Center for Subsurface Modeling Support
Robert S. Kerr Environmental Research Laboratory
U.S. Environmental Protection Agency
P.O. Box 1198
Ada, Oklahoma 74820

USEPA Region III
841 Chestnut Building
Philadelphia, PA 19107

EPA

INTRODUCTION TO THE WELLHEAD ANALYTIC ELEMENT MODEL

June 5 - 7, 1995
Philadelphia, Pennsylvania

WhAEM

INTRODUCTION TO W*h*AEM: The Wellhead Analytic Element Model

USEPA Region III
841 Chestnut Building, Philadelphia, PA

Monday, June 5, 1995

1:00-2:15 Introduction
- Course objectives, approach
- Wellhead Protection overview (Slides)
- W*h*AEM=GAEP+CZAEM
  - Digital maps
  - Capture zone delineation

2:15-2:30 Break

2:30-4:30 Calculated Fixed Radius- Vincennes, Indiana

CZAEM Tutorial (Basics)
- Example 1, Well in uniform flow
- Ex. 2, Well near a river
- Ex. 3, Critical pumping of well near a river

4.30 Adjourn

Tuesday, June 6

8:30-9:45 W*h*AEM Tutorial
- Introduce Vincennes, Indiana wellfield as case study
- Map preparation
- GAEP operations
- digitizing demo

9:45-10:00 Break

10:00-11:30
- aquifer data input
- file operations
- element operations

11:30-1:00 lunch

1:00-2:15 CZAEM operations

tracing capture zones
refinement of initial conceptual model using the method of images

2:15-2:30 Break

2:30-4:30 Vincennes Summary (Slide show)

4:30 adjourn

Wednesday, June 7

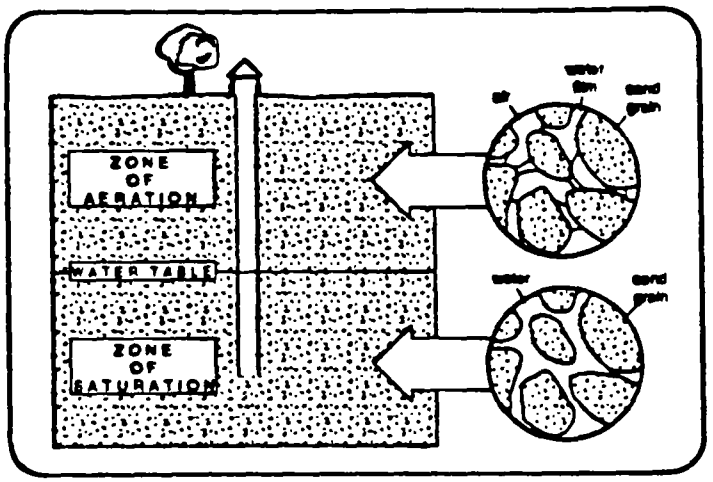
8:30-9:45 CZAEM Tutorial (advanced)
Ex. 4, Contaminant pump-out system
Ex. 5, Data manipulation and model refinement
Ex. 6, Data file and graphics control

