of combining the slurry wall with pumping. For example, this study dramatized that required pumping rates varied by over an order of magnitude with and without the slurry wall. Moreover, this study helped to determine the design capacity of a water treatment system by determining the volume of ground-water extraction for each scenario.

This study demonstrated that the hydrogeologic system would be modified by the proposed corrective action and provided a mechanism for predicting these impacts. The Region noted that they will monitor the effectiveness of the selected corrective action and if necessary the corrective action and/or the model application will be modified as additional information is gained. This type of review, often called a post audit, is strongly encouraged by ground-water modeling experts.

The calibration report provides an example of the use of residual analysis to evaluate the model calibration.

Areas that should be covered in model calibration documentation include:

1. Explicitly establishing and documenting a reasonable range of parameter values to be used in the calibration of the model;
2. Documenting the model residuals and the residual analysis;
3. Documenting the sensitivity of the model to variations in model parameters;
4. Documenting the impact of grid spacing and time step on the numerical accuracy of the model;
5. Documenting the criteria being used to terminate the calibration process; and
6. Documenting the evaluation of the spatial and temporal distribution of residuals.

Contacts:

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Modeling Documents:

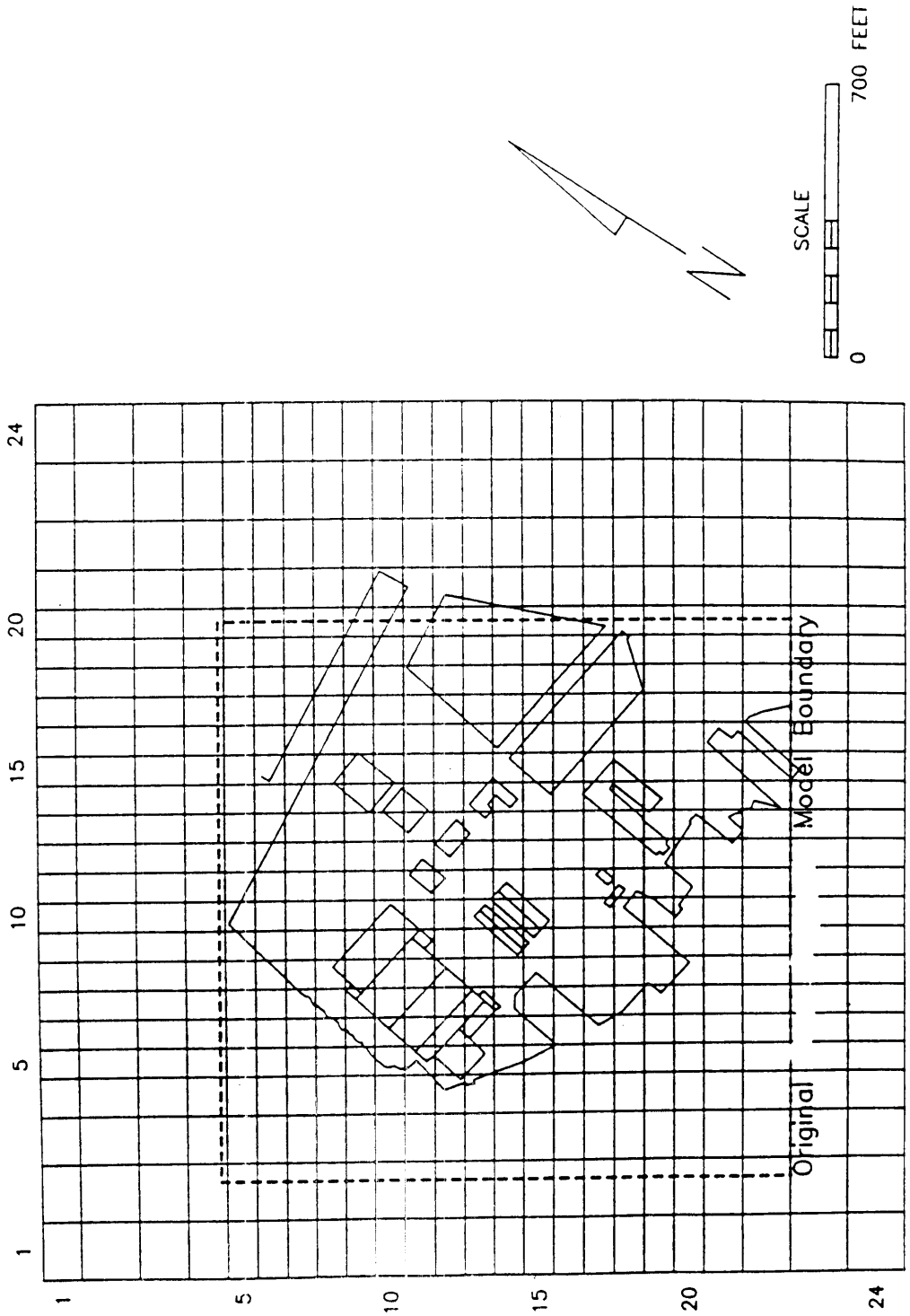
Please contact the above people for specific modeling documents.

Figure 3.1-1

Site Location

Figure 3.1-2

Finite Difference Model Grid



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## 3.2 - Summary Description #2

# 3.2

# Model Applications
# Summary Description #2

Decision Objective:

The United States Army's (Army) Aberdeen Proving Ground O-Field site was modeled in the early phases of a site investigation to assist in screening corrective actions for the site. Specifically, the objective of the modeling was to:

1. Provide a framework for the characterization of contaminant releases and plumes;
2. Determine if contamination was migrating to other aquifers or surrounding surface water bodies; and
3. Predict the probable hydrologic and chemical effects of relevant remedial actions.

This modeling was performed as a requirement of a RCRA permit that EPA issued to the U.S. Department of Army. In turn, the U.S. Army Environmental Management Office of the Aberdeen Proving Ground contracted with the U. S. Geological Survey (USGS) to conduct the modeling that is the focus of this case study. The EPA Region reviewed the modeling results to ensure that the site was modeled as accurately as possible and that the above decision objectives were met.

Background:

O-Field site is a 259 acre area located within the 79,000 acre Aberdeen Proving Ground Army installation and is surrounded by Army testing ranges. O-Field lies on a neck that extends into the Chesapeake Bay and is directly bordered on the west by the Gunpowder River and on the north and east by a tributary of the Gunpowder River, Watson Creek. (See Figures 3.2-1 and 3.2-2.) Watson Creek, which is better described as a pond, discharges into the Gunpowder River through a man-made culvert that restricts tidal flushing and therefore causes high organic loading in the creek. To the south of O-Field lie other Army testing ranges. The site topography is relatively flat with the highest elevation being about 19 feet above sea level.

O-Field includes two sub areas, Old O-Field and New O-Field. Old O-Field was periodically used from the late 1930's into the 1950's for the disposal of munitions and chemical-warfare agents. Disposal at New O-Field began in 1950 and continued for an unspecified period. Disposal materials at New O-Field included ordnance, contaminated material, laboratory quantities of chemical-warfare agents and dead animals. The primary activity in later years at New O-Field was the destruction of material by burning.

At both New and Old O-Field, containerized and uncontainerized material was disposed in unlined and uncovered trenches, pits and directly on the ground. Beginning in 1949, sporadic cleanup efforts were initiated with the goal of destroying some of the explosives. Periodically during the cleanup operations, explosions ruptured container casings and directly exposed contaminants. Today, most of the pits and trenches have been covered with soil.

In 1976, the Army recommended an assessment of the Aberdeen Proving Ground to determine the potential for off-post migration of chemical contaminants. Observation wells installed at O-Field in 1978 showed the presence of arsenic and chlorinated organic solvents in the ground water. Analysis of surface water and soil samples indicated that the ground water was transporting arsenic into Watson Creek. A limited resampling of ground and surface water in 1984 confirmed these findings.

An observation well network was developed in 1985 when eleven existing wells were supplemented with 21 additional wells installed at eight locations. All well drilling was performed using a remote control drill, bombproof shelters and other extraordinary safety and security procedures due to the possibility of encountering buried ordnance or chemical-warfare agents. An additional five wells were installed in 1987 when quarterly sampling indicated the possibility that contaminants might be present beyond the area covered by the original observation well network.

Geologic Summary:

O-Field is located on unconsolidated sand, clay and silt of the Atlantic Coastal Plain. Beneath the Coastal Plain sediments lies a basement complex of Precambrian to Paleozoic crystalline rocks and Mesozoic rift-basin sedimentary rocks. The depth to the pre-Cretaceous basement rocks at O-Field is approximately 650 feet.

The site hydrogeology was investigated to only a 200 hundred foot depth because of the difficulties associated with remote drilling operations and the improbability that contamination had extended to this depth. Four aquifers were discovered but only the upper three were investigated. These three consisted of a water table aquifer and two confined aquifers with the lowest confined aquifer occurring at a depth of 70 to 90 feet. (See Figure 3.2-3.)

The uppermost soils at O-Field are silt to silty lean clay and below this layer lies a low permeability, tan to grey sand with some silt. Lenses of gray clay underlie the sand followed by silty sand where the water table begins. Extensive excavation and explosions have probably destroyed much of the natural strata of the site to a depth of 10 to 12 feet.

The water table aquifer lies 9 to 15 feet below ground surface with an average saturated thickness of ten feet that varies seasonally by as much as three feet. This aquifer is present across the site and is composed of brown to reddish-brown quartz

sand interbedded with discontinuous silt and clay layers. The sand is medium grained in the central areas of the site and becomes finer to the east and north and coarser to the northeast. The water table aquifer is underlain by a confining layer composed of highly plastic black to gray or greenish gray clay. The depth of this confining layer is 11 to 30 feet below ground surface and ranges in thickness from 0.5 to 5 feet. The presence of contamination below this layer indicates that the confining layer is either leaky or discontinuous.

The upper confined aquifer is below this confining layer. This aquifer lies 20 to 30 feet below the ground surface with a thickness that varies from 13 feet in the east and south to less than a foot as it nears the Gunpowder River to the west. The aquifer probably remains confined beneath the Watson Creek shoreline but loses its confining bed beneath the deeper parts of the creek. This aquifer is composed of dark grey to brown, medium to coarse-grained sand interbedded with gravel and discontinuous clay lenses. This aquifer is underlain by a confining layer composed of dense, black to dark grey clay. The depth of this confining layer is 20 to 39 feet below ground surface and ranges in thickness from 43 to 60 feet. The extent, thickness and low permeability of this confining bed are probably adequate to prevent contaminant migration or significant water movement from the upper confined aquifer to the lower confined aquifer.

The lower confined aquifer lies approximately 80 feet below ground surface and is 10 to 20 feet thick. There is little information on the extent and lithology of this aquifer. Downhole gamma, spontaneous-potential and resistance logs as well auger behavior during drilling suggests that it is composed of a highly permeable, gravel like material.

Ground-Water Hydrology Summary:

Water flow in the aquifers underlying this site is complex due to the surface-water interactions and lagging tidal cycles in Watson Creek. Ground water in the water-table and upper confined aquifer generally flows from south to north/northeast towards Watson Creek. A ground-water divide that lies to the west of Old O-Field causes a portion of the ground water to bypass Old O-Field and flow into the Gunpowder River. (See Figure 3.2-4.) A gross estimate of the ground-water flow rate is 50 feet/year.

The water-table aquifer derives most of its recharge from vertical infiltration of precipitation. Additional recharge occurs by lateral movement of ground water as discussed above and periodically by Watson Creek, which overflows its banks during periods of high tides. Discharge is primarily to Watson Creek and the Gunpowder River.

Recharge to the upper confined aquifer is by downward leakage from the overlying water-table aquifer. Discharge is by slow upward leakage through the confining bed to the water table aquifer in down gradient areas and by leakage to surface water bodies where the confining bed has eroded.

The hydraulic gradient indicates that the ground water in the lower confined aquifer flows toward the west-northwest, possibly discharging into the Gunpowder River. The heads in this aquifer are typically higher than those in the upper confined aquifer. Thus, in the unlikely event that there are pathways for downward contaminant migration between the upper and lower confined aquifers, the hydraulic gradient would oppose all such flow except for the density driven migration of free product.

Ground-Water And Surface Water Contamination Summary:

The ground water in both the water table and the upper confined aquifer at O-Field contains inorganic and organic contaminants. Inorganic contaminants include arsenic, iron, manganese, zinc, boron, antimony, cadmium and chloride. For example, arsenic concentrations range from 1.96 parts per million (ppm) in the water-table aquifer to 0.0016 ppm in the upper confined aquifer. Dominant organic contaminants are chlorinated aliphatic hydrocarbons, aromatic hydrocarbons and chemical-warfare degradation products which contain sulfur and phosphorus. Concentrations of thiodiglycol, a degradation product, ranged from 1000 ppm to 5 ppm in the water-table aquifer. In general the highest contaminant concentrations are measured in the water-table aquifer, although higher concentrations of boron and 1,1,2,2-tetrachloroethane are present in the upper confined aquifer than in the water-table aquifer. The arsenic and cadmium concentrations found exceed EPA drinking water maximum contaminant levels. The concentrations of chloride, iron, manganese and zinc exceed 1987 EPA secondary maximum contaminant levels.

The distribution of individual dissolved contaminants varies areally in the water table and upper confined aquifer. For example, the concentrations of arsenic and organic contaminants are highest along the northeastern side of Old O-Field. However, iron is present as two distinct plumes, one along the eastern side and one along the northeastern side of Old O-Field. The areal distribution of contaminants at New O-Field could not be evaluated because of the limited number of wells at the site.

Although low concentrations of organic contaminants have been detected in water samples from the lower confined aquifer, hydraulic gradients and the lithology and thickness of the overlying bed make it unlikely that O-Field operations have contaminated the lower confined aquifer.

A surface water quality study in 1985 of Watson and nearby creeks found unusually high organic loading in Watson Creek and dissolved inorganic constituents that exceed EPA chronic toxicity levels for freshwater and saltwater aquatic life. The lateral migration of ground-water contaminants into Watson Creek is thought to be partially responsible for the surface water contamination. Ultimately, this surface water contamination may migrate into the Gunpowder River.

Modeling Summary:

The U. S. Geological Survey's (USGS) three dimensional flow code, MODFLOW, was used to model this site in a quasi three dimensional, steady state mode. Two model layers were used, one layer simulating the water-table aquifer and the second layer simulating the underlying confining layer and the upper confined aquifer. The lower boundary of the second layer coincides with the top of a fifty foot thick layer of dense clay below the upper confined aquifer. The low permeability and continuity of the clay was thought to justify its use as a no-flow boundary for this model application and thus eliminated the need to model the lower confined aquifer. The model was found to be relatively insensitive to this assumption as discussed below.

A 66-row by 61-column finite-difference grid was constructed and aligned with the principal direction of flow. The grid extends to the south and considerably beyond O-Field to coincide with surface water bodies that could be modeled under steady state conditions as constant head boundaries. Grid cell dimensions varied between 20 and 2375 feet with the smallest cells located directly over the areas of interest. Changes in cell size were limited to no more than 1.5 times the size of adjacent cells.

Boundary conditions modeled included surface water bodies, no-flow regions, drains, and leakage between the layers. Vertical hydraulic conductivities were based upon typical values for similar soil types, limited field data and model calibration. The water-table aquifer was bounded at most locations by constant head boundaries which represented the shoreline of surface water bodies. At the two areas where the water-table aquifer extended beyond the modeled area the ground-water flow was parallel to the model boundaries and thus these areas were modeled as no-flow boundaries.

The lateral boundaries of the upper confined aquifer were specified as no-flow boundaries. However, a relatively high vertical hydraulic conductivity was specified for those portions of the overlying confining layer that lay beneath surface water bodies and thus these areas of the modeled layer responded almost as if they had been established as constant head boundaries. Consequently, as the modeled portion of the upper confined aquifer is almost entirely surrounded by surface water bodies this layer was effectively modeled with constant head boundaries with one exception. That exception was determined to be far enough from O-Field that the no-flow boundary had negligible effects on simulations within O-Field.

Preliminary calibration of the steady-state model was achieved by setting average annual recharge constant and adjusting model coefficients, primarily the horizontal hydraulic conductivity of the water-table aquifer and the transmissivity of the upper confined aquifer. These coefficients were adjusted within a range of reasonable values based upon field measurements. The calibration was considered acceptable if the simulated and observed average annual heads agreed within 0.5 feet. The model was then recalibrated against observed head data for a period of

elevated ground-water levels. During this second calibration the horizontal hydraulic conductivity and transmissivity values obtained from the first calibration were held constant and recharge was uniformly increased until the predicted heads acceptably matched the observed heads Horizontal hydraulic conductivity and transmissivity were then adjusted slightly to improve the match. These new values were then used to once again calibrate the model against the average annual observed heads. This process was repeated until the model met the calibration criteria under both hydrologic scenarios.

Because of uncertainties about the actual recharge and hydraulic conductivities at O-Field, several alternative solutions to the steady state model were then generated by varying both recharge and hydraulic conductivity. Based upon recharge estimates and field measurements of horizontal hydraulic conductivity, the recharge was varied between 9 and 16 inches per year and the hydraulic conductivity was uniformly adjusted by the same percentage. The resulting head configurations still closely matched the observed heads. These alternative hydrogeologic system representations were used to model the system responses to the remedial alternatives evaluated also. Thus, the impact of hydrogeologic uncertainty upon the results of the remedial alternatives modeled could be quantified.

A sensitivity analysis of the calibrated flow model was performed for a range of recharge, hydraulic conductivity and transmissivity values. This analysis indicated that heads in the water-table aquifer were relatively insensitive to variations in the vertical hydraulic conductivity of the confining layer or transmissivity of the confined aquifer. Heads in the confined aquifer were somewhat more sensitive to these variations. The sensitivity analysis also indicated that simulated heads in both aquifers were very sensitive to changes in the horizontal hydraulic conductivity and recharge of the water-table aquifer.

The assumption that the lower confined aquifer did not need to be modeled was also examined during the sensitivity analysis. Simulations of a modified version of the model that included the lower confined aquifer as a third layer demonstrated that significant head variations in the lower confined aquifer had a minimal impact on the head in the upper two aquifers. This confirmed that simulation of the ground-water system as a two layer system was adequate for the purposes of this modeling effort .

Five remedial actions and a sixth no-action scenario were evaluated. These remedial actions were evaluated on the basis of their ability to lower ground-water levels within the disposal areas and to limit lateral or vertical movement of water through the disposal areas. The remedial actions evaluated included: installation of an impermeable cap; installation of subsurface barriers; installation of a ground-water drain; ground-water pumping to control water levels; ground-water pumping to recover contaminants; and no action. All remedial actions were also simulated

with the alternative model configurations described above to quantify the impact of hydrogeologic uncertainty upon each remedial alternative's predicted effectiveness.

The impermeable cap remedial alternative was simulated by establishing areas of no ground-water recharge. The subsurface hydraulic barriers were simulated by reducing horizontal hydraulic conductances in the model cells representing the barriers. These conductances were calculated to represent a 5 foot thick barrier with a horizontal hydraulic conductivity of 0.001 feet per day and accounted for the fact that the barriers did not comprise the entire cell. The ground-water drain was simulated by lowering the surface elevation of an existing natural drain to 1.5 feet above sea level during the period of record.

Ground-water pumping to control water levels was simulated with the addition of three pumping wells upgradient from Old O-Field and two wells upgradient from New O-Field. Each of these wells were simulated at pumping rates of 2,900, 5,800, 10,000 and 21,600 gallons per day (gal/d) but Old O-Field and New Old Field wells were simulated separately. The pumping was simulated with and without impermeable covers. Similarly, ground-water pumping to recover contaminants (pump-and-treat) was simulated with the addition of two wells adjacent to the southeastern side of Old O-Field and two wells adjacent to the northeastern side of New O-Field. Again, each of these wells was pumped at rates of 2,900, 5,800, 10,000 and 21,600 gal/d; Old O-Field and New O-Field wells were simulated separately; and the pumping was simulated with and without impermeable covers on the respective disposal areas.

Modeling Results Summary:

The simulations indicated that covering Old O-Field with an impermeable cap would lower water levels beneath the site by less than 1 foot. An impermeable cap over New O-Field would be even less effective and reduce water levels by only 0.3 feet. Ground-water velocities appear to be sufficient to compensate for the loss of recharge water intercepted by the caps. However, the reduction of precipitation infiltration into the unsaturated zone at the fill could decrease the amount of contaminant leaching.

Subsurface hydraulic barriers upgradient from Old O-Field resulted in water level declines below Old O-Field of about 1 foot but produced increases in water levels at New O-Field. Thus while potentially reducing contaminant leaching at Old O-Field the barriers may also increase leaching at New O-Field. Complete encapsulation of Old O-Field with hydraulic barriers and an impermeable cap was also simulated and was shown to provide short term aquifer protection. However, the concentrations of some contaminants would likely increase in solution and should the encapsulating walls fail at some future point, the concentrations of some contaminants in the ground water would then increase.

The simulation of subsurface barriers at the New Old-Field reduced water levels at the disposal trenches by 2.5 feet but increased water levels by 2 feet on the

upgradient side. These reductions increased to 3.5 to 4.5 feet with the addition of an impermeable cap.

The simulation of deepening an existing natural drain lowered water levels in the water table aquifer beneath both Old and New O-Field. In turn, a ground-water divide developed between the drain and Old O-Field and contaminant movement from Old O-Field towards the drain probably would not occur. However, during periods of low ground-water levels or high surface water levels, brackish surface water would enter the drain and recharge parts of the water-table aquifer with brackish surface water.

Pumping to manage water levels at Old O-Field indicated that the water-table aquifer would be drawn down by 0.7 to 1.0 feet when the wells were pumped at 5800 gal/d per well. When an impermeable cap was added the drawdown increased by 0.5 feet. However, some simulations within the range of hydrogeologic uncertainty demonstrated that a pumping rate of 5800 gal/d per well or more could induce contaminants to migrate to previously uncontaminated areas.

Pumping rates of 10,000 and 21,600 gal/d per well were required at New O-Field to reduce ground-water levels by 1.0 and 2.3 to 3.5 feet respectively. However, both rates would produce hydraulic gradient reversals extending to the disposal trenches and thus induce the movement of contaminants toward the wells.

The simulations predicted that pump-and-treat at a rate of 2900 gal/d per well in combination with an impermeable cap would intercept the bulk of ground-water contamination at Old O-Field in the spring, summer and fall. This rate would have to be increased to 5800 gal/d in the winter when ground-water levels are higher. However, this higher rate could induce the movement of water from Watson Creek into the aquifer if it is maintained throughout the year. Pump-and-treat at New O-Field resulted in drawdowns of 1.1 to 1.8 feet for pumpage of 5800 gal/d and 2.2 to 3.5 feet for pumpage of 10,000 gal/d. As little is known about the extent of contamination under New O-Field, no conclusions could be drawn as to whether this would intercept the bulk of the contamination. New O-Field simulations at these rates did not show inducement of infiltration of creek water but the proximity of the hydraulic grade reversal to the creek implies that infiltration would probably be induced if a 5800 gal/d per well pumping rate was maintained during dry summer months.

If no remedial actions are taken at O-Field, the simulations indicated that mobilization and transport of organic and inorganic contaminants will continue, primarily because the seasonal and recharge induced water levels rise above the base of the buried contamination. The ground water contaminants, in turn, will continue to discharge to Watson Creek. If the contaminants in the creek attain sufficient concentrations, then the depletion mechanisms in the creek may be inadequate to prevent contaminant migration from the creek into the Gunpowder River.

Strengths And Interesting Features Of This Study:

In this case study, a model was applied in the early phases of a site investigation to assist in characterizing the contaminant releases and plumes, the future migration of contaminants and to explore and screen potential remedial alternatives. Because of the hazards associated with sampling at this site, only limited hydrogeologic data was available when the modeling began. Perturbations in the ground-water system caused by tidal induced changes in the elevations of the surrounding surface water bodies further complicated the modeling. Nevertheless, data acquired after this modeling was completed confirmed the general flow field and the surface water and ground-water interactions predicted by the model.

A major effort was made to ensure that the model application would accurately predict the system response during both the average and the extreme hydrogeologic conditions found at the site. Specifically, the model was calibrated against two different sets of observed conditions; one representing average annual head observations, the other representing a period of time when significantly higher than average heads were observed. The calibration continued until the model application accurately predicted system response under both sets of conditions.

This modeling effort quantified the impact of the hydrogeologic uncertainty upon the results of the simulations. Alternative solutions to the steady state model application were developed by increasing and decreasing recharge and horizontal hydraulic conductivity within ranges defined by field measurements and professional judgement. These alternative solutions closely matched the observed heads, and therefore, were judged to bound the set of reasonable representations of the ground-water system. In turn, these alternative representations of the system were used to bracket the range of system responses to the remedial alternatives evaluated.

An analysis of the sensitivity of the calibrated model application to changes in hydrogeologic parameters was also performed. As a part of this analysis the sensitivity of the model predictions to modeling the site as a two layer system was investigated. The sensitivity analysis indicated that the two-layer representation was sufficient for the purposes of the study.

The model application provided the EPA Region with the framework for selecting the most appropriate remedial alternative. It provided guidance in determining the goals and objectives of the remediation effort. Based upon the results of the modeling described in this case study, ground-water extraction was selected as the preferred remedial action. The model application was subsequently used to evaluate alternative extraction systems.

Contacts:

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Modeling Documents:

Please contact the above people for specific modeling documents.

Figure 3.2-1

Site Location

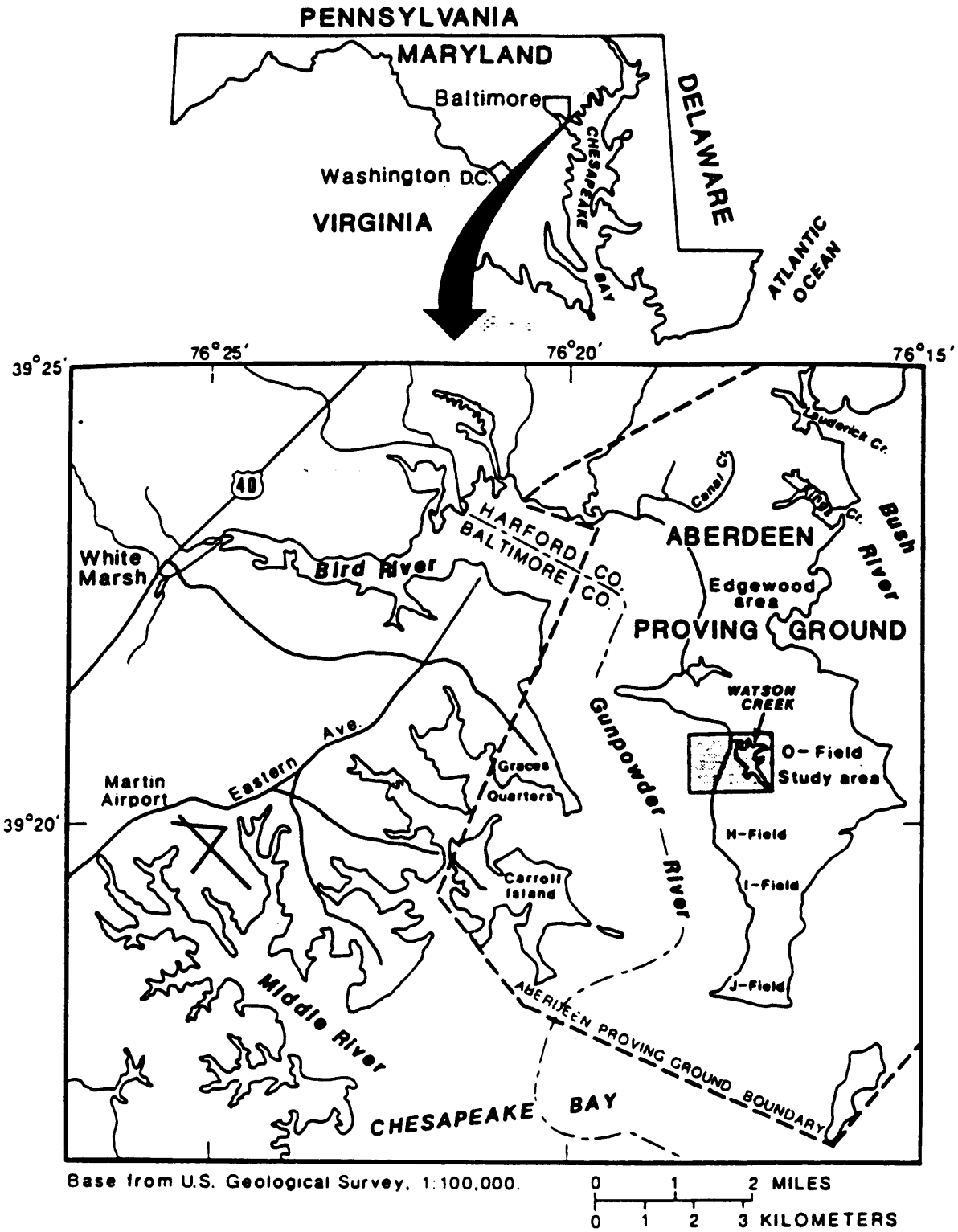
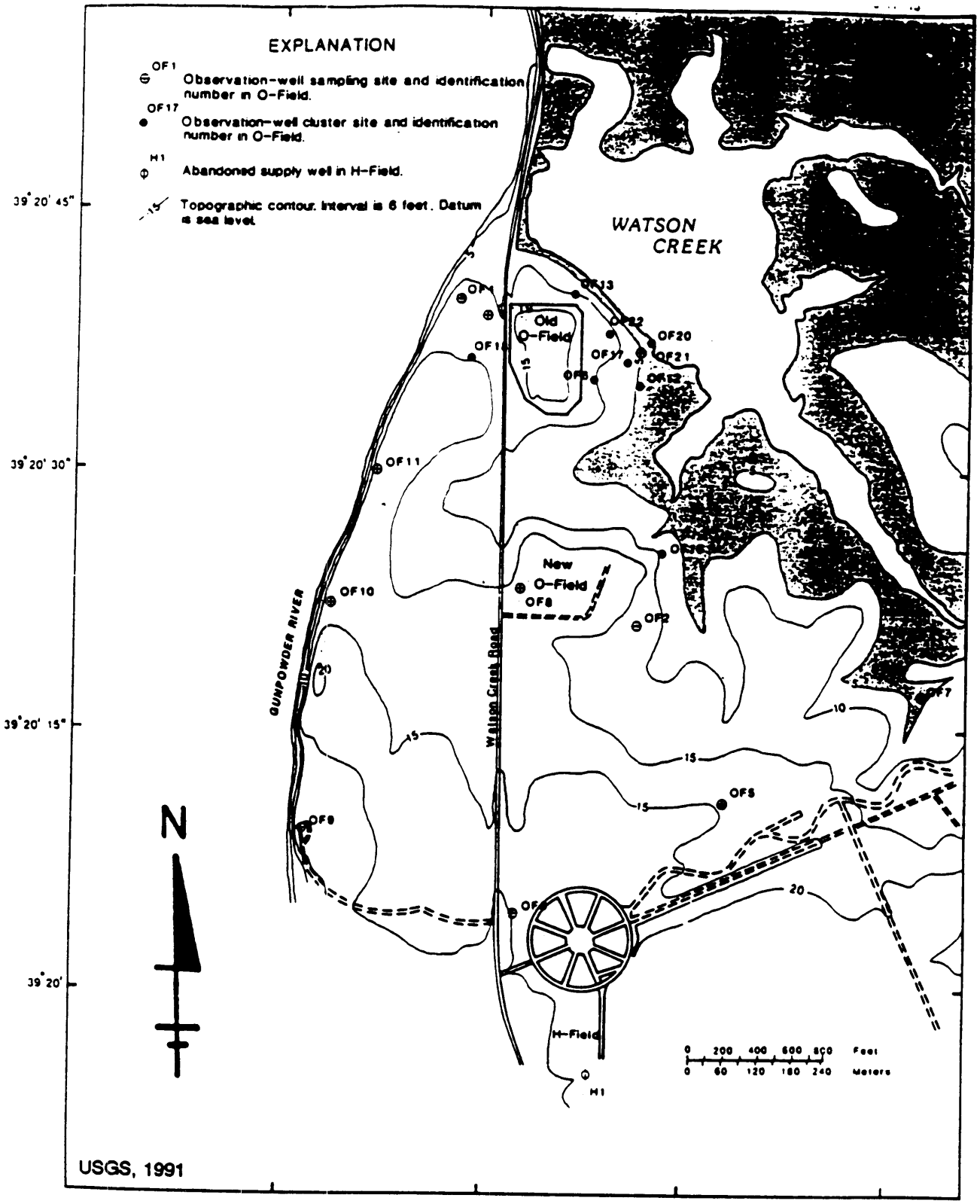


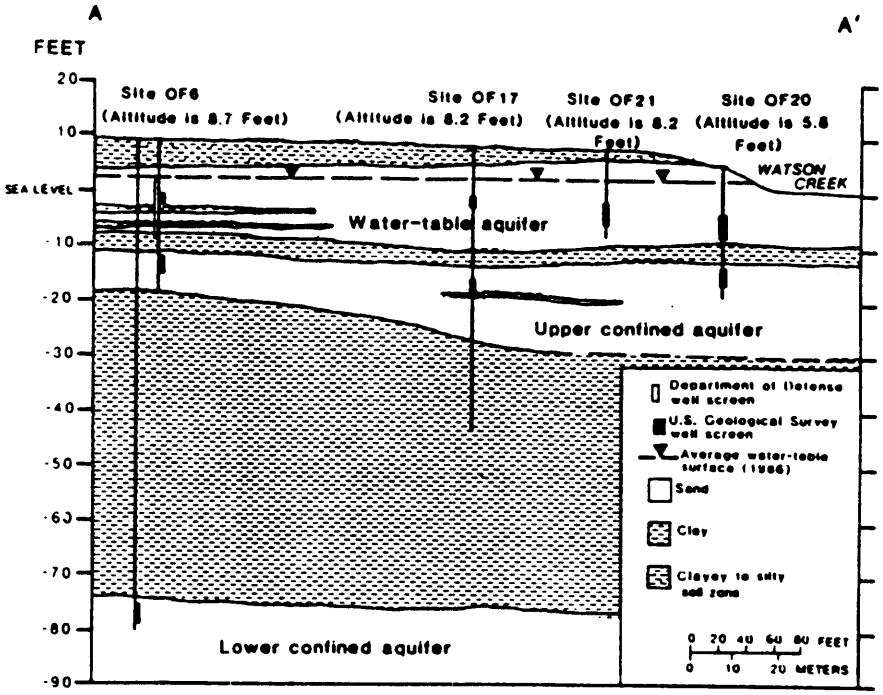
Figure 3.2-2

Detailed Site Location

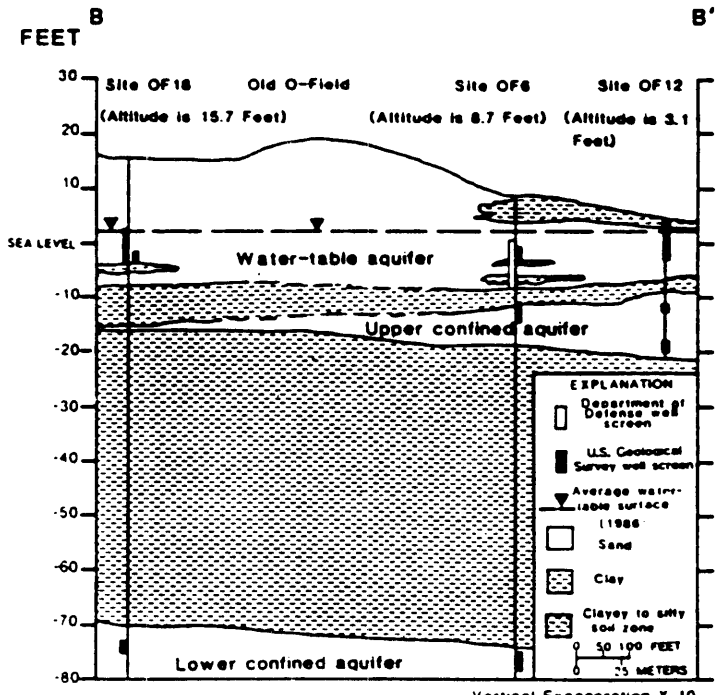


# Figure 3.2-3

## Sample Hydrogeologic Sections



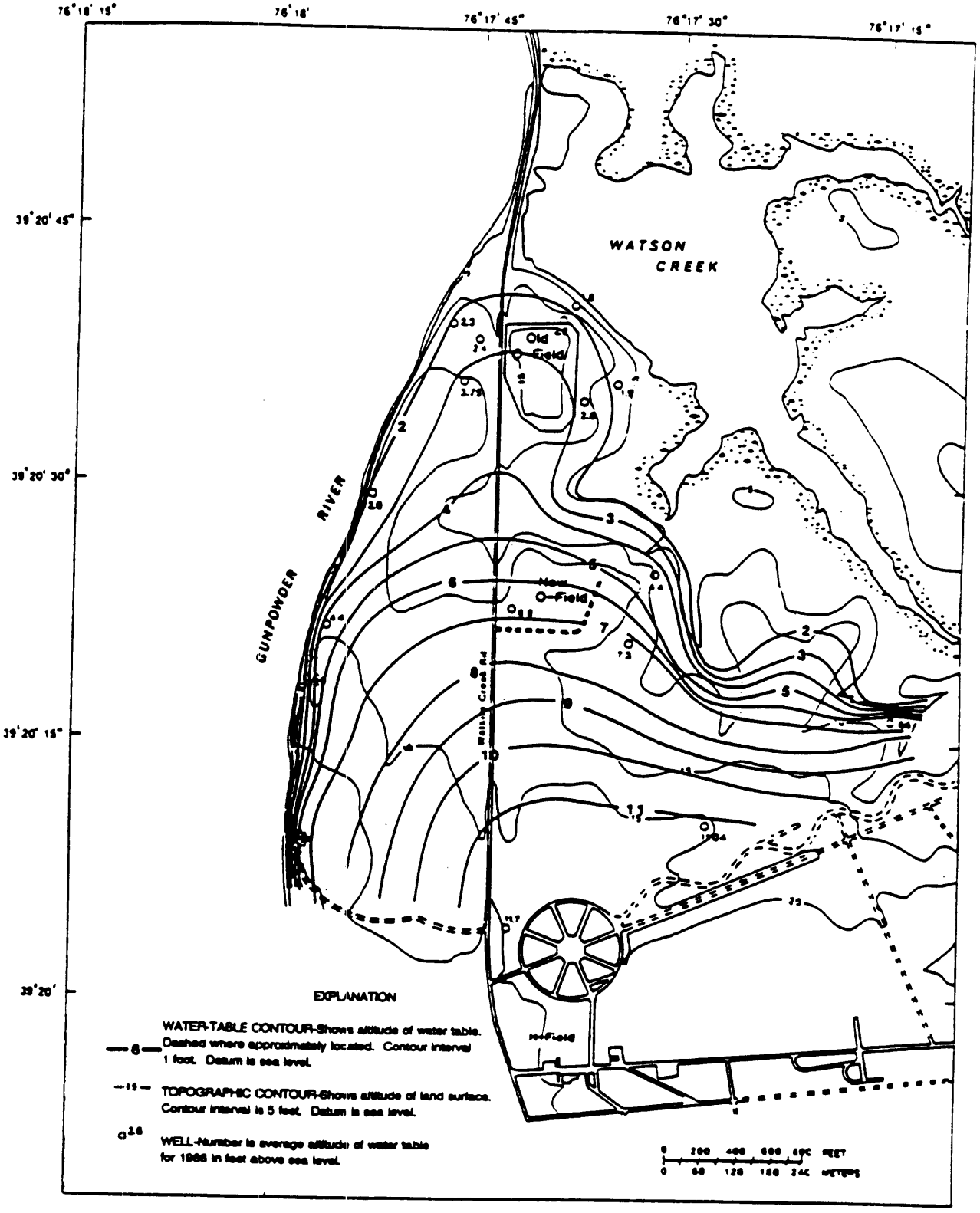

HYDROGEOLOGIC SECTION A-A' Vertical Exaggeration X 4




HYDROGEOLOGIC SECTION B-B' Vertical Exaggeration X 10

Figure 3.2-4

Site Water-Table Contours



## 3.3 - Summary Description #3

# 3.3

# Model Applications
# Summary Description #3

Decision Objective:

This fund-lead site was modeled during the Remedial Design (RD) to ensure an appropriate design while minimizing design costs. Specifically, additional information on the ground-water flow and contaminant fate and transport was required to design a ground-water extraction and collection system that had been specified in the Record of Decision (ROD). The EPA contractor proposed additional field investigations including an extensive drilling program to obtain the needed design information. EPA suggested that much of the required information could be obtained through the use of ground-water modeling, thus significantly reducing design costs. The contractor agreed to the modeling effort and specific modeling objectives were established. These objectives were to:

1. Delineate the maximum possible extent of the contaminant plume in January 1993, when the pump and treat system is scheduled to begin operation;
2. Estimate the mass of contamination per unit volume of the aquifer;
3. Conceptualize extraction well alignment designs; and
4. Evaluate the design alternatives.

An EPA contractor working under an Alternative Remediation Contracting System contract did the modeling that is the subject of this case study. The EPA project manager reviewed the modeling work.

Background:

This is a six acre site located in a 250 home residential area with homes within 100 feet of the site. (See Figure 3.3-1.) Other land use in the area includes some commercial development along a state highway southeast of the site and agricultural activities southeast of the same highway. The site is an inactive manufacturing facility and is currently used for minor non-production activities, primarily warehousing. Located on the site are process, office and warehouse buildings. (See Figure 3.3-2.) A tank farm and a laboratory have been removed from the site. The site topography is relatively flat but exhibits occasional low rises and gentle depressions. The average annual precipitation is approximately 35 inches and the mean monthly temperatures range from 26° F to 72° F.

This site was used to manufacture and repackage non-lubricating automotive fluids from the early 1960s to 1978. During the facility's operation, a number of releases and a major fire contributed to the site contamination. Undocumented

releases of chlorinated hydrocarbons into the vadose zone occurred south of the process buildings. Documented releases of diethyl ether occurred in 1972 when an underground pipeline was ruptured during excavation. Chlorinated organics, benzene and other solvents were released during a two day fire in 1978. During this fire numerous tanks and drums ruptured and their contents were spread onto unpaved areas by the water used to fight the fire. The unsaturated zone soil was thought to be the primary remaining source of contamination at the site.

History of Investigation

The owner of the site installed six on-site monitoring wells in 1972. Contaminant levels detected in these wells and nearby residential wells indicated that the contamination was moving off-site. Consequently, under an agreement with the state agency responsible for environmental protection, the owner began supplying bottled water to homes with contaminated wells in 1973. After the 1978 fire, the owner began removing underground tanks. Then in 1980, 15 more monitoring wells were installed at 9 locations. In 1982, the state agency initiated legal actions against the site owner to force site remediation. The following year the owner began operating a ground-water treatment system.

The site was placed on the National Priorities list (NPL) in 1984 and at that time EPA assumed the lead enforcement role. In 1985, the owner agreed to fund a remedial investigation and feasibility study (RI/FS) under an Administrative Order of Consent. The completion of that study was funded by EPA when the owner filed for bankruptcy in 1986. The state, in 1986, extended a public water supply to the residents in the area near the site. In 1988, the ground-water treatment system was closed down by the site owner due to financial problems.

In 1988, the Record of Decision (ROD) was issued. The ROD specified soil and ground-water remediation including a contaminated soil flushing system, a ground-water extraction and collection system and a ground-water treatment (air stripping) and discharge system. The ROD further specified that the aquifer within the 1.5 parts per billion contaminant concentration isopleth would have to be restored to drinking water standards.

Geologic Summary:

This site is located in an area dominated by glacial sediments deposited in a northeast-southwest trending belt. The two major types of deposits are glacial outwash with post glacial alluvium and ice-contact outwash deposits. Both types of deposits contain fine sand to coarse gravel with occasional large cobbles and are very poorly sorted. Sixteen borings made in the vicinity of this site indicate that the glacial sediments extend to an average depth of 117 feet below the surface. Underlying the site are clay, silty sand, sand and gravel facies which laterally intergrade with one another and result in laterally discontinuous layers.

The uppermost soils at the site consist of a 5 to 10 foot upper layer of fine sand and a lower 115 to 125 foot sand layer. (See Figures 3.3-3 and 3.3-4.) Underlying the lower sand layer is a 20 to 25 foot clay layer and then a layer composed of sands and gravel with occasional minor clay lenses. One boring on the eastern boundary of the site indicated the presence of a five foot silty clay layer just below the upper fine sand layer. This silty clay layer was presumed to be a very small localized lense as no other borings showed evidence of this layer. A large clay lense, however, begins just east of the site 50 feet below the ground surface. This lense extends over 3000 feet to the west and rises to thirty feet below the surface. It reaches a maximum thickness of 20 feet. Several small gravel beds where detected also in the lower parts of the lower sand layer.

Ground-Water Hydrology Summary:

The site hydrogeology is composed of three distinct hydrogeologic units. The uppermost unit is an unconfined aquifer that is encountered at approximately 30 feet below the ground surface with a saturated thickness of 70 to 90 feet in the site area and increasing to a thickness of 135 feet just over a mile and a half to the west. This aquifer corresponds to the lower sand layer discussed previously. The second hydrologic unit, a confining layer of sandy clay that varies between 7 and 22 feet in thickness near the site but thins to a two foot thickness a mile to the west, lies below the aquifer. The third hydrogeologic unit, a confined aquifer, whose confined head is approximately one and one half feet lower than the head of the upper aquifer lies below this confining layer. This lower aquifer corresponds to the layer of sands and gravel with occasional minor clay lenses discussed above. The thickness of this confined aquifer is unknown as none of the borings reached bedrock.

