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Evaluation of the Air Force Installation Restoration Advisory System

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INSTALLATION RESTORATION ADVISORY SYSTEM

THESIS

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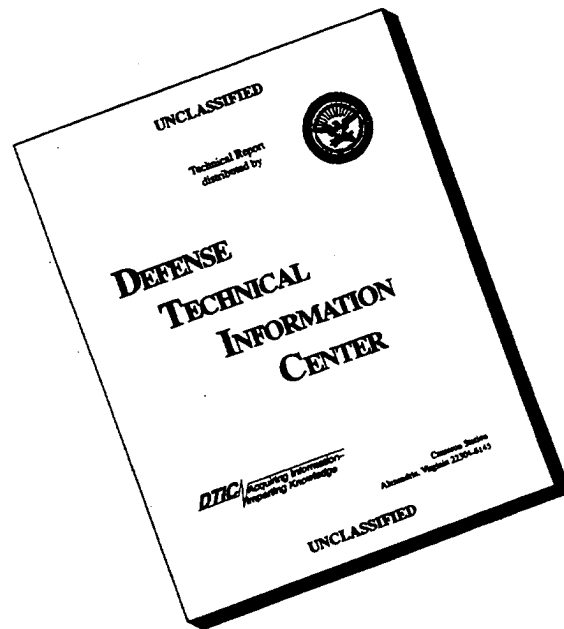
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EVALUATION OF THE AIR FORCE

INSTALLATION RESTORATION ADVISORY SYSTEM

THESIS

Presented to the Faculty of the School of Engineering

Air University

in Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering and Environmental Management

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Abstract

This research is intended to evaluate the Air Force's Installation Restoration Advisory System Workstation software and documentation. Groundwater modeling is the biggest aid to Air Force Installation Restoration decision makers in making their conclusions about what to do with their hazardous waste sites where the groundwater is contaminated. The Advisory System aids the user in determing if a site poses a potential problem, and if so assists the user in selecting an apporpriate groundwater transport model. The decision of what type of model is most suitable is based upon the user's conceptual site model and the decision is made by the model selection algorithm CHOICE, contained within the Advisory System. The research consisted of reviewing the components of the Advisory System separately, reviewing the types of groundwater models available to the System, and testing the CHOICE algorithm by applying it to an Air Force Installation Restoration Program site, located at Robins Air Force Base, Georgia. The conclusions of the research are that the System is usable in its present state, once some documentation errors are corrected, that the controlling factor in model selection is the user's own concept of the site, and that further modification of the CHOICE algorithm is required to incorporate all of the models available to the System.

EVALUATION OF THE AIR FORCE INSTALLATION RESTORATION ADVISORY SYSTEM

Chapter One - Introduction

Background

Groundwater contamination exists in 85% of the U.S. Environmental Protection Agency's (EPA) 1208 National Priorities List (NPL) sites; those sites deemed contaminated enough to qualify for the 'Superfund'. In addition to the NPL sites, there are an additional 33,000 contaminated sites in the EPA's Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Informational System (CERCLIS) (Olsen and Kavanaugh, 1993:42). If the 85% proportion holds constant for the remaining CERCLIS sites, that means another 28,050 sites with contaminated groundwater. There are also over 1700 sites identified by the Resource Conservation and Recovery Act (RCRA) as requiring clean up (Olsen and Kavanaugh, 1993:42), an unidentified number of leaking underground storage tanks, and over 21,000 contaminated sites throughout the Department of Defense (DOD, 1995: 71). Since 50% of the population of the U.S. uses groundwater as its primary drinking source, this is an immense problem (Jensen, 1993: 250). These sites must be cleansed.

The Department of Defense (DOD) is engaged in its own program to identify, assess, and remediate hazardous waste sites at its bases. The Air Force's Installation Restoration Program (IRP) is modeled after CERCLA and RCRA and is currently estimated to have a final cost of $26.5 billion (DOD, 1995: B-7-2). Combining the public and private sectors, the estimated cost for groundwater contamination where a source can be pinpointed is

over $750 billion with an estimated cleanup time of 75 years (Bredehoeft, 1994: 97). In the IRP alone, over 75% of the sites involve groundwater contamination.

One of the most important sources of information for a groundwater decision maker comes from groundwater flow and contaminant transport models. These models are used to estimate the amount of contaminant in the groundwater, the location of the contaminant, the velocity of the groundwater, and the effect various treatment alternatives will have on the contaminated groundwater (Goltz, 1991:24).

There are numerous computer-based models available presently, both public domain and privately owned. Deciding what type of model is appropriate for a specific site and under what conditions a specific model is valid is an extremely complicated issue. The user must choose between the (presumed) greater accuracy of a complicated numerical model and the easier to use, less data-intensive analytical model (Medina, 1994b, v). This thesis will focus on these decisions and how they are made.

To assist Air Force IRP decision makers in these complex issues, the Air Force's Armstrong Laboratory awarded a contract to Miguel A. Medina and Timothy L. Jacobs of Duke University in 1991. The intent of the contract was to create a groundwater advisory system that would "define the magnitude, extent, direction and rate of movement of identified contaminants; identify significant public health and environmental hazards of migrating pollutants; recommend candidate remedial actions; maintain databases of model parameters; and accomplish other supporting tasks (Medina, 1994b, 1)." Their final report was accepted in June of 1994.

Specific Problem

The purpose of this research is to analyze the Installation Restoration Advisory System, concentrating upon the CHOICE model-selectionalgorithm created by Medina and Jacobs, by applying the Advisory System to an actual IRP site.

Research Objectives

The specific objectives of the research are to:

1. Determine if a typical IRP site's reports contain the data necessary to allow CHOICE to make a decision and subsequently model the site. Since there are numerous reports throughout a site's history, we will be looking at the chronological changes in the database to ascertain when the CHOICE algorithm is most effective.

2. Perform a sensitivity analysis on the CHOICE algorithm to determine the variables or assumptions that most directly effect the model selection.

3. Determine if the package is usable in its current form. Can the package do what it is designed to do presently, or are changes required for it to function as the Air Force requires?

Scope and Limitations

1. The case study will be limited to one IRP site, Landfill No. 2 (LF02) located at Robins Air Force Base (RAFB), Georgia. The site has been under the supervision of the author for three years.

2. The optimization algorithm embedded within the groundwater advisory system will not reviewed because it is outside the scope of this research.

Overview

IRP decision makers utilize groundwater transport models to estimate the amount of contaminant in the groundwater, the location of the contaminant, and the effect various remediation alternatives will have on the hazardous sites. This Chapter has overviewed groundwater modeling and the problems involved in the process, the most important being what model to use at a specific site. A groundwater advisory system has been created by Medina and Jacobs for the Air Force to help answer this question. This chapter has identified questions about the algorithm that the Air Force wants answered and described the exact scope of the research.

Chapter II discusses the background associated with the research. The chapter discusses how models are created, their limitations, and why groundwater modeling is essential to the Air Force IRP program. Next, the chapter reviews the different types of models available within the groundwater advisory system, the mathematics involved with each, and how they compare with one another. The chapter concludes with a brief discussion about some of the components of the groundwater advisory system.

Chapter III begins with an in-depth review of the CHOICE algorithm. It then presents a brief review of the IRP program and LF02. We then describe our methodology for testing the Advisory System by using the data from LF02. We conclude by testing the Advisory System with the LF02 data.

In Chapter IV we begin by describing our methodology for answering the research objectives. We then analyze CHOICE's decisions and look for what variables are most important in those decisions. We also assess the user interfaces, pre- and post processors

attached to the various models in the groundwater advisory system for ease of use and ease of interpretation, and the documentation provided with the system. We close with conclusions, offer suggestions to improve the system, and provide recommendations for further research.

Chapter 2 - Background

Groundwater Modeling

Remediation has been in progress at some sites since the mid-1970's; however the majority of the sites remain contaminated and costs continue to rise. In the realm of groundwater clean up, the amount of research required before any remediation begins is enormous, and as time passes the costs increase. Historically, more money is spent in investigation than in actual remediation. In the Air Force, until recently the mix has been 60-70 percent investigation and 30-40 percent remediation actions. Fiscal year 1994 is the first year ever that more money was spent on remediation than investigation (DOD, 1995: 65).

For a typical groundwater cleanup site, an 80% increase in cost and a 300% increase in clean up time from the initial estimates is about average (Olsen and Kavanaugh, 1993: 3). A good deal of the blame for these overruns can be laid upon groundwater models and the process whereby they are created. One must first be able to reliably predict the rate and direction of groundwater flow before contaminant transport can be modeled and only then can you create a plan and implement a groundwater remediation scheme (EPA, 1992: 1). Other problems which drive the increases vary, but can almost invariably be traced back to an incomplete or incorrect conceptual site model (CSM). If the conceptual model is wrong in the beginning, the remainder of the modeling efforts will be a waste of time and money (EPA, 1992: 8).

The EPA, which regulates the majority of the Air Force's groundwater modeling activities, has created a template which groundwater modelers are expected to follow (Fig. 1) (EPA, 1992: 6). This template illustrates an iterative process in which improvement is made as data becomes available to refine the conceptual model, as well as the mathematical model which is built from the conceptual model. The EPA defines a model as "a simplified version of a real-world system...that approximately simulates the relevant excitation response relations in the real world system (EPA, 1992: 2)." Real-world systems are incredibly complex and simplifications must be made in order to make a decision in a reasonable time frame. These simplifications are introduced as a set of assumptions that must be posed in terms of a mathematical model. The mathematical model consists of partial differential equations together with appropriate boundary conditions and initial conditions that express conservation of mass and that describe continuous variables (for example, hydraulic head) over the region of interest (Mercer and Faust, 1981: 2). There are numerous assumptions to be made, both in the choice of the process to be modeled and the way they are implemented in the model (Carrera et al, 1993: 203). These assumptions are the foundation upon which the modeler bases his model with differing assumptions leading to different models. The CHOICE algorithm by selects an appropriate model based upon the users inputs and assumptions.

The first step in the modeling process is the creation of a conceptual model. The modeler first obtains all the relevant data possible and attempts to create an internally consistent framework (Mercer, 1991: 1). This data is then translated into a mathematical model in the form of governing equations, with associated boundary and initial conditions.

Figure 2-1 EPA Model Selection Process
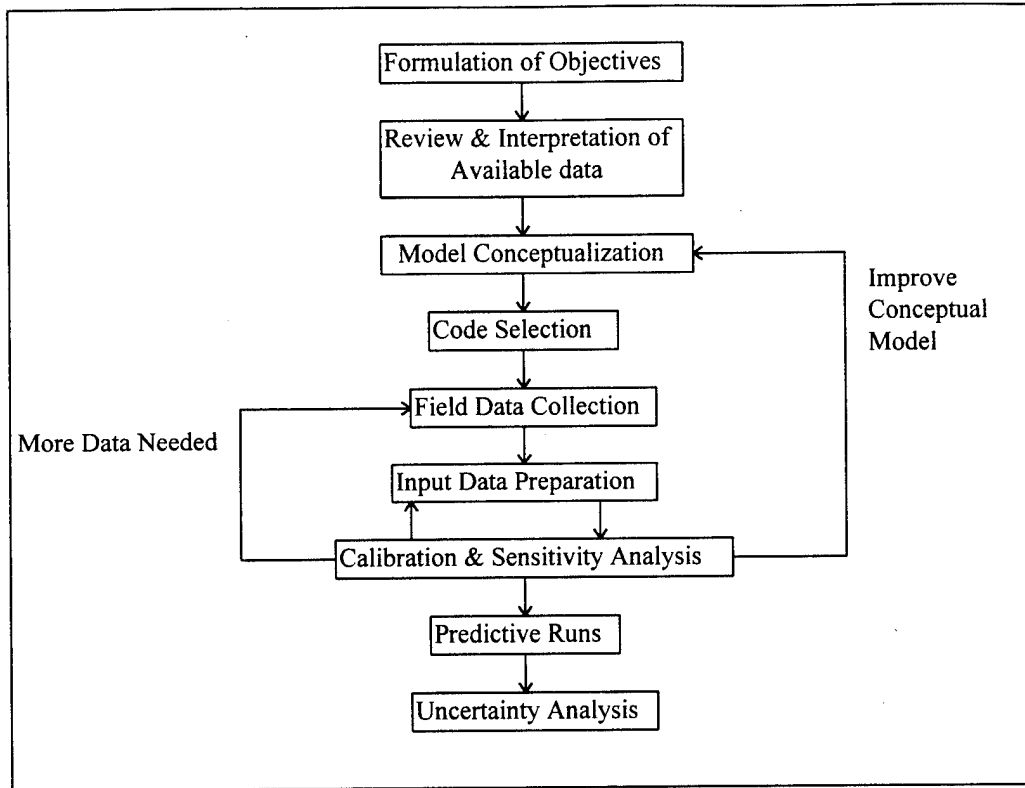
There are numerous causes for an improper model to be created: not enough data gathered (a minimum of one year is recommended to account for seasonal variations in groundwater flow); incorrect assumptions; improper model selection, and others (Mercer, 1991: 3). But the most likely problem is that when modeling natural phenomena, modelers seldom know the **true** physical and chemical processes they are attempting to model (EPA, 1992: 7). Even if the modelers somehow did know the processes, translating this understanding into mathematical models for numerical implementation would be a formidable task. The complex computer programs available today use numerous simplifying assumptions to try to accurately model the natural processes.

Replacing the simplifying assumptions with actual representations of the processes would complicate the programs beyond practicality. Therefore, it is not surprising that model predictions are highly inaccurate and in some cases completely wrong (Carrera et al, 1993: 201).

If these groundwater models are so inaccurate and unreliable, why do engineers, geologists, and hydrogeologists all use them? Because they have no other alternatives (EPA, 1992: 8). If we don't use the models, as inaccurate and questionable as they are, we have no reasonable way to know the location of the contaminant or where it is going other than testing the water as it comes out of the ground. That option cannot be allowed to happen for health safety reasons. Consequently, we try to continually improve the models and our understanding of the processes linked to them.

Model conceptualization is somewhat subjective and dependent on the modeler's ingenuity, experience, scientific background, and way of looking at the data (Carrerra et al, 1993: 203). Taking the subjectivity out of the modeling process is necessary for a site to be handled correctly through the years at an Air Force base with its turnover in personnel. It was for this purpose that the Air Force contracted Medina and Jacobs to create the groundwater advisory system to help IRP managers choose the correct groundwater model to utilize at their respective sites.

Mathematical Background for Groundwater Modeling

The flow of groundwater can customarily be described by one mathematical equation, usually in terms of hydraulic head. When water quality becomes an issue, then an additional equation(s) to the groundwater flow equation must be solved for the

concentration(s) of the chemical specie(s). Such models are termed solute transport models (Mercer and Faust, 1991: 3). The first step in creating the model is to determine the boundaries of the region to be modeled. The boundaries may be physical (impermeable region, specified flux, or constant hydraulic head) or chosen for convenience (a small area of a larger aquifer). Then the general aquifer parameters must be researched so that the model can be run.

Once a solute transport model is completed, it can be used to predict the future behavior of the aquifer modeled. It allows estimation of: (a) recharge (both natural and induced) due to leakage from confining beds, (b) effects of boundaries and boundary conditions, (c) the effects of well locations and spacing, and (d) the effects of various withdrawal (or injection) rates (Mercer and Faust, 1981: 6). There are other purposes for prediction including the one we are interested for this research, which is the estimation of the rates of movement of hazardous waste from sanitary landfills.

All groundwater flow modeling starts with the flow equation, which is based upon the principles of conservation of mass, energy, and momentum. These principles require that the net quantity (mass, energy, and momentum) leaving or entering a system during a given time interval be equal to the change in the amount of that quantity stored in the volume (Mercer and Faust, 1981: 11). This results is a set of partial differential equations in three dimensional space, normally using the Cartesian coordinate system. The final result is the unsteady saturated groundwater flow equation for three dimensions:

Equation 2-1

$$\overline{\nabla} \cdot \overline{\overline{K}} \cdot \overline{\nabla} h + R = S_s \frac{\partial h}{\partial t}$$

Where h is the hydraulic head, $\overline{\overline{K}}$ is the hydraulic conductivity tensor, R is the general source/sink term, S_S is the specific storage, and $\overline{\nabla}$ is a differential operator. In general, $\overline{\overline{K}}$, S_S, and R can vary from point to point in an aquifer (they are all functions of x, y, and z). Equation 2-1 is what is called a diffusion-type equation and it uses the principles of mass and momentum conservation.

Thus far we have reviewed an equation to model the flow of fluids within a porous media. A step up in complexity is modeling transport, which deals with predicting the movement and concentration of contaminant-laden groundwater (Van der Heijde, 1993: 8). These equations are much more difficult because there is more than one liquid to deal with at the same time. When there are other processes involved, such as solute transport, a more general form of Equation (2-1) is needed. Saturated flow is still assumed.

Equation 2-2

$$\overline{\nabla} \cdot \frac{\rho \, \overline{\overline{k}}}{\mu} \cdot (\overline{\nabla} p + \rho \, g \, \overline{\nabla} z) + \rho \, R = \frac{\partial \, (\phi \, \rho)}{\partial \, t}$$

Where ρ is water density, g is the gravitational constant, μ is dynamic viscosity, ϕ is porosity and $\overline{\overline{k}}$ is the intrinsic permeability tensor. Generally ρ is constant, while μ, R, and ϕ will depend on the fluid pressure, the concentration of dissolved materials, and the fluid temperature.

In order to accurately describe the transport of chemical species in groundwater, the transport equation must be solved simultaneously with the groundwater flow equation. The groundwater flow equation can be used to determine the velocity field, but to

determine the movement of the material an additional equation is required. The requisite equation is created by again creating a mass balance and may be written:

Equation 2-3

$$\overline{\nabla} \cdot \phi \, \overline{\overline{D}} \cdot \overline{\nabla} C - \overline{\nabla} \cdot \overline{q} \, C + R C^* = \frac{\partial \, (\phi \, C)}{\partial \, t}$$

Where C is the material concentration, C^* is the concentration of the source/sink term, and $\overline{\overline{D}}$ is the dispersion tensor. This equation is more popularly known as the advection-dispersion equation. The equation accurately describes solute transport, but determining the actual transport parameters required for solving the equation is usually quite difficult, if not impossible. Another term may be added to Equation (2-3) to handle chemical and other processes occurring within the aquifer. These processes include, but are not limited to, precipitation, oxidation/reduction, adsorption, ion exchange, and decay (Mercer and Faust, 1981: 12). There are three different categories of models that have been created to solve the solute transport equation: analytical models, semi-analytical models, and numerical models. The different model types are based upon different approaches to solving the solute transport equation.

Models of CHOICE

The CHOICE algorithm has thirteen groundwater transport models from which to select, ranging from one-dimensional analytical solution models to three-dimensional numerical models incorporating sorption and solute decay. The analytical models all require stronger assumptions to be made about the site for the models to be valid, while the numerical models have weaker assumptions and thus will accept nearly all sites. The

trade-off is made up in ease of use: the numerical models require a significant amount of data and expertise to prepare while the analytical codes are reasonably easy to set up and use.

There are three numerical models (MODFLOW, SUTRA, and BIOPLUME II) that are incorporated into the groundwater advisory system but cannot be selected by CHOICE because they are outside of its scope of knowledge. An analytical model, EPASF, is also included in the advisory system, but cannot be recommended by CHOICE either, only selected directly by the user. EPASF is used to model surface water that has been impacted by leachate, which is again outside of CHOICE's scope. In another section of the advisory system labeled Uncertainty Analysis there are three more models that have been modified to use Monte Carlo analysis to estimate the hydraulic parameters of interest to modelers (e.g. hydraulic conductivity and dispersivity). The models are ODAST-MC, TDAST- MC and MOC-MC. We shall review the analytical models first, followed by the semi-analytical, numerical, and Monte Carlo-modified models.

Analytical Models

The analytical approach uses calculus techniques to obtain an exact solution to the groundwater transport equation. The solution could be in terms of, for example, sines, cosines, exponentials or error functions. These analytic functions are typical of solutions derived in the Cartesian coordinate system. Each orthogonal coordinate system has different analytic expressions associated with it (Cleary, 1994: 4-38).

We will simplify Equation (2-3) by assuming the media being modeled is homogenous and isotropic, the flow is under steady state conditions, and there is no recharge or discharge. Unfortunately, there is a three-dimensional term in the equation, $\overline{\overline{D}}$. This term can also be simplified by assuming x_1 is in the direction of the velocity vector v, then $v_1 = v$, $v_2 = 0$, and $v_3 = 0$, and $D_{11} = \alpha_L v$, $D_{22} = D_{33} = \alpha_T v$, and $D_{ij} = 0$ if $i \neq j$. This simplification assumes α_L and α_T are the longitudinal and lateral transmissivities, respectively. These assumptions finally lead to the equation that can be solved with analytical techniques to create a closed form solution when the x axis is assumed to be aligned with the velocity vector:

Equation 2-4

$$D_L \frac{\partial^2 C}{\partial^2 x^2} + D_T \frac{\partial^2 C}{\partial^2 y^2} - v \frac{\partial C}{\partial x} - \lambda R C = R \frac{\partial C}{\partial t}$$

Where λ = natural logarithm of 2 divided by the half-life of the contaminant, called the radioactive decay constant (Javandel, Doughty, and Tsang, 1985: 13). Equation (2-4) is the form of the solute transport equation used by two of the models CHOICE can choose from (ODAST and TDAST). The other analytical models use this form with minor modifications for their specific assumptions to be valid. A brief description of each of the analytical models, including their respective assumptions and limitations follows:

ODAST   One-dimensional analytical model (assumes $\frac{\partial}{\partial y} = 0$) consisting of an infinitely long, homogenous, isotropic media with a steady-state, uniform, saturated flow. Contaminant is injected at one end of the model at time t_0 so that the concentration varies as an exponential function of time. It will calculate the concentration at a distance x from the origin and any time t, while allowing user inputs for decay and adsorption. The model assumes

a confined aquifer with a constant thickness and a **fully penetrating** source. One noticeable limitation is that ODAST cannot handle constant head boundaries, such as rivers (Javandel, Doughty, and Tsang: 1984: 14).

TDAST Two-dimensional analytical model consisting of a homogeneous, isotropic, porous media having a unidirectional steady-state, saturated flow. Utilizing a Cartesian coordinate system with the x axis oriented along the flow path of the contaminant, and initially free of contaminant, the model assumes a confined aquifer in which a contaminant is injected at time t_0, along a strip *2a* long perpendicular to flow along the y axis. The concentration of the solute is assumed to diminish exponentially with time. The model will calculate the ratio C/C_0 at any point (x,y) downstream from the origin at any time t. TDAST has the same basic limitations as ODAST (Javandel, Doughty, and Tsang: 1984: 18-19).

PLUM2D An analytical two-dimensional model for calculating the tracer concentration distribution in a homogenous, non-leaky, confined aquifer with uniform regional flow from multiple point sources. The model assumes that the medium is a confined aquifer consisting of a porous, infinite x,y plane, that the source is constant and fully penetrating. The contaminant may be subject to linear sorption and first order decay in the aqueous phase within the porous medium (Medina, 1994b: 40).

DUPVG A two-dimensional analytical model in the x-z plane (substitute $\dfrac{\partial^2 C}{\partial^2 z^2}$ in place of $\dfrac{\partial^2 C}{\partial^2 y^2}$ in Equation (4)), which considers the longitudinal and vertical distribution of contaminants. The source is represented by an infinitely long recharge basin of fixed width which recharges the aquifer at a constant rate, and there is assumed to be no pre-exisiting regional flow pattern. The model is used to calculate the approximate velocity distribution within the saturated zone and thus the contaminant distribution. Other assumptions made by the model include that the rise of the free surface is substantially less than the initial saturated thickness of the aquifer, away from the source the velocity field is essentially horizontal, and the boundaries are assumed to be constant head. There are three important limitations of the model. The first is that the solution is based upon the assumption that the distance to the constant head boundary is infinite, thus when the boundary is close to the source, the distribution of contaminants may not be accurate. Second, there can be no regional flow other than that of the source. Finally, the contaminant must be conservative (Medina, 1994b: 45-46).

