AN ABSTRACT OF THE THESIS OF

Alan H.Rea for the degree of Master of Science in Agricultural Engineering presented on November 7, 1988.

Title: Assessing Groundwater Vulnerability to Contamination Using Finite Element Modeling and Geographic Information Systems

Abstract approved: ______________________________
Jonathan D. Istok

A method was developed for assessing the vulnerability of groundwater to contamination from contaminant sources at the soil surface, using a numerical groundwater flow model linked to a digital map database. The method was applied using the pcARC/INFO Geographic Information System (GIS) to input, store, and manipulate base maps, resulting in a database of digital maps for the alluvial aquifer system in the Willamette Valley of western Oregon. Digital elevation maps were created by digitizing topographic maps of land surface (1:250,000 scale), water surface, and the base of the Tertiary-Quaternary sedimentary deposits (1:500,000 scales). Soil association and aquifer unit maps digitized from 1:500,000 scale map sheets were also used. Data were extracted from ARC/INFO to the SURFER

software package to create a 3-D surface model for each of the digital elevation maps. An ARC/INFO point coverage was then used to store and overlay these surfaces, allowing the creation of maps of depth to water, saturated thickness, and water table gradient. These data became the input to a numerical finite element groundwater flow model. The model solves a dual formulation problem for the potential function and the stream function to calculate the time-of-travel for water to flow from the surface to the water table and laterally for 100 meters as an index of groundwater vulnerability. A cluster analysis is used to condense the data and form a training data set for a multiple regression model. The regression model is fit to the results of the finite element model with an R-squared of greater than 0.96. The simpler regression model is then used for mapping travel times for the entire study area. When properly calibrated against the finite element model and when combined with the digital map database and Geographic Information System (GIS) procedures described, the regression model can be conveniently used to assess the vulnerability of groundwater to contamination over large areas.

APPROVED:

Dr. J.D. Istok, Assistant Professor of Agricultural and Civil Engineering in charge of major

Dr. A.G. Hashimoto, Head of Department of Agricultural Engineering

Dean of Graduate School

Date thesis is presented November 7, 1988

Assessing Groundwater Vulnerability to Contamination Using Finite Element Modeling and Geographic Information Systems

by

Alan H. Rea

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed November 7, 1988

Commencement June 1989

ACKNOWLEDGEMENT

It would not be possible to fully acknowledge all the contributions of the many people who have in some way influenced the contents of this thesis. It is certainly true that I have not worked in a vacuum, and oftentimes even seemingly insignificant comments of friends, family, and colleagues have been important in shaping the ideas contained in this thesis.

Of the people most directly involved in my thesis project, I owe the most gratitude to my major professor, Dr. Jack Istok. Without his continuing guidance, inspiration, and effort, this thesis would never have come into being. He found the funds to support me on an assistantship and to buy expensive software when it was sorely needed, even though the project was not supported by any outside funding. I am indeed fortunate to have enjoyed such freedom in choosing a thesis project, and I can only hope that the quality of this research is deserving of such an opportunity.

Special thanks is due to Doug Nebert and the rest of the staff of the Portland office of the U.S. Geological Survey, Water Resources Division. The training and access to the computer system which they provided was critical to the successful completion of this project. Thanks also to Dr. Jon Kimerling and the OSU Department of Geography for allowing me to use their computer system and software.

I would also like to thank my minor professor, Dr. Fred Ramsey, and my committee members, Dr. Andy Hashimoto and Dr. Dave Myrold for the time and effort they have given to this project. Many thanks also to Janet Lee for her valuable programming advice and for writing the program for calculating gradients. Thanks also to Joan Istok for her efforts in drawing the illustrations, often on short notice. The staff, faculty, and fellow graduate students of the Agricultural Engineering Department have all provided support, assistance, and conversation which has made my experience in the department an enjoyable one.

The love and support of my family, and particularly that of my parents, has been an inspiration to me through all my life. Mere thanks can never approach repayment of that debt. Finally, the love and companionship of my wife, Liu Yi has become a central portion of my life during these years, and it is to her that I wish to dedicate this work.

CONTRIBUTION OF AUTHORS

This thesis is composed of two manuscripts of journal articles, along with a general introduction and literature review, general conclusions, and general bibliography. I wrote all the papers and did all of the Geographic Information Systems and computer programming work, with the exceptions noted in the text and preface. The second author, Dr. Jonathan Istok, was my major professor and extensively reviewed and discussed with me the rough drafts of all the articles and provided editorial comments. The third author of the first paper, Mr. Douglas Nebert, provided much assistance in the early stages of the project in the form of instruction on the computer systems and software. He also reviewed the draft of the first paper, provided his comments, and provided Figure I.1. Mr. Ed Volke and Ms. Leslie Patrick, of the U.S. Geological Survey, also reviewed drafts of the first paper and provided helpful critiques.

TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

This project began as part of a cooperative effort of many organizations in the State of Oregon to assess the threat of agricultural pesticides to the groundwater of the state. The U.S. Geological Survey, Water Resources Division was cooperating with the Oregon Department of Environmental Quality, the Oregon Water Resources Department, the U.S. Environmental Protection Agency, and the Soil Conservation Service of the U.S. Department of Agriculture to digitize maps to be used in the analysis. Other efforts included well sampling programs and investigations of areas which appear to have groundwater contamination problems.

In the summer of 1986, when I began working on this project, a few of the maps had been digitized, but funding for the vulnerability analysis had been discontinued. Although interest in the analysis still existed within the agencies, they were unable to devote their resources to an unfunded project. The staff at the Water Resources Division of the U.S. Geological Survey agreed to provide me with some training and access to the computer system and software at their Portland office.

This thesis is a result of the work which followed. The initial stages of the work were completed as I worked at the Portland office of the USGS under status as a volunteer. In December, 1987 I began using the facilities of the OSU Department of Geography, which had just received a copy of the Geographic Information System software for personal computers. We subsequently purchased a copy of the software and received it in late February of 1988. From that time on, most of the work was done on our own system, although some portions of the work still had to be done on the larger computer in Portland.

ASSESSING GROUNDWATER VULNERABILITY TO CONTAMINATION USING FINITE ELEMENT MODELING AND GEOGRAPHIC INFORMATION SYSTEMS

INTRODUCTION AND LITERATURE REVIEW

There is a need for an improved methodology for assessing the *vulnerability* of groundwater resources to contamination from surface-applied chemicals. Regulatory agencies and resource managers need to be able to evaluate the risks to the environment and to public health posed by the manufacture, transport, use, and disposal of potentially dangerous chemicals. An important component of this risk evaluation process is the determination of those areas within an aquifer system that are most *vulnerable.*

Vulnerability is defined here as the degree to which the hydrogeologic characteristics of an area contribute to the likelihood of the groundwater becoming contaminated if a contaminant is introduced at the soil surface. In general, this means that the faster a contaminant can move from the surface to the groundwater aquifer and the faster a contaminant plume can spread laterally in the aquifer, the more vulnerable the groundwater resource is. As defined, vulnerability can be evaluated solely from hydrogeologic information.

It is important to note that this definition of vulnerability does not consider the likelihood of the contaminant being introduced at the surface, nor does it consider the value of the groundwater resource potentially endangered by the contamination. This definition also does not include the evaluation or assessment of the transport characteristics of any particular contaminant, the level of contamination, or whether such a level poses a threat to a certain use of the groundwater resource. These factors are components of an evaluation of risk, but it is advantageous to treat vulnerability as a separate issue. The broader issue of pollution potential, which includes the other components of risk, may be then addressed in light of the assessed *vulnerability* of the groundwater resource.

In the United States, a vast amount of natural resource information has been collected and is available in the form of maps. For a given area, several such maps may be available, showing a variety of geologic and hydrologic information. A relatively new technology, known as Geographic Information Systems (GIS) now allows the use of digital computers to store, combine, and analyze map-based information. This technology greatly reduces the time and expense of creating new maps by combining the information already available in the many separate map themes. The new map themes can provide the information needed for sophisticated analysis techniques that would not be practical using manual techniques.

The ability to store, combine, and manipulate spatially distributed data makes the GIS a powerful tool for many kinds of natural resource assessments. GIS has been used for a wide variety of hydrologic studies. For example, Ventura, et al. [1988] used a GIS to estimate soil erosion in Wisconsin and to produce maps of the additional efforts needed to achieve erosion control goals. Hession and Shanholtz [1988] used a GIS for allocating resources to critical areas for reducing nonpoint-source agricultural pollution in the Chesapeake Bay drainage basin in Virginia. Nebert and Anderson [1987] demonstrated the use of GIS in evaluating regional groundwater quality in an agricultural area of eastern Oregon. Schmidt [1987] used a GIS to map groundwater contamination "susceptibility" in Wisconsin. This is essentially the same problem dealt with in this project.

Rea and Istok [1987] reviewed a number of methods for evaluating groundwater vulnerability to contamination. They found that the approach used in most of the previous methods was based on the method developed by LeGrand [1964, 1983]. For example, Phillips, et al. [1977] designed a "soil-waste interaction matrix" for evaluating the suitability of waste disposal sites. Silka and Swearingen [1978] designed the "Surface Impoundment Assessment" (SIA) method. Aller et al. [1985] proposed a method called DRASTIC, which assigns numerical scores to hydrogeologic characteristics of a site to obtain the DRASTIC index for the hydrogeologic setting. DRASTIC was designed specifically to evaluate vulnerability over large areas, using generalized information. Schmidt [1987] developed a rating system similar to DRASTIC (but specific to Wisconsin hydrogeology,) and used digitized computer maps to map groundwater vulnerability in Wisconsin.

The most serious flaw in the above methods lies in the way the index scores are calculated. All of these methods first assign ratings to each of several hydrogeologic and other factors. For example, DRASTIC assigns ratings between one and ten to each of seven factors. These ratings are then multiplied by constant weighting factors and added to form the index value. The ratings and weights are determined subjectively by the designers of the method based on experience, and they are not tied directly to groundwater flow equations or to empirically measured quantities. The ratings are *ordinal* numbers, they reflect a general order, but not a true *ratio* relationship. Arithmetic operations such as the addition and multiplication used in DRASTIC are not valid for ordinal numbers. Rea and Istok [1987] showed that serious arithmetic inconsistencies can arise from the use of these operations on ordinal numbers.

The U.S. Environmental Protection Agency (EPA), Office of Solid Waste and Emergency Response [1986] proposed the "Time-of-Travel" (TOT) method. The main idea is that the vulnerability of groundwater at a site can be represented by the speed at which water travels in the subsurface. The approach is to estimate, using Darcy's Law, the time required for water to travel the first 100 feet (30.5 m) along a flow line originating in a hazardous waste facility such as a landfill. Small TOT's indicate fast movement of water in the system and therefore indicate high groundwater vulnerability to contamination.

As originally conceived, the TOT method breaks down under conditions where the site is far above the water table, [Rea and Istok, 1987]. The problem is that much, if not all, of the first 100 feet of a flow line in such a situation would be vertical. Such vertical flow downward occurs under a gradient of unity, whereas lateral flow in aquifers typically occurs under gradients of less than 0.01. Therefore, the computed TOT at a site with a water table at 100 feet depth would be much smaller (indicating higher vulnerability) than the TOT at a site with the water table just below the hazardous waste facility.

We conclude that all of the previous methods have flaws and that a better method of assessing groundwater vulnerability is needed. The availability of new technology such as GIS makes it practically feasible now to take a more quantitative approach to assessing groundwater vulnerability, while using even the very generalized information available for regional studies.

The primary goal of this project was to develop a general method which could be used by resource managers to identify areas of the most vulnerable groundwater for planning purposes. The work is presented in two papers. The first paper in the series deals with the procedures for using the GIS to develop and manage the digital database of map information used in the vulnerability assessment. The procedures were applied to develop a database of digital map information for a study area in the Willamette Valley of western Oregon. The second paper deals with the development of a numerical groundwater flow model used to assess the vulnerability of groundwater to contamination. The database was used to test the vulnerability model and then to produce general maps of groundwater vulnerability from the results of the model.

CHAPTER I. DEVELOPMENT OF A DIGITAL MAP DATABASE

Assessing Groundwater Vulnerability to Contamination: I. Development of a Digital Map Database

ALAN H. REA AND JONATHAN D. ISTOK

Oregon State University, Corvallis, Oregon

DOUGLAS NEBERT

U.S. Geological Survey, Portland, Oregon

ABSTRACT

A method was developed for assessing the vulnerability of groundwater to contamination from contaminant sources at the soil surface, using a numerical groundwater flow model linked to a digital map database. In this paper, the method was applied using the pcARC/INFO[1] Geographic Information System (GIS) to input, store, and manipulate base maps, resulting in a database of digital maps for the alluvial aquifer system in the Willamette Valley of western Oregon. Digital elevation maps were created by digitizing topographic maps of land surface (1:250,000 scale), water surface, and the base of the Tertiary-Quaternary sedimentary deposits (1:500,000 scales). Soil association and aquifer unit maps digitized from 1:500,000 scale map

---

1 Use of brand or product names in this report is for identification purposes only and does not constitute endorsement by Oregon State University or the U.S. Geological Survey.

sheets were also used. Data were extracted from ARC/INFO to the SURFER software package to create a 3-D surface model for each of the digital elevation maps. An ARC/INFO point coverage was then used to store and overlay these surfaces, allowing the creation of maps of depth to water, saturated thickness, and water table gradient. These data became the input to a numerical groundwater flow model (described in the second paper) used to assess the vulnerability of groundwater to contamination.

I.1. INTRODUCTION

There is a need for an improved methodology for assessing the *vulnerability* of groundwater resources to contamination from surface-applied chemicals. Regulatory agencies and resource managers need to be able to evaluate the risks to the environment and to public health posed by the manufacture, transport, use, and disposal of potentially dangerous chemicals. An important component of this risk evaluation process is the determination of those areas within an aquifer system that are most *vulnerable.*

Vulnerability is defined here as the degree to which the hydrogeologic characteristics of an area contribute to the likelihood of the groundwater becoming contaminated if a contaminant is introduced at the soil surface. In general, this means that the faster a contaminant can move from the surface to the groundwater aquifer and the faster a contaminant plume can spread in the aquifer, the more vulnerable the groundwater resource is. As defined, vulnerability can be evaluated solely from hydrogeologic information.

In the United States, a vast amount of natural resource information has been collected and is available in the form of maps. For a given area, several such maps may be available, showing a variety of geologic and hydrologic information (map themes). A relatively new technology, called a Geographic Information System (GIS) now allows the use of digital computers to store, combine, and analyze map-based information. This technology greatly reduces the time and expense of creating new maps by combining the information already available in the many separate map themes. The new maps can provide the information needed for sophisticated analysis techniques that would not be practical using manual techniques.