The upper unconfined aquifer is no longer used as a drinking water supply in the immediate site area because of contamination. Two miles to the west of the site are three municipal wells which produce more than a million gallons per day from this aquifer. The cone of depression caused by the operation of these wells may eventually enhance the off-site movement of contaminated ground-water towards the west. The direction of flow in this aquifer is generally west-southwest with a velocity of approximately 0.5 feet per day. Both pump and slug test data were used to estimate the hydraulic properties of this aquifer. The pump test data indicated an average aquifer hydraulic conductivity and transmissivity of 0.0775 cm/sec. and 148,000 gpd/ft, respectively, assuming an average aquifer thickness of 90 feet. The slug test data indicated an average aquifer hydraulic conductivity and transmissivity of 0.0489 cm/sec. and 98,000 gpd/ft, respectively.

The lower confined aquifer was not extensively studied for the purposes of remediating this site because of: (1) the presence of the confining layer above the aquifer, (2) prior sampling which indicated no presence of contamination in the lower aquifer and (3) the relatively small difference in head between the two aquifers.

Ground-Water Contamination Summary:

Eighteen contaminants were found at the site, with ten being selected as indicator compounds. These included 1,1-DCE, 1,1-DCA, 1,1,1-TCA and Benzene. The Remedial Investigation (RI) identified the unsaturated zone underlying two areas of the site as the major sources of contamination. The RI also speculated that there was potentially one other on-site source and several additional off-site sources of contamination based upon the location and discontinuity of the contaminant plume. This plume begins beneath the site and extends west-southwest beyond the site property boundaries. The plume may not be continuous within its boundaries and the thickness of the plume diminishes as it extends off-site. The contaminated zone reaches the bottom of the upper aquifer at the site and at a minimum extends 1500 feet downgradient .

The on-site ground-water contamination was being partially contained by two purge wells that operated from 1983 to the spring of 1988. These wells had a combined pumping rate of 200 gallons per minute which resulted in a maximum drawdown of about one foot. When these wells were operating they apparently contained the plume within the western and northern site boundaries. Since they ceased operation, significant additional contaminant migration has occurred.

Modeling Summary:

Analytic and analytic/numeric models and graphical techniques were used to investigate the site and to evaluate the effectiveness of ground-water extraction alternatives. This approach was chosen after a review of project objectives, the limited quantity and poor quality of the available field data, the modeling budget and project time constraints.

The modeling was divided into three phases. The objective of the Phase One modeling was to determine the maximum extent of contamination in the upper aquifer. An analytical function driven variation of the fate and transport model Random Walk and the analytic transport model PLUME were used in this phase. The objective of the Phase Two modeling was to conceptualize remedial design alternatives. Graphical Javandel type curve analysis procedures were used to determine the minimum number of pumping wells, discharge rates and recovery well locations under different pumping scenarios. Then time related zones of capture for each alternative were determined using the the U.S. EPA Wellhead Protection Area Model (WHPA). Finally, the aquifer drawdown resulting from each alternative was simulated using the analytic ground-water flow model WELFLO. The objective of the Phase Three modeling was to evaluate the most promising remedial design alternatives. Again, Random Walk was used in this phase to: (1) estimate the discharge rates, average concentration and mass of contaminants in the extraction well discharge; (2) evaluate and compare the remedial alternatives and (3) identify areas of uncertainty in design features. This case study will focus on the use of the Random Walk model in phases one and three.

The analytical function driven variation of the Random Walk model was chosen, based on the advice of an outside consultant, to verify the results of the PLUME model. Random Walk was suggested because of the modeling objectives, data limitations and the outside consultant's detailed familiarity with the model. This version of the Random Walk model utilizes an analytic function based upon the Theis equation to generate the flow field. The numeric Random Walk model is applied to simulate the fate and transport of the contaminants.

The simplifying assumptions associated with the analytic flow component of the Random Walk model required that the aquifer be treated as homogeneous, isotropic and infinite in areal extent. Thus, no site-specific boundary conditions or spatial variability in aquifer characteristics could be modeled. Moreover, unidirectional, steady state ground-water flow had to be assumed. The modeling team established a uniform hydraulic conductivity, saturated thickness, transmissivity, hydraulic gradient and aquifer porosity for the modeled area based upon information obtained from the RI report and field data.

For the Phase One modeling, three contaminants were originally selected: the most toxic (1,1-DCE), the most mobile (1,1-DCA) and the most pervasive (1,1,1-TCA). However, initial modeling efforts indicated that insufficient soil and ground-water data were available to develop or calibrate contaminant transport models for 1,1-DCE or 1,1-DCA. As 1,1,1-TCA had migrated and persisted farther downgradient than the other contaminants the modeling team felt that focusing solely on 1,1,1-TCA was valid and appropriately conservative.

The site conceptual model developed by the modeling team hypothesized that the downgradient plume developed primarily through the dissolution of 1,1,1-TCA retained in aquifer pores at residual saturation. This was in contrast to prior studies of the site which suggested that the major contaminant source lay in the unsaturated zone and was percolating into the saturated zone. Initially, the modeling team had accepted this latter hypothesis and developed a batch flushing model to simulate the migration of the contaminant into the saturated zone. However, when the results of the batch flushing model were compared with observed phenomena, there were major discrepancies. For example, only 2 to 4 percent of the contamination in the aquifer could be accounted for under this hypothesis.

After a careful review and some initial skepticism about the validity of the batch flushing model results, the modeling team hypothesized that the source term lay in the saturated zone. They searched peer reviewed ground-water literature for examples of similar conceptual models and found three. Then, additional site sampling including a soil gas survey was initiated. The results of this sampling indicated very limited soil contamination, thus further supporting the new hypothesis that the source term lay in the saturated zone.

The particle tracking component of the Random Walk model was then used to model the 1,1,1-TCA dissolution from the 1,1,1-TCA mass stored at residual

saturation in the saturated zone. This included the rate of loading of 1,1,1-TCA from the unsaturated zone by percolation to the ground water, minus the mass removal of 1,1,1-TCA from the ground-water system, during the historic operation of the purge wells described previously. This approach resulted in a source term that varied as a function of time and dropped to zero during the historical operation of the purge wells. The longitudinal and transverse dispersivities, background concentrations, and organic carbon partition coefficients utilized in the model were based upon field data and established EPA methods. All ground-water contamination was assumed to exist in the dissolved phase; and, consequently, dense, nonaqueous phase liquid migration was not simulated. Biodegradation and volatilization was also ignored.

The calibration of the Random Walk model was restricted to the contaminant fate and transport component. This version of Random Walk assumes a unidirectional flow field which can not be directly calibrated against observed piezometric heads. Field data from the RI report was used to establish the flow field parameters. Calibration of the contaminant transport model was achieved by adjusting the flow direction, flow velocity and dispersivity until predicted concentration values matched observed concentrations. These modifications were within reasonable parameter ranges and in the case of the flow direction were based upon additional field data. The source release term was held constant during the calibration process.

The calibration of the model presented a number of challenges. First, the data used to calibrate the model was obtained from prior studies conducted by the site owner's contractors. A review of that data indicated numerous data quality problems including transcription errors, false positive and false negative indications, conflicting sampling dates and surface maps of conflicting scales. Second, data from nested monitoring wells indicated the presence of a vertical contaminant concentration gradient. However, the direction and magnitude of this gradient varied inconsistently from one monitoring location to another.

The modeling team established a two-tier calibration target after analyzing these constraints and the primary model objective, which was to predict the extent of the contaminant plume at the beginning of operation of the extraction system. For those wells where the field data indicated no contamination, the model would have to indicate no contamination. For those wells where field data indicated contamination, the model concentrations would have to be within one half an order of magnitude of the measured values at that location. Furthermore, at nested monitoring wells, the average of the measured values would be used for model calibration. The model was then calibrated against three different sampling events spanning an 8 year period utilizing field data from up to 19 wells.

Recognizing the limitations of the calibration data and in turn the calibration process, the contractor initiated a new round of sampling at 23 monitoring wells under stringent quality assurance procedures. This data was not available until the calibration of the model had been completed. The modeling team, however, was

able to use this data to verify the model calibration. The success of this verification surprised the modeling team. With only one exception the model accurately simulated all wells where no contamination was detected. At those wells where field data indicated evidence of contamination, the residuals between the simulated and observed values were much closer than the one half order of magnitude calibration target used. Moreover, at the downgradient monitoring well that lay directly on the center line of the plume, the measured and simulated concentration value varied by only one part per billion.

Modeling Results Summary:

The Phase One modeling results indicated that the 1,1,1-TCA plume will have migrated 625 meters downgradient and 225 meters laterally by 1993. This migration has occurred in spite of the operation of two purge wells from 1983 to 1988. The modeling team was careful to note that they were more confident of the delineation of the plume boundary than the predicted concentrations within the plume because of model and data limitations.

Based upon these results, 15 extraction well alternatives were developed in Phase Two using Javandel type curve analysis, the GPTRAC module of the U.S. EPA Well Head Protection Area Model (WHPA), and the analytic model WELFLO. This analysis indicated that under ideal conditions only one extraction well discharging at 100 gallons per minute would be required. However, recognizing the limitations associated with the Phase One modeling and the models used in this second phase, two additional alternatives utilizing three and five wells respectively were chosen for further consideration in the Phase Three modeling. The location of the capture zone of one alternative is shown in Figure 3.3-5.

The efficiency, flexibility and the mass of contaminants in the extraction well discharges for these three alternative were then evaluated in Phase Three using the Random Walk model. The efficiency of each alternative was defined as a function of the pumping rate, the volume of water requiring treatment and the time required to restore the ground water to clean-up goals. While the pumping rates for the three alternatives were found to be very similar, the five well alternative was found to meet the cleanup goals in one quarter the time of the other two alternatives. The five well alternative, moreover, would significantly reduce the volume of water requiring treatment.

The flexibility of each alternative was defined as the ability of the alternative to operate efficiently when the actual aquifer response to the pumping varied significantly from the response predicted by the modeling. In particular, the modeling team was concerned about the possibility of unmodeled heterogeneity in aquifer properties and the distribution of contaminant concentrations within the plume. The five well alternative was again found to be the preferred alternative because it allowed the operation of each of the five extraction wells to be tailored to the specific characteristics of that part of the plume and aquifer within which the well was located.

EPA has awarded a contract for the construction of the five well ground-water extraction system developed as part of this modeling effort. This system is expected to be in place in early 1993. A ground-water monitoring program has been proposed which will allow the monitoring of the remediation progress and the ongoing validation of this ground-water modeling application.

Strengths And Interesting Features Of This Study:

In this case study, a model was utilized as part of the remedial design process. The modeling was initiated at the suggestion of EPA in order to reduce the magnitude and cost associated with additional site sampling. The model chosen represented a compromise between the level of detail and accuracy desired by the designers, the available data and the modeling budget. In fact, during the development of the modeling objectives, the modeling team attempted to use both a simple analytic and a finite difference contaminant transport model before abandoning the former for its lack of specificity, and the latter because of the limited site data available.

One of the more interesting aspects of this case is that both EPA and the contractor agreed that the modeling reduced the design costs by $450,000. Part of this cost reduction was due to the use of the model to delineate the plume boundary in lieu of locating the boundary by means of an extensive drilling program. The other part of the cost reduction occurred as a result of the modeling process which led to the identification of an error in the source characterization.

Previously it had been hypothesized that the source lay in the unsaturated zone. Consequently, soil flushing had been specified as a remedial action in the ROD. While trying to develop the source term for the model, the modeling team began to question this hypothesis. Based upon the results of a batch flushing model, a search of peer-reviewed literature for similar cases, and additional field sampling, the modeling team determined that the source term most probably lay in the saturated zone. Thus, the need for the design and implementation of the soil flushing system specified in the ROD was eliminated. This resulted in considerable design cost savings and will result in considerable additional construction and operational cost savings.

Another interesting aspect of this modeling was that the Phase One modeling was actually performed twice using two different models. First the site was modeled using PLUME. Then at the suggestion of an outside consultant the site was remodeled using Random Walk. There was a high degree of correlation between the model results. However, such correlation is not necessarily evidence that a site was modeled properly. Rather it demonstrates that for this same conceptual model, these two models produce very similar results.

Both EPA and the contractor noted that this case is another example of how the use of modeling early in the remedial investigation process could have improved the entire remediation effort. Specifically, it was noted that a very simple analytic

model could have improved the sampling plan and monitoring well locations in prior site studies. This in turn would have increased the possibility that a more accurate numerical model could have been used during the design process, possibly resulting in a more efficient design.

Contacts:

For further information about this ground-water study please contact:

Bob Whippo Region 5 Tel. # (312) 886-4759

Modeling Documents:

Please contact the above person for specific modeling documents.

Figure 3.3-1

Site and Contaminant Plume Location

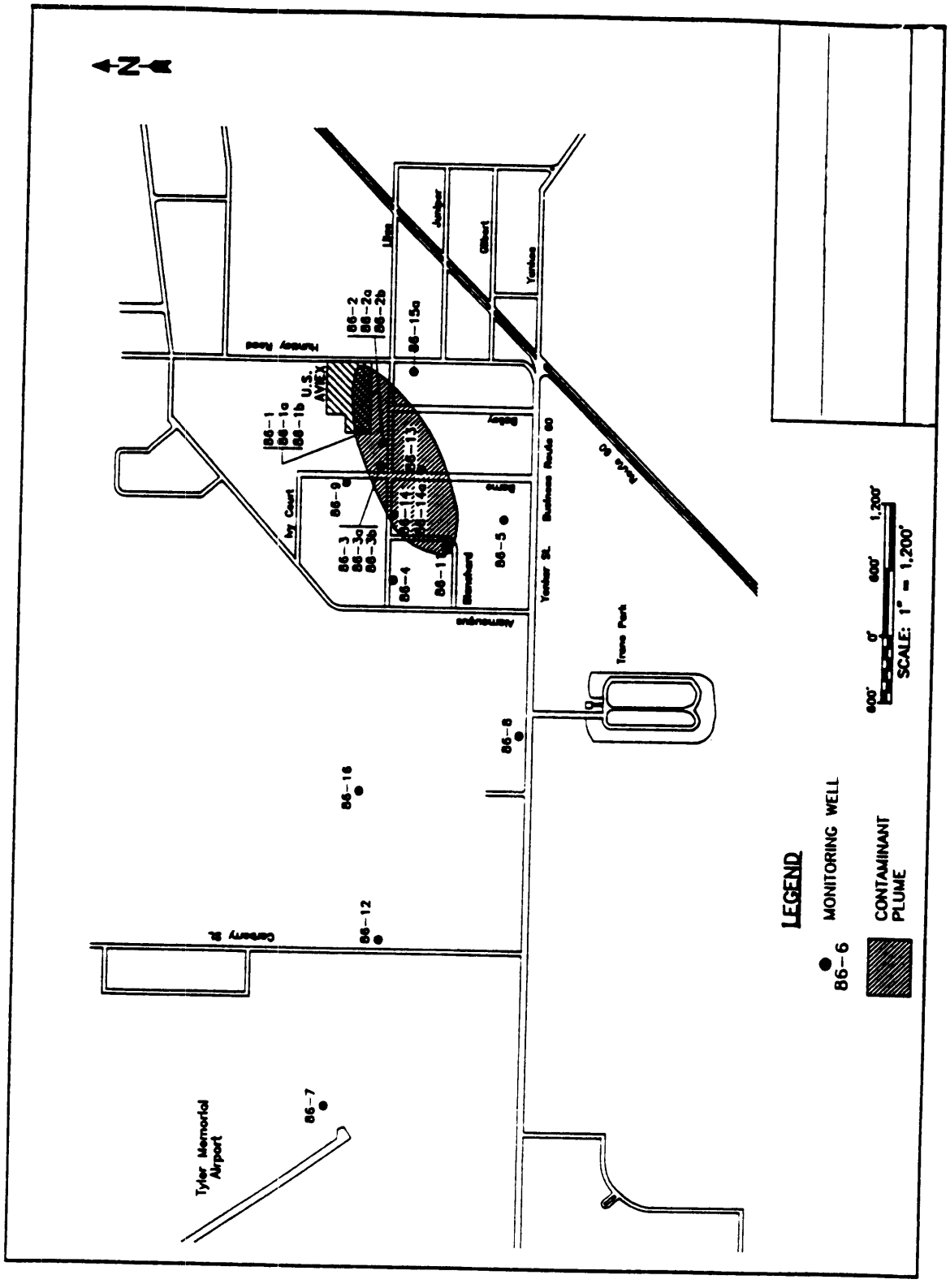
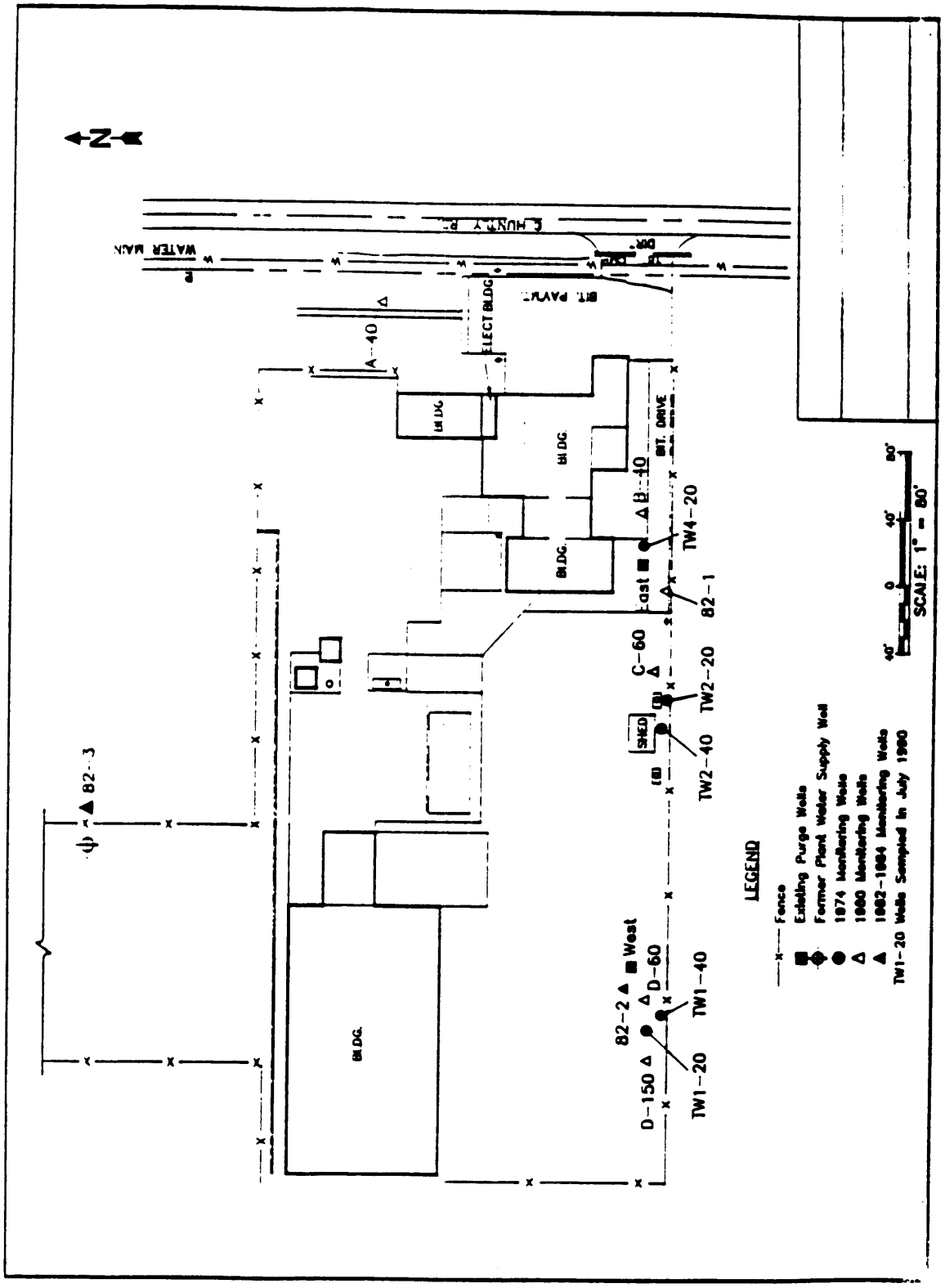


Figure 3.3-2

Detailed Site Location and Monitoring Wells



## Figure 3.3-3

## Sample Hydrogeologic Section

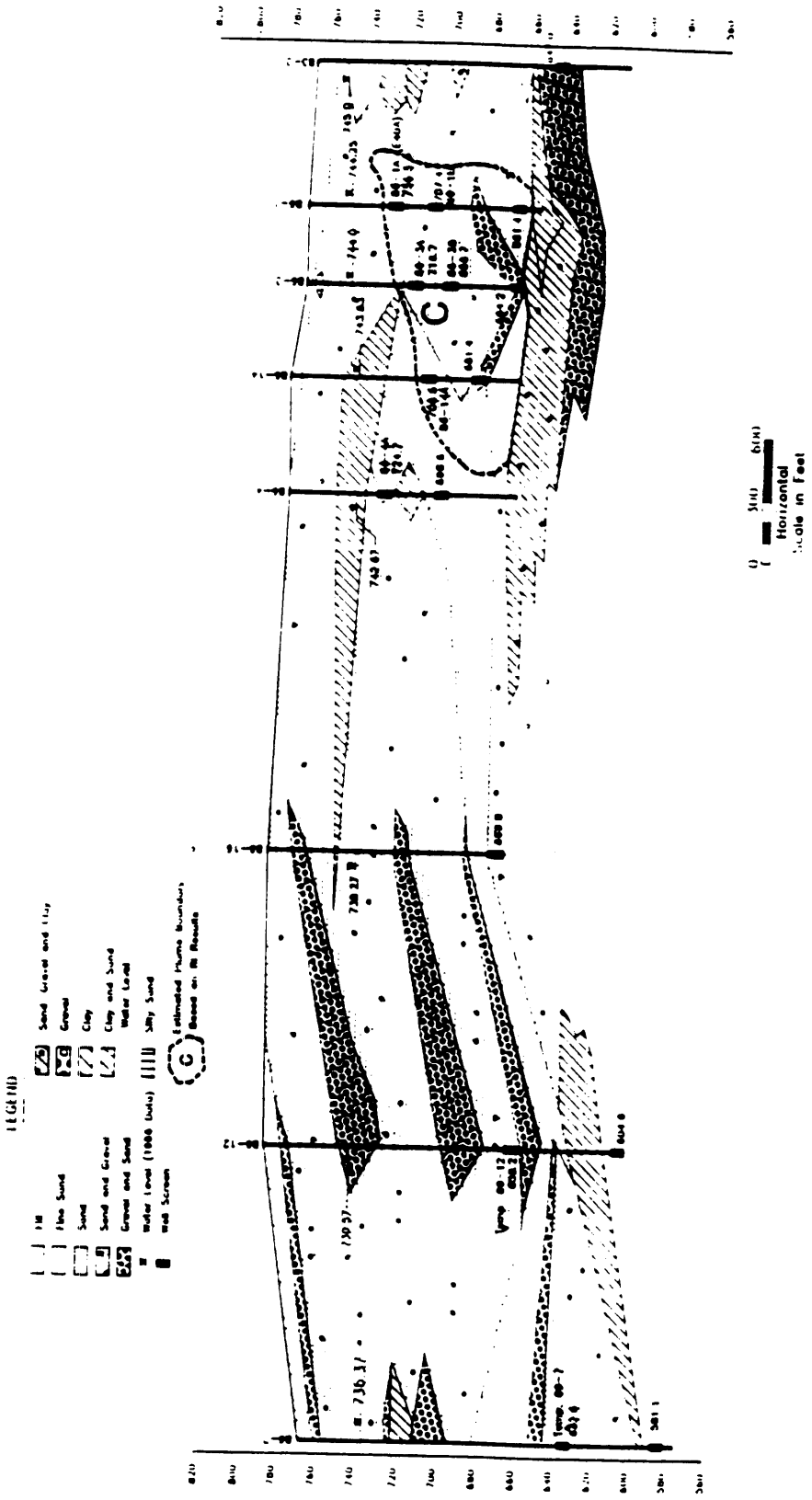


Figure 3.3-4

Location of Sample Hydrogeologic Section

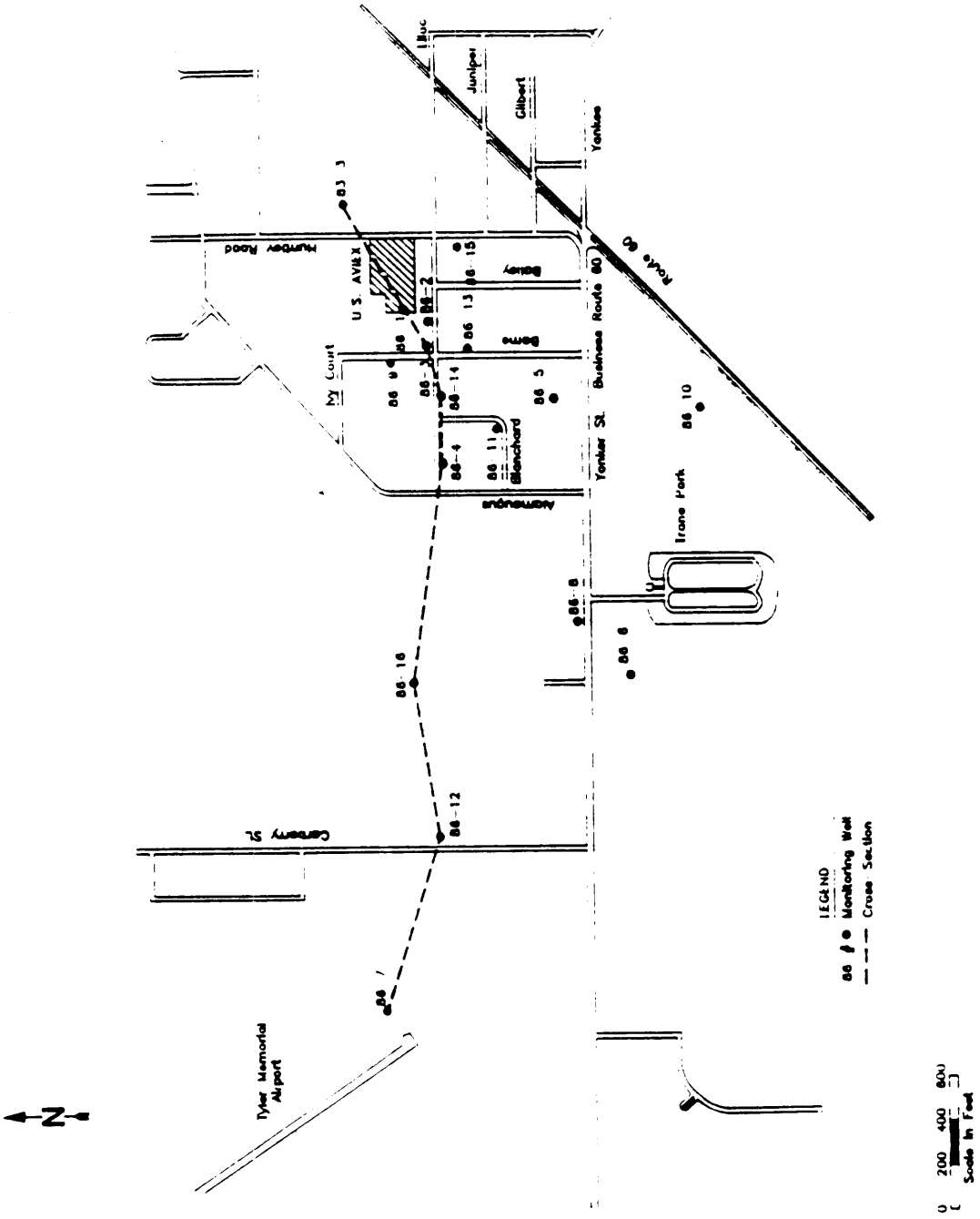
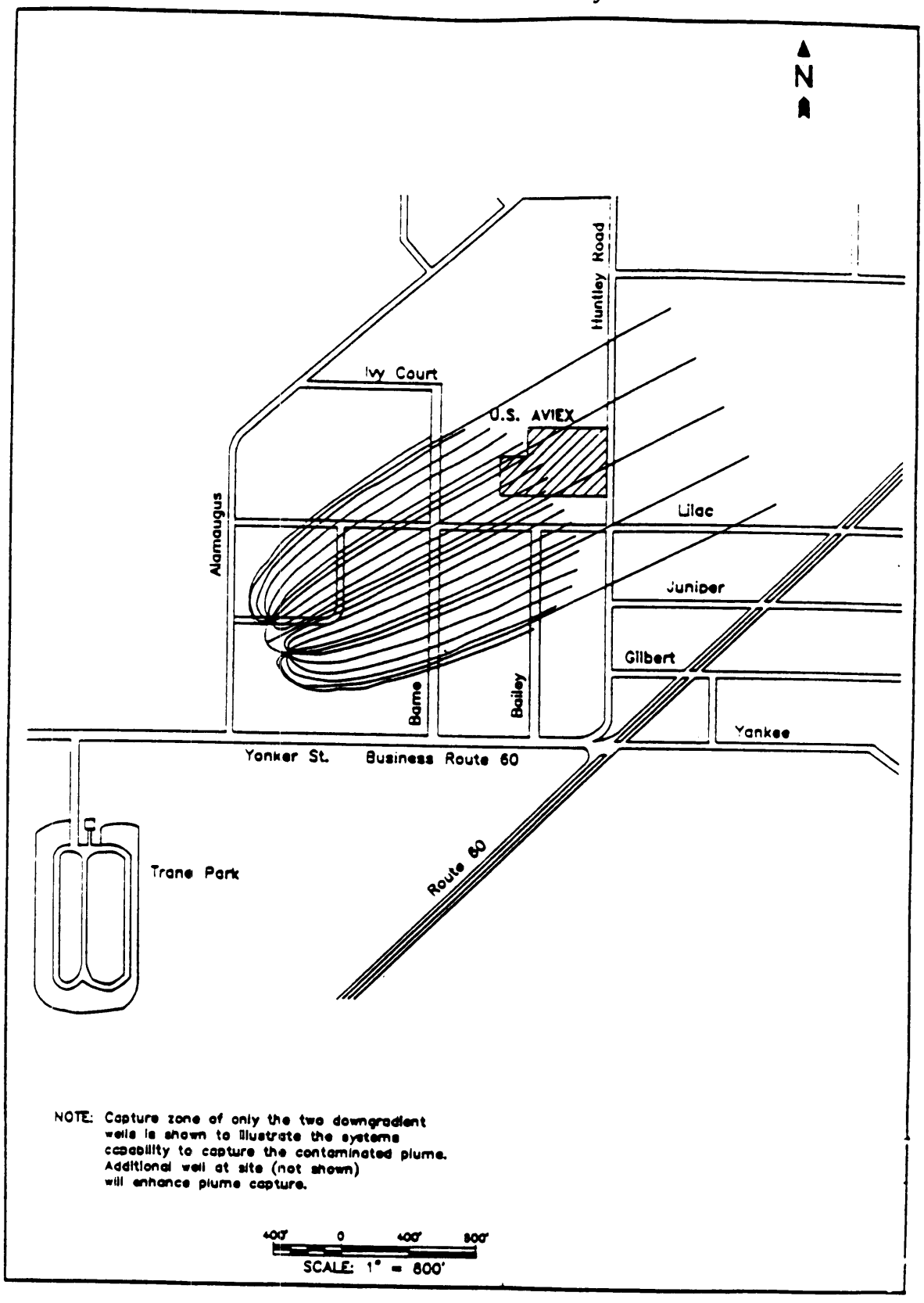


Figure 3.3-5

Capture Zone Analysis



## 3.4 - Summary Description #4

# 3.4

# Model Applications
# Summary Description #4

Decision Objective:

This enforcement lead site was modeled by EPA during the remedial design (RD) to ensure an appropriate RD and remedial action (RA). Specifically, information on the ground-water flow and contaminant fate and transport was required to support RD and RA negotiations. As this was an enforcement lead site, the objective of EPA in conducting this modeling was to gather sufficient information to be able to review the responsible party's characterization of the nature and extent of contamination at the site and the remedial design.

The modeling was deemed necessary because it was recognized in the Record of Decision (ROD) that the design objectives and remedial action specified in the ROD were based upon incomplete knowledge of both the sources and the actual extent of the contamination and the contaminant plume. Consequently, EPA determined that a limited modeling effort would assist in better understanding the site and the effectiveness of the proposed pump and treat remedial design. In support of these decision objectives the following four modeling objectives were established:

1. Identify potential off-site contaminant migration;
2. Examine the proposed pump and treat extraction well alignment;
3. Improve (if necessary) the extraction well alignment design; and
4. Determine the time required to clean the site.

The modeling that is the subject of this case study was performed by an EPA contractor under a Technical Enforcement Support at Hazardous Waste Sites contract. The modeling work was reviewed by both the EPA project manager and an EPA hydrogeologist.

Background:

This site is comprised of 18 acres located in an industrial corridor adjacent to an interstate in a major western metropolitan area. The site abuts a major railroad line and is surrounded by other small industries. (See Figure 3.4-1.) Located on the site are abandoned and active tank farms and a filled and abandoned sump. There is also a capped evaporation pond, the contents of which are unknown. The site topography is generally flat and low lying with a vacant swampy area to the south. The nearest residential area is within a quarter mile of the site and the total population within a one mile radius of the site is less than 5000.

Operations at the site began in 1957 and included the production of herbicides and pesticides; the production of sodium hypochlorite; refilling and distributing chlorine and ammonia cylinders; and the packaging and distribution of acids, caustics and organic solvents. Information related to the historical operations at the site indicates that the uncontrolled release of contaminates may have begun in the very first year of operation and may have continued through 1989. These releases are believed to have been the result of both disposal practices and spills.

Examples of disposal practises that led to releases include: the use of unlined settlement and evaporation ponds for process wastewater discharge; the discharge of industrial and process waste materials to an on-site septic tank and drain field; and the dumping of wastewater, pesticide and herbicide tank wash water on the ground. Examples of spills included a 4000 to 8000 gallon spill of muriatic acid that occurred during the unloading of a rail tanker and a hydrochloric acid spill due to a tank rupture. Sources of contamination include the former evaporation pond which was filled with earthen materials and capped with concrete in 1980, a process drain system and sump, settlement ponds (location unknown), a leach field, dioxin removal wastes and contaminated soil.

History of Investigation

Beginning in 1980, the site was operated as a RCRA Interim Status Hazardous Waste Storage Facility. Between 1983 and 1989, the owner/operator of the site was cited for several violations by a state agency responsible for RCRA enforcement. In 1984, that agency advised the owner/operator of an alleged release from the property to the environment and then initiated a Preliminary Assessment and a follow-up Site Investigation. Additional field investigations were conducted by the state agency between 1985 and 1987.

In 1986, CERCLA enforcement activities were initiated. This led to an emergency action by EPA later that year to remove drums, cylinders and contaminated material from the site. In 1987, EPA proposed that the site be placed upon the National Priorities List. In 1988, the owner/operator agreed to undertake a Remedial Investigation/Feasibility Study (RI/FS) which was completed in March 1990. In 1989, the owner/operator notified the relevant agencies of its intent to close its RCRA Part A Interim Status Storage Facility. In 1990, additional site sampling was initiated under EPA's "Make Sites Safe" initiative. This sampling found evidence of high levels of dioxin on that part of the site where contaminated materials had been removed as part of EPA's 1986 emergency action. Consequently, actions to stabilize the contaminants on the site pending remediation were initiated.

In March 1991, the Record of Decision (ROD) was issued. In the ROD, EPA with the concurrence of the state, specified soil and ground-water remediation measures at the site but reserved the right to further modify the ground-water remedy because the ground-water contamination had not been fully characterized. The ground-water remedy specified consisted of a pump and treat system utilizing approximately ten wells to capture and treat the contaminant plume. These wells were proposed to

be located along the northern and western boundaries of the site and to be operated at an extraction rate of two gallons per minute.

Geologic Summary:

This site is located in a valley that was part of a Pleistocene great basin lake. The surficial geology of the valley is the result of successive expansions and contractions of that great basin lake and glacial surges and retreats. The valley consists of alluvial deposits which overlie and merge with deep, unconsolidated lacustrine sediments. The alluvial deposits typically consist of silt and sand in the first several feet and mostly fine pebble gravel to a depth of 5 feet or more. These deposits are of a deltaic type and are associated with the development of the valley drainage network. The underlying lacustrine deposits consist of clay, silt, sand and gravel facies that laterally intergrade with one another and result in laterally discontinuous layers.

The uppermost soils at the site consist of a 2 to 6 foot layer of mixed fill material and a 2 to 5 foot layer of clay to silty clay material beneath the fill material. Underlying the clay material is a sand to clayey to silty sand layer that extends to a depth of 15 to 18 feet and below this point a clayey layer begins. Two borings to depths of 27 and 50 feet indicated that this clayey layer extends to at least a depth of 50 feet and exhibits interfingering (clay, silt and sand) characteristic of the general geology of the valley. A fluvial paleochannel consisting of fine to coarse grained sand appears to meander across the center of most of the site. The top of this channel lies 7 to 9 feet below the surface of the site and the channel is approximately 6 to 8 feet deep.

Ground-Water Hydrology Summary:

There is some disagreement regarding the ground-water hydrology. Prior studies by the responsible party's consultants indicated that the site hydrogeology is consistent with the regional hydrogeology and is composed of three distinct hydrogeologic units. These studies indicated that the uppermost unit is a shallow unconfined aquifer that begins 3 to 5 feet beneath the site and extends to a depth of 15 to 18 feet. This aquifer corresponds to the sand to clayey to silty sand layer discussed in the above paragraph. Below this shallow aquifer lies the second hydrogeologic unit, a relatively impermeable confining layer which acts as a single confining bed that ranges from approximately 40 to 100 feet in thickness. This unit corresponds to the clayey layer described in the above paragraph. Below this confining unit lies a confined aquifer that consists of Quaternary deposits of clay, silt, sand and gravel. The maximum thickness of this aquifer is greater than 1000 feet.

The state agency responsible for environmental enforcement disagrees with the concept that there are two completely distinct aquifers underneath the site. They take the position that the second hydrologic unit is not truly impermeable as there are interfingerings of sand and silt in the clay layer. Consequently, they believe that

there is communication between the upper and lower hydrologic unit and all three units should be considered as one aquifer with shallow and deep portions. The modeling team did not feel it was necessary to resolve this discrepancy in the conceptual model given EPA's decision objectives and the fact that the modeling focused solely on the upper 13.5 feet of the shallow aquifer.

The shallow unconfined aquifer is not used as a drinking water supply because of its poor quality (e.g. high total dissolved solids, sulfide and chloride) and the low yields to wells. The direction of flow in this aquifer is generally to the west-northwest, which is consistent with the regional flow direction. In the late summer there are several localized deviations in the flow pattern as several ground-water mounds build and dissipate. The transmissivity of this aquifer is estimated to be 77 $ft^2$ per day. The recharge to this aquifer is primarily from upward flow through the confining layer from the underlying confined aquifer and infiltration from irrigation, precipitation and a nearby drainage ditch. This drainage ditch which runs adjacent to the site is hydraulically connected to the shallow unconfined aquifer. In the spring this ditch appears to recharge the aquifer while during the summer that portion of the aquifer underlying the site appears to contribute 1.1 to 1.4 gallons per minute to the flow in the ditch.

The deep confined aquifer is a primary source of drinking water for the surrounding metropolitan area. Pumping tests from other studies indicate that the transmissivity of this aquifer ranges from 4000 to 10,000 $ft^2$. This aquifer was not extensively studied for the purposes of managing this site because of the presence of a thick confining layer above the aquifer and the upward movement of water from this aquifer to the shallow aquifer.

Ground-Water Contamination Summary:

A wide variety of contaminants was found at the site including VOCs, SVOCs, Pesticides, Herbicides, Dioxins and Furans. The major sources of contamination on the site include a process drain system, a former evaporation pond, a yard drain system and a septic system. The primary contaminants of concern in the ground water are the indicator chemicals TCE, PCE, PCP and 2,4-D. Ground-water samples from monitoring wells indicated that these contaminants exceed maximum contaminant levels (MCLS) as established under the Safe Drinking Water Act by up to three orders of magnitude. These contaminants are widely dispersed horizontally and vertically in the shallow aquifer underlying the site. (See Figure 3.4-1.) However, ground-water samples from monitoring wells below the shallow aquifer do not indicate that the contamination has extended into the confining layer separating the shallow aquifer from the deep confining aquifer.

At the time the ROD was issued, the extent and origin of the contaminated water found on the northern portion of the site had not been fully characterized. The ROD anticipated that further investigations and subsequent ground-water

remediation decisions would have to be made prior to the initiation of remedial actions.

Modeling Summary:

A series of analytic and analytic/numeric models were used to investigate the site. An analytic modeling approach was chosen as a function of EPA's decision objectives and resource constraints. As this was an enforcement lead site, EPA's responsibility was to review the responsible party's remediation plan and activities to ensure they met regulatory and legal requirements. Thus, EPA's objective in conducting this modeling was not to develop a definitive remedial design but to gather sufficient information to be able to review the responsible party's characterization of the site and the RD.

New information, received since the issuance of the ROD, suggested the need for the RD/RA to address ground-water contamination not previously thought to be connected with the site. Evidence suggested that the plume in the shallow aquifer may have migrated off-site. EPA desired to explore this possibility and to examine its impact upon the proposed remedial design. As these were review and not design objectives, these decision objectives were not considered sufficient to warrant the costs associated with a full fledged numerical modeling effort at this stage in the remediation process. Moreover, EPA and their contractor believed that current data on the site was not sufficient to support a numerical model. Consequently, an analytic modeling approach was chosen.

The modeling was divided into two phases. The objective of the phase one modeling was to determine the maximum extent of chloride and TCE contamination in the shallow aquifer. An analytical function-driven variation of the fate and transport model Random Walk was used in this phase. The objective of the phase two modeling was to examine the effectiveness of proposed and alternative extraction well designs. Two models were used in this phase. The analytic flow model THWELLS was used to determine well field drawdown. Then the capture zones for the ground-water remedial alternatives were estimated using the particle tracking module of the U.S. EPA Wellhead Protection Area (WHPA) model called GPTRAC. This case study will focus on phase one of the modeling which is the use of the Random Walk model to delineate the contaminate plume and potential sources.

The analytical function-driven variation of the Random Walk model was chosen for the phase one modeling because of its relative simplicity, prior contractor experience and prior contractor verification of the model through a comparison of its results with that of another well-respected model. This version of the Random Walk model utilizes an analytic function based upon the Theis equation to generate the flow field. Then the numeric Random Walk model is applied to simulate the fate and transport of the contaminants.

The simplifying assumptions associated with the analytic flow component of the Random Walk model required that the aquifer be treated as homogeneous, isotropic and infinite in areal extent. Thus, no site specific boundary conditions or spatial variability in aquifer characteristics could be modeled. Moreover, unidirectional, steady state ground-water flow had to be assumed. The modeling team established a uniform hydraulic conductivity, saturated thickness, transmissivity, hydraulic gradient and aquifer porosity for the modeled area based upon information obtained from the RI report and the ROD. They assumed that there was no precipitation recharge to the aquifer.

Chloride was chosen as one of the two contaminants to be modeled because it is mobile and non-retarded. Thus, its plume would represent the outermost limits of the plumes of the other contaminants of interest. Moreover, since chloride is a conservative substance, it was hypothesized that the successful replication in the model of the existing chloride plume would be evidence that the simplifying assumptions of the analytic flow model did not unduly compromise the model results given EPA's decision objectives. TCE was selected as the other contaminant to be modeled because it is relatively toxic and ubiquitous to the site.

The particle tracking component of the Random Walk model was used to model the chloride releases as slugs that began in 1982 at four potential sources. The TCE releases were modeled as continuous releases that began in 1957 at eight potential sources. The location of the sources and the timing of the releases were inferred from soil and ground-water chemistry, information in the RI and the ROD and model calibration. The longitudinal and transverse dispersivities, background concentrations and organic carbon partition coefficients were based upon field data and established EPA methods. All ground-water contamination was assumed to exist in the dissolved phase and consequently dense, nonaqueous phase liquid migration was not simulated. Biodegradation and volatilization were also ignored.

The calibration of the Random Walk model was restricted to the contaminant fate and transport component. This version of Random Walk assumes a unidirectional flow field which can not be directly calibrated against observed piezometric heads. Field data from the RI report was used to establish the flow field parameters. Moreover, as was noted above, it was thought that the successful calibration of the chloride plume would serve as an indication of the appropriateness of the assumed flow field. Calibration of the contaminant transport model was achieved by adjusting the number, location and release terms of the sources until simulated concentrations matched field observations for twelve on-site monitoring wells. The calibration process was terminated when:

- The mean model error and standard deviation of errors were less than 10 percent of the largest observed field concentration;
- The regression analyses of field data versus model results yielded a correlation coefficient squared ($r^2$) value greater than 0.90, (an $r^2$ value of

1.0 indicates perfect correlation between the field data and the model data); and

- The shapes of the simulated plumes approximated the shapes of the plumes observed in the field.

The calibration of the contaminant transport model required that the grid nodes in the model be close to the physical location of the monitoring wells on the site. Considerable effort was made to do this, but in order to determine the predicted contamination concentrations at the monitoring wells, linear interpolation routines ultimately had to be developed In retrospect, the modeling team realized that by varying the location of the origin of the model grid, the grid nodes could have been located precisely over the monitoring well locations thus eliminating the need to interpolate the contaminate concentrations and possibly improving the calibration. It was noted, however, by the modeling team that the shifting of the grid would become very time consuming with a large number of wells.

Difficulties were encountered calibrating the model. These difficulties caused the modeling team to explore the possibility of the existence of undocumented on and off-site sources. In an iterative fashion, sources were added to the model until all calibration targets were met, the simulated plumes approximated the field observable plumes and $r^2$ values of 0.92 and 0.99 were obtained for the chloride and TCE models respectively. (See Figures 3.4-2 and 3.4-3.) The reasonableness of the location of these hypothetical contaminate sources was examined using site information and aerial photographs of the site taken in the 1960's and 1980's. Interestingly, these photographs had not been available to the modeling team during the calibration process, yet wherever a hypothetical source had been introduced into the model in order to effect a better calibration, the aerial photographs provided confirming evidence of the existence of a potential source at that location.