EPAGW   Analytical model developed by the EPA for analysis of restrictions on land-based disposal, modeling the transport of the contaminant subject to hydrolysis and retardation. The model uses Monte Carlo simulation to create all the relevant hydrogeological variables using a national data set. The model attempts to simulate the expected risk over the range of hydrogeological conditions that are expected to occur in the region. The assumptions of steady-state, uniform flow apply. Limitations of the model are that it can only be applied in Monte Carlo mode, that it can only calculate a concentration at a point along the axis of flow, and that it only calculates a steady-state concentration ($\partial/\partial t = 0$). The assumptions of steady-state, uniform flow apply, and sources of flow other than the source are not allowed (Medina, 1994b: 48-49).

EPASF   Analytical EPA surface water model used to assess the impacts of waste disposal sites on surface waters. It estimates groundwater contaminant transport using either one- or three-dimensional flow, with or without dispersion. Since any modeling of the interaction between surface water and groundwater is extremely difficult, people are, by default, forced to use an analytical model such as EPASF to model them. The assumptions of steady-state, uniform flow apply (Medina, 1994b: 53).

Semi-Analytical Models

There are two semi-analytical models included in the advisory system, LTIRD and RESSQ. LTIRD is used in purely radial flow situations, while RESSQ is more powerful and has more possible uses. The advection-dispersion equation for radial flow in a plane may be written as:

Equation 2-5

$$\frac{1}{r}\frac{\partial}{\partial r}\left[Dr\frac{\partial C}{\partial r}\right] - V\frac{\partial C}{\partial r} = \frac{\partial C}{\partial t}$$

LTIRD uses a Laplace transform to solve the plane radial flow equation in terms of the Airy function:

Equation 2-6

$$L_D = \frac{1}{s} \cdot \exp\left(\frac{r_D - r_{DW}}{2}\right) \cdot \left(\frac{Ai(Y)}{Ai(Y_0)}\right)$$

Where L_D = Laplace Transform of dimensionless concentration, s = Laplace transform

parameter, r = radius of flow, r_D = r/α_L, r_{DW} = dimensionless well (source) diameter, Y =

$s^{-2/3}(sr_D+1/4)$ and Y_0 = $= s^{-2/3}(sr_{DW}+1/4)$. The Airy function can then be

asymptotically expanded to create a solution for the region of interest (Medina, 1994a:

53-54).

Another semi-analytical method, used by RESSQ, is based upon the theory of the

Complex Velocity Potential (CVP). The CVP's main drawback is that it only applies

only to steady-state two-dimensional fluid flows in homogeneous media. The CVP is

based upon the analytic function $W = \phi + i\psi$ with the following properties:

1. ψ and ϕ are conjugate harmonic functions in that they satisfy Laplace's equation. That is to say $\nabla^2\phi = \nabla^2\psi = 0$.
2. The functions ψ and ϕ are the stream and velocity potential functions, respectively.
3. Curves of velocity potentials ϕ = constant and streamlines ψ = constant intersect each other at right angles (Javandel, Doughty, and Tsang, 1985: 35).

Velocity potential is usually defined as $\phi = Kh+c$ so that a component of the

specific discharge (Darcy Velocity) in any arbitrary direction x is $q_x = -\frac{\partial \phi}{\partial x} = -K\frac{\partial h}{\partial x}$.

The stream function can then be obtained with a known velocity potential using the

following equations: $\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y}$ and $\frac{\partial \phi}{\partial y} = -\frac{\partial \psi}{\partial x}$. The complex velocity potential of a

Equation 2-7

$$W = \phi + i\psi = -U(x + iy)(\cos\alpha - i\sin\alpha) + c$$

$$\phi = -U(x\cos\alpha + y\sin\alpha) = constant$$

$$\psi = -U(x\sin\alpha - y\cos\alpha) = constant$$

The latter equations represent equipotentials and streamlines, respectively. The components of specific discharge in the x direction has become: $q_x = -\dfrac{\partial\phi}{\partial x} = U\cos\alpha$.

The complex velocity potential of a source strength m located at Z_0 is then

$W = m\ln(Z - Z_0) + c$ and if the source is a well being recharged at rate Q and the aquifer thickness is b, then $m = \dfrac{-Q}{2\pi b}$. The components of specific discharge then, in the x

direction is $q_x = -\dfrac{\partial\phi}{\partial x} = \dfrac{Q}{2\pi b}\dfrac{(x - x_0)}{(x - x_0)^2 + (y - y_0)^2}$.

The Laplace equation is a partial differential equation and therefore the principle of superposition applies: as many flow components as needed can be superimposed to obtain the expression for the complex velocity potential of the entire system. Then at any point with coordinate (x,y), the components of the specific discharge for the overall system may be written as:

Equation 2-8

$$q_x = -\frac{\partial\phi}{\partial x} = U\cos\alpha - \sum_{j=1}^{N}\frac{Q_j}{2\pi b}\frac{(x - x_j)}{(x - x_j)^2 + (y - y_j)^2} + \sum_{k=1}^{M}\frac{Q_k}{2\pi b}\frac{(x - x_k)}{(x - x_k)^2 + (y - y_k)^2}$$

Equation 2-9

$$q_y = -\frac{\partial\phi}{\partial y} = U\sin\alpha - \sum_{j=1}^{N}\frac{Q_j}{2\pi b}\frac{(y - y_j)}{(x - x_j)^2 + (y - y_j)^2} + \sum_{k=1}^{M}\frac{Q_k}{2\pi b}\frac{(y - y_k)}{(x - x_k)^2 + (y - y_k)^2}$$

Where Q_j = rate of discharge from well j;
Q_i = rate of recharge of well i (Medina, 1994a: 59).

Given this information, the components of the average pore water velocity for an individual fluid particle moving though the overall fluid system may be written as $v_{cx}=q_x/nR$ and $v_{cy} = q_y/nR$. Where n is the porosity of the medium and R is the retardation factor. Then, if the path line traveled by a contaminant particle is divided into increments dl, which are traversed in time intervals dt, the projections of dl on the x and y axis are given by dx and dy respectively, where $dx = v_{cx}dt = q_x \dfrac{dt}{nR}$ $dy = v_{cy}dt = q_y \dfrac{dt}{nR}$

and $dl = (dx^2 + dy^2)^{1/2} = (q_x^2 + q_y^2)^{1/2} \dfrac{dt}{nR}$ (Javandel, Doughty, and Tsang, 1985: 42).

Finally, if a contaminant particle is at a point (x_j, y_j) at time t, its new position at time $t + \Delta t$ on the same streamline can be calculated by the use of the following equations:

Equation 2-10

$$x_{j+1} = x_j + \Delta x = x_j + q_x \frac{\Delta t}{nR}$$

Equation 2-11

$$y_{j+1} = y_j + \Delta y = y_j + q_y \frac{\Delta t}{nR}$$

The computer code RESSQ incorporated into the groundwater advisory system utilizes these equations to create and follow particles. RESSQ draws the flow pattern in the aquifer by tracing streamlines from injection wells. It calculates the concentration of a given solute at a well as a function of time based on the arrival of streamlines paths (Javandel, Doughty, and Tsang, 1985: 42).

Numerical Models

Numerical methods are required to solve complex equations in heterogeneous and anisotropic formations. These methods are not subject to the many restrictive assumptions required for analytic solutions (e.g. homogeneity, isotropy, horizontal flow). Yet their mathematical basis is actually less complex than that of analytic models. Numerical solutions involve approximating continuous partial differential equations with a set of discrete equations at points (nodes) in time and space. The region and time period of interest are divided in some fashion, resulting in an equation or set of equations for each subregion and time step. These equations are combined to form a system of algebraic equations that must be solved for each time step (Mercer and Faust, 1981: 25).

The accuracy and stability of numerical transport models depend upon, amongst other numerical and programming features, two dimensionless numbers; one controlling the space discretization (model's grid size) and the other time discretization (time step). The first number is the Peclet number which is:

Equation 2-12

$$P_e = \frac{V \, \Delta x}{D}$$

Where V = groundwater interstitial (pore) velocity
D = dispersion coefficient
Δx = space increment

When the Peclet number increases, the advective portion of the transport equation becomes dominant and the solution to the equation becomes difficult to be accurately evaluated. Hence the grid must be designed so that $P_e \leq 2$. The second dimensionless number of interest is the Courant number:

Equation 2-13

$$C_r = \frac{V \, \Delta t}{\Delta x}$$

Where V = groundwater interstitial (pore) velocity
  Δt = time step
  Δx = space increment

In all cases the Courant number should be less than one. If it is not, there will be errors and instability introduced by the time discretiztion. Therefore in each time-step, the transport of a particle should not be greater than the model grid space increment, Δx (Ferreira, 1988: 700).

The methods used to calculate the pressure and solute concentration are the finite difference method, the finite element method, the method of characteristics, and the random walk method. The methods differ in the evaluation of variable-dependent coefficients, the spatial discretization of the region, and the way they handle advection and dispersion.

Finite Difference Method

The first step in utilizing the finite difference method is to establish a grid throughout the region of interest. Associated with the grid are node points that represent the position at which the solution of the unknown values are to be obtained. There are two common types of grids: mesh-centered and block centered (Fig. 2-2).

Figure 2-2 Two Common Types of Finite Difference Grids

Node Point

Mesh-Centered   Block Centered
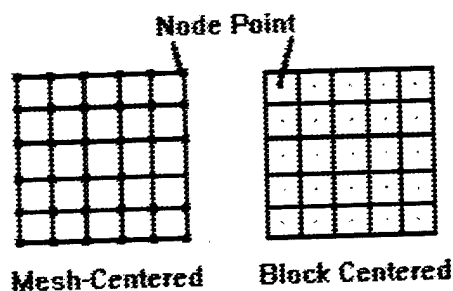
Mesh-centered grids are convenient for problems where values of the hydraulic head are specified on the boundaries, whereas block-centered grids are better for problems where the flux is specified across the boundary (Mercer and Faust, 1981: 26). The grids shown above are regular (the spacing in the x and y directions are the same). Grids are required to be regular or rectangular.

Each node is surrounded by a region with interfaces that are normal to the coordinate axes; these regions are called nodal blocks, cells, or elements. The partial derivative of a given variable is expressed in terms of the difference between two nodes. For example the x component of the concentration gradient $\partial C / \partial x$ at the interface $i \pm 1/2$ is

approximated by $\dfrac{C_{i\pm1} - C_i}{x_{i\pm1} - x_i}$. Using the finite-difference approximation, the nodal value of C_i is algebraically related to its neighboring two values for a one-dimensional problem, or its six neighbors for a three-dimensional problem (Javandel, Doughty, and Tsang, 1985: 69-70).

A powerful attribute of the finite difference method is that the 1/2 in the arithmetic mean calculations can be changed to other fractional weighting factors. An example

would be the approximation for $\partial C / \partial x$ can changed to be $\dfrac{C_{i+1/2} - C_{i-1/2}}{x_{i+1/2} - x_{i-1/2}}$ which is called

the central weighting because it approximates the central difference in space. This is a

very accurate approximation, but solutions using this method tend to oscillate when the

velocity of the flow is high. Because of this problem other weighting schemes have been

created; these include the upstream weighting where $C_{i+1/2} = C_{i+1}$ and the backward

difference, whereby $C_{i+1/2} = C_{i-1}$ (Javandel, Doughty, and Tsang, 1985: 71). Each of these

methods also have problems associated with them, but the three methods together create a

very accurate approximation, with a minimal error probability.

Finite Element Method

The finite element method has the advantage over the finite difference method in the

specification of the distribution of the nodes and the use of irregular meshes to discretize

the region. The finite element method uses curves to connect the regions around the

nodes. Different shapes may be used for the elements. For example two-dimensional

triangular elements use three nodal vertices, a quadrilateral element has four corner nodes,

or a three-dimensional orthorhombic element has eight corner nodes (see Fig. 2-3).

Figure 2-3 Example of Finite Element Meshing
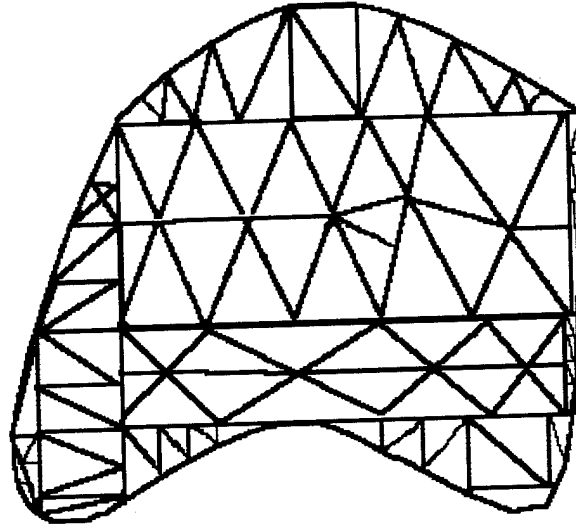
A model may use any combination of elements its requires to cover the area to be modeled adequately (Javandel, Doughty, and Tsang, 1984: 71).

The value of a variable in an equation is interpolated in terms of the values of the variable at the corner nodes. The finite element numerical equations use either the weighted residual Galerkin scheme or the variational approach. In the Galerkin approach, a trial solution made of an expansion of the interpolated (basis) functions is substituted into the differential equations. The residual of the trial solution is integrated over the element and the residuals are eventually forced to zero by requiring orthogonality of the residuals to the basis functions used in the trial solution. In the variational approach, the trial solutions, which are expansions of the basis functions, are substituted into the functional integrals. The differential operators in the functional integrals operate on the basis functions in the same manner the weighted residual procedure of the Galerkin formulation. In both approaches, unknown terms are evaluated at the Gaussian points within an element. This approach is different from the finite difference method where the

coefficients are calculated at the interfaces between the elements. The finite element method, because it interpolates the basis functions over more than two points, can evaluate gradients in both normal and tangential directions and handle tensorial quantities more easily.

Method of Characteristics

The method of characteristics separates the transport process into advection along characteristic lines and pure dispersion in a coordinate system at rest relative to the advective movement. The principle can be used by moving the coordinate grids, or by particle tracking. While the convective transport is calculated by moving particles, which are indicators of contaminant concentration, the dispersive redistribution of concentration between particles is performed on a fixed grid. Therefore, the method requires consecutive switching from cellular to particle concentrations (Kinzelbach, 1987: 658).

Random Walk Method

The random walk method is also a particle tracking method. Each particle represents a fixed mass of pollutant and both the advective and dispersive transport are represented by particle movement. Advective transport is completed by stepping along the direction of the flow field while dispersive transport is accomplished by adding random movements to the particle. The random movements are statistically related to the size of the dispersion. The movement of a single particle is of no interest. It is only when many particle paths are superimposed upon one another and a consecutive counting of mass in each cell of the grid is accomplished that a contaminant concentration may be calculated (Kinzelbach, 1987: 659).

A brief description of each of the numerical models which are part of the advisory system, including their respective assumptions and limitations follows:

MOC   Two-dimensional numerical model used to simulate non-conservative contaminant transport in saturated aquifers. It computes changes in spatial concentration distribution over time caused by advective transport, hydrodynamic dispersion, mixing, recharge dilution, and a variety of chemical reactions (first-order decay, sorption, and ion exchange). The model assumes that fluid density variations, viscosity changes, and temperature gradients do not affect the velocity distribution. Even with all these limitations, MOC does allow for the modeling of heterogeneous and/or anisotropic aquifers. It uses the finite difference method to solve the groundwater flow equation and the Method of Characteristics (hence the name) to solve the solute transport equation (Goode and Konikow, 1989: 5).

RANDOM WALK   Numerical model allowing the modeling of convection, dispersion, and chemical reactions. It is based on the finite difference solution to the groundwater flow equation, a particle-in-a-cell solution for conservative solute transport and a random walk technique for the dispersive effects on solute transport. The program is limited to two dimensions, but within those confines it can do a multitude of things. It can model nonsteady flow in heterogeneous aquifers in unsaturated flow conditions. It also allows for pulsed pumping, recharge, evapotranspiration and flow from springs (Medina, 1994b: 66-67).

MODFLOW   Three-dimensional numerical model for modeling groundwater flow utilizing a block-centered finite-difference method to solve the necessary equations. The model allows layers to be created, and within these layers flow may be confined or unconfined or a mixture of both. Flows from outside the aquifer (for example flows to wells, areal recharge, evapotranspiration, and flows to drains or through riverbeds) are also allowed. The user is allowed to choose to solve the model using the Strongly Implicit Procedure or the Slice-Successive Overrelaxation Procedure. With the modules added to the original MODFLOW package, modeling of contaminant transport is available to the user (Medina, 1994b: 69).

SUTRA   Two-dimensional finite element model used for modeling the relationships between saturated and unsaturated fluid-density-dependent groundwater flow incorporating energy transport and chemically reactive single species solute transport (Medina, 1994b: 71).

| BIO-PLUME II | Two-dimensional numerical model used to simulate the transport of dissolved hydrocarbons under the influence of oxygen-limited biodegradation. It also simulates reaeration and anaerobic biodegradation as a first-order decay in the hydrocarbon concentrations. It computes the changes in hydrocarbon concentration over time due to convection, dispersion, mixing, and biodegradation (Medina, 1994b: 73). |

Monte Carlo Analysis

A set of values for the hydraulic parameters (recharge, transmissivity, conductivity) is required to solve the transport equation, using any computer model. The parameters mentioned cannot be measured at a regional scale, so in a model they become effective rather than measurable. Measurements of the parameters only give an indication of the order of magnitude (Brooks, Lerner and Tobias, 1994: 2993). For most models, it is necessary to assume the parameters remain uniform throughout the entire flow regime. Unfortunately, in reality the materials in question are seldom, if ever, uniform. In the numerical approach, material properties are represented by parameters that are either assumed to remain constant over discrete subregions of the flow field or are allowed to vary slowly in space. This rate of change is usually much slower than the rate of variation of the actual material properties. In these cases the parameters cannot be regarded as representative of the true material characteristics but only, at best, some average quantities related to the parameters. The approach has been to assume that the measured values of a material property at various point within a geologic formation can be regarded as belonging to a statistical population having a univariate probability distribution. When we do this we are saying that the measurements are independent of one another and are controlled by the same probability law at each point.

The recognition that the hydraulic properties of porous materials can be described in statistical terms has led some researchers (such as Medina and Jacobs) to investigate the effect of random distributions of parameters in the governing equations on the flow of water through such materials. The tool required for such investigations are stochastic models. These models are different from deterministic models in that some of their input functions are uncertain and therefore the model output must be described in probabalistic terms rather than deterministic ones (Neumann: 1982: 81-82).

Simply running a model in a deterministic mode using the best estimates of the parameters will not provide sufficient information for a decision, because the uncertainty surrounding the data has not been taken into account. Deterministic models will fail because the correct parameter values needed for models are not known at all the required locations (Van der Heijde, 1993: 51).

The alternative used by the groundwater advisory system is to explicitly consider the uncertainty through the use of stochastic methods such as the Monte Carlo analysis. The Monte Carlo analysis requires that the distributions and their respective parameters be specified for the variables having the greatest impact on contaminant transport (Medina, 1994a: 8). In most cases only an estimate of the mean and variance of the parameters are known. An estimate of the cumulative distribution function for the contaminant concentration is then developed from this data (Medina, 1994a: 9). The three models included in the advisory system that make use of the Monte Carlo analysis are outlined below.

ODAST-MC   In Monte Carlo mode, the input concentration and regional flow velocity both become random variables (Medina, 1994b: 75). The velocity is not

directly generated: it is assumed to result from hydraulic gradient, porosity, dispersivity, and hydraulic conductivity. Hydraulic conductivity may be generated directly from the simulation via a log-normal probability distribution. However this method does not take into account the known relationship between hydraulic conductivity and other parameters, so another option is also offered. This option is to generate a distribution of conductivities from the underlying variables of mean particle size and porosity (Medina, 1994a: 31).

TDAST-MC   This model is adapted the same way as ODAST-MC, except that the variable D_T (sic: transverse dispersivity) must also be generated (Medina, 1994a: 33).

MOC-MC   The Monte Carlo analysis in the MOC model is used in the specification of spatially covariant hydraulic conductivity fields, where it is expected that hydraulic conductivity values will tend to show a higher degree of similarity between nodes that are close together in space. The procedure also simulates a situation during which contaminant input begins following the failure of a containment structure, prior to which there is no contamination. There are four parameters that may be varied by the procedure: Probability of Failure (in years); Leachate Release Concentration; Hydraulic Conductivity Random Field; and Background Concentration (Medina, 1994b: 80-82).

Comparing Models and Methods

One of the primary objectives of the groundwater advisory system is to select a model based upon the characteristics of a site. To make this selection, it must compare the models it has to choose from and select the model best suited to the site. To aid in understanding the CHOICE algorithm, we'll next make some basic model comparisons. With the number of commercially obtainable models presently available a systematic comparison of all of them is impossible. Even with the limited number of models to choose from within the advisory system, a comparison of all of them against one another is outside of the scope of this research. The different models contained within the

groundwater advisory system are based upon the mathematical methods reviewed earlier. The best way to understand the reasoning by which CHOICE will make a decision is to know the strong and weak points of the differing methods. Consequently, we will review the mathematical methods, then create a table explaining the most significant differences.

Mathematical Methods

The EPA has said that the preferable method of solution is the analytical one, because once such a solution is derived, it can be used for a variety of cases. However, for most cases of practical interest, use of the analytical methods is not possible due to irregularity of the modeled domain's shape, the heterogeneity of the domain with respect to various coefficients, and various nonlinearities (EPA, 1992: 7). Therefore, numerical methods are to be employed in most cases

There are advantages and disadvantages to all three methods. For the analytical methods the positive aspects include the fact that they are simple to use with minimal required data, little experience is required to utilize the methods, the solutions are almost always stable and not subject to the numerical dispersion problems that plague numerical methods, they can handle anisotropic transmissivities and dispersion coefficients, and the methods arrive at answers quickly, making the method very economical. On the down side, analytical methods are limited to certain idealized situations, and therefore are not often applicable to field problems, they cannot handle inhomogeneous media, and they cannot handle boundaries that are not orthogonal without additional assumptions being made (Cleary, 1994: 4-39).

Semi-analytical methods also have their advantages and disadvantages. On the positive side, semi-analytical methods can handle multiple sources of contamination and recharge/discharge features, where analytical methods would fail. The methods also require only simple data input and do not require the design of a mesh as fully numerical methods do. Lastly, the methods are a good indicator of whether a more sophisticated and costly study will be required. There are four negatives to the semi-analytical methods chosen for inclusion into the advisory system. The first is that they do not consider mass transport by dispersion and diffusion which leads to prediction of travel times much longer than actual values and may also underestimate the true impact of a contaminant source. Second, the techniques are based on two-dimensional flow and any situation requiring three-dimensional flow will require simplification before the methods can be utilized. Third, the semi-analytical methods cannot handle heterogeneous or anisotropic permeabilities. Finally, the methods are only appropriate for steady-state flow problems (Javandel, Doughty, and Tsang, 1985: 65).

Lastly there are the various numerical methods. The primary advantage the numerical methods have is that they can handle spatial and temporal variations in system properties such as hydraulic conductivity, porosity, and dispersivity. Additionally, numerical methods can easily handle complex boundary conditions and three-dimensional time-dependent problems. There are only two noticeable disadvantages working with numerical methods. The first is that often errors due to numerical dispersion overshadow the physical dispersion of the solute within a porous medium. The second disadvantage is that learning the method and doing the research to obtain the data required to run the

numerical methods takes a considerable amount of time (Javandel, Doughty, and Tsang, 1984: 90). The following table compares the advantages and disadvantages of the methods included in the groundwater advisory system. In creating the table, a number of sources were used (Ferreira, 1988; Kinzelbach, 1987; Mercer and Faust, 1981; Kolodny, 1989; and Cleary, 1994).