The ability to store, combine, and manipulate spatially distributed data makes the GIS a powerful tool for many kinds of natural resource assessments. GIS has been used for a wide variety of hydrologic studies. For example, Ventura, et al. [1988] used a GIS to estimate soil erosion in Wisconsin and to produce maps showing the additional efforts needed to achieve erosion control goals. Hession and Shanholtz [1988] used a GIS to identify priority areas for reducing nonpoint-source agricultural pollution in the Chesapeake Bay drainage basin in Virginia. Nebert and Anderson [1987] demonstrated the use of GIS in evaluating regional groundwater quality in an agricultural area of eastern Oregon. Schmidt [1987] used a GIS to map groundwater contamination "susceptibility" in Wisconsin. This is essentially the same problem dealt with in this project. Schmidt's susceptibility rating scheme is discussed in Paper II [Rea and Istok, this issue].

The primary goal of this project was to develop a general method which could be used by resource managers to identify areas of the most vulnerable groundwater for planning purposes. The work is presented in two papers. This paper describes some basic concepts of GIS and presents procedures for using the GIS to develop and manage the digital database of map information used in the vulnerability assessment. In a prototype application, the procedures were applied to develop a database of digital map information for a study area in the Willamette Valley of western Oregon. The second paper in the series, [Rea and Istok, this issue], deals with the development of a numerical groundwater flow model used to assess the vulnerability of groundwater to contamination. The vulnerability model was applied to the digital database to produce maps of groundwater vulnerability. Although the input data from the base maps was too generalized to provide great accuracy in the resulting map, the prototype application has helped to refine the procedures and to identify critical data needs for future studies of groundwater vulnerability.

I.2. GEOGRAPHIC INFORMATION SYSTEM CONCEPTS

Two kinds of information are represented by features or symbols on a map. First, the location of a map feature is implied by the position of its symbol on the map. Second, attribute information, representing one or more characteristics of the map feature, is often shown by the size, shape, color, or label of the symbol. A GIS must store both kinds of information about each map feature. The GIS is thus a combination of a geographic data processor, which manages the spatial nature of map information, and a tabular database manager, which manages attribute information.

One of the most powerful functions of the GIS is the "overlay." The overlay is the digital analogy to the process of laying transparent map layers on top of each other. The process can create a new integrated data layer that is a combination of two or more parent layers. As long as the map coverages are stored in the same coordinate system and map projection, the information in the separate coverages can be overlaid and thereby integrated to create new maps showing all combinations of spatial and attribute information from the original map layers.

Another type of GIS function is the representation of three-dimensional continuous surfaces, such as the elevation of the land surface. The essence of this function is that the elevation at any point in the area of interest can be interpolated from points with known elevations. A common method of representing these 3-D surfaces on maps is by using contour lines. We will see that the GIS provides other ways to represent 3-D surfaces, sometimes with better results.

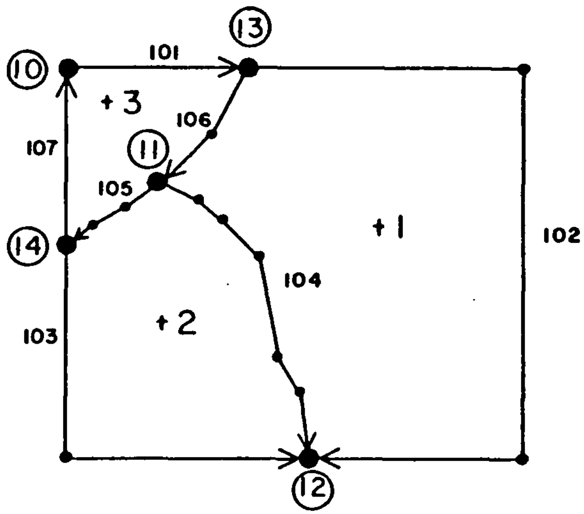
Two data formats are commonly used for GIS applications: vector format, and grid (also known as raster) format. Both data formats handle location and attribute data differently, and both formats were used in this project.

I.2.1 Vector Format (The ARC/INFO Data Structure)

ARC/INFO, a product of Environmental Systems Research Institute (ESRI), of Redlands, California, is a vector-based GIS in which map features are represented by points, lines, or areas. The system stores the locations of these features and their attributes in a set of related data files called a "coverage". "ARC" is the main program, and "INFO" is a database management product of the Henco company. ARC uses the file structure and data management capabilities of INFO to organize and manipulate the data files.

Lines, or "arcs," are input as a series of straight line segments between points. The endpoints of an arc are called "nodes", while the points between the nodes are called "vertices" (Figure I.1). An area, or "polygon," is represented by the lines making up its boundary and a point in its interior known as a "label". Individual point features may also be stored. The coordinates of map features are stored in separate files from the attribute data and the "topology" information. Topology is the set of relationships in space between map features. For example, in Figure I.1 arc #104 begins at node #11 and ends at node #12, and polygon #1 is to its left, while polygon #2 is to its right. ARC/INFO builds its own topology once the map has been digitized properly. The system also includes a "cleaning" function which corrects digitizing errors, such as lines which cross slightly when they should just meet.

Once a map has been digitized and has had its topology built, attribute information can be added to the map coverage. ARC/INFO maintains two main types of attribute files: an "Arc Attribute Table," (AAT) and a "Polygon Attribute Table" (PAT). Examples of these files are also illustrated in Figure I.1. A third type of file, the "Point Attribute Table" (also PAT), is treated as a special case of a polygon with an area and perimeter of zero. Each attribute table contains identification information used to relate the features to their map coordinates and topological information, and may also contain a set of



Explanation

● Node (11) Node identity
• Vertex 101 Arc identity
+ Label 1 Polygon identity

POLYGON ATTRIBUTE TABLE		
Poly-ID	Area	Perimeter
1	7.0	17.0
2	4.2	13.0
3	2.8	5.0

ARC ATTRIBUTE TABLE					
Arc-ID	Length	LeftPoly	RightPoly	FromNode	ToNode
101	2.1	0	3	10	13
102	13.4	0	1	13	12
103	8.2	2	0	14	12
104	6.8	1	2	11	12
105	1.2	2	3	11	14
106	1.4	1	3	13	11
107	2.2	0	3	14	10

Figure I.1. Illustration of arc-node topology for a polygon coverage in ARC/INFO.

user-defined attribute items. All of the items in the feature attribute tables are accessible to the user for database query operations. More information on the data structure can be found in the pcARC/INFO Starter Kit Users Guide [ESRI, 1987].

The triangular irregular network (TIN) topology is a vector-based method of representing 3-D surfaces in a GIS. Surfaces are represented by triangular polygons with known z-values (elevations) at their corners. The elevation of any point on the surface can be determined by interpolation from the elevations of the corner of the triangle it falls within. The TIN software package that works with ARC/INFO is not available for personal computers at this time, so a grid format based system was used for interpolating 3-D surfaces.

I.2.2 Grid Format (The SURFER Data Structure)

The grid data format is considerably simpler in concept and implementation than the vector format. Attribute data are stored in a single file as an array of numbers. The map location corresponding to an attribute value is implied by the value's position in the array.

The software package used for 3-D surface modeling in this project is called "SURFER," published by Golden Graphics, of Golden, Colorado. It uses a rectangular grid data structure. This format is well suited to 3-D surface modeling when estimating the value of the z variable continuously over the range of x and y. A key feature of the SURFER package that was useful for this project was its function of "gridding" or interpolating data for all grid points from a set of arbitrarily located x and y coordinates with known z values (attributes). The form of the interpolation algorithm, as well as the maximum distance from each grid point to search for input data points can be specified by the user.

The user can specify the grid cell size or number of columns and rows to define a grid. By decreasing the spacing between rows and columns in the grid, one can increase the resolution with which the surface is represented. However, this also increases the size of the data file and the computation time required for processing. Therefore, a decision must be made to determine the optimal grid cell size which will provide acceptable resolution and keep within the limits imposed by the computer hardware and software being used.

I.3. GENERAL APPROACH

Figure I.2 is a schematic diagram of the method developed to assess groundwater vulnerability. The base maps are first digitized and stored in the GIS. The three elevation maps are then passed through linkage programs to the gridding routine and interpolated elevation data for the grid points are passed back to the GIS. The water table gradient is calculated from the interpolated water table elevations at the grid points in a separate program. Overlay and other GIS operations are performed on the maps in the GIS to create the database of information needed by the groundwater flow model, such as maps of the depth to water, water table gradient, and saturated thickness at each grid point. These data are statistically analyzed and the grid points are combined into groups using a cluster analysis. Data files for each group of similar grid points are passed to the model for calculation of travel times. A statistical regression model was developed from the groundwater flow model results for each group and applied to the entire set of grid. The groundwater flow model and statistical analyses are discussed in Paper II [Rea and Istok, this issue]. The display capabilities of the GIS were then used to produce maps of the estimated travel times, which serve as indicators of vulnerability.

The ARC/INFO commands are given for clarity in the following descriptions of the GIS procedures that were used in this project.

The groundwater flow model requires information about the thicknesses and hydraulic conductivities of the soil and aquifer, the depth to the water table, the saturated thickness of the aquifer, and the slope or gradient of the water table. This information can be derived from digitized maps of aquifer materials, soil associations, elevation of the land surface, elevation of the water table, and elevation of the base of the alluvial aquifer deposits. The appropriate information is digitized from the base maps and converted into a common map projection and coordinate system using ARC/INFO.

Once a base map of topographic data is digitized into ARC/INFO and has had its topology built, the data are extracted for gridding in SURFER. The UNGENERATE command in ARC/INFO is used to create a file containing the arc-ID numbers and x and y coordinates for each digitized vertex on the contour lines. A separate file is created containing the arc-ID numbers and the corresponding elevations for each contour line. For point elevations such as benchmarks, the UNGENERATE command with the "point option" is used to create a file with point-ID numbers, and x and y coordinates. Another file is created with the point-ID

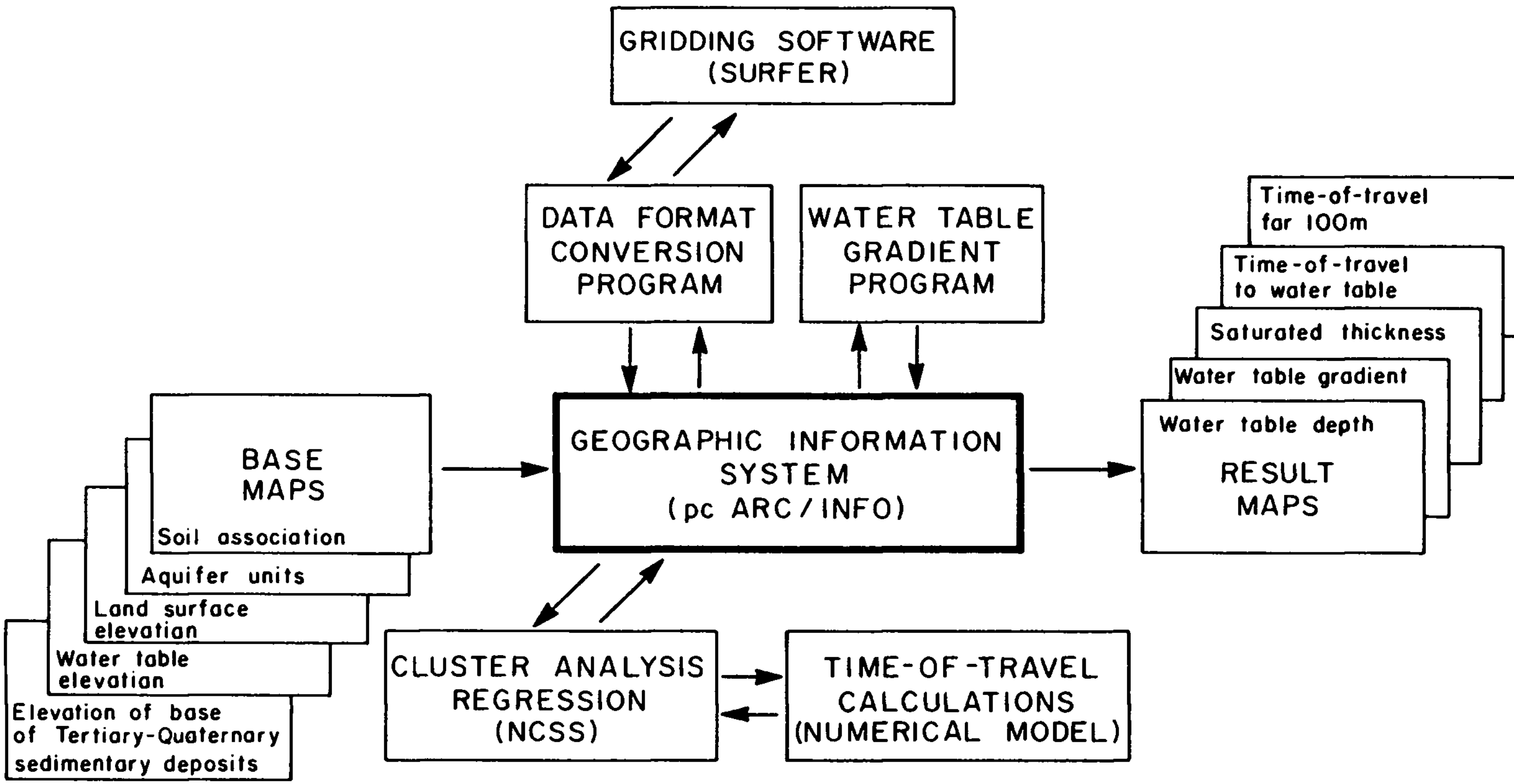


Figure I.2. Schematic diagram of vulnerability assessment method.

numbers and their corresponding elevation attributes. A FORTRAN program reads these files and creates a file of x, y, z coordinates (where z represents the elevation attributes) in the format used by SURFER for import files. The data are then imported into SURFER, where values for each point in a rectangular grid are interpolated.

A second FORTRAN program converts the gridded data files from the SURFER grid file format to a format that can be read by ARC/INFO. The program assigns an ID number to each point, and writes an ASCII file containing the ID number and attribute value for each point in the grid. This file is then read into an INFO database file. The JOINITEM command is used to add the attribute value to the proper record in the PAT file, using the ID number as the item relating the two files.

This program also provides the option of writing a file in the format for the GENERATE command in ARC/INFO. The program calculates the x and y coordinates for each grid point, and outputs a file containing the point ID number and its x, y coordinates for each point in the grid. The GENERATE command can then be used to create an ARC/INFO point coverage directly from this file. This option is used the first time a grid is made to insure that the points in the ARC/INFO map coverage are identical to the points in the SURFER grid file. All subsequent grid files use this file as a template to ensure consistency.