9:45-10.00 Break

10.00-11:15 GAEP Features (advanced)
edititing
options
utilities

11:15 Adjourn

Slide # D-02



Saturated-Unsaturated Zone

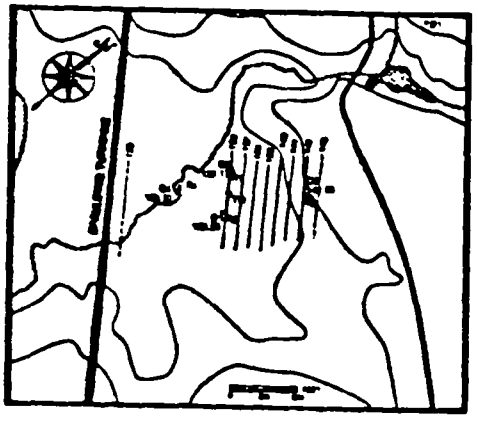
Source: Horsley & Witten, Inc., 1991

Slide # D-04

Water Table Map, Sand and Gravel Aquifer

Source: USGS, 1984

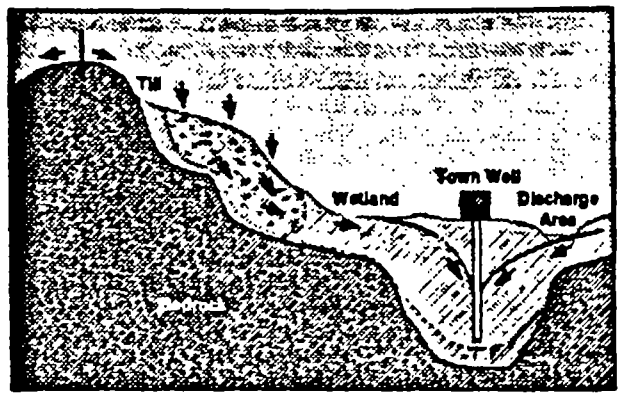
Slide # D-05



Water Table Map, Bedrock Aquifer, Dover, New Hampshire

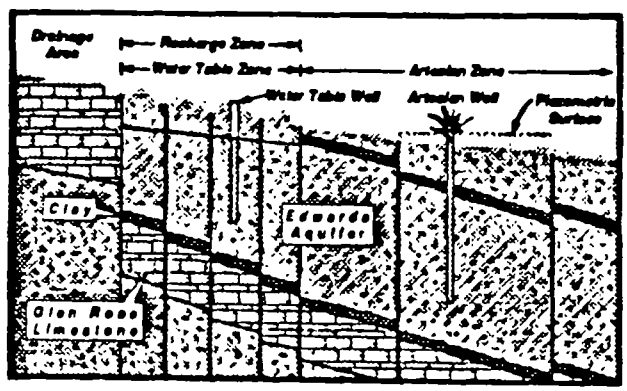
Source: Griswold and Vernon, in press

Slide #D-07



Buried Valley Aquifer

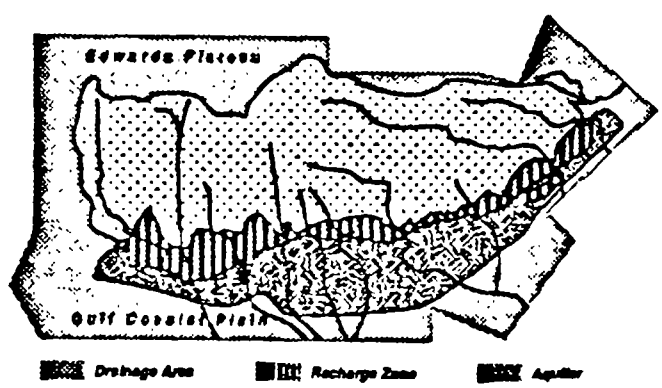
Slide # D-09