Table 2-1 Summary of Differences Between Numerical Methods

Advantages	Disadvantages
Finite Difference Method	
Intuitively Basic Grid Easy Data Input Easy to Program Matrix Equations Created are Easily Handled	Low Accuracy for Some Problems Regular Grids Doesn't Handle Curved Boundaries Well
Finite Element Method	
Flexible Geometry High Accuracy Easily Included Evaluates Cross-Product Terms Best Can Align Axis with Direction of Flow Easily Doesn't Smear Out "Sharp Fronts"	Advanced Mathematical Basis Difficult Data Input Requirements Difficult to Program Galerkin Procedure Errors in Input Leads to Problems that are Difficult to Detect
Method of Characteristics	
Uses Finite Difference Grid - Easy to use Most Cost Effective (Training, Input Time, Computing Time) Handles "Sharp Front" Problems Best	Two-Dimensional Only
Random Walk	

Handles Radial Flow Problems Best
Handles Convective Probems with Decaying
    Pollutants Easily
Only Numerical Method that can Handle
    Scaled Dispersivities
	Two-Dimensional Only

Computer Models

When selecting a model it is important to select the appropriate degree of simplification in each case (EPA, 1992: 2). The selection of the model to be used at a site depends upon a number of things but amongst the most important are budgetary and time constraints. If a quick decision is needed, a numerical model is out of the question. On the other hand, if the site is very complex, with variations across the site in a number of hydraulic parameter readily evident from a cursory inspection, a numerical model is the only choice available to a modeler. The following table presents an attempt to put all the major advantages and disadvantages of the varying numerical methods together as they pertain to the groundwater advisory system.

Table 2-2 Summary of Model Advantages and Disadvantages

MODEL	TYPE	ADVANTAGES	DISADVANTAGES
ODAST	Analytical	Easiest to use	Only 1-Dimension, Strict Assumptions
TDAST	Analytical	Easiest 2-D model	Single or Line Source Only Full Penetration Assumption
PLUM2D	Analytical	Multiple Sources	Full Penetration Assumption Source Must Have Constant Strength
DUPVG	Analytical	Allows for Unconfined Aquifers	Only x-z Plane Movement Calculated Only Source Flow Allowed as Input Many Assumptions Required for Use
EPAGW	Analytical	Uses Regional Data Monte Carlo Analysis Built In	Only Monte Carlo Analysis Allowed Can Only Calculate Steady-State Complicated Input Files Required
EPASF	Analytical	Only Surface Water Model in Advisory System Monte Carlo Analysis Built-In	Rough Estimate Only Complicated Input Files
LTIRD	Semi-Analytical	Only Radial Flow Model	Narrow Range of Applications When Radial Flow Dominates Onl
RESSQ	Semi-Analytical	Wide Application Range	Neglects Dispersion and Decay Two-Dimensional Only Complicated Input Files
MOC	Numerical, Method of Characteristics	Finite Difference Grid-Easy Easiest Numerical Model to Learn	Two Dimensional Only Narrower Range of Use than Rando Walk
RANDOM WALK	Numerical, Random Walk	Widest Range of Use by CHOICE	Difficult to Learn Complicated Input Two-Dimensional Only
MODFLOW	Numerical, Finite Difference	Three-Dimensional Widest Range of Uses Possible	Most Difficult Input Files of All Mainly Flow Situations Limited to Basic Tracer Transport
SUTRA	Numerical, Finite Element	Allows for Unsaturated Flow Incorporates Chemical & Energy Reactions	Very Specialized Problems Only Two-Dimensional Only
BIOPLUME II	Numerical, Finite Difference Method of Characteristics	Simulates Dissolved Oxygen Transport and Biodegradation	Very Narrow Range of Applications
ODAST-MC	Analytical, Monte Carlo	Easy to Use MC Analysis	One-Dimensional Only
TDAST-MC	Analytical, Monte Carlo	Easy to Use MC Analysis	
MOC-MC	MOC, Monte Carlo	Allows Use of MC Analysis	Extremely Complicated Input Files

Before a method of solution or model is chosen to represent a site, the decision that a site is indeed contaminated and a hazard to the environment must be made. To address this question, the groundwater advisory system begins with the LeGrand Preliminary Analysis.

LeGrand's Preliminary Analysis

The LeGrand system of evaluating sites was created to fill a pressing need in site analysis. A method was needed to give a first-look approximation of the danger a site posed if it was contaminated, as well as noting the positive and negative aspects of the site as regards to groundwater contamination (LeGrand; 1983,23). It was created in 1983 to give environmental professionals a tool with which to gauge how safe a proposed or existing site was with regard to groundwater contamination. The analysis asks questions about the hydrogeology of a proposed site and rates the site. The required answers are of the type that they should be readily available for any site. The rating given is both numeric and opinion. A typical site will be given a numeric score (from 0 to 36) and a rating from excellent (no problems should arise if there is contamination) to very poor (if contamination should be present there will be a large scale problem).

The key parameters assessed by the method are: a) distance to a water supply or boundary; b) depth to the water table; c) hydraulic gradient, magnitude and direction; and permeability and sorption potential (LeGrand; 1983, 20-21). After these initial questions are answered, the analysis continues by asking the modeler to attach up to two special modifiers to the rating. The modifiers do not change the rating, but rather identify special

parameters that must be addressed at the site in question, such as groundwater mounding, wetland issues, or artesian aquifers underneath the water table aquifer.

As implemented in the Advisory System, the LeGrand analysis should be used to rate sites at an Air Force base to identify those sites that could/will pose problems regarding groundwater contamination. After the sites with higher scores have been identified, the CHOICE algorithm can be run to determine the scope of the contamination problem. There are other screening models available, such as the Air Force's old Automated Defense Priority Model (ADPM), but the authors of the groundwater advisory system chose to use Legrand's system for two reasons: (a) they wrote the code and had it personally approved by H.E. LeGrand; and (b) they were familiar with the code and it suited the needs of the advisory system. Additionally, they thought that ADPM was more geared towards subsurface contamination than they needed, so they stuck with LeGrand's system (Medina, 1995: 1).

There are two apparent problems with the method: accurate data and trained experts are required to use the system (LeGrand; 1983, 24). Measuring the distance from a identified site to a base boundary or water supply well and measuring the depth of the water table are easy tasks to accomplish. Measuring the gradient of the water table and identifying the materials the aquifer consists of are also fairly easy tasks, but they are time-consuming and expensive, unless they have been accomplished previously. These four parameters are the lynchpins of the entire analysis. Accurate data is essential for any modeling process, but especially so for LeGrand's method: if one of the four elements is measured incorrectly, the rating is rendered null and void.

After LeGrand's analysis is completed, the advisory system allows the user to choose between the Impact Scenario Definition and the CHOICE algorithm to assist the user in selecting a computer model to represent the site. The CHOICE algorithm shall be reviewed in Chapter III.

The last section of the advisory system to be reviewed in this Chapter is the Impact Scenario Definition. The Impact Scenario Definition pathway is another way to select some of the models contained within the advisory system. The Scenario Definition pathway adopts a very general approach to potential risk resulting from groundwater contamination. For regulatory purposes, contaminants may be monitored in the environment for either environmental standards or human exposure standards and the contaminants may be either in the groundwater or in "downstream" surface waters impacted by the contaminated groundwater. These possibilities lead to the three scenarios for the analysis of standard violation or human exposure which may result from a contaminated site. These scenarios are included in the advisory system, along with one more for the modeling of plume extent (Medina, Butcher and Marin, 1988: 100). The scenarios available to the advisory system are:

1. Groundwater pollution
2. Surface water contaminated by leachate
3. Consumption of fish contaminated by leachate
4. General modeling of plume extent, including development over time

The first scenario allows the selection of the EPAGW model, MOC, or a selection of analytical solutions (PLUM2D, ODAST, TDAST, LTIRD, or DUPVG) depending on kind of site the user was ready to model. The second and third scenarios use the EPASF model exclusively. This are the only pathways for the advisory system to recommend that

2-32

particular model. The last scenario allows the user to choose from a selection of analytical

models (the same as in the first scenario), RESSQ, MOC, or RANDOM WALK.

The Scenario Definition decisions are based entirely upon what type of risk the user

is looking at, whereas CHOICE looks at the type of site the user is reviewing.

Chapter 3 - Advisory System

The first step in modeling a contaminated groundwater site is determining if the site may be potentially contaminated. To accomplish this determination, the advisory system has incorporated LeGrand's Preliminary Analysis.

LeGrand's Preliminary Analysis

To test the accuracy of the advisory system's LeGrand analysis procedure, we used data from the Department of Energy's Hazardous Waste Remedial Actions Program (HAZWRAP) RCRA Facility Investigation (RFI) as inputs to the questions. The tabulated results are attached as Appendix A. The analysis was performed twice, with two different people answering the questions, for quality assurance . The analysis' scale runs from 0 to 29, so the difference between the two runs, two points, is minor. According to LeGrand, this difference is acceptable (LeGrand, 1984: 25). There were no differences between the written LeGrand procedure and the computerized version. The questions were phrased the same, the answers were phrased the same and weighted the same. The only differences in the two analyses were in the way two of the questions were answered. Because of the way the questions were phrased, two different interpretations were acceptable and used. This difference reflects the variance in individual interpretation of any subjective questionnaire.

The purpose of the LeGrand Analysis is to tell the user if the site being analyzed is a potential problem. Since LF02 is a known problem, the conclusion of the Analysis should

be (and was) that the site has the potential to be a trouble spot. This conclusion validates the advisory system's implementation of the LeGrand analysis for this particular site.

Since the Analysis reported the site to be a potential source of contamination, the next step in our case study was to utilize the Impact Scenario Definition and CHOICE model selection algorithm to decide which groundwater model would be best suited for the site's characteristics.

Impact Scenario Definition

The Impact Scenario Definition pathway adopts a fully generalized approach to potential risk resulting from groundwater contamination. The contamination may be in the groundwater or in "downstream" surface waters that are impacted by the contaminated groundwater. There are three impact scenarios: violation of an environmental standard for contaminant concentrations in groundwater, violation of a standard in surface water contaminated by groundwater leachate, and exposure of humans through consumption of fish from surface water contaminated by groundwater leachate. In many instances, a site will need to be evaluated under multiple scenarios, as well as for different contaminants. The underlying rationale for the Impact Scenario Definition pathway is first to determine the impact scenario involved, then present the array of applicable models for selection to determine the amount of risk involved with the site (Medina et al, 1988: 100).

CHOICE Algorithm

The CHOICE algorithm was first written in 1987 by Jonathan B. Butcher. It was written for the State of North Carolina to assist the state regulatory agencies with their

respective permitting processes (Medina et al, 1988: 9). Medina updated CHOICE for the Air Force's use by adding an algorithm to decide between the two numerical models contained within the algorithm (Medina and Jacobs, 1994b: Source Code).

The original objective of the algorithm was to determine whether there was an appropriate analytical solution available with which the site being reviewed could be analyzed. When such a solution was not available, in some instances CHOICE indicates that semi-analytical methods would be appropriate while in others, more complex numerical methods would be required (Medina et al, 1988: 10).

To accomplish this aim, Butcher created a very elaborate decision algorithm to look for instances where an analytical solution would be suitable. If none of the analytical models were suitable for the site, i.e. if the site was in the least bit heterogeneous, then the algorithm recommended RESSQ or the selection of a numerical model (MOC or RANDOM WALK). The user was forced to make their own selection of a numerical model because there was no selection criteria within the groundwater advisory system at that time. This additional selection criteria was added by Medina in 1992.

In the broadest sense, the logic used by the algorithm presently is the same as when it was created. The program first asks questions of the user to quickly eliminate the analytical models if possible, then selects between a semi-analytical model (RESSQ), or a numerical model. If a numerical model is selected, it chooses between MOC or RANDOM WALK. If the analytical models cannot be quickly eliminated from consideration, the algorithm commences with questions to specify exactly which analytical model is most appropriate. At this point the algorithm may still recommend either RESSQ

or one of the numeric models depending upon the answers input by the user. The entire algorithm depends upon the user's site knowledge and interpretation of the questions asked by CHOICE.

CHOICE's first step is to characterize the site. The first question asked, "The site can be characterized as:" followed by a list of typical hazardous waste site types, will be used later in the process. . The site descriptions are as follows:

1. Wastewater lagoon
2. Spray irrigation of wastewater
3. Land application of sludge
4. Individual rotary distributor

5. Landfill
6. Injection of waste into a confined aquifer
7. Septic tanks
8. Direct user selection of model

The question fulfills two purposes. First, if the site can be modeled with an analytical model, the type of site is critical, as will be seen later. Second, if the site is susceptible to leaching (for instance a landfill), the HELP (Hydrologic Evaluation of Landfill Performance) model will be used prior to beginning the model selected by CHOICE to estimate the rate of leaching. The HELP model cannot be reached by the user directly, only through interaction with CHOICE. The leachate rate calculated by HELP will then be used at a later point as input to whatever model is selected by CHOICE. A point that needs to be made is that CHOICE also allows the user to directly select a model of his/her preference at this time. The flow charts on the next few pages and following explanations demonstrate the logic followed by the algorithm.

A walk through of the entire algorithm is required to fully understand the theory behind its decisions. We will concentrate on the diamond-shaped text boxes in the Flow

Charts because those represent decisions that must be made by CHOICE, based upon

input from the user.

Begin CHOICE Algorithm

Start

Identify Site Type

Are Analytical Models Appropriate? — Yes → Chart # 2

No

Is the modeled region homogeneous? — Yes → *RESSQ*

No
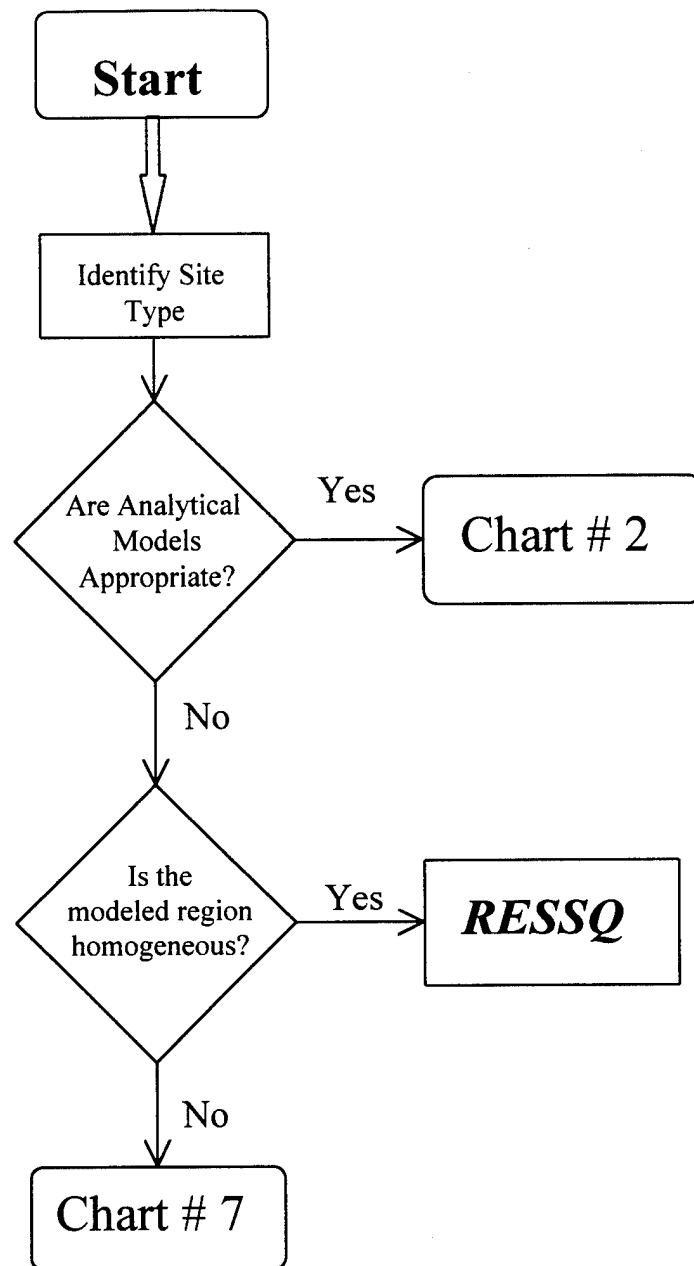
Chart # 7

Flow Chart No. 1

Selection of Analytical Model

```
                    ┌─────────────┐
                    │    Start    │
                    └─────────────┘
            ┌───────────┬───────────┐
            ▼           ▼           ▼
  ┌──────────────┐ ┌──────────┐ ┌──────────────┐
  │Land Application│ │Wastewater│ │Spray Irrigation│
  │of Sludge/ Landfill│ │ Lagoon │ │or Single Rotary│
  └──────────────┘ └──────────┘ │Disrtibutor   │
                        │        └──────────────┘
                        ▼                │
                    ◇ Effectively ◇      │
         Yes ───────   Lined?    ─────── No
          │              ◇               │
          ▼                              ▼
                               ┌──────────────┐
  ┌──────────────┐ ┌──────────┐│Source may be │
  │Aquifer approx.│ │ Aquifer  ││recahrging aquifer:│
  │homogeneous in │ │characteristics││Estimate mounding│
  │area of interest?│ │Unknown or ill│└──────────────┘
  └──────────────┘ │ defined? │        │
          │        └──────────┘        ▼
          ▼              │        ┌──────────────┐
  ┌──────────────┐       │        │  Chart # 3   │
  │ Chart # 3a   │       ▼        └──────────────┘
  └──────────────┘  ┌──────────┐
                    │  EPAGW   │
                    └──────────┘
```
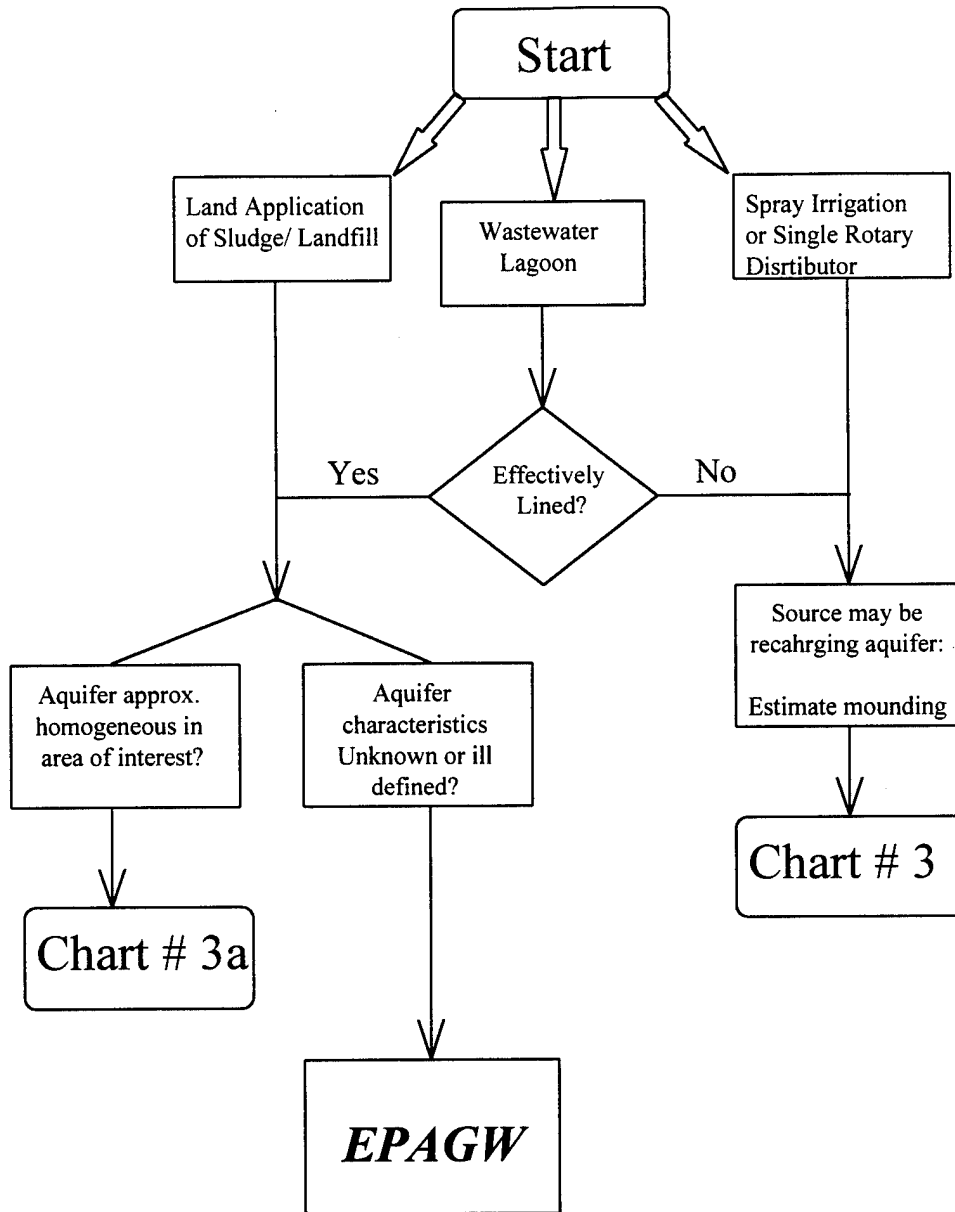
Flow Chart No. 2

Selection of Analytical Model - Cont.

Chart # 3

R/b < 5%
Non-radial Flow:
Confined Solution

R/b ≥ 30%
Dupuit Approx.
Not Valid

5% ≤ R/b ≤ 30%
Dupuit Approx.
Acceptable

Chart # 3a

Chart # 7

Chart # 6

Perimeter of Interest Close to Source?

No → Chart # 4

Yes

Full Penetration Analysis Appropriate?