A third FORTRAN program can extract data from the point map coverage and convert it to a SURFER grid file. Then the graphics display capability of SURFER can be used to create contour maps or 3-D surface representations of any numeric attribute item in the PAT of the point map coverage.

Another variable needed by the model is the water table gradient. A FORTRAN program was written to read a data file of water table elevations extracted from the ARC/INFO point coverage and to calculate the gradient for each grid point from its elevation and that of adjacent grid points using a finite difference approximation.

Once all of the data are stored in an ARC/INFO point coverage, GIS operations can be used to manipulate the digital maps. The first operation to be used is the "CLIP." This overlay operation is analogous to a "cookie-cutter," and is used to cut out the area of interest from the surrounding area in a map. This eliminates unnecessary points from the files, reducing storage space and processing time.

The next GIS operation is to calculate the depth to the water table and the saturated thickness for each grid point. These are calculated from the interpolated elevations of the land surface, the water table, and the base of the Tertiary-Quaternary sedimentary deposits at each point in the grid. This process is in essence the overlaying of the 3-D surfaces. The "IDENTITY" command is then used to overlay the grid points on the soils map and to include the soil association code in the PAT for each grid point. The relationships between the different layers of information stored for each grid point are shown in Figure I.3.

Once all the required data are stored in the PAT of the ARC/INFO point coverage, it can be used to create new maps, such as maps of the depth to water and the water table gradient. The data are also extracted and sent to the statistical analyses and groundwater flow model, which generate travel times for each point in the grid. These travel times can be joined into the PAT and plotted as maps using ARC/INFO.

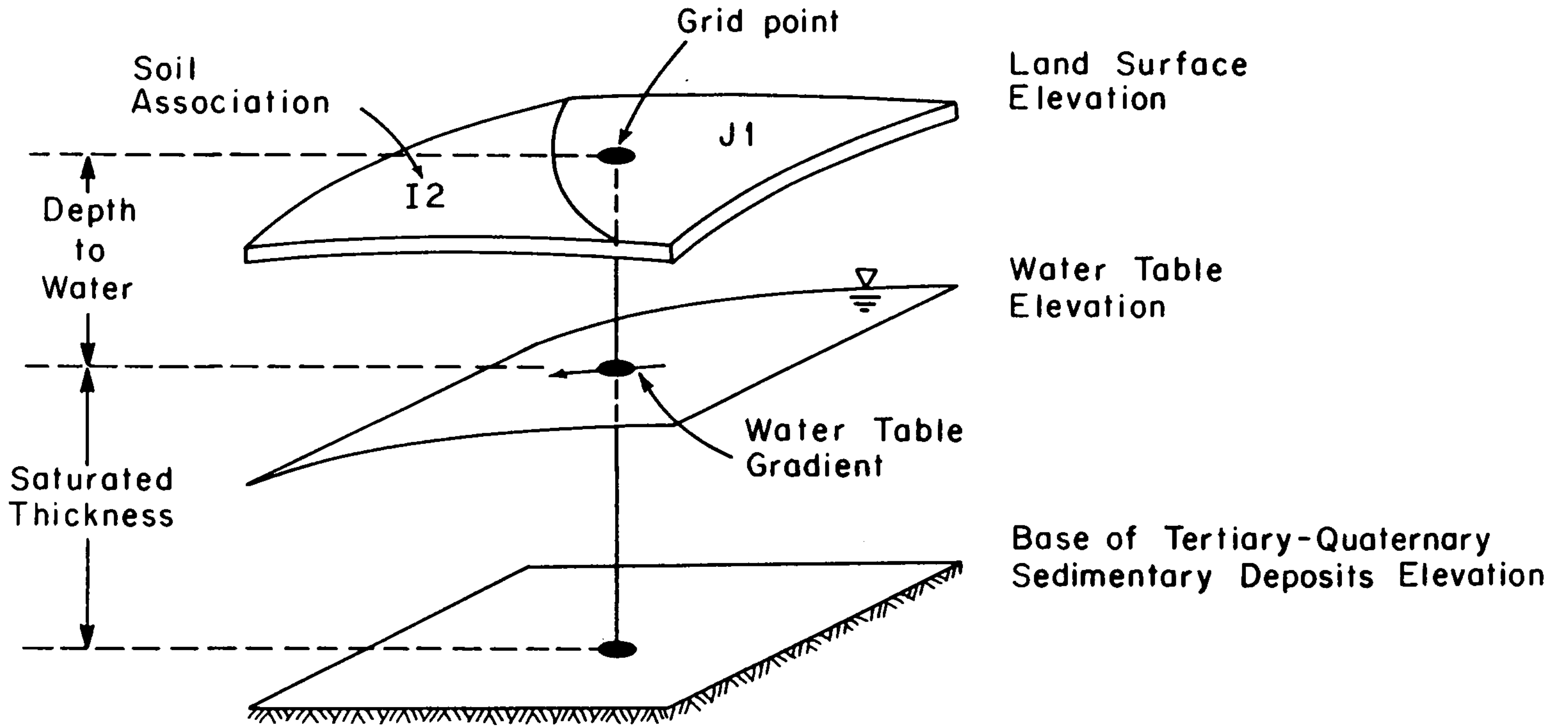


Figure I.3. Relationships between data layers.

I.4. APPLICATION

A study area to test this approach was selected based on the availability of sufficient published maps of hydrogeologic data (Figure I.4). Stable base maps at the 1:500,000 scale showing the generalized aquifer units in western Oregon, contour maps of water levels and elevations of the base of the Tertiary-Quaternary sedimentary deposits in Aquifer Unit I were available from McFarland [1983]. The aquifer units map was digitized previously by the Oregon Water Resources Department. The water surface contours and elevation of the base of the Tertiary-Quaternary sedimentary deposit contours were digitized by the first author for this project. Selected well locations and well log data from a series of Oregon Groundwater Reports [Frank and Collins, 1978], [Frank and Johnson, 1972], [Gonthier, 1983], [Hampton, 1963], and [Price and Johnson, 1965], were also digitized and used to fill in areas where the maps by McFarland provided too little information.

A General Soil Map of Oregon [U.S. Department of Agriculture, Soil Conservation Service, 1986] had been previously digitized by the Water Resources Division, U.S. Geological Survey, Portland, Oregon, under an agreement with the U.S. Soil Conservation Service. The scale of the paper source map was 1:500,000.

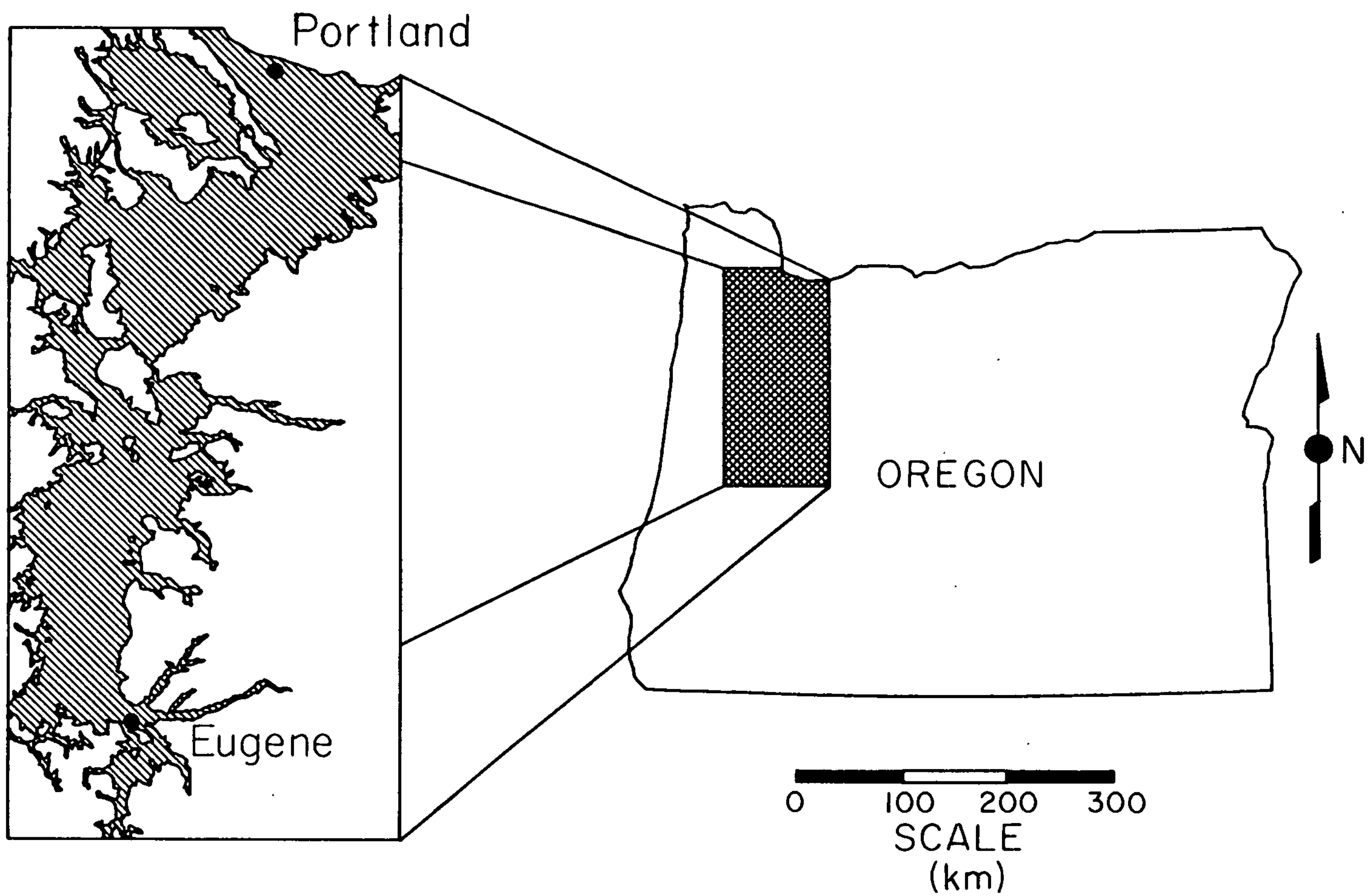


Figure I.4. Map showing location of study area and Aquifer Unit I (shaded area in inset map).

The elevation of the land surface was digitized by the first author from paper USGS topographic sheets (1:250,000 scale). Only the contours falling inside of, or one contour higher than the aquifer unit boundary, were digitized. These generally corresponded with the lower elevations and flatter areas in the Willamette Valley. Contours on the surrounding mountains were not digitized to prevent the high elevation values from skewing the interpolation of elevations on the valley floor toward unreasonably high values. Because contour lines were very far apart in many parts of the study area, point elevations were added from the topographic sheets to ensure that there would be enough points in the neighborhood of each grid point for the interpolation algorithm to use.

A grid cell size of 2000 meters by 2000 meters was selected, resulting in a grid of 105 rows and 50 columns. This size was chosen primarily due to a practical limit on the number of points SURFER could handle, both in terms of memory requirements and computation time. An octant search including the nearest 5 points within a 36,000 meter radius was used for gridding the base of the Tertiary-Quaternary sedimentary deposits map. A quadrant search including the nearest 2 points within a 15,000 meter radius was used for gridding both the land surface and the water surface maps. An inverse-distance-squared interpolation algorithm was used for all of the maps. (See the SURFER Information Manual [Golden Software, 1987] for more discussion of search methods and interpolation algorithms.)

The Aquifer Unit map coverage was used to CLIP out only those points that fell within the boundaries of Aquifer Unit I. After clipping, a few of the grid points did not have enough adjacent points for the water table gradient calculation. Rather than attempt to estimate the gradient at those points from elevations further than 2000 meters away, these points were deleted from the map coverage using the RESELECT command.

Since topographic maps are subject to a certain amount of error (generally less than or equal to one-half of the contour interval,) it is not unreasonable to expect that errors may be present in two maps, and that these errors may be magnified when the maps are overlaid. These errors would be most noticeable in areas where the actual distance between the two overlaid surfaces is small. Given the methods used and the varying accuracy of the different source maps, it is entirely possible for the interpolated elevation of the water table to be higher than the interpolated elevation of the land surface at a particular grid point. This means the calculated depth to water would be negative.

After overlaying, computed water table depths were negative for one very large area (Figure I.5). The area is a broad, very flat river terrace. Contour lines for the land surface occur only where the river cuts through this terrace and at the sides of the valley. When interpolating for the elevations at grid points in the central part of the terrace the interpolation algorithm used many data points from the contours along the river. Data points from contours near the valley sides may also have been included, but they were much further away, and received little weight. For this reason, the algorithm estimated the elevation at these points to be very near the elevation of the 100-foot (30.5 m) contours near the river. However, the benchmarks and airfield elevations show that the nearly flat terrace is actually at about 170 feet (51.8 m) elevation. The water table in the area is at about 150 feet (45.8 m) elevation.