Hydrologic Cross-Section--
Edwards Aquifer

Source: Texas Water Commission, 1988

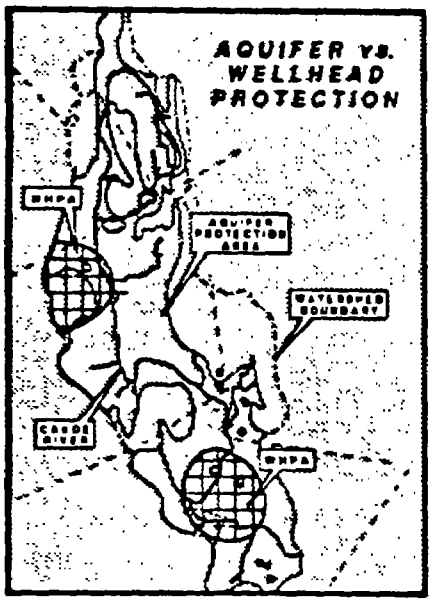
Slide # D-10



Plan View--
Edwards Aquifer

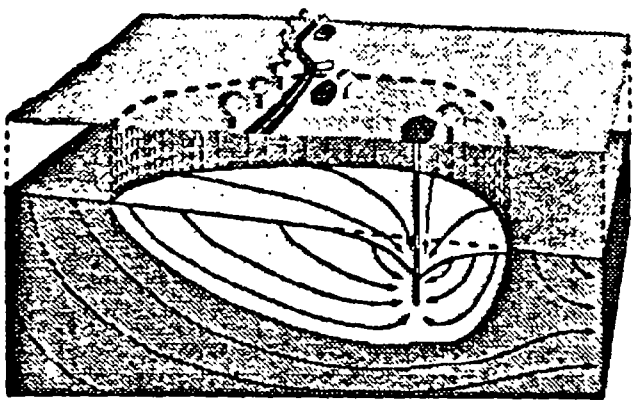
Source: Texas Water Commission, 1988

Slide # D-11



Aquifer vs. Wellhead Protection

Slide # D-12



Aquifer vs. WHPA-- Cross-Section

Slide # D-14

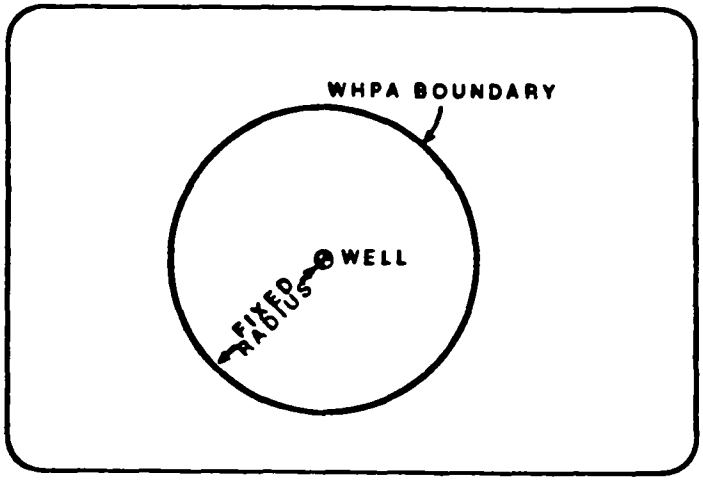
DELINEATION

METHODS OF DELINEATION

- Arbitrary Fixed Radius
- Calculated Fixed Radius
- Simplified Variable Shapes
- Analytical Methods
- Numerical Methods
- Hydrogeologic Mapping