No → Chart # 6a

Yes

ODAST
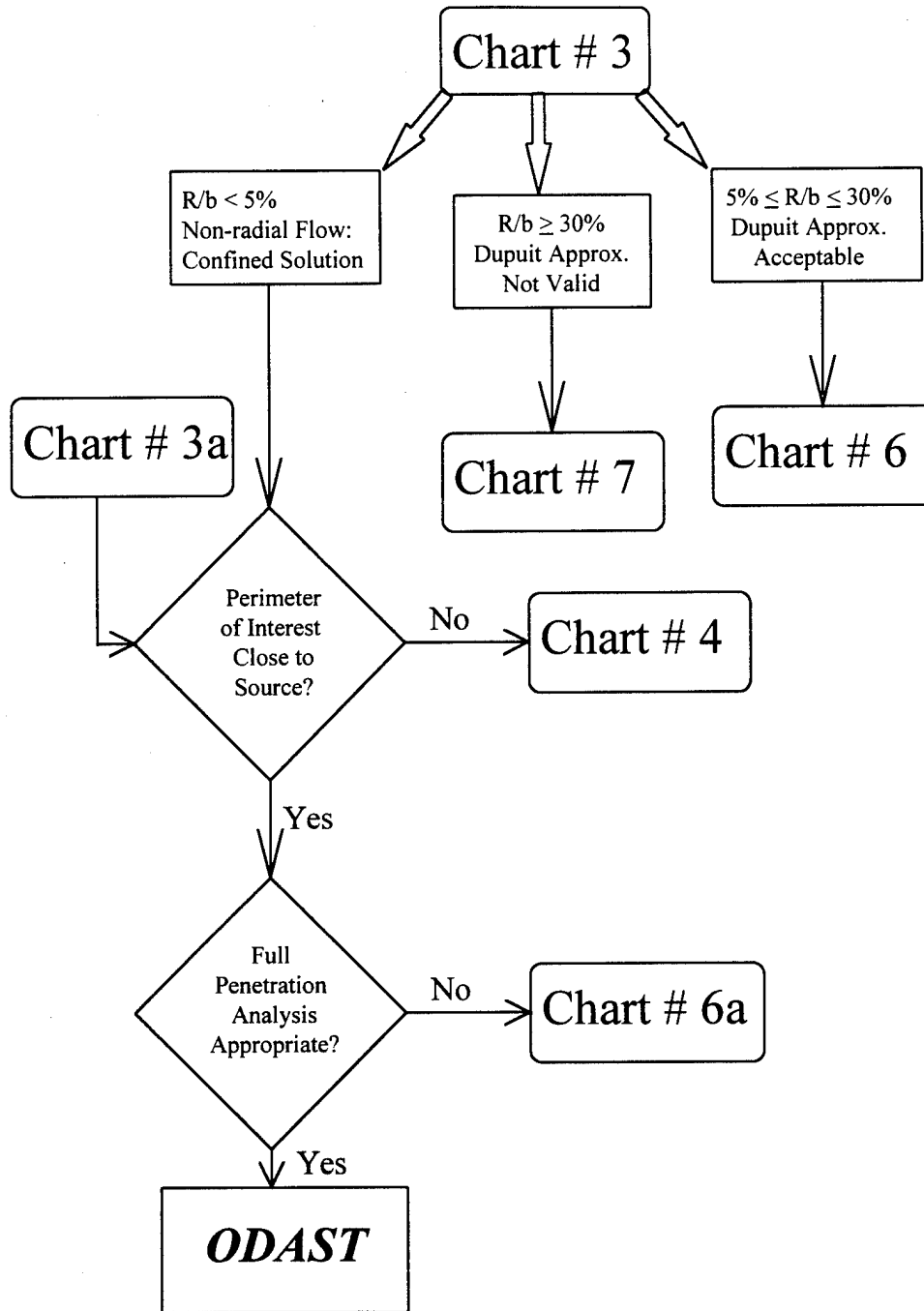
Flow Chart No. 3

Selection of Analytical Model - Cont.

Chart # 4

Single point, area, or line source

Multiple point sources; source strengths constant

Other Situations

Chart # 7

Full Penetration Analysis Appropriate?

No

Yes

PLUM2D

Source Strength Constant

Source Strength Decaying Exponentially

Chart # 5

Full Penetration Analysis Appropriate?

No

Chart # 7

Yes

TDAST
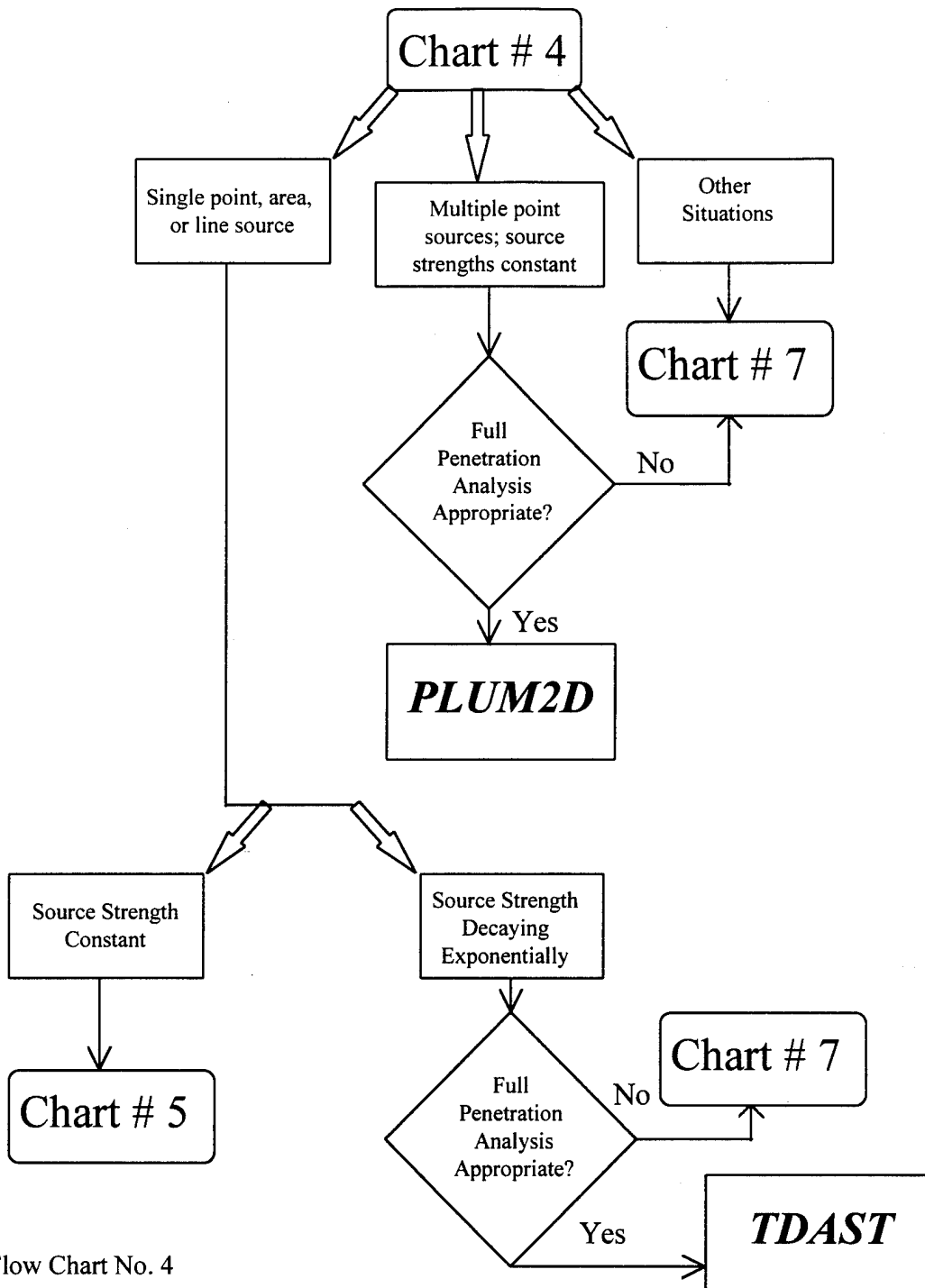
Flow Chart No. 4

Selection of Analytical Model - Cont.

Chart # 5

Point Source

Source has significant width

Focused Source

Uniform Areal Source

TDAST

Full Penetration Analysis Appropriate?

No →

Expected Maximum Impact Along Main Flow Axis?

No →

RESSQ

Yes ↓

PLUM2D

Yes ↓

EPAGW
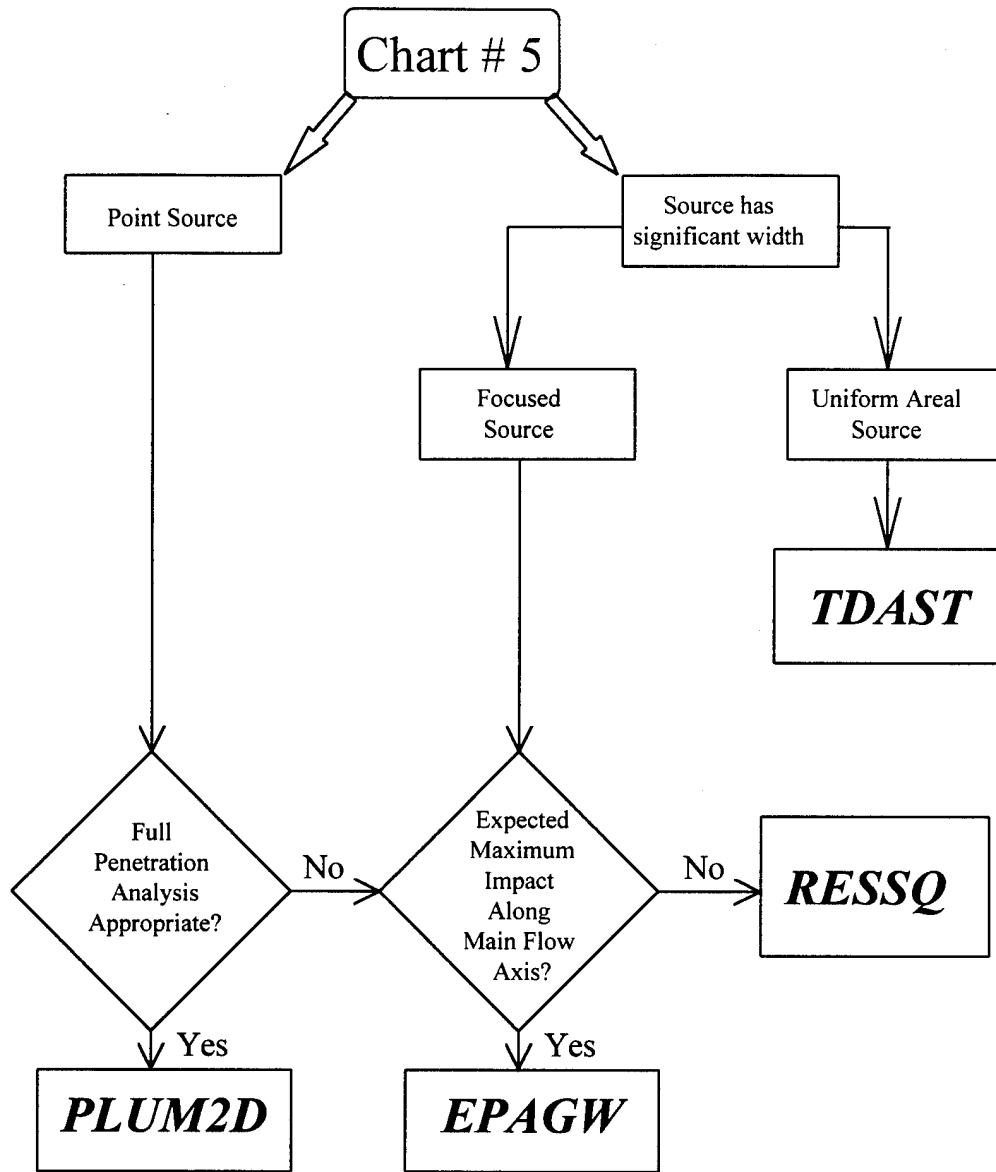
Flow Chart No. 5

Selection of Analytical Model - Cont.

```
                        ┌─────────────┐
                        │  Chart # 6  │
                        └─────────────┘
            ┌───────────────┼───────────────┐
            ▼               ▼               ▼
  ┌──────────────────┐ ┌──────────────────┐ ┌──────────────┐
  │   Perimeter of   │ │   Perimeter of   │ │    Other     │
  │ Compliance near  │ │ Compliance       │ │  Situations  │
  │ Source,          │ │ farther from     │ │    Apply     │
  │ Treatable as a   │ │ Source,          │ │              │
  │ Line             │ │ Treatable as a   │ └──────────────┘
  └──────────────────┘ │ Point            │        │
            │          └──────────────────┘        ▼
            │                    │         ┌──────────────┐
  ┌──────────────┐               │         │  Chart #7    │
  │  Chart #6a   │─              │         └──────────────┘
  └──────────────┘               │
            │                    │
            ▼                    ▼
      ◇ Regional            ◇ Regional
        Flow                  Flow
        Unimportant;   No     Important;    No
        Source Decay  ────┐   Source Decay ────►  ┌─────────┐
        Unimportant ◇     │   Unimportant ◇       │  LTIRD  │
            │             │       │               └─────────┘
           Yes            │      Yes
            ▼             │       ▼
      ┌──────────┐        │   ┌──────────┐
      │  DUPVG   │        └──►│  RESSQ   │
      └──────────┘            └──────────┘
```
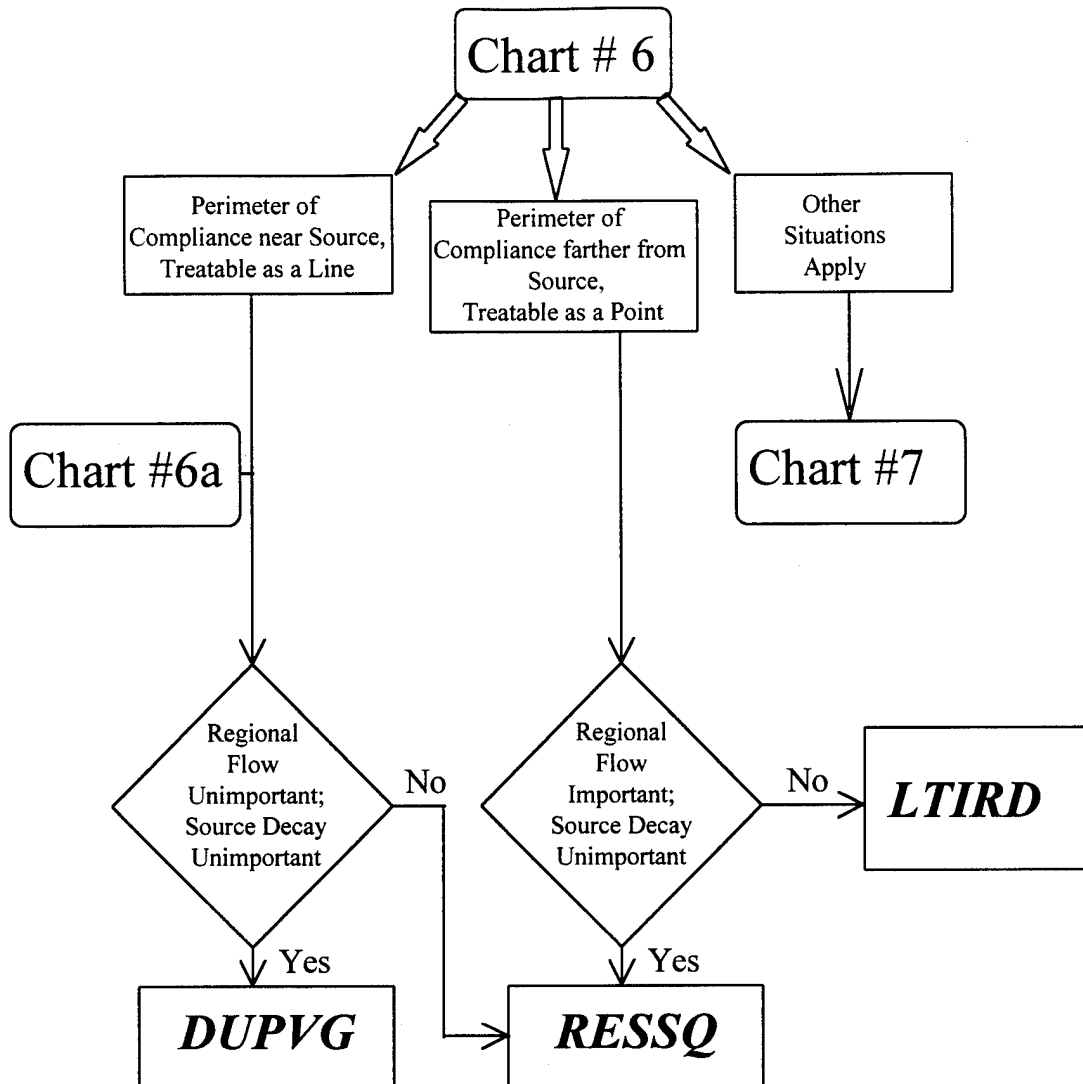
Flow Chart No. 6

Selection of Numerical Model

Chart #7

Variable Grid Size Not Needed — No →

Yes ↓

D_x & D_y < 10 times D_L — No →

Yes ↓

Ratio of D_L to D_T <10 — No →

Yes ↓

Flow Parallel to Grid Axes — No →

Yes ↓

Storativity Doesn't Vary Significantly — No →

Yes ↓

No part of Aquifer changes from Confined to Unconfined or Vice Versa

Yes → MOC

No → RANDOM WALK

Flow Chart No. 7

3-12
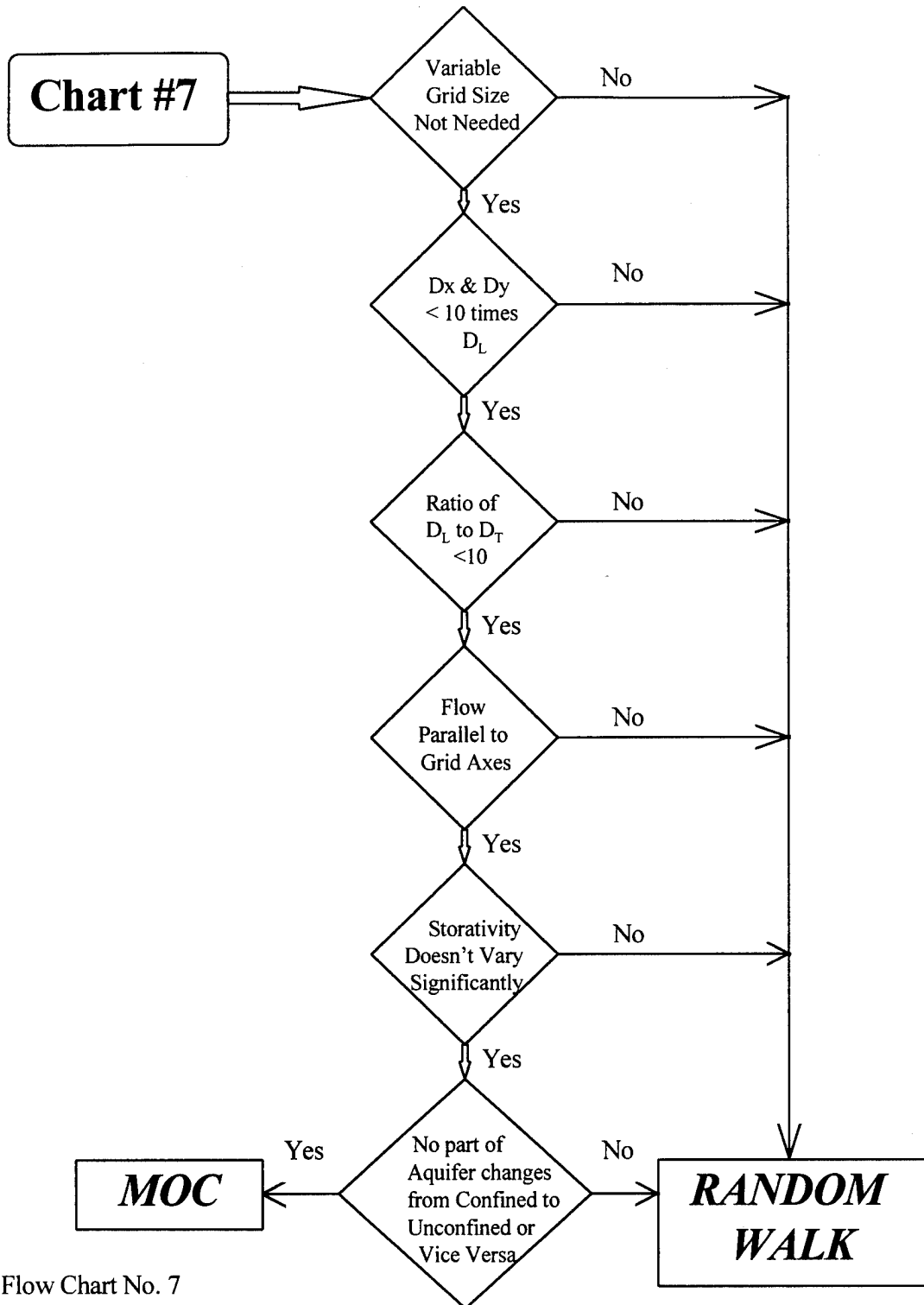
Flow Chart No. 1 starts by showing the theory mentioned before: eliminate the analytical

models, if possible, then decide between semi-analytical (RESSQ) and numerical models.

The determining factor for the latter decision is whether in the user's CSM the site is

homogeneous or not. If the site is homogeneous, CHOICE will advise using RESSQ, if

not it will recommend selecting one of the numerical models (Flow Chart No. 7). To

determine if the site is amenable to analytical modeling, the system asks the user to

"CHECK IF ANALYTICAL SOLUTION is clearly inappropriate according to currently

available data." The code then has six statements about site conditions. If any one of the

six is true about the site being modeled, analytical methods are not appropriate. The six

statements are:

1. The horizontal extent of the region of interest in the aquifer is KNOWN to be near (say 250 ft.) to a distinct hydrogeologic boundary, such as an intersecting river, aquitard or distinct inhomogeneity in the medium.
2. The region of interest is in an aquifer that is distinct the aquifer directly affected by the site. For example, a site may impact a shallow water table aquifer while the region of interest for modeling is in an underlying system separated by an aquitard.
3. Contaminant of interest is an immiscible liquid in water or has a specific gravity significantly different from that of water.
4. Flow in the vicinity of the site is strongly affected by pumping wells or other hydraulic controls.
5. Impacted aquifer is a fractured rock system.
6. Source input must be treated as a slug injection.

Only if none of the above statements apply will CHOICE advance to Chart No. 2.

If any of the statements do apply, the heterogeneity of the site will be addressed and

either RESSQ will be recommended or the algorithm will jump to Flow Chart No. 7 to

decide between the two numerical models.

The bulk of CHOICE's decisions are based upon the scenario in which a site can be modeled by an analytical model, so that is what we will address in the most depth. Flow Chart No. 2 begins the analytical model selection process, using the data garnered from the first question asked, about the type of site being modeled. If the site is a landfill or an area where sludge was applied, the important question asked is whether the aquifer, which at this point is assumed to be confined, has known characteristics and can be approximated by an infinite slab in the region of interest, or are the aquifer characteristics ill-defined? If the characteristics cannot be accurately defined, CHOICE will recommend EPAGW because it possesses a regional database of hydrogeologic data that can be used to start the modeling process. If, on the other hand, the characteristics are known, and the aquifer can legitimately be modeled as an infinite slab, the program will proceed to Flow Chart No. 3a. Another type of site is one where contaminants were/are sprayed on to the area or where an individual rotary distributor was used. In these instances, groundwater mounding is assumed to take place and the program advances to Flow Chart No. 3. The last type of site considered is that of a wastewater lagoon. At this type of site the algorithm, with input from the user has to decide whether the lagoon has been effectively lined. The question about the lining is important because if the lagoons has been lined, infiltration to the groundwater will be minimized, whereas if there was no effective liner, infiltration from the lagoon will make an impact upon the regional water flow. If there was an effective liner, CHOICE will join the landfill process as shown. If there was no liner, or an existing liner is know to be ineffective, an estimate of the groundwater mounding must be accomplished. A third possibility is considered by the algorithm:

Liner integrity is unknown. In this instance, CHOICE assumes the worst case and proceeds to calculate the groundwater mounding.

Flow Chart No. 3 concentrates on the problem of groundwater mounding. The program begins by estimating the long term head rise (R) due to recharge using the Hantush method. CHOICE then uses R to calculate the ratio of long term head rise to the aquifer thickness (b). This R/b ratio is the first deciding factor in the chart. The user has the option of either letting the program calculate R from user inputs or directly inputting the ratio. If the user opts to let the computer calculate the ratio, the following numbers are asked for:

Radius of recharge area (ft),
Rate of recharge (gpd/sq ft) >
Hydraulic conductivity (cm/sec) >
Storage coefficient (dimensionless) >
Initial saturated thickness (ft) >
Time horizon of recharge (days) >
Initial depth to water table >

The next step is based upon the R/b ratio. If R/b is less than 0.05, than the flow can be modeled as essentially non-radial and approximated by confined aquifer solution methods. With this R/b ratio, it is possible to model a landfill site with a homogeneous aquifer as well as the wastewater lagoon, because the assumptions required for both create the same type of model. The two site types are assumed from this point on to be equivalent to one another. The next question asked has to do with the relationship between the source boundaries and the region of interest. If the site is not located near the edge of the source, CHOICE moves on to Flow Chart No. 4. If, on the other hand, the edge of the source is close to the site, another decision must be made. The last question

in this train of questions is whether a full penetration analysis is adequate or partial penetration effects are thought to be important. If the full penetration is considered adequate, then the ODAST model may be used. Otherwise, the program goes to Flow Chart No. 6a.