This problem illustrates the fact that contour lines occur only where there are *changes* in elevation. Contour lines cannot provide much information about the elevation of a flat surface. The only information contour lines provide about the elevation of the surface between the contours are the maximum and minimum limits of elevation the surface could have. This is not a problem in steeply sloping terrain, since the contours are relatively close

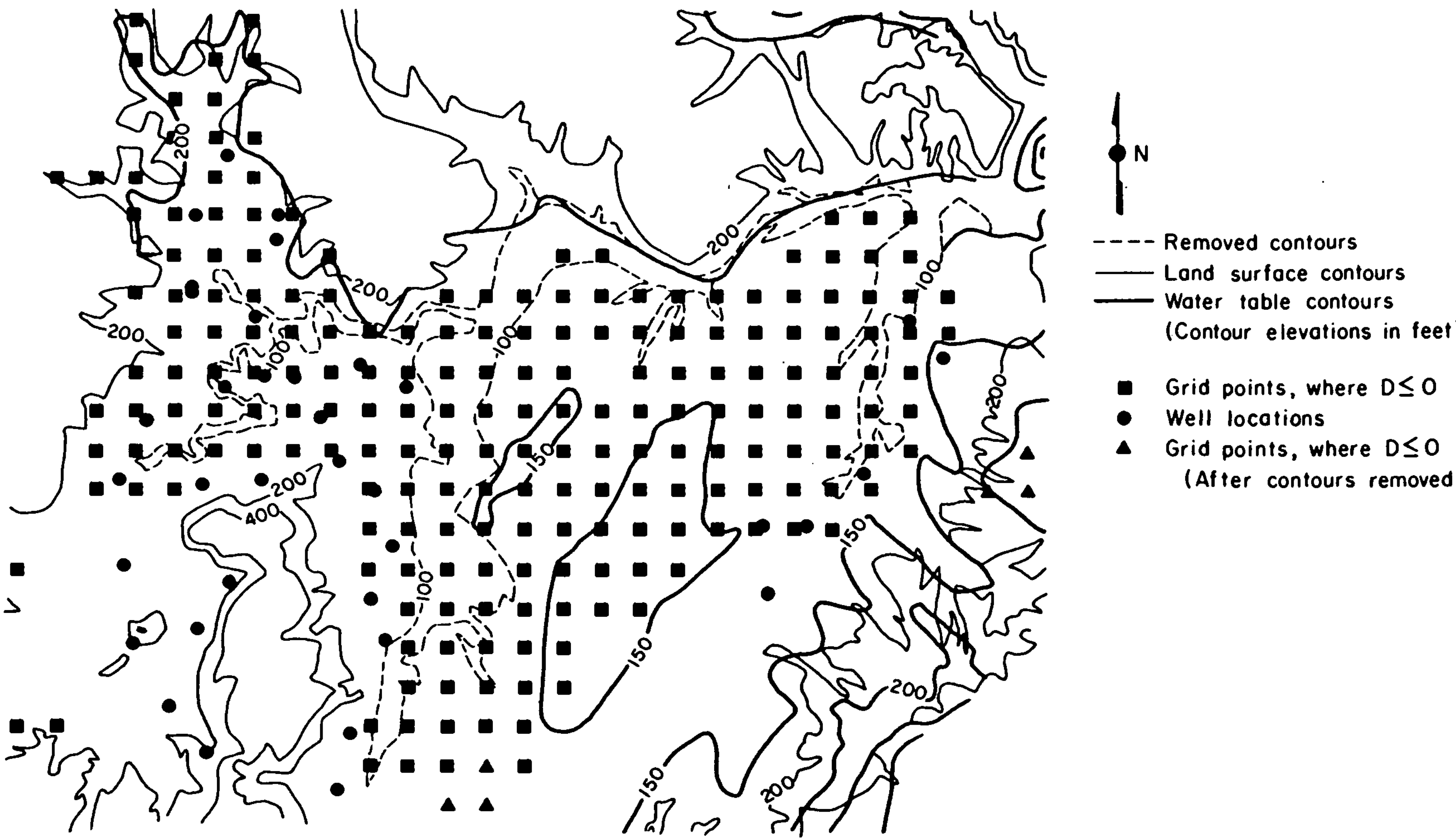


Figure I.5. Map showing negative depths to water.

together. We have seen, however, that the errors can be quite dramatic in flatter areas. Note that the surfaces involved in groundwater applications are often very gently sloping, especially water tables or potentiometric surfaces. Therefore great care should be taken when using contour lines to provide elevations for groundwater applications.

The solution to this problem for this study was to add elevation data from published well logs [Frank and Collins, 1978], [Frank and Johnson, 1972], [Gonthier, 1983], [Hampton, 1963], [Price and Johnson, 1965]. The logs provided elevations for the land surface and water table at the well locations. The well locations were digitized and the elevations were added to the input data files for SURFER. The contour lines along the river (dashed lines in Figure I.5), which were skewing the results, were also deleted from the map. After re-gridding the land surface and water table surfaces, only a few points scattered throughout the study area still had negative computed depths to water. Points with computed depths of less than -10 m (-33 ft), (more than half the water surface contour interval in error,) were deleted.

Negative values of saturated thickness were also computed for a few points located around the edges of the valley and in areas of higher elevation. This may be an indication that the bedrock is outcropping at the surface, or at least is very near the surface in these areas. The vulnerability model assumes that the base of the Tertiary-Quaternary sedimentary deposits is the lower boundary of the saturated zone. Since this assumption may not be valid in these areas on the margins of the valley, these points were also deleted from the study area.

The end result of the above clipping and deletion operations was a grid of 1433 points that had a complete data set (i.e. interpolated values for all map themes). All modeling operations were carried out on this set of points.

I.5. RESULTS

As a result of this project, a number of new maps were produced for the study area. Some of these are simple combinations of the previously available information, made possible by the overlay capability of the GIS. The maps of depth to water (Figure I.6) and saturated thickness (Figure I.7) are examples of this kind of map. Other maps were the result of calculations on one or more of the data layers. The water table gradient map (Figure I.8) and time-of-travel maps (see Paper II, [Rea and Istok, this issue]) are examples of these.

Figure I.6 is a map of the calculated depth to water in the study area. Although it was created using data from existing published maps, it represents new information that was not previously available. We can readily see from this map that the water table is fairly near the surface (less than 20 meters) over much of the southern two-thirds of the Willamette Valley. The water table is considerably deeper in the northeastern part of the valley. This area is hilly and has considerably more complex topography than the rest of the Willamette Valley.

Figure I.7 is a map of the saturated thickness of the Tertiary-Quaternary sedimentary deposits. This map was created by subtracting the interpolated elevation of the base of the deposits from the interpolated water table elevation at each grid point. Note that a contour map of saturated thickness was also available in McFarland [1983]. A comparison of the generated map and McFarland's manually prepared map shows good agreement. Both maps show that most of the southern half of the Willamette Valley has a saturated thickness of less than 30 meters, while the northern half has a saturated thickness that is mostly greater than 60 meters. Again, the northeast portion of the area is the most complex.

Figure I.8 is a map of the calculated water table gradients for the study area. This is also a new map. We see that generally, the gradients are smaller in the central and western portions of the Willamette Valley. Most of the gradients are less than 0.25%. Again, we see that the northeast portion of the study area is much more complex than the rest of the area.

The data from these three maps, along with the soils map, were used by the groundwater flow model discussed in Paper II [Rea and Istok, this issue] for the travel time calculations.

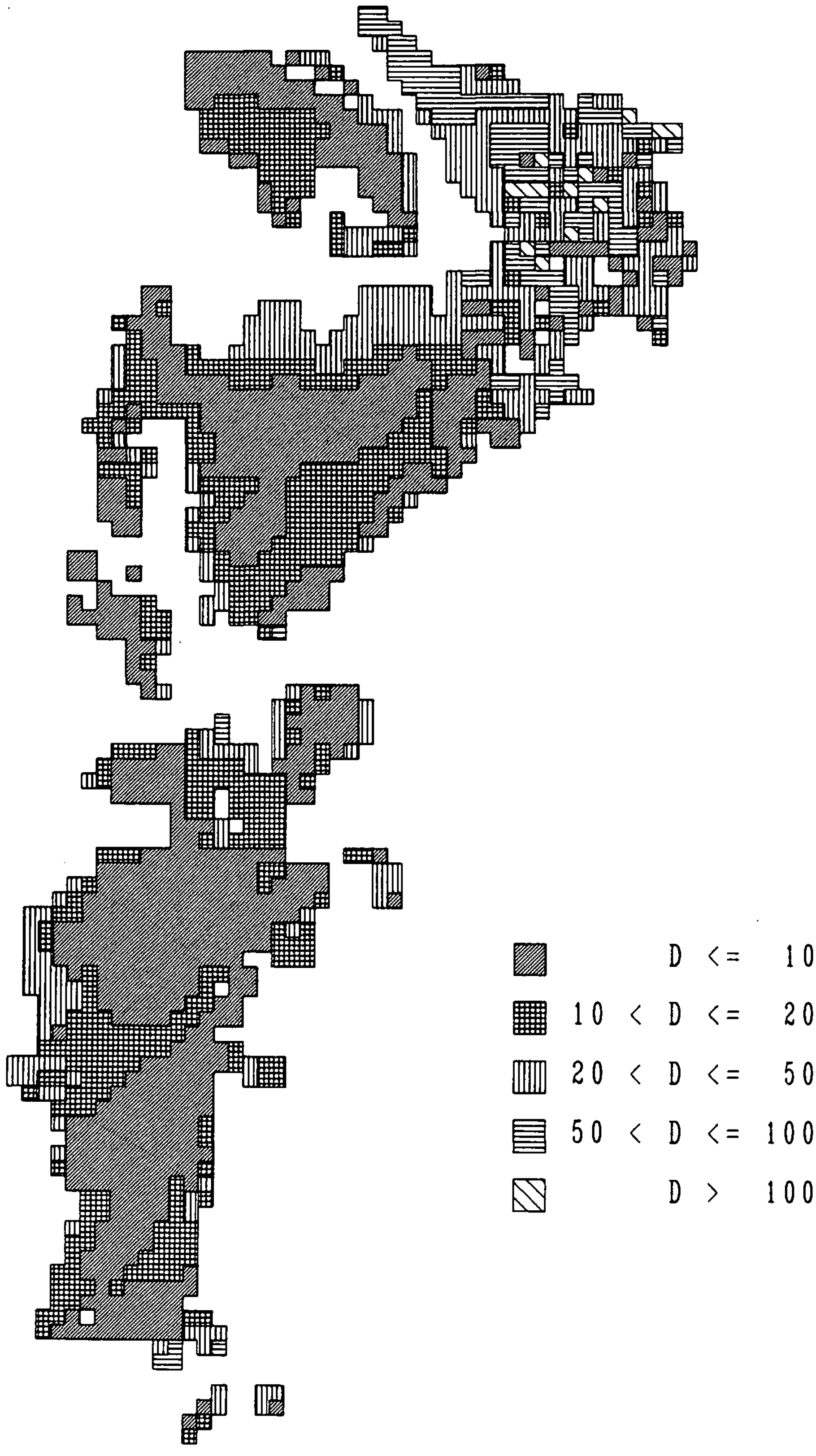


Figure I.6. Depth to water, D (meters).

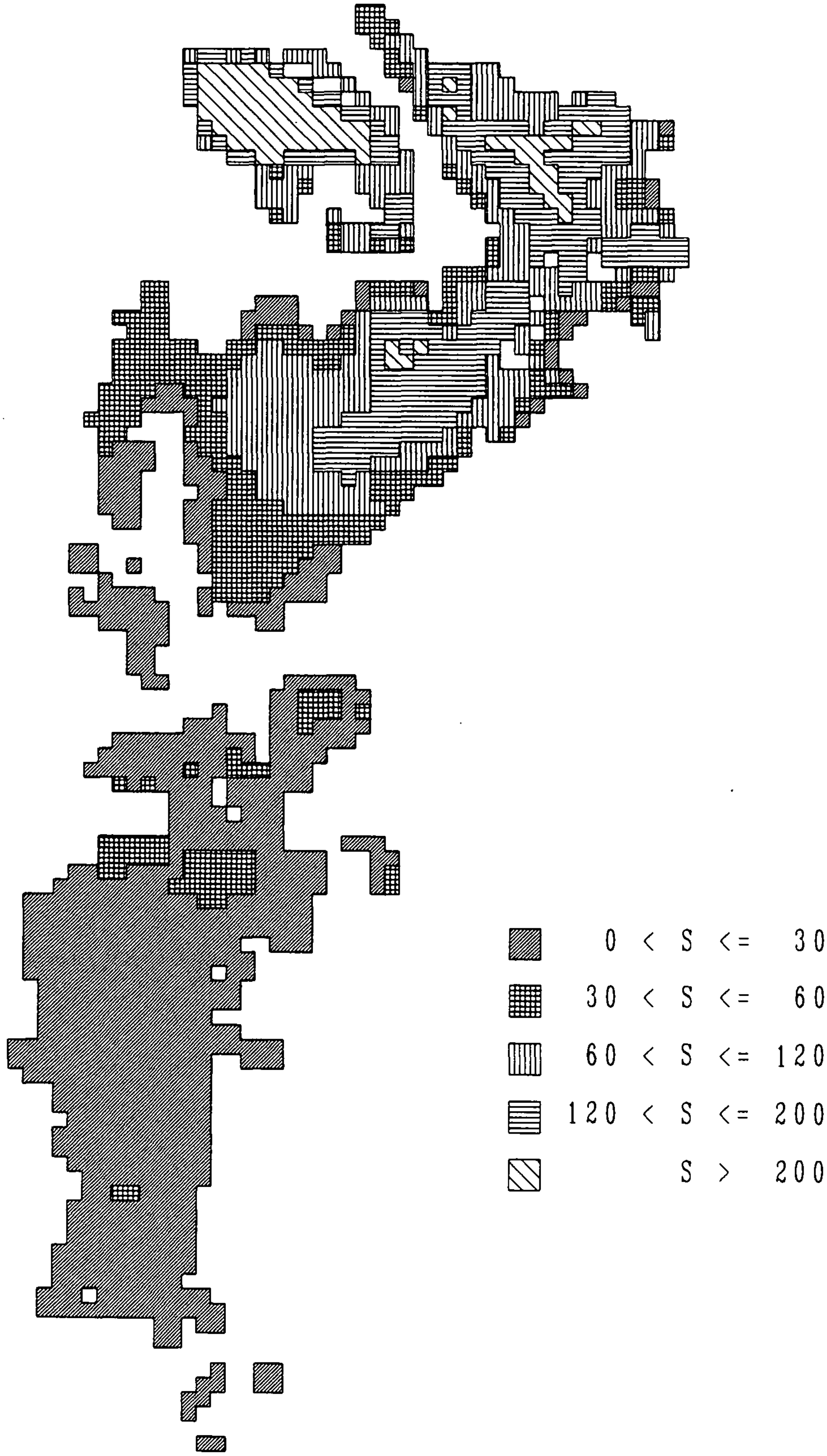


Figure I.7. Saturated thickness, S, (meters).