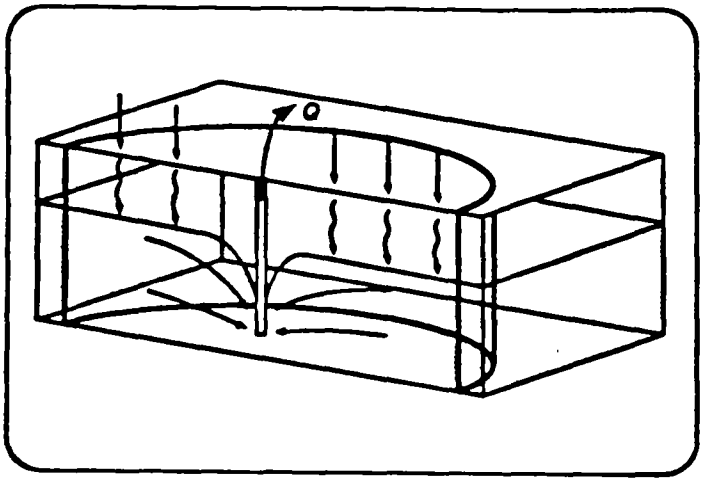
Methods of Delineation

Slide # D-15



WHPA Delineation Methods: Arbitrary (Discretionary) Fixed Radius

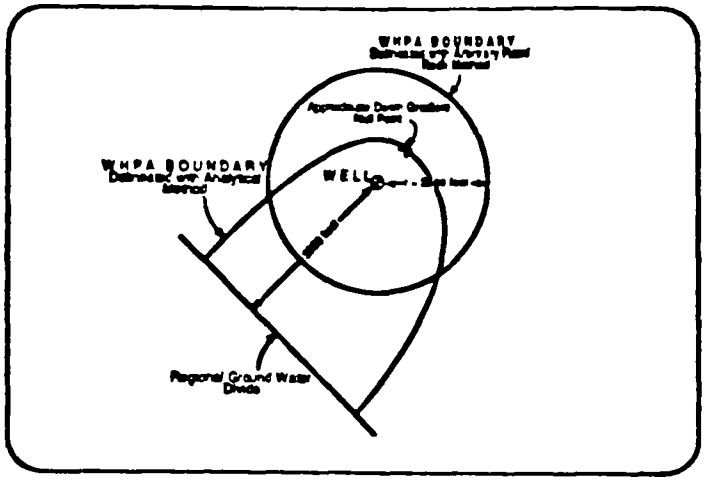
Slide # D-16



WHPA Delineation Methods: Calculated Fixed Radius

Source: Horsley & Witten, Inc., 1991

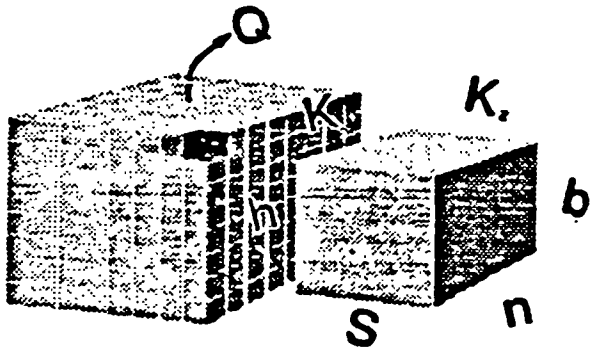
Slide # D-20



WHPA Delineation Methods: Combination

Slide # D-21

Typical Computer Modeling Grid



Numerical Modeling

Source: Horsley & Witten, Inc., 1991

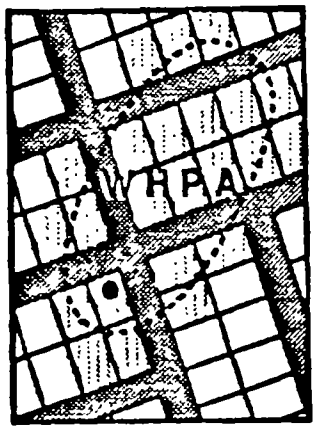
Slide # D-22

LINKING DELINEATION WITH MANAGEMENT

- Relationship of WHPA Boundaries to Parcel Boundaries
- Relationship of WHPA Boundaries to Jurisdictional Boundaries

Linking Delineation with Management

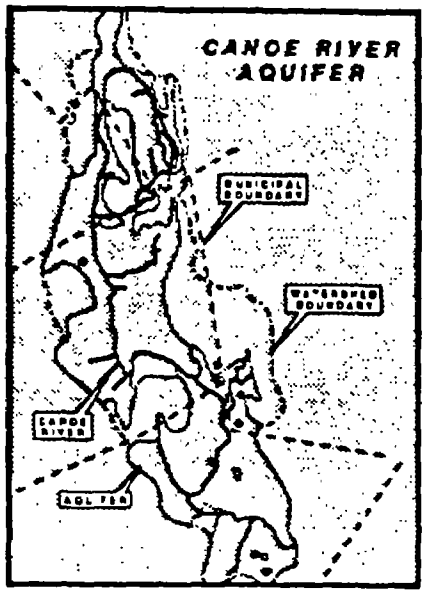
Slide # D-23



WHPA vs. Parcel Boundaries

Source: Horsley & Witten, Inc., 1991

Slide # D-24



Aquifer vs. Municipal Boundaries

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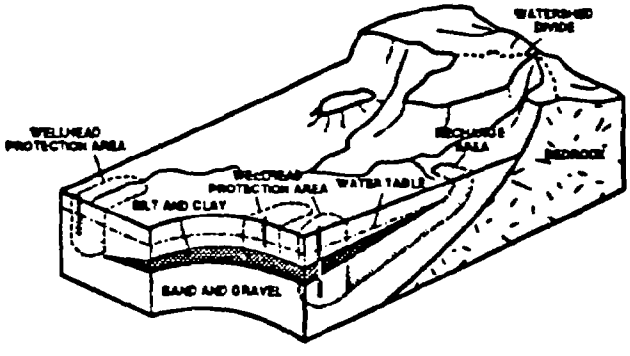

WHPAs in Arid and Semi-Arid Regions

Source: Horsley & Witten, Inc., 1991

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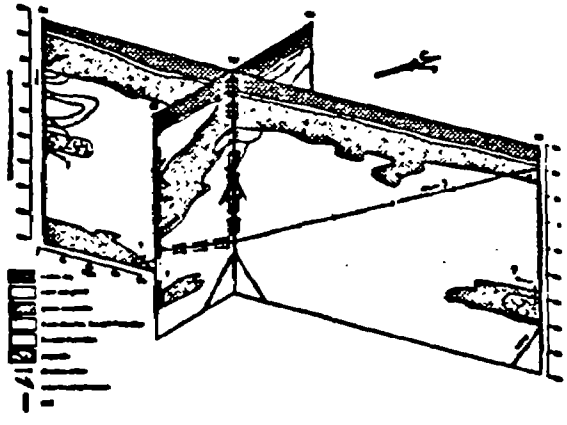