In the above scenario, the ratio of R/b was less than 0.05. If R/b is between 0.05 and 0.3 another solution is called for. In this case, the Dupuit assumptions are assumed to be good. In 1863 Dupuit noticed that in most groundwater flows, the slope of the phreatic surface was very small, and a small θ lead to the assumptions that the equipotential surfaces are vertical and that flow was essentially horizontal. The important advantage gained by the assumptions is that a two-dimensional (x,z) problem has been reduced to a one-dimensional problem, in which the vertical component of flow is ignored (Bear, 1972: 362). With these assumptions in place, the algorithm moves ahead to Flow Chart No. 6.

The last possibility arising from the R/b computation is that the ratio is greater than 0.30. In this case, there is radial flow and the Dupuit assumptions are not valid, meaning there is a vertical component of flow to consider. At this point, the algorithm recommends a numerical model be used to model sites (Chart 7).

Flow Chart No. 4 arises from the case where there is non-radial flow in confined aquifer and the source cannot be considered an infinite line source. The first decision to be made is what kind of source(s) are to be modeled. There are three choices:

1. Single areal, line or point sources.
2. Multiple point sources, of varying strength.
3. Other situations.

In the first scenario, there is only one source which may be considered a point, areal, or line source. The important thing to CHOICE is that there is only one source. After that has been verified, the source strength must be identified by the user. The source strength may be modeled either as constant or decaying exponentially with time. If the source strength is to be modeled as a constant, the program advances to Flow Chart No. 5. If the source cannot be considered constant, then the question of full penetration analysis again becomes important. If the site can be modeled as fully penetrating, CHOICE will recommend TDAST, but if the site must be considered partially penetrating, analytical solutions are not possible and the algorithm will recommend the numerical model option (Chart 7).

A second scenario is possible, wherein there are multiple point sources in the aquifer, all with constant strengths. In this case, the question of full penetration come up once again. If the site can be assumed to be fully penetrating the program will recommend PLUM2D. If the assumption cannot be held for the site, CHOICE will again recommend a numerical model be used (Chart 7).

The easiest scenario of the three is if other source situations apply. In this instance, CHOICE will once again suggest using a numerical model (Chart 7).

Flow Chart No. 5 comes from a situation where the site is susceptible to groundwater mounding, has an R/b ratio less than 0.05, is located far from an edge of the source, with a single source of constant strength. With this backdrop, there are two possibilities for the source. It can either be a point source or it can present a significant in relation to the points of interest for modeling. In the first case, the next step is the full

penetration analysis once again. If full penetration is appropriate, CHOICE will recommend the analytic model PLUM2D. If the full penetration analysis is not appropriate, another question must be answered by the user. The user must decide if the expected maximum impact will be along the main axis of flow or not. If the maximum effect will be along the axis, analytical solutions are appropriate and CHOICE will recommend EPAGW; otherwise it will recommend a preliminary analysis using RESSQ. The other option for Flow Chart No. 5 is a source with a significant width (a line source). In this case, the user has even more decisions to make. The first decision is whether the source concentration has a main direction (focus) or whether the source is a large area of uniformly distributed strength (a two-dimensional source). If the source is two-dimensional, CHOICE will recommend TDAST. If the source is focussed, the question about maximum impact arises again with the same answers. If the maximum impact will be along the main flow axis, EPAGW will be selected; if not RESSQ will be.

The next to last flow chart, Flow Chart No. 6, will be in effect for a site where groundwater mounding is possible, the R/b ratio is between 5% and 30%, with the Dupuit assumptions valid. In this case the applicable solutions depend upon the distance from the site to the source. The user is given three choices:

1. The region of interest is located close to the edge of the source, so that the source can be treated as being infinite in the lateral direction, in relation to the observation point of interest. The initial gradient of the water table less than 1 percent.
2. The region of prediction interest is located far enough from the source so that the source can be approximated as a point. The distance is great enough so that full penetration of the aquifer is a reasonable assumption.
3. NEITHER of the above is adequate.

The first case, where a site has an R/b ratio of less than 0.05, with a site close to the source, but without the full penetration assumption being applicable requires another decision to be made by the user. The user must decide which of the following is most appropriate for the site:

1. Regional flow regime is thought to be unimportant in relation to recharge-induced radial flow. Contaminant reactivity is very low and decay is not considered very important.
2. Regional flow regime is considered important in modeling the transport of the contaminant(s).
3. Analysis requires consideration of decay.

In the first mini-case, with regional flow considered unimportant, the analytical model DUPVG is selected for the user. If regional flow is deemed important by the user, or decay of the source must be considered, then radial flow is assumed, the Dupuit assumption is not valid, and CHOICE recommends RESSQ.

Going back to the first choice of the chart, another option for the user is to model the site as far enough from the source so that the source can be approximated as a point and the full penetration assumption can be reasonably applied. In this case, the regional flow question is again asked. If regional flow is considered unimportant, the analytical model LTIRD is applicable. Otherwise, CHOICE will choose RESSQ for the user.

The last chart (Flow Chart 7) is a representation of the logic used by CHOICE to decide between the two numerical models. Since a number of answers lead to this chart, it is fairly important to the algorithm as a whole. The first step is actually not shown on the chart. The program, after recognizing from user inputs that the situation has complex flow conditions, asks the user whether he/she prefers a deterministic or stochastic (Monte Carlo analysis) model. If the Monte Carlo simulation is requested, the MOC-MC model

will be used, with the HELP model preceding it if called for by the site characteristics. If

the user asks for a deterministic model, then CHOICE begins its decision process.

In the same manner as the analytical method elimination, a number of statements

are made. If any of them are false, then the algorithm will recommend RANDOM

WALK. Only if all the requirements are met, will MOC be selected as the model to be

used. One of the limiting conditions mentioned in the text of the program is that

RANDOM WALK has a 40x40 maximum grid size while MOC is limited by the

Advisory System to to a 20x20 grid. The statements made that the decision is based on

are:

1. A variable grid size is required or desired.
2. Due to the aquifer size, the grid increments in the X or Y direction must be larger than 10 times the transverse dispersivity.
3. The ratio of longitudinal to transverse dispersivity is greater than 10.
4. Flow patterns are likely to be predominantly non-parallel to the grid axes.
5. The storage coefficient varies significantly over the area to be modeled.
6. Hydrogeology changes from confined to water table or vice versa during the simulation in all or part of the aquifer.
7. None of the above apply.

Only by choosing number "7. None of the above apply." will CHOICE select MOC as

the model to be used. All other options will lead to the selection of RANDOM WALK as

the model of choice.

In all cases except for RESSQ, when a model is selected the program asks the user

what type of impact standard that they want to review: Is the standard an environmental

standard or is the modeler looking at human exposure? After that question, the program

indicates which model has been chosen and asks the modeler to accept or reject the

choice. The next-to-last step, if applicable, is to ask whether the user wishes to call the

HELP model to estimate the vertical infiltration rates from the site. The user has the option of either running HELP or inputting the infiltration rates directly.

The last step is to ask what contaminant is being studied and what the standard is for the contaminant. The program uses this standard in the graphical post-processors of the models to show whether the prediction is above or below the standard in question.

Testing of the Advisory System

One of the research objectives was to ascertain whether the reports generated for a typical IRP site contained the data required by CHOICE to recommend a model. To test the Advisory System, we gathered data from an actual IRP site, and used the data as input to the Advisory System to obtain results. The IRP site selected was LF02, at Robins AFB, Georgia

LF02, Robins Air Force Base, Georgia

LF02 is located in the central portion of Robins Air Force Base (RAFB), and consists of two separate hazardous waste sites. The first is Landfill No. 2, which was operated from 1951 to 1963, covering an area of approximately 22 acres. The landfill operation was by a trench and fill method. This method consisted of trenches being dug to a depth of approximately 20 feet (generally below the water table), waste being placed into the trenches, and a daily cover of boiler ash being placed over the waste. Wastes disposed of in the landfill included general refuse from the base, household wastes, and some industrial wastes. In addition to the actual landfill, the area includes a Fire Protection Training Area (FPTA).

FPTA No. 1 was operated from 1943 until the mid-1950's. FPTA01 consisted of an unlined pit surrounded with earthen dikes. The site was used about twice a week, with the common method of operation being the Base Fire Department emptying drums of contaminated fuel, oil, solvents, and ignitable chemicals on water-saturated ground, lighting the mixture, and extinguishing the mixture until it would no longer burn. (HAZWRAP, 1991: 2-6).

RAFB is located at the juncture of two geologic units: the Quaternary alluvium (river floodplain material) and the underlying Ripley-Providence Formation. The rise in topography from east to west and the pinching out of alluvial peat and clay deposits in the western portion of LF02 are the indicators of the geologic contact.

Groundwater flow in the area of the site is divided between the surficial water table aquifer and the underlying Providence Aquifer, which are separated intermittently by the peat/clay layer. Where the surficial fill materials overlie the peat/clay alluvial deposits, groundwater mounding has occurred. The mounding has saturated the lower portion of the surficial fill, with the aqueous phase that is in contact with the refuse designated as leachate. The average groundwater velocity within the mound is estimated to range from 0.4 to 1.9 ft/day.

There is a vertical component of flow in the site, downward from the surficial fill towards the Providence Aquifer. Where there is a peat/clay layer this movement is hindered, but the layer is not continuous across the site.

For the Providence Aquifer, the average groundwater velocity is estimated to be 1.3 ft/day. The vertical component of the flow in the Providence Aquifer is upward. The

reason for this upward flow is that at the site the Ocmulgee River and associated wetlands

are a regional discharge area for the Providence Aquifer (HAZWRAP, 1991: 4-29).

Investigations into LF02 began in 1982. The studies are summarized in Appendix B

along with the entire CSM for LF02.

LF02 and CHOICE

In order to analyze the algorithm as thoroughly as possible, the decision was made

to run the program twice, with differing stages of data. The first run used data from a

1985 report accomplished by Water and Air Research, Inc. titled Stage II, Phase I

investigation while the second run used data resulting from the RCRA Facility

Investigation (RFI) completed in 1991. The reports are separated by six years, and the

amount of data collected in the investigations are vastly different. These two cases were

analyzed to study the algorithm's reaction to different amounts of data being available.

An overview of the decisions made by CHOICE is shown on the flow charts on the next

two pages.

CHOICE - Phase II, Stage 1 Data

Start

Site is a Landfill:
No. 5

Analytical
Models are not
Appropriate.

Contaminants of Interest are
Immiscible/have s.g.>water

The modeled
region is
homogeneous.

HELP Model
Required

RESSQ

```
                    ┌─────────────┐
                    │    Start    │
                    └─────────────┘
                           │
                           ▼
                  ┌──────────────────┐
                  │ Site is a Landfill: │
                  │      No. 5       │
                  └──────────────────┘
                           │
                           ▼
                        ◇ Analytical
                          Models are not
                          Appropriate.            ⬭ Contaminants of Interest are
                                                     Immiscible/have s.g.>water

                                                   ⬭ The area is not homogenous
                                                      There are 2 aquifers

                        ◇ The modeled
                          region is not
                          homogeneous.

  ┌───────────┐                           ┌───────────┐
  │  MOC-MC   │                           │  RANDOM   │
  │           │                           │   WALK    │
  └───────────┘                           └───────────┘
        ▲                                       ▲
        │                                       │
  ┌───────────┐        ◇ Part of the     ┌───────────────┐
  │ Stochastic │ ◄──     aquifer changes   ──► │ Deterministic │
  └───────────┘          from Confined to    └───────────────┘
                         Unconfined
```

Phase II, Stage 1 Data

The first input required by CHOICE from the user is the site type. For this research the site is a landfill, with the correct response being "5. Landfill." The next step was to determine if an analytical solution was appropriate for the site. At this stage of the investigation, not enough was known about the site to say there was a distinct inhomogeneity in the medium, nor was there known to be two aquifers present at the site. But any of the contaminants of interest (Chlorobenzene; 1,2-Dichlorobenzene, or Trichloroethene) qualify as immiscible liquids and/or have specific gravities different from that of water. Chlorobenzene is not very soluble in water and has a specific gravity of 1.1, 1,2-Dichlorobezene is slightly soluble with a specific gravity of 1.3 and TCE is slightly soluble in water with a specific gravity of 1.6 (Bolz and Tuve, 1987: 382). With this data, the program concluded that analytical methods are not appropriate.

The next step in the program's logic was to check to see if the site was amenable to semi-analytical modeling. At this stage, circa 1985, the region would probably be modeled as homogenous, because none of the wells drilled for Phase II, Stage I were within the confines of the actual landfill and therefore showed generally homogeneous site conditions. The only monitoring well showing the region to be heterogeneous was well LF2-2, which is located downgradient from the site (HAZWRAP, 1991: 4-11). From this input the program concluded the aquifer was not drastically inhomogenous in the region of interest. The next question asked was whether the HELP model would be needed to estimate the vertical infiltration rate at the site. With no knowledge of the actual infiltration rates, the HELP model was required. After requesting HELP, CHOICE

indicated the model to be used was RESSQ and asked if that was acceptable. After

accepting the recommendation, CHOICE asked for the contaminant studied and its

Standard (Chlorobenzene and 70 µg/l, respectively). At this point CHOICE had done its

work and the user was sent to HELP to begin modeling the site.

RFI Data

As was the case above, the site is a landfill so the answer to the program's first

question is "5. Landfill." The next step in CHOICE's logic is to eliminate analytical

models, if possible. In this instance, the additional investigation revealed a distinct

inhomogeneity in the area (the peat/clay layer pinching out under the site), that there were

two aquifers to be addressed, and the contaminants of interest are immiscible in water

and/or significantly different in specific gravity from water. Consequently, CHOICE

advanced to the decision of whether semi-analytical models were appropriate. With the

data gathered from the investigations, the aquifer could not be considered homogeneous

in the region to be modeled. CHOICE thus concluded there were complex flow situations

and began its numerical model selection routine by asking if the user prefers a Monte

Carlo or Deterministic solution. The purpose of this research was to test the ability of the

algorithm as much as possible, so the selection was for a deterministic model. CHOICE

then allowed the user to select the most representative site conditions from its list. The

hydrogeology of the site changes from confined aquifer to unconfined aquifer within the

area to be modeled, so "6." was chosen. At this point the program asked if the standard

to be used was an environmental standard or human exposure, queried the user about the

HELP model, indicated the model selected was RANDOM WALK and asked the user to

accept or reject its recommendation. The last step before beginning actual modeling was inputting the contaminant studied and its Standard. If we had selected a stochastic model, CHOICE would have recommended the MOC-MC model, then followed with the questions about standards and HELP.

After putting in the last bit of required data, the algorithm is finished and the advisory system begins the creation of a model for the site. Now we shall analyze the various components of the system, in Chapter IV.

Chapter 4 - Analysis and Conclusions

To analyze the groundwater advisory system in a thorough manner, we shall look at the software first, followed by the documentation. After analyzing the system, we shall draw some conclusions about the system, ensure the research questions from Chapter 1 have been answered, and close out this research with a few proposals for further research into this area.

Analysis of Groundwater Advisory System Software

One point to make before beginning the analysis of the advisory system is that this research was conducted only with the DOS version of the groundwater advisory system. There is a UNIX version available as well, but the computers available at AFIT were unable to run it without major adjustments to the source code being made, which was outside of the scope of this research.

We shall analyze the pieces of the groundwater advisory system as they appear in the main menu of the program. . The first option available, as can be seen in Fig. 4-1, is the LeGrand Method for Preliminary Analysis. Figure 4-1 is a copy of the screen of the main menu of the program as it is shown on a monitor of a DOS-based computer.

Figure 4-1 Main Menu for Groundwater Advisory System
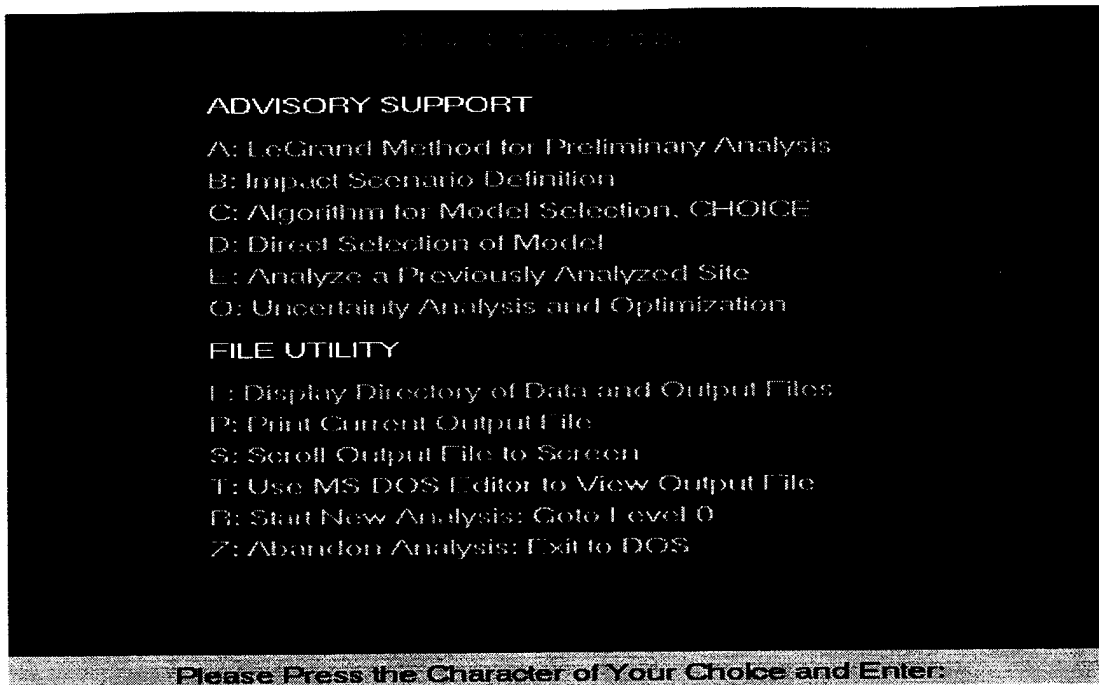
LeGrand's Method for Preliminary Analysis

The object of incorporating LeGrand's Analysis into the advisory system was to standardize the evaluation of potential waste sites (Medina and Jacobs, 1994b: 19). The method requires data that is readily available from a site that has had very little investigation done and will provide a answer as to whether the site will or will not probably be a problem in the future. The implementation provided in the advisory system is a direct implementation of the original analysis written by H.E. LeGrand, who reviewed the code and approved it. It does what it is designed to do within the confines of the advisory system: it predicts whether a site could cause trouble in the future base upon very little investigative data.

Impact Scenario Definition

The next item on the main menu is the Impact Scenario Definition, which was included as an alternative way to choose some of the models contained within the advisory system. The title of the section is ambiguous and misleading. At first glance, the title leads one to think the section has to do with defining the different scenarios for contamination, which it does not do. The user can use this section to select a model, but the word "Definition" in the title is misleading because there are only four possibilities to choose from and the section gives no assistance to the user in defining the type of the site being modeled. There are three other things notable about this section of the program. The first is relatively minor. When the fourth scenario, general modeling of plume extent, is chosen, the second option of available models is "Semi-analytical models." Yet there is only one model under that heading, RESSQ. Either the heading should read RESSQ, or there should be another semi-analytical model available to the user. The second notable item is more important, and it again deals with the fourth scenario. If the fourth modeling option, RANDOM WALK, is selected, the program gives the user a run time error and returns to the main menu. Therefore, the pathway to call RANDOM WALK has an error in it and requires attention.

The final notable item is a major problem: There is an error in the program plum2d.exe, the executable file for the model PLUM2D. When the program is prompted for an error message appears:

PLUM2D.for(507) : run-time error F6501: READ(MODEL.DAT) - end of file encountered

This error appears within the advisory system and also if the program is attempted from a DOS prompt. Where the error is located is beyond the author's expertise to locate and it has been bought to the attention of the authors of the advisory system.

The program, with a few exceptions, ran as it was designed to. But the question arises as to whether this section of the Advisory System is necessary. CHOICE has been updated recently to reflect changes in modeling, while the Impact Scenario Definition portion of the program is unchanged since its creation in 1988. With the Air Force starting to use relative risk as a factor in IRP decisions, this part of the Advisory System could conceivably be of immense use, if it was updated to reflect all the models available to the Advisory System and the way risk is calculated for the Air Force.

Algorithm for Model Selection, CHOICE

The title of the algorithm, from the first screen once the program starts is "CHOICE ALGORITHM FOR USER GUIDANCE IN CONTAMINANT TRANSPORT MODEL SELECTION." The stated purpose of the algorithm is to consider a wide range of groundwater modeling situations, and, in each case to determine whether there is an appropriate analytical solution with which Monte Carlo analysis of the risk associated with the site can be analyzed. When such a solution is not available semi-analytical methods will be appropriate for some instances. Otherwise, more complex numerical models will be required for the site (Medina and Jacobs, 1994b: 24).

CHOICE fails in its stated objective because even when a site allows an analytical solution to be applied, CHOICE does not call for a Monte Carlo analysis, except in the cases of the models that have the analysis built in, EPAGW and EPASF. In the case that

analytical models are not appropriate, CHOICE does what it was designed to do, namely advise whether to use a semi-analytical model or numerical model.

The main stumbling block with CHOICE was getting to the analytical models. The assumptions required for an analytical model to be considered valid and appropriate are numerous and strict so it is not surprising that it is difficult to find a site that is capable of being modeled by an analytical model, but the authors of CHOICE went through a lot of work to specify the exact situations where an analytical model could be used. The majority of the time the algorithm will select either RESSQ or one of the numerical models because it is so difficult to reach a situation where analytical methods are suitable. This logic doesn't follow the theory of Occam's Razor, whereby the simplest of competing models is always to be preferred to the more complex (Mercer, 1991: 3).

The authors of the algorithm worked with two other researchers in analyzing CHOICE's decision process and published their results. The results were that for 500 runs of the algorithm, 441 times CHOICE selected either RESSQ or a numerical model (Reich, Medina, Shieh, and Jacobs, 1995: 24). The conclusion drawn by the research was that the developers both implicitly and in some cases explicitly biased the selection of the more complex codes since groundwater modeling is a complex undertaking (Reich, Medina, Shieh, and Jacobs, 1995: 14).

Putting all of that aside, let us review CHOICE for its own merits. We noticed one good point, one minor unfavorable point, two major unfavorable points, and one questionable area in the algorithm. In reverse order, the questionable point is why in the first screen of the algorithm is there an option for the direct user selection of a model.

The reason the user is utilizing CHOICE in the first place is to obtain assistance in choosing a model for a site. There is an option in the main menu for the direct selection of models. It is not logical to start CHOICE to select a model without running the algorithm.

The first of the major unfavorable points is that CHOICE cannot call the model PLUM2D. This discrepancy was mentioned above in the discussion of the Impact Scenario Definition, but is important enough to mention again. The other major problem is that the HELP model has two difficulties associated with it. The first difficulty is that if the user leaves HELP, even inadvertently, they cannot return without running CHOICE again, and any data already input is lost. The other difficulty lies in the absence of any assistance for the program. Almost all of the models within the advisory system come with a user interface, a preprocessor, and a post-processor to assist the user in utilizing the models. These other processors shall be addressed later, but the user interface for HELP has a error in it. If the user requests help, the program goes to a document called help.doc which is one line of text which says "this is a help file for HELP". The program is complicated to use and hard to understand, even if it did have on-line help, which is expected by most computer users.