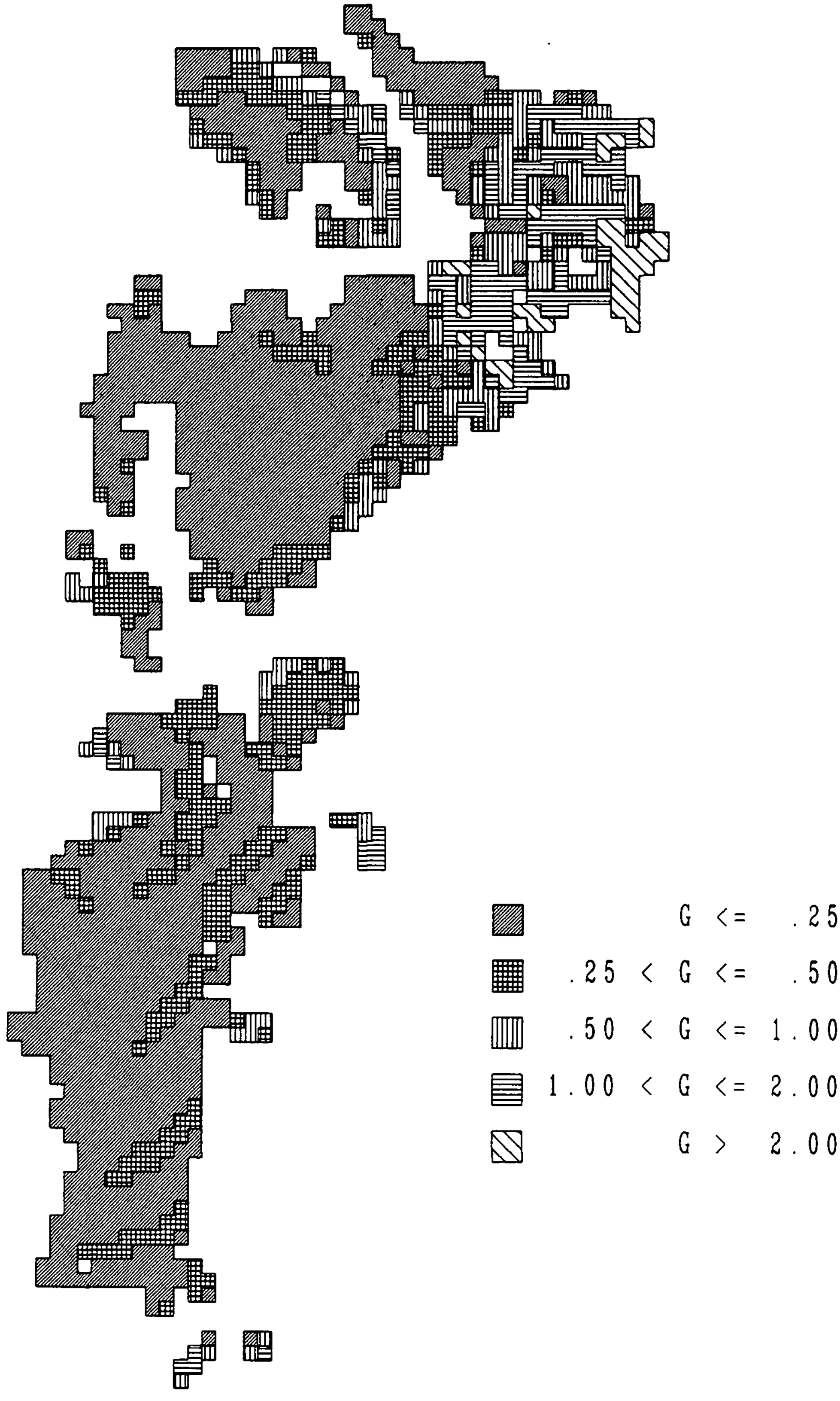


Figure I.8. Water table gradient, G, (%).

I.6. DISCUSSION

As a result of the application of the methodology discussed above, much has been learned about the kind of data needed for this kind of study, and many needed improvements to the digital database have been identified. The contour interval for the water level and base of the Tertiary-Quaternary deposits maps was 50 feet (15.2 m), while the interval was 100 feet (30.5 m) for the land surface elevation maps. We can be confident only that the contour elevations are accurate to within 1/2 the contour interval, or 50 feet (15.2 m) for the land surface, and 25 feet (7.6 m) for the water level contours. We find that the difference between these two values, the depth to water, is calculated at less than 50 feet (15.2 m) over about 63% of the study area and depths of less than 25 feet (7.6 m) were calculated for about 34% of the area. Although the accuracy is improved somewhat by the addition of benchmarks and well log data, it would appear that the elevation maps are not as accurate as would be needed to calculate depth to water over the study area. A similar comment would be true of the saturated thickness calculations.

The elevation models for land surface, water table, and bedrock, could be improved for this study area by using well locations and drilling records as a point coverage. This is more detailed and more accurate information than the generalized contour lines from the 1:500,000 scale maps. Also, since elevations of the water level and the land surface would be measured at each well point, travel times could be calculated from the original data, rather than from interpolated values. The map of well locations would also serve as a valuable database upon which to build a more detailed database of aquifer properties. For instance, additional information from the well logs, such as pump test results could be included, rather than just the land surface and water surface elevations. The well locations are more difficult and time-consuming to digitize, however, and such an effort was beyond the scope of this project.

The soil map used was a very general map of soil associations. A soil association is made up of a few (typically two to four) soil series that tend to appear together on the landscape. This is used to facilitate mapping at smaller scales, since a soil series map at the 1:500,000 scale would have many map units that would be too small to be distinguishable. In naming the associations, the soils series are listed in order of the portion of the total area that they account for. For this project, the properties of the predominant soil series (the first named) in each association was assumed to be representative of the area mapped as a particular soil association. It is important to note, however, that even though soils may be associated in space over the landscape, they need not be similar soils in any way to be included in the same soil association. Most of the soil associations in the study area were, in fact, made up of soils with similar hydrologic properties. Larger scale soil series maps would provide much better information, but digitizing these was beyond the scope of this project.

Another large gap in the database is in the information regarding the hydraulic conductivity of the "vadose zone," the material below the soil profile and above the water table. This information is difficult to find in any form, particularly for large areas. For this project, it was assumed that the lower soil horizon was similar material to the material in the vadose zone, and the properties of the lower soil horizon were extended to this zone. Also, very little information was available on the spatial distribution of the hydraulic conductivity of the aquifer materials. McFarland [1983] reports only ranges and median values for hydraulic conductivities of the aquifer units. A constant value of aquifer hydraulic conductivity (the median) had to be assumed for the entire study area. Considering the sensitivity of the vulnerability model to this parameter [Rea and Istok, this issue], better information on the spatial distribution of hydraulic conductivities should be a top priority for any future studies of this area.

Another aspect of map information is the time for which the information is valid. Water levels, for example, can change over time, and somehow this should be accounted for in the database of map information. No data were available with the map of water levels regarding what points in time the mapped levels represented. The dates of the measurements are recorded for most of the well logs and could be included if well locations were digitized.

Of all the computing tasks, the most time-consuming task was that of gridding the input data layers in SURFER. As mentioned above, it would be preferable to use well locations and records for much of the type of information used in this project. Instead of gridding in SURFER, an alternate method would be to calculate a set of interpolation functions for the 3-D surface based upon the geometry of the set of well points. This set of interpolation functions could be generated once, but used for every surface that is to be calculated using the same set of well points. This would save a great deal of computing time. It should also be possible to identify certain layers of materials from the well logs and to relate these layers between all the wells which penetrate them. In this way, 3-D surface models of the contacts between all of these layers could be constructed.

I.7. CONCLUSIONS

It is clear from the above discussion that the data available from the maps used in this study are not adequate for detailed analysis. Instead of the generalized information from small-scale maps, much better information could be obtained from well logs. For regional studies, a sampling of well logs could be selected and travel times calculated for each well location. The estimated travel times could then be generalized for the study area from the sample of well locations used. This method would avoid the use of interpolated values for the surface elevations and eliminate the possibility of calculating negative depths to water or other such errors.

In addition to better data on the elevations of the surfaces, much better information on the spatial distribution of hydraulic conductivities of the soil, vadose zone, and aquifer materials is needed. Larger-scale soils maps and well logs might be good sources of this information. The time of measurement should also be included in the database for those quantities which may change significantly over time.

Although these improvements in the database are recommended for future studies of this nature, the usefulness of the current study is not negated. A great deal has been learned about the use of generalized maps for estimating the necessary data. Also, the general framework and linkage programs of the method for interfacing the digital map database with a groundwater flow model have been developed and validated. The method is workable and needs only better input data to achieve more accurate results. The necessary data are commonly available, but would require a significant digitizing effort to make it usable in the GIS.

I.8. REFERENCES

ESRI, *pcARC/INFO Starter Kit Users Guide,* Environmental Systems Research Institute, Inc., Redlands, California, 1987.

Frank, F.J. and Collins, C.A., *Groundwater in the Newberg Area, Northern Willamette Valley, Oregon: Oregon Water Resources Department Groundwater Report 27,* 1978.

Frank, F.J. and Johnson, N.A., *Ground-Water Data in the Corvallis-Albany Area, Central Willamette Valley, Oregon: Oregon State Engineer Ground Water Report 17,* 1972.

Golden Software, Inc., *SURFER Information Manual,* Golden, CO, 1987.

Gonthier, J.B., *Groundwater Resources of the Dallas-Monmouth Area, Polk, Benton, and Marion Counties, Oregon: Oregon Water Resources Ground Water Report 28,* 1983.

Hampton, E.R., *Records of Wells, Water Levels and Chemical Quality of Ground Water in the Molalla-Salem Slope Area, Northern Willamette Valley, Oregon: Oregon State Engineer Ground Water Report 2,* 1963.

Hession, W.C. and Shanholtz, V.O., A geographic information system for targeting nonpoint-source agricultural pollution, *Journal of Soil and Water Conservation, Vol. 43, No. 3,* 264-266, 1988.

McFarland, W.D., *A Description of Aquifer Units in Western Oregon,* U.S. Geological Survey Open-File Report 82-165, Portland, Oregon, 1983.

Nebert, D.D. and Anderson, D., Utilization of geographic information systems technology in the assessment of regional ground-water quality, *Irrigation Systems for the 21st Century,* American Society of Civil Engineers, New York, 370-377, 1987.

Price, D., and Johnson, N.A., *Selected Ground Water Data in the Eola-Amity Hills Area, Northern Willamette Valley, Oregon: Oregon State Engineer Ground Water Report 7,* 1965.

Rea, A.H. and Istok, J.D., Assessing Groundwater Vulnerability to Contamination, 2, Time-of-Travel Calculations, *Water Resour. Res.,* this issue.

Schmidt, R.R., *Groundwater Contamination Susceptibility in Wisconsin, Report 5, Wisconsin's Groundwater Management Plan,* Wisconsin Department of Natural Resources, 1987.

U.S. Dept. of Agriculture, Soil Conservation Service, *General Soil Map, State of Oregon,* 1986.

Ventura, S.J., Chrisman, N.R., Conners, K., Gurda, R.F., and Martin, R.W., A land information system for erosion control planning, *Journal of Soil and Water Conservation, Vol. 43, No. 3,* 230-233, 1988.

CHAPTER II. TIME-OF-TRAVEL CALCULATIONS

Assessing Groundwater Vulnerability to Contamination: II. Time-of-Travel Calculations

ALAN H. REA AND JONATHAN D. ISTOK

Oregon State University, Corvallis, Oregon

ABSTRACT

A numerical (finite element) groundwater flow model for assessing the vulnerability of groundwater to contamination from surface sources is developed. The model solves a dual formulation problem for the potential function and the stream function to calculate the time-of-travel for water to flow from the surface to the water table and laterally for 100 meters as an index of groundwater vulnerability. The model is applied to a sample data set for the Willamette Valley in western Oregon. A cluster analysis is used to condense the data and form a training data set for a multiple regression model. The regression model is fit to the results of the finite element model with an R-squared of greater than 0.96. The simpler regression model is then used for mapping travel times for the entire study area. When properly calibrated against the finite element model and when combined with the digital map database and Geographic Information System (GIS) procedures described in the first paper of this

series, the regression model can be conveniently used to assess the vulnerability of groundwater to contamination over large areas.

II.1. INTRODUCTION

There is a need for an improved methodology for assessing the *vulnerability* of groundwater resources to contamination from surface-applied chemicals. Regulatory agencies and resource managers need to be able to evaluate the risks to the environment and to public health posed by the manufacture, transport, use, and disposal of potentially dangerous chemicals. An important component of this risk evaluation process is the determination of those areas within an aquifer system that are most *vulnerable*.

Vulnerability is defined here as the degree to which the hydrogeologic characteristics of an area contribute to the likelihood of the groundwater becoming contaminated if a contaminant is introduced at the soil surface. In general, this means that the faster a contaminant can move from the surface to the groundwater aquifer and the faster a contaminant plume can spread in the aquifer, the more vulnerable the groundwater resource is. As defined, vulnerability can be evaluated solely from hydrogeologic information.

It is important to note that this definition of vulnerability does not consider the likelihood of the contaminant being introduced at the surface, nor does it consider the value of the groundwater resource potentially endangered by the contamination. This definition also does not include the evaluation or assessment of the transport characteristics of any particular contaminant, the level of contamination, or whether such a level poses a threat to a certain use of the groundwater resource. These factors are components of an evaluation of risk, but it is advantageous to treat vulnerability as a separate issue. The broader issue of pollution potential, which includes the other components of risk, may be then addressed in light of the assessed *vulnerability* of the groundwater resource.

Rea and Istok [1987] reviewed a number of methods for evaluating groundwater vulnerability to contamination. They found that the approach used in most of the previous methods was based on the method developed by LeGrand [1964, 1983]. For example, Phillips, et al. [1977] designed a "soil-waste interaction matrix" for evaluating the suitability of waste disposal sites. Silka and Swearingen [1978] designed the "Surface Impoundment Assessment" (SIA) method. Aller et al. [1985] proposed a method called DRASTIC, which assigns numerical scores to hydrogeologic characteristics of a site. DRASTIC was designed specifically to evaluate vulnerability over large areas, using generalized information. Schmidt [1987] developed a rating system similar to DRASTIC (but specific to Wisconsin hydrogeology,) and used digitized computer maps to estimate and map groundwater vulnerability in Wisconsin.

The most serious flaw in the above methods lies in the way the index scores are calculated. All of these methods first assign ratings to each of several hydrogeologic and other factors. For example, DRASTIC assigns ratings between one and ten to each of seven factors. These ratings are then multiplied by constant weighting factors and added to form the index value. The ratings and weights were determined subjectively by the designers of the method based on experience. The ratings are *ordinal* numbers, they reflect a general order, but not a true *ratio* relationship. Arithmetic operations such as the addition and multiplication used in DRASTIC are not valid for ordinal numbers. Rea and Istok [1987] showed that serious arithmetic inconsistencies can arise from the use of these operations on ordinal numbers.

The U.S. Environmental Protection Agency (EPA), Office of Solid Waste and Emergency Response [1986] proposed the "Time-of-Travel" (TOT) method. The main idea is that the vulnerability of groundwater at a site can be represented by the speed at which water travels in the subsurface. The approach is to estimate, using Darcy's Law, the time required for water to travel the first 100 feet (30.5 m) along a flow line originating in a hazardous waste facility such as a landfill. Small TOT's mean high groundwater velocities and therefore indicate high groundwater vulnerability to contamination.

As originally conceived, the TOT method breaks down under conditions where the site is far above the water table, [Rea and Istok, 1987]. The problem is that much, if not all, of the first 100 feet of a flow line in such a situation would be vertical. Such vertical flow downward occurs under a gradient of unity, whereas lateral flow in aquifers typically occurs under hydraulic gradients of less than 0.01. Therefore, the computed TOT at a site with a water table at 100 feet depth would be much smaller (indicating higher vulnerability) than the TOT at a site with the water table just below the hazardous waste facility.

We conclude that all of the previous methods have flaws and that a better method of assessing groundwater vulnerability is needed. The availability of new technology such as GIS makes it practically feasible now to take a more quantitative approach to assessing groundwater vulnerability, while using even the very generalized information available for regional studies.