Fence Diagram, Bedrock Aquifer in Dover, New Hampshire

Source: Vernon and Griswold, in press

Slide # D-33

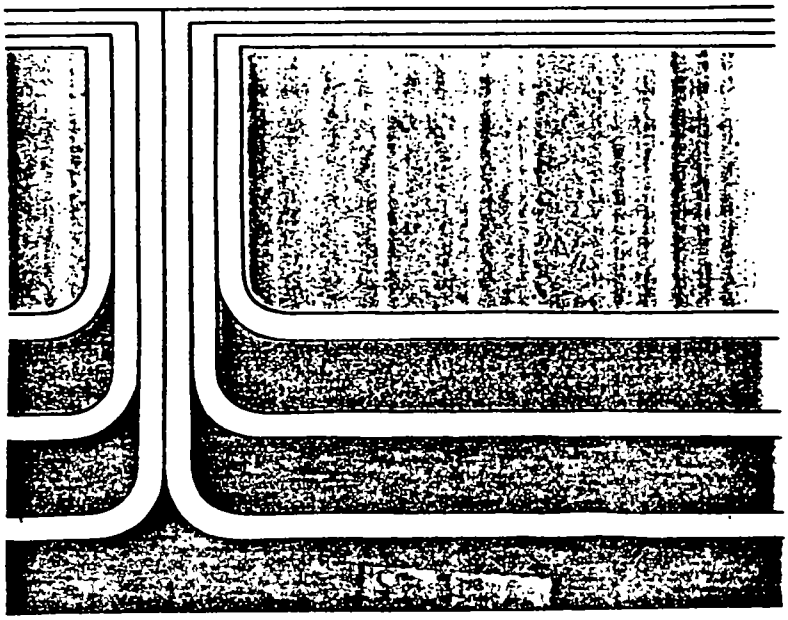
Dover, New Hampshire, Bedrock Aquifer WHPA

Source: Vernon and Griswold, in press

United States Environmental Protection Agency | Office Of Water (WH-550G) | LRAENEE | EPA 570/9-91-009 June 1991

EPA

Delineation Of Wellhead Protection Areas In Fractured Rocks



DELINEATION OF A REFINED WELLHEAD PROTECTION AREA FOR BEDROCK PUBLIC SUPPLY WELLS, CHARLESTOWN, RHODE ISLAND

by

Douglas L. Heath
Ground Water Management Section
United States Environmental Protection Agency - New England
Boston, Massachusetts

in cooperation with the
Rhode Island Department of Environmental Management
and the
Town of Charlestown, Rhode Island

April, 1995

U.S. Environmental Protection Agency

REQUEST FOR ASSISTANCE

RFA-95-1: FRACTURED CARBONATE ROCK GEOHYDROLOGY

The USEPA Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, is seeking assistance by cooperative agreement with non-profit organizations (minimum 5% cost sharing required) or by interagency agreement with Federal Agencies qualified to conduct research in the geohydrology of fractured carbonate rock aquifers. The focus of the research should be to summarize, demonstrate, and extend the understanding of the capture zone concept for pumping wells as applied to fractured carbonate rock aquifers. It is anticipated that a balance between computer modeling/scientific visualization and field observations will be demonstrated in a cost-effective characterization at a dedicated field site. Insights are expected as to the significance of preferred flow pathways and long-term storage zones within capture zones, with particular attention to aquifer remediation and protection. The project is anticipated as a three-year project, beginning no later than October 1, 1995, with the EPA share of the budget not to exceed $500,000 for the three-year period, pending availability of funds. Interested sources must request a solicitation package containing a scope of work, evaluation criteria, and additional instructions in writing before the response date of April 21, 1995. FAX requests may be directed to (405) 436-8597. Telephone requests for the solicitation package or technical information will not be accepted.

Contact Point:

Stephen Kovash
U.S. Environmental Protection Agency
Robert S. Kerr Environmental Research Laboratory
P.O. Box 1198
919 Kerr Research Drive
Ada, Oklahoma 74820

Historical Perspectives

We are pleased to present our readers with the opportunity to read a classical contribution to the historical literature of ground-water science. We try to highlight the contributions of the greatest names in our field. Readers are urged to recommend appropriate contributions to be included in this section of GROUND WATER.