The minor negative point is that there is a misspelling in the program. After a series of questions, the user is prompted that multiple sources are in place in a confined aquifer and their "strenghts" are not decaying. This oversight is a minor problem, and easily corrected, but points to a lack of quality control that must be addressed by the authors.

The good point is that upon completing the algorithm and allowing it to run the model of its choice, if the user re-enters CHOICE, the first question is whether the user wishes to apply a numerical model for more advanced analysis or restart CHOICE. The algorithm is assuming the user has run the model of choice and received output and wishes to use that output as input for a more complicated model. The numerical models are generally not suitable for the first iteration of modeling because of data constraints. A bonus to using a simpler model first is that it is easier to run sensitivity studies then, before the full blown three dimensional modeling begins (Franz and Rowe, 1993: 436). The best solution to modeling, when time allows, is to use two types of models in conjunction with one another (Van der Heijde, 1993: 10).

Direct Selection of Model

The fourth option in the main menu is the direct selection of a model. This alternative allows for selection of <u>any</u> of the models of the advisory system, except for the models modified for Monte Carlo Analysis. We shall analyze three elements of each model. The elements are the models' user interface or shell, their respective pre-processors and their post processors which assist in data input and interpretation, and each program's plotting capabilities, if any. A review of the models themselves is outside of the scope of this research. This section shall be broken into three parts, the first for the analytical models; the second for RESSQ, MOC, and RANDOM WALK; and the last for the models that are only available via direct selection: MODFLOW, SUTRA, and BIOPLUME II.

Analytical Models

ODAST & TDAST

The first two models available are ODAST and TDAST, which are quite similar. They share the same mouse-driven graphical user-interface (GUI) shell and use approximately the same data (TDAST uses x and y coordinates, while ODAST uses only requires x coordinates). The pre-processor they share is the best one contained in the advisory system. It has a help screen that explains all the data input requirements and the requirements are already laid out ahead of time, all the user has to do is plug in the data. The post processors are also GUIs and easy to use, but the TDAST post processor is not as good as ODAST's. ODAST's post-processor plots the concentrations as requested and explains the plots very well, while TDAST's gives the concentrations requested as a DOS text file. Unfortunately, the only place where the format of the output is explained is in the source code of the model. There is a problem with ODAST's plotting package when it is used with Microsoft's Windows 3.1 operating system. ODAST plots the results, then when a key is pressed, the plotting package asks the user if they wish to print the plot. If the user answers "yes" the program looks for a printer, fails to find one, then exits the advisory system and presents a DOS prompt. This occurred on three different personal computers, two of which were attached to the AFIT network. If the user answers "no" the program goes back to the main menu, and all the user's responses are placed in the middle of the screen instead of at the bottom where the cursor is located.

The last part of the programs are the output files. The data in the output files includes the site name, the date and time of the data run, any comments the user made

and the resulting output. In TDAST there is no ability to plot the output, although the data is presented in the output file in a way to allow plotting very easily.

PLUM2D and DUPVG

The problems encountered with PLUM2D have already been documented. DUPVG has an excellent GUI shell, with a help screen attached to the pre-processor to explain the data input requirements that is user-friendly. Once the program is run the data is again presented as a text file, which is misleading because the post-processor is titled "Plot File." Yet there is no ability to actually plot the output data. This viewable output file is very useful. It shows the date and time of the run, the control information (the hydraulic parameters input by the user), and the results of the model. The data is presented in tables which allow the data to be plotted by other software packages, but the advisory system cannot accomplish the plotting itself.

EPAGW and EPASF

EPAGW and EPASF lack the excellent pre- and post processors of the previous models. Indeed, upon selecting either model, the user is placed in a DOS/FORTRAN environment, with no shell and no help available. Both models are discussed extensively in the User's Manual, but once the program starts there is no help immediately available. Both models present their results in the form of graphs that are not explained anywhere in the documentation. The graphs are probabalistic in nature, but neither an explanation of their creation nor a guide to interpreting them is available.

LTIRD

LTIRD has a few quirks that are not readily visible to the user. The first is that asking the program for help from the top bar, under Utilities sends the user back to the main menu while asking for help by pressing the F1 key opens a text file describing the program. Only by starting the GUI preprocessor and then asking for help can the user obtain a description of the data requirements and the format for them. Then once the data is input and the model is run, the output can be obtained from two locations. The user has the option of choosing either "Plot File" or "Output File." Both lead to the same data because there again is no plotting capability within the advisory system to handle the output data.

RESSQ, MOC, and RANDOM WALK
RESSQ

RESSQ also has a GUI shell containing pre- and post processors. Like LTIRD, once preRESSQ is begun, asking for help allows the user to look at the data requirements and their required format. There are differences in the input setup of RESSQ compared to the analytical models because of its nature. The model has an input file like the analytical models, then two additional input fields for injection and production wells. The well input fields require coordinates, rate of injection/production, and well radius. The documentation on CHOICE refers to RESSQ a number of times as a preliminary analysis, possibly to be used as a precursor to a numerical model. A site just beginning to be investigated would not be likely to have any injection or production wells, so for a preliminary analysis, these fields would be turned off. Fortunately, as often as RESSQ is selected by CHOICE, the model does have the ability to plot the results of its

calculations. The plotting package is different from that of ODAST. Once the plot is complete, the user is asked to press "1" to change the boundaries of the plot, then "1" to print the plot, or press "2" if the printer available is a Hewlett-Packard printer. No problems arose printing the plot requested. Pressing the return key will send the user back to the shell. The output file is organized as the preceding ones that possess the shells, with all the required data shown first, then the results of the computations.

MOC and RANDOM WALK

MOC is one of the numerical models that is available to CHOICE, and as discussed earlier in this chapter, will see a lot of use. It has the shell running on top of the actual program as the majority of the other programs so far have had. Unfortunately, the shell is there in name only. Starting the input process sends the user to a FORTRAN program named PREMOC written by the International Ground Water Modeling Center (IGWMC) in November of 1989 (Medina and Jacobs, 1994b: Source Code). There is help available once PREMOC is begun, but the help modules were written by the IGWMC, not by Medina and Jacobs, who wrote the help available in the other shells, which describe the data requirements and format. There is plotting capability with MOC, but the input file provided as an example caused an error and no plotting was available for review. The error also did not allow the creation of an output file, so that aspect of the program was not analyzed either. Curiously, the input file was available and looked like other the models analyzed in the DOS editor. No explanation of the format of the data was available though, which was provided by the other shells.

RANDOM WALK, like MOC has a shell running on top of the model that exists in name only. The pre-processor is a FORTRAN program, like RANDOM WALK. No additional help screen like those of the analytical models was available. There was an example available and it was run by the author to analyze the model. There is an option in the shell to post process the data, but all it contained was the output file. There was no capability to plot the results of the model. The output file was much more user-friendly than that of MOC, showing the control data and the results in a tabular form, in a easily plottable format.

MODFLOW, SUTRA, and BIOPLUME II
MODFLOW

MODFLOW requires extremely complicated input files. The shell running atop the model has two pre-processors to assist the user. The first is PREMOD, created by Geotrans, Inc. in 1988 (Medina and Jacobs, 1994b: Source Code) while the other is ModelCad, created by Geraghty & Miller, Inc. in 1989 (Medina and Jacobs, 1994b: Source Code). The ModelCad version is more up-to-date and user friendly, using a GUI format, while PREMOD uses a FORTRAN format to create the input files. Once the data is input and the model is run, the post-processor was again created by Medina and Jacobs, and shows all the control data and results of the model in a readable format.

SUTRA once again has a shell running atop the actual mode in name only. Calling the help from the Utilities sub-menu brings up the text file written by the creator of SUTRA. The so-called PreSUTRA calls the MS-DOS editor, with no instructions and no pre-existing format. The input file command does call the DOS editor again, with the

example input and output file names in the format required by SUTRA at least, so some work is accomplished by the shell. The PostSUTRA command and the output file command lead to the same text file, which is created by SUTRA itself. A program capable of plotting SUTRA output files exists, named SUTRA-PLOT but is not included in the advisory system, so there is no capability of plotting any results of the model. A problem encountered with the program is that the grid size is locked in by the source code and cannot be changed. This means that any modeling to be done with SUTRA will always have to be done with a limited grid size, no matter what size the site is.

BIOPLUME II again has a shell written by the personel at Duke, which is only there to call programs written by others. The help key calls the description of the program written by the creators of the model, the pre-processor command calls "Loader" which is the Bioplume Data Editing Program, again written by the creators of the model, and the Postprocessor calls a FORTRAN menu to allow the creation of file that can be plotted with Golden Software's SURFER program. The only original work done by the advisory system is in calling the DOS text editor to view the output files.

Uncertainty Analysis and Optimization

The last section of the main menu to be analyzed is Uncertainty Analysis. This section contains the Monte Carlo analysis models ODAST-MC, TDAST-MC and MOC-MC. The first model is ODAST-MC, which looks remarkably like the original model when the model is selected. The only difference is in the title slide of the shell program which states the model is ODAST-MC and not ODAST. The shell itself is the same, and no differences are noticed until PreODASTMC is begun. Then in place of three input

files there are five. The first three mirror ODAST with the remaining inputs setting up the Monte Carlo analysis by providing the mean values, standard deviations, and parameter distributions of the controlling parameters and the parameters controlling the analysis it self (number of runs, and the observation point of the analysis). Once the model is run, the difference is again apparent because instead of plotting concentration versus time, the post processor enters a Cumulative Frequency Plotter. The output file is user-friendly, showing the date and time of the run, the number of Monte Carlo runs, the mean values of the parameters, and the probability of failure for the model.

TDAST-MC is like ODAST-MC in that the shell is almost identical to the one used by TDAST, with the differences only appearing once the input file is called. In place of the 15 x, 15 y, and 8 t values allowed by TDAST. TDAST-MC limits the user to an x,y coordinate and one time value. Additionally, of course, TDAST-MC requires the same Monte Carlo data as ODAST-MC required (number of runs and parameter distributions). The Frequency Plotter is the same as ODAST-MC utilized and the output file has the same format as that of ODAST-MC.

MOC-MC uses a version of PREMOC that was updated for Monte Carlo simulation by Jonathan B. Butcher in 1986 (Medina and Jacobs, 1994b: Source Code). After that difference, MOC-MC is the same as ODAST-MC and TDAST-MC. It uses the same Frequency Plotter and the same generic output file.

Now we shall analyze the documentation that was received with the software.

Analysis of Groundwater Advisory System Documentation

Taken in its entirety, the documentation accompanying the software was satisfactory. It accomplished its mission in that with the documentation, the program could be loaded on to a DOS-based personal computer, and run by a user reasonably familiar with the general theory of contaminant transport and the DOS operating system. However, there are shortcomings, some serious, with the documentation that must be addressed before the Air Force begins wide-spread use of the advisory system. The User's Manual, hereafter specified as the Manual, for the advisory system is broken into six sections which is how we shall separate the analysis. We shall cite both highlights and defects of the documentation as we review the Manual section by section. The first section is the Introduction, which contains sub-sections on the objectives of the system, a brief background, an overview of the components of the system and a description of the scope of the Manual.

Introduction

The Introduction section as a whole was well written and well organized. The Background section discussion of the IRP is essential to inform a user that is unfamiliar with the IRP of the aims of the program and the necessity of an advisory system to assist users in choosing models and modeling sites. The discussion of when to use models in the IRP process is especially useful in detailing when models will be most useful in a site's life cycle. Another good point contained in the section is that in the description of the system the Manual mentions the fact that as more field data comes in, the modeling cycle should begin again. This is extremely important to notice, otherwise inexperienced modelers might be tempted to create a CSM, obtain an response from a model, and

assume that response is correct. That does not happen in real life situations. As time goes by and more data comes in, modelers must update their CSMs. When CSMs are changed, different models are likely to be required, or if the same model is needed, more data means a more detailed model and more exact answers.

There are problems with the section, however. The description of the overview and components of the advisory system on page 4 mentions the model selection algorithm CHOICE, but does not mention the Impact Scenario Definition, which can also select models. In fact, nowhere in the Manual is the Impact Scenario Definition mentioned, other than in a picture of the Main Menu located on page 18. Another minor problem with the section is that on page 7, the Manual shows all the numerical codes available to the advisory system, then mentions that CHOICE, under the appropriate circumstances, will choose between the "two available numerical codes." The two codes that are available to CHOICE are not mentioned, nor is there an explanation there as to why there are codes unavailable to the algorithm. On page 30, the Manual explains that the three codes outside of CHOICE's realm were added for the modeling of complex hydrogeological environments. This explanation should be moved to page 7 to help the user understand CHOICE's limitations. In addition, BIOPLUME II is not used for complex environments, it is used model natural attenuation of oxygen-limited biodegradation in porous media.

The last two problems with the section are also located on page 7. The description of the logic followed by CHOICE mentions flow charts which identify the model to be used and the Dupuit approximation as one of the deciding factors in that decision. The

Dupuit approximation is a mathematical assumption that is likely to outside of the realm of most modelers expertise, and is an extremely important decision point within the algorithm, yet it is not defined further for the user.

The flow charts mentioned are not available in the Manual. They are mentioned again on page 24, when the Manual describes CHOICE in depth, as available in the Technical Report furnished by the authors to the Air Force, but they are not contained within the Manual itself. If anyone wishes to understand the logic followed by the algorithm, they must request the Technical Report from Armstrong Laboratories (Medina and Jacobs, 1994a: 19-25).

Installing the Advisory System

The Installation section of the Manual is separated into two parts; one for the DOS environment and one for the UNIX environment. The DOS environment section was clear, concise, and accurate. No problems were incurred while followings its directions for installing the advisory system on to a DOS-based personal computer. The UNIX environment instructions were another matter, unfortunately. The instructions contained within the Manual were superseded by a document file contained on the UNIX source code disk named "makefile.doc" dated June 21, 1995, which is the same date as the Manual itself. The instructions in makefile.doc are the same as those in the Manual with the exception of a few more lines of instruction. These instructions prompt the user to change the three of the UNIX codes that have been installed to reflect the new home directory of the advisory system. Unfortunately, this was not the only oversight in the UNIX instructions. Having made the changes required by the instructions, we tried to

install the advisory system on two different hosts at AFIT. In neither case were we successful because the advisory system was looking for directories and programs that do not exist on our machines. We had already decided to concentrate the research efforts on the DOS-based model as explained earlier, so after numerous attempts at installing the advisory system on different systems at AFIT we stopped and proceeded with the research solely with the DOS version.

User's Guide for the DOS Version

The first thing noticeable about the section is that the Manual spells the title "Users Guide" which is incorrect. The title should read User's with the apostrophe showing that the Guide is possessed by the User.

The best aspect of the User's Guide is that it shows pictures of the actual screens in the text as they appear on the monitor, albeit in black and white. These screen dumps give the reader a feel for what to expect to see when they are actually using the advisory system. If something other than what is shown in the Manual appears on their monitor they then know that there is a problem and can attempt to remedy the situation. Another admirable quality of the section is the description of LeGrand's analysis. The write-up is clear, concise, and follows the procedure as it appears in the program exactly. The only problem with the write-up is that it does not contain a matrix which is contained in LeGrand's book (LeGrand, 1983). Instead, the Manual declares that the input the user is required to enter "is best read from the matrix diagram provided in LeGrand (Medina and Jacobs, 1994b: 24)." The user has the option of estimating the data, but the most accurate data comes from using the actual matrix, as the author did for this research. If the matrix

is necessary it should be included in the text. If it is not required, it souldn't be mentioned.

The next subsection describes the access the user has to the models contained in the advisory system. The Manual again does not mention the Impact Scenario Definition as a method of selecting a model, it only mentions direct selection of a particular model or utilizing CHOICE to pick out the most appropriate model for a particular site. The section does another excellent job of presenting the screens that the user will see as CHOICE begins and runs. The screens shown; the main menu, the ones pertaining to RESSQ, and the one showing how to decide between the two numerical models, happen to be those that occurred when the LF02 data was used to test the algorithm. According to Reich *et al* (1995: 24) those screens will also be the ones seen the majority of the time by users of the algorithm. Another bonus in the sub-section is the inclusion of the limitations of and assumptions that are required for HELP to be in force for it to be accurate. The brief write-up on HELP also gives the user the typical sequence of input required by the program. The last commendable portion of the subsection is the recommendation that user request a minimum of 500 runs when using the Monte Carlo analysis. Without this recommendation, the user wouldn't know how many runs to use. The example provided with the advisory system used 50 but without the 500 minimum runs, the programs cannot accurately create an accurate cumulative distribution.

There are a number of problems with the sub-section to go along with its admirable quantities. The first difficulty arises in the write-up of the HELP model. There is no description of the data requirements, only the sequence of steps to follow. The user has

no idea what data the model requires until CHOICE begins the model as requested. The next three problems have to do CHOICE as well.

First, when CHOICE is running, it mentions that it will use the Hantush method to compute the R/b ratio, which is a significant computation if the site is to use an analytical model. Unfortunately, there is no description or mention of the method in the Manual. So users, unless they are familiar with the method beforehand, must estimate R by answering the questions posed within the program. The data requirements for the method are different from what would normally be expected to come from a site investigation. Accurate answers to these questions will require more investigations be completed specifically to provide the required data.

Secondly, the assumption of full penetration is never fully explained within the text. Again, if the site is to use an analytical model, this assumption is important in the decision process, yet is never explained to the user. The user is assumed to be familiar with the general theory of contaminant transport, and the penetration assumption may or may not be part of a particular user's knowledge base. It is an esoteric enough assumption that a brief explanation needs to be incorporated into the Manual for those people who do not know the assumption thoroughly beforehand.

The last difficulty with CHOICE also has to do with an assumption made within the analytical decision portion of CHOICE. One of the last questions asked is if the impact of the contaminant is assumed to be along the main axis of flow. This is basically asking the user to guess where the main portion of the plume presently is or is going to be. Once the model begins, the user will select the axis of flow, but asking him/her where the

contaminant will impact is putting the cart before the horse. Once the model has been run, an estimate of the concentration of the contaminant at different points in the site will be available. Then, the user will know where the main impact of the contamination will be and can answer the question.

The next two problems deal with the preprocessors and graphics attached to the models of the system. The Manual states that once a model has been selected, either by CHOICE or directly, the system will automatically invoke the appropriate data preprocessor to facilitate data preparation (Medina and Jacobs, 1994b: 30). This statement is incorrect. What the manual should say is that upon a model being selected, most of the models will start the user interfaces attached to them. The interfaces are described in Section V of the Manual and discussed earlier in this Chapter. Part of the description in Section V should be moved to page 30 to explain to the user what to expect, as well as a screen dump like those mentioned before, showing one of the interfaces. There is an example of one of the shells (MODFLOW) on page 71 of the Manual that should be located where the discussion about the shells takes place.

The last problem has to do with the graphics output from the Monte Carlo analyses. The Manual states that for each observation point the data runs will be sorted into an ascending order, the probability of exceeding the standard calculated, and a cumulative frequency plot displayed (Medina and Jacobs, 1994b: 31). There are two problems with this statement. The first is that this is the standard possibly being exceeded is not defined. CHOICE asks the user what type of Standard is the reference for the model and then what the Standard is, but the Manual does not mentions this procedure. It only

mentions a standard being exceeded. The second problem is there is no example of this type of plot until page 80 and there is no explanation anywhere on how to interpret the data. The last problem with the plots is that if the user inputs 0.50 as the Standard, the plot shows it as 5.0 E-1. It is not difficult to understand, but the first time a user looks at a plot, the shift might confuse him/her.

The last subsection in the User's Guide is Input/Output formats for Specific Models. Each model is discussed in depth, explaining what assumptions are required for each model, what data is required, and the format the model requires the data. This is a lengthy (42 pages) subsection, so as we did earlier in discussing the actual models, we shall separate the analyses into three parts, plus one other: one segment for the analytical models; one for RESSQ, MOC and RANDOM WALK; one for MODFLOW, SUTRA, and BIOPLUME II; and one more for the Monte Carlo models.

Analytical Models

The summaries of the analytical models were, taken as a whole, the best written of the subsection. The write-up of ODAST was the best of the group. It took three pages to explain the mathematics of analytical model, what most of the assumptions required for the specific model meant, what data was required, and introduced the preprocessor that is used for many of the models. The best thing about the ODAST write-up was the inclusion of pictures of the screens showing what the preprocessor looked like and how the data was to be input. It also showed what an example plot and example output file looked like. Unfortunately, this was the only instance of showing an example output file in the entire subsection. TDAST's summary quite similar to ODAST's because of the

similarity of the models. For TDAST, only one screen was shown, which had only one line different than that of the same screen shown for ODAST. The screens that should have been shown were the ones that were different from that of ODAST, those that requested the second dimension (y) data.

The PLUM2D synopsis was well written, including a picture of the preprocessor screen and what the graphical output should look like. Since PLUM2D could not be run, that is all we can say about the model. The next model is DUPVG and its summary was well written with nothing to distinguish it, positively or negatively.

The next two models, EPAGW and EPASF, share the lack of a user interface, which is not mentioned in the Manual, as well as two other problems. This lack should have been addressed in the Manual. Previous parts of the Manual lead the user to expect a user friendly interface after selecting a model, and with these two models they do not get one. A second problem is that both models require extensive site hydrogeology data. The summary for EPAGW states that regional data sets in the correct format are being created, but limited by data availability. Therefore, the user should take one of the provided data sets and edit it as required. There are presently four data sets in the system, an EPA national data set, and three from North Carolina. The data requirements are spelled out well, which is fortunate since there is no help within the program itself.

The last model is LTIRD. The summary is very short, with no explanation of the mathematics it uses to model the radial flow. A good explanation of the mathematics is contained in the Technical Report, but is not contained in the Manual. The other problem

with the summary is that it does not mention that it has the same shell and preprocessor as most of the other analytic models.

RESSQ, MOC and RANDOM WALK

RESSQ's summary was the most detailed of any of the models, lasting 10 pages. Because of its semi-analytical nature, it required a very detailed explanation of its limitations and guiding assumptions that was well written. The next part of the summary was a brief description of the mathematical basis of the program and its many input requirements. The last part of the summary were pictures of the preprocessor screens, a picture what the input file should look like, and an example of what a plot should look like. This was the last summary that was useful to a user.

The summaries for MOC and RANDOM WALK consist of a very brief (less than one page each) description of the assumptions the model is built on and a description of the model. The user is then informed that the program documentation can be found elsewhere, with the source codes. There is no explanation of what data is required, what format it has to be in, how the preprocessors run, what the output should look like, or anything. The only thing provided by the Manual is a picture of what a plot from MOC should look like and a picture of the starting screen from preRANDOM WALK that is not the same as shown currnetly when the program runs.

MODFLOW, SUTRA, and BIOPLUME II

The best thing that can be said about these portions of the Manual is that it is here that the picture of the shell is shown. The three summaries average two pages in length, consisting mainly of the assumptions required for the respective models and references to the source documents. The most detailed of the three is MODFLOW, which lists the

various modules that are included, along with their respective references, and mentions the shell, which is the first time it has been mentioned, even though the majority of the preceding models had it as well. The summaries for SUTRA and BIOPLUME II do not contain a list of the required data, the format of the data, or discuss their respective controlling assumptions. The only practical items contained in the summaries are the references to look for if a user wished to utilize one of the models.

Monte Carlo Simulations

The summaries of ODAST-MC and TDAST-MC are two paragraphs and one paragraph long respectively. The summaries state that the models use the ODAST and TDAST models that have been modified to accept stochastic data inputs and then show the pictures of the screens as they appear in the program. On the other hand, the description of MOC-MC is eight pages long with no pictures of the program's screens. It is very detailed, and well-written, but so complicated that a picture of the screens would have been very welcome. The required data is listed, but there is no example of the required format, nor is there an example of the output.