Because of budget limitations a sensitivity analysis was not performed to determine the potential variations in the results as a function of changes in key parameters or the removal of hypothetical sources. In retrospect, the modeling team felt additional resources should have been requested to perform a sensitivity analysis.

Modeling Results Summary:

The phase one modeling results indicated that the ground-water contamination moved much further off-site than was estimated in the ROD. Moreover, the model simulations suggested the possibility of off-site sources of chloride and TCE contamination. (See Figure 3.4-4.) Specifically, the model indicated that the plume had migrated almost 450 feet north and a 150 feet west of the site and covered a surface area over 1/3 larger than the contaminant plume defined in the ROD.

Four potential chloride sources and eight potential TCE sources were identified. One of the chloride sources and three of the TCE sources were located off-site. None of these potential off-site sources had been identified in the ROD. Consequently, EPA's concerns about the completeness of the field characterization were supported by the modeling results.

The phase one results were then used to evaluate the proposed and alternative pump and treat extraction well designs. This evaluation (not part of this case study) determined that the proposed design of the pump and treat extraction wells would not fully capture the contaminant plume because the plume had migrated so far off-site. Moreover, it was determined that the proposed pumping rate would de-water the aquifer.

Based upon the information developed in this modeling effort, EPA directed the Responsible Party to initiate further site characterization including a search for additional off-site sources. The Agency also requested that the design of the extraction wells be reviewed. However, the Agency and the modeling team were careful to not assign certitude to the model results. As was stated in the modeling report, the simplifications associated with the use of analytic models and the limited field data available required that the results of this modeling effort be used with great care. Thus the Agency limited the use of the model results to:

1. Estimate the maximum downgradient and lateral extent of ground-water contamination;
2. Focus future field activities;
3. Provide insight into the location of additional potential sources; and
4. Provide preliminary ideas regarding the conceptual design of pump and treat alternatives.

Strengths And Interesting Features Of This Study:

In this case study, a model was applied late in the remedial process to review the completeness and accuracy of the site characterization and remedial design specified in the ROD. The decision and modeling objectives of this model application were carefully limited so as not to exceed the limitations of the model and available data.

Perhaps the most striking aspect of this case was that the entire modeling effort required only 180 hours. This was possible because the decision objectives of the modeling effort were limited in such a way that relatively simple models and simplifying assumptions could be used. Nonetheless, the information gained from the modeling could be used to guide field characterization activities and to raise significant concerns about the characterization of the site and the design of the proposed extraction wells. The ultimate consequences may be a considerable cost savings through the implementation of a more appropriate remedial design.

Another interesting aspect of this study was the use of the model to identify the location of previously undocumented potential sources of contamination and the post modeling corroboration through the use of aerial photographs. This is an example of the power of relatively simple models when they are carefully used as preliminary investigation tools.

In retrospect, the Region noted that it might have been useful to conduct this type of modeling during the RI/FS phase of the cleanup. The Region also noted that additional modeling might be required later, once the additional site characterization activities are completed. The Region suspected that should additional modeling be performed, the level of certainty they would then require would necessitate the use of a more sophisticated model and significantly more data.

Contacts:

For further information about this ground-water study please contact:

| | | |
|---|---|---|
| Bert Garcia | Region 8 | Tel. # (303) 293-1537 |

Modeling Documents:

Please contact the above person for specific modeling documents.

# Figure 3.4-1

## Chloride Concentrations

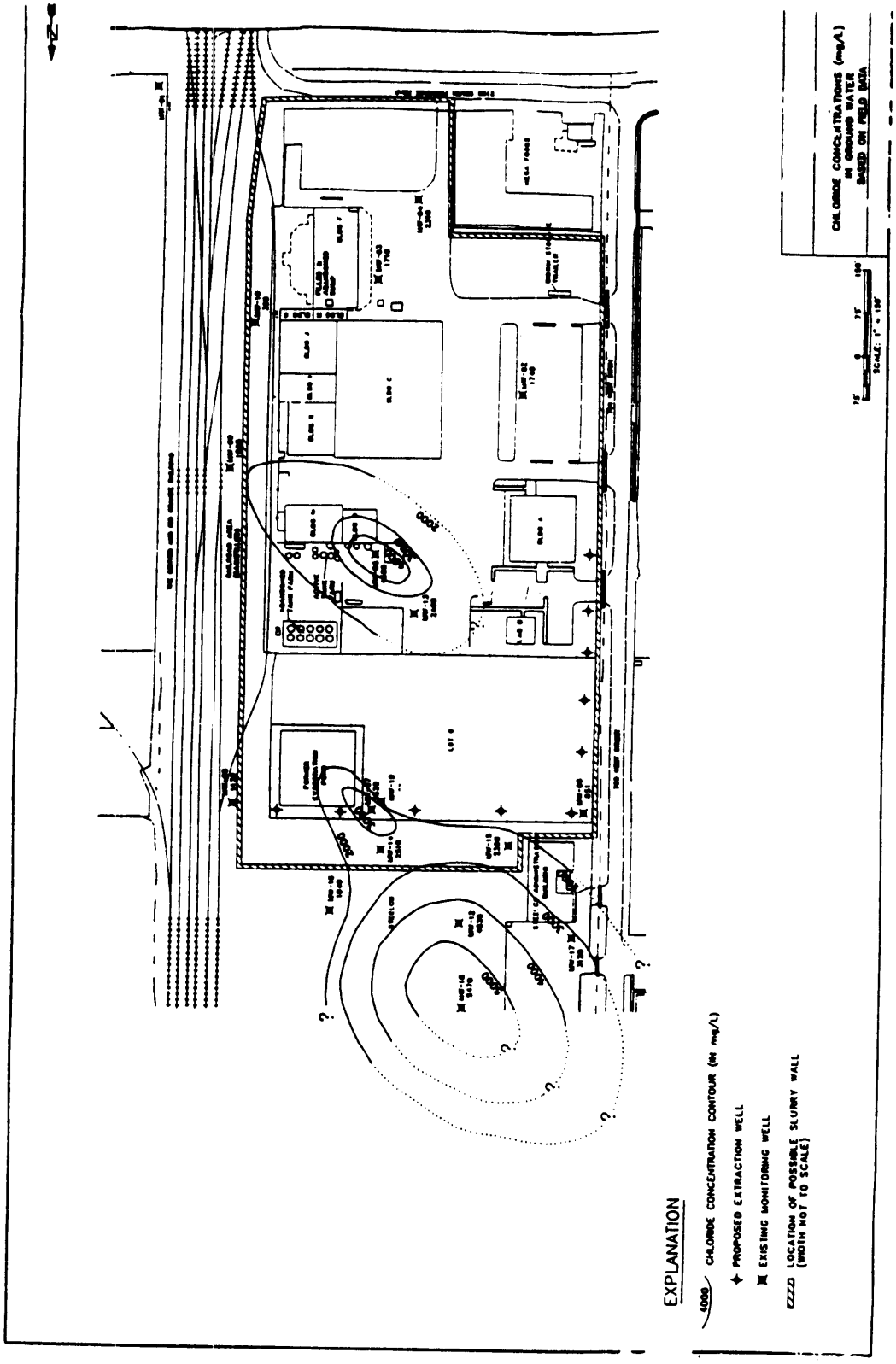
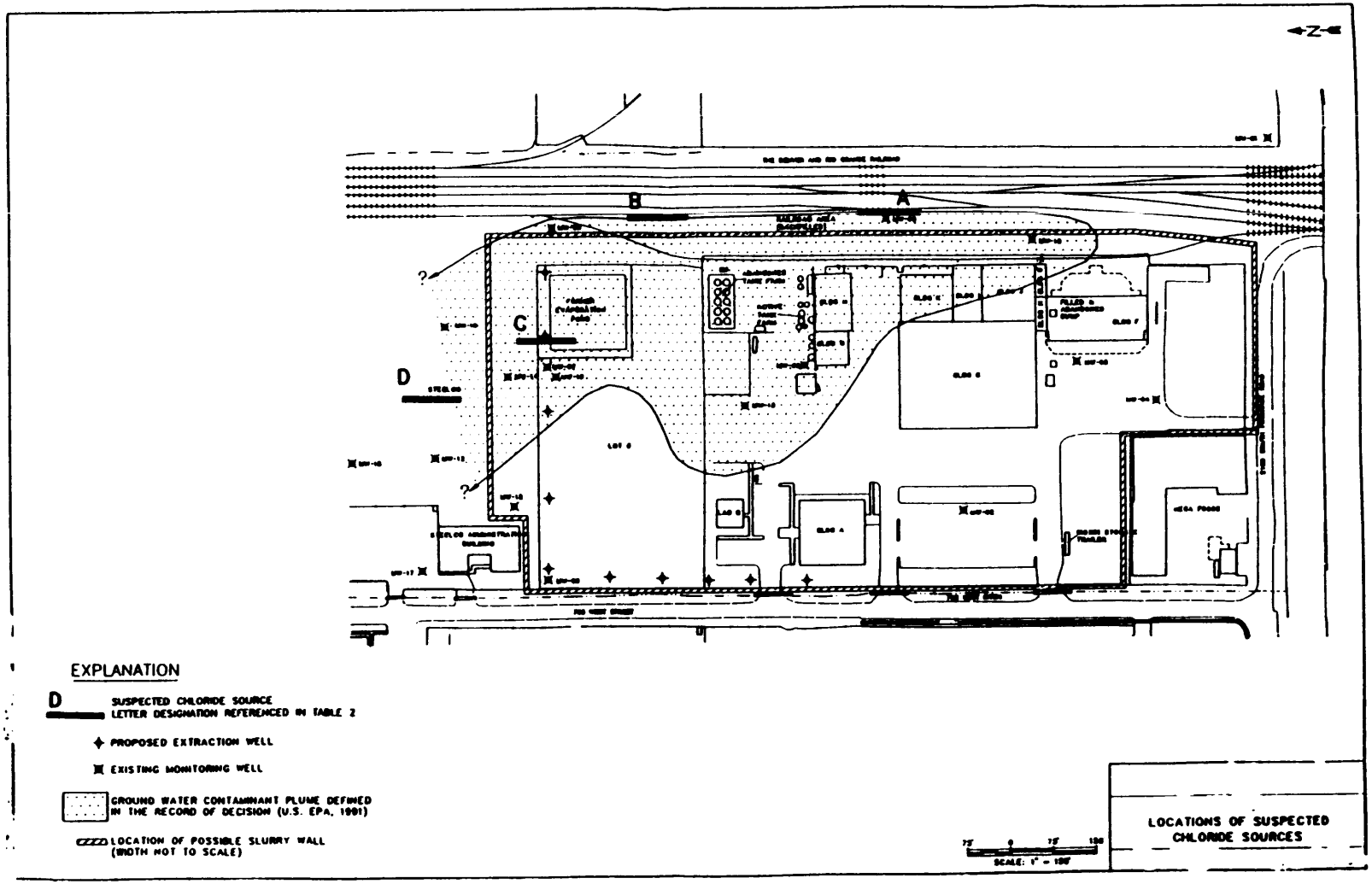


Figure 3.4-2

Location of Suspected Chloride Sources



# Figure 3.4-3

## Model Calibration - Chloride

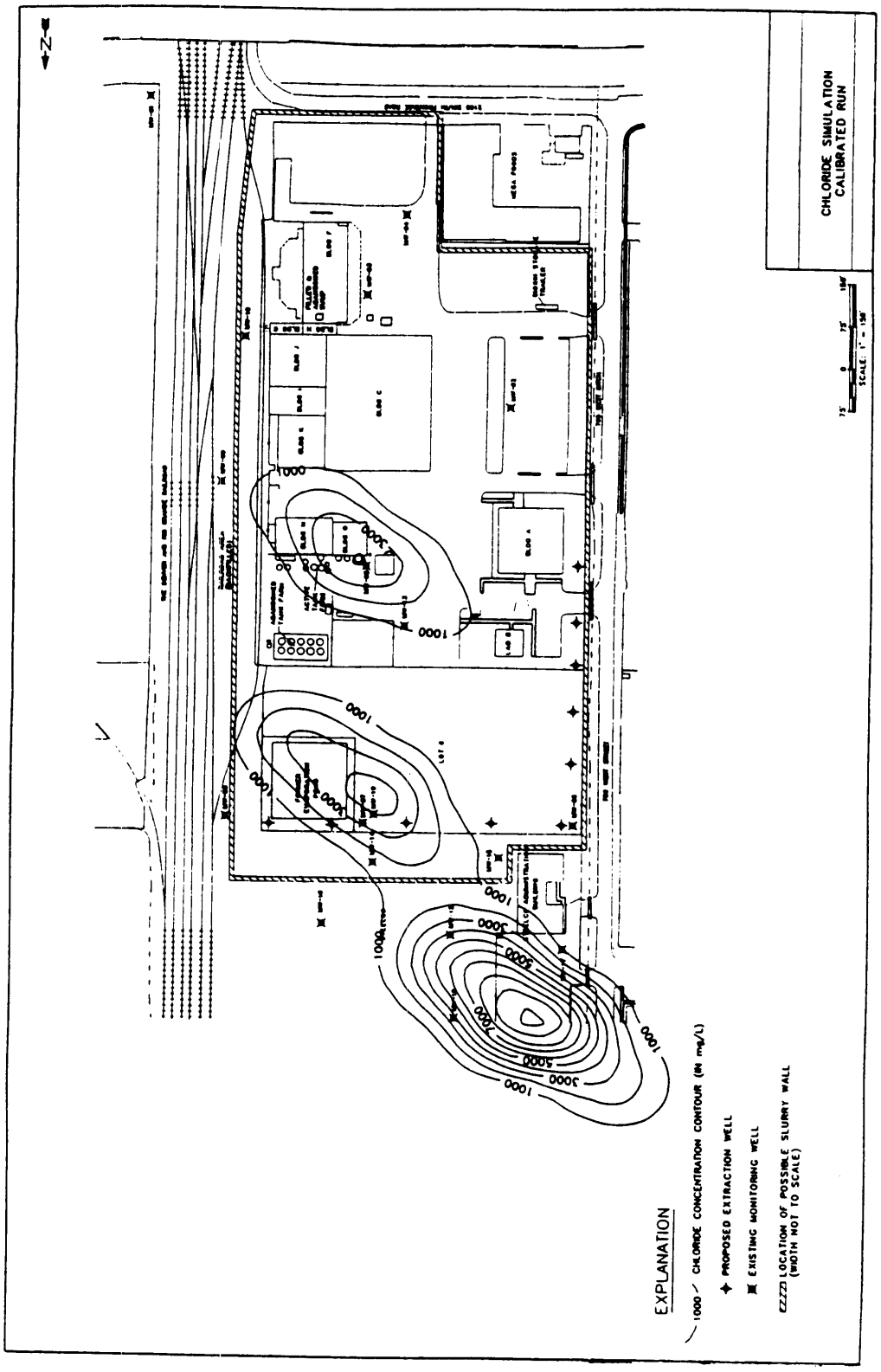
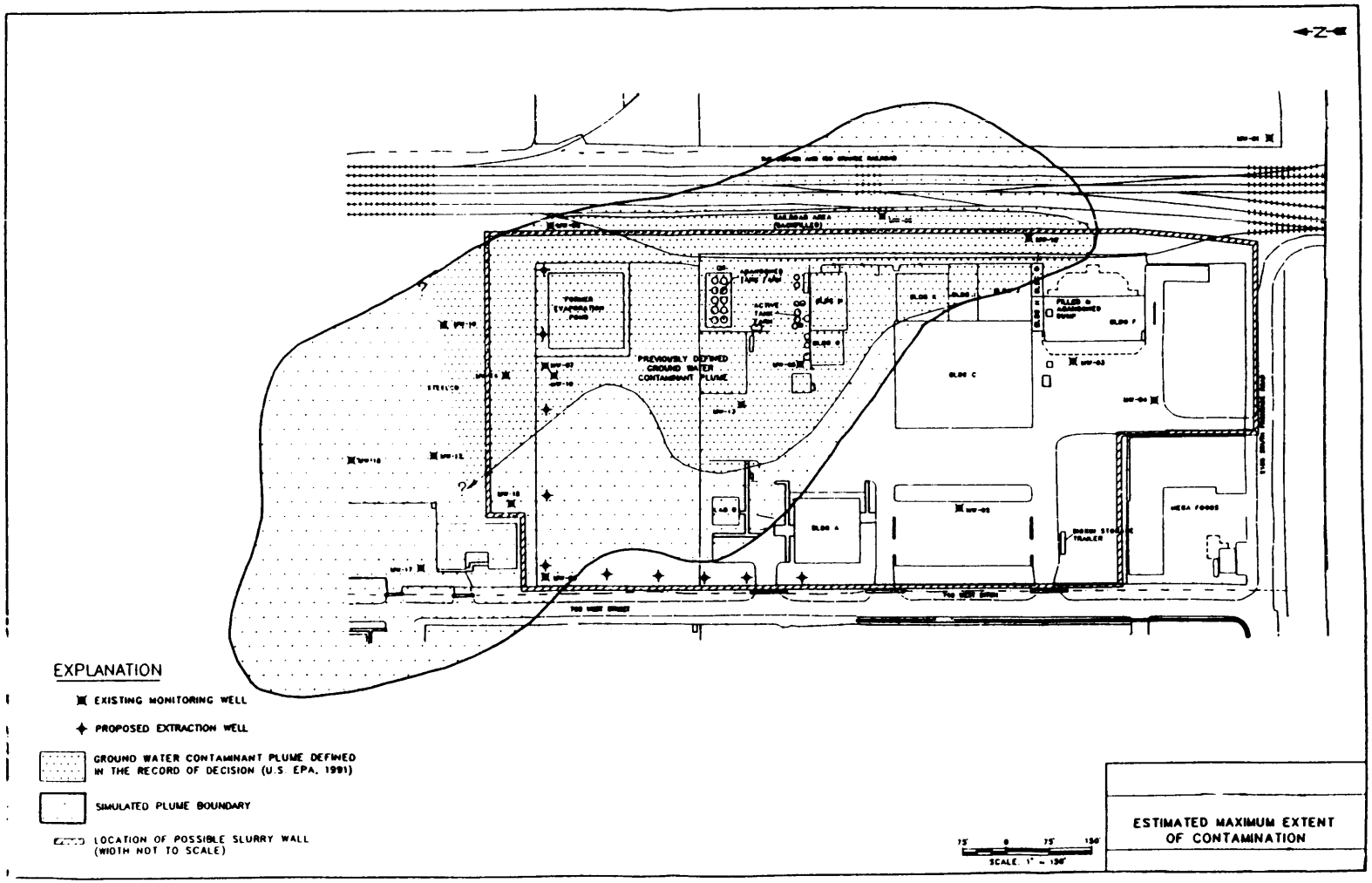


Figure 3.4-4

Estimated Maximum Extent of Contamination



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## 3.5 - Summary Description #5

# 3.5

# Model Applications
# Summary Description #5

Abstract:

Purpose of Model Application: To support the 30% Remedial Design[1] of a ground-water extraction and treatment system.

Type of Site: Former Hazardous Waste Landfill located next to a populated residential area.

Models Used: WHPA(GPTRAC module); THWELLS.

Type of Models: Analytical.

Result of Study: The model demonstrated that six wells installed at the site with a combined capacity of 150 to 800 gallons per minute would meet the remedial design requirements. The range of flow rates is due to uncertainty in site parameters. Once the wells are installed, they will be tested to determine the actual design flow rates.

Decision Objectives:

The U.S. Environmental Protection Agency (EPA) Region tasked an environmental contractor to perform a Remedial Design (RD) of a former hazardous waste landfill facility based on the EPA's recommended alternative, as outlined in the Record of Decision (ROD) for this site. During this process, two decision objectives were established: (1) To prevent migration of ground-water contamination off-site; and (2) To ensure that the waste material did not become saturated with ground-water. To meet these objectives, it was decided to design a ground-water extraction and treatment system at the site. A ground-water model was developed and utilized to support the 30% RD of this system.

Strengths and Interesting Features of the Model Application:

This is the first case study that demonstrates the utilization of the model Assessment Framework[2] with a model application. The contractor who performed the modeling was involved in the development of some of the model applications described in case studies in the Ground-Water Modeling Compendium (EPA 500-B-92-006, October 1992). During the development of those case studies, the contractor became aware of the Assessment Framework which he then applied to this model application.

The contractor decided to use an observational approach[3] to the design. This involved using a simple analytical model, rather than a numerical model, to perform preliminary design. Predictive sensitivity analysis[4] was performed to assess the uncertainty in the design of extraction wells, as well as the range of possible flow rates. The actual design flow rates will be determined by testing the wells after their installation. Use of analytical models effected cost savings and rapid development of the modeling results.

This study demonstrated the importance of organizing all the site data in a comprehensive manner as part of the development of a conceptual model. For example, a QA check of the water level data showed that the datum upon which water level measurements were based had changed since the time the monitoring wells were originally installed. Thus, water level data had to be adjusted for this changed datum. Another example is that by preparing hydrogeologic cross-sections, the contractor was able to determine that the water table was not in contact with the landfill waste material but was within two feet at its eastern end. Thus, an extraction system for dewatering purposes was only needed on the eastern side of the landfill.

The results of the model application demonstrated that a total of six extraction wells with flow rates ranging from 25 to 133 gallons per minute per well (or 150 to 800 gpm combined flow) would meet the objectives of containing (and capturing) the contaminant plume and provide contingency on the eastern side of the landfill for dewatering to maintain water levels below the waste material (in the case of water level rise).

Site Background Information:

The site is an inactive landfill occupying 30 acres in a Midwestern rural residential area. Prior to 1966, the site was a sand and gravel pit. In September 1966, the site began operating as a landfill and accepted an assortment of municipal, commercial, and industrial wastes. The State estimated that 780,000 tons of solid wastes and solvents had been disposed at the site. In addition, it was reported that up to 1,000,000 gallons of chemical and liquid wastes were directly deposited at the landfill from 55-gallon drums or from tanker trucks. The composition of these wastes included latex, oil, solvents, and industrial chemicals. Large amounts of flyash had also been accepted. Operations continued at the site until May 1980 when local authorities ordered closure of the landfill. The area was subsequently covered with clean soil and seeded. A base map of the site is included on Figure 3.5-1.

A fence that completely enclosed the site was installed to prevent nearby residents from accessing the landfill. The contaminated ground-water migrating off-site posed the largest threat to nearby residences and the environment. Based on accounts of waste disposal and the ground-water mounding under the landfill, landfilled wastes were probably acting as a continuing source of contamination.

History of the Site Investigation:

A number of years after closure, the site was proposed for the National Priorities List (NPL) as a result of community concern. The EPA Region ordered a remedial investigation/feasibility study (RI/FS) and began field work consisting of collecting and analyzing surface and subsurface soils, sediments, soil gas, and ground-water samples.

During this RI, it was found that the most extensive body of contaminated materials consisted of the wastes and waste-soil mixtures in the landfilled portions of the site; and residential and monitoring well samples collected on and near the site indicated that the sand and gravel aquifer beneath and west of the site was contaminated.

Interim remedial measures were taken at the site, including installation of a methane venting system (MVS) after explosive levels of methane were found along the landfill boundaries and at nearby residences. The system consisted of 12 gas extraction wells along the northern, southern, and western boundaries of the landfill.

After sampling 67 residential and commercial wells, the EPA Region found ground-water contaminated with volatile organic compounds (VOCs) in 10 private wells up to 1,000 feet west of the site. Three of these wells contained elevated levels of vinyl chloride. Air-stripping units were installed to remove vinyl chloride and other VOCs. The private wells were shut down and an alternate water supply was provided to approximately 100 residences downgradient (west) of the site. At the conclusion of the FS, the EPA specified a remedial action for the site in a ROD.

Geologic Setting:

The site is within an area that was affected by Pleistocene-age glaciation. It is marked by a distinct hummocky topography and rolling terrain. Elevations range from 1,100 to 1,200 feet above mean sea level.

Regional glacial features identified in the area include irregularly shaped knolls and hills (kames) of gravel, undrained depressions (kettles), level-to-sloping outwash plains, end moraines, and ground moraines. Glacial deposits in the area generally consist of interbedded sand and gravel with lesser amounts of silt and clay. The deposits range between 50 and 210 feet in thickness and serve as an important aquifer for residential water supplies.

Figure 3.5-2 illustrates the site geology in a north-south cross-section across the landfill. Glacial deposits overlie Pennsylvanian-age consolidated sedimentary bedrock. The glacial deposits include: (1) an upper unit (which is generally unsaturated), (2) a lower unit (the zone modeled), and (3) a glacial till overlying bedrock. Both the upper and lower units are subdivided into fine-grained and coarse-grained portions.

The unconsolidated glacial deposits are separated from bedrock by an unconformity which also defines the configuration of the bedrock surface at the site. The bedrock is about 400 feet thick and consists of 250 feet of interbedded sandstone, limestone, siltstone, shale, and coal underlain by 150 feet of sandstone and conglomerate rock formations. The bedrock is also an important source of water for about half of the residential wells in the area. These wells are primarily installed in the sandstone member.

Hydrogeology:

The climate is typical of the upper midwestern United States. The average annual temperature is 49.5° Fahrenheit (F). The coldest month is January with an average temperature of 25.1° F and the warmest month is July with an average 71.6° F. The average annual precipitation is 35.9 inches with most of the rainfall occurring in the spring and summer months.

Figure 3.5-1 shows the location of the site in relation to the regional ground-water flow system. Water in the regional system flows primarily from east to west, discharging to a ditch to the west and south of the site. A major discharge area west of the site is shown on the map as an area of ponded water and marshy ground. Generalized elevations of the regional ground-water system are also shown. Regional flow in the bedrock appears to "mirror" flow in the overlying glacial aquifer system.

The RI identified a localized flow system surrounding the site. This area is a zone of recharge. A ground-water high or "mound" resulting from a buildup of precipitation exists under the landfill and contributes to the formation of leachate. The water in the local system flows primarily westward and downward, except for a small area of discharge to a ditch just east of the site. The dynamics of flow in the local system are more complex than that of the regional system, i.e., this system has both horizontal and vertical flow. The local system merges into the regional flow system at a depth of 10 feet and does not exist more than 200 feet away from the landfill.

One of the major concerns of the EPA Region was the level of the water table below the landfill and whether the landfill intersected this water table. By drawing cross-sections and plotting the water levels, the modeling team was able to determine that the water table is currently within two feet of the bottom of the waste material. A temporal analysis of water level data indicates that the probability for rising water levels is low; however, the RD allows for this contingency.

For purposes of this model application, the main zone of interest was the regional flow system. Figure 3.5-3 shows a potentiometric surface map for this zone. The average hydraulic gradient of the regional flow was moderate and was about equal to 0.001 feet/foot. The range in hydraulic conductivities as determined from slug tests was 1 foot per day to 200 feet per day. The lower values were for glacial till, and the higher values were obtained in the sand and gravel glacial aquifer.

Ground-Water Contamination:

According to the RI, ground-water contamination at the site was confined to shallow portions of the upper sand and gravel aquifer. Samples from residential and monitoring wells showed minor-to-significant ground-water contamination by VOCs, semivolatile organic compounds (SVOCs), and metals. Benzene and 1,2-dichloroethane were the compounds of greatest concern found in monitoring well samples. Drinking water standards for barium were exceeded in two residential wells; three downgradient residential wells contained vinyl chloride in excess of maximum contaminant levels (MCLs); and nickel exceeded ambient water quality criteria (AWQC) levels in eight downgradient residential wells. Contaminants found in excess of MCLs and AWQCs were vinyl chloride, benzene, 1,2-dichloroethane, barium, nickel, and lead.

Figure 3.5-4 shows the extent of the dissolved organics and metals plume at the site at the time of the RI.

Modeling Summary:

Project Management

A draft work plan for RD was submitted to the EPA by the environmental contractor. An important component of this plan was to perform the modeling to design the ground-water extraction system at the site.

The ground-water modeling project team was composed of:

1. A contractor project manager who wrote the work plan and was familiar with the project decision objectives.
2. A modeler who was located in a different office than the project manager.
3. A technical person with modeling experience who performed the peer review of the model application.

The first step was to translate the decision objectives to modeling objectives. This was done by the project manager and the modeler (upon acceptance of the work plan by the EPA Region). The modeling objectives were developed as follows:

1. The extraction system should be designed to capture all of the contaminant plume 200 feet north and south of the site.
2. The extraction wells should be located to capture the organics plume rather than the dissolved metals plume.
3. The water levels in the aquifer should be maintained below the landfill by dewatering if necessary.
4. The level of analysis required should be based on the requirements of 30% RD.

5. Due to the wide range of conditions at the site, the preliminary design should be based on a worst-case scenario developed by performing a predictive sensitivity analysis.

Assumptions Due to the Project Scope:

After development of the modeling objectives, the project team assessed how to best achieve the overall project objectives within budgetary and time constraints. Based on that assessment, the project team decided that the best approach to the project would involve: (1) preparation of a conceptual model that was as simple as possible but that would incorporate the features important for 30% design, and (2) utilization of an analytical model to perform the analysis. By using an analytical model, the objectives could be achieved in a cost-effective manner within a short time frame.

Due to the fact a simple model was selected and that the available data was limited, the project team expected that there would be a certain amount of uncertainty in the model results. Therefore, it was decided to use an observational approach. This would involve quantifying the uncertainty using predictive sensitivity analysis and installing extraction wells at the site with flow capacities within this range of uncertainty. The actual flow rates would be determined by well testing.

Model Development Plan:

To achieve the modeling objectives, the model development plan was developed internally by the design contractor to include the following steps:

1. Collect and review available data on the site.
2. Organize the data prior to development of a conceptual model, if needed.
3. Prepare a conceptual model of the site; outline assumptions of this conceptual model.
4. Select a model code to represent the conceptual model and to meet the modeling objectives; outline assumptions of the model code.
5. Perform model setup and input estimation.
6. Perform predictive sensitivity analysis to identify the worst-case scenario.
7. Run the model and evaluate the results.

Data Review:

The modeling team reviewed the available data and the historical work performed at the site. The team determined that the data collected through previous field investigations had not been organized into a comprehensive conceptual

understanding of the site. Therefore, more work was required under the data organization task than originally anticipated.

Data Organization:

To organize the data properly prior to development of the conceptual model, the modeling team performed the following tasks:

1. Tabulated the available well data; divided wells into shallow, intermediate, and deep aquifer zones.
2. Prepared hydrogeologic cross-sections showing the site geology, thickness, and elevation of the landfill material, and location of the water table. (Figure 3.5-2 shows one of these new cross-sections.)
3. Prepared new potentiometric surface maps for the shallow and intermediate aquifer zones. (Figure 3.5-3 shows the new potentiometric surface map for the intermediate zone.)
4. Evaluated the existing data on hydraulic conductivity, hydraulic gradient and direction, aquifer thickness, and porosity. Determined baseline ("average") values and range of uncertainty. (See section on Model Setup and Input Estimation for the reported values.)

The modeler performed a Quality Assurance (QA) check on this data and discovered that the datum on which water level measurements were based had changed since the time that the monitoring wells were originally installed. A correction was applied to the water level data to account for this change.

Preparation of the Conceptual Model:

In order to meet the modeling objectives, a simple conceptual model (shown on Figure 3.5-5) was developed. This conceptual model incorporated the following components:

1. A single-layer, unconfined aquifer system of constant thickness and uniform properties.
2. A uniform flow gradient to represent regional flow.
3. Arbitrary boundaries at an infinite distance away from the site.

Assumptions of the Conceptual Model:

Additional assumptions of the conceptual model were as follows:

1. The local or shallow flow system underlying the landfill, although it contained vertical flow components, was not considered to significantly impact the extraction system. (See Assumptions Due to the Project Scope.)

2. The bedrock underlying the site, although it contained flow, would not impact the extraction system design. (See Assumptions Due to the Project Scope.)
3. The model results within the area of interest at the site (e.g., marshy land to the west) would not be impacted if regional hydrologic features (shown on Figure 3.5-2) were not incorporated.
4. The aquifer system, as a whole, could be represented by "average" properties.
5. There were no significant stresses caused by pumping other than the proposed extraction system.
6. The impact of installation of a multi-layer cap would not be considered.

Model Code Selection:

Based on the modeling objectives, the GPTRAC module of the EPA's Wellhead Protection Area (WHPA) model was selected to perform the capture zone analysis. In addition, the International Ground-Water Modeling Center (IGWMC) THWELLS model was selected to perform drawdown analysis for dewatering at the site.

The reasons for selecting these models are listed below:

1. Based on the modeling objectives, the modeling team decided that analytical models, rather than numerical models, could meet the objectives of 30% design. This decision would allow the model to be constructed quickly and cost-effectively.
2. The WHPA model was selected due to its analytical nature and because it could perform the required capture zone analysis.
3. The THWELLS model was selected because it could calculate the drawdown produced by extraction wells proposed for dewatering.
4. Other factors in the selection of these models were that the modeler had experience with these model codes and, therefore, did not require training to use them; and the codes had been developed and were supported by nationally recognized institutions.

Assumptions Due to the Model Code:

The selection of these codes imposed a number of additional constraints on the representation of the conceptual model in the analytical model. These constraints required that the representation of the conceptual model be limited to:

1. A single-layer aquifer (2-D);
2. An unconfined, homogeneous, isotropic, infinite acting aquifer;
3. Horizontal, steady-state flow;
4. Uniform flow gradient;

5. Input of "average" aquifer properties; and
6. Fully penetrating extraction wells.

The main impact of these assumptions is two-fold: (1) the real variability (heterogeneity) of the geologic deposits could not be represented, and (2) the actual flow dynamics at the site had to be simplified. The project team recognized these limitations of the model. In order to address the uncertainty due to these assumptions, predictive sensitivity analysis was performed. (See section on Scenario Representation.)

Model Setup and Input Estimation:

The analytical module of WHPA requires input of "average" values. Given below are the baseline average values entered and the range (from minimum to maximum) in which the values were changed during predictive sensitivity analysis. The minimum and maximum values were based on site data and professional judgment.

| Input Parameter | Baseline Avg. | Minimum | Maximum |
|---|---|---|---|
| Hydraulic Conductivity (ft/day) | 46.3 | 23.1 | 92.6 |
| Hydraulic Gradient (ft/ft) | 0.001 | 0.0005 | 0.0015 |
| Gradient Direction (degrees) | 167. | 142. | 192. |
| Saturated Thickness (ft) | 100. | 50. | 150. |
| Effective Porosity | 0.3 | 0.225 | 0.375 |
| Pumping Rate (gpm) | 75. | 38. | 800. |

Model Calibration:

As discussed above, the WHPA requires input of "average" parameters and it runs in steady-state. Therefore, the WHPA model cannot be calibrated. To increase confidence in the model results, predictive sensitivity analysis was performed. (See Scenario Representation.)

Scenario Representation:

The first step in modeling the scenarios was to determine the minimum number and the optimum location of wells to meet the modeling objectives. The project manager relayed to the modeler that a maximum of 10 extraction wells could be used. Based on preliminary modeling runs with the baseline input parameters, the modeler was able to determine that three wells located just west of the landfill would meet the first decision objective of containing the organics plume.

After closely examining the water level data interpretation and making a comparison with the base of the landfill site (see section on Hydrogeology), the modeler was able to determine that only the eastern section of the landfill was close to the water table. By using this knowledge in combination with additional preliminary modeling runs, the modeler was able to determine that only three wells

located in the eastern section of the landfill would be required to meet the objective of maintaining water levels below the bottom of the waste material by dewatering.

The next step, based on the modeling objectives, was to determine the worst-case scenario by performing predictive sensitivity analysis. The width of the capture zone was calculated for the possible range of each input parameter (given in the section on Model Setup and Input Estimation) by running the model. The value of the parameter which gave the worst-case scenario (i.e., smallest capture zone) was identified as:

| Input Parameter | Worst Case |
|---|---|
| Hydraulic Conductivity (ft/day) | 92.6 |
| Hydraulic Gradient (ft/ft) | 0.0015 |
| Gradient Direction (degrees) | 192. |
| Saturated Thickness (ft) | 150. |
| Effective Porosity | 0.375 |

Modeling Results Summary:

Under the worst-case scenario, the flow rates of the extraction wells had to be increased from 150 to 800 gpm to capture the entire plume. Figure 3.5-6 shows the location of the extraction wells and the capture zones as determined by the GPTRAC module of WHPA. By using the worst-case scenario, a factor of safety was built into the design.

Upon completion of capture zone analysis, input data used for the worst-case scenario were input into the THWELLS model to determine the amount of drawdown generated by the six extraction wells. Figure 3.5-7 shows that a drawdown of 5.6 feet is maintained across the site by pumping at a rate of 800 gpm. These results are considered conservative because they are based on the worst-case scenario combination of input parameters.

Overall Effectiveness:

The model results were used in the context of an observational design approach to expedite clean-up of this Superfund site. The model demonstrated that six extraction wells were needed, indicated where they should be located, and provided a range of potential flow rates. Based on these results, extraction wells will be installed at the site and a pump test will be performed to determine the actual design flow rates needed.

The EPA Region considered this approach and the model results to be a timely and cost-effective means of meeting the regulatory requirements.

Contacts for Further Information:

For further information about this ground-water study, please contact:

| | | |
|---|---|---|
| Linda Kern | EPA Region V | Telephone: (312) 886-7341 |
| Dr. Luanne Vanderpool | EPA Region V | Telephone: (312) 353-9296 |

Relevant Modeling Documents:

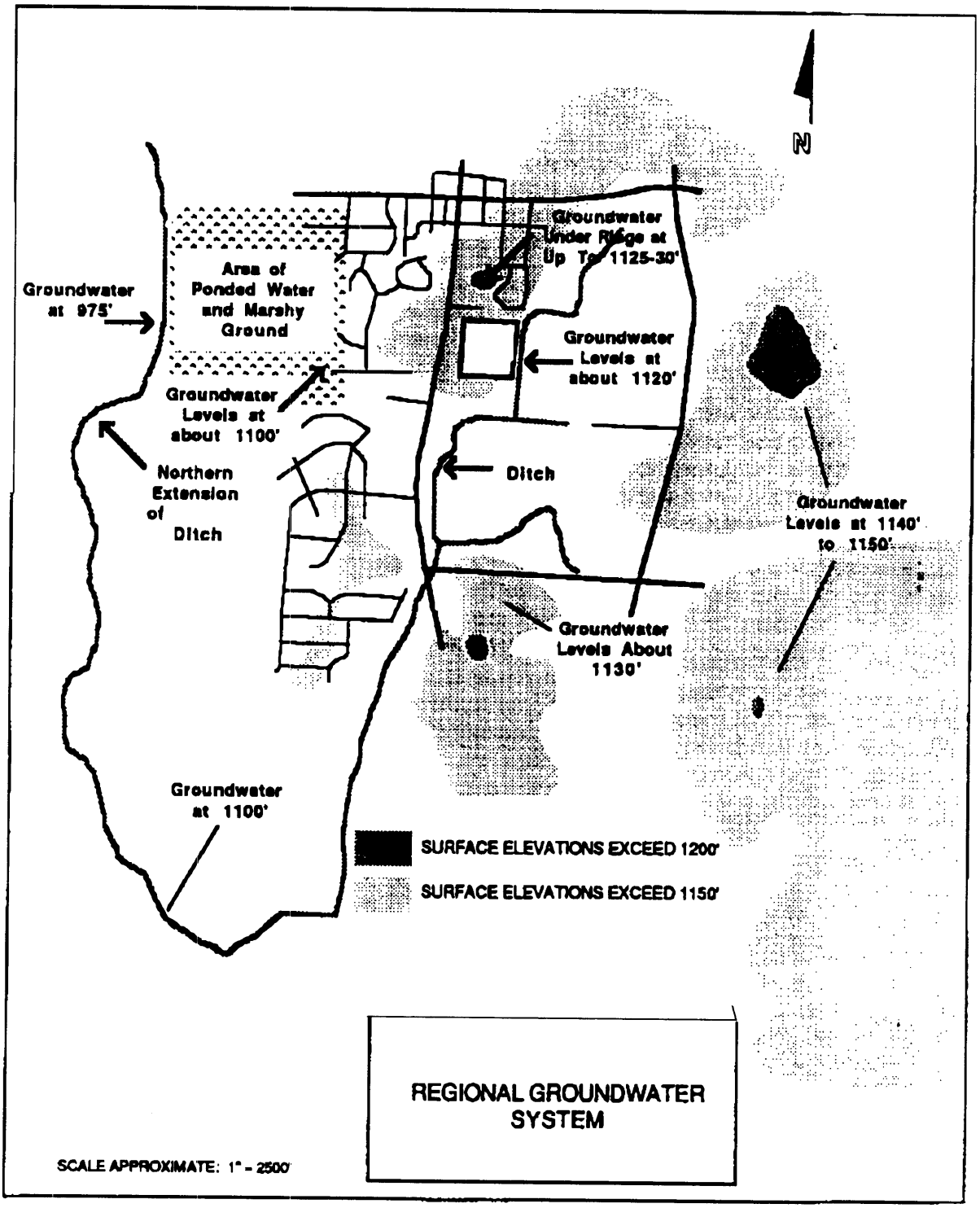
Please contact the people listed in the previous section for specific modeling documents related to this case study.

End Notes:

1. 30% Remedial Design represents the first part of the detailed design process after approval of the conceptual design for the site.
2. See the Assessment Framework in the Ground-Water Modeling Compendium (EPA 500-B-92-006, October 1992).
3. The observational approach (originally developed for soil mechanics) addresses the uncertainty associated with limited site data and the immediate need for a remediation system by utilizing simple models to develop a design that will remain effective over the range of possible hydrogeologic conditions that may be found at the site. A remediation system is then installed quickly and its performance is regularly monitored and adjusted as necessary.
4. Predictive sensitivity analysis is a procedure to quantify the effect of uncertainty in parameter values on the prediction. Ranges and estimated future stresses are simulated to examine the impact on the model's prediction.