Revisiting the Membrane Analog—A Conceptual and Communication Tool

by Forest Arnold, Roy F. Weston, Inc., 215 Union Boulevard, Suite 600, Lakewood, Colorado 80228

Abstract

Membrane analogs were used before the advent of computers as physical models of stresses on the water-table surface. Measurement of the membrane deflection can be related to equations representing pumping stresses. Although numerical models using computer techniques have replaced membrane analogs due to their greater accuracy and versatility, the membrane analog remains an inexpensive way to conceptualize the effect of different boundary conditions, nearby surface-water bodies and pumping stresses, and is useful in preparing input data sets for numerical modeling. The membrane analog is also a visual way to communicate modeling results and modeling scenarios to nonmodelers. A small office-sized membrane analog can be constructed for less than $25.00 and can be stored on a shelf or under a desk, for ready access.

Introduction

Membrane analogs were used before computers and numerical modeling to represent ground-water movements and stresses. They were set up in engineering labs as large frames covered with a sheet of latex and a mechanism for precisely lowering and measuring rods to represent well discharge or other stresses and discharge points (Todd, 1959; Strack, 1989; Hansen, 1952). These measurements were quantified and related to known equations about ground-water mechanics. Moire pattern techniques were developed using the membrane analog to represent the superposition of field solutions for two-dimensional problems (Freeze, 1971; De Josselin de Jong, 1961). Other physical models used before numerical modeling include: electrical analog models, Hele-Shaw models, and sand tank experiments (Todd, 1959).

These physical models are no longer used for quantitative experiments due to the advent of more powerful numerical techniques. However, the analog models continue to be used as conceptual and teaching tools. Several limitations to the older membrane analogs include the following: they were relatively expensive to set up and took up a lot of space, and the latex membranes tended to break down over time. The updated membrane analog described in this paper is smaller, portable, and made of more durable materials not available then. It can be constructed for less than $25.00.

In the conceptualization stage of modeling, it is important to be able to compare different scenarios quickly. Unless one is an extraordinary draftsman, it is difficult to sketch out three-dimensional representations of the water-table surface. The effects of complex boundaries and stresses can be easily represented in three dimensions on a membrane analog.

The membrane analog is not a quantitative tool, but it can be scaled to be reasonably accurate in a relative sense. The membrane grid surface spacing can be measured to represent distances of drawdown and capture zones. The addition of more or less pressure to points representing wells will reflect changes in drawdown and capture zones due to different pumping rates. For more complex sites, calculations with analytical packages such as Hydropal I and II (Watershed Research, Inc., 1988) or Walton's Welflo or Conmig (Walton, 1989) will suffice to properly scale the placement on the membrane surface.

In addition, the membrane analog is very useful for communicating model results, possible scenarios, and uncertainties to nonmodelers. People relate to visual images. The membrane analog makes modeling concepts visual and makes it easier for nonmodelers to understand. This allows other colleagues to ask questions and have input early in the modeling process because they understand the conceptual framework. This can save time later and makes the modeling process more approachable. People who would be put off by the computer and mathematical modeling can often relate better to the membrane analog than a complex printout.

Methods and Materials

Materials and Methods of Construction

1. Membrane surface—use white spandex instead of latex, which is available at fabric stores.
2. Mark the surface with a permanent marker using a ¼ to ½ inch grid.
3. Stretch the membrane on a needlepoint hoop 14 inches or bigger. The circular layout avoids corner effects and works better than a square or rectangular frame. The double hoop and locking mechanism make it possible to adjust membrane tension for different problems (see Figure 1).
4. Obtain two to three flexible architect's rulers, or cut a long one into pieces. They will be used to represent line sinks and area sinks for rivers and lakes, and for complex geologic boundaries, mounds, quarries, and mines.
5. Obtain 8-12 blocks of wood of different thicknesses to support rulers for mounds, area sinks, and other features.
6. Obtain eightpenny or larger nails to represent wells. Use wood dowels or strips with holes in the wood to represent spatial placement of wells. The holes in the dowels should provide enough room to hold the nails in place but allow them to slide up and down to reflect different pumping rates.