User's Guide for the UNIX Version

This section of the Manual was not utilized and therefore not be analyzed.

Operating System Considerations

The last section of the manual discusses the hardware requirements of the system, and how the system is organized. The best element of the section is about the user interfaces and preprocessors discussed earlier, which needs to move into another, earlier, part of the manual.

Conclusions

The evaluation of the groundwater advisory system revealed the following:

a. The user's conceptual site model drives the model selection process. The amount of data present in a site's investigation report will not matter to the CHOICE algorithm unless in the report there is data to change the user's CSM. Once a CSM has been built, which will happen early in the investigative process, the model chosen by the advisory system will not change unless the CSM changes significantly.

b. The single most important assumption driving the model selection decision is heterogeneity. The CHOICE algorithm is predisposed to disallow analytical models, as discussed earlier, and when this occurs, the deciding factor for model selection becomes heterogeneity: if the site is homogeneous, CHOICE selects RESSQ, while if the site is heterogeneous, one of the analytical models will be chosen. For most sites, the assumption of heterogeneity can be made early in the site investigation, from data already available. Records searches, drilling logs, and site vicinity geology, all of these give indications to the user as to the site's aquifer characteristics without any investigation into the site itself. In some instances, the assumption will change once (if) investigations are begun, and that is why the advisory system is run multiple times throughout a site's life-cycle.

c. The system may be run by a site manager that is an engineer. A hydrogeological background is preferred, but an engineer will be able to utilize the system if further

definitions are provided in the Manual to explain assumptions made by the separate models.

Suggestions to Improve the Groundwater Advisory System

The following suggestions are aimed at improving the usability and user-friendliness of the advisory system.

a. The concept of running of a numerical model after either an analytical or semi-analytical model should be expanded upon. The idea is touched upon briefly and discussed in the software analysis section of Chapter III.

b. The models that do not have a user interface should receive them. The interfaces provide a way to help the user prepare the required data and present the finished data for presentation. All of the models should have GUI interfaces to input data and view in- and output files. The models that have these amenities presently are easy to learn and to use, while the remainder require much more preparation to use.

c. There are numerous documentation shortfalls that could be corrected. The most pressing of these needs are the incorporation of the CHOICE logic flow charts and an explanation on how to interpret a cumulative frequency plot.

d. The LeGrand Preliminary Analysis should be updated to accept GUI input. Presently, the majority of the models allow data to be input in a mouse-driven format, while the LeGrand data input is accomplished by laborious repetition of keystrokes.

e. Plotting of the results of the models should be available for all models. This will require an outside plotting program such as Golden's *Surfer* but looking at a plot is easier to interpret than reams of tabulated data.

f. Provide the user a list or table of the data requirements of the advisory system as a whole. For instance, there are four types of data required to develop a numerical model:

    a. boundary conditions
    b. initial conditions,
    c. aquifer and contaminant characteristics
    d. stresses to the system (pumps and external influences) (Cichowicz and Ficke, 1984: 51).

A list of this type for each class of models would give the user an idea if they had the data required for that class of models or if more data would be required.

Recommendations for Further Research

Future research into the groundwater advisory system is required for it to be utilized by Air Force personnel to its fullest capacity. The areas that require immediate attention are:

a. Comparing the Unix version of the advisory system with the DOS version. There are differences according to personnel at Armstrong Laboratories, and in some ways the UNIX version is reputed to better.

b. Reviewing the optimization aspect of the advisory system.

c. Modifying the CHOICE algorithm to allow the selection of the numerical models currently part of the advisory system, but outside of CHOICE (MODFLOW, SUTRA, and BIOPLUME II).

Appendix A - LeGrand's Preliminary Analysis Results

The LeGrand analysis was run twice: once by the project engineer and once by a co-worker using the data from the HAZWRAP RFI. It was run twice to test the senesitivity of the program to different input. The difference between the two scores was two points, which is considered acceptable (LeGrand, 1983: 25). The questions asked and the respective answers (in italics), PE from the project engineer and RFI from HAZWRAP's data follow.

```
The Legrand Analysis can be applied solely
to a site's hydrogeology, or to hydrogeology
with use plan.
         Indicate your choice for the present analysis:

1) Hydrogeology (Stage 1) only.
2) Full Legrand analysis.
3) Quit.
```

PE: Full LeGrand Analysis
RFI: Full LeGrand Analysis

```
The advisory system will lead you through the
formation of the various Legrand ratings. However,
these also may be directly input. Choose one of
the following:

1) Input completed Legrand stages 1 and 2.
2) Input completed stage 1 (hydrogeology) only.
3) Go through complete Legrand analysis procedure.
```

PE: Go through complete LeGrand analysis procedure.
RFI: Go through complete LeGrand analysis procedure.

```
           STEP 1
Choose distance on ground between site and nearest
water supply (or specified boundary) from the following
table.
----------------------------------------------------------
                  (feet)              (meters)
     0          > 6200 ft.          > 2000 meters
     1          3100-6200           1000-2000
     2          1001-3100           300-999
     3          501-1000            150-299
     4          251-500             75-149
     5          161-250             50-74
     6          101-160             35-49
     7          61-100              20-34
     8          31-60               10-19
     9          0-30                0-9
```

PE: 5 (250 feet)
RFI: 2 (2,200 feet)

```
Certain geological conditions may alter this rating.
Which of the following apply?
    1    The water table lies in permeable consolidated rock.
    2    The water table lies in poorly permeable rock.
    3    The water table is located above bedrock.
```

PE: 3
RFI: 1

The two analyses now diverge briefly because of the differing answers. Only the

project engineer is asked the next question.

```
            STEP 2
Estimate the shallowest depth to the water table belo
base of contamination source more than 5% of the year
from the following table:
--------------------------------------------------------
                    (feet)                    (meters)
    0              > 200 feet              > 60 meters
    1              91-200                   30-60
    2              61-90                    20-29
    3              36-60                    12-19
    4              26-35                     8-11
    5              16-25                     5-7
    6               9-15                     3-4
    7               3-8                     1.5-2.5
    8               1-2                     0.5-1
    9              < 1                      < 0.5
```

PE: 9 (Less than one foot)

```
            STEP 3
Choose the most appropriate description of the general
water table gradient from the following table:
--------------------------------------------------------
    0    Gradient away from all water supplies that are located
         closer than 1000 meters from the site.
    1    Gradient is almost flat.
    2    A gradient of less than 2% exists towards the water
         supply, but this is not anticipated direction of flow.
    3    Gradient less than 2% towards the water supply, and this
         is the anticipated direction of flow.
    4    Gradient greater than 2% towards the water supply, but
         this is not the anticipated direction of flow.
    5    Gradient greater than 2% towards the water supply, and this
         is the anticipated direction of flow.
```

PE: 3
RFI: 3

```
    STEP 4

CHOOSE DESCRIPTOR OF THICKNESS OF
UNCONSOLIDATED MATERIAL OVERLYING BEDROCK
FROM THE FOLLOWING TABLE (IN FEET)

--------------------------------------------------------
    0    BEDROCK AT LAND SURFACE
    1    LESS THAN 10 FT (< 3 M)
    2    10-27 FT.       (3-9 M)
    3    28-45 FT.       (10-14 M)
    4    46-59 FT.       (15-19 M)
    5    60-74 FT.       (20-24 M)
    6    75-94 FT.       (25-29 M)
    7    MORE THAN 95 FT. (> 30 M)
--------------------------------------------------------
```

PE: 7
RFI: 7

```
NOW CHOOSE A DESCRIPTOR FOR UNDERLYING
BEDROCK MATERIAL:
     1        UNCONSOLIDATED MATERIAL OVERLIES
              SHALE OR OTHER POORLY PERMEABLE
              CONSOLIDATED ROCK
     2        UNCONSOLIDATED MATERIAL OVERLIES
              PERMEABLE CONSOLIDATED ROCK
              (FRACTURED, JOINTED OR CAVERNOUS)
```

PE: 1
RFI: 1

```
CHOOSE DESCRIPTOR OF TYPE OF UNCONSOLIDATED
MATERIAL FROM THE FOLLOWING TABLE
-------------------------------------------
     1      CLAY
     2      CLAY WITH NO MORE THAN 50% SAND
     3      SAND WITH 15-30 % CLAY
     4      SAND WITH LESS THAN 15% CLAY
     5      CLEAN FINE SAND
     6      CLEAN GRAVEL OR COARSE SAND
-------------------------------------------
```

PE: 4
RFI: 4

```
     STEP 5

YOU WILL NOW BE ASKED TO EXPRESS THE
DEGREE OF CONFIDENCE YOU HAVE IN THE
VALUES CHOSEN IN THE PREVIOUS STEPS.
SELECT ONE OF THE FOLLOWING LETTERS:

     A     CONFIDENCE IN ESTIMATES OF VALUES OF
           PARAMETERS IS HIGH AND ESTIMATED
           VALUES ARE CONSIDERED TO BE
           FAIRLY ACCURATE.
     B     CONFIDENCE IN ESTIMATES OF VALUES OF
           PARAMETERS IS FAIR
     C     CONFIDENCE IN ESTIMATES OF VALUES OF
           PARAMETERS IS LOW, AND ESTIMATED
           VALUES ARE NOT CONSIDERED TO BE
           ACCURATE.
```

PE: B
RFI: A

```
     STEP 6

IS THE DISTANCE FROM THE SOURCE OF
CONTAMINATION MEASURED TO:
     W:      A WELL.
     S:      A STREAM OR PERENNIAL SPRING.
     B:      A PROPERTY BOUNDARY?
```

PE: S
RFI: S

```
Now select up to two special identifiers
from the following table:
_____
C...SPECIAL CONDITIONS REQUIRE THAT A
    COMMENT OR EXPLANATION BE ADDED TO
    EVALUATION.
D...CONE OF PUMPING DEPRESSION NEAR A SOURCE
    OF CONTAMINATION.  THIS MAY
    CAUSE DIVERSION TOWARD PUMPED WELL.
E...DISTANCE RECORDED IS THAT FROM A WATER
    SUPPLY TO THE EDGE OF AN EXISTING PLUME,
    RATHER THAN ORIGINAL CONTAMINANT SOURCE.
F...SOURCE IS LOCATED ON A GROUNDWATER DIS-
    CHARGE AREA, SUCH AS A FLOOD PLAIN, WHERE
    MINIMAL GROUNDWATER INTRUSION IS EXPECTED.
K...SITE LOCATED IN KARST TYPOGRAPHY, OR
    UNDERLAIN BY CAVERNOUS LIMESTONE.
M...MOUNDING OF THE WATER TABLE BENEATH A
    CONTAMINATION SITE - COMMON BENEATH
    WASTE SITES WITH LIQUID INPUT.
P...PERCOLATION MAY NOT BE ADEQUATE FOR
    SITE.  THIS WILL SHOW UP IN THE PERMEABILITY-
    SORPTION DIGIT.
Q...DESIGNATES A RECHARGE OR TRANSMISSION
    PART OF AN EXTENSIVE AQUIFER THAT IS
    SENSITIVE TO CONTAMINATION.
R...RADIAL OR PARTIAL RADIAL FLOW FROM A
    HIGH WATER-TABLE POSITION. (TWO OR MORE
    SITE RATINGS MAY BE NEEDED.
T...INDICATES THAT THE WATER TABLE IS IN
    FRACTURED OR CAVERNOUS ROCK

Y...ONE OR MORE CONFINED (ARTESIAN) AQUIFERS
    UNDERLIE THE WATER TABLE AQUIFER

0...OMIT THIS DESCRIPTOR
Z...RETURN TO TOP OF MENU
_____
```

PE: F and Y

RFI: M and Y

The following descriptors all apply to LF02: E, F, M, and Y. Choosing the descriptors

is a personal decision and left up to the person analyzing the site.

PE: Hydrogeologic Description: 23-5936-Absfy
    Grade = E
    Hydrogeologic Rating: Poor to Very Poor
    Very poor hydrogeologic site rating

RFI: Hydrogeologic Description: 21-6636-
    Grade = E
    Hydrogeologic Rating: Poor to Very Poor
    Very poor hydrogeologic site rating

```
COMPUTE PAR RATING(1) OR INPUT FROM
NOMOGRAM(2)? --->1
```

PE: 1

RFI: 1

```
                        LEGRAND/PAR MATRIX
Choose category best describing sensitivity of underlying aquifer:
1. Sensitive aquifer characteristics: A very permeable extensive aquifer
is overlain by very permeable material or is exposed at the surface in
its recharge zone. (An aquifer designated as sole source under SDWA is
included.)
2. Moderately sensitive aquifer characteristics: An aquifer of variable
permeability and moderate extent which is overlain by moderately perme-
able material in the recharge zone and is or can be an important
drinking water source.
3. Insensitive aquifer characteristics: An aquifer of moderately low
permeability and/or slight extent and importance. This would include
deep confined aquifers, aquicludes (no water bearing materials) and may
include saltwater beds of any permeability in areas where no freshwater
occurs.
```

PE: 2

RFI: 2

```
                                  LEGRAND/PAR MATRIX
  Within this category, sensitivity is estimated on a scale of 1 to 4
  as:
      1. Relatively insensitive for this category.
      2.
      3.
      4. Highly sensitive for this category.
```

PE: 3

RFI: 3

```
                                  LEGRAND/PAR MATRIX
  Select category represening most significant contaminant:

   1. Chemical mfg; high toxicity.      12. Textile finishing, pulp mills.
   2. Chemical mfg; mod. toxicity.      13. Rubber, plastics manufacturing.
   3. Septic tank & cesspool systems.   14. Animal wastes.
   4. Landfills, municipal.             15. Radioactive wastes.
   5. Landfills, toxic waste.           16. Wood, paper, textile (solids).
   6. Glass, cement mfg.                17. Heavy metals ions.
   7. Oil & gas, extracting            18. Soaps and detergents.
   8. Oil & gas, refining              19. Pesticides.
   9. Stone, sand, clay mining.        20. Oils, including gasoline.
  10. Metal, coal mining.              21. Municipal sludges.
  11. Livestock feedlots.
```

PE: 5

RFI: 5

```
  LEGRAND/PAR MATRIX

  Within this category, contaminant severity is estimated on a scale of
  1-5 as:
      1. Severity estimated as relatively very low for this category.
      2. Low.
      3. Moderate.
      4. High.
      5. Severity estimated as relatively very high for this category.
```

PE: 4

RFI: 4

```
Engineering site modifications (if any)
are expected to have the following effect:

First, on Aquifer Sensitivity:

   1. increase.
   2. no change.
   3. slight decrease.
   4. substantial decrease.
```

PE: 2

RFI: 2

```
Engineering site modifications (if any)
are expected to have the following effect:

Second, on Contaminant Severity:

   1. increase.
   2. no change.
   3. slight decrease.
   4. substantial decrease.
```

PE: 3
RFI: 4

PE: *Situation Rating = +9F*
          Site Unacceptable, Contamination Probable
          Based on the LeGrand Analysis, Rejection of this Site is recommended.

RFI: *Situation Rating = +9H*
          Site Unacceptable, Contamination Probable
          Based on the LeGrand Analysis, Rejection of this Site is recommended.

At this point the LeGrand Analysis is complete and the user may repeat the procedure,

changing some inputs and comparing the results to the original.

Appendix B - Conceptual Site Model for LF02

Mission of the IRP

The primary objectives of the IRP are the identification, investigation, research and development, and cleanup of contamination from hazardous substances, pollutants, and contaminants at Air Force installations. IRP decision makers need the information that comes from groundwater flow and contaminant transport models. The models are used to determine the effect of various treatment alternatives on the contaminated groundwater (Goltz, 1991: 24). Because of the data requirements of these models, the IRP program has been accused of studying sites too long and not accomplishing enough remediation actions. FY94 was the first year that money spent on remediation actions was more than the amount spent on studying sites.

LF02 was identified at the inception of the IRP program as a probable contamination source. Investigations into LF02 began in 1982, and there have been four studies conducted:

1982	Phase I Records Search (conducted by Engineering Science, Inc.)
1985	Phase II, Stage 1 Confirmation/Quantification (Water and Air Research, Inc.)
1989	Phase II, Stage 2 Confirmation/Quantification (Engineering Science, Inc.)
1991	RCRA Facility Investigation Report [RFI] (HAZWRAP)

(HAZWRAP, 1991: 3-1)

The purpose of Phase I was to identify potential contamination sites based upon researching the historical documents of the base. No field investigations were involved in Phase I. Phase II, Stage 1 field activities were limited to confirming or denying the presence of contaminants at the sites identified in Phase I. The data were preliminary in nature, with no quality assurance/quality control precautions taken and therefore of little use to a modeler. Once the Phase II, Stage 1 analysis confirmed contamination, Phase II, Stage 2 began, attempting to determine the nature and extent of the contamination (HAZWRAP,1991: 3-1).

In 1988, the State of Georgia granted Robins AFB a RCRA Hazardous Waste Facility Permit. In the permit, LF02 was identified as a RCRA Solid Waste Management Unit and therefore must be cleansed according to the RCRA clean up process. The Georgia State Environmental Protection Division (GEPD) acknowledged that the base had accomplished a great deal of work at the site and rather than obtaining a complete and independent data set, the RFI was intended only to fill data gaps identified as a result of the previous work (HAZWRAP, 1991: 3-13). From this data a CSM was constructed.

Robins Air Force Base Landfill No. 2

History

Landfill No. 2 is located in the central portion of Robins Air Force Base (RAFB), north of 2nd Street and west of Hannah Road. Landfill No. 2 and Fire Protection Training Area No. 1 (FPTA 1) make up IRP site LF02. A general site map is presented as Attachment 1 and a detailed site map is presented as Attachment 2.

Landfill No. 2 was operated from 1951 to 1963, covering an area of approximately 22 acres. The landfill operation was by a trench and fill method. This method consisted of trenches being dug to a depth of approximately 20 feet (generally below the water table), waste being placed into the trenches, and a daily cover of boiler ash being placed over the waste. Wastes disposed of in the landfill included general refuse from the base, household wastes, and some industrial wastes. Also reportedly disposed of in the landfill was 40 tons of off-specification malathion. In addition to the wastes disposed of in the landfill, there was a location on the west side of the landfill for burning scrap lumber (HAZWRAP, 1991: 2-5).

Only 15 to 30 pounds of non-salable, expired shelf life chemicals and about 20 pounds per year of DDT were indicated to be disposed of in the landfill. On the other hand wastes from the Industrial Waste Treatment Plant (IWTP) and the sanitary wastewater treatment facilities were possibly disposed of in the landfill. The following table summarizes the inorganic waste types generated while the landfill was open and presents the estimated annual waste quantities generated. The treatment facilities discharged to the east-west ditch and the primary sludges were applied to the area around LF02 or were landfilled (HAZWRAP, 1991: 2-9).

Table B-1 Summary of Industrial Operation and Wastes Discharged to Sewer

Operation	Waste Material	Waste Quantity
Corrosion Control	Phosphoric Acid Cleaner	9,600 gal/yr
	Chromic Acid Cleaner	9,600 gal/yr
Electroplating Shop	Chrome Baths	300 gal/yr
	Waste Acid Cleaner Sludges	200 lbs./yr
	Cyanide Baths	500 gal/yr
	Waste Alkaline Cleaners	1,600 gal/yr
Battery Shop	Waste Acids	300 gal/yr

FPTA 1 was operated from 1943 until the mid-1950's. No exact location has been determined, but the author has seen photographs from the late 1940's showing a FPTA located on the west side of Landfill No. 2. FPTA 1 consisted of an unlined pit surrounded with earthen dikes. The site was used about twice a week, with the common method of operation being the Fire Department emptying drums of contaminated fuel, oil, solvents, and ignitable chemicals on water-saturated ground, lighting the mixture, and extinguishing the mixture until it would no longer burn. From 1943 until 1950 high-pressure water was used as the extinguishing agent. After 1950, protein foam replaced the high-pressure water (HAZWRAP, 1991: 2-6).

The following table is a summary of waste materials and estimated volumes reportedly sent to the FPTA.

Table B-2 Summary of Ignitable Chemicals and Petroleum Compounds Burned in FPTA1

Waste Material	Total Estimated Volume (gal/yr)
Paint residue and wastes, thinners, solvents, and strippers	22,000
PD680, hydraulic fluids, and waste oils	14,000
Trichloroethene (TCE)	12,000
Trichloroethane (TCA)	12,000
Tetrachloroethene (PCE)	7,800
Methyl Ethyl Ketone (MEK)	3,400
Acetone	1,200
Methylene Chloride	1,200
Phenolic Carbon Remover	1,200
Polysulfide Sealant	1,200
Toluene	900

Geology

Surface elevations generally rise from the wetlands and floodplain to the east of the site, towards the base facilities to the west. The elevations vary from 250 feet above National Geodetic Vertical Datum (NGVD) in the wetlands to 290 feet at the fuel farm to the west. The elevations in LF02 range from 250 to 260 feet (HAZWRAP, 1991: 4-1).

Surface drainage across the site flows to the southeast along two drainage ditches. These ditches discharge into a larger ditch south of the site, which then flows east and discharges into Horse Creek (Ref Attachment 2). Just to the west of LF02 there are two more IRP sites, Landfill No. 1 (LF01) and the JP-4Spill Site. LF01 was used from 1943 until 1951, while the JP-4 spill site is the site of a series of fuel spills totaling over 60,000 gallons. A net groundwater discharge to the surface waters was detected in 1988 (HAZWRAP, 1991: 4-2).

RAFB is located at the juncture of two geologic units: the Quaternary alluvium (Ocmulgee river floodplain material) and the underlying Ripley-Providence Formation. The rise in topography from east to west and the pinching out of alluvial peat and clay

deposits in the western portion of LF02 are the indicators of the geologic contact. There were three separate investigations into the stratigraphy of the site, totalling 29 wells and 16 soil borings. Phase II, Stage 1 (WAR, 1985) drilled wells LF2-1 through LF2-3 while Stage II, Phase 2 (ES, 1988) drilled wells LF2-4 through LF2-20 and soil borings B1-B16. the investigations were completed by the HAZWRAP RFI drilling wells RI-5-1-W through RI-5-9-W. The subsurface soils are grouped into five strata, of which four are of interest to a modeler. The four units, from surface downwards, are the Surficial Fill, Alluvium, Ripley-Providence Formation, and Cusseta Formation (HAZWRAP, 1991: 4-12). A cross-section of the site is presented as Attachment 5.

Surficial Fill

The depth of the fill is estimated at up to 14 feet, consisting of refuse and poorly graded sand or silty sand. The refuse was encountered beneath a two to four foot fill cover and was found to be 6 to 11 feet deep. It consisted of metal, glass, plastic, cinders, wood, and shingles (HAZWRAP, 1991: 4-13).

Alluvium

The alluvium materials were discovered in the eastern portion of the site, to a depth of 190 feet, ranging in thickness from 20 to 60 feet. The materials pinch out in the western portion of the site, where the alluvial deposits contact the Ripley-Providence Formation. The alluvial deposits consist of a peat/clay backswamp deposit underlain by sand and gravel. The peat/clay layer consists of peat underlain by clay. The peat thickness ranges from 1 to 6 feet, with the thinnest portions laying under Landfill No. 2. The clay under the peat ranged in depth from 2 to 8 feet. Two wells in the site (RI-5-6-W and

LF2-3; Attachment 4) did not show any clay underneath the peat. The sand and gravel underneath the peat/clay layer consist of the same material as the Ripley-Providence Formation. Therefore the separation shown on the attachments between the two layers is only an approximation (HAZWRAP, 1991: 4-13).