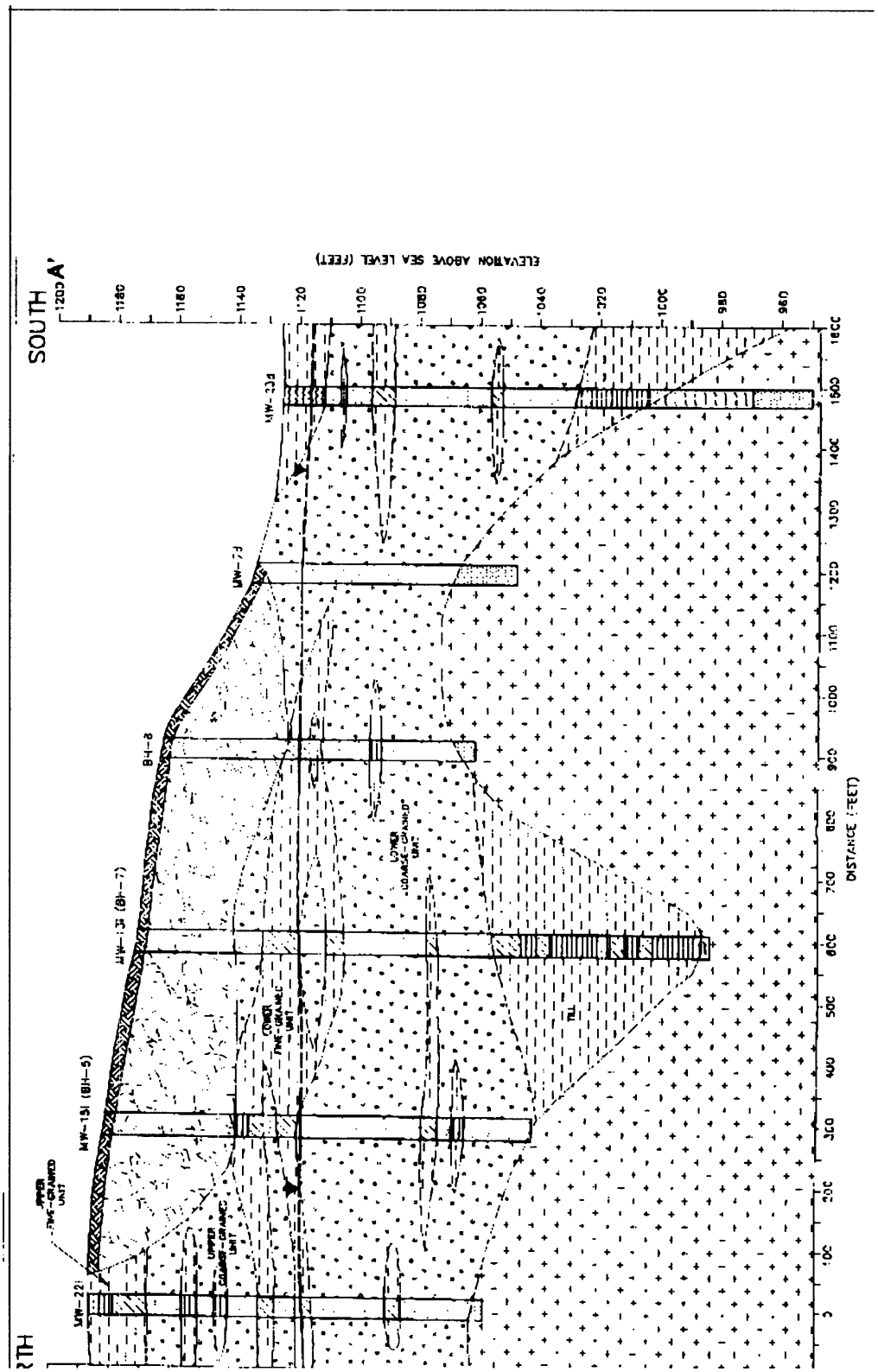
Figure 3.5-1

Base Map of Site



# Figure 3.5-2

## North-South Cross-Section of Site Geology



# Figure 3.5-3

## Potentiometric Surface Map of Zone

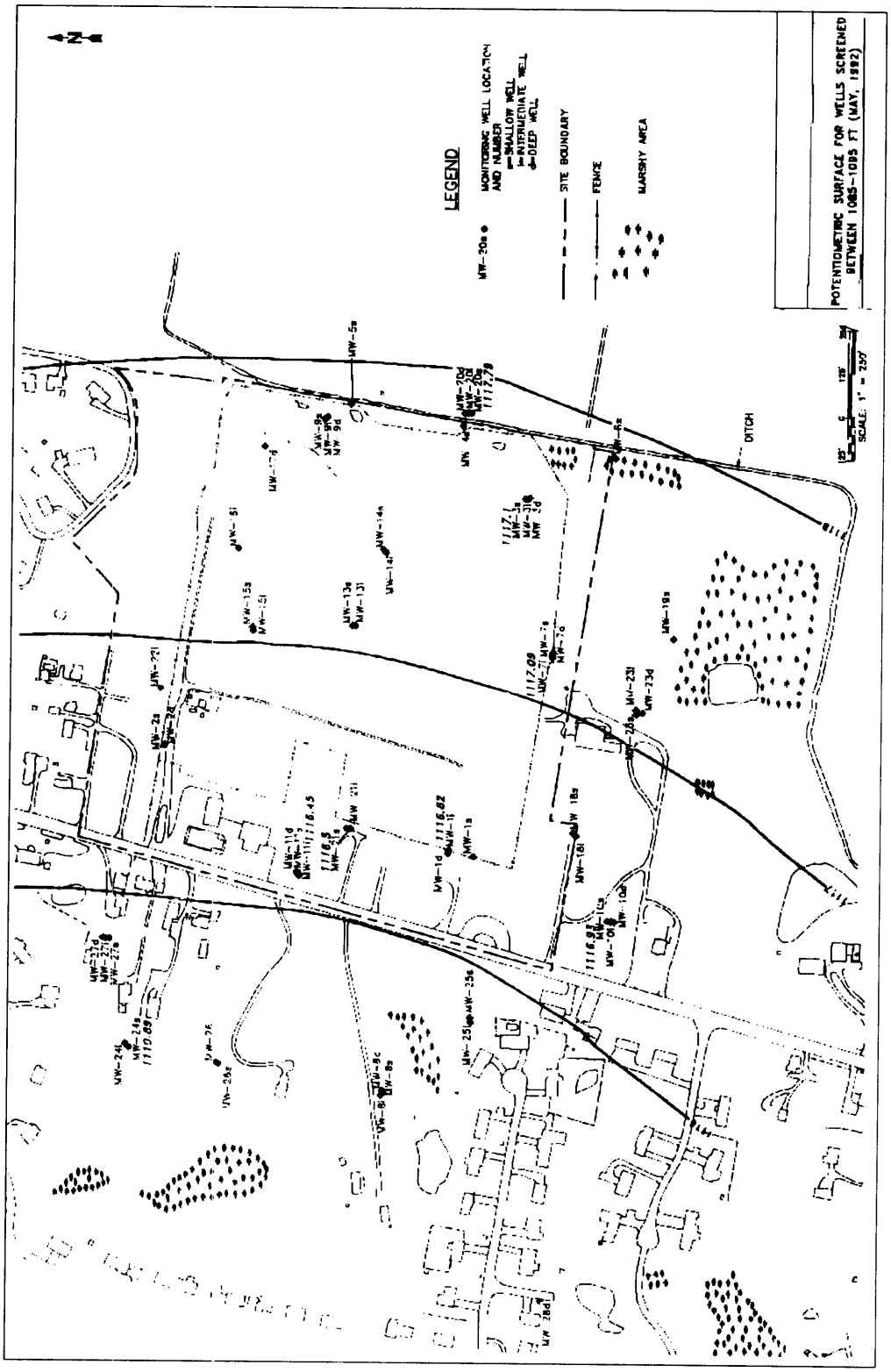


Figure 3.5-4

Dissolved Organics and Metals Plume

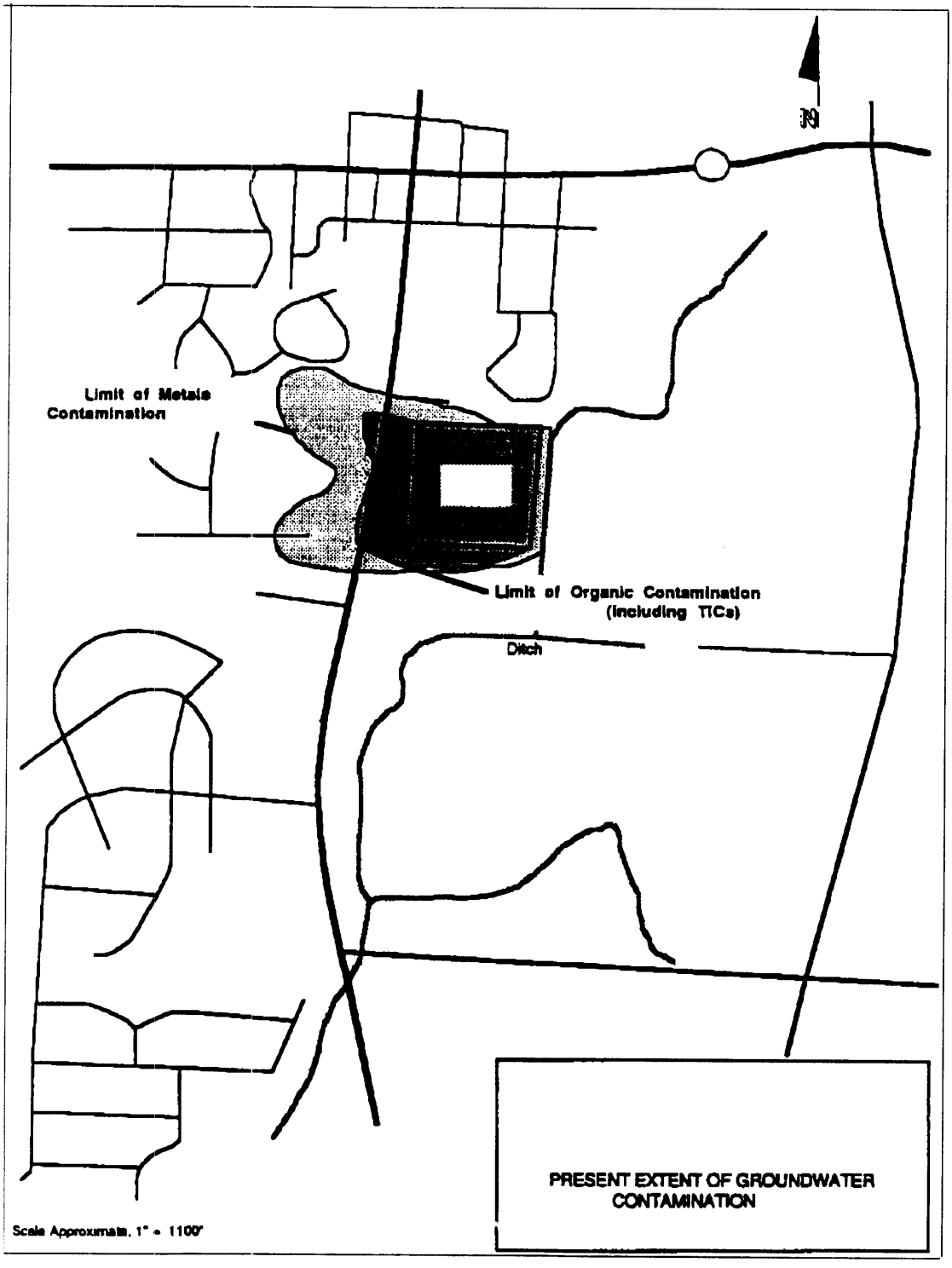
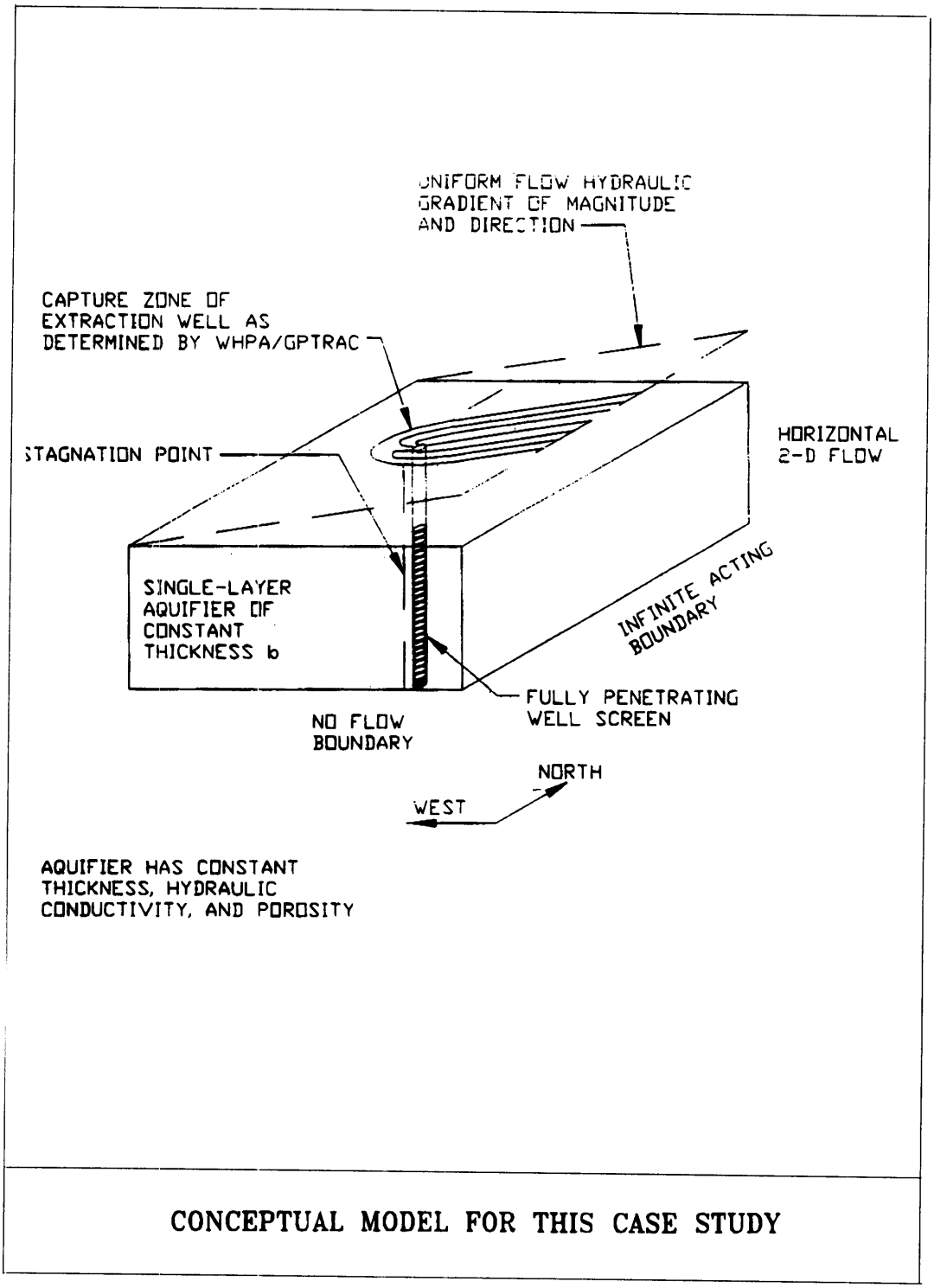


**Figure 3.5-5**

**Simple Conceptual Model**




CONCEPTUAL MODEL FOR THIS CASE STUDY

# Figure 3.5-6

## Location of Extraction Wells

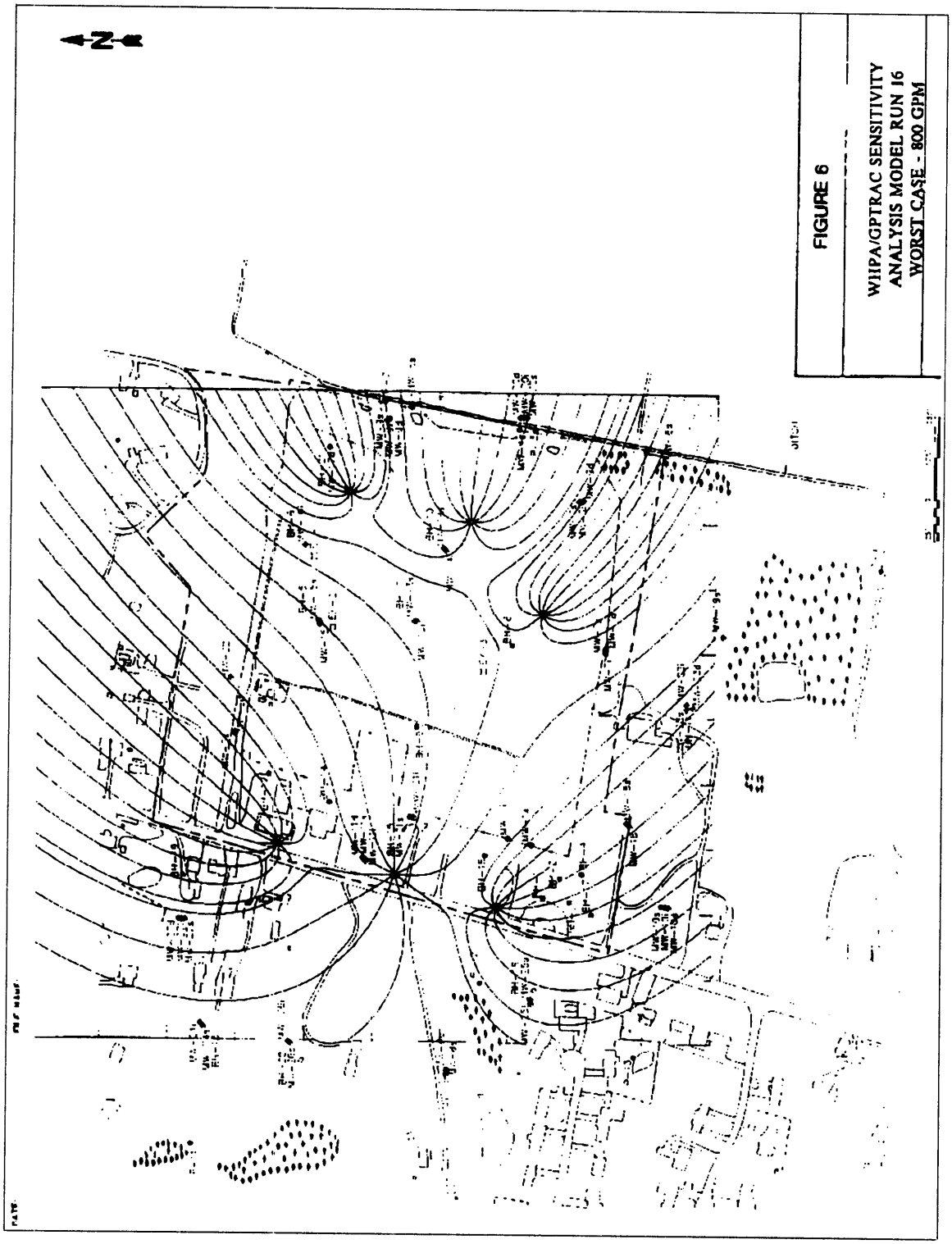
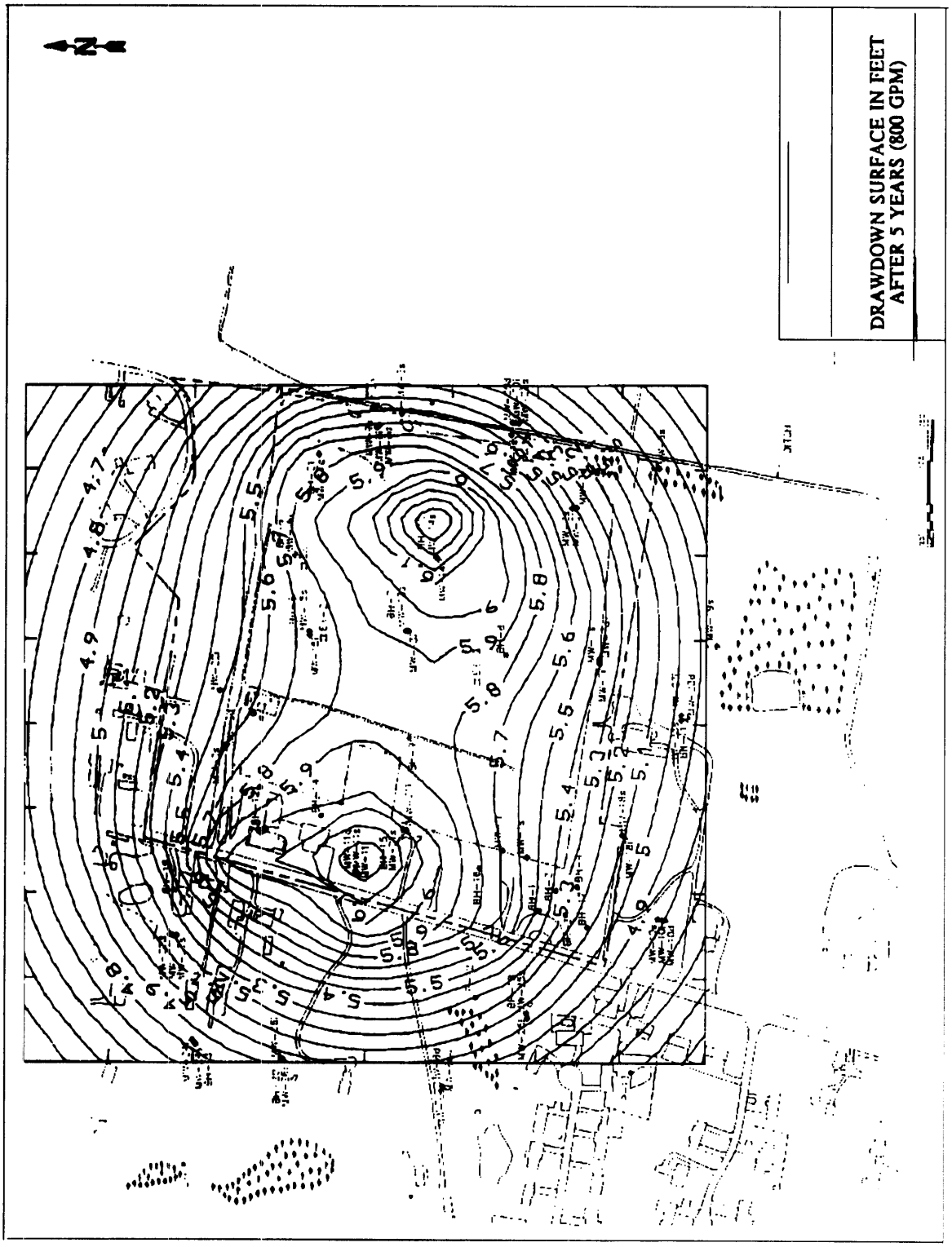


**Figure 3.5-7**

**Drawdown Across the Site at 800 gpm**



## 3.6 - Summary Description #6

# 3.6

# Model Applications
# Summary Description #6

Abstract:

Purpose of Model Application: To perform a detailed analysis of alternatives for ground-water and soil remediation in conjunction with a Feasibility Study (FS).

Type of Site: Former Processing Center for waste industrial chemicals. The soil underlying the site is contaminated with organic compounds with concentrations up to 150,000 micrograms/kilogram (ug/kg). A dissolved ground-water plume has been identified that extends as much as 1,500 feet from the site and lies 35 feet below the ground surface.

Models Used: MODFLOW; MOC.

Types of Models: Numerical; Finite-Difference.

Result of Study: Results provided by the ground-water models led to the recommendations made in the FS, thereby supporting the U. S. Environmental Protection Agency's (EPA) timely decision regarding the best way to remediate the site. Based on these results and recommendations, the EPA installed a multi-media cap and a plume stabilization well at the site. Installation of this well prevented the off-site migration of contamination, except for only one of the most mobile contaminants.

Decision Objectives:

The EPA Region tasked an environmental contractor to perform the FS to determine site remediation alternatives at a former processing center for waste industrial chemicals. The project decision objectives, developed to support the FS, were: (1) To determine the potential effectiveness of each alternative; (2) To define the potential range of clean-up times for each remediation option identified in the FS; and (3) To develop a better understanding of the flow dynamics at the site. Ground-water model applications were developed to support these decision objectives.

Strengths and Interesting Features of the Model Application:

The site hydrogeology was complex and the site was highly contaminated with organic compounds; therefore, numerical models were selected to perform a detailed analysis of extraction schemes in support of the FS. The selected modeling approach combined two numerical models: MODFLOW (to model groundwater

flow) and MOC (to model contaminant transport). This approach was considered innovative at the time because there was no software available that could perform transport modeling in conjunction with MODFLOW. (Note that MODPATH and MT3D became available later.)

The flow model was set up using MODFLOW as a two-layer system representing the shallow and deep aquifer systems at the site. The semi-confining layer was represented as a quasi-three-dimensional (quasi-3D) layer through input of vertical conductance. Boundary conditions were set up using a combination of physical hydrologic boundaries and artificial boundaries.

An embedded model application[1] was set up using MOC and shallow aquifer zone heads generated by MODFLOW. The two-dimensional (2D) MOC model was used because flow in the shallow aquifer is considered primarily horizontal. The heads from the calibrated MODFLOW model were used to set up constant head boundaries on the outside of the MOC grid.

Another interesting feature of this model application was the choice of indicator compounds for the transport simulations. Generally, it is common practice to select the most volatile and the more mobile compounds. Instead, two indicator compounds were chosen to represent the range of behavior of the contaminants of concern. The highly mobile compounds were represented by 1,2-dichloroethane and the less mobile compounds by tetrachloroethene. By selecting representative indicator compounds, the modelers were able to determine that an optimal system designed to remediate the more mobile contaminants would not be simultaneously effective in remediation of the less mobile contaminants. As a result, additional extraction wells would be required in the center of the less mobile plume, in order to remediate the less mobile contaminants. The model application demonstrated the importance of modeling the less mobile compounds (as well as highly mobile and volatile compounds).

Five extraction scenarios were evaluated in support of the FS study and an additional one was evaluated for negotiations support for the Record of Decision (ROD). The ground-water model showed the importance of installing a multi-media cap and a plume stabilization well at the site. Both remedial actions were implemented by the EPA. This provided an opportunity to evaluate the modeling results for accuracy and efficiency. The multi-media cap virtually reduced the amount of rainfall to zero; and the extraction well (for plume stabilization) contained most of the contaminants, except the highly mobile ones. Therefore, the importance of selecting the most representative indicator compound was demonstrated.

Site Background Information:

The site is located southwest of a large town near a Midwestern metropolitan area. From 1970 until early 1980, the site was operated as a processing center for waste industrial chemicals. The chemical processing activities included reclamation

and recycling, destruction by incineration, production of chemical fuels, and storage of chemicals. When these activities were halted by state and federal regulatory agencies in 1980, the site contained approximately 50,000 drums and 98 bulk-storage tanks filled with various chemicals. Many tanks and drums had deteriorated and leaked, thus contaminating the soil and ground-water.

The site comprises about 12 acres of relatively flat terrain surrounded by farmland. Within one mile north of the site is a community of about 100 homes, some of which have private wells used for lawn irrigation, but potable water is supplied to these homes by the municipal water system. East of the site is a municipal airport and industrial park; a water supply system drawing from five production wells is located less than one mile from the site. The airport facilities were built in the early 1940s as a military training base and flight school. The base was turned over to the nearby town after World War II for use as a municipal airport and industrial park. There is very little information regarding activities in the base area from the late 1940s through the 1960s. However, it is known that the base area was leased to a chemical company which had contracts with the military services for the testing of rocket propellants.

History of the Site Investigation:

Prior to cessation of chemical processing activities at the site, the State declared the site a serious health and fire hazard. The State filed suit against the site operator for improper handling and disposal of hazardous wastes. Local residents complained of a variety of physical ailments and property damage caused by emissions from the incinerator. Crop damage was alleged to have occurred, and cattle in nearby fields became sick and died. The State filed a contempt of court petition against the site owner because violations of the conditions of the order. The site was closed and placed in a state court-appointed receivership in early 1980.

Soon after closure, the site became an immediate threat to public health and the environment during heavy rainstorms due to potentially explosive chemical reactions in the deteriorating drums on-site. Local residents detected vapors rising from the site, and the immediate area was evacuated. Stormwater ran through the site into a ditch that emptied into a tributary of a navigable river. The EPA Region Emergency Response Team arrived on-site and immediately implemented containment operations to stop the migration of waste chemicals via surface-water run-off. Several chemicals defined as Section 311 hazardous substances, in 40 CFR 116, had been found in the ditch. The response team also found approximately 50,000 55-gallon drums and 98 large tanks. A few months later, the response team completed its action at the site. The immediate action concluded with the relocation of an estimated 45,000 drums to staging areas on the site. The action did temporarily stop surface run-off. Subsequently, ground-water and soil studies were conducted at the site.

A surface clean-up was begun during which all wastes were removed from the site for disposal. Then, a Superfund Remedial Investigation (RI) commenced at the

site to evaluate the extent and severity of the soil and ground-water contamination remaining after the surface clean-up. The RI report was completed, at which time the FS was begun to evaluate the soil and groundwater remediation alternatives. A major component of the FS was the use of numerical modeling to predict the impact of alternative extraction well, containment barrier, and soil clean-up options on the contaminant migration.

Geologic Setting:

The site is within an area of relatively flat terrain surrounded by farmland. Elevations range from 565 to 575 feet above mean sea level. The site is located on a gently sloping plain which drains toward the east fork of a navigable river, which was a glacial floodway during the Pleistocene age. The river is 6,000 feet northwest of the site. The land surface slopes gradually at a gradient of less than 10 feet per mile. Figure 3.6-1 is a base map of the site, including surface geology.

The sediments in the area are predominantly glacial-fluvial in origin. They are unconsolidated deposits of sand and gravel, silt and clay, and fine sand. In the site area, the sediments are 75 to 80 feet thick and overlie bedrock of Mississippian age.

Three geologic facies have been identified at the site: (1) sand dune/outwash facies (shallow aquifer), (2) lacustrine facies (confining layer), and (3) outwash facies (deep aquifer). These facies are represented as separate physical layers in the conceptual model and as two layers separated by a quasi-3D layer in the numerical flow model. The geometry of these deposits has been defined through the preparation of a series of structure contour maps and isopach maps of the site. The top of the sand dune facies is ground surface.

The sand dune/outwash facies, which comprise the shallow aquifer system, are composed of a series of wind-deposited layers of fine sand with some silt; the lower part of the sand is fairly clean, medium-to-coarse grained sand, with some gravel present. The facies vary in thickness from 18 feet at the southern end of the site to as much as 50 feet thick north of the site. Figure 3.6-2 is a structure contour map of the base of the sand dune/outwash facies and the top of the lacustrine facies (confining layer).

The lacustrine facies, which comprises the confining layer, consists of lake deposits that formed in shallow water or marsh that once existed at the site. The deposits consist of interbedded fine sand, silt, clay, and thin carboneous and peat layers. The confining layer is up to 50 feet thick at the southern end of the site and thins to as little as 20 feet thick at the north. Figure 3.6-3 is an isopach map of the lacustrine facies.

The outwash facies comprising the deep aquifer system is composed of coarse sand and gravel. It is thickest at the east end of the site where it is 22 feet thick, and it thins to as little as 1.3 feet northwest of the site. Based on the structure contour map

of the top of the outwash facies (Figure 3.6-4), an area exhibiting a subsurface hill-like feature exists at the southeastern corner of the site.

It is believed that this is a geological feature known as a glacial kame, a hill of sand or gravel. Figure 3.6-5 shows an isopach map for the outwash facies.

The bedrock is a red shale formation of Mississippian age which is considered an aquiclude. The bedrock surface slopes gently to the southeast.

Hydrogeology:

The average annual temperature at the site is 75° Fahrenheit (F). The coldest month is January with an average temperature of 30.4° F and the warmest month is July with an average temperature of 75.8° F. The average annual precipitation is 41.3 inches, and the mean monthly precipitation is 3.44 inches, with most of the rainfall occurring in the spring and early summer months.

The regional flow dynamics at the site are fairly complex. Surface run-off drains to the east fork of a river, approximately 1.5 miles to the northwest. The site is within an area with a significant amount of excess water available for recharge. The average annual run-off is 14.4 inches per year, and most of the water seeps into the ground. The shallow aquifer system comes into contact with a ditch north of the site, which contains water throughout the year. Water in the shallow system continues to flow to the northwest where it discharges into the major river system. Water in the deep system, however, flows primarily to the south.

Figure 3.6-6 shows the potentiometric surface map of the shallow aquifer system. The shallow system is unconfined, with depth to water being 4 to 6 feet from the ground surface. Ground-water flow is to the north-northwest. The horizontal hydraulic gradient varies from 0.00240 to 0.0039 feet/feet.

Figure 3.6-7 shows the potentiometric surface map of the deep aquifer system. The deep system is primarily confined throughout the site by the lacustrine facies. Ground-water flow is primarily to the south and is impacted by five water supply wells located to the east of the site at the municipal airport. The average horizontal hydraulic gradient is 0.0035.

Vertical flow through the confining layer is primarily downward. Calculated hydraulic gradients across the confining layer are within the range of 0.05 to 0.56 feet/feet. The lower range is at the northern end of the site, where the two potentiometric surfaces appear close to one another. The higher gradients are to the southern end of the site.

The estimated hydraulic properties of both the shallow and deep aquifers are based primarily on slug test data; however, one pumping test was performed in the deep aquifer. The shallow aquifer has an estimated hydraulic conductivity of 28 to 79 feet per day. The hydraulic conductivity's of the deep aquifer ranges from 3 to 482

feet per day based on slug test data alone. A more representative value as obtained from the pumping test was 153 feet per day. Based upon these estimates, the horizontal velocity of the shallow aquifer was estimated to range from 103 to 289 feet per year while that of the deep aquifer ranges from 188 to 637 feet per year.

Ground-Water Contamination:

At the time of the RI report, it was concluded that the shallow aquifer system was contaminated with organic compounds. Contamination was found both in the soil and in the ground-water. Figure 3.6-8 shows the distribution of the ground-water plume. Concentrations as high as 370,000 micrograms per liter (μg/L) of total hazardous organic compounds were found in the ground-water underlying the site. The plume reached as far as 1,100 feet downgradient of the site.

Figure 3.6-9 shows the distribution of contamination on a northwest-southeast cross-section. It is clear from this cross-section that the plume follows the flow of ground-water in the shallow system to the northwest. A small area of contamination in the deep aquifer system was also identified.

Modeling Summary:

Project Management

To support the objectives of the RI/FS study, a ground-water model was prepared. The ground-water modeling team was composed of:

1. A contractor project manager.
2. A modeler.
3. An expert hydrogeologist.
4. An expert in contaminant transport.
5. Two technical personnel who performed Quality Assurance (QA) peer review.

The first step in the process was to formulate the modeling objectives based on the management decision objectives. Given below is a list of modeling objectives developed for this study:

1. Develop a conceptual flow model of the site that incorporates all of the hydrogeologic features which may have a significant impact on ground-water flow.
2. Extend the conceptual model as necessary to ensure that the effectiveness of remediation alternatives could be evaluated.
3. Identify suitable indicator compounds for plume contaminants modeling.

4. Examine and evaluate alternative extraction schemes, in terms of plume containment, aquifer restoration, and clean-up times.

Assumptions Due to the Project Scope:

After development of the modeling objectives, the project team assessed how best to achieve the overall project objectives. The team recognized that the sophistication of the required modeling might exceed the capabilities of existing models. Consequently, the team decided to utilize only the public domain models that had source code available. Thus, the code could be modified if required. Moreover, to reduce modeling costs and increase the accessibility of the modeling application, it was decided to choose a model that could be run on a microcomputer.

Model Development Plan:

To achieve the modeling objectives, a model development plan was implemented based on the following steps:

1. Perform data review and data organization tasks in conjunction with the RI study.
2. Develop a conceptual model for ground-water flow.
3. Select a suitable model code based on the representational needs of the conceptual model and the code's ability to model the proposed remediation alternatives.
4. Perform model setup and input estimation of the ground-water flow model; including setup of a suitable finite-difference grid.
5. Calibrate the flow model.
6. Determine the best way to represent the contaminant plume and residual sources at the site within the limitations of the selected code.
7. Determine the best way to model various extraction schemes in support of the FS remediation alternatives.
8. Run the model, evaluate the results, and make recommendations to the EPA about the most optimal and cost-effective remediation alternatives.

Data Review:

The data review was performed as part of the RI study. The RI study area was designated as that area within a 2,000-foot radius of the site (covering 14 acres). The well inventory area was much larger, however, covering a 6,000-foot radius. Thus, residential wells located outside of the study area northwest of the site and five large capacity water supply wells located at the municipal airport to the east lay within the study area. Moreover, there were 46 monitoring wells at the site, including 16 wells drilled during the RI study.

In addition, 28 soil samples from the shallow aquifer were subjected to physical property tests, and gamma logs were run in 18 monitoring wells. Water levels were measured in the monitoring wells on a monthly basis.

Data Organization:

After the data were collected and reviewed, the following data organization tasks were performed (in support of ground-water modeling):

1. Preparation of four geologic cross-sections.
2. Preparation of structure contour maps for the confining layer, deep aquifer zone, and bedrock (Figures 3.6-2 and 3.6-4). Isopach maps were also prepared (Figures 3.6-3 and 3.6-5).
3. Preparation of potentiometric surface maps for the shallow and deep aquifer zones (Figures 3.6-6 and 3.6-7).
4. Plotting of ground-water contaminant concentrations on map and cross-section (Figures 3.6-8 and 3.6-9).

In addition, all of the data collected was presented in tables in the RI.

Preparation of the Conceptual Model:

A detailed conceptual model was developed (shown on Figure 3.6-10) in order to meet the study objectives. The conceptual model incorporated the following components:

1. A multi-layer aquifer system representing the shallow aquifer, confining layer, and deep aquifer systems. The actual elevations (shown on Figures 3.6-3, -4, and -5) were input into the model.
2. Incorporation of the non-uniform flow fields in both the shallow and deep aquifers. The shallow aquifer is unconfined and the deep is semi-confined.
3. Incorporation of both physical hydrologic boundaries and artificial boundaries. (See discussion of boundary conditions below.)

An important component of the conceptual model was the setup of boundary conditions:

1. Shallow aquifer: A constant head boundary along the ditch north of the site was established with no-flow boundaries to the east, west, and south. The constant head boundary at the ditch was a real physical boundary; as was the no-flow boundary to the south based on identification of a ground-water divide. The east and west no-flow boundaries were based on flow patterns in the shallow aquifer.
2. Deep aquifer: A constant head along all boundaries, except the west edge, was established. The west edge was treated as a no-flow

boundary. The north, south, and west boundaries were based on inferred flow patterns in the deep aquifer. The east constant head boundary was located at the center of a well field located near a municipal airport. The heads along this boundary were calculated using the Jacob equation assuming an "average" flow from the municipal water supply wells.

Assumptions of the Conceptual Model:

Additional assumptions of the conceptual model were that:

1. A quasi-3D model was adequate to represent the flow patterns in the multi-layer aquifer system. In a quasi-3D model, it is assumed that flow in the confining layer is vertical; whereas, flow in the shallow and deep systems is primarily horizontal.
2. The bedrock underlying the site was a no-flow boundary.
3. A small east-west creek north of the site was believed to have an insignificant impact on ground-water flow and was ignored in the model.
4. The primary recharge to the aquifer was from infiltrating rainwater and seepage from run-off.
5. The aquifer was in a dynamic steady-state condition. (Although heads vary in the aquifer throughout the year, the hydraulic gradients are always the same).

Model Code Selection:

Based on the modeling objectives and the conceptual model developed, two numerical model codes were selected. Both were developed by the United States Geological Survey (USGS); both are numerical models; and both use a mathematical technique called finite-difference to simulate ground-water flow and contaminant transport.

MODFLOW was selected to model ground-water flow because it is capable of modeling multi-layer aquifers, handling the varying properties within each layer, and handling confined, unconfined, and leaky aquifers. Another reason for the MODFLOW selection was that it is a widely accepted and tested model.

MOC was selected to model contaminant transport. By itself, MOC is limited to single-layer aquifers and has high computational requirements. However, by relying on MODFLOW to generate an accurate flow field, a smaller embedded model grid could be used by MOC and the simulation could be limited to the shallow aquifer system (which is where the bulk of the ground-water contamination exists). A modified version of the code was used. This version, modified by J.V. Tracy, included the effects of adsorption and decay.

Assumptions Due to the Model Code:

The selection of these codes imposed a number of additional constraints on the representation of the conceptual model in the analytical model. These constraints required that the representation of the conceptual model be limited to:

1. A multi-layer; quasi-3D aquifer system.
2. An unconfined aquifer type for the shallow aquifer; confined for the lower.

Model Setup and Input Estimation:

The first step was to set up the finite-difference grids to be used in the model simulations. Figure 3.6-11 shows the contaminant transport grid embedded in the flow model grid.

The flow grid covers an area of approximately 9,100 by 7,600 feet and has 40 columns and 42 rows. Near the center of the grid, the cell dimensions are 100 by 100 feet. The cell size is gradually expanded toward the edges of the grid to a maximum dimension of 850 feet.

Interpretations of the site data are shown on Figures 3.6-2, -3, -5, and -6. These figures were utilized to set up the geometry within each layer in MODFLOW. The potentiometric surface for the shallow aquifer is shown on Figure 3.6-6. Figure 3.6-2 was used to input the bottom elevation of the shallow aquifer. The shallow aquifer is represented by Model Layer 1. The confining layer was represented as a quasi-3D layer with a vertical conductance, which is the vertical conductivity of 1.67 x 10-3 feet/day divided by thickness of the confining bed at each grid point (shown on Figure 3.6-3). The bottom layer was represented by a transmissivity (the hydraulic conductivity times the thickness of the deep aquifer, shown on Figure 3.6-5).

The input arrays to the model as described above were constructed with the aid of a geostatistics technique called kriging to provide a smooth spatial distribution. The shallow aquifer was given a hydraulic conductivity of 57 feet/day and the lower aquifer a value of 153 feet/day. The conductivity of the upper aquifer was adjusted during the calibration process (along with the distributed recharge to the aquifer).

To determine the specified head at the eastern boundary of Model Layer 2 required application of the 1942 Jacob solution for steady-flow to wells in a leaky confined aquifer. Input into the Jacob solution included a uniform gradient of 2.5 feet per 1,000 feet sloping downward to the south, and constant thicknesses of 20 feet for the deep aquifer and 40 feet for the confining layer.

An embedded model grid was set up for contaminant transport as shown on Figure 3.6-11. The transport grid contained 24 rows by 28 columns and each cell was 125 feet by 167 feet in areal size. A smaller transport grid (not shown) was also set up for some of the simulations. This grid was 28 rows by 28 columns and each cell was 75 by 75 feet in areal size.

Model Calibration:

The flow model was calibrated in Model Layer 1 (representing the shallow aquifer) to the head data presented on Figure 3.6-6. The best match was obtained by using a uniform distributed recharge of 7 inches per year and the following hydraulic conductivities (K) in Model Layer 1:

1. K = 57 feet/day in rows 1-25.
2. K = 10 feet/day in rows 26-32.
3. K = 20 feet/day in rows 33-42.

The conductivity of 57 feet per day prevails over most of the region of interest and is within the range of values determined by slug tests. Only a visual comparison of simulated contours with Figure 3.6-6 was performed (no mean error was calculated).

Model Layer 2, which represented the deep aquifer, was not calibrated because there were very limited data to calibrate against.

The calibrated heads for Model Layer 1 were used to establish boundary conditions for the contaminant transport model. A computer program was written by the modeler to transfer the head values from the flow model (using MODFLOW) to the transport model (using MOC). This step was required because the two grids were different. Constant heads were placed around the boundaries of the transport grid. The same parameter values used in the calibrated flow model were used in the transport model. The contaminant transport model was not calibrated because a historical record of plume movement was not available.

Plume/Source Representation:

The first step in representing the contaminant plume observed at the site and its associated sources was to identify representative indicator compounds. Field investigations had detected more than 100 different organic compounds in the soil and ground-water. Simulating solute transport for each compound would have been impractical. Instead, two indicator compounds were chosen to represent the range of behavior of the contaminants of concern. The highly mobile compounds were represented by 1,2-dichloroethane and the less mobile compounds by tetrachloroethene. Based on the data collected, the highly mobile compounds had leached rapidly out of the soil into the ground-water. For the less mobile compounds, the leaching process was still ongoing. The two types of compounds were handled in the model in the following way:

1. For the highly mobile compounds, it was assumed that no source remained, but that a residual plume existed in the ground-water. This was handled by inputting the residual concentrations measured in December 1984 into the model. Note: The assumption that no source

remained was not entirely accurate, but was a simplification made by the modeling team to meet the modeling objectives.

2. For the less mobile compounds, it was assumed that a residual source remained in the unsaturated zone, as well as a dissolved plume in the ground-water. For the dissolved plume, the residual concentrations measured in December 1984 were input into the model. The residual source in the unsaturated zone was handled in a unique way as discussed below:

The MOC code did not have the capability to represent a residual source concentration from the unsaturated zone; therefore, it was modified by the modeler to perform this function. The MOC code can model a continuous source of solution by specifying a recharge concentration on a cell-by-cell basis. However, it does not allow for a decrease in concentrations over time. The modeler modified the MOC code to recalculate the recharge concentrations for each time increment in the simulation. Thus, the residual source in the unsaturated zone could be incorporated into the model application. (Note: This modification was tested by the modeler.) The input array of plume concentrations was determined by preparing an interpretation of measured depth-averaged solute concentration for the two indicator compounds and by combining modeling judgment with kriging.

The transport parameters input into the model were:

| Parameter | Value |
|---|---|
| Effective porosity | 0.25 |
| Longitudinal dispersivity | 30. |
| Transverse dispersivity | 10. |
| Retardation Factors | |
| 1,2-dichloroethane | 2.0 |
| Tetrachloroethene | 9.2 |

The parameters were based mostly on representative values reported in the technical literature. None of these parameters were measured in the field.

Scenario Representation:

Seven groundwater extraction, injection, and treatment alternatives, including a no action alternative, were considered. To optimize ground-water extraction, five ground-water extraction schemes were examined for each alternative.

1) Extraction wells only.
2) Extraction wells preceded by an interim plume stabilization well.
3) Extraction wells in combination with injection wells.
4) Extraction wells combined with partial containment within a slurry wall around the site.

5) Three off-site extraction wells to contain the plume.

The following assumptions were made:

1. Each well was assumed to be fully penetrating.
2. Whichever scenario was selected, it was anticipated that the final remedy would not be implemented for up to five years. Therefore, predictions had to be made regarding future locations of existing plumes.
3. At the same time that the extraction wells were to be installed and turned on, a multi-media cap would be installed over the landfill site. This cap affected the schemes in two ways: (1) the cap eliminated recharge over the 12 acres of the site, which in turn modified the steady-state ground-water flow patterns in the shallow aquifer; and (2) the cap eliminated the leaching source into the solute transport model.
4. The pumping rates for the extraction wells were limited to produce drawdown less than 2/3 of saturated thickness, because it was not considered practical to drawdown each well to its maximum level.

All extraction schemes had to be optimized prior to comparative analysis. Optimization involved making numerous simulations with MODFLOW and looking at the number, location of wells, and combination of pumping rates that would result in the quickest removal of contaminated ground-water.

Figure 3.6-12 shows the predicted location of the 1,2-dichloroethane plume after five years of simulation; and Figure 3.6-13 shows the predicted location of the tetrachloroethene plume. Also shown on both figures is the well configuration for Scheme 1 and associated capture zones.

Model Results Summary:

The well configuration for Scheme 1 is shown on Figures 3.6-12 and 3.6-13. The three on-site wells would be installed in five years and would be located within the tetrachloroethene plume but somewhat downgradient of its center. These three wells would reverse the natural flow gradients in a region north of the site but would be unable to create flow reversal as far north as the tip of the 1,2-dichloroethane plume. The northernmost part of this plume would be captured by the off-site well. The flow rate for the off-site well was limited so it would not reduce the effectiveness of the three on-site wells. The solute transport simulations were run until the maximum simulated concentrations in the aquifer were less than the 10-6 excess cancer risk concentration. For 1,2-dichloroethane, restoration of the aquifer would require 20 years; and for tetrachloroethene, the restoration was projected at 35 years.

Scheme 2 considered the installation (in two-and-one-half years) of a single off-site well as an interim plume stabilization measure. Another two-and-one-half years later, three on-site wells would be installed along with the multi-media cap,

bringing the total extraction system up to four wells (similar to Scheme 1). It was expected that early commencement of off-site extraction would have a significant beneficial effect on the configuration of the contaminant plume by the time the full system began operation. Figure 3.6-14 shows the location of all wells and the predicted 1,2-dichloroethane plume after the five years of simulation.

Because the plume stabilization well would capture contaminants before they traveled far off-site, the off-site well could be moved closer to the site. Also, due to the beneficial effect of the plume stabilization well, the 1,2-dichloroethane plume is considerably smaller than for Scheme 1 (Figure 3.6-12) and is, therefore, easier to clean-up with the four wells of Scheme 2. Moreover, even when the flow rates of the center well were reduced, the simulations showed that 1,2-dichloroethane was cleaned up significantly faster than in Scheme 1. However, the scheme had little effect on clean-up times of tetrachloroethene, probably due to its low mobility.

In order to determine if the clean-up time of tetrachloroethene could be improved, an injection well was modeled in the center of the tetrachloroethene plume in Scheme 3 as shown on Figure 3.6-15.