The objective of this study was to refine and extend ideas from previous methods of assessing groundwater vulnerability to take advantage of the data storage, retrieval, and manipulation capabilities of modern computers. The first paper in this series described the development of the digital database of map information and the use of a Geographic Information System (GIS) for managing the data needed for the vulnerability assessment. This paper focuses on the development and the application of a new method for assessing the vulnerability of ground-water to contamination from surface sources.

The first criterion used in the development of the new method was that the method should be tied to physical processes in a direct way. It is recognized that an application of any method to a real situation will necessarily involve professional judgement to interpret the hydrogeologic data. It is preferable, however, that the use of judgement be limited to the actual description of the hydrogeologic environment, rather than being included as an integral part of the method itself.

The second criterion was that the method should permit direct comparison between sites or areas with regard to their relative vulnerability. A corollary of this criterion was that the method should be independent of scale, so that the method could be applied with equal validity to site-specific investigations and regional studies. Differences should be in the level of detail represented in the data used, rather than in the actual method of assessing vulnerability.

The third criterion was that the method should be practically feasible. The most elegant method is of little use if the data it requires are commonly unavailable. Therefore the method should focus on using the kinds of data that are commonly available.

II.2. METHODOLOGY: The Time-of-Travel Approach

The approach used for this project was similar to that proposed by the EPA [Office of Solid Waste, 1986] for hazardous waste facilities. However, the distance over which travel times were calculated was the lateral distance, rather than distance along the streamline, as the earlier method had specified. In our method, a numerical groundwater flow model is used to calculate the positions of streamlines and to calculate travel times in a generalized, two-dimensional flow domain.

II.2.1 Description of Flow Domain

It is assumed that water is ponded at the soil surface (Figure II.1). The water flowing downward creates a 'mound' in the water table, but does not change the water table gradient except within a small distance (10 m) from the center of the mound. Two-dimensional, steady-state, saturated flow is assumed from the soil surface vertically downward to the water table, then in the aquifer along the local water table gradient. The soil and aquifer material layers are assumed to be parallel to the water table. Any number of layers of material can be specified, each with its own hydraulic properties. The bottom boundary is assumed to be impermeable and parallel to the water table. There is no recharge other than through the mound.

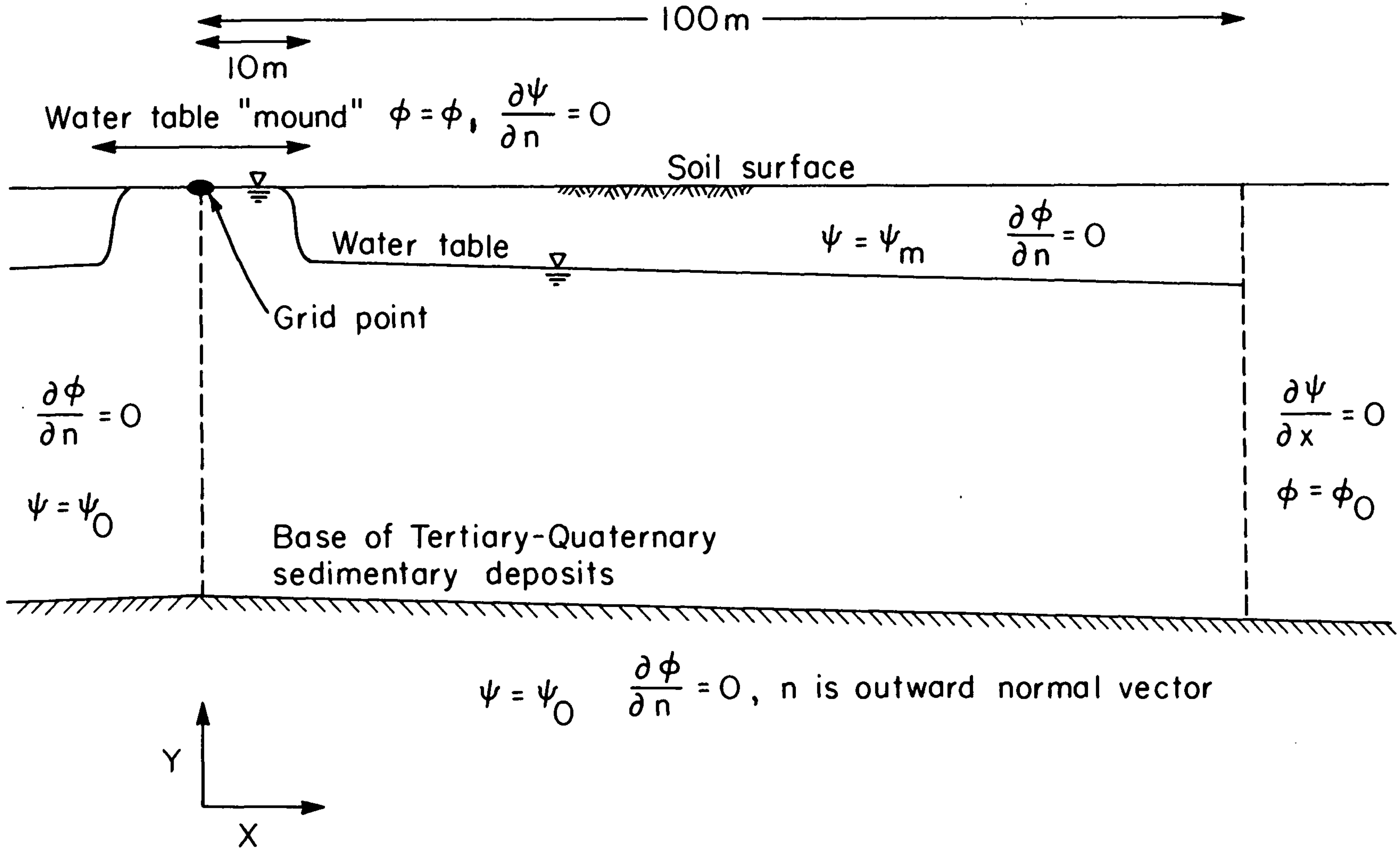


Figure II.1. Boundary conditions for groundwater flow model.

The model calculates the travel time from the soil surface to the water table and the travel time for 100 meters lateral distance. The model was also tested for lateral distances of 1000 meters.

The assumption of saturated flow is very broad, and the computed travel times do not accurately represent the actual time required for water to flow through a soil profile and into the aquifer under natural conditions. The assumption was appropriate for this study for two reasons. First, the information necessary to model unsaturated flow in the vadose zone is much more difficult to obtain and is not commonly available for regional studies. The second reason the assumption of saturated flow was made is that it represents a "worst case scenario" for vulnerability assessment, resulting in the shortest travel times.

If sufficient information were available, nothing in the rest of the method precludes the use of a more complex model. For example, the Pesticide Root Zone Model (PRZM) [Carsel, et al., 1984] is an unsaturated zone model that could be used in conjunction with the Time-of-Travel concept and the procedures developed for the use of a Geographic Information System to manage the database of digital map information needed by the model.

II.2.2 Theory

The steady state, saturated groundwater flow equations can be written using either potentials (i.e. hydraulic heads) or stream functions [Frind and Matanga, 1985]. A dual formulation of the groundwater flow equations, using both potentials and stream functions was used in the numerical model. The potential formulation was solved to obtain heads and velocities, while the stream function formulation was solved to obtain the locations of stream-lines.

For coordinate axes oriented along the principal directions of permeability, the governing equation for the potential function formulation is [Frind and Matanga, 1985]:

$$\frac{\partial}{\partial x}\left(\mathbf{K}_x \frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mathbf{K}_y \frac{\partial \phi}{\partial y}\right) = 0 \tag{1}$$

where ϕ is the potential function, and $\mathbf{K}_x$ and $\mathbf{K}_y$ are the components of saturated hydraulic conductivity in the x and y directions, respectively. The governing equation for the stream function formulation is:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mathbf{K}_y} \frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mathbf{K}_x} \frac{\partial \psi}{\partial y}\right) = 0 \tag{2}$$

where ψ is the stream function. These governing equations are of the same form and can be solved using the same method. This is done by substituting $1/K_y$ for K_x and $1/K_x$ for K_y when the equation is solved for the stream function.

The finite element method was used to solve equations (1) and (2). Finite element methods have been used for many groundwater flow problems and have been compared favorably with actual measured data of contaminant plumes [Frind, et al., 1985]. Many excellent references can be found detailing the application of the finite element method to groundwater flow and contaminant transport. Wang and Anderson [1982] provide a clear introductory approach to groundwater modeling using both the finite difference and finite element methods. Istok [Draft] provides a complete and thorough coverage of the use of the finite element method for groundwater and contaminant transport modeling.

The Time-of-Travel model used in this project was modified from the finite element programs in Istok [Draft] and expanded to include the stream function solution and Time-of-Travel calculations. For simplicity, only linear triangular elements were used. The solutions to the governing equations were obtained using the method of weighted residuals (Galerkin's method).

Equation (1) was first solved to obtain values of hydraulic head at each node in the mesh. The components of the velocity vectors in the x and y directions are calculated for each element. This is done for each element in the flow domain using Darcy's Law with the computed heads at the element's nodes and the components of hydraulic conductivity.

After the heads and velocities were determined, the positions of the streamlines were calculated. Equation (2) was solved to obtain the value of the stream function at each node in the mesh. Linear interpolation was then used to determine the intersection points between the sides of each element and the streamlines (lines of constant stream function) which passed through it. The length of each segment of streamline was calculated from this information. Five interior streamlines for the mesh were chosen, at $\psi = 1,2,\ldots,5$.

The boundary conditions and geometry of the finite element mesh were chosen to simplify the solution and to provide a general description of groundwater recharge from a point source (Figure II.2). On the diagram, specified head (Dirichlet) boundaries for the potential function are A-B, C-D, and D-F. No-flow (Neumann) boundaries for the potential function are A-E-F, and B-C. Specified stream function (Dirichlet) boundaries are A-E-F, and B-C-D. Zero flux (Neumann) boundaries for the stream function are A-B and D-F. The groundwater flow will be from the land surface at A-B to boundary D-F.

The mesh is oriented in the direction of groundwater flow away from point A. Point A corresponds to each point in a grid laid out at 2000 meters spacing over the study area. The times required for water to travel from boundary A-B to the water table and to boundary D-F are to be evaluated for each grid point. Different values for the thicknesses and hydraulic conductivities of the layers, the depth to the water table, and the gradient are possible, resulting in a unique mesh geometry for each grid point. The meshes generated had between 35 and 65 nodes and between 40 and 90 elements. Details of how the data for the grid points are handled as layers in a GIS, are in [Rea et al., this issue].

Once the velocity vectors and the positions of the streamlines in the flow domain are known, the travel time along each streamline can be calculated. The resultant velocity vector will always be parallel to the streamline, by definition. Therefore, the travel time for water along a streamline, TOT_i is given by:

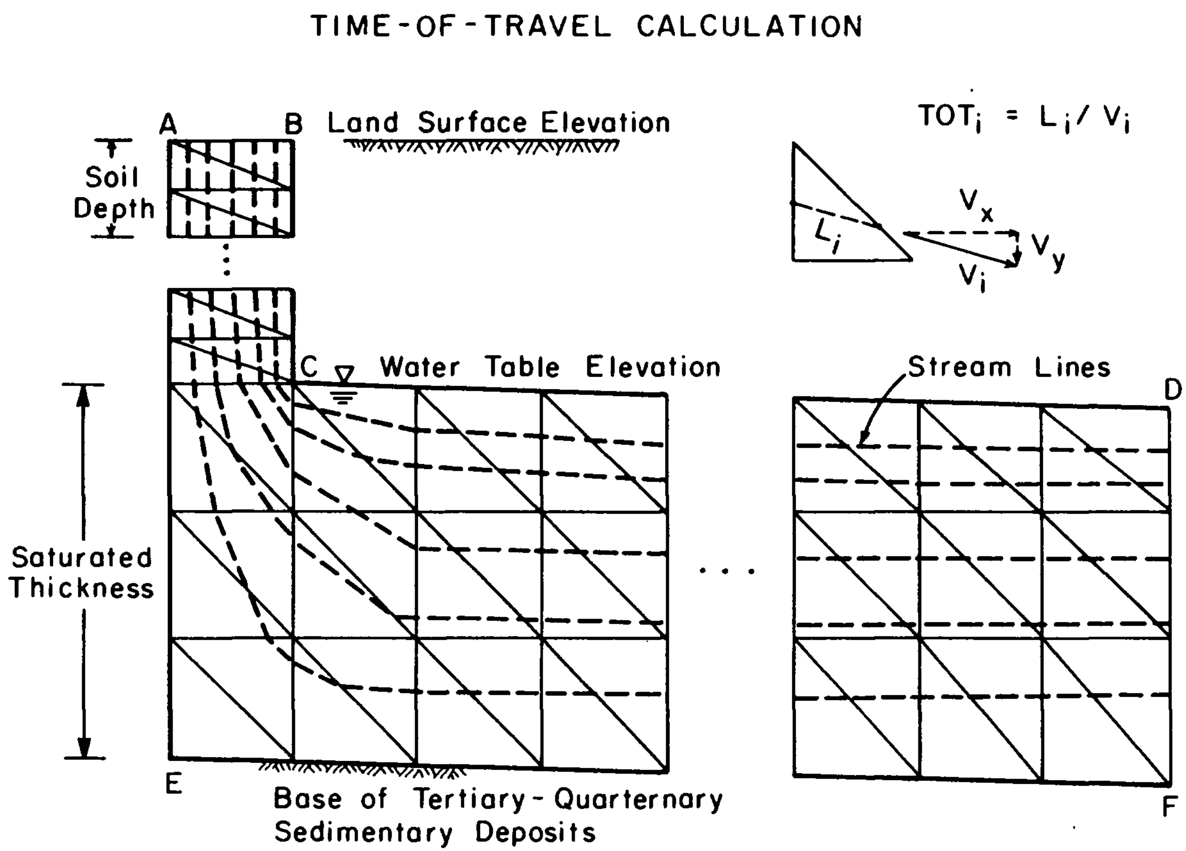


Figure II.2. Finite element mesh.

$$TOT_i = \frac{L_i}{v_i} \tag{3}$$

where i is the streamline number, L is the length of the streamline, and v is the apparent groundwater velocity tangent to the streamline. The shortest time for all the streamlines is the critical one, and this is reported as the time-of-travel, TOT. When rewritten for the finite element method, the Time-of-Travel is given by:

$$TOT = \min \sum_{j=1}^{m} \sum_{i=1}^{n} \frac{L_{ij}}{v_{ij}} \tag{4}$$

where m is the number of streamlines, and n is the number of elements the streamline passes through.