Ripley-Providence Formation

The Ripley-Providence Formation was found on the west side of the site, near the fuel storage tanks and fuel farm. At these locations, it was located at the ground surface or under the surficial fill, where the alluvial deposits pinch out. The depth of the formation ranges from 50 to 100 feet. The formation consists of sand with layers and lenses of clay and gravel. The sand was coarse to fine, with 1 to 10 percent fines. The clay layers/lenses range from 5 to 7 feet in thickness and were encountered in most wells bored at the site, at differing depths, showing the layers are not continuous throughout the site (HAZWRAP, 1991: 4-14).

Cusseta Formation

The Cusseta Formation underlies the Ripley-Providence Formation at the site. It was found at depths of 154 to 150 feet, with another base water supply well also showing a clay layer at approximately this depth. The formation consists of a white to dark grey clay ranging in thickness from 15 to 25 feet(HAZWRAP, 1991: 4-15).

Hydrogeology

Groundwater flow in the area of the site is divided between the Providence Aquifer and the Blufftown Aquifer, which are separated by the Cusseta aquitard. Where the surficial fill materials overlie the peat/clay alluvial deposits, groundwater mounding has

occurred. The mounding has saturated the lower portion of the surficial fill, with the aqueous phase that is in contact with the refuse designated as leachate. The potentiometric surface map showing the groundwater mounding is presented as Attachment 3.

The horizontal groundwater flow is radially away from the groundwater mound. To model the groundwater flow, the flow velocity must be calculated using Darcy's Equation.

$$V = \frac{K * i}{n}$$

Where V= average linear velocity
K= hydraulic conductivity
i = hydraulic gradient, and
n = effective porosity

For this site, the hydraulic conductivity of the fill was estimated to range from 1.6×10^{-2} to 6.0×10^{-2} cm/sec based upon a slug test. The hydraulic gradient was estimated to range from 0.013 to 0.017 ft/ft and finally the effective porosity was estimated to range from 40 to 0 percent. The average groundwater velocity from this data is estimated to range from 0.4 to 1.9 ft/day.

There is a vertical component of flow in the site, downward from the surficial fill towards the Providence Aquifer. Where there is peat/clay layer this movement is hindered, but the layer is not continuous across the site.

For the Providence Aquifer, K is estimated to be 2.0×10^{-2} based upon a pump test, while i is estimated to be 0.003 ft/ft and n was estimated to be 0.20, which leads to an average groundwater velocity of 1.3 ft/day. The vertical component of the flow in the Providence Aquifer is upward. The reason for this upward flow is that at the site the

Ocmulgee River and associated wetlands are a regional discharge area for the Providence

Aquifer. A hydraulic connection has been reported between the Providence and Blufftown

Aquifers, which means that the Cusseta aquitard is acting as a leaky confining unit

(HAZWRAP, 1991: 4-29).

Table B-3 LF02 Conceptual Site Model Information

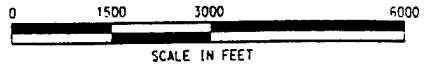| Media	Background Concentration	Source of Data	Contaminant	Regulatory Limit	Maximum Concentration
Soil	VOC's below MDL Chromium ranged from MDL to 26.3 mg/kg	-34 drilled borings -50 hand augers -28 monitor wells	Benzene Chlorobenzene Chromium	24,000 µg/kg 1.6E+06 µg/kg 400,000 µg/kg	3,200 µg/kg 26,000 µg/kg 39,400 µg/kg
Surface Water	Everything below MDL	-8 surface water samples	Benzene Chlorobenzene 1,2-DCB TCE Arsenic Chromium Lead	5 µg/l 70 µg/l 3,200 µg/l 5 µg/l 50 µg/l 50 µg/l 15 µg/l	1.1 µg/l 21 µg/l 9 µg/l 80 µg/l 9 µg/l 3.5 µg/l 7.3 µg/l
Sediment	VOC's BMDL Chromium ranged from 900 to 26,300 µg/kg	-5 sediment samples	Benzene Chlorobenzene 1,2-DCB Chromium	24,000 µg/kg 1.6E+06 g/kg 7.2E+06 g/kg 400,000 g/kg	7 µg/kg 150 µg/kg 32 µg/kg 52,100 µg/kg
Groundwater	Highest concentrations of TCE (10,000 µg/l) detected upgradient	-28 monitor wells -1 well point -1 Groundwater Probe Survey	1,4-DCB Benzene TCE Arsenic Chromium Lead Chlorobenzene	75 µg/l 5 µg/l 5 µg/l 50 µg/l 50 µg/l 15 µg/l 70 µg/l	280 µg/l 190 µg/l 10,000 µg/l 1,100 µg/l 650 µg/l 480 µg/l 1,700 µg/l

Attachments:
1. General Site Map
2. Detailed Site Map
3. Potentiometric Surface Map
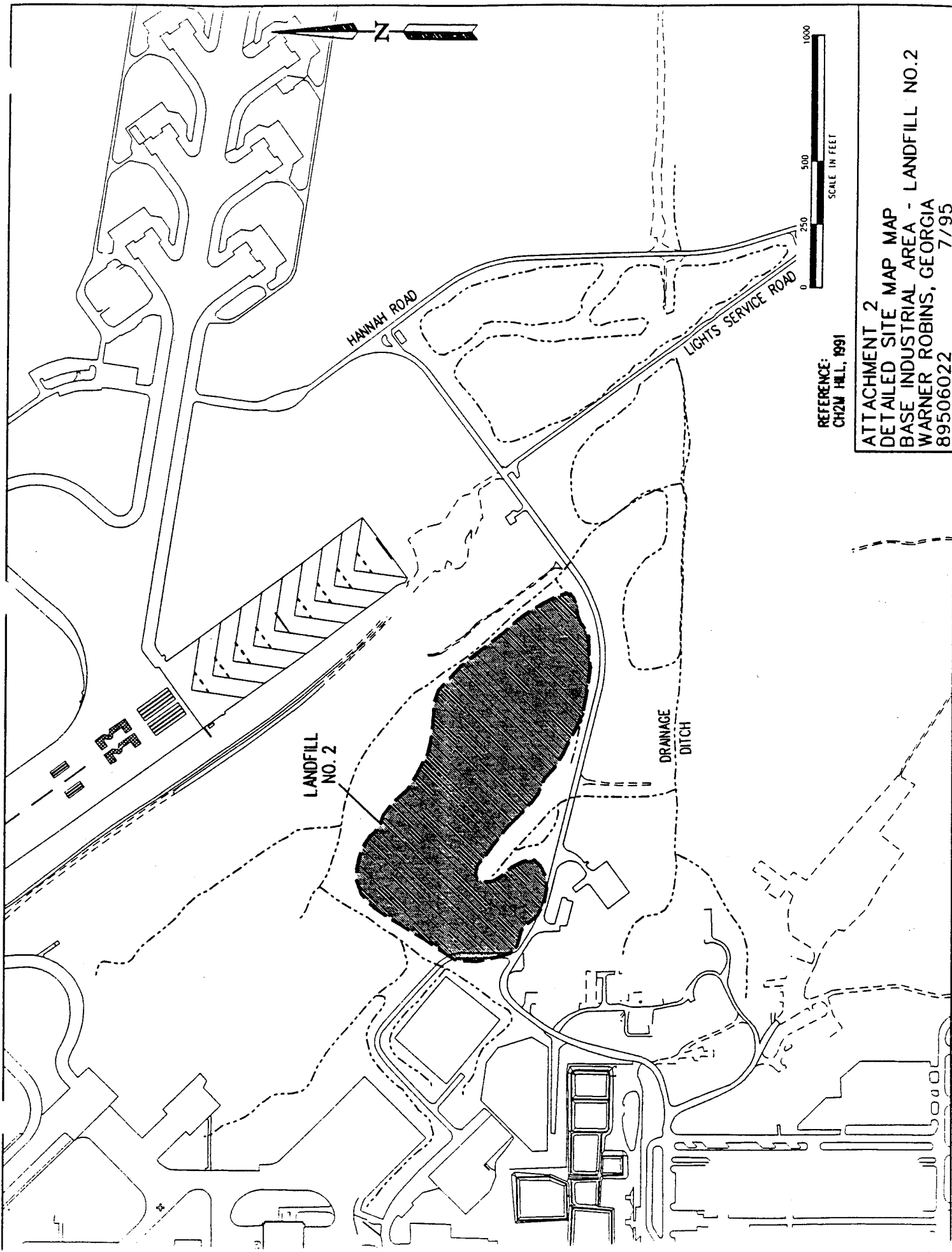4. Sampling Location Map
5. Conceptual Site Model
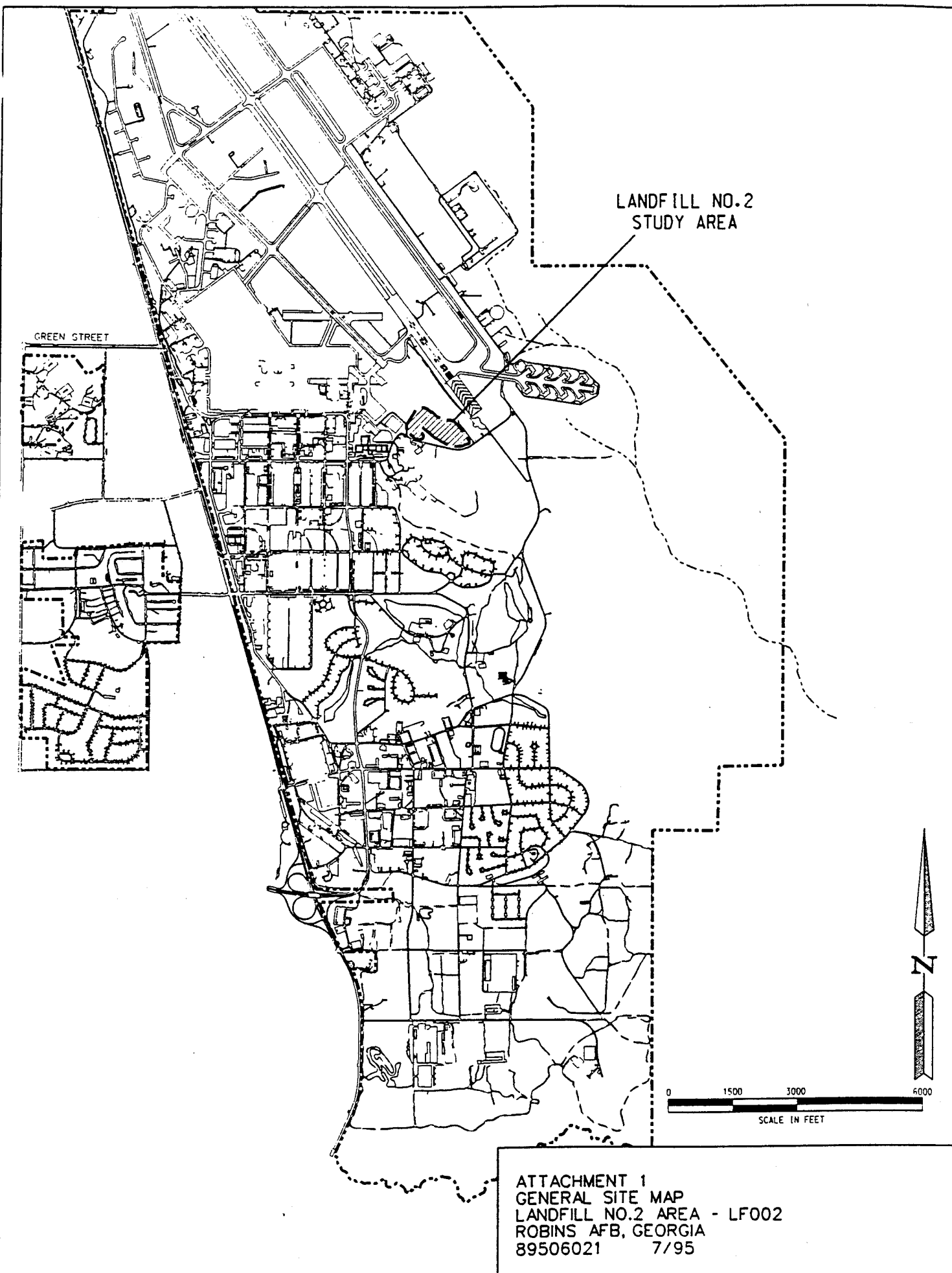
LANDFILL NO.2
STUDY AREA

GREEN STREET

N

| 0 | 1500 | 3000 | | 6000 |

SCALE IN FEET

ATTACHMENT 1
GENERAL SITE MAP
LANDFILL NO.2 AREA - LF002
ROBINS AFB, GEORGIA
89506021   7/95

N

HANNAH ROAD

LIGHTS SERVICE ROAD

LANDFILL NO. 2

DRAINAGE DITCH
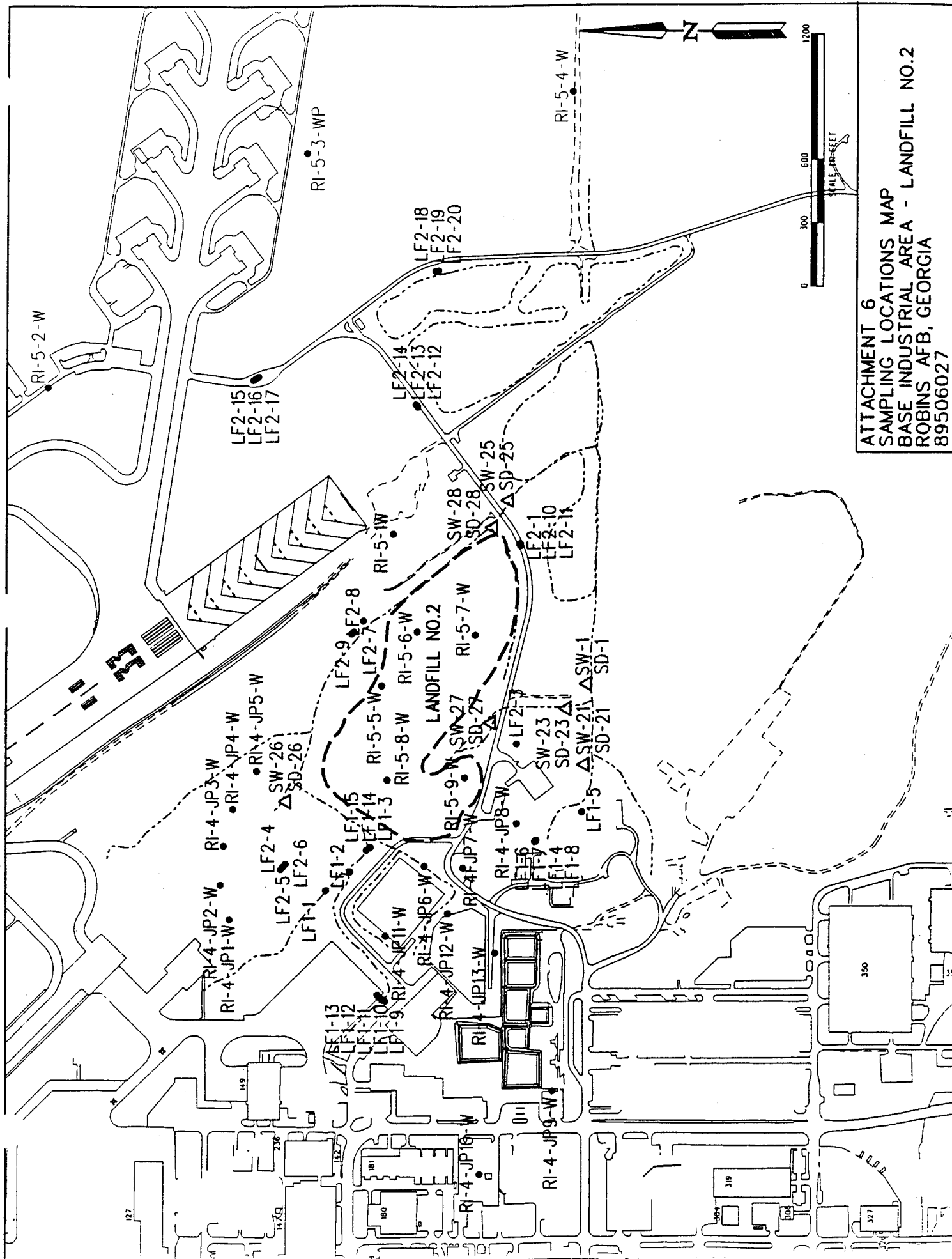
SCALE IN FEET

0   250   500   1000

APPROXIMATE LOCATION
OF LANDFILL NO. 2

SCALE: 1" = 1500'

ATTACHMENT 3
POTENTIOMETRIC SURFACE MAP
BASE INDUSTRIAL AREA - LANDFILL NO. 2
ROBINS AFB, GEORGIA
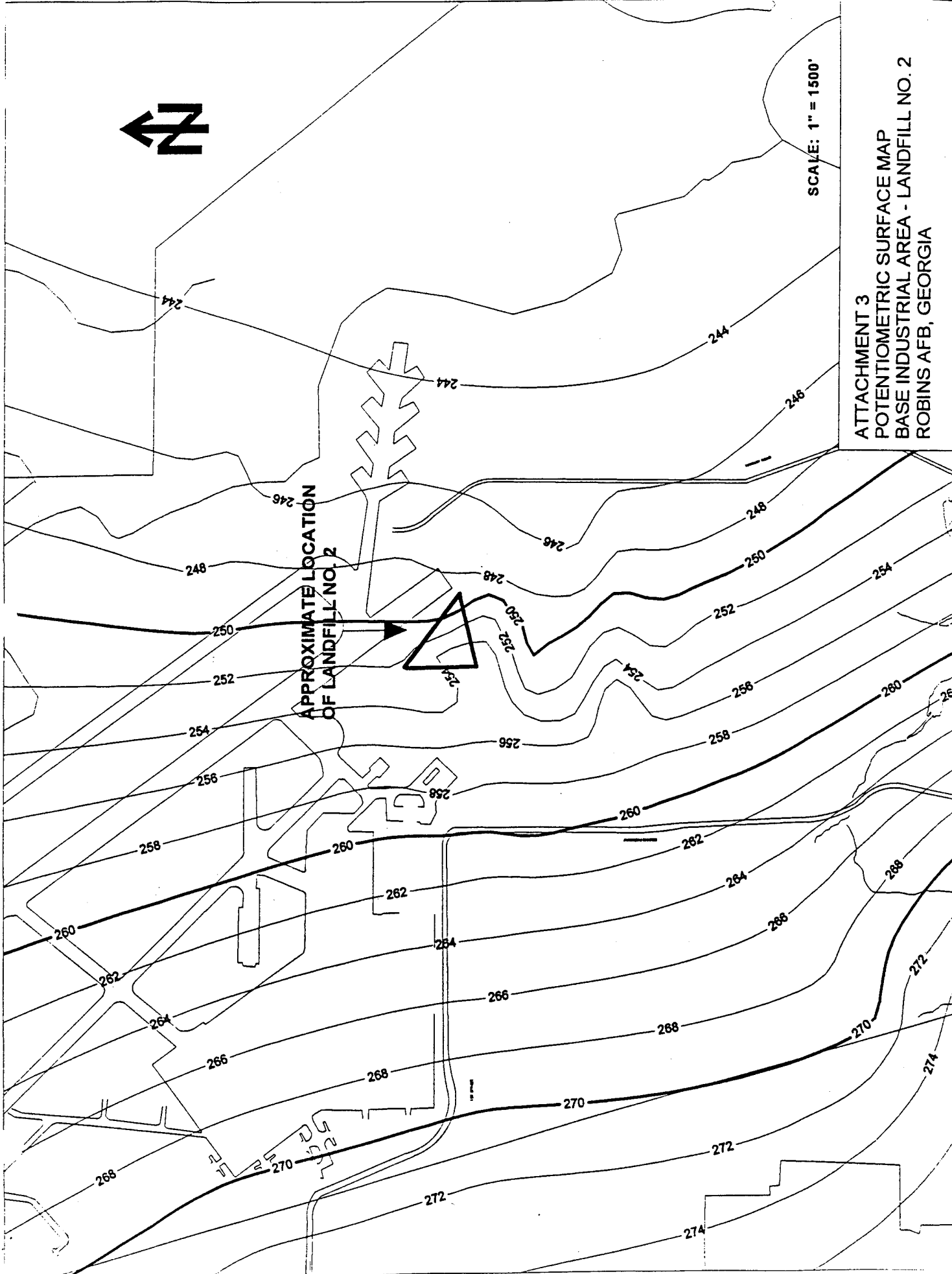
ATTACHMENT 6
SAMPLING LOCATIONS MAP
BASE INDUSTRIAL AREA - LANDFILL NO.2
ROBINS AFB, GEORGIA
89506027

QUATERNARY UNITS (SANDS, CLAYS &PEAT)

PROVIDENCE UNITS

CUSSETTA UNITS

BLUFFTOWN UNITS

HORSE CREEK

ALERT PAD

FILL

DIRT ROAD

HANNAH ROAD

RUNWAY

FILL

QUATERNARY UNITS

IT-2

FPTA3

BLUFF

BLUFFTOWN BLUFF

JP-4 DRILL SITE

AST TANK FARM

IT-4

IWTP

ROBINS PARKWAY

B140

B112

B125

B181

B180

BIA

2nd STREET

WATER TABLE

PROVIDENCE UNITS (SANDS &SOME CLAYS)

CUSSETTA UNITS (CLAYS &SOME SAND)

BLUFFTOWN UNITS (MAIN AQUIFER)

LEGEND

GROUNDWATER CONTAMINATION ABOVE REGULATORY LIMITS

FREE PRODUCT (JP-4)

GROUNDWATER FLOW DIRECTION

ATTACHMENT 8
CONCEPTUAL SITE MODEL
BASE INDUSTRIAL AREA - LANDFILL NO.2
ROBINS AFB, GEORGIA
89506025   7/95

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Vita

Mr. Dale M. Fox ███

He graduated from Loyoal Marymount University with a Bachelor's Degree in Civil Engineering on 13 May 1988 and was commissioned a Second Lieutenant in the United States Air Force at the same time. His first active duty assignment was as the Design Civil Engineering for the 3498th Civil Engineering Squadron, Goodfellow AFB, from February 1989 to May 1991. His second assignment was as the Civil Engineering Chief of Operations, for the 12th Missile Warning Group, Thule Air Base Greenland. He then entered the Air Force Institute of Technology in June of 1992. He left the active duty Air Force on 31 December 1992. He subsequently entered the United States Civil Service as a GS-12 Environmental Engineer at Robins AFB, Georgia on 11 January 1993. He worked as an Environmental Engineer in the Environmental Restoration Division of the Environmental Management Directorate at Robins until re-entering the Air Force Institute of Technology in July 1994. While at Robins, he closed four Installation Restoration Program sites, and was the acting manager for six more sites. Mr. Fox's immediate family is his wife, the former Kelly M. Dinan.

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13. ABSTRACT *(Maximum 200 words)*

This research is intended to evaluate the Air Force's Installation Restoration Advisory System Workstation software and documentation. Groundwater modeling is the biggest aid to Air Force Installation Restoration decision makers in making their conclusions about what to do with their hazardous waste sites where the groundwater is contaminated. The Advisory System aids the user in determing if a site poses a potential problem, and if so assists the user in selecting an apporpriate groundwater transport model. The decision of what type of model is most suitable is based upon the user's conceptual site model and the decision is made by the model selection algorithm CHOICE, contained within the Advisory System. The research consisted of reviewing the components of the Advisory System separately, reviewing the types of groundwater models available to the System, and testing the CHOICE algorithm by applying it to an Air Force Installation Restoration Program site, located at Robins Air Force Base, Georgia. The conclusions of the research are that the System is usable in its present state, once some documentation errors are corrected, that the controlling factor in model selection is the user's own concept of the site, and that further modification of the CHOICE algorithm is required to incorporate all of the models available to the System.

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