In Schemes 1 and 2, well interference between the three on-site wells caused low hydraulic gradients in the area of the highest contaminant concentrations. Installing an injection well in the middle of the plume would eliminate this area of stagnation (or low gradient) and increase the hydraulic gradient toward the extraction wells. A special model grid of 75-foot square cells was required in this scheme to handle the highly diverging and converging flows caused by the addition of an ejection well. Scheme 3 significantly reduced the clean-up times for tetrachloroethene; however, this scheme did not work as well for removing 1,2-dichloroethane as did Schemes 1 and 2.

Scheme 4 looked at the installation of a slurry wall around the most contaminated part of the aquifer as shown on Figure 3.6-16.

Inside the slurry wall, a single well would be installed to maintain upward flow through the confining layer and to prevent contamination of the deep aquifer. Outside the slurry wall, aquifer restoration would be accomplished by a system of five extraction wells. Ground-water flow and contaminant transport simulations were conducted only for that part of the aquifer outside of the slurry wall. The slurry wall acted as a barrier to flow, thereby tending to cause zones of low hydraulic gradient in the aquifer. This increased the clean-up times for 1,2-dichloroethane. Furthermore, the costs of the slurry wall option were higher than the costs of the other extraction schemes. Because of these factors, Scheme 4 was not considered a reasonable option.

During the public comment period after the FS, Scheme 5 was proposed and consisted entirely of off-site wells. The configuration of this system is shown on Figure 3.6-17.

The objectives of this system were different than the other four schemes. More emphasis was placed on controlling plume migration and on ease of construction, and less on rapid aquifer restoration. Consequently, the pumping rates were not optimized to produce the highest gradients or to minimize the extent of stagnation regions, but were optimized to maintain an effective capture zone. The well capture zones, indicated by Figure 3.6-17, show that this system would not be able to control the entire 1,2-dichloroethane plume predicted.

In addition to the extraction scenarios, two other scenarios using the ground-water model were reviewed during the FS study. The first involved removing contaminated soils from the site. Simulations showed that installation of a multi-media cap was more effective than soil removal. The second scenario was soil remediation with in-situ washing. In this option, installation of the site cap would be postponed for six years while spray irrigation would be used to increase contaminant leaching from the soil. The model showed that soil washing would cause an increase in aquifer remediation time; therefore, it was not further considered.

Overall Effectiveness:

The EPA was satisfied with the modeling results and was able to make decisions about an effective remedial action needed at the site. Based on the ground-water model results and the recommendations made in the FS, the EPA installed a multi-media cap (Figure 3.6-14). The cap is considered to be an effective solution, preventing further leaching of contaminants through the unsaturated zone. The FS recommended installation of at least one plume stabilization well similar to that shown on Scheme 2 (Figure 3.6-14). Additional investigations after the decision documents required the EPA to modify this scheme. These investigations showed 1,4-dioxane traveled faster and further than did 1,2-dichloroethane. Therefore, the EPA decided to install two plume stabilization wells to prevent further migration of 1,4-dioxane. One of these wells was located 300 feet from the source, and the other 1,000 feet from the source.

Contacts for Further Information:

For further information about this ground-water study, please contact:

| | | |
|---|---|---|
| Jeff Gore | EPA Region V | Tel.# (312) 886-6552 |
| Dr. Luanne Vanderpool | EPA Region V | Tel.# (312) 353-9296 |

Relevant Modeling Documents

Please contact the people listed in the previous section for specific modeling documents related to this case study.

End Notes:

1. An embedded model application is a subset of a larger model application; thus, the embedded model application considers only a part of the area modeled in the larger model application.

Figure 3.6-1

Base Map of Site

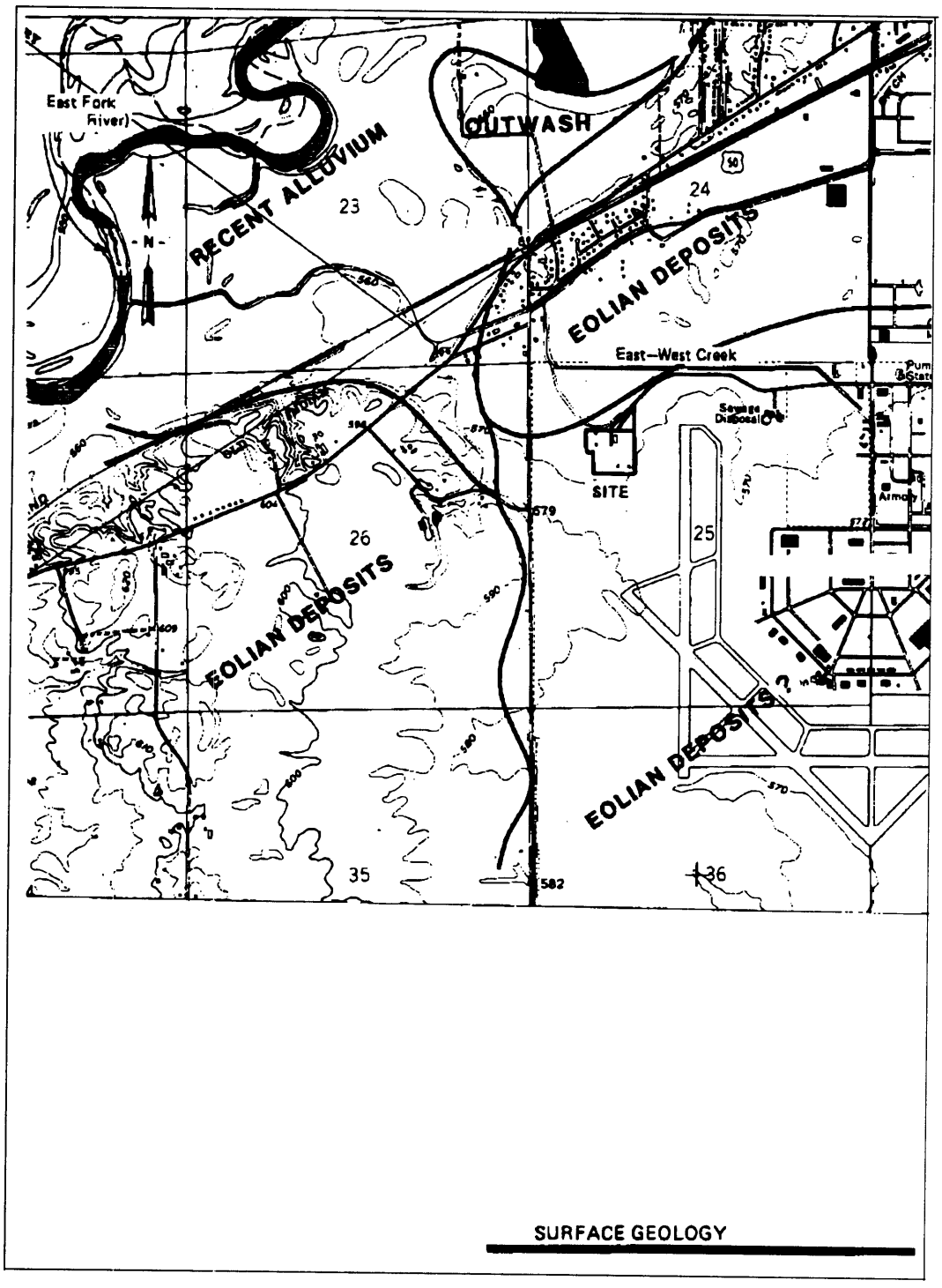


Figure 3.6-2

Structure Contour Map of Base

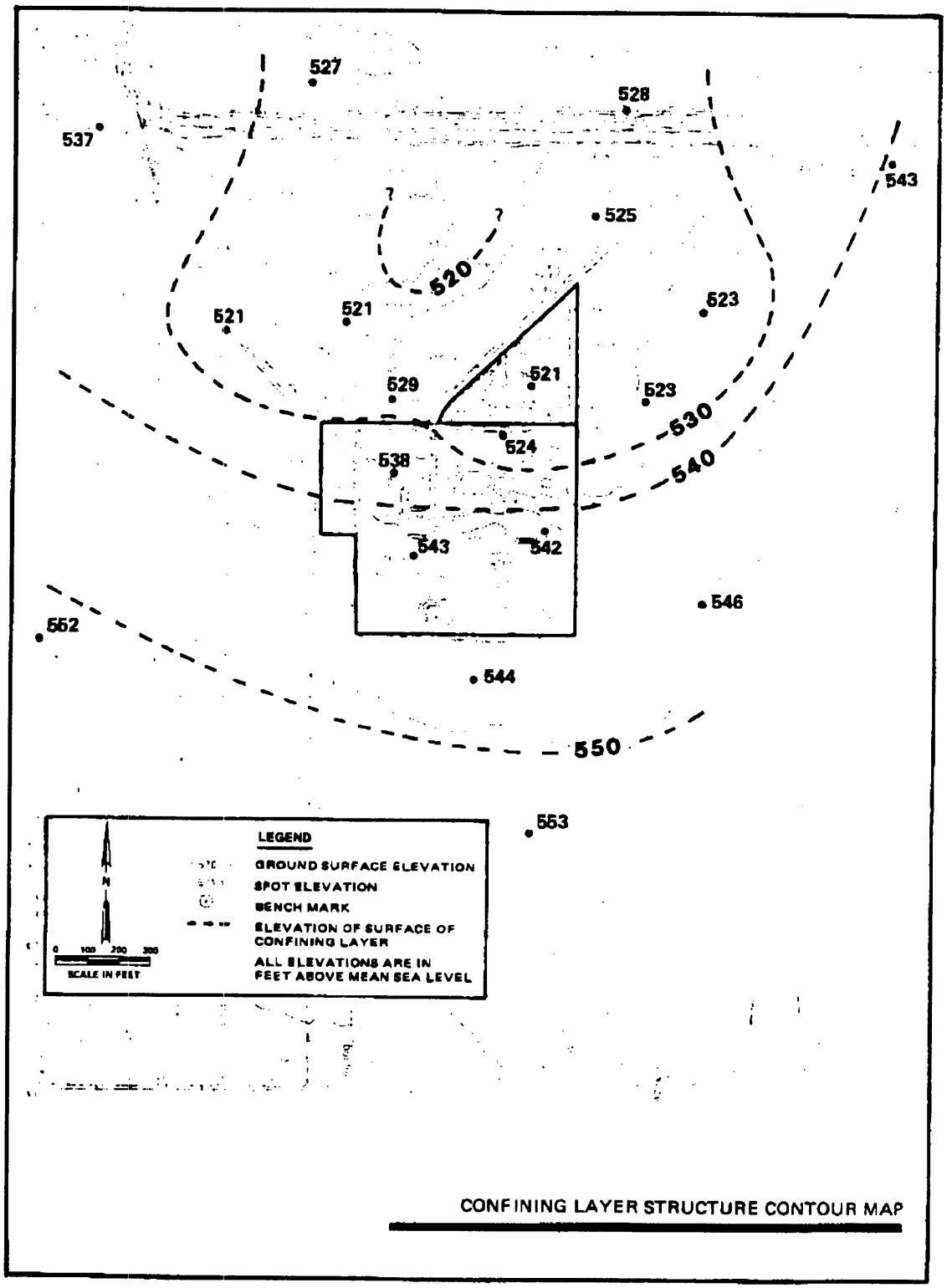


Figure 3.6-3

Isopach Map of Lacustrine Facies

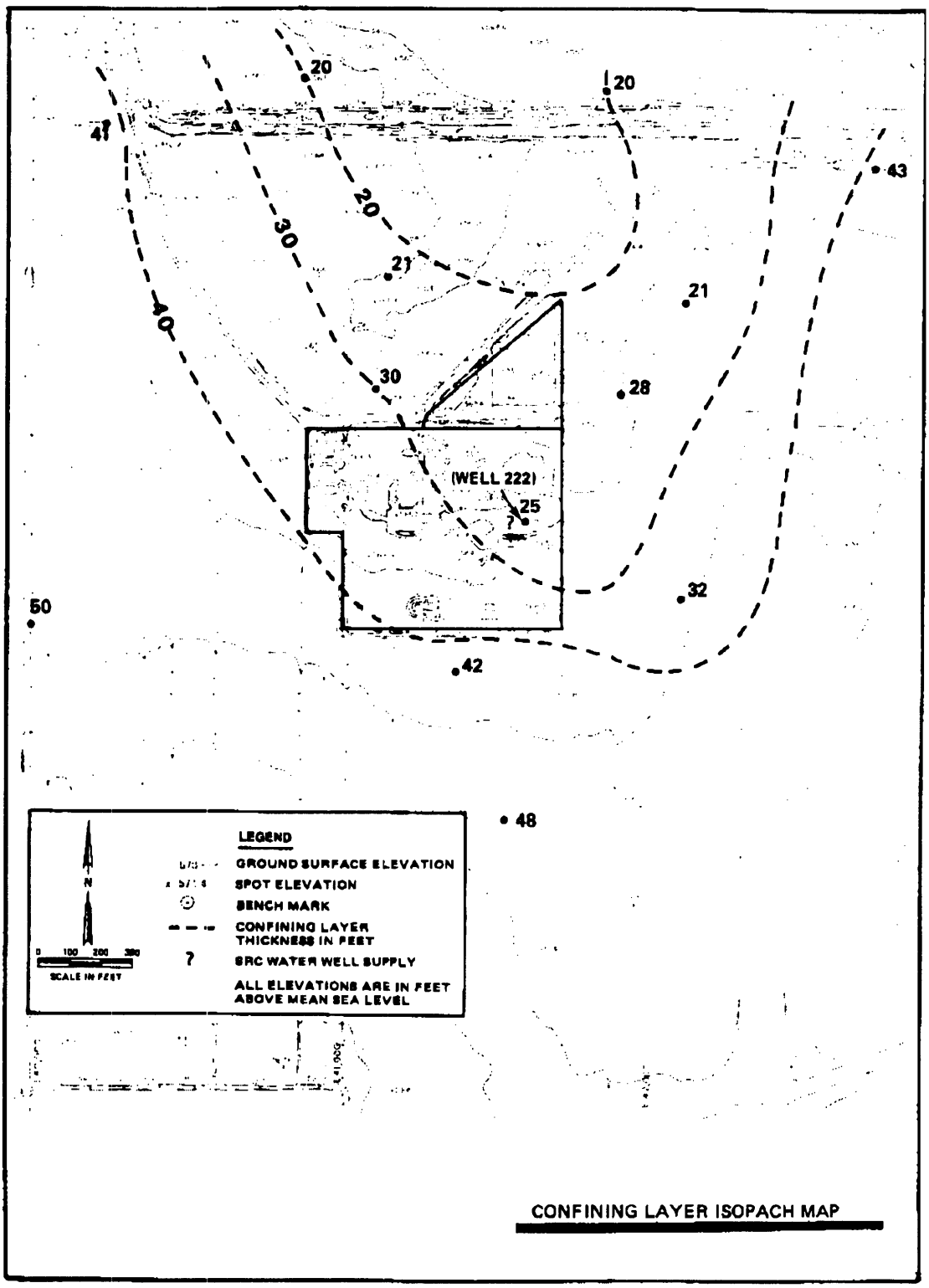


Figure 3.6-4

Structure Contour Map of Top of Outwash Facies

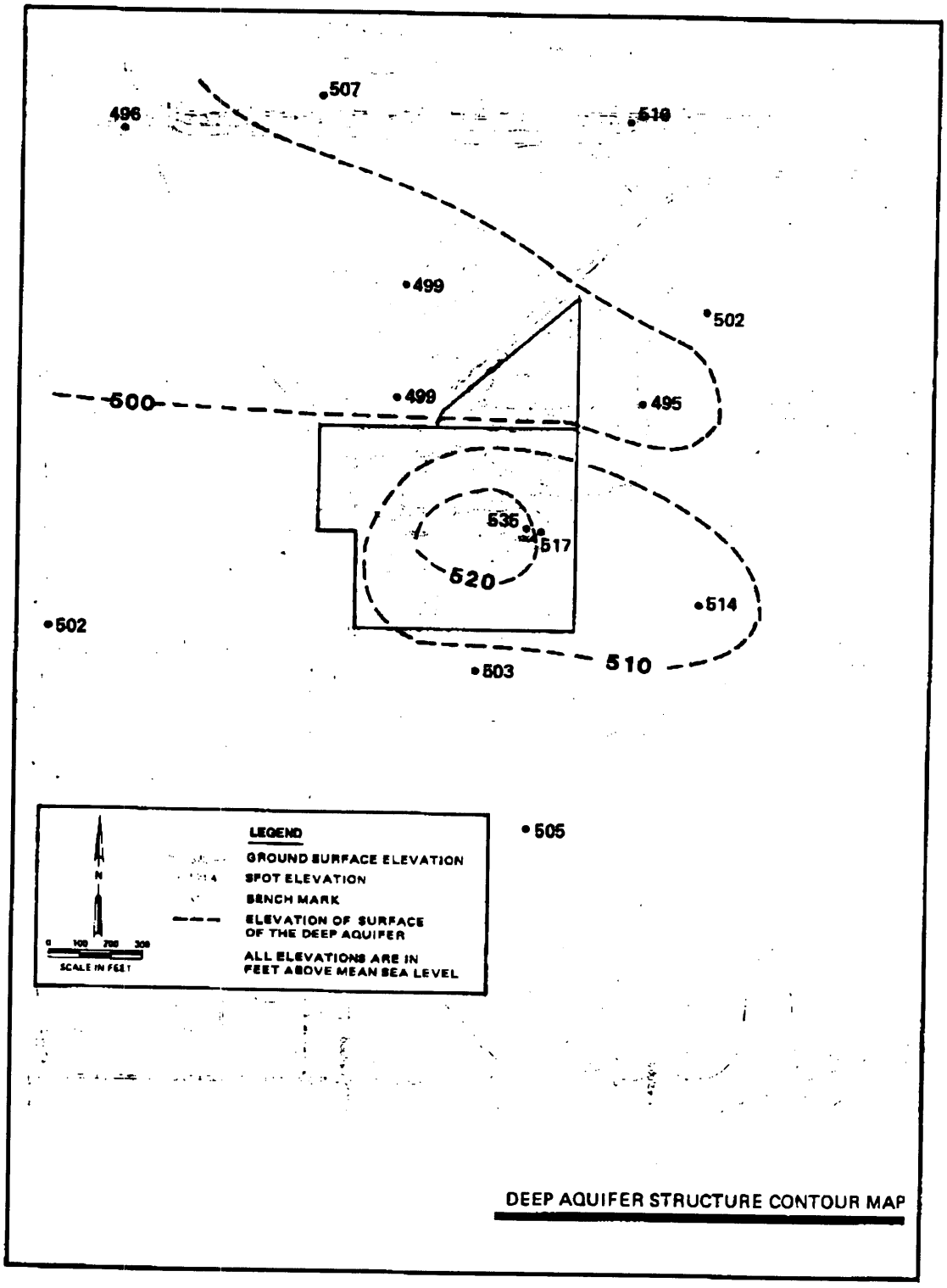


Figure 3.6-5

Isopach Map of Outwash Facies

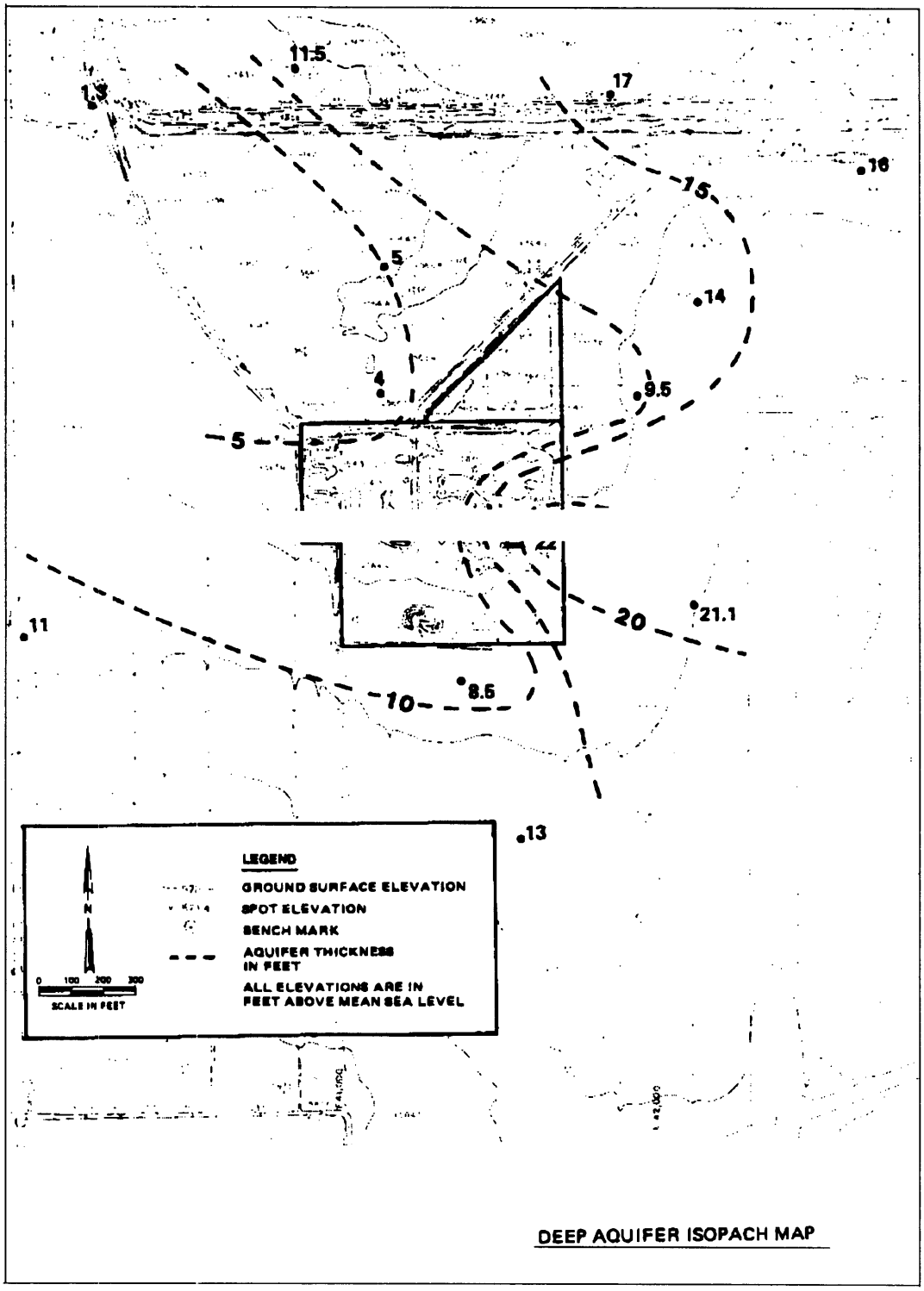


Figure 3.6-6

Potentiometric Surface Map of Shallow Aquifer System

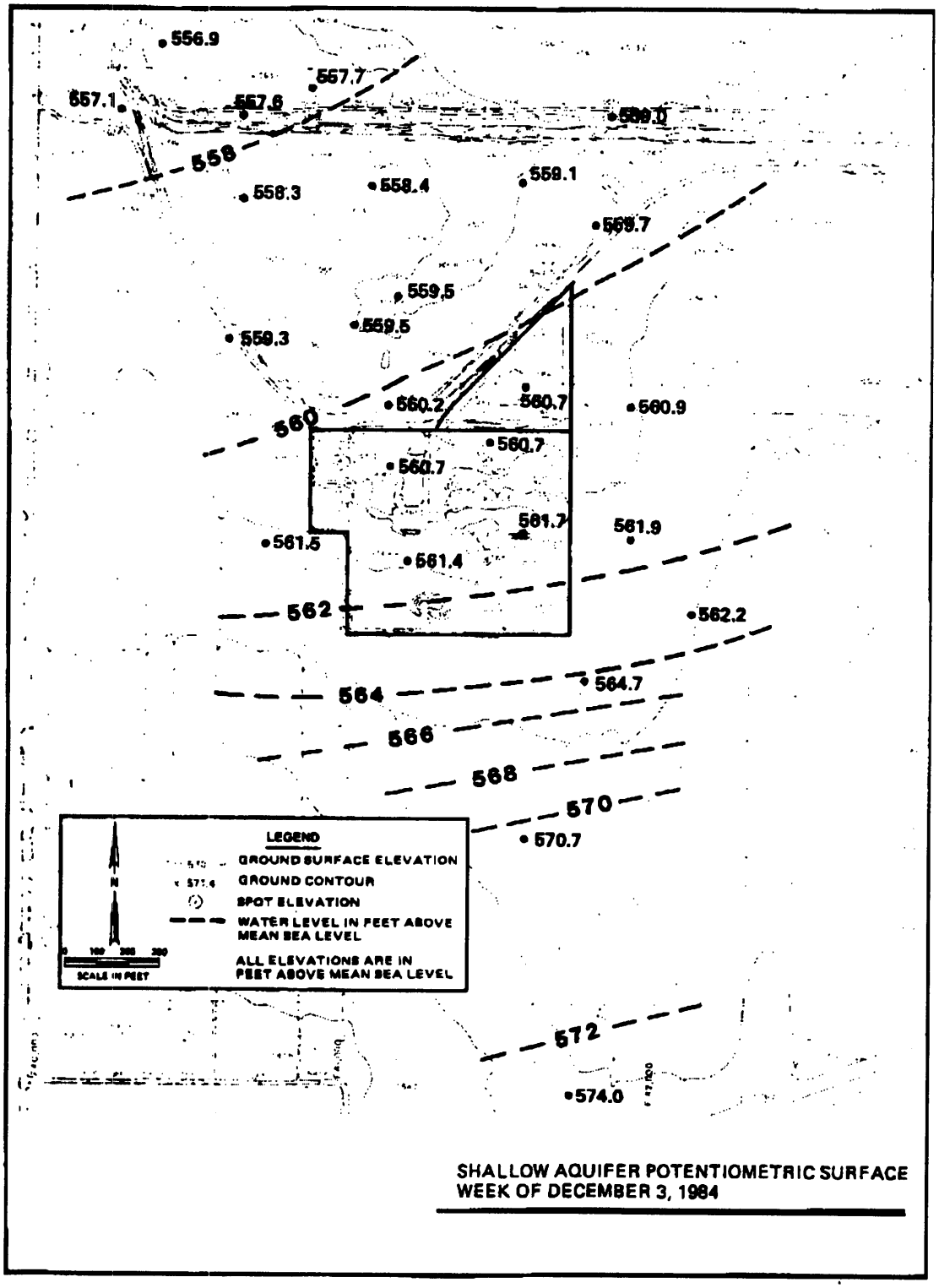


Figure 3.6-7

Potentiometric Surface Map of Deep Aquifer System

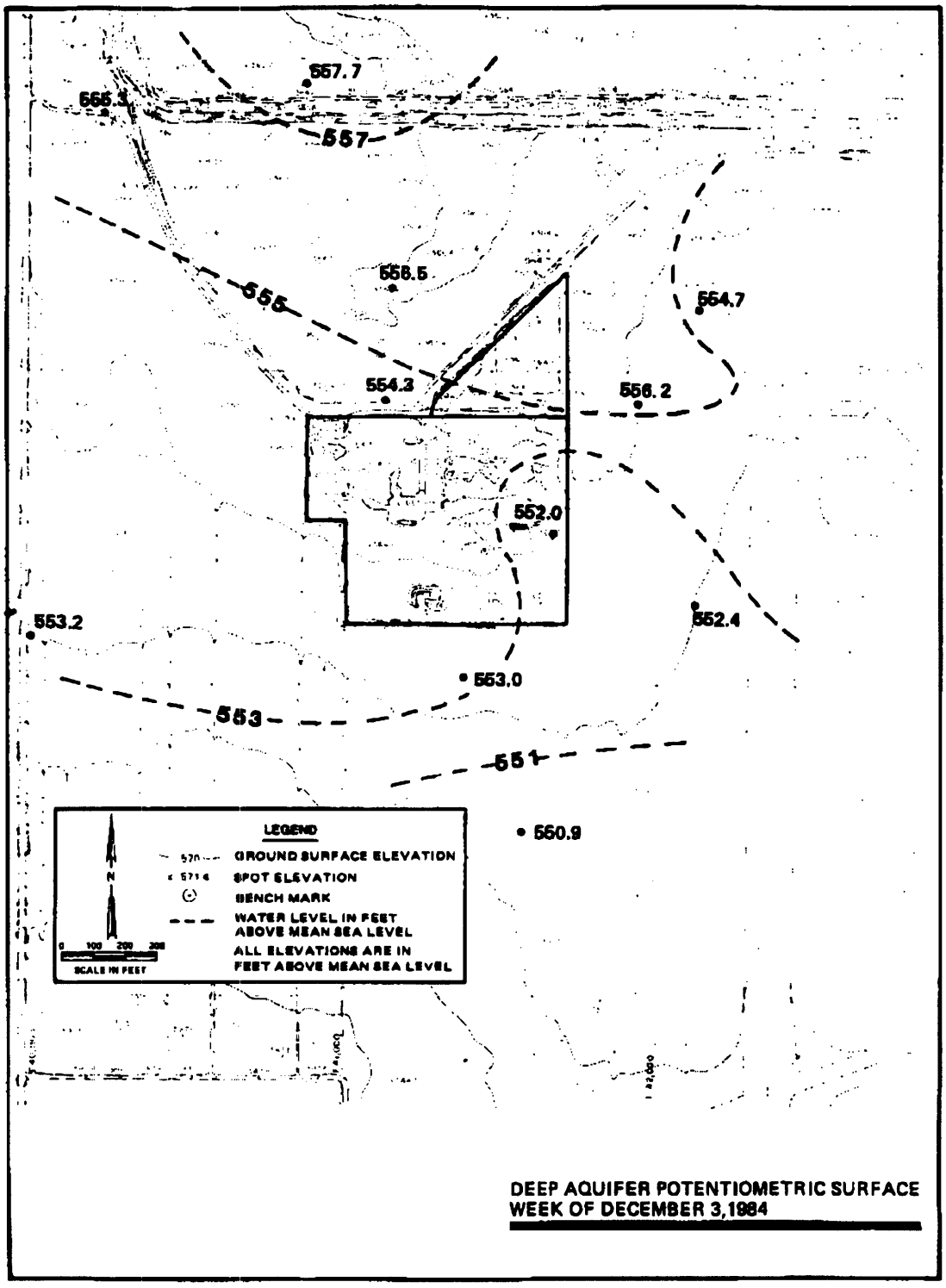


Figure 3.6-8

Distribution of Ground-Water Plume

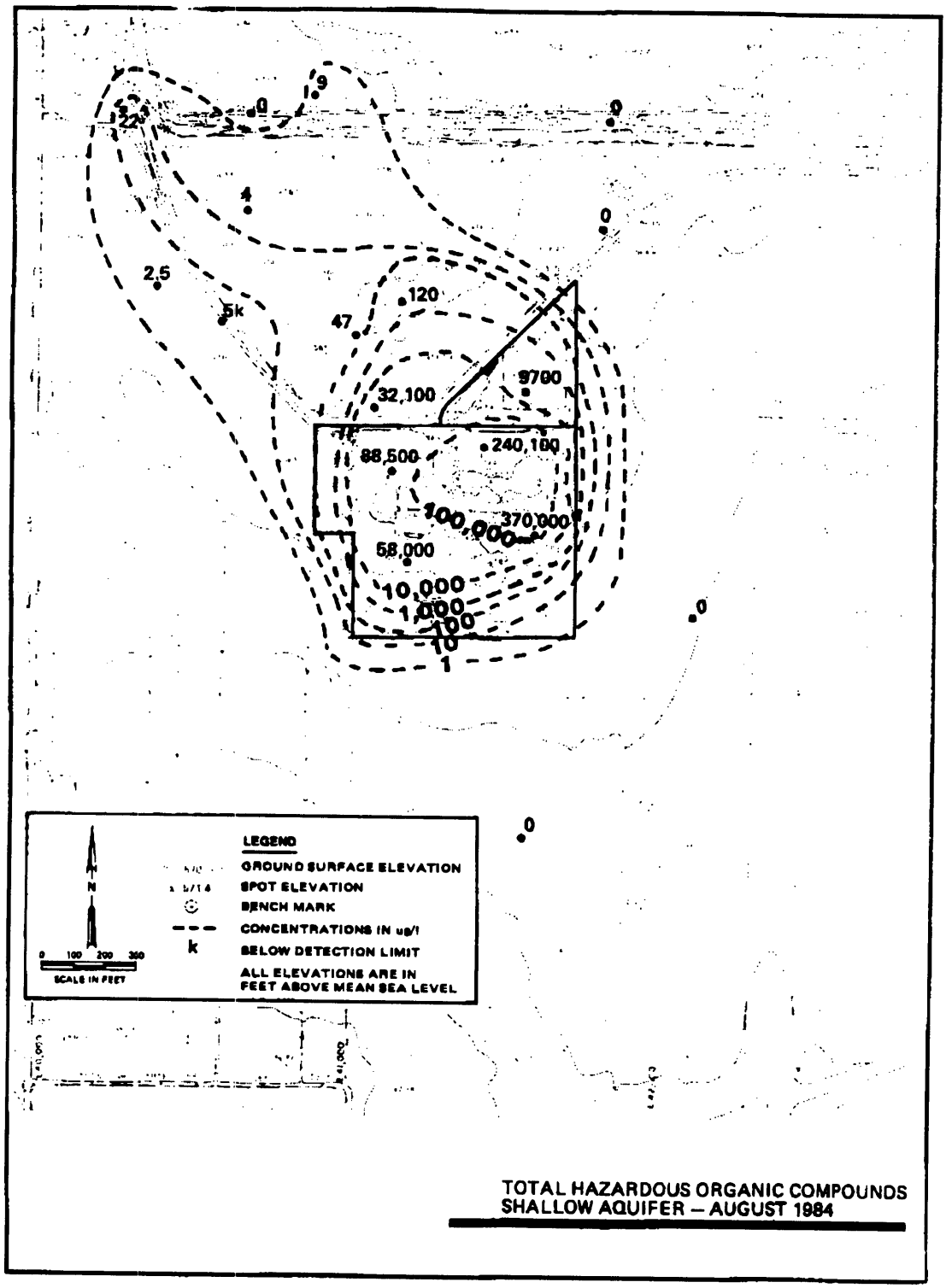
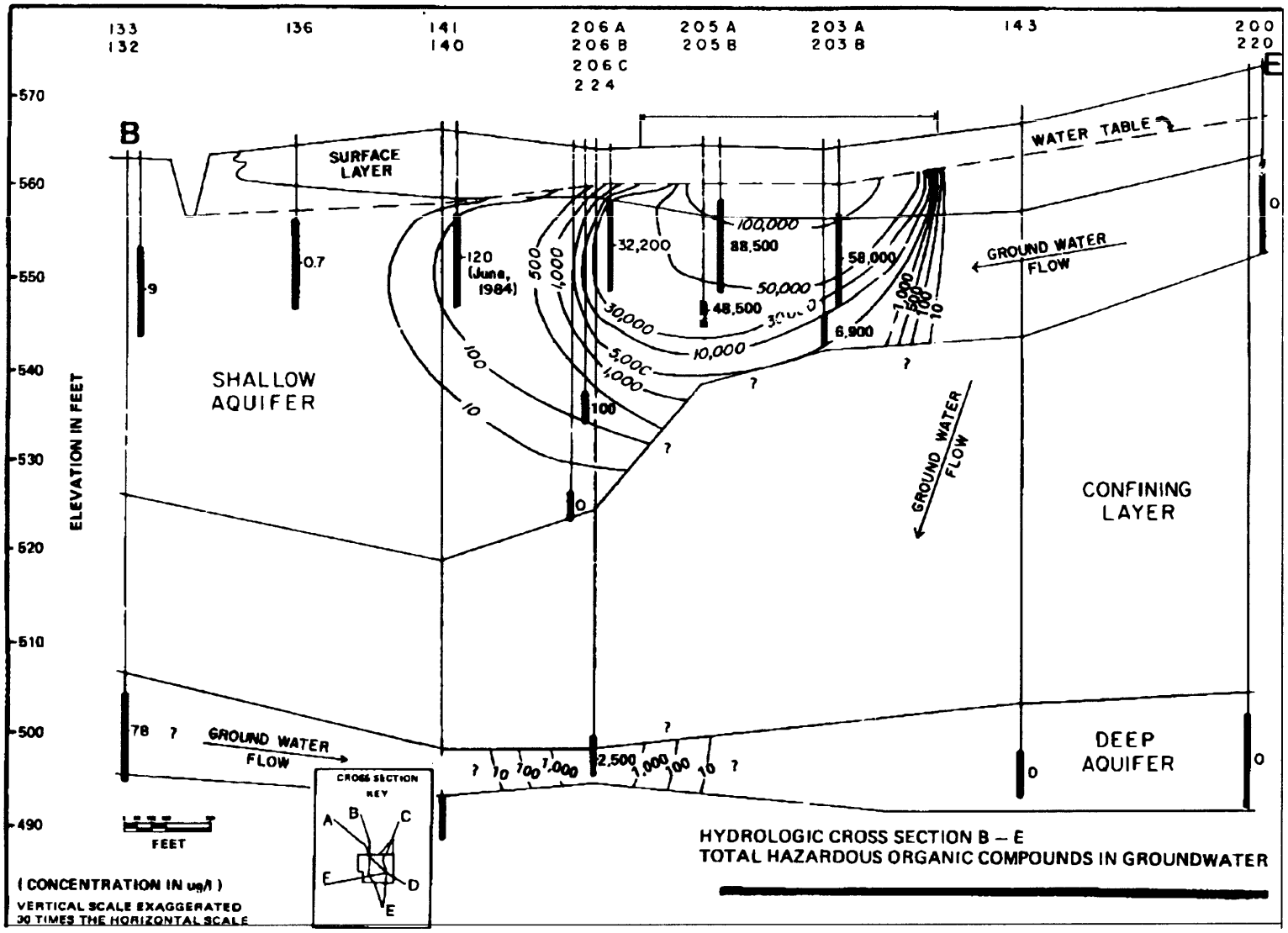


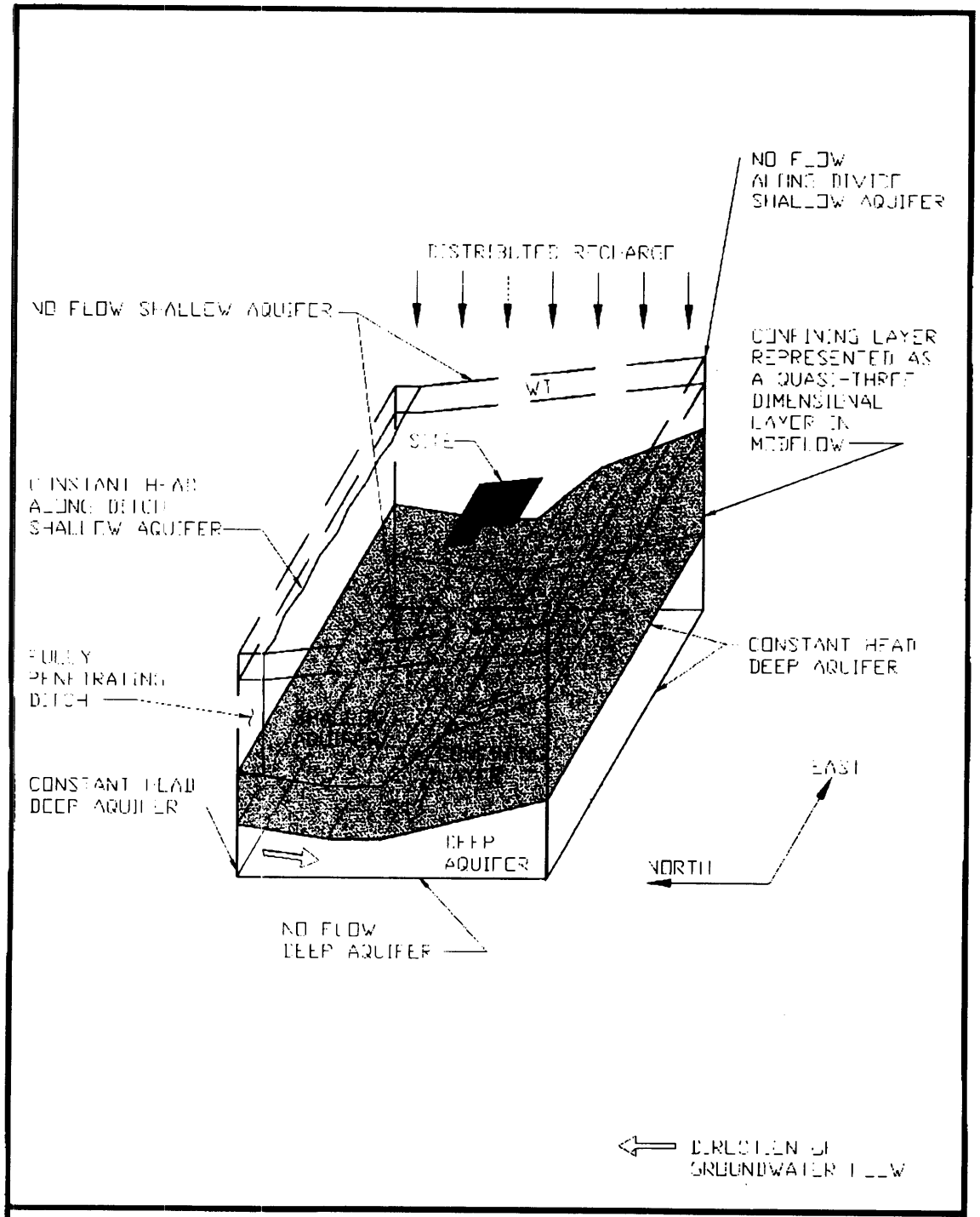
Figure 3.6-9

Northwest-Southeast Cross-Section of Contamination Distribution



## Figure 3.6-10

## Detailed Conceptual Model




BLOCK DIAGRAM OF
THE CONCEPTUAL MODEL USED IN THIS STUDY

# Figure 3.6-11

## Embedded Model Grid for Contamination Transport

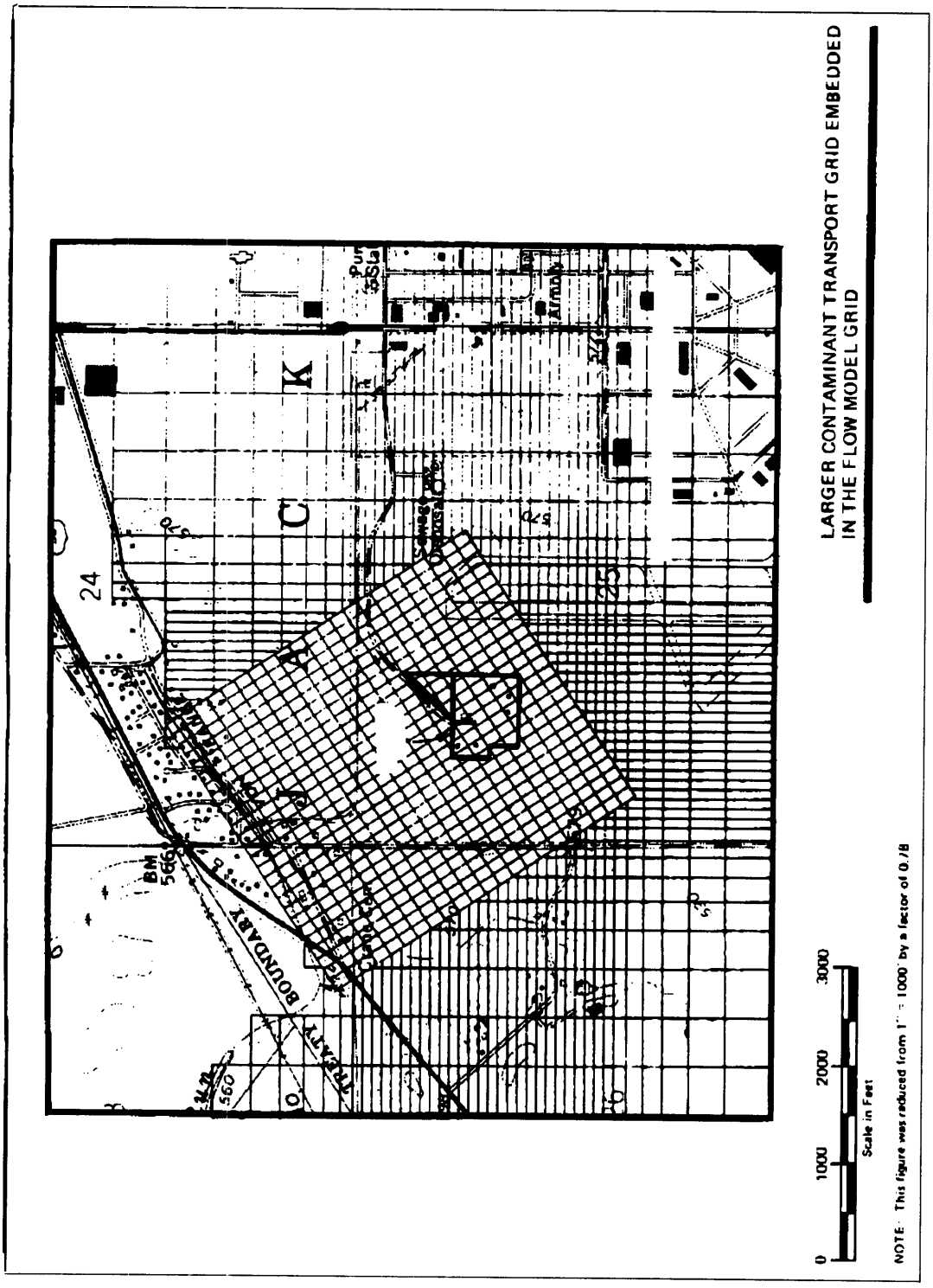
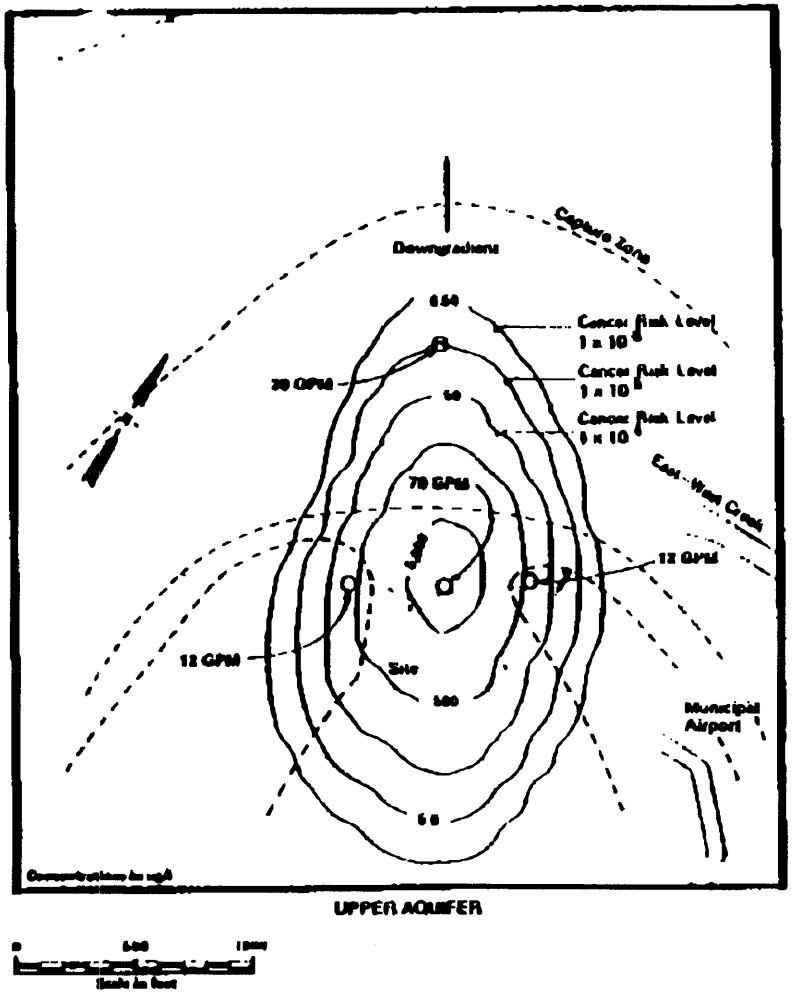