II.3. APPLICATION

The vulnerability model was used to determine travel times for a study area in western Oregon's Willamette Valley. The input data for the model comes from maps of hydrogeologic information. A map of the study area and a description of the map database were presented in Paper I [Rea et al., this issue] . The end result of the GIS manipulations was a set of 1433 points on a regular grid at 2000 meter intervals. Values for soil type, depth to water, water table gradient, and saturated thickness were extracted for each grid point.

A multivariate cluster analysis was used to reduce the number of calculations made with the numerical model. Cluster analysis is a method for combining observations of many variables into groups, or "clusters," so that the clusters are as homogeneous as possible [Mardia, et al. 1979]. The procedure can be visualized by plotting the observations as points in n-dimensions, with each variable represented as a coordinate axis in space. The observations are then combined in such a way that the points nearest to each other in space are included in the same cluster.

Because soil association is a categorical variable, the cluster analysis was performed separately on groups of soil associations. The twelve soil associations present in the study area were combined into seven groups with similar average hydraulic conductivities of the soil profiles. The seven groups of soil associations were: I6-J1-J4, C7-I3-J3, I1-I7, I2, I4, and I5. The observations for depth to water, gradient, and saturated thickness in each group of soil associations were clustered into 15 to 20 clusters by the K-means algorithm [Hintze, 1986]. The means of each variable within the 117 clusters created were used as input for the numerical model. Finite element meshes were constructed for the 117 cluster means and the travel times were computed for each mesh.

II.4. RESULTS

II.4.1 Sensitivity Analysis

A sensitivity analysis was run using the data for soil association I1 to see how important each variable is in the model. Each variable was changed over its range of values, while all other variables were held constant at their medians. Water table gradient and aquifer conductivity were the most important variables for the 100 meter (TOT_{100}) and 1000 meter (TOT_{1000}) travel times. Depth to water and soil conductivity were most important for the travel time to the water table ($TOT_{W.T.}$). See Table 1. The 1000 meter travel time and the 100 meter travel times reflect the influence of the variables in a similar way. Since the 1000 meter travel time tells us little new information, it was not calculated for the entire study area. Note also that the least information was available on the distribution and range of values of the aquifer hydraulic conductivity [Rea et al., this issue], so this parameter was varied over an extremely large range. This causes the model to show a greater sensitivity to this parameter than would be the case if better information on aquifer conductivity were available.

		TOT (days)			TOT/TOT_{median}		
		W.T.	100 m	1000 m	W.T.	100 m	1000 m
GRADIENT	PERCENTILE						
0	0	5.2	13237.6	1487543	1.00	12.06	115.47
0.0002	10	5.2	4059.8	67985	1.00	3.70	5.28
0.0006	25	5.2	1955.6	25949	1.00	1.78	2.01
0.0013	50	5.2	1097.7	12883	1.00	1.00	1.00
0.0023	75	5.3	650.9	7056	1.00	0.59	0.55
0.0043	90	5.3	359.4	3810	1.00	0.33	0.30
0.0393	100	5.1	45.5	423	0.98	0.04	0.03
THICKNESS(m)	PERCENTILE						
0.3	0	5.4	1137.9	12663	1.03	1.04	0.98
7.4	10	5.3	1064.6	12699	1.00	0.97	0.99
14.1	25	5.2	1066.1	12825	1.00	0.97	1.00
27.1	50	5.2	1097.7	12883	1.00	1.00	1.00
48.0	75	5.2	1221.5	12968	1.00	1.11	1.01
131.3	90	5.2	1384.7	12995	1.00	1.26	1.01
211.8	100	5.2	1611	13061	1.00	1.47	1.01
DEPTH (m)	PERCENTILE						
-7.2	0	---	---	---	---	---	---
1.4	10	1.0	1106.8	12903	0.18	1.01	1.00
5.2	25	3.4	1133.4	12916	0.66	1.03	1.00
9.6	50	5.2	1097.7	12883	1.00	1.00	1.00
15.2	75	7.5	1079.3	12875	1.44	0.98	1.00
22.1	90	10.4	1076.2	12861	1.98	0.98	1.00
60.2	100	26.0	1084.5	12862	4.95	0.99	1.00
SOIL K(m/d)							
0.89	minimum	11.336	1202.2	12965	2.16	1.10	1.01
1.84	mean	5.247	1097.7	12883	1.00	1.00	1.00
2.78	maximum	3.471	1008.7	12725	0.66	0.92	0.99
AQUIFER K (m/d)							
6.096	minimum	5.320	6278.6	118359	1.01	5.72	9.19
60.96	median	5.247	1097.7	12883	1.00	1.00	1.00
1219	maximum	5.231	67.7	657	1.00	0.06	0.05

Table II.1. Results of sensitivity analysis for soil association Il.

II.4.2 Regression Analysis

A multiple regression analysis was performed on the 117 cluster means and the computed travel times. With $TOT_{W.T.}$ as the dependent variable and depth to water and average hydraulic conductivity as independent variables, an r^2 value of 0.99 was achieved with the following regression model:

$$\ln(TOT_{W.T.}) = 1.037 \cdot \ln(D) - 0.9881 \cdot \ln(K) - 0.1107 \qquad (5)$$

where D is the depth to water in meters and K is the average hydraulic conductivity over the layers above the water table in meters per day. $TOT_{W.T.}$ is in days. Note that this equation would reduce to Darcy's Law for vertical flow (gradient of unity) if the first two constants were 1 and the third was 0. If the finite element model were to use one-dimensional flow from the surface to the water table, the regression equation should reduce exactly to Darcy's Law.

With the TOT_{100} in days as the dependent variable and water table gradient, saturated thickness, depth to water, and average hydraulic conductivity as independent variables, an r^2 value of 0.96 was achieved with the following regression model:

$$\ln(TOT_{100}) = 8.597\times10^{-3}\cdot D + 2.067\times10^{-3}\cdot S - 0.839\cdot\ln(G) - 0.196\cdot\ln(K) + 1.111 \qquad (6)$$

where S is the saturated thickness in meters and G is the water table gradient, expressed as a fraction.

The above regression equations were used to calculate travel times for every grid point in the study area. Due to the presence of the logarithm terms, the regression equations become undefined for some of the grid points. For the $TOT_{W.T.}$ computations, 74 points had calculated depths to water of ≤ 0, and were deleted. For the TOT_{100} computations, 39 records had calculated water table gradients of 0, and G's for those records were set to an arbitrary small value (1×10^{-4}).

II.4.3 TOT Maps

Figure II.3 is a map of the computed $TOT_{W.T.}$ for the study area. Most of the study area has a computed $TOT_{W.T.}$ of less than 75 days. A small number of points, mostly in the northeastern portion of the study area and around the edges of the valley, had computed $TOT_{W.T.}$'s higher than 300 days.

Computed values of TOT_{100} were more evenly distributed among classes, and the spatial patterns were more complex (Figure II.4). Also, we find large TOT_{100}'s in some areas that had relatively small $TOT_{W.T.}$'s, and vice versa. Other areas seem to have consistently small or consistently large travel times on both maps. Compare the areas marked A, B, and C on both maps.

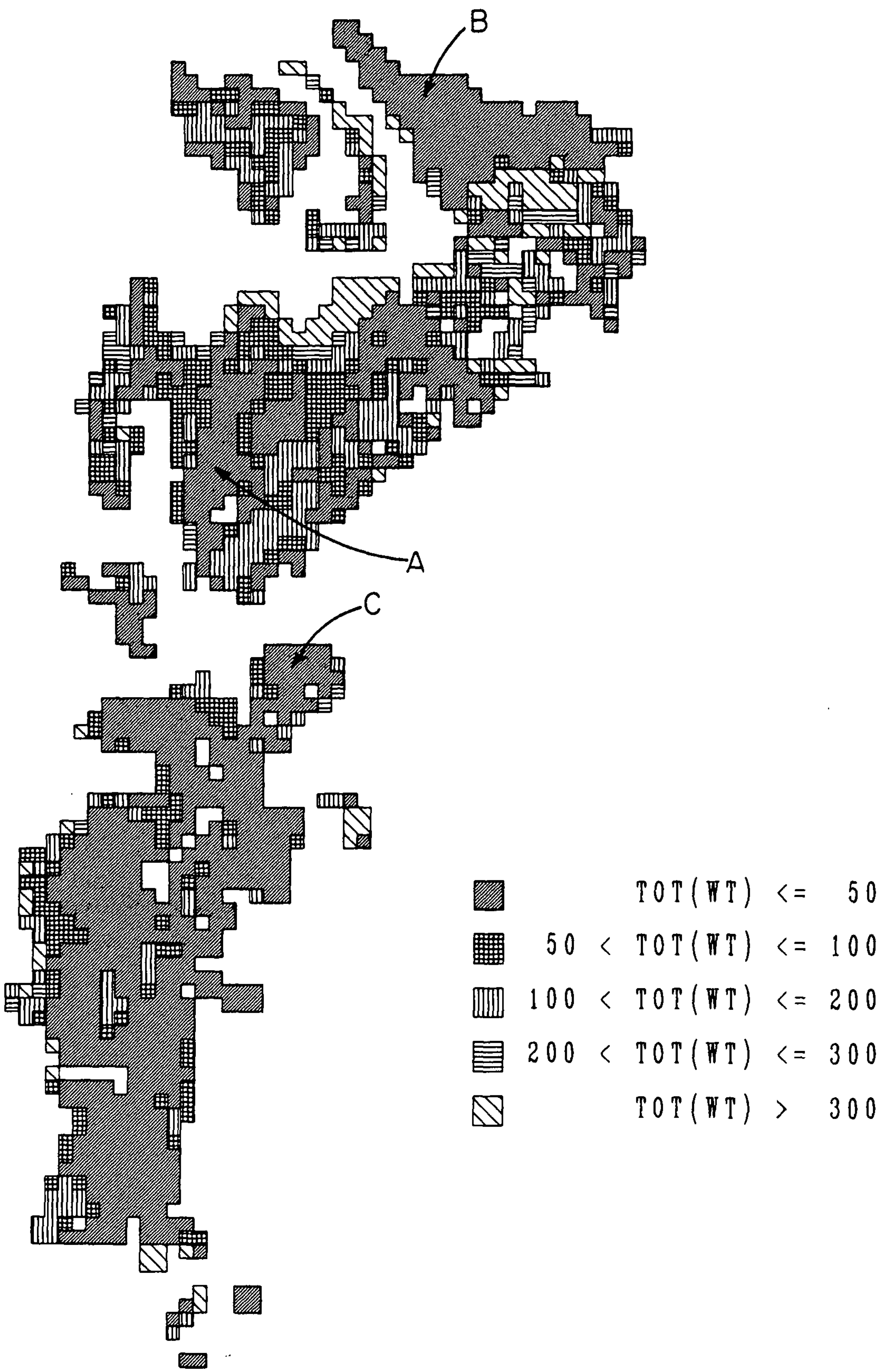


Figure II.3. Time-of-travel to water table (days).

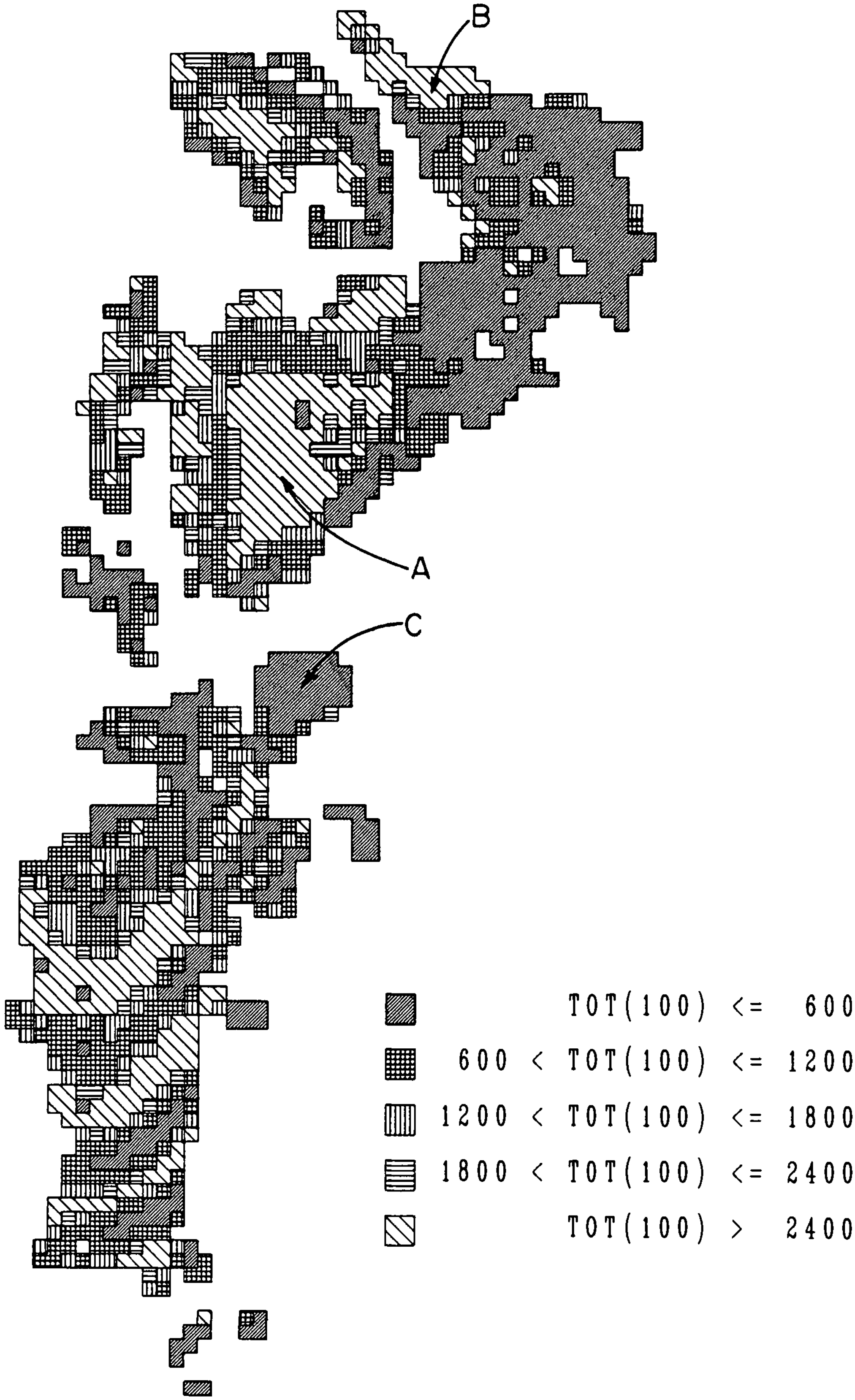


Figure II.4. Time-of-travel for 100 meters (days).