Figure 3.6-12

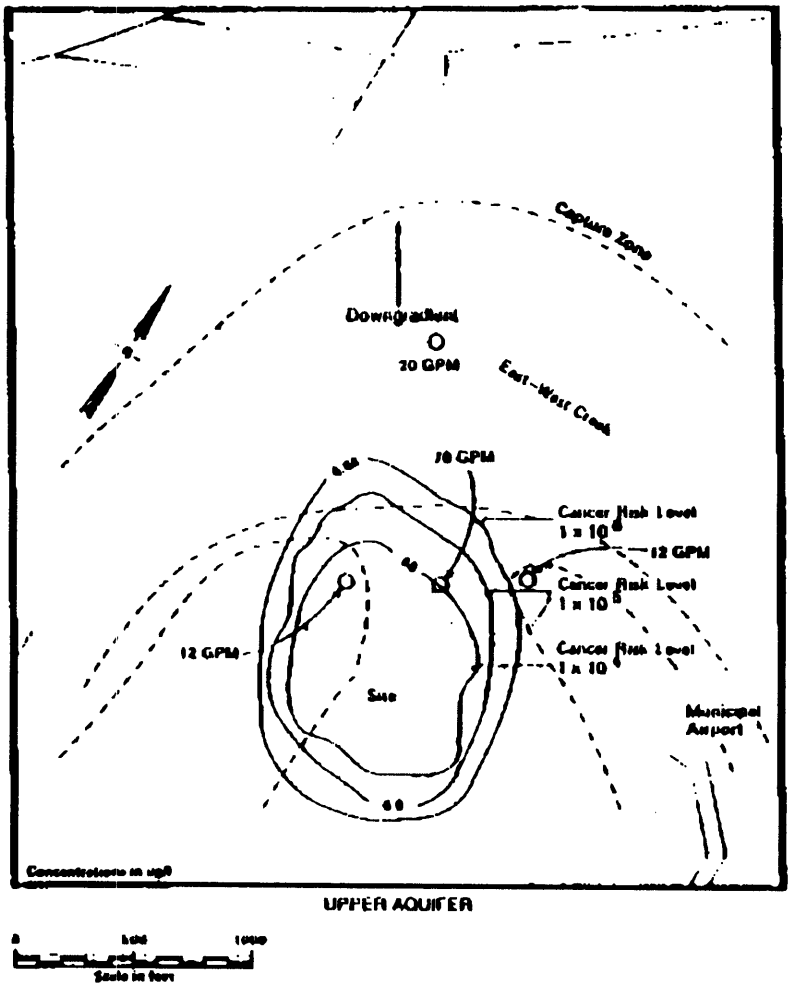
Predicted Location of 1,2-dichloroethane Plume




Predicted 1, 2-Dichloroethane Plume in
1989 and Well Configuration for Scheme 1

# Figure 3.6-13

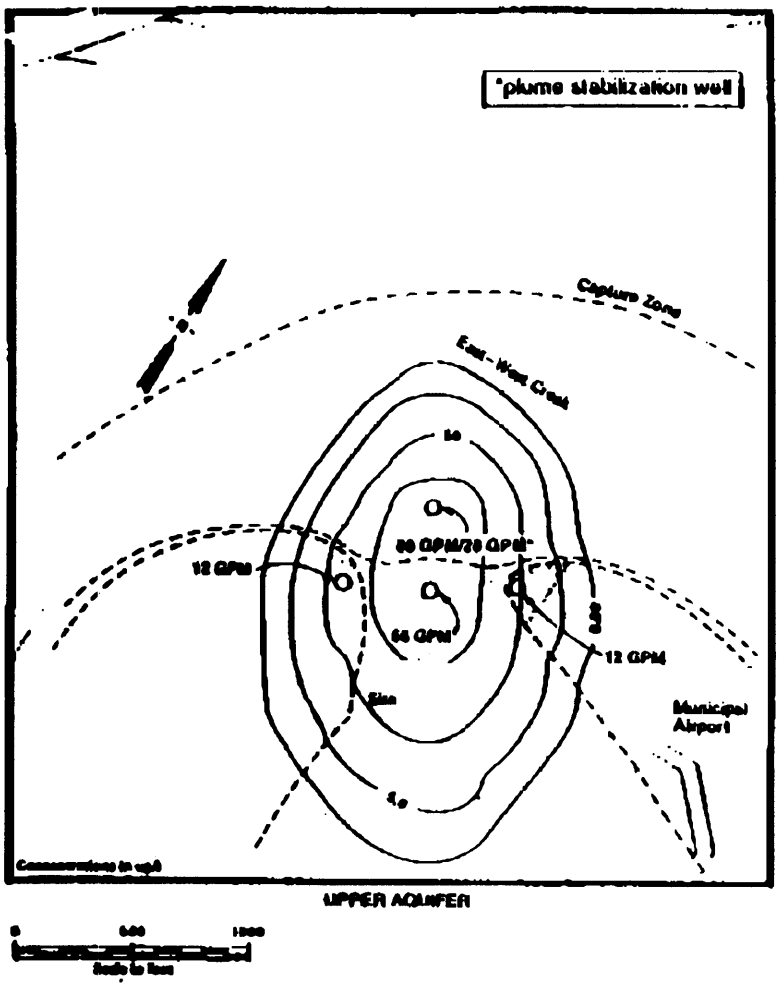
## Predicted Location of Tetrachloroethene Plume




Predicted Tetrachloroethene Plume in
1989 and Well Configuration for Scheme 1

Figure 3.6-14

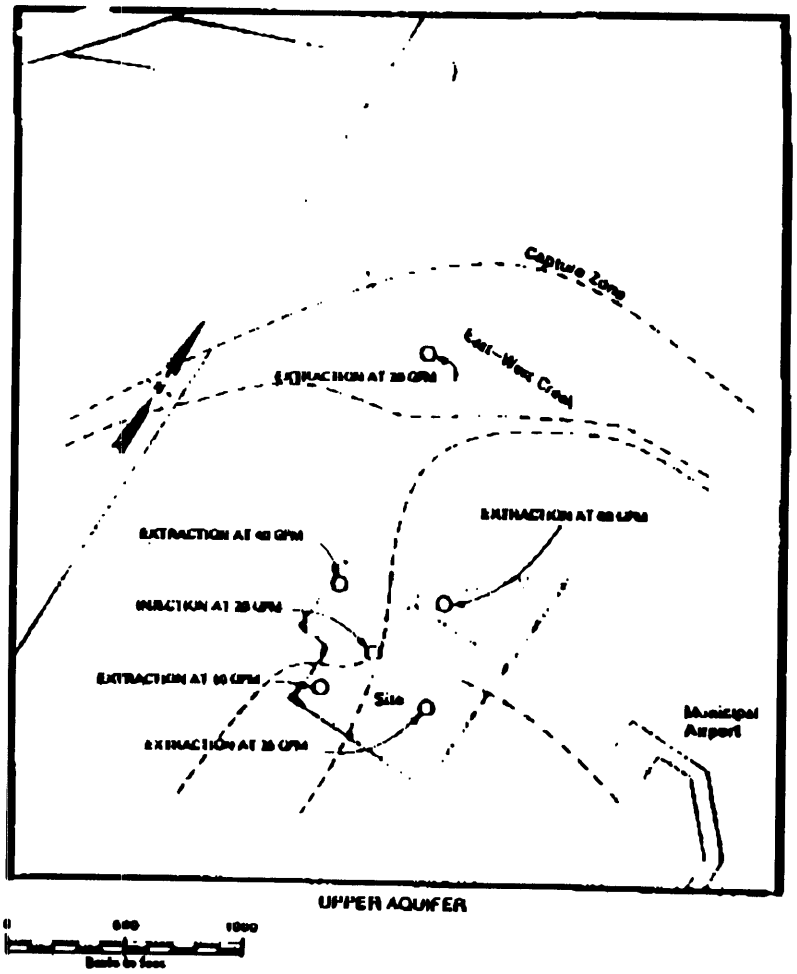
Location of All Wells and Predicted 1,2-dichloroethane Plume




Well Configuration for Scheme 2, and
Predicted 1, 2-Dichloroethane Plume in 1989
After Plume Stabilization

Figure 3.6-15

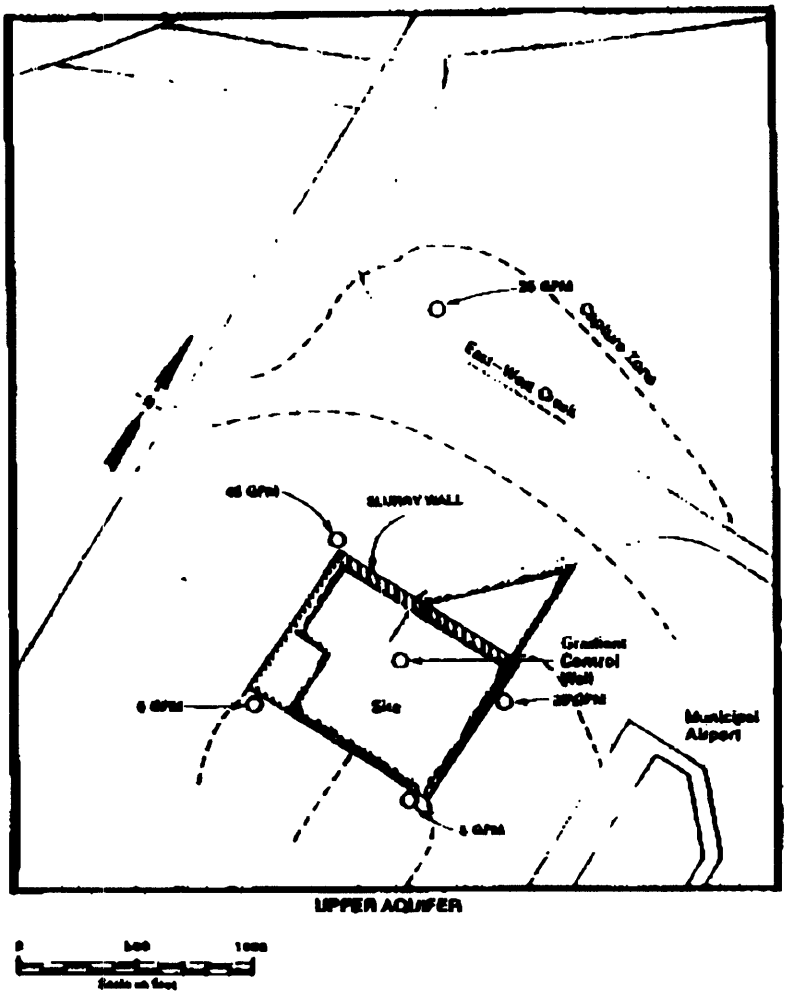
Hypothetical Placement of an Injection Well for Scheme 3




Well Configuration for Scheme 3

Figure 3.6-16

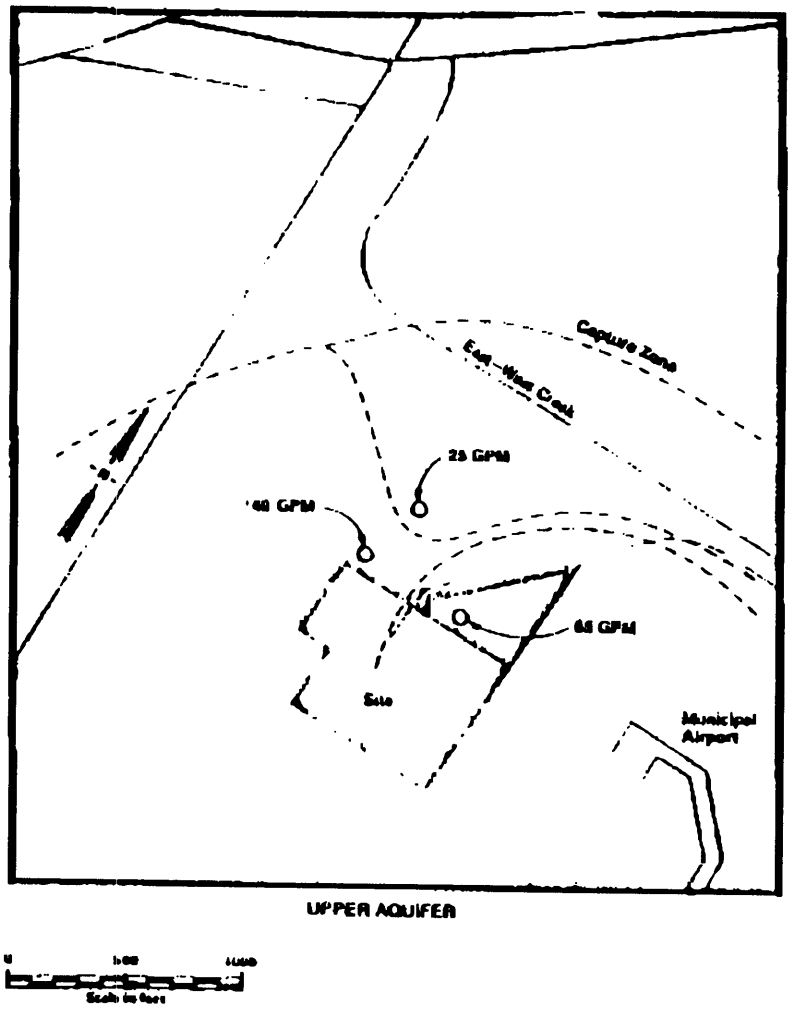
Slurry Wall Installation for Scheme 4




Well and Slurry Wall Configuration for
Scheme 4

Figure 3.6-17

Configuration of Off-Site Wells for Scheme 5




Well Configuration for Scheme 5

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# 4.0

# Model Descriptions

## Introduction

This section provides summary and detailed descriptions for eight groundwater models that were selected as the initial set of models to be considered as part of this pilot project. The eight models are:

- MOC
- MODFLOW
- PLASM
- RANDOM WALK
- AT123D
- MT3D
- MODPATH
- WHPA Modules
  - GPTRAC
  - MWCAP
  - RESSQC
  - MONTEC

While these models are generally well known and have been used often in EPA programs, the inclusion of them in the *Compendium* does not represent an endorsement of them by OSWER for any specific purpose. In the future, OSWER may develop guidelines for application of models under certain conditions or for specified types of analyses, and add other models to the *Compendium*. At this time, the descriptions are provided as general reference information only.

## Fact Sheets

The beginning of this section contains a two-sided Fact Sheet for each of the models and their modules. These were developed based on comments received from EPA Regional office staff, who identified a need to have quick access to some

overview of the models' characteristics, scope, and applicability, as well as the name of a contact for technical support and more information.

## Model Descriptions

The latter part of this section contains more detailed information on the same set of eight models. This information was extracted from a computerized database maintained by the International Ground Water Modeling Center (IGWMC) in Golden, Colorado. The information has been re-formatted, and in some cases, sub-sections have been re-numbered and re-ordered, but the information itself has been modified only slightly. IGWMC's database contains information on many more ground-water models. Using data that comes directly from the IGWMC database will maintain the integrity of the information, if for example, OSWER wishes to expand this portion of the *Compendium* in the future by taking larger extracts from the IGWMC database.

## Modeling Data Requirements

There is often confusion about how modeling data requirements are determined and the relationship between data requirements and the model (code). It is important to understand that the determination of a modeling application's general data requirements should precede the selection of a model. Furthermore, the determination of the type, quantity, and accuracy of the data required for the modeling application can be complex because it is dependent upon:

1. *Management's reasons for performing the modeling and the subsequent accuracy and level of detail required of the modeling results.* For example, a preliminary screening of alternative remedial technologies conducted as part of a remedial investigation and feasibility study can usually be modeled with less detail than a remedial design being modeled as part of the remedial design phase.

2. *The physical processes and the characteristics of the site being modeled.* For example, chemical fate and transport processes often require considerably more types of data than flow processes. Moreover, the quantity and the accuracy required of the data are often a function of the types of chemicals being modeled or the level of heterogeneity of the site.

3. *The engineering objectives of the modeling.* For example, the types and quantity of data required to determine the effectiveness of a deep hydraulic barrier design are often different from the data required to analyze a network of ground-water extraction wells.

Once the data requirements have been determined, a model can be selected which will support these data requirements and provide management with the

information they need to make informed decisions. Thus, the decision objectives, process and site characteristics, and engineering objectives are the factors which primarily determine a model application's data requirements and, in turn, govern the selection of a particular model.

To determine if a model will support an application's data requirements, the reader is referred to the model descriptions that follow and the model documentation that is usually available from the model's authors or the International Ground Water Modeling Center.

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**Model Type:** Solute Transport

# MOC
## ( USGS-2D-TRANSPORT, KONBRED)
## Version 3.0
## Release Date: 11/89

**Summary Updated** May 1994

MOC is a ground-water flow and mass transport model. It provides capabilities for two dimensional simulation of non-conservative solute transport in heterogeneous, anisotropic aquifers. It computes changes in time in the spatial concentration distribution caused by convective transport, hydrodynamic dispersions, mixing or dilution from recharge, and chemical reactions. The chemical reactions include first-order sorption irreversible rate reaction (e.g. radioactive decay), equilibrium-controlled sorption with linear, Freundlich or Langmuir isotherms, and monovalent and/or divalent ion-exchange reactions. MOC solves the finite difference approximation of the ground-water flow equation using iterative ADI and SIP. It uses the method of characteristics followed by an explicit procedure to solve the transport equation. MOC uses a subgrid of the flow grid for simulation of containment transport.

Note: A version of MOC called MOC Dense simulates two dimensional density dependent flow and transport in a crossectional plane. The specific characteristics of MOC Dense are not incorporated in this summary.

### *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| ○ | ● | ◐ | ◐ | ◐ | ◐ | ● | ○ | ◐ | ◐ | ○ | ○ | ◐ | ○ | ◐ | ◐ | ◐ | ◐ | ○ | ◐ | ○ | ◐ |

**Key**

- ● Likely
- ◐ Possibly
- ○ Not Likely
- Not Applicable N/A

### *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | | 2 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | ✓ | B | P | P | P | P |

**Key**

- Model: M
- Pre or Post Processor: P
- Both: B
- Neither: X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

| | | | | | |
|---|---|---|---|---|---|
| **Hardware Platforms:** | Prime<br>DEC VAX<br>IBM PC/XT/AT<br>IBM 80386/486<br>Apple Macintosh | **Preprocessors:** | PREMOC<br>MODELCAD | **Postprocessors:** | POSTMOC<br>MOCGRAF |

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium.*

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
(405) 436-8606

### *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

International Ground Water Modeling Center
Colorado School of Mines
Golden, CO 80401, USA
(303) 273-3103

U.S. Geological Survey
WRD WGS - Mail Stop 433
National Center
Reston, Virginia 22092

Scientific Software Group
P.O. Box 23041
Washington D.C. 20026-3041
(703) 620-9214

Geraghty & Miller, Inc.
Modeling Group
1895 Preston Drive, Suite 301
Reston, Virginia 22091
(703) 476-0335

**Model Type:** Saturated Flow

# MODFLOW

**Summary Updated:** May 1994

## Version 3.2
## Release Date: 10/89

MODFLOW is a modular, block-centered finite difference model for the simulation of two dimensional and quasi- or fully-three-dimensional, transient ground-water flow in anisotropic, heterogeneous, layered aquifer systems. It calculates piezometric head distributions, flow rates and water balances. The model includes modules of flow towards wells, through riverbeds, and into drains. Other modules handle evapotranspiration and recharge. Various textual and graphic pre-and postprocessors are available.

Note: Several particle tracking programs including ModPath utilize Modflow output to simulate contaminant transport. The specific characteristics of these particle tracking programs are not incorporated in this summary.

### *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| ○ | ● | ◐ | ● | ● | ● | ◐ | ◐ | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Key**

Likely ●

Possibly ◐

Not Likely ○

Not Applicable N/A

### *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| ✓ | | | ✓ | ✓ | ✓ | | ✓ | ✓ | 3 | ✓ | ✓ | | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | | | | | B | P | P | X | P |

**Key**

Model

M

Pre or Post Processor

P

Both

B

Neither

X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

**Hardware Platforms:** DEC VAX 11/780, IBM PC/XT/AT, PRIME 750, IBM 80386/486, Apple Macintosh, Intel 80386/80486

**Preprocessors:** PREMOD, MODELCAD

**Postprocessors:** POSTMOD

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium.*

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
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P.O. Box 1198
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(405) 436-8606

### *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

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# PLASM

## Version - Illinois State Water Survey

## Release Date: 1985

PLASM (Prickett Lonnquist Aquifer Simulation Model) is a finite difference model for simulation of transient, two-dimensional or quasi-three-dimensional flow in a single or multi-layered, heterogeneous, anistropic aquifer system. The original model of 1971 consisted of a series of separate programs for various combinations of simulation options. Later versions combined most of the options in a single code, including variable pumping rates, leaky confined aquifer conditions, induced infiltration from a shallow aquifer or a stream, storage coefficient conversion between confined and waterable conditions, and evapotranspiration as a function of depth to watertable. The model uses the iterative alternating implicit method (IADI) to solve the matrix equation.

### *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Solid Waste Disposal | | | | Liquid Waste Disposal | | | | | Leakage | | | | |
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| ○ | ● | ◐ | ● | ● | ◐ | ◐ | ◐ | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Key**

Likely ●

Possibly ◐

Not Likely ○

Not Applicable N/A

### *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| ✓ | | | ✓ | ✓ | ✓ | | ✓ | ✓ | 3 | ✓ | ✓ | | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| ✓ | ✓ | ✓ | | | | ✓ | | ✓ | | | | | M | X | X | X | X |

**Key**

Model

M

Pre or Post Processor

P

Both

B

Neither

X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

**Hardware Platforms:** DEC VAX, IBM PC/XT/AT, IBM 360, 370

**Preprocessors:** PREPLASM, MODELCAD

**Postprocessors:** None

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium.*

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
(405) 436-8606

### *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

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**Model Type:** Solute Transport

**Summary Updated:** May 1994

# RANDOM WALK

## Version - Illinois State Water Survey

## Release Date: 7/81

RANDOM WALK/TRANS is a numerical model to simulate two-dimensional steady or transient flow and transport problems in heterogeneous aquifers under water table and/or confined or leaky confined conditions. The flow is solved using a finite difference approach and the iterative alternating direction implicit method. The advective transport is solved with a particle-in-cell method, while the dispersion is analyzed with the random walk method.

Note: A number of other versions of Random Walk including analytical function driven versions are available. The specific characteristics of these other versions including output capababilities vary considerably.

### *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| ○ | ● | ◐ | ● | ● | ○ | ○ | ○ | ◐ | ○ | ○ | ○ | ○ | ○ | ◐ | ◐ | ◐ | ◖ | ○ | ◐ | ○ | ◐ |

**Key**

- Likely ●
- Possibly ◐
- Not Likely ○
- Not Applicable N/A

### *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| ✓ | ✓ | | ✓ | | ✓ | | ✓ | ✓ | 2 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | B | X | X | X | X |

**Key**

- Model: M
- Pre or Post Processor: P
- Both: B
- Neither: X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

**Hardware Platforms:** Cyber 175, VAX 11/780, IBM PC/XT/AT

**Preprocessors:** PREWALK, MODELCAD

**Postprocessors:** POSTWALK

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium*.

**Technical Assistance:**

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Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
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## *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

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(703) 476-0335

**Model Type:** Mass Transport

# AT123D

**Summary Updated:** May 1994

Version 1.1
Release Date: 5/92

AT123D is a generalized analytical transient, one- two-, and/or three-dimensional computer code developed for estimating the transport of chemicals in an isotropic, homogeneous, confined aquifer system with uniform flow. The model handles various source configurations (including point source, line source, and areal source) and release characteristics. The transport mechanisms include advection, longitudinal as well as horizontal and vertical transverse hydro–dynamic dispersion, diffusion, linear adsorption, and first-order decay/degeneration and chemical losses to the atmosphere. The model calculates concentration distribution in space and time using Green's function.

## *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Liquid Waste Disposal | | | | | Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ |

**Key**

Likely ●

Possibly ◐

Not Likely ○

Not Applicable N/A

## *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Uniform | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| | ✓ | ✓ | ✓ | | ✓ | | ✓ | | 1 | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | | ✓ | |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| | | | | ✓ | | | ✓ | | ✓ | | ✓ | | M | P | X | X | P |

**Key**

Model

M

Pre or Post Processor

P

Both

B

Neither

X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

| | | | | | |
|---|---|---|---|---|---|
| **Hardware Platforms:** | IBM PC/XT/AT<br>Other platforms with Fortran compiler | **Preprocessors:** | Part of some model package | **Postprocessors:** | Part of some model package |

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium*.

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
(405) 436-8606

### *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |

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University Park, PA 16802

**Model Type:** Mass Transport

# MT3D

**Summary Updated:** 10/29/93

## Version 1.8
## Release Date: October 1992

MT3D is a three-dimensional contaminant transport model using a hybrid method of characteristics. Two numerical techniques are provided for the solution of the advective-dispersive reactive solute transport equation: the method of characteristics (MOC) and the modified method of characteristics (MMOC). The MMOC method overcomes many of the traditional problems with MOC, especially in 3D simulations, by directly tracking nodal points backwards in time and by using interpolation techniques. MT3D selectively uses the MOC or the MMOC technique dependent on the problem at hand. The transport model is so structured that it can be used in conjunction with any block-centered finite difference flow model such as the USGS MODFLOW model.

### *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| ○ | ● | ◐ | ● | ● | ● | ◐ | ◐ | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |

**Key**

Likely ●

Possibly ◐

Not Likely ○

Not Applicable N/A

### *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | 3 | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | M | P | P | P | P |

**Key**

Model

M

Pre or Post Processor

P

Both

B

Neither

X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

| | | | | | |
|---|---|---|---|---|---|
| **Hardware Platforms:** | IBM PC or compatible | **Preprocessors:** | Part of model package | **Postprocessors:** | Part of model package |

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in section ? of the *Compendium*.

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
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P.O. Box 1198
Ada, OK 74820
(405) 332-8800

### *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

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Phone: 405/332-8800

**Model Type:** Particle Tracking

# MODPATH

**Summary Updated:** May 1994

## Version 1.2
## Release Date: 1990

MODPATH is a postprocessing package to compute three-dimensional pathlines based on the output from steady-state simulations obtained with the USGS MODFLOW ground-water flow model. The package consists of two FORTRAN 77 computer programs: 1) MODPATH, which calculates pathlines, and 2) MODPATH-PLOT, which presents results graphically. MODPATH uses a semi-analytical particle tracking scheme, based on the assumption that each directional velocity component varies linearly within a grid cell in its own coordinate direction. Data is input to MODPATH through a combination of files and interactive dialogue. The MODPATH-PLOT program comes in two versions, one for use with the DISSPLA graphics routines library, and one that uses the Graphical Kernel System (GKS).

### *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| ○ | ● | ◐ | ● | ● | ● | ◐ | ◐ | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Key**

Likely ●

Possibly ◐

Not Likely ○

Not Applicable N/A

### *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | 3 | ✓ | | ✓ | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| ✓ | ✓ | ✓ | | | | | ✓ | | | | ✓ | | M | X | B | B | P |

**Key**

Model
M

Pre or Post Processor
P

Both
B

Neither
X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

**Hardware Platforms:** Prime, IBM PC/386/486

**Preprocessors:** MPATHIN EM (Techsoft, Inc.), Model CAD (Geraghty & Miller)

**Postprocessors:** None

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium.*

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
(405) 436-8606

### *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |

**Distributed By:**

International Ground Water Modeling Center
Colorado School of Mines
Golden, CO 80401, USA

Scientific Software Group
P.O. Box 23041
Washington, D.C. 20026-3041
Tel. (703) 620-9214

Geraghty & Miller, Inc.
Modeling Group
10700 Park Ridge Blvd., Suite 600
Reston, VA 22091
Tel. (703) 758-1200

**Model Type:** Ground-water Flow

# WHPA - GPTRAC

**Summary Updated:** May 1994

Version 2.2
Release Date: 9/93

WHPA-GPTRAC is the WHPA module used to delineate time-related capture zones for pumping wells in homogeneous aquifers with steady & uniform ambient ground-water flow (semi-analytical option) and also delineates time-related capture zones about pumping wells for steady ground-water flow fields (numerical option). Effects of well interference are accounted for. WHPA is an integrated program of analytical and semi-analytical solutions for the ground-water flow equation coupled with pathline tracking. It is designed to assist technical staff with delineation of wellhead protection areas. Developed for the U.S. EPA's Office of Groundwater Protection, the package includes modules for capture zone delineation in a homogeneous aquifer with 2-dimensional steady-state flow options for multiple pumping/injection wells and barrier or stream boundary conditions.

## *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| N/A | ● | ○ | ◐ | ◐ | ◐ | ◐ | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Key**

Likely ●

Possibly ◐

Not Likely ○

Not Applicable N/A

## *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| ✓ | | | ✓ | | ✓ | | ✓ | ✓ | 2 | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| ✓ | ✓ | ✓ | | | | | | | | | | | M | X | M | M | M |

**Key**

Model
M

Pre or Post Processor
P

Both
B

Neither
X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

**Hardware Platforms:** IBM PC/AT

**Preprocessors:** Menu Driven

**Postprocessors:** Display Results

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium.*

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
(405) 436-8606

### *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

International Ground Water Modeling Center
Colorado School of Mines
Golden, CO 80401
USA

Center for Subsurface Modeling Support
R. S. Kerr Environmental Research Laboratory
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
Phone: (405) 436-8500

**Model Type:** Ground-water Flow

# WHPA - MWCAP

**Summary Updated:** May 1994

Version 2.1
Release Date: 4/92

WHPA-MWCAP is the WHPA module used to delineate steady-state, time-related or hybrid capture zones for pumping wells in homogenous aquifers with steady and uniform ambient ground-water flow. If multiple wells are examined, the effects of well interference are ignored. WHPA is an integrated program of analytical and semi-analytical solutions for the ground-water flow equation coupled with pathline tracking. It is designed to assist technical staff with delineation of wellhead protection areas. Developed for the U.S. EPA's Office of Groundwater Protection, the package includes modules for capture zone delineation in a homogeneous aquifer with 2-dimensional steady-state flow with options for multiple pumping/injection wells and barrier or stream boundary conditions.

## *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| N/A | ● | ○ | ◐ | ◐ | ◐ | ◐ | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Key**

- Likely ●
- Possibly ◐
- Not Likely ○
- Not Applicable N/A

## *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| ✓ | | | ✓ | | ✓ | | ✓ | ✓ | 2 | ✓ | | ✓ | | | | | ✓ | | | ✓ | | ✓ | |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| | ✓ | | | | | | | | | | | | M | X | M | M | M |

**Key**

- Model M
- Pre or Post Processor P
- Both B
- Neither X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

**Hardware Platforms:** IBM PC/AT

**Preprocessors:** Menu Driven

**Postprocessors:** Display Results
Dot Matrix
Laser Printers
Pen Plotters

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium.*

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
(405) 436-8606

## *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

International Ground Water Modeling Center
Colorado School of Mines
Golden, CO 80401
USA

Center for Subsurface Modeling Support
R. S. Kerr Environmental Research Laboratory
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
Phone: (405) 436-8500

**Model Type:** Ground-water Flow

# WHPA - RESSQC

**Summary Updated:** May 1994

## Version 2.1
## Release Date: 4/92

WHPA-RESSQC is the WHPA module used to delineate time-related capture zones around pumping wells, or contaminant fronts around injection wells, for multiple pumping and injection wells in homogeneous aquifers of infinite areal extent with steady and uniform ambient ground-water flow. Well interference effects are accounted for. WHPA is an integrated program of analytical and semi-analytical solutions for the ground-water flow equation coupled with pathline tracking. It is designed to assist technical staff with delineation of wellhead protection areas. Developed for the U.S. EPA's Office of Groundwater Protection, the package includes modules for capture zone delineation in a homogeneous aquifer with 2-dimensional steady-state flow with options for multiple pumping/injection wells and barrier or stream boundary conditions.

### *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| N/A | ● | ○ | ◐ | ◐ | ◐ | ◐ | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Key**

Likely ●

Possibly ◐

Not Likely ○

Not Applicable N/A

### *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Analytic | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| ✓ | | | ✓ | | ✓ | | ✓ | ✓ | 2 | ✓ | | ✓ | | | | | ✓ | | | ✓ | | ✓ | |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| | ✓ | | | | | | | | | | | | M | N | M | M | M |

**Key**

Model

M

Pre or Post Processor

P

Both

B

Neither

X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

**Hardware Platforms:** IBM PC/AT

**Preprocessors:** Menu Driven

**Postprocessors:** Display Results
Dot Matrix
Laser Printers
Pen Plotters

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium.*

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
(405) 436-8606

## *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

International Ground Water Modeling Center
Colorado School of Mines
Golden, CO 80401
USA

Center for Subsurface Modeling Support
R. S. Kerr Environmental Research Laboratory
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
Phone: (405) 436-8500

**Model Type:** Ground-water Flow

# WHPA - MONTEC

**Summary Updated:** May 1994

Version 2.1
Release Date: 4/92

WHPA-MONTEC is the WHPA module for Monte Carlo analysis of uncertainty and a particle-tracking postprocessor for numerical flow models such as MODFLOW and PLASM, using a two-dimensional rectangular grid. WHPA is an integrated program of analytical and semi-analytical solutions for the ground-water flow equation coupled with pathline tracking. It is designed to assist technical staff with delineation of wellhead protection areas. Developed for the U.S. EPA's Office of Groundwater Protection, the package includes modules for capture zone delineation in a homogeneous aquifer with 2-dimensional steady-state flow with options for multiple pumping/injection wells and barrier or stream boundary conditions.

## *Scope*

| Remedial Design Feature | | | | | | | | Contaminant Source Type: Solid Waste Disposal | | | | Contaminant Source Type: Liquid Waste Disposal | | | | | Contaminant Source Type: Leakage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capping, Grinding & Revegetation | Groundwater Pumping | Wastewater Injection | Interceptor Trenches | Impermeable Barriers | Subsurface Draining | Solution Mining | Excavation | Uncontrolled Dumps | Sani. & Secured Landfills | Deep Subsurface Burial | Leachate | Wastewater Impound. | Deep Subsurface Injection | Land Spraying | Discharge To Surf. Water | Ind. Sewage Disposal | Surface Storage Facilities | Subsurface Storage Faci. | Subsurface Transport Sys. | Subsurface Disposal Faci. | Surface Spills |
| N/A | ● | ○ | ◐ | ◐ | ◐ | ◐ | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

**Key**

- Likely ●
- Possibly ◐
- Not Likely ○
- Not Applicable N/A

## *Technical Characteristics*

| Model Processes | | | Flow System | | | | Aquifer Type | | Flow Characteristics (Saturated) | | | Transport Processes | | | Fate & Transfer Processes | | Flow Solution Technique | | | Parameter Representation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flow | Transport | Transfer | Single Aquifer | Multiple Aquifer | Saturated Zone | Unsaturated Zone | Confined | Unconfined | Dimension | Steady State | Transient | Advection | Diffusion | Dispersion | Fate | Transfer | Statistical | Finite Difference | Finite Element | Homogeneous | Heterogeneous | Isotropic | Anisotropic |
| ✓ | | | ✓ | | ✓ | | ✓ | | 2 | ✓ | | ✓ | | | | | ✓ | | | ✓ | | ✓ | |

| Flow Boundary Conditions | | | Transport Boundary Conditions | | | Flow Output | | | Transport Output | | | | Output Format | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specified Value | Specified Flux | Value Dependent Flux | Specified Value | Specified Flux | Value Dependent Flux | Head/Pressure/Potential | Fluxes/Velocities | Water Budget | Conc. in Aquifer/Soil | Concentrations in Well | Velocities | Mass Balance | ASCII File | Contours | Flow Lines | Particle Paths | Plots |
| | ✓ | ✓ | | | | | | | | | | | M | X | M | M | M |

**Key**

- Model: M
- Pre or Post Processor: P
- Both: B
- Neither: X

## *Definitions*

**Boundary Conditions:**

**Specified Value** - Values of head, concentration or temperature are specified along the boundary. (Dirichlet Condition)

**Specified Flux** - Flow rate of water, contaminent mass or energy is specified along the boundary. (Neumann Condition)

**Value Dependent Flux** - A specified flux is given for a specified value. (Cauchy Condition)

**Hardware Platforms:** IBM PC/AT

**Preprocessors:** Menu Driven

**Postprocessors:** Display Results, Dot Matrix, Laser Printers, Pen Plotters

Detailed information on this model, sources of distribution, and postprocessors and preprocessors is available in the *Ground-Water Modeling Compendium.*

**Technical Assistance:**

Dr. David S. Burden, Director
Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory (RSKERL)
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
(405) 436-8606

### *Availability*

| Usability | | | | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|
| Public Domain | Documentation | User Support | Preprocessors | Postprocessors | Mult. Hardware Platforms | Verification | Peer Review | Previous EPA Use | Case Studies |
| ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |

**Distributed By:**

International Ground Water Modeling Center
Colorado School of Mines
Golden, CO 80401
USA

Center for Subsurface Modeling Support
R. S. Kerr Environmental Research Laboratory
U.S. Environmental Protection Agency
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Ada, OK 74820
Phone: (405) 436-8500

# Model Description For

# MOC
# (USGS-2D-TRANSPORT/KONBRED)

**SOURCE:**
**INTERNATIONAL GROUND WATER MODELING CENTER (IGWMC)**

# MOC
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# MOC

## 1. Model Identification

1.1. Model Name(s)
- USGS-2D-TRANSPORT
- MOC
- KONBRED

1.2. Date of First Release
- 11/76

1.3. Current Version
- 3.0

1.4. Current Release Date
- 11/89

1.5. Author
- 1. Konikow, L.F.
- 2. Bredehoeft, J.D.

## 2. Model Information

2.1. Model Category
- ground-water flow
- mass transport

2.2. Model Developed For
- general use (e.g. in field applications)

2.3. Units of Measurement Used
- SI system
- metric units
- US customary units
- any consistent system

2.4. Abstract

MOC is a two-dimensional model for the simulation of non-conservative solute transport in heterogeneous, anisotropic aquifers. It computes changes in time in the spatial concentration distribution caused by convective transport, hydrodynamic dispersion, mixing or dilution from recharge, and chemical reactions. The chemical reactions include first-order irreversible rate reaction (e.g. radioactive decay), equilibrium-controlled sorption with linear, Freundlich or Langmuir isotherms, and monovalent and/or divalent ion-exchange reactions. MOC solves the finite difference approximation of

the ground-water flow equation using iterative ADI and SIP. It uses the method of characteristics followed by an explicit procedure to solve the transport equation.

2.5. Data Input Requirements:

Data input requirements are provided in the model documentation and are discussed in the introduction to Section 4.0 of the *Compendium*.

2.6. Versions Exist For The Following Computer Systems

- minicomputer
- workstations
- mainframe
- microcomputer

- Make/Model
  - -- Prime
  - -- DEC VAX
  - -- IBM PC/XT/AT
    - - operating system
      MS DOS
  - -- IBM 80386/486
    - - operating system
      MS DOS
      OS/2
      Unix
  - -- Apple Macintosh

2.7. System Requirements

- core memory (RAM) for execution (bytes)
  - -- 640Kb (standard IBM PC version)
- mass storage (disk space in bytes)
  - -- at least 2Mb for data files
- numeric/math coprocessor
  - -- (for micro computers)
- compiler required
  - -- (for mainframe)

2.8. Graphics Requirements

- none

2.9. Program Information

- programming language/level
  - -- Fortran 77
- number of program statements (total)
  - -- 2000

## 3. General Model Capabilities

3.1. Parameter Discretization
- distributed

3.2. Coupling
- none

3.3. Spatial Orientation
- saturated flow
- 2D-horizontal
- 2D-vertical

3.4. Types of Possible Updates
- parameter values
- boundary conditions

3.5. Geostatistics and Stochastic Approach
- none

3.6. Comments
- This model has restart capability

## 4. Flow Characteristics

4.1. Flow System Characterization
- Saturated Zone

- System
  -- single aquifer

- Aquifer Type(s)
  -- confined
  -- semi-confined (leaky-confined)

- Medium
  -- porous media

- Parameter Representation
  -- homogeneous
  -- heterogeneous
  -- isotropic
  -- anisotropic

- Flow Characteristics (Saturated Zone)
  -- laminar flow
  -- linear (Darcian flow)

-- steady-state
-- transient

- Flow Processes Included
  -- areal recharge
  -- induced recharge (from river)

- Changing aquifer conditions
  -- in space
  -- variable thickness

- Well Characteristics
  -- none

- Unsaturated Zone
  -- none

4.2. Fluid Conditions

- Single Fluid Flow
  -- water

- Flow of Multiple Fluids
  -- none

- Fluid Properties
  -- constant in time/space

4.3. Boundary Conditions

- First Type - Dirichlet
  -- head/pressure

- Second type - Neumann (Prescribed Flux)
  -- injection/production wells
  -- no flow boundary
  -- areal boundary flux
  -- ground-water recharge

- Third Type - Cauchy
  -- head/pressure-dependent flux

4.4. Solution Methods for Flow

- General Method
  -- Numerical

- Spatial Approximation
  - -- finite difference method
  - -- block-centered

- Time-Stepping Scheme
  - -- Crank-Nicholson

- Matrix-Solving Technique
  - -- SIP
  - -- iterative ADIP

4.5. Grid Design

- Cell/Element Characteristic
  - -- constant cell size
  - -- variable cell size

- Possible Cell Shapes
  - -- 2D-square
  - -- 2D-rectangular

- Maximum Number of Nodes
  - -- 2000

4.6. Flow Output Characteristics

- Simulation Results
  - -- Head/Pressure/Potential
    - - ASCII file (areal values)
    - - ASCII file (hydrograph)

- Water Budget Components
  - -- ASCII file (global total area)

## 5. Mass Transport Characteristics

5.1. Water Quality Constituents

- any component(s)
- single component
- total dissolved solids (TDS)
- inorganics
- organics
- radionuclides

5.2. Processes Included

- (Conservative) Transport
  - -- advection
  - -- dispersion (isotropic; anisotropic)
  - -- diffusion

- Phase Transfers
  - -- Solid <-> Liquid
    - sorption equilibrium isotherm
    - linear
    - Langmuir
    - Freundlich

- Fate
  - -- first-order radioactive decay (single mother/daughter decay)
  - -- first-order chemical decay
  - -- first-order microbial decay

5.3. Boundary Conditions

- First Type - Dirichlet
  - -- Chemical processes embedded in transport equation
  - -- concentration

- Second Type - Neumann (Prescribed Solute Flux)
  - -- areal boundaries
  - -- injection wells
  - -- point sources
  - -- line sources
  - -- areal sources

5.4. Solution Methods for Transport

- General Method
  - -- numerical
  - -- uncoupled flow and transport equation

- Spatial Approximation
  - -- finite difference method
  - -- block-centered
  - -- particle-tracking

- Time-Stepping Scheme
  - -- fully explicit

- Matrix-solving Technique
  - -- method of characteristics

5.5. Output Characteristics for Transport

- Simulation Results
  - -- Concentration in Aquifer/Soil
    - ASCII file (areal values)
    - ASCII file (time series)

- Mass Balance Components
  -- ASCII file (global total area)

## 6. Evaluation

6.1. Verification/Validation
- verification (analytic solutions)
- laboratory data sets
- field datasets (validation)
- synthetic datasets
- code intercomparison

6.2. Internal Code Documentation (Comment Statements)
- incidental

6.3. Peer (Independent) Review
- concepts
- theory (math)
- coding
- accuracy

## 7. Documentation and Support

7.1. Documentation Includes
- model theory
- user's instructions
- example problems
- code listing

7.2. Support Needs
- Can be used without support
- Support is available
  -- from author
  -- from third parties

7.3. Level of Support
- limited
- support agreement available

## 8. Availability

8.1. Terms
- available
- public domain
- proprietary

8.2. Form
- source code only (tape/disk)
- source and compiled code
- compiled code only

## 9. Pre and Post Processors

9.1. Data Preprocessing
- name: PREMOC
  - -- separate (optional) program
  - -- generic (can be used for various models)
  - -- textual data entry/editing

- name: MODELCAD
  - -- separate (optional) program
  - -- generic (can be used for various models)
  - -- textual data entry/editing
  - -- graphic data entry/modification (e.g manual grid design, arrays)
  - -- data reformatting (e.g. for GIS)
  - -- error-checking
  - -- help screens

9.2. Data Postprocessing
- name: POSTMOC
- separate (optional) program
- reformatting (e.g. to standard formats)

## 10. Institution of Model Development

10.1. Name
- U.S. Geological Survey

10.2. Address
- National Center
  Reston, Virginia

10.3. Type of Institution
- federal/national government

## 11. Remarks

The MOC package distributed by the International Ground Water Modeling Center includes a preprocessor (PREMOC) to prepare input files, a postprocessor (POSTMOC) to reformat parts of the output file to allow the import the results in graphic display programs, and two versions of the MOC simulation program, MOCADI and MOCSIP. MOCADI and MOCSIP are identical apart from the methods used to solve the finite difference flow equations. The IGWMC distributes both IBM-PC and mainframe versions.

Contact the International Ground Water Modeling Center for latest information:

IGWMC USA: Inst. for Ground-Water Res. and Educ.,
Colorado School of Mines,
Golden, CO 80401, USA.

IGWMC Europe: TNO Institute of Applied Geoscience,
P.O. Box 6012, 2600JA Delft,
The Netherlands.

IBM-PC, Macintosh and mainframe versions of the MOC code are also available from:

Scientific Software Group
P.O. Box 23041
Washington, D.C. 20026-3041
(703) 620-9214

MOCGRAF is a program developed by TECSOFT, Inc. to provide graphics capability to MOC. It uses the output from MOC to contour heads and concentrations and to plot velocity vectors. It supports a variety of graphic screen formats, printers and plotters. MOCGRAF requires TECSOFT's TRANSLATE program. MOCGRAF is available from Scientific Software Group

MACMOC is the implementation of the USGS Method of Characteristics Solute Transport Model (MOC) for the Apple Macintosh. The data input editor, simulation code and output postprocessor are integrated in a single application. Graphic output includes head and concentration contouring, and velocity vector plotting. It requires a Macintosh Plus with System 6.02 and Finder 6.1 or higher and at least 2Mb RAM. MACMOC is available from the Scientific Software Group.

Notes on computer program updates have been published by the USGS, Reston, Virginia, on the following dates:

| | | |
|---|---|---|
| 1. May 16, 1979 | 7. Jul. 26, 1985 | 13. Oct. 20, 1986 |
| 2. Mar. 26, 1980 | 8. Jul. 31, 1985 | 14. Mar. 2, 1987 |
| 3. Dec. 4, 1980 | 9. Aug. 2, 1985 | 15. Mar. 5, 1987 |
| 4. Aug. 26, 1981 | 10. Aug. 8, 1985 | 16. Jan. 29, 1988 |
| 5. Oct. 12, 1983 | 11. Aug. 12, 1985 | 17. Nov. 21, 1988 |
| 6. Jun. 10, 1985 | 12. Jul. 2, 1986 | 18. Jul. 20, 1989 |

A modification of this model to track representative water of tracer particles initially loaded along specific lines has been developed by Garabedian and Konikow (1983):

TRACK (see IGWMC key # 0741).

The code has been modified by Hutchinson to allow head-dependent flux as a boundary condition:

Hutchinson, C.B. et al. 1981. Hydrogeology of Well-field Areas near Tampa, Florida. USGS Open-File Report 81-630.

A modification to allow linear and non-linear sorption isotherms and first-order decay was introduced in 1982:

Tracy, J.V. 1982. Users Guide and Documentation for Adsorption and Decay Modifications of the USGS Solute Transport Model. NUREG/CR-2502, Div. of Waste Management, Off. of Nuclear Material Safety and Safeguard, U.S. Nuclear Regulatory Comm., Washington, D.C.

MODELCAD is a graphical oriented, model-independent preprocessor to prepare and edit input files for two- and three-dimensional ground-water models, including aquifer properties, boundary conditions, and grid dimensions. The program prepares input files for MODFLOW, MOC, PLASM and RANDOM WALK, among others. File formatting routines for other models are available upon request. Contact:

Geraghty & Miller Modeling Group
1895 Preston White Drive
Suite 301, Reston, VA 22091
(703) 476-0335

Strecker,E.W., W-S. Chu, and D. P. Lettenmaier. 1985. Evaluation of Data Requirements for Groundwater Contaminant Transport Modeling. Water Resources Series, Techn. Rept. 94, Univ. of Washington, Seattle, Wash.

In this study a parameter identification algorithm was used together with the USGS-MOC code and applied to two synthetic aquifers, evaluating the effects of data availability and uncertainty on ground-water contaminant transport prediction. The parameter identification algorithm is based on constrained least-squares minimization.

Also:

Strecker, E.W., and W-s. Chu. 1986. Parameter Identification of a Ground-Water Contaminant Transport Model. Ground Water, Vol. 24(1), pp. 56-62.

A modified version of the 1978 version of the USGS MOC model has been presented by Kent et Al. (1983; see references). Modifications include water-table option for flow and non-linear sorption. The same authors developed a menu-driven, preprocessor for their version of MOC. For more information contact Dr. Douglas C. Kent, School of Geol., Oklahoma State University, Stillwater, Oklahoma.

A stochastics-based analysis of the performance of the MOC model in remedial action simulations is discussed in:

El-Kadi, A.I. 1988. Applying the USGS Mass-Transport Model (MOC) to Remedial Actions by Recovery Wells. Ground Water, Vol. 26(3), pp. 281-288.

An IBM PC/386 extended memory version of this model is also available from:

Geraghty & Miller, Inc.
Modeling Group
1895 Preston Drive, Suite 301
Reston, VA 22091
tel.: 703/476-0335
fax: 703/476-6372

## 12. References

Pinder, G.F. and H.H. Cooper. 1970. A Numerical Technique for Calculating the Transient Position of the Saltwater Front. Water Resources Research, Vol. 6(3), pp. 875-882.

Bredehoeft, J.D., and G.F. Pinder. 1973. Mass Transport in Flowing Groundwater. Water Resources Research, Vol. 9(1), pp. 194-210.

Konikow, L.F., and J.D. Bredehoeft. 1974. Modeling Flow and Chemical Quality Changes in an Irrigated Stream-Aquifer System. Water Resources Research, Vol. 10(3), pp. 546-562.

Konikow, L.F., and J.D. Bredehoeft. 1978. Computer Model of Two-Dimensional Transport and Dispersion in Ground Water. USGS Techniques of Water Resources Investigations, Book 7, Chapter 2, U.S. Geological Survey, Reston, Virginia.

Kent, D.C., J. Alexander, L. LeMaster, and J. Wagner. 1983. Interactive Preprocessor Program for the U.S.G.S. Konikow Solute Transport Model. Oklahoma State University, School of Geology, Stillwater, Oklahoma.

Kent, D.C., M.M. Hoque, L. LeMaster, and J. Wagner. 1983. Modifications to the U.S.G.S. Solute Transport Model. School of Geology, Oklahoma State University, Stillwater, Oklahoma.

Goode, D.J., and L.F. Konikow. 1989. Modification of a Method-of-Characteristics Solute Transport Model to Incorporate Decay and Equilibrium-Controlled Sorption or Ion Exchange. USGS Water Resources Investigations Report 89-4030, U.S. Geological Survey, Reston, Virginia.

## 13. Users

Spinazola, J.M., J.B. Gillespie, and R.J. Hart. Ground-Water Flow and Solute Transport in the Equus Beds Area, South Central Kansas, 1940-79. Water-Resources Investig. Rept. 85-4336, Lawrence, Kansas.

The transport model was used to study the movement of chloride in the past and under the various proposed pumping development schemes. The sources of the chloride is oilfield brine moving towards the wellfields and the Arkansas river.

Robertson, J.B. 1974. Digital Modeling of Radioactive and Chemical Waste Transport in the Snake River Plain Aquifer at the National Reactor Testing Station, Idaho. USGS Open-File Report IDO-22054. U.S. Geological Survey, Boise, Idaho.

Konikow, L.F. 1977. Modeling Chloride Movement in the Alluvial Aquifer at the Rocky Mountain Arsenal, Colorado. USGS Water Supply Paper 2044, U.S. Geological Survey, Denver, Colorado.

Sohrabi, T. 1980. Digital Transport Model Study of Potential Nitrate Contamination from Sceptic Tank Systems near Edmond, Oklahoma. Rept. 80-38, National Center for Ground Water Research, University of Oklahoma, Norman, Okla.

Sophocleous, M.A. 1984. Groundwater Flow Parameter Estimation and Quality Modeling of the Equus Beds Aquifer in Kansas, USA. Journ. of Hydrology, Vol. 69, pp. 197-222.

In an accompanying Technical Completion Report of the Kansas Water Resources Research Institute at the University of Kansas, Lawrence, Sohocleous et al. compares the MOC code with Pinder's ISOQUAD-4 code and Grove's finite difference solute transport code.

Freeberg, K.M. 1985. Ground Water Contaminant Modeling Applied to Plume Delineation and Aquifer Restoration at an Industrial Site. M.Sc. Thesis, Dept. of Env. Sciences and Eng., Rice Univ., Houston, Texas.

Groschen, G.E. 1985. Simulated Effects of Projected Pumping on the Availability of Fresh Water in the Evangeline Aquifer in an Area Southwest of Corpus Christi, Texas. USGS Water Resources Investigations Report 85-4182, Austin, Texas.

Chapelle, F.H. 1986. A Solute Transport Simulation of Brackish Water Intrusion near Baltimore, Maryland. Ground Water, Vol. 24(3), pp 304-311.

The model was used to estimate the future movement of the brackish-water plume in the coarse sands and gravels of the Patuxent Formation based on

alternative strategies of aquifer use. (see also Maryland Geological Survey Report of Investig. 43 (1986)).

Davis, A.D. 1986. Deterministic Modeling of Dispersion in Heterogeneous Permeable Media. Ground Water, Vol. 24(5), pp. 609-615.

Perez, R. 1986. Potential for Updip Movement of Saline Water in the Edwards Aquifer, San Antonio, Texas. USGS Water Resources Investigations Report 86-4032, U.S. Geological Survey, Austin, Texas.

Bond, L.D., and J.D. Bredehoeft. 1987. Origins of Seawater Intrusion in a Coastal Aquifer--A Case Study of the Pajaro Valley, California. Journ. of Hydrology, Vol. 92, pp.363-388.

Mixon, F.O., A.S. Damle, R.S. Truesdale, and C.C. Allen. 1987. Effect of Capillarity and Soil Structure on Flow in Low permability Saturated Soils at Disposal Facilities. EPA/600/2-87/029, Hazardous Waste Eng. Research Lab., U.S. Environmental Protection Agency, Cincinnati, Ohio.

Patterson, C-V. 1987. Risk Analysis of Annular Disposal of Oil and Gas Well Brines. M.Sc. Thesis, Dept. of Systems Eng., Case Western Reserve University, Cleveland, Ohio.

Al-Layla, R., H. Yazicigil, and R. de Jong. 1988. Numerical Modeling of Solute Transport Patterns in the Damman Aquifer. Water Resources Bulletin, Vol. 24(1), pp. 77-85.

Used to predict the extent of the saline intrusion in this carbonate rock aquifer in the Kingdom of Saudi Arabia and studying the effects of changes in the hydrologic regime on TDS concentration. The model was modified to include the effects of salt gradients resulting from vertical leakage into the host aquifer.

Satkin, R.L., and P.b. Bedient. 1988. Effectiveness of Various Aquifer Restoration Schemes under Variable Hydrogeologic Conditions. Ground Water, Vol. 26(4), pp. 488-498.

Yager, R.M. and M.P. Bergeron. 1988. Nitrogen Transport in a Shallow Outwash Aquifer at Olean, Cattaraugus County, New York. Water-Resources Investigations Report 87-4043, U.S. Geological Survey, Ithaca, New York.

# Model Description For

# MODFLOW

**SOURCE:**
**INTERNATIONAL GROUND WATER MODELING CENTER (IGWMC)**

# MODFLOW
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# MODFLOW

## 1. Model Identification

1.1. Model Name(s)
- MODFLOW

1.2. Date of First Release
- 6/83

1.3. Current Version #
- 3.2

1.4. Current Release Date
- 10/89

1.5. Authors
- 1. McDonald, M.G.
- 2. Harbaugh, A.W.

## 2. Model Information

2.1. Model Category
- ground-water flow

2.2. Model Developed For
- general use (e.g. in field applications)
- research (e.g. hypothesis/theory testing)
- demonstration/education

2.3. Units of Measurement Used
- SI system
- metric units
- any consistent system

2.4. Abstract

MODFLOW is a modular, block-centered finite difference model for the simulation of two-dimensional and quasi- or fully-three-dimensional, transient ground-water flow in anisotropic, heterogeneous, layered aquifer systems. It calculates piezometric head distributions, flow rates and water balances. The model includes modules for flow towards wells, through riverbeds, and into drains. Other modules handle evapotranspiration and recharge. Various textual and graphic pre- and postprocessors are available.

2.5. Data Input Requirements:
Data input requirements are provided in the model documentation and are discussed in the introduction to Section 4.0 of the *Compendium*.

2.6. Versions Exist for the Following Computer Systems
- supercomputer
- minicomputer
- workstations
- mainframe
- microcomputer

- Make/Model
  - -- IBM-PC/XT/AT
    - operating system
      DOS 2.1 or later
  - -- DEC VAX 11/780
  - -- PRIME 750
  - -- Macintosh
  - -- Intel 80386/80486 based computers

2.7. System Requirements
- core memory (RAM) for execution (bytes)
  - -- 640Kb (standard IBM PC version)
- mass storage (disk space in bytes)
  - -- at least 2Mb for data files
- numeric/math coprocessor
  - -- (for micro computers)
- compiler require
  - -- (for mainframe)

2.8. Graphics Requirements
- none

2.9. Program Information
- programming language/level
  - -- Fortran 77
- number of program statements (total)
  - -- 5000 lines
- size of runtime (compiled) version (bytes)
  - -- 580Kb (IBM-PC version)

## 3. General Model Capabilities

3.1. Parameter Discretization
- distributed

3.2. Coupling
- N.A.

3.3. Spatial Orientation
- saturated flow
- 2D-horizontal
- 2D-vertical
- 3D-layered (quasi 3D)

3.4. Types of Possible Updates
- parameter values
- boundary conditions

3.5. Geostatistics and Stochastic Approach
- optional

3.6. Comments
- This model has restart capability.

## 4. Flow Characteristics

4.1. Flow System Characterization
- Saturated Zone

- System:
  - -- single aquifer
  - -- single aquifer/aquitard system
  - -- multiple aquifer/aquitard systems

- Aquifer Type(s)
  - -- confined
  - -- semi-confined (leaky-confined)
  - -- unconfined (phreatic)

- Medium:
  - -- porous media

- Parameter Representation
  - -- homogeneous
  - -- heterogeneous

-- isotropic
-- anisotropic

- Flow Characteristics (Saturated Zone)
  -- laminar flow
  -- linear (Darcian flow)
  -- steady-state
  -- transient

- Flow Processes Included
  -- areal recharge
  -- induced recharge (from river)
  -- evapotranspiration

- Changing Aquifer Conditions
  -- in space
    - variable thickness
    - confined/unconfined
    - pitching aquitard
  -- in time
    - desaturation(saturated/unsat.)
    - confined/unconfined
    - resaturation of dry cells

- Well Characteristics
  -- partial penetration

4.2. Fluid Conditions

- Single Fluid Flow
  -- water

- Flow of Multiple Fluids
  -- N.A.

- Fluid Properties
  -- constant in time/space

4.3. Boundary Conditions

- First Type - Dirichlet
  -- head/pressure

- Second Type - Neumann (Prescribed Flux)
  -- injection/production wells
  -- no flow boundary
  -- areal boundary flux
  -- ground-water recharge

- -- seepage face
- -- springs
- -- induced infiltration

- Third Type - Cauchy
  - -- head/pressure-dependent flux
  - -- free surface (steady-state; movable)

4.4. Solution Methods for Flow

- General Method
  - -- Numerical

- Spatial Approximation
  - -- finite difference method
  - -- block-centered

- Time-Stepping Scheme
  - -- fully implicit

- Matrix-Solving Technique
  - -- Iterative
  - -- SIP
  - -- LSOR

4.5. Grid Design

- Cell/Element Characteristic
  - -- constant cell size
  - -- variable cell size
  - -- 3D-hexahedral

- Possible Cell Shapes
  - -- 2D-square
  - -- 2D-rectangular
  - -- 3D-cubic

- Maximum Number of Nodes
  - -- 9999

4.6. Flow Output Characteristics

- Simulation Results
  - -- Head/Pressure/Potential
    - - binary file (areal values)
    - - ASCII file (areal values)
    - - binary file (hydrograph)
    - - ASCII file (hydrograph)

- -- Fluxes/Velocities
  - binary file (areal values)
  - ASCII file (areal values)
  - binary file (temporal values)
  - ASCII file (temporal values)
- -- Water Budget Components
  - ASCII file (cell-by-cell values)
  - ASCII file (global total area)

## 5. Evaluation

5.1. Verification/Validation
- verification (analytical solutions)
- synthetic datasets
- code intercomparison

5.2. Internal Code Documentation (Comment Statements)
- sufficient

5.3. Peer (Independent) Review
- concepts
- theory (math)
- coding
- accuracy
- documentation
- usability

## 6. Documentation and Support

6.1. Documentation Includes
- model theory
- user's instructions
- example problems
- code listing
- program structure and development
- verification/validation

6.2. Support Needs
- Can be used without support
- Support is available
  - -- from author
  - -- from third parties

6.3. Level of Support
- limited
- support agreement available

## 7. Availability

7.1. Terms
- available
- public domain
- proprietary

7.2. Form
- source code only (tape/disk)
- source and compiled code
- compiled code only
- paper listing of source code

## 8. Pre and Post Processors

8.1. Data Preprocessing
- name: MODELCAD
  - -- separate (optional) program
  - -- graphic data entry/modification (e.g manual grid design, arrays)
  - -- (semi-) automatic grid generation
  - -- data reformatting (e.g. for GIS)
  - -- error-checking
  - -- help screens

- name: PREMOD
  - -- part of model package (dedicated)
  - -- textual data entry/editing

8.2. Data Postprocessing
- name: POSTMOD
  - -- part of model package (dedicated)
  - -- textual data display on screen/printer
  - -- reformatting (e.g. to standard formats)

## 9. Institution of Model Development

9.1 Name
U.S. Geological Survey

9.2. Address
Ground Water Branch
WRD WGS - Mail Stop 433
National Center
Reston, Virginia 22092

9.3. Type of Institution
- federal/national government

## 10. Remarks

The code is available from the U.S.G.S. on tape ($40). Contact Arlen Harbaugh (see contact address). The documentation (paper copy $69.95, microfiche $3.50) is available from:

U.S. Geological Survey
Open-File Service Section
Branch of Distribution
Box 25425, Federal Center
Denver, CO 80225

Various MODFLOW implementations for IBM-PC and main frame systems are also available from the International Ground Water Modeling Center (see also MARS # 3983, 3984, 3985, and 3986), including MODFLOW PC for IBM PC/XT/AT (640K), and MODFLOW PC/EXT for extended memory Intel 80386/80486 based computers (2Meg,4Meg) which includes a preconditioned conjugate gradient solver and a stream-flow routing package.

IGWMC USA: Inst. for Ground-Water Res. and Educ.,
Colorado School of Mines,
Golden, CO 80401, USA.

IGWMC Europe: TNO Institute of Applied Geoscience,
P.O. Box 6012, 2600JA Delft,
The Netherlands.

Wagner, Heindel and Noyes Inc. has implemented MODFLOW on a Hewlett-Packard microcomputer (series 200). Contact Jeffrey E. Noyes, Geologist:

Wagner, Heindel and Noyes, Inc.
285 North St.
Burlington, Vermont 05401
phone: (802) 658-0820.

Various implementations of MODFLOW are available from:

Scientific Publications Co.
P.O. Box 23041
Washington, DC 20026-3041
phone: 703/620-9214
fax: 703/620-6793.

Versions included:

MODFLOW/PC for IBM PC/XT/AT (640K)

MODFLOW/EM for extended memory Intel 80386/80486 based computers (2Meg,4Meg) which includes a preconditioned conjugate gradient solver and a stream-flow routing package.

MOCGRAF is a program developed by TECSOFT, Inc. to provide graphics capability to MODFLOW. The menu-driven MODGRAF program uses the output from MODFLOW to automatically contour heads and drawdowns from each layer, stress period and time step and superpose velocity vectors on the head contour plots. The program requires TECSOFT's TRANSLATE program. A special 80386/486 version is available. Contact:

Scientific Software Group
P.O. Box 23041
Washington, D.C. 20026-3041
phone 703/620-9214.

MODPATH: a particle-tracking program developed by the USGS for use with the MODFLOW model. MODPATH calculates the path a particle would take in a steady-state three-dimensional flow field in a given amount of time. It operates as a post-processor for MODFLOW using heads, cell-by-cell flow terms and porosity to move each particle through the flow field. The program handles both forward and backward particle tracking. (See also IGWMC Key 3984).

MODPATH-PLOT: a graphic display program for use with MODPATH-PC. It uses the Graphical Kernal System (GKS) to produce graphical output on a wide range of commonly used printers and plotters. MODPATH-PLOT comes with MODPATH.

MACMODFLOW: this is the Macintosh implementation of the MODFLOW model. It supports the standard Macintosh user-interface. The simulation code is integrated with the input data editor and the graphic post-processor. Extensive data-checking is employed and simulation stops are trapped with control returning to the program. Graphic functions include contouring of heads, drawdowns, hydraulic conductivity, transmissivity, and plots of the finite difference grid. This version of MODFLOW is available from Scientific Software Group.

PATH3D is a general particle tracking program for calculating ground-water paths and travel times. The program uses the head solution of the USGS modular finite difference model MODFLOW. The program is available from:

S.S. Papadopulos and Assoc., Inc
12250 Rockville Pike
Suite 290
Rockville , Maryland 20852

MODELCAD is a graphical oriented, model-independent pre- processor to prepare and edit input files for two- and three-dimensional ground-water models, including aquifer properties, boundary conditions, and grid dimensions. The program prepares input files for MODFLOW, MOC, PLASM and RANDOM WALK, among others. File formatting routines for other models are available upon request. Contact:

Geraghty & Miller Modeling Group
1895 Preston White Drive
Suite 301
Reston, VA 22091
Phone: (703) 476-0335.

A related program contains a preconditioned conjugate gradient method for the solution of the finite difference approximating equations generated by MODFLOW (Kuiper 1987; see references). Five preconditioning types may be chosen: three different types of incomplete Choleski, point Jacobi or block Jacobi. Either a head change or residual error criteria may be used as an indication of solution accuracy and interation termination. A later version of this solver is included in the extended memory PC version from IGWMC, Scientific Software and Geraghty & Miller Modeling Group.

A computer program to summarize the data input and output from MODFLOW is described by Scott (1990; see references). This program, the Modular Model Statistical Processor, provides capabilities to easily read data input to and output from MODFLOW, calculate descriptive statistics, generate histograms, perform logical tests using relational operators, calculate data arrays using arithmic operators, and calculate flow vectors for use in a graphical display program. The program is written in Fortran 77 and tested on a Prime 1/model 9955-II.

A computer program for simulating aquifer-system compaction resulting from ground-water storage changes in compressible beds has been published by Leake and Prudic (1988; see references). This program can be incorporated in MODFLOW as the INTERBED-STORAGE-PACKAGE. (see also MARS 3985).

STR1 is a computer program written for use in MODFLOW to account for the amount of flow in streams and to simulate stream-aquifer interaction. The program is known as the Streamflow Routing Package (Prudic 1989; see references.) (see also MARS 3896).

PCG2 (Hill 1990; see references) is a numerical code to be used with the USGS MODFLOW model. It uses the preconditioned conjugate-gradient method to solve the equations produced by the MODFLOW model. Both linear and nonlinear flow conditions may be simulated. PCG2 includes two preconditioning options: modified Cholesky preconditioning and polynomial preconditioning. Convergence of the solver is determined using both head-change and residual criteria. Non linear problems are solved using Picard iterations. This solver is included in various extended memory PC versions.

An IBM PC/386 extended memory version of this model is also available from:

Geraghty & Miller, Inc.
Modeling Group
1895 Preston Drive
Suite 301
Reston, VA 22091
tel.: 703/476-0335
fax: 703/476-6372

## 11. References

McDonald, M.G. and A.W. Harbaugh. 1983. A Modular Three-Dimensional Finite-Difference Ground Water Model. Open-File Report 83-875, U.S. Geological Survey, Reston, Virginia.

Kuiper, L.K. 1987. Computer Program for Solving Ground-Water Flow Equations by the Preconditioned Conjugate Gradient Method. Water-Resources Investigations Report 87-4091, U.S. Geological Survey, Austin, Texas.

Leake, S.A., and D.E. Prudic. 1988. Documentation of a Computer Program to Simulate Aquifer-System Compaction using the Modular Finite-Difference Ground-Water Flow Model. Open-File Report 88-482, U.S. Geological Survey, Tuscon, Arizona.

McDonald, M.G., and A.W. Harbaugh. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Book 6, Modeling Techniques, Chapter A1, U.S. Geological Survey, Reston, Virginia.

Prudic, D.E. 1989. Documentation of a Computer Program to Simulate Stream-Aquifer Relations using a Modular, Finite-Difference, Ground-Water Flow Model. Open-File Report 88-729, U.S. Geological Survey, Carson City, Nevada.

Hill, M.C. 1990. Preconditioned Conjugate Gradient 2 (PCG2), A Computer Program for Solving Ground-Water Flow Equations. Water Resources Investigations Report 90-4048, U.S. Geological Survey, Denver, Colorado.

Scott, J.C. 1990. A Statistical Processor for Analyzing Simulations Made Using the Modular Finite-Difference Ground-Water Flow Model. Water-Resources Investigations Report 89-4159, U.S. Geological Survey, Oklahoma City, Oklahoma.

## 12. Users

Brahana, J.V., and T.O Mesko. Hydrogeology and Preliminary Assessment of Regional Flow in the Upper Cretaceous and Adjacent Aquifers in the Northern Mississippi Embayment. Water-Resources Investig. Rept. 87-4000, U.S. Geolog. Survey, Nashville, Tennessee.

McDonald, M.G., 1984. Development of a Multi-Aquifer Well Option for a Modular Ground Water Flow Model. In: Proceedings Practical Applications of Ground Water Models, Columbus, Ohio, August 15-17, 1984, pp. 786- 796. National Water Well Association, Dublin, Ohio.

Bailey, Z.C., 1985. Hydrologic Effects of Ground and Surface Water Withdrawals in the Howe Area, LaGrange County, Indiana. Water Resources Investig. Report 85-4163, U.S. Geological Survey, Indianapolis, Indiana.

Grannemann, N.G. and F.R. Twenter, 1985. Geohydrology and Ground Water Flow at Verona Well Fields, Battle Creek, Michigan. Water Resources Investig. Report 85-4056, U.S. Geological Survey, East Lansing, Michigan.

Kuniansky, E.L., 1985. Complex Depositional Environment at Baton Rouge, Louisiana, Requires Innovative Model Layering. In: Proceedings Practical Applications of Ground Water Models, Columbus, Ohio, pp. 122-143. National Water Well Association, Dublin, Ohio.

Lindgren, H.A., 1985. Hydrologic Effects of Ground and Surface Water Withdrawals in the Milford Area, Elkart and Kosciusko Counties, Indiana. Water Resources Investig. Report 85-4166, U.S. Geological Survey, Indianapolis, Indiana.

Spinazola, J.M., J.B. Gillespie and R.J. Hart, 1985. Ground Water Flow and Solute Transport in the Equus Beds Area, South-Central Kansas, 1940-79. Water Resources Investig. Report 85-4336, U.S. Geological Survey, Lawrence, Kansas.

Trudeau, D.A. and A. Buono, 1985. Projected Effects of Proposed Increased Pumpage on Water Levels and Salinity in the Sparta Aquifer Near West Monroe, Louisiana. Technical Report No. 39, Louisiana Dept. of Transportation and Development, Baton Rouge, Louisiana.

Weatherington - Rice, J.P., 1985. A Three-Dimensional Ground Water Modeling Study for Development of the New Well Field at London Correctional Institute in Madison County, Ohio. In: Proceedings Practical Applications of Ground Water Models, Columbus, Ohio, pp. 197-211. Nat. Water Well Association, Dublin, Ohio.

Yager, R.M. 1985. Simulation of Ground Water Flow Near the Nuclear Fuel Reprocessing Facility at the Western New York Nuclear Service Center, Cattaraugus County, New York. Water Resources Investig. Report 85-4308, U.S. Geological Survey, Albany, New York.

Delin, G.N. 1986. Hydrogeology of Confined-Drift Aquifers near the Pomme De Terre and Chippewa Rivers, Western Minnesota. Water Resources Investig. Report 86-4098, U.S. Geological Survey, Minneapolis, Minnesota.

Mandle, R.J. and A.L. Kontis, 1986. Directions and Rates of Ground Water Movement in the Vicinity of Kesterson Reservoir, San Joaquin Valley, California. Water Resources Investig. Report 86-4196, U.S. Geological Survey, Sacramento, California.

Martin, P. and C. Berenbrock, 1986. Ground Water Monito ring at Santa Barbara, California: Phase 3-- Development of a Three-Dimensional Digital Ground Water Flow Model for Storage Unit I of the Santa Barbara Ground- Water Basin. Water-Resources Investig. Report 86-4103, U.S. Geological Survey, Sacramento, California.

Tucci, P., 1986. Ground Water Flow in Melton Valley, Oak Ridge Reservation, Roane County, Tennessee - Preliminary Model Analysis. Water Resources Investig. Report 85-4221, U.S. Geological Survey, Nashville, Tenn.

Zitta, V.L. and T.K. Pang, 1986. Application of a Groundwater Model to Critical Areas in Northeast Mississippi. Department of Civil Engineering, Water Resources Research Institute, Mississippi State University, Mississippi State, Mississippi.

Bergeron, M.P. 1987. Effect of Reduced Industrial Pumpage on the Migration of Dissolved Nitrogen in an Outwash Aquifer at Olean, Cattaraugus County, New York. Water-Resources Investig. Report 85-4082, U.S. Geological Survey, Ithaca, New York.

Kernodle, J.M. R.S. Miller and W.B. Scott. 1987. Three- Dimensional Model Simulation of Transient Ground Water Flow in the Albuquerque-Belen Basin, New Mexico. Water Resources Investig. Report 86-4194, U.S. Geological Survey, Albuquerque, New Mexico.

Kidd, R.E., and W.S. Mooty. 1987. Simulation of the Flow System in the Shallow Aquifer, Dauphin Island, Alabama. In: E.J. Edwards (ed.), Proceed. 17th Mississippi Water Resources Conference, Jackson, Mississippi, March 25-26, 1987, pp. 99-107. Water Resources Research Inst., Mississippi State Univ., Mississippi State, Mississippi.

Kyllonen, D.P., and K.D. Peter. 1987. Geohydrology and Water Quality of the Inyan Kara, Minnelusa, and Madison Aquifers of the Northern Black-Hills, South Dakota and Wyoming, and Bear Lodge Mountains, Wyoming. Water-Resources Investigations Report 86-4158, U.S. Geological Survey, Rapid City, South Dakota.

Phillips, S.W. 1987. Hydrogeology, Degradation of Ground- Water Quality, and Simulation of Infiltration from the Delaware River into the Potomac Aquifers, Northern Delaware. Water-Resources Investig. Rept. 87-4185, U.S. Geol. Survey, Towson, Maryland.

Pool, D.R. 1987. Hydrogeology of McMullen Valley, West- Central Arizona. Water-Investigations Report 87-4140, U.S. Geological Survey, Tuscon, Arizona.

Risser, D.W. 1987. Possible Changes in Ground-Water Flow to the Pecos River Caused by Santa Rosa Lake, Guadalupe County, New Mexico. Water-Resources Investigations Report 85-4291, U.S. Geological Survey, Albuquerque, New Mexico.

Weiss, E. 1987. Ground-Water Flow in the Navajo Sandstone in Parts of Emery, Grand, Carbon, Wayne, Garfield, and Kane Counties, Southeast Utah. Water-Resources Investigations Report 86-4012, U.S. Geological Survey, Denver, Colorado.

Zitta, V.L., and T-K. Pang. 1987. Application of a Layered Groundwater Model to Critical Areas in Northeast Mississippi. In: E.J. Hawkins (ed.), Proceedings 17th Mississippi Water Resources Conference, Jackson, Mississippi, March 25-26, 1987, pp, 89-94. Water Resources Research Inst., Mississippi State Univ., Mississippi State, Mississippi.

Aucott, W.R. 1988. The Predevelopment Ground-Water Flow System and Hydrologic Characteristics of the Coastal Plain Aquifers of South Carolina. Water-Resources Investigations Report 86-4347, U.S. Geological Survey, Columbia, South Carolina.

Bailey, Z.C. 1988. Preliminary Evaluation of Ground- Water Flow in Bear Creek Valley, The Oak Ridge Reservation, Tennessee. Water-Resources Investigations Report 88-4010, U.S. Geological Survey, Nashville, Tennessee.

Brown, J.G., and J.H. Eychaner. 1988. Simulation of Five Ground-Water Withdrawal Projections for the Black Mesa Area, Navajo and Hopi Indian Reservations, Arizona. Water-Resources Investigations Report 88-4000, U.G. Geological Survey, Tuscon, Arizona.

Buckles, D.R., and K.R. Watts. 1988. Geohydrology, Water Quality, and Preliminary Simulations of Ground-Water Flow of the Alluvial Aquifer in the Upper Black Squirrel Creek Basin, El Paso County, Colorado. Water-Resources Investigations Report 88-4017, U.S. Geological Survey, Denver, Colorado.

Danskin, W.R. 1988. Preliminary Evaluation of the Hydrogeologic System in Owens Valley, California. Water- Resources Investigations Report 88-4003, U.S. Geological Survey, Sacramento, California.

Davies-Smith, A., E.L. Bolke, and C.A. Collins. 1988. Geohydrology and Digital Simulation of the Ground- Water Flow System in the Umatilla Plateau and Horse Heaven Hills Area, Oregon and Washington. Water- Resources Investigations Report 87-4268, U.S. Geological Survey, Portland, Oregon.

Emmons, P.J. 1988. A Digital Simulation of the Glacial- Aquifer System in Sanborn and Parts of Beadle, Miner, Hanson, Davison, and Jerauld Counties, South Dakota. Water-Resources Investigations Report 87-4082, U.S. Geological Survey, Huron, South Dakota.

Fenemor, A.D. 1988. A Three-Dimensional Model for Management of the Waimea Plains Aquifers, Nelson. Publication 18, Hydrology Centre, Dept. of Scientific and Industrial Research, Christchurch, New Zealand.

Fretwell, J.D. 1988. Water Resources and Effects of Ground-Water Development in Pasco County, Florida. Water-Resources Investigations Report 87-4188, U.S. Geological Survey, Tallahassee, Florida.

Hamilton,F.A., and J.D. Larson. 1988. Hydrogeology and Analysis of the Ground-Water Flow System in the Coastal Plain of Southeastern Virginia. Water- Resources Investigations Report 87-4240, U.S. Geological Survey, Richmond, Virginia.

Hansen, D.S. 1988. Appraisal of the Water Resources of the Big Sioux Aquifer, Moody County, South Dakota. Water-Resources Investigations Report 87-4057, U.S. Geological Survey, Huron, South Dakota.

Johnson, M.J., C.J. Londquist, J. Laudon, and H.T. Mitten. 1988. Geohydrology and Mathematical Simulation of the Pajaro Valley Aquifer System, Santa Cruz and Monterey Counties, California. Water-Resources Investigations Report 87-4281, U.S. Geological Survey, Sacramento, California.

Laczniak, R.J., and A.A. Meng III. 1988. Ground-Water Resources of the York-James Peninsula of Virginia. Water-Resources Investig. Rept. 88-4059, U.S. Geol. Survey, Richmond, Virginia.

McAda, D.P., and M. Wasiolek. 1988. Simulation of the Regional Geohydrology of the Tesque Aquifer System near Santa Fe, New Mexico. Water-Resources Investigations Report 87-4056, U.S. Geological Survey, Albuquerque, New Mexico.

Morgan, D.S. 1988. Geohydrology and Numerical Model Analysis of Ground-Water Flow in the Goose Lake Basin, Oregon and California. Water-Resources Investigations Report 87-4058, U.S. Geological Survey, Portland, Oregon.

Yates, E.B. and J.H. Wiese. 1988. Hydrogeology and Water Resources of the Los Osos Valley Ground-Water Basin, San Luis Obispo County, California. Water-Resources Investigations Report 88-4081, U.S. Geological Survey, Sacramento, California.

Ackerman, D.J. 1989. Hydrology of the Mississippi River Valley Alluvial Aquifer, South-Central United States --A Preliminary Assessment of the Regional Flow System. Water-Resources Investig. Rept. 88-4028, U.S. Geol. Survey, Little Rock, Arkansas.

Coen III, A.W. 1989. Ground-Water Resources of Williams County, Ohio, 1984-86. Water-Resources Investigations Report 89-4020, U.S. Geological Survey, Columbus, Ohio.

Duwelius, R.F., and T.K. Greeman. 1989. Geohydrology, Simulation of Ground-Water Flow, and Ground-Water Quality at Two Landfills, Marion County, Indiana. Water-Resources Investigations Report 89-4100, U.S. Geological Survey, Indianapolis, Indiana.

Freckleton, J.R. 1989. Geohydrology of the Foothill Ground-water Basin near Santa Barbara, California. Water-Resources Investig. Report 89-4017, U.S. Geological Survey, Sacramento, California.

Imes, J.L. 1989. Analysis of the Effect of Pumping on Ground-Water Flow in the Springfiled Plateau and Ozark Aquifers near Springfield, Missouri. Water-Resources Investigations Report 89-4079, U.S. Geological Survey, Rolla, Missouri.

A model of 42 by 42 mile area was calibrated under predevelopment and transient pumping conditions. The model then was used to quantify hydraulic properties of the aquifer and confining unit and the hydrologic budget.

Lima, V. de, and J.C. Olimpio. 1989. Hydrogeology and Simulation of Ground-Water Flow at Superfund-Site Wells G and H, Woburn, Massachusetts. Water-Resources Investigations Report 89-4059, U.S.Geological Survey, Boston, Massachusetts.

(The calibrated three-dimensional ground-water flow model of the stratified drift area was designed as a tool for predicting the steady-state and transient effects of pumpage in the vicinity of public supply wells.)

Martin, Jr., A., and C.D. Whiteman, Jr. 1989. Geohydrology and Regional Ground-Water Flow of the Coastal Lowlands Aquifer System in Parts of Louisiana, Mississippi, Alabama, and Florida--A Preliminary Analysis. Water-Resources Investigations Report 88-4100, U.S. Geological Survey, Baton Rouge, Louisiana.

Summer, D.M., B.E. Wasson, and S.J. Kalkhoff. 1989. Geohydrology and Simulated Effects of Withdrawals on the Miocene Aquifer System in the Mississippi Gulf Coast. Water-Resources Investig. Rept. 87-4172, U.S. Geological Survey, Jackson, Mississippi.

Watson, L.R., R.J. Shedlock, K.J. Banaszak, L.D. Arihood, and P.K. Doss. 1989. Preliminary Analysis of the Shallow Ground-Water System in the Vicinity of the Grand Calumet River/Indiana Harbor Canal, Northwestern Indiana. Open-File Report 88-492, U.S. Geological Survey, Indianapolis, Indiana.

Yobbi, D.K. 1989. Simulation of Steady-State Ground Water and Spring Flow in the Upper Floridan Aquifer of Coastal Citrus and Hernando Counties, Florida. Water-Resources Investig. Rept., U.S. Geol. Survey, Tallahassee, Florida.

Young, H.W., and G.D. Newton. 1989. Hydrology of the Oakley Fan Area, South Central Idaho. Water- Resources Investigations Rept. 88-4065, U.S. Geolog. Survey, Boise, Idaho.

Bair, E.S., R.A. Sheets, and S.M. Eberts. 1990. Particle-Tracking Analysis of Flow Paths and Traveltimes from Hypothetical Spill Sites within the Capture Area of a Wellfield. Ground Water, Vol. 28 (6), pp. 884-892.

Velocity fields computed from simulated flows from a steadystate, three-dimensional numerical model of a glacial drift/carbonate-bedrock aquifer system were used in conjunction with a particle tracking program to delineate traveltimes related capture areas of a municipal wellfield and compute flow paths from a hypothetical spill site.

# Model Description For

# PLASM

SOURCE:
INTERNATIONAL GROUND WATER
MODELING CENTER
(IGWMC)

# PLASM
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# PLASM

## 1. Model Identification

1.1. Model Name(s)
- PLASM

1.2. Date of First Release
- 1971

1.3. Current Release Date
- 1985

1.4. Authors
- 1. Prickett, T.A.
- 2. Lonnquist, C.G.

## 2. Model Information

2.1. Model Category
- ground-water flow

2.2. Model Developed For
- general use (e.g. in field applications)
- research (e.g. hypothesis/theory testing)
- demonstration/education

2.3. Units of Measurement Used
- SI system
- metric units
- US customary units
- any consistent system

2.4. Abstract

PLASM (Prickett Lonnquist Aquifer Simulation Model) is a finite difference model for simulation of transient, two-dimensional or quasi-three-dimensional flow in a single or multi-layered, heterogeneous, anisotropic aquifer system. The original model of 1971 consisted of a series of separate programs for various combinations of simulation options. Later versions combined most of the options in a single code, including variable pumping rates, leaky confined aquifer conditions, induced infiltration from a shallow aquifer or a stream, storage coefficient conversion between confined and watertable conditions, and evapotranspiration as a function of depth to water table. The model uses the iterative alternating implicit method (IADI) to solve the matrix equation.

2.5. Data Input Requirements:
Data input requirements are provided in the model documentation and are discussed in the introduction to Section 4.0 of the *Compendium*.

2.6. Versions Exist for the Following Computer Systems
- minicomputer
- workstations
- mainframe
- microcomputer

- make/model
  -- IBM 360,370
  -- DEC VAX
  -- IBM PC/XT/AT

2.7. System Requirements
- core memory (RAM) for execution (bytes)
  -- 640K (for IBM PC version)
- mass storage (disk space in bytes)
  -- 1M
- numeric/math coprocessor
  -- (for micro computers)
- compiler required
  -- (for mainframe)

2.8. Graphics Requirements
- none

2.9. Program Information
- programming language/level
  -- Fortran IV

## 3. General Model Capabilities

3.1. Parameter Discretization
- distributed

3.2. Spatial Orientation
- saturated flow
- 2D-horizontal
- 3D-layered

3.3. Types of Possible Updates
- parameter values
- boundary conditions

3.4. Geostatistics and Stochastic Approach
- none

3.5. Comments
- This model has restart capability.

## 4. Flow Characteristics

4.1. Flow System Characterization
- Saturated Zone

- System
  - -- single aquifer
  - -- single aquifer/aquitard system
  - -- multiple aquifer/aquitard systems

- Aquifer Type(s)
  - -- confined
  - -- semi-confined (leaky-confined)
  - -- unconfined (phreatic)

- Medium
  - -- porous media

- Parameter representation
  - -- homogeneous
  - -- heterogeneous
  - -- isotropic
  - -- anisotropic

- Flow characteristics (saturated zone)
  - -- laminar flow
  - -- linear (Darcian flow)
  - -- steady-state
  - -- transient

- Flow processes included
  - -- areal recharge
  - -- induced recharge (from river)
  - -- evapotranspiration

- Changing aquifer conditions
  - -- in space
    - variable thickness
    - confined/unconfined
  - -- in time
    - confined/unconfined
- Well characteristics
  - -- none

4.2. Fluid Conditions

- Single Fluid Flow
  - -- water
- Flow of Multiple Fluids
  - -- N.A.
- Fluid Properties
  - -- constant in time/space

4.3. Boundary Conditions

- First Type - Dirichlet
  - -- head/pressure
- Second Type - Neumann (Prescribed Flux)
  - -- injection/production wells
  - -- no flow boundary
  - -- areal boundary flux
  - -- ground-water recharge
  - -- induced infiltration
- Third Type - Cauchy
  - -- head/pressure-dependent flux

4.4. Solution Methods for Flow

- General Method
  - -- Numerical
- Spatial Approximation
  - -- finite difference method
  - -- node-centered
- Time-Stepping Scheme
  - -- fully implicit

- Matrix-Solving Technique
  - -- Iterative
  - -- iterative ADIP
  - -- Direct
  - -- Gauss elimination

4.5. Grid Design

- Cell/Element Characteristic
  - -- constant cell size
  - -- variable cell size

- Possible Cell Shapes
  - -- 2D-square
  - -- 2D-rectangular

- Maximum Number of Nodes
  - -- 5000

4.6. Flow Output Characteristics

- Simulation Results
  - -- head/pressure/potential
    - - ASCII file (areal values)
    - - ASCII file (hydrograph)
  - -- water budget components
    - - ASCII file (cell-by-cell values)
    - - ASCII file (global total area)

## 5. Evaluation

5.1. Verification/Validation

- verification (analytical solutions)
- field datasets (validation)
- synthetic datasets
- code intercomparison

5.2. Internal Code Documentation (Comment Statements)

- incidental

5.3. Peer (Independent) Review

- concepts
- theory (math)
- coding
- accuracy
- documentation

- usability
- efficiency

## 6. Documentation and Support

6.1. Documentation Includes
- model theory
- user's instructions
- example problems
- code listing
- program structure and development
- verification/validation

6.2. Support Needs
- Can be used without support
- Support is available
  - -- from author
  - -- from third parties

6.3. Level of Support
- limited

## 7. Availability

7.1. Terms
- available
- public domain
- proprietary
- restricted public domain
- purchase
- license

7.2. Form
- source code only (tape/disk)
- source and compiled code
- compiled code only
- paper listing of source code
- (depends on version)

## 8. Pre and Post Processors

8.1. Data Preprocessing

- name: PREPLASM
  - -- part of model package (e.g. under a shell; dedicated)
  - -- textual data entry/editing
  - -- error-checking

- name: MODELCAD
  - -- separate (optional) program
  - -- graphic data entry/modification (e.g manual grid design, -- arrays)
  - -- (semi-) automatic grid generation
  - -- data reformatting (e.g. for GIS)
  - -- error-checking
  - -- help screens

## 9. Institution of Model Development

9.1. Name

Illinois State Water Survey

9.2. Address

P.O. Box 232
Urbana, Illinois 61801

9.3. Type of Institution

state/provincial government

## 10. Remarks

A modified version of PLASM to analyze hydrologic impacts of mining is documented in in a report of the U.S. Office of Surface Mining (1981; see user references).