II.5. DISCUSSION

Using the time-of-travel as an index of vulnerability provides many benefits. First, it is based on the physical process of flow in a porous medium. This process is reasonably well understood, and can be modeled with partial differential equations. These equations can be solved numerically using a computer program with acceptable accuracy. Programs for this purpose are very common in the literature and have been tested against measured flow conditions many times. This approach uses commonly available data, and works equally well for regional studies and detailed site investigations.

Saturated flow conditions were assumed throughout the flow domain because the data needed for unsaturated flow modeling is not commonly available for regional studies, and also because it is the worst case scenario for vulnerability assessment. Dispersion of a conservative solute is not considered in the approach because dispersivities of soil and aquifer materials are also not commonly available. Since the goal of the approach is to provide a means of *comparison* between areas, these assumptions are reasonable.

The clusters formed by the cluster analysis often had large variances and there was considerable overlap between the clusters. For this reason, the cluster classifications were not used to assign the travel times calculated for the cluster means to each observation in the clusters. Instead, the clusters were used as a training set for a multiple regression analysis. The cluster analysis does provide a means of grouping the multivariate data based on actual observations. This ensures that the combinations of the different variables used in the training set for the regression analysis are similar to the combinations actually observed. This allows us to apply a simple regression model to the 1433 grid points rather than running the finite element flow model for each grid point separately. It may also be possible to develop more general regression models, using data over larger ranges of the variables to calibrate the regression models to the finite element models. This would result in a method that is based on physical processes and easy to use.

The lateral distance from point A to boundary D-F in Figure II.1, for which the time-of-travel calculation is made, is somewhat arbitrary. By changing the distance considered, the relative importance of the various input variables is changed. For example, the TOT_{100} will include much more influence of the properties of the aquifer than would the TOT for 10 meters. Likewise, the $TOT_{W.T.}$ will be influenced a great deal by the properties of the soil, while a TOT_{100} would be less influenced by the soil properties.

Just as the different TOT values emphasize different hydrologic factors, they also give different information. Comparison of the two maps above (Figures II.3 and II.4) indicates that they show different information. In comparing the areas marked A, B, and C on both maps, we see that often the $TOT_{W.T.}$ for an area may be small while the TOT_{100} for the same area may be large. For some purposes, such as a study of a pesticide which is applied over a large area, the most important TOT value might be the $TOT_{W.T.}$, especially if there are drinking water wells in the area. For another study, however, the important consideration may be how fast the contamination moves away from a location. An example of this might be a study of point sources of contaminant or a chemical that degrades over time in the aquifer. For this purpose, the important TOT value may be for 100 or 1000 meters lateral distance, or even more. In short, the time-of-travel concept can be used to show different kinds of vulnerability or pollution potential, depending upon the specific purpose at hand.

For these reasons, the authors choose not to arbitrarily decide upon a certain lateral distance to be used for vulnerability assessment. Instead, we leave that decision to a user of the method to make, considering the needs and circumstances of a specific task. In doing so, there is a risk of losing the ability to compare the results of different studies. For this reason, it is *imperative* that the lateral distance used always be reported with calculated time-of-travel values. The $TOT_{W.T.}$ and TOT_{100} seem to provide a good combination of vulnerability information, and are recommended for general purposes.

II.6. CONCLUSIONS

Cluster analysis can be used to condense the data set to create a training data set against which multiple regression models can be calibrated with acceptable accuracy. The regression model then provides a simple and fast way to calculate travel times for a very large number of grid points. This appears to be a useful technique when dealing with very large data sets.

The method developed in this paper shows great promise for assessing groundwater vulnerability to contamination for regional or site-specific studies. The method is tied to the physical processes of groundwater transport by theoretical relations which have been well accepted in the literature. The theoretical relations can be solved using numerical techniques which are also well known and well accepted. The travel times calculated in the method provide a simple and direct way to compare the relative vulnerability of the groundwater resources of different areas, or specific sites. The Geographic Information System is the key to making the vulnerability analysis practically feasible. The GIS provides a powerful means of managing large amounts of spatial information. Using the GIS, we are able to build data files for the finite element model using commonly available data and apply a simple model many times so as to represent the spatial variability present in the natural environment. Using the methods outlined in these two papers, the time-of-travel calculation may be used together with the GIS as a powerful and flexible tool for comparing the relative vulnerability of groundwater aquifers to contamination from surface sources.

II.7. REFERENCES

Aller, L., Bennett, T., Lehr, J. H., and Petty, R. J., *DRASTIC: A Standardized System for Evaluating Ground-water Pollution Potential Using Hydrogeologic Settings, EPA/600/2-85/018,* U.S. Environmental Protection Agency, Ada, OK, 1985.

Carsel, R.F., Smith, C.N., Mulkey, J., Dean, J.D., and Jowise, P., *Users Manual for the Pesticide Root Zone Model (PRZM), Release 1, PB85-158913,* U.S. Environmental Research Lab., Athens, GA, 1984.

Frind, E.O. and Matanga, G.B., The Dual Formulation of Flow for Contaminant Transport Modeling, 1, Review of Theory and Accuracy Aspects, *Water Resour. Res., Vol. 21, No. 2,* 159-169, February, 1985.

Frind, E.O., Matanga, G.B., and Cherry, J.A., The Dual Formulation of Flow for Contaminant Transport Modeling, 2, The Borden Aquifer, *Water Resour. Res., Vol. 21, No. 2,* 170-182, February, 1985.

Hintze, J. L., *Number Cruncher Statistical System, Version 4.21,* Dr. Jerry Hintze, Kaysville, Utah, 1986.

Istok, J.D., *Groundwater Flow and Solute Transport Modeling by the Finite Element Method,* Draft Manuscript.

LeGrand, H.E., System for Evaluating the Contamination Potential of Some Waste Sites, *Am. Water Works Assoc. Journal, Vol. 56, No. 8,* 959-974, 1964.

LeGrand, H.E., *A Standardized System for Evaluating Waste Disposal Sites,* National Water Well Assoc., Worthington, OH, 2nd ed., 1983.

Mardia, K.V., Kent, J.T., and Bibby, J.M., *Multivariate Analysis,* Academic Press, London, 1979.

Office of Solid Waste and Emergency Response, *Criteria for Identifying Areas of Vulnerable Hydrogeology Under the Resource Conservation and Recovery Act, Statutory Interpretive Guidance, Guidance Manual for Hazardous Waste Land Treatment, Storage and Disposal Facilities,* U.S. EPA, Wash., D.C., 1986.

Phillips, C.R., Nathwani, J.S., Mooij, H., Development of a Soil-Waste Interaction Matrix for Assessing Land Disposal of Industrial Wastes, *Water Research, Vol. 11,* 859-868, 1977.

Silka, L.R., and Swearingen, T.L., *A Manual for Evaluating Contamination Potential of Surface Impoundments, EPA-570/9-78-003,* U.S. EPA, Wash., D.C., 1978.

Rea and Istok, Groundwater Vulnerability to Contamination: A Literature Review, *Proceedings of the Irrigation and Drainage Specialty Conference,* American Society of Civil Engineers, Portland, Oregon, July 28-30, 1987.

Rea, A.H., Istok, J.D., and Nebert, D., Assessing Groundwater Vulnerability to Contamination, 1, Development of a digital map database, *Water Resour. Res.*, this issue.

Schmidt, R.R., *Groundwater Contamination Susceptibility in Wisconsin, Report 5, Wisconsin's Groundwater Management Plan,* Wisconsin Department of Natural Resources, 1987.

Wang, H.F. and Anderson, M.P., *Introduction to Groundwater Modeling, Finite Difference and Finite Element Methods,* W.H. Freeman and Company, New York, 1982.

CONCLUSIONS

It is clear from the above discussion that the data available from the maps used in this study are not adequate for detailed analysis. Instead of the generalized information from small-scale maps, much better information could be obtained from well logs. For regional studies, a sampling of well logs could be selected and travel times calculated for each well location. The estimated travel times could then be generalized for the study area from the sample of well locations used. This method would avoid the use of interpolated values for the surface elevations and eliminate the possibility of calculating negative depths to water or other such errors.

In addition to better data on the elevations of the surfaces, much better information on the spatial distribution of hydraulic conductivities of the soil, vadose zone, and aquifer materials is needed. Larger-scale soils maps and well logs might be good sources of this information. The time of measurement should also be included in the database for those quantities which may change significantly over time.

Although these improvements in the database are recommended for future studies of this nature, the usefulness of the current study is not negated. A great deal has been learned about the use of generalized maps for estimating the necessary data. Also, the general framework and linkage programs of the method for interfacing the digital map database with a groundwater flow model have been developed and validated. The method is workable and needs only better input data to achieve more accurate results. The necessary data are commonly available, but would require a significant digitizing effort to make it usable in the GIS.

Cluster analysis can be used to condense the data set to create a training data set against which multiple regression models can be calibrated with acceptable accuracy. The regression model then provides a simple and fast way to calculate travel times for a very large number of grid points. This appears to be a useful technique when dealing with very large data sets.

The method developed in this project shows great promise for assessing groundwater vulnerability to contamination for regional or site-specific studies. The method is tied to the physical processes of groundwater transport by theoretical relations which have been well accepted in the literature. The theoretical relations can be solved using numerical techniques which are also well known and well accepted. The travel times calculated in the method provide a simple and direct way to compare the relative vulnerability of the groundwater resources of different areas, or specific sites. The Geographic Information System is the key to making the vulnerability analysis practically feasible. The GIS provides a powerful means of managing large amounts of spatial information. Using the GIS, we are able to build data files for the finite element model using commonly available data and apply a simple model many times so as to represent the spatial variability present in the natural environment. Using the methods outlined in these two papers, the time-of-travel calculation may be used together with the GIS as a powerful and flexible tool for comparing the relative vulnerability of groundwater aquifers to contamination from surface sources.

BIBLIOGRAPHY

Aller,L., Bennett, T., Lehr, J. H., and Petty, R. J., *DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings, EPA/600/2-85/018,* U.S. Environmental Protection Agency, Ada, OK, 1985.

Carsel, R.F., Smith, C.N., Mulkey, J., Dean, J.D., and Jowise, P., *Users Manual for the Pesticide Root Zone Model (PRZM), Release 1, PB85-158913,* U.S. Environmental Research Lab., Athens, GA, 1984.

ESRI, *pcARC/INFO Starter Kit Users Guide,* Environmental Systems Research Institute, Inc., Redlands, California, 1987.

Frank, F.J. and Collins, C.A., *Groundwater in the Newberg Area, Northern Willamette Valley, Oregon: Oregon Water Resources Department Groundwater Report 27,* 1978.

Frank, F.J. and Johnson, N.A., *Ground-Water Data in the Corvallis-Albany Area, Central Willamette Valley, Oregon: Oregon State Engineer Ground Water Report 17,* 1972.

Frind, E.O. and Matanga, G.B., The Dual Formulation of Flow for Contaminant Transport Modeling, 1, Review of Theory and Accuracy Aspects, *Water Resour. Res., Vol. 21, No. 2,* 159-169, February, 1985.

Frind, E.O., Matanga, G.B., and Cherry, J.A., The Dual Formulation of Flow for Contaminant Transport Modeling, 2, The Borden Aquifer, *Water Resour. Res., Vol. 21, No. 2,* 170-182, February, 1985.

Golden Software, Inc., *SURFER Information Manual,* Golden, CO, 1987.

Gonthier, J.B., *Groundwater Resources of the Dallas-Monmouth Area, Polk, Benton, and Marion Counties, Oregon: Oregon Water Resources Ground Water Report 28,* 1983.

Hampton, E.R., *Records of Wells, Water Levels and Chemical Quality of Ground Water in the Molalla-Salem Slope Area, Northern Willamette Valley, Oregon: Oregon State Engineer Ground Water Report 2,* 1963.

Hession, W.C. and Shanholtz, V.O., A geographic information system for targeting nonpoint-source agricultural pollution, *Journal of Soil and Water Conservation, Vol. 43, No. 3,* 264-266, 1988.

Hintze, J. L., *Number Cruncher Statistical System, Version 4.21,* Dr. Jerry Hintze, Kaysville, Utah, 1986.

Istok, J.D., *Groundwater Flow and Solute Transport Modeling by the Finite Element Method,* Draft Manuscript.

LeGrand, H.E., *A Standardized System for Evaluating Waste Disposal Sites,* National Water Well Assoc., Worthington, OH, 2nd ed., 1983.

LeGrand, H.E., System for Evaluating the Contamination Potential of Some Waste Sites, *Am. Water Works Assoc. Journal, Vol. 56, No. 8,* 959-974, 1964.

Mardia, K.V., Kent, J.T., and Bibby, J.M., *Multivariate Analysis,* Academic Press, London, 1979.

McFarland, W.D., *A Description of Aquifer Units in Western Oregon,* U.S. Geological Survey Open-File Report 82-165, Portland, Oregon, 1983.

Nebert, D.D. and Anderson, D., Utilization of geographic information systems technology in the assessment of regional ground-water quality, *Irrigation Systems for the 21st Century,* American Society of Civil Engineers, New York, 370-377, 1987.

Office of Solid Waste and Emergency Response, *Criteria for Identifying Areas of Vulnerable Hydrogeology Under the Resource Conservation and Recovery Act, Statutory Interpretive Guidance, Guidance Manual for Hazardous Waste Land Treatment, Storage and Disposal Facilities,* U.S. EPA, Wash., D.C., 1986.

Phillips, C.R., Nathwani, J.S., Mooij, H., Development of a Soil-Waste Interaction Matrix for Assessing Land Disposal of Industrial Wastes, *Water Research, Vol. 11,* 859-868, 1977.

Price, D., and Johnson, N.A., *Selected Ground Water Data in the Eola-Amity Hills Area, Northern Willamette Valley, Oregon: Oregon State Engineer Ground Water Report 7,* 1965.

Rea and Istok, Groundwater Vulnerability to Contamination: A Literature Review, *Proceedings of the Irrigation and Drainage Specialty Conference,* American Society of Civil Engineers, Portland, Oregon, July 28-30, 1987.

Schmidt, R.R., *Groundwater Contamination Susceptibility in Wisconsin, Report 5, Wisconsin's Groundwater Management Plan,* Wisconsin Department of Natural Resources, 1987.

Silka, L.R., and Swearingen, T.L., *A Manual for Evaluating Contamination Potential of Surface Impoundments, EPA-570/9-78-003,* U.S. EPA, Wash., D.C., 1978.

U.S. Dept. of Agriculture, Soil Conservation Service, *General Soil Map, State of Oregon,* 1986.

Ventura, S.J., Chrisman, N.R., Conners, K., Gurda, R.F., and Martin, R.W., A land information system for erosion control planning, *Journal of Soil and Water Conservation, Vol. 43, No. 3,* 230-233, 1988.

Wang, H.F. and Anderson, M.P., *Introduction to Groundwater Modeling, Finite Difference and Finite Element Methods,* W.H. Freeman and Company, New York, 1982.