An extended and updated single aquifer version of PLASM for the IBM-PC is available from:

T.A. Prickett
6 G.H. Baker Drive
Urbana, IL 61801
phone: 217/384-0615.

This version is the same as published in Bulletin 55, except for the multi-layered option and the confined/unconfined storage conversion.

The IGWMC distributes a mainframe version of PLASM running on the DEC/VAX 11 series. The Center distributes also an IBM-PC version. This latter version comes as a program package including separate codes for confined (CONPLASM) and watertable (UNCPLASM) conditions and a textual preprocessor for input data preparation (PREPLASM). Contact:

IGWMC USA: International Ground Water Modeling Center,
Colorado School of Mines, Golden, Colorado, USA, or
TNO Inst. of Applied Geoscience, P.O. Box 6012, 2600JA
Delft, The Netherlands.

IGWMC Europe: TNO Institute of Applied Geoscience,
P.O. Box 6012, 2600JA Delft,
The Netherlands.

For earlier microcomputer versions of PLASM see IGWMC Key # 6010 and 6011 (MARS historic data base).

MODELCAD is a graphical oriented, model-independent pre-processor to prepare and edit input files for two- and three-dimensional ground-water models, including aquifer properties, boundary conditions, and grid dimensions. The program prepares input files for MODFLOW, MOC, PLASM and RANDOM WALK, among others. File formatting routines for other models are available upon request. Contact:

Geraghty & Miller Modeling Group
1895 Preston White Drive
Suite 301
Reston, VA 22091
Phone: (703) 476-0335.

The IBM-PC version of this program is also available from:

National Water Well Association
Ground Water Bookstore
P.O. Box 182039
Dept. 017
Columbus, Ohio 43218
Tel. (614) 761-1711

The version available from the National Water Well Association runs on IBM PC or compatible and has been prepared by Koch and Associates and includes interactive data preparation. The code is directly available from Koch and Associates. Contact:

Ann Koch
2921 Greenway Drive
Ellicot City, Maryland 21043
tel. 301/461-6869.

## 11. References

Prickett, T.A. and C.G. Lonnquist. 1971. Selected Digital Computer Techniques for Groundwater Resource Evaluation. Bulletin 55. Illinois State Water Survey, Urbana, Ill.

Texas Water Development Board, Systems Engineering Division. 1974. GWSIM - Groundwater Simulation Program, Program Documentation and User's Manual. Texas Dept. of Water Resourc., Austin, Texas.

Prickett, T.A. and C.G. Lonnquist. 1976. Methods de Ordenador para Evaluacion de Recursos Hidraulicos Subterraneas. Boletin 41. (Spanish version of Bulletin 55, ISWS). Ministerio de Obras Publicas, Direccion General de Obras Hidraulicos, Madrid, Spain.

Texas Dept. of Water Resources. 1979. Program Description of GWSIM. In: Mathematical Simulation Capabilities in Water Resources Systems Analysis, Eng. and Environm. Systems Section, Report LP-16, revised November 1979.

Instituto Geologico Y Minero de Espana. 1981. Modelos Multicapa -- Tomo II: Listados de Programas, Ministreio de Industria Y Energia, Madrid, Spain.

Instituto Geologico Y Minero de Espana. 1981. Modelos Multicapa -- Tomo I: Manuales de Utilizacion. Ministerio de Industria Y Energia, Madrid, Spain.

Instituto Geologico Y Minero de Espana. 1982. Modelos Monocapa en Regimen Transitorio -- Tomo II: Listados de Ordenador. Ministerio de Industria Y Energia, Madrid, Spain.

Instituto Geologico Y Minero de Espana. 1982. Modelos Monocapa en Regimen Transitorio -- Tomo I: Manuales de Utilizacion. Dirrecion de Aguas Subterraneas y Geotecnia, Ministerio de Industria y Energia, Madrid, Spain.

## 12. Users

T.R. Knowles developed two models based on PLASM for the Texas Dept. of Water Resources, Austin, Texas. See models GWSIM (IGWMC key # 0681) and GWSIM II (IGWMC key # 0680).

Beltran, J.M.A., L.L. Garcia, and M.R.L. Madurga. 1973. Estudio de la Explotacion de los Aquiferos del Llano de Palma de Mallorca Mediante un Modelo Digital Simplificado. Boletin 38, Dirrecion General de Obras Hidraulicas, Ministerio de Obras Publicas, Madrid, Spain.

Karanjac, J., M. Altunkaynak, and G. Ovul. 1976. Mathematical model of Elazig-Uluova Plain, Republic of Turkey. Ministry of Energy and Natural Resources. Geotechnical Services and Groundwater Division, Ankara, Turkey.

Naymik, T.G. 1979. The Application of Digital Model for Evaluating the Bedrock Water Resources of the Maumee River Basin, Northwestern Ohio. Lawrence Livermore Laboratory. University of California. Livermore, California.

U.S. Department of the Interior. 1981. Office of Surface Mining -- Reclamation and Enforcement. Ground Water Model Handbook (H-D3004-021-81-1062D). Office of Surface Mining. Western Technical Service Center. Denver, Colorado.

Yazicigil, H. and L.V.A. Sendlein. 1981. Management of Ground Water Contaminated by Aromatic Hydrocarbons in the Aquifer Supplying Ames, Iowa. Groundwater, Vol. 19(6), pp. 648-665.

Grosser, P.W. 1984. Application of Ground Water Models to the Identification of Contaminant Sources. In: Proceed. Conf. on Practical Applications of Ground Water Models, Columbus, Ohio, pp. 452-461. Nat. Water Well Assoc., Dublin, Ohio.

Khaleel, R. and D.M. Peterson. 1984. A Quasi Three- Dimensional Ground Water Flow Model for the Mesilla Bolson, New Mexico. In: Proceed. Conf. on Practical Applications of Ground Water Models, Columbus, Ohio, pp. 52-67. Nat. Water Well Assoc., Dublin, Ohio.

Martin, P.L. 1984. The Use of a Numerical Model in Predicting the Effectiveness of a Dewatering System. In: Proceed. Conf. on Practical Applications of Ground Water Models, Columbus, Ohio, pp. 759-777. Nat. Water Well Assoc., Dublin, Ohio.

Osiensky, J.L., G.V. Winter, and R.E. Williams. 1984. Monitoring and Mathematical Modeling of Contaminated Ground Water Plumes in Fluvial Environments. Ground Water, Vol. 22(3), pp. 298-306.

Potter, S.T. and W.J. Gburek. 1984. Seepage Face Simulation Using the Illinois State Water Survey Ground Water Model. In: Proceed. Conf. on Practical Applications of Ground Water Models, Columbus, Ohio, pp. 674-700. Nat. Water Well Assoc., Dublin, Ohio.

Ritchey, J.D. 1984. Method for Including the Effects of River Stage and Precipitation on Ground Water Levels in an Aquifer Model. In: Proceed. Practical Applications of Ground Water Models, Columbus, Ohio, pp. 649-673. Nat. Water Well Assoc., Dublin, Ohio.

Sevi, E.A., T.M. Cosgrave, and F.L. Fox. 1984. Sequential Horizontal and Vertical Cross-Sectional Modeling of a Small Site. In: Proceed. Conf. on Practical Applications of Ground Water Models, Columbus, Ohio, pp. 621-633. Nat. Water Well Assoc., Dublin, Ohio.

Singh, R., S.K. Sondhi, J. Singh, and R. Kumar. 1984. A Ground Water Model for Simulating the Rise of Water Table under Irrigated Conditions. Journ. of Hydrol., Vol. 71, pp. 165-179.

Kalinski, R.J. 1985. Investigation and Computer Simulation of Stream-Aquifer Relationship at Elm Creek, Nebraska. In: Proceed. Practical Applications of Ground Water Models, Columbus, Ohio, pp. 146-161. Nat. Water Well Assoc., Dublin, Ohio.

Song, S. and A.O. Akan. 1985. Ground Water Management by Linear Programming with Sample Applications to the Eastern Shore of Virginia Aquifer. In: Proceed. Conf. on Practical Applications of Ground Water Models, Columbus, Ohio, pp. 90-107. Nat. Water Well Assoc., Dublin, Ohio.

Contractor, D.N., S.M.A. El-Didy, and A.S. Ansary. 1986. Numerical Modeling of Groundwater Flow and Water Quality at Underground Coal Gasification Sites. DOE/ LC/11053-2151. Office of Fossil Energy, U.S. Dept. of Energy, Laramie, Wyoming. (pp.7-50).

## *Model Description For*

# *RANDOM WALK*

**SOURCE:**
**INTERNATIONAL GROUND WATER MODELING CENTER (IGWMC)**

# RANDOM WALK
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# RANDOM WALK

## 1. Model Identification

1.1. Model Name(s)
- RANDOM WALK

1.2. Date of first release
- 7/81

1.3. Current Release date
- 7/81

1.4. Authors
- Prickett, T.A.
- Naymik, T.G.
- Lonnquist, C.G.

## 2. Model Information

2.1. Model Category
- ground-water flow
- mass transport

2.2. Model Developed For
- general use (e.g. in field applications)
- research (e.g. hypothesis/theory testing)
- demonstration/education

2.3. Units of Measurement Used
- metric units
- US customary units
- any consistent system

2.4. Abstract

RANDOM WALK/TRANS is a numerical model to simulate two-dimensional steady or transient flow and transport problems in heterogeneous aquifers under water table and/or confined or leaky confined conditions. The flow is solved using a finite difference approach and the iterative alternating direction implicit method. The advective transport is solved with a particle-in-a-cell method, while the dispersion is analyzed with the random walk method.

2.5. Data Input Requirements

Data input requirements are provided in the model documentation and are discussed in the introduction to Section 4.0 of the *Compendium*.

2.6. Versions Exist for the Following Computer Systems

- minicomputer
- workstations
- mainframe
- microcomputer

  -- make/model
    - Cyber 175
    - VAX 11/780
    - IBM PC/XT/AT or compatible

2.7. System Requirements

- core memory (RAM) for execution (bytes)
  -- 640K (for IBM PC version)
- mass storage (disk space in bytes)
  -- at least 2Mb for data files
- numeric/math coprocessor
  -- (for micro computers)
- compiler required
  -- (for mainframe)

2.8. Graphics Requirements

- none

2.9. Program Information

- programming language/level
  -- Fortran IV

## 3. General Model Capabilities

3.1. Parameter Discretization

- distributed

3.2. Coupling

- none

3.3. Spatial Orientation

- saturated flow
- 2D-horizontal

3.4. Geostatistics and Stochastic Approach
- random walk

## 4. Flow Characteristics

4.1. Flow System Characterization
- Saturated Zone

- System
  - -- single aquifer
  - -- single aquifer/aquitard system

- Aquifer Type(s)
  - -- confined
  - -- semi-confined (leaky-confined)
  - -- unconfined (phreatic)

- Medium
  - -- porous media

- Parameter representation
  - -- homogeneous
  - -- heterogeneous
  - -- isotropic
  - -- anisotropic

- Flow characteristics (saturated zone)
  - -- laminar flow
  - -- linear (Darcian flow)
  - -- steady-state
  - -- transient

- Flow processes included
  - -- areal recharge
  - -- induced recharge (from river)
  - -- evapotranspiration

- Changing aquifer conditions
  - -- in space
    - - variable thickness
    - - confined/unconfined
  - -- in time
    - - confined/unconfined

- Well characteristics
  - -- none

4.2. Fluid Conditions

- Single Fluid Flow
  - -- water

- Flow of Multiple Fluids
  - -- N.A.

- Fluid Properties
  - -- constant in time/space

4.3. Boundary Conditions

- First Type - Dirichlet
  - -- head/pressure

- Second Type - Neumann (Prescribed Flux)
  - -- injection/production wells
  - -- no flow boundary
  - -- areal boundary flux
  - -- ground-water recharge
  - -- springs
  - -- induced infiltration

- Third Type - Cauchy
  - -- head/pressure-dependent flux

4.4. Solution Methods for Flow

- General Method
  - -- Numerical

- Spatial Approximation
  - -- finite difference method
  - -- node-centered

- Time-Stepping Scheme
  - -- fully implicit

- Matrix-Solving Technique
  - -- Iterative
  - -- iterative ADIP
  - -- Direct
  - -- Gauss elimination

4.5. Grid Design

- Cell/Element Characteristic
  - -- constant cell size
  - -- variable cell size

- Possible Cell Shapes
  - -- 2D-square
  - -- 2D-rectangular

- Maximum Number of Nodes
  - -- 5000

4.6. Flow Output Characteristics

- Simulation Results
  - -- head/pressure/potential
    - ASCII file (areal values)
    - ASCII file (hydrograph)
  - -- fluxes/velocities
    - ASCII file (areal values)
  - -- water budget components
    - ASCII file (cell-by-cell values)
    - ASCII file (global total area)

## 5. Mass Transport Characteristics

5.1. Water Quality Constituents

- any component(s)
- single component
- total dissolved solids (TDS)
- inorganics
- organics
- radionuclides

5.2. Processes Included

- (Conservative) Transport
  - -- advection
  - -- dispersion
  - -- isotropic
  - -- anisotropic
  - -- diffusion

- Phase Transfers
  - -- equilibrium
  - -- isotherm

- Fate
  - -- first-order radioactive decay (single mother/daughter decay)
  - -- first-order chemical decay

5.3. Boundary Conditions

- First Type - Dirichlet
  - -- Chemical processes embedded in transport equation
  - -- concentration

- Second Type - Neumann (Prescribed Solute Flux)
  - -- areal boundaries
  - -- injection wells
  - -- point sources
  - -- line sources
  - -- areal sources

5.4. Solution Methods for Transport

- General Method
  - -- numerical
  - -- uncoupled flow and transport equation

- Spatial Approximation
  - -- finite difference method
  - -- node-centered
  - -- particle-tracking

- Time-Stepping Scheme
  - -- fully implicit

- Matrix-Solving Technique
  - -- Random Walk
  - -- direct
  - -- Gauss elimination

5.5. Output Characteristics for Transport

- Simulation Results
  - -- concentration in aquifer/soil
    - - ASCII file (areal values)
    - - ASCII file (time series)
  - -- concentration in well
    - -- ASCII file (time series)

- -- velocities (from given heads)
  - - ASCII file (areal values)
- -- mass balance components
  - -- ASCII file (cell-by-cell values)
  - -- ASCII file (global total area)

## 6. Evaluation

6.1. Verification/Validation
- verification (analytic solutions)
- code intercomparison

6.2. Internal Code Documentation (Comment Statements)
- incidental

6.3. Peer (Independent) Review
- concepts
- theory (math)

## 7. Documentation and Support

7.1. Documentation Includes
- model theory
- user's instructions
- example problems
- program structure and development
- code listing
- verification/validation

7.2. Support Needs
- Can be used without support
- Support is available
  - -- from author
  - -- from third parties

7.3. Level of Support
- limited

## 8. Availability

8.1. Terms
- available
- public domain

- proprietary
- purchase

8.2. Form
- source code only (tape/disk)
- source and compiled code
- compiled code only
- paper listing of source code

## 9. Pre and Post Processors

9.1. Data Preprocessing
- name: PREWALK (IGWMC)
  - -- separate (optional) program
  - -- textual data entry/editing
  - -- data reformatting
  - -- error-checking

- name: MODELCAD
  - -- separate (optional) program
  - -- generic (can be used for various models)
  - -- textual data entry/editing
  - -- graphic data entry/modification (e.g manual grid design, arrays)
  - -- data reformatting (e.g. for GIS)
  - -- error-checking
  - -- help screens

9.2. Data Postprocessing
- name: POSTWALK (IGWMC)
  - -- separate (optional) program
  - -- textual data display on screen/printer
  - -- reformatting (e.g. to standard formats)

## 10. Institution of Model Development

10.1. Name

Illinois State Water Survey

10.2. Address

P.O. Box 5050
Sta.A
Urbana, IL 61820

10.3. Type of Institution
- state/provincial government

## 11. Remarks

Various microcomputer versions are available among others from the International Ground Water Modeling Center:

IGWMC USA: Inst. for Ground-Water Res. and Educ.,
Colorado School of Mines,
Golden, CO 80401, USA.

IGWMC Europe: TNO Institute of Applied Geoscience,
P.O. Box 6012
2600JA Delft
The Netherlands.

Code is available from:
Bob Sinclair
Director of Computer Service
Illinois State Water Survey
Box 5050
Station A
Champaign, IL 61820
telephone (217) 333-4952
at cost of magnetic tape, copying and postage.

Code is also available from:
Thomas A. Prickett
6 G.H. Baker Drive
Urbana, IL 61801
Phone 217/384-0615

A modified version of PLASM and RANDOM WALK to analyze hydrologic impacts of mining is documented in U.S. Office of Surface Mining (1981; see user references). Program codes are available through Boeing Computer Network.

MODELCAD is a graphical oriented, model-independent pre-processor to prepare and edit input files for two- and three-dimensional ground-water models, including aquifer properties, boundary conditions, and grid dimensions. The program prepares input files for MODFLOW, MOC, PLASM and RANDOM WALK, among others. File formatting routines for other models are available upon request. Contact:

Geraghty & Miller Modeling Group
1895 Preston White Drive
Suite 301, Reston, VA 22091
(703) 476-0335

## 12. References

Prickett, T.A. and C.G. Lonnquist. 1971. Selected Digital Computer Techniques for Groundwater Resource Evaluation. Bulletin 55, Illinois State Water Survey, Champaign, Illinois.

Naymik, T.G. and M.J. Barcelona. 1981. Characterization of a Contaminant Plume in Groundwater, Meredesia, Illinois. Ground Water, Vol. 19(5), pp. 517-526.

Prickett, T.A., T.G. Naymik and C.G. Lonnquist. 1981. A Random-Walk Solute Transport Model for Selected Groundwater Quality Evaluations. Bulletin 65, Illinois State Water Survey, Champaign, Illinois.

Naymik, T.G. and M.E. Sievers. 1983. Groundwater Tracer Experiment (II) at Sand Ridge State Forest. Illinois State Water Survey Division, Illinois Dept. of Energy and Natural Resources, Report 334, Champaign, Illinois, pp. 1-105.

## 13. Users

U.S. Office of Surface Mining. 1981. Groundwater Model Handbook. Rept. H-D3004-021-81-1062D, U.S. Dept. of Interior, Western Technical Service Center, Denver, Colorado.

Royce, B., M. Garrell, A. Kahn and E. Kaplan. 1983. A Methodology for Modeling the Migration of Eor Chemicals in Fresh Water Aquifers. Prepared for Bartlesville Energy Technology Center, Order No. DE-AP19-82BC99996, U.S. Dept. of Energy, West Virginia.

Johnson, R. and S.A. Dendrou. 1984. Evaluation of the Potential Water Supply Impacts Posed by the Transgulf Pipeline, Broward County, Florida. In: Proceed. Practical Applications of Ground Water Models, Columbus, Ohio, August 15-17, 1984, pp. 584-601. Nat. Water Well Assoc., Dublin, Ohio.

Wright, S.J. 1984. Modeling Contaminant Migration Under the Influence of a Series of Pumping Wells. In: Proceed. Practical Applications of Ground Water Models, Columbus, Ohio, August 15-17, 1984, pp. 462-477. Nat. Water Well Assoc., Dublin, Ohio.

Herweijer, J.C., G.A. Van Luijn and C.A.J. Appelo. 1985. Calibration of a Mass Transport Model Using Environmental Tritium. Journ. of Hydrology, Vol. , pp.

Naymik, T.G. and M.E. Sievers. 1985. Characterization of Dyetracer Plumes: In Situ Field Experiments. Ground Water, Vol. 223(6), pp. 746-752.

American Petroleum Institute. 1986. Cost Model for Selected Technologies for Removal of Gasoline Components from Groundwater. API Publication No. 4422, American Petroleum Institute, Washington D.C.

Anderson, M.P. and C.J. Bowser. 1986. The Role of Groundwater in Delaying Lake Acidification. Water Resources Research, Vol. 22(7), pp. 1101-1108.

Taylor, M.D., M.K. Leslie, and R.C. Johnson. 1989. Groundwater Modeling Key to Isolating Contamination. Water and Waste Water International, February 1989.

# Model Description For

# AT123D

**SOURCE:**
**INTERNATIONAL GROUND WATER MODELING CENTER (IGWMC)**

# AT123D
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# AT123D

## 1. Model Identification

1.1. Model Name
- AT123D

1.2. Date of First Release
- 1979

1.3. Current Version
- 1.1

1.4. Current Release date
- 5/92

1.5. Authors
- 1. Yeh, G.T.
- 2. et al.

## 2. Model Information

2.1. Model Category
- mass transport

2.2. Model Developed For
- general use
- demonstration/education

2.3. Units of Measurement Used
- metric units
- any consistent system

2.4. Abstract

AT123D is a generalized analytical transient, one- two-, and/or three-dimensional computer code developed for estimating the transport of chemicals in an isotropic, homogeneous, confined aquifer system with uniform flow. The model handles various source configurations (including point source, line source, and areal source) and release characteristics. The transport mechanisms include advection, longitudinal as well as horizontal and vertical transverse hydro-dynamic dispersion, diffusion, linear adsorption, and first-order

decay/degeneration and chemical losses to the atmosphere. The model calculates concentration distribution in space and time using Green's function.

2.5. Data Input Requirements
Data input requirements are provided in the model documentation and are discussed in the introduction to Section 4.0 of the *Compendium*.

2.6. Versions Exist for the Following Computer Systems
- minicomputer
- mainframe
- microcomputer
- make/model
  - -- VAX 11/780
  - -- IBM PC/XT/AT

2.7. System Requirements
- compiler required (e.g., for mainframe)
- language
  - -- FORTRAN

2.8. Graphics Requirements
- none

2.9. Program Information
- programming language/level
  - -- FORTRAN IV

## 3. General Model Capabilities

3.1. Parameter Discretization
- distributed

3.2. Coupling
- N.A.

3.3. Spatial Orientation
- saturated flow
- ID-horizontal
- ID-vertical
- 2D-horizontal
- 2D vertical
- 3D-fully

## 4. Mass Transport Characteristics

4.1. Water Quality Constituents

- any component(s)
- single component
- total dissolved solids (TDS)
- inorganics
- organics
- radionuclides

4.2. Processes Included

- (Conservative) Transport
  - -- advection
  - ~~-- isotropic~~
  - ~~-- anisotropic~~
  - **-- longitudinal dispersion**
  - **-- transverse dispersion**
  - -- diffusion

- Phase Transfers
  - -- solid <-> liquid
    - sorption
    - equilibrium isotherm
    - linear

- Fate
  - -- first-order radioactive decay
  - -- single mother/daughter decay
  - -- first-order chemical decay
  - -- first-order microbial decay

4.3. Boundary Conditions

- First type - Dirichlet
  - -- Chemical processes embedded in transport equation
  - -- concentration

- Second type - Neumann (Prescribed Solute Flux)
  - -- areal boundaries
  - -- injection wells
  - -- point sources
  - -- line sources

4.4. Solution Methods for Transport
- General Method
  - -- areal sources
  - -- uncoupled flow and transport equation

- Analytical
  - -- single solution
  - -- superposition

4.5. Output Characteristics for Transport
- Simulation Results
  - -- concentration in aquifer/soil
    - - ASCII file (areal values)

## 5. Evaluation

5.1. Verification/Validation
- verification (analytical solutions)

5.2. Internal Code Documentation (Comment Statements)
- incidental

5.3. Peer (Independent) Review
- concepts
- theory (math)
- coding
- documentation

## 6. Documentation and Support

6.1. Documentation Includes
- model theory
- user's instructions
- example problems
- program structure and development
- code listing
- verification/validation

6.2. Support Needs
- Can be used without support
- Support is available
  - -- from third party

6.3. Level of Support
- limited

## 7. Availability

7.1. Terms
- available
- public domain

7.2. Form
- source code only (tape/disk)
- source and compiled code
- paper listing of source code

## 8. Pre and Post Processors

8.1. Data Preprocessing
- data preprocessing available
- part of model package (e.g. under a shell; dedicated)

8.2. Capabilities (Preprocessing)
- textual data entry/editing
- error-checking

8.3. Data Postprocessing
- data postprocessing (output manipulation)
- part of model package (e.g. under a shell; dedicated)

8.4. Capabilities (Postprocessing)
- textual data display on screen/printer
- reformatting (e.g. to standard formats)

## 9. Institution of Model Development

9.1. Name
- Oak Ridge National Laboratory

9.2. Address
- Environmental Sciences Division
  Oak Ridge, Tennessee 37830

9.3. Type of Institution
- research institute

## 10. Remarks

This model is available from the International Ground Water Modeling Center:

IGWMC USA: Institute for Ground-Water Research and Education
Colorado School of Mines
Golden, CO 80401
USA

IGWMC Europe : TNO Institute of Applied Geoscience
P.O. Box 6012, 2600 JA Delft
The Netherlands

## 11. References

Yeh, G.T. 1981. AT123D: Analytical Transient One-, Two-, and Three-Dimensional Simulation of Waste Transport in the Aquifer System. ORNL-5602, Oak Ridge National Lab., Oak Ridge, Tennessee.

Thomas, S.D., B. Ross, and J.W. Mercer. 1982. A Summary of Repository Siting Models. NUREG/CR-2782, U.S. Nuclear Regulatory Commission, Washington, D.C.

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# Model Description For

# MT3D

**SOURCE:**
**INTERNATIONAL GROUND WATER MODELING CENTER (IGWMC)**

# MT3D
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# MT3D

## 1. Model Identification

1.1. Model Name
- MT3D (Modular Transport in 3 Dimensions

1.2. Date of First Release
- 1990

1.3. Current Version
- 1.5

1.4. Current Release Date
- 3/92

1.5. Authors
- 1. Zheng, C.

## 2. Model Information

2.1. Model Category
- mass transport

2.2. Model Developed For
- research (e.g. hypothesis/theory testing)
- general use (e.g. in field applications)

2.3. Units of Measurement Used
- metric units

2.4. Abstract

MT3D is a three-dimensional contaminant transport model using a hybrid method of characteristics. Two numerical techniques are provided for the solution of the advective-dispersive reactive solute transport equation: the method of characteristics (MOC) and the modified method of characteristics (MMOC). The MMOC method overcomes many of the traditional problems with MOC, especially in 3D simulations, by directly tracking nodal points backwards in time and by using interpolation techniques. MT3D selectively uses the MOC or the MMOC technique dependent on the problem at hand. The transport model is so structured that it can be used in conjunction with any block-centered finite difference flow model such as the USGS MODFLOW model.

2.5. Data Input Requirements

Data input requirements are provided in the model documentation and are discussed in the introduction to Section 4.0 of the *Compendium*.

2.6. Versions Exist for the Following Computer Systems

- minicomputer
- mainframe-microcomputer
- make/model
  - -- IBM PC or compatible
- operating system
  - -- DOS 2.0 or higher

2.7. System Requirements

- core memory (RAM) for execution (bytes)
  - -- 3.5Mb extended memory
- mass storage (disk space in bytes)
  - -- 3Mb
- numeric/math coprocessor (for microcomputers)
- compiler required (e.g. for mainframe)
- language
  - -- FORTRAN 77

2.8. Graphics Requirements

- none

2.9. Program Information

- programming language/level
  - -- FORTRAN 77

## 3. General Model Capabilities

3.1. Parameter Discretization

- distributed

3.2. Spatial Orientation

- saturated flow
- 3D-fully
- 3D-layered

## 4. Mass Transport Characteristics

4.1. Water Quality Constituents
- any component(s)
- single component
- total dissolved solids (TDS)
- inorganics
- organics
- radionuclides

4.2. Processes Included
- (Conservative) Transport
  - -- advection
  - -- longitudinal dispersion
  - -- transverse dispersion
  - -- diffusion

- Phase Transfers
  - -- solid <-> liquid
    - - sorption
    - - equilibrium isotherm
    - - linear
    - - Langmuir
    - - Freundlich

- Fate
  - -- first-order radioactive decay
  - -- single mother/daughter decay
  - -- first-order chemical decay
  - -- first-order microbial decay

4.3. Boundary Conditions
- First Type - Dirichlet
  - -- chemical processes embedded in transport equation
  - -- concentration

- Second Type - Neumann (Prescribed Solute Flux)
  - -- areal boundaries
  - -- injection wells
  - -- point sources
  - -- line sources

4.4. Solution Methods for Transport
- General Method
  - -- areal sources
  - -- uncoupled flow and transport equation

- Time-Stepping Scheme
  - -- fully implicit

- Spatial Approximation

- Matrix-Solving Technique
  - -- numerical
  - -- particle-tracking
  - -- method of characteristics

4.5. Output Characteristics for Transport
- Simulation Results
  - -- concentration in aquifer/soil
    - - ASCII file (areal values)
    - - ASCII file (time series)
  - -- concentration in well
    - - ASCII file (time series)
  - -- mass balance components
    - - ASCII file (global total area)

## 5. Evaluation

5.1. Verification/Validation
- verification (analytical solutions)

5.2. Internal Code Documentation (Comment Statements)
- incidental

## 6. Documentation and Support

6.1. Documentation Includes
- model theory
- user's instructions
- example problems
- program structure and development
- verification/validation

6.2. Support Needs
- Support is available
  - -- from author
  - -- from third party

6.3. Level of Support
- full

## 7. Availability

7.1. Terms
- available
- public domain
- proprietary

7.2. Form
- source code only (tape/disk)
- source and compiled code

## 8. Pre and Post Processors

8.1. Data Postprocessing
- data postprocessing (output manipulation)
- part of model package (e.g. under a shell; dedicated)

8.2. Capabilities (Postprocessing)
- textual data display on screen/printer
- reformatting (e.g. to standard formats)

## 9. Institution of Model Development

9.1. Name
- S.S. Papadopulos & Assoc., Inc.

9.2 Address
- 12250 Rockville Pike
  Rockville, Maryland

9.3 Type of Institution
- consultant

## 10. Remarks

The MT3D code is distributed together with a version of the USGS flow model MODFLOW, including the PCG2 solver. The code has been developed with support of the U.S. Environmental Protection Agency and is available from:

Center for Subsurface Modeling Support
R.S. Kerr Environmental Research Laboratory
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, OK 74820
Phone: 405/332-8800

## 11. References

Zheng, C. 1990. MT3D, A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems. Report prepared by S.S. Papadopulos & Associates, Inc., Rockville, Maryland, for EPA/RSKERL, Ada, Oklahoma.

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# Model Description For

# MODPATH

**SOURCE:**
**INTERNATIONAL GROUND WATER MODELING CENTER (IGWMC)**

# MODPATH
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# MODPATH

## 1. Model Identification

1.1. Model Name
- MODPATH

1.2. Date of First Release
- 1988

1.3. Current Release Date
- 1988

1.4. Authors
- 1. Pollock, D.W.

## 2. Model Information

2.1. Model Category
- particle tracking

2.2. Model Developed For
- general use (e.g. in field applications)

2.3. Units of Measurement Used
- metric units
- US customary units
- any consistent system

2.4. Abstract

MODPATH is a postprocessing package to compute three-dimensional pathlines based on the output from steady-state simulations obtained with the USGS MODFLOW ground-water flow model. The package consists of two FORTRAN 77 computer programs: 1) MODPATH, which calculates pathlines, and 2) MODPATH-PLOT, which presents results graphically. MODPATH uses a semi-analytical particle tracking scheme, based on the assumption that each directional velocity component varies linearly within a grid cell in its own coordinate direction. Data is input to MODPATH through a combination of files and interactive dialogue. The MODPATH-PLOT program comes in two versions, one for use with the DISSPLA graphics routines library, and one that uses the Graphical Kernel System (GKS).

2.5. Data Input Requirements

Data input requirements are provided in the model documentation and are discussed in the introduction to Section 4.0 of the *Compendium*.

2.6. Versions Exist for the Following Computer Systems

- minicomputer
- workstations
- mainframe
- microcomputer
- make/model
  - -- Prime
  - -- IBM PC/386

2.7. System Requirements

- core memory (RAM) for execution (bytes)
  - -- 640K
- mass storage (disk space in bytes)
  - -- 3M
- numeric/math coprocessor (for micro computers)
- compiler required (e.g. for mainframe)
- language
  - -- FORTRAN 77
- resident software
  - -- DISSPLA or GKS routines

2.8. Graphics Requirements

- type/mode/convention
  - -- various
- resident graphics drivers
  - -- DISSPLA or GKS
- plotter make/model
  - -- various

2.9. Program Information

- programming language/level
  - -- FORTRAN 77

## 3. General Model Capabilities

3.1. Parameter Discretization

- distributed

3.2. Spatial Orientation
- saturated flow
- ID-horizontal
- ID-vertical
- 2D-horizontal
- 2D-vertical
- 3D-fully
- 3D-layered

## 4. Flow Characteristics

4.1. Flow System Characterization
- Saturated zone

- System
  - -- single aquifer
  - -- single aquifer/aquitard system
  - -- multiple aquifer/aquitard systems

- Aquifer Type(s)
  - -- confined
  - -- semi-confined (leaky-confined)
  - -- unconfined (phreatic)

- Medium
  - -- porous media

- Parameter Representation
  - -- homogeneous
  - -- heterogeneous
  - -- isotropic
  - -- anisotropic

- Flow Characteristics (Saturated Zone)
  - -- laminar flow
  - -- linear (Darcian flow)
  - -- steady-state

4.2. Fluid Conditions
- Single fluid flow
  - -- water

4.3. Boundary Conditions
- First type - Dirichlet
- Second type - Neumann (Prescribed Flux)
- Third type - Cauchy

4.4. Solution Methods for Flow

- General Method
  - -- semi-analytical
  - -- approximate analytical solution

4.5. Grid Design

- Cell/Element Characteristic
  - -- constant cell size
  - -- variable cell size

- Possible Cell Shapes
  - -- 2D-square
  - -- 2D-rectangular
  - -- 3D-cubic

- Maximum Number of Nodes
  - -- 5000
    - -3D-hexahedral

4.6. Output Characteristics

- Simulation Results
  - -- streamlines/pathlines
    - - binary file (spatial values)
    - - ASCII file (spatial values)
    - - screen display (spatial values)
    - - paper copy (spatial values)
    - - graphics (spatial values)
  - -- traveltimes
    - - binary file (areal values)
    - - ASCII file (areal values)
    - - screen display (areal values)
    - - paper copy (areal values)
    - - graphics (areal values)
  - -- isochrones
    - - binary file (areal values)
    - - ASCII file (areal values)
    - - screen display (areal values)
    - - paper copy (areal values)
    - - graphics (areal values)

## 5. Evaluation

5.1. Internal Code Documentation (Comment Statements)
- incidental

5.2. Peer (Independent) Review
- concepts
- theory (math)
- documentation

## 6. Documentation and Support

6.1. Documentation Includes
- model theory
- user's instructions
- example problems
- program structure and development
- code listing

6.2. Support Needs
- Can be used without support
- Support is available
  - -- from author
  - -- from third party

6.3. Level of Support
- limited

## 7. Availability

7.1. Terms
- available
- public domain

7.2. Form
- source code only (tape/disk)
- source and compiled code
- compiled code only
- paper listing of source code

## 8. Pre and Post Processors

8.1. Data Preprocessing
- data preprocessing available
- include in simulation model (dedicated)

8.2. Capabilities (Preprocessing)
- textual data entry/editing

8.3. Data Postprocessing
- data postprocessing (output manipulation)
- include in simulation model (dedicated)

8.4. Capabilities (Postprocessing)
- textual data display on screen/printer
- graphic display spatial data
- graphic plotting

## 9. Institution of Model Development

9.1. Name
- Water Resources Division, U.S. Geological Survey

9.2. Address
- 411 National Center
  Reston, VA 22092

9.3. Type of Institution
- federal/national government

## 10. Remarks

MODPATH: a particle-tracking program developed by the USGS for use with the MODFLOW model. MODPATH calculates the path a particle would take in a steady-state three-dimensional flow field in a given amount of time. It operates as a postprocessor for MODFLOW using heads, cell-by-cell flow terms, and porosity to move each particle through the flow field. The program handles both forward and backward particle tracking. (See also IGWMC Key 3984.)

MODPATH-PLOT: a graphic display program for use with MODPATH-PC. It uses the Graphical Kernal System (GKS) to produce graphical output on a wide range of commonly used printers and plotters. MODPATH-PLOT comes with MODPATH.

This model is available from the International Ground Water Modeling Center:

IGWMC USA
Institute for Ground-Water Research and Education
Colorado School of Mines
Golden, CO 80401
USA

IGWMC Europe
TNO Institute of Applied Geoscience
P.O. Box 6012, 2600 JA Delft
The Netherlands

This model is also available from:

Scientific Software Group
P.O. Box 23041
Washington, D.C. 20026-3041
Tel. 703/620-9214

An IBM PC/386 extended-memory version of this model is also available from:

Geraghty & Miller, Inc.
Modeling Group
10700 Park Ridge Blvd., Suite 600
Reston, VA 22091
Tel. 703/758-1200
Fax 703/758-1204

MPATHIN is a textual input processor for MODPATH, prepared by TECSOFT, Inc., and available from Scientific Software Group, Washington, D.C.

## 11. References

Pollock, D.W. 1989. Documentation of Computer Programs to Compute and Display Pathlines Using Results from the U.S. Geological Survey Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Open-File Report 89-381, U.S. Geological Survey, Reston, Virginia.

Pollock, D.W. 1990. A Graphical Kernel System (GKS) Version of Computer Program MODPATH-PLOT for Displaying Path Lines Generated from the U.S. Geological Survey Three-Dimensional Ground-Water Flow Model. Open-File Report 89-622, U.S. Geological Survey, Reston, Virginia.

Pollock, D.W. 1988. Semianalytical Computation of Path Lines for Finite-Difference Models. Ground Water, Vol. 26(6), pp. 743-750.

# Model Description For

# WHPA

**SOURCE:**
**INTERNATIONAL GROUND WATER MODELING CENTER (IGWMC)**

# WHPA
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# WHPA

## 1. Model Identification

1.1. Model Name
- WHPA (Well Head Protection Area delineation model)

1.2. Date of First Release
- 2/90

1.3. Current Version
- 2.1

1.4. Current Release Date
- 04/92

1.5. Authors
- 1. Blandford, T.N.
- 2. Huyakorn, P.S.

## 2. Model Information

2.1. Model Category
- ground-water flow

2.2. Model Developed For
- general use (e.g. in field applications)

2.3. Units of Measurement Used
- metric units
- US customary units
- any consistent system

2.4 Abstract

WHPA is an integrated program of analytical and semi-analytical solutions for the ground-water flow equation coupled with pathline tracking. It is designed to assist technical staff with delineation of wellhead protection areas. Developed for the U.S. EPA's Office of Groundwater Protection, the package includes modules for capture zone delineation in a homogeneous aquifer with 2-dimensional steady-state flow with options for multiple pumping/injection wells and barrier or stream boundary conditions. Also included are modules for Monte Carlo analysis of uncertainty and a particle-tracking

postprocessor for numerical flow models such as MODFLOW and PLASM, using a two-dimensional rectangular grid.

WHPA-GPTRAC is the WHPA module used to delineate time-related capture zones for pumping wells in homogeneous aquifers with steady & uniform ambient ground-water flow (semi-analytical option) and also delineates time-related capture zones about pumping wells for steady ground-water flow fields (numerical option).

WHPA-MWCAP is the WHPA module used to delineate steady-state, time-related or hybrid capture zones for pumping wells in homogenous aquifers with steady and uniform ambient ground-water flow. If multiple wells are examined, the effects of well interference are ignored.

WHPA-RESSQC is the WHPA module used to delineate time-related capture zones around pumping wells, or contaminant fronts around injection wells, for multiple pumping and injection wells in homogeneous aquifers of infinite areal extent with steady and uniform ambient ground-water flow. Well interference effects are accounted for.

WHPA-MONTEC is the WHPA module for Monte Carlo analysis of uncertainty and a particle-tracking postprocessor for numerical flow models such as MODFLOW and PLASM, using a two-dimensional rectangular grid.

2.5. Data Input Requirements

Data input requirements are provided in the model documentation and are discussed in the introduction to Section 4.0 of the *Compendium*.

2.6. Versions Exist for the Following Computer Systems

- microcomputer
- make/model
  - -- IBM PC/AT
- operating system
  - -- DOS 2.0 or higher

2.7. System Requirements

- core memory (RAM) for execution (bytes)
  - -- 640K

2.8. Graphics

- type/mode/convention
  - -- CGA

2.9. Program Information
- programming language/level
  - -- FORTRAN 77

## 3. General Model Capabilities

3.1. Parameter Discretization
- distributed

3.2. Coupling
- N.A.

3.3. Spatial Orientation
- saturated flow
- 2D-horizontal

3.4. Types of Possible Updates
- parameter values
- boundary conditions

3.5. Geostatistics and Stochastic Approach
- Monte Carlo simulation

3.6 Comments
- This model has restart capability.

## 4. Flow Characteristics

4.1. Flow System Characterization
- Saturated Zone

- System
  - -- single aquifer

- Aquifer Type(s) Present
  - -- confined
  - -- semi-confined (leaky-confined)
  - -- unconfined (phreatic)

- Medium
  - -- porous media

- Parameter Representation
  - -- homogeneous
  - -- heterogeneous
  - -- isotropic
  - -- anisotropic

- Flow Characteristics (Saturated Zone)
  - -- laminar flow
  - -- linear (Darcian flow)
  - -- steady-state

4.2. Fluid Conditions
- Single Fluid Flow
  - -- water

4.3. Boundary Conditions
- First type - Dirichlet
  - -- head/pressure

- Second type - Neumann (Prescribed Flux)
  - -- injection/production wells
  - -- no flow boundary
  - -- areal boundary flux
  - -- groundwater recharge

4.4. Solution Methods for Flow
- General Method
  - -- analytical
    - - single solution
    - - superposition
  - -- semi-analytical
    - - continuous in time, discrete in space
    - - approximate analytical solution

4.5. Grid Design
- maximum number of nodes
  - -- 0

4.6. Flow Output Characteristics
- Simulation Results
  - -- head/pressure/potential
    - - ASCII file (areal values)
    - - screen display (areal values)
    - - graphics (areal values)

- -- head differential/drawdown
  - ASCII file (areal values)
  - screen display (areal values)
  - graphics (areal values)
- -- streamlines/pathlines
  - screen display (spatial values)
  - graphics (spatial values)
- -- traveltimes
  - ASCII file (areal values)
  - screen display (areal values)
- -- isochrones
  - screen display (areal values)
  - graphics (areal values)

## 5. Evaluation

5.1. Verification/Validation
- verification (analytical solutions)

5.2. Peer (Independent) Review
- concepts - theory (math)
- documentation
- usability

## 6. Documentation and Support

6.1. Documentation Includes
- model theory
- user's instructions
- example problems
- verification/validation

6.2. Support Needs
- Can be used without support
- Support is available
  - -- from author

6.3. Level of Support
- full

## 7. Availability

7.1. Terms
- available
- public domain

7.2. Form
- compiled code only

## 8. Pre and Post Processing

8.1. Data Preprocessing
- data preprocessing available
- include in simulation model (dedicated)

8.2. Capabilities (Preprocessing)
- textual data entry/editing
- error-checking
- help screens

8.3. Data Postprocessing
- data postprocessing (output manipulation)
- include in simulation model (dedicated)

8.4. Capabilities (Postprocessing)
- textual data display on screen/printer
- graphic display spatial data

## 9. Institution of Model Development

9.1. Name
- Hydrogeologic, Inc.

9.2. Address
- Herndon, Virginia

9.3. Type of Institution
- consultant

## 10. Remarks

This model is available from the International Ground Water Modeling Center:

| | |
|---|---|
| IGWMC USA | Institute for Ground-Water Research and Education<br>Colorado School of Mines<br>Golden, CO 80401<br>USA |
| IGWMC Europe | TNO Institute of Applied Geoscience<br>P.O. Box 6012, 2600 JA Delft<br>The Netherlands |

## 11. References

Blandford, T.N., and P.S. Huyakorn. 1991. WHPA; A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0. U.S. Environmental Protection Agency, Office of Ground-Water Protection, Washington, D.C.

## 12. Users

Kilborn, K., H.S. Rifai, and P.B. Bedient. 1992. Connecting Groundwater Models and GIS. Geo Info Systems, Vol 2, No. 2, pp. 26-31. Discussing the linkage of WHPA with System 9 GIS of Computervision running on a SUN workstation. The linkage is illustrated for a project for the city of Houston, Texas. Based on: The Integration of Groundwater Models and Geographic Information Systems (GIS), Technical Papers 1991, ACSM-ASPRS Annual Convention, Volume 2, pp. 150-159.

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