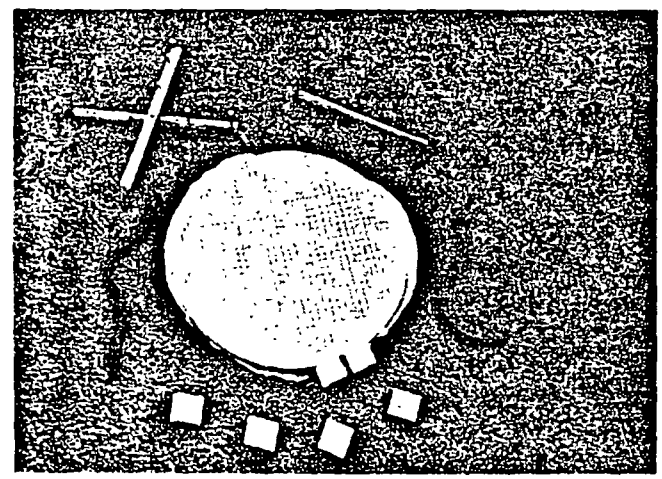


Fig. 1. The membrane analog and equipment for representing wells and water bodies.

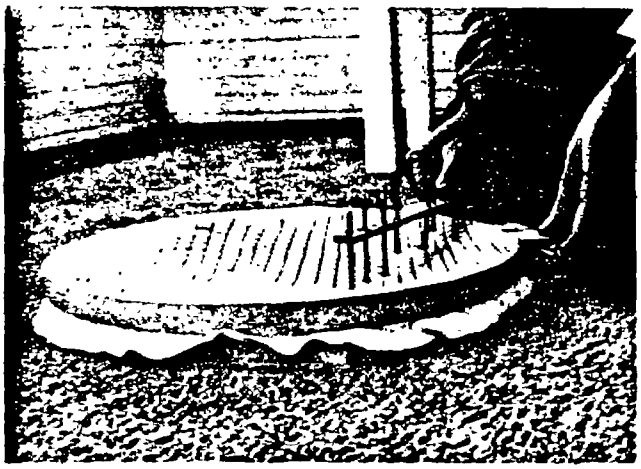


Fig. 2. A simulation of simultaneous injection and pumping wells.

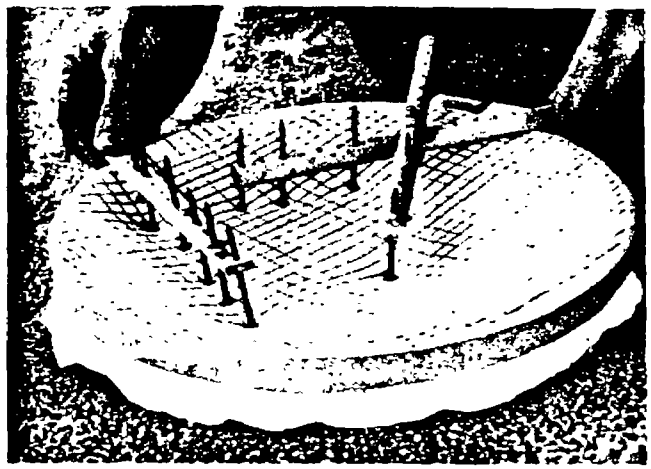


Fig. 3. A simulation of a complex well field.

Methods of Representing Hydrogeologic Features

To represent a single pumping or injection well, a pen, pencil eraser, or nail can be applied to depress the membrane surface. For pumping wells, the top of the membrane is depressed, while for injection wells the underside of the membrane is depressed (see Figure 2). The strength of the pumping can be adjusted by the depth of depression. For multiple wells, nails in one or more dowels can be used. The strength of the well can be adjusted by pulling in or out on the nails. For complex well patterns, use two dowels with a pivot in the middle and multiple holes (see Figure 3).

Line sinks to represent streams and rivers can be represented by shaping the flexible arichitect's rule into the appropriate stream shape and placing it on the surface of the membrane. Fishing weights can be placed on the rule to further depress the line sink or to hold it in place. The effects of a losing stream can be represented by placing the ruler on wood blocks to support it underneath the membrane surface, thereby reflecting a mound (see Figure 4).

Area sinks to represent lakes or wetlands can be represented by shaping the flexible architect's ruler into the shape of the lake and placing it on the surface of the membrane. An influent lake or landfill mound can be represented by placing the ruler on wood blocks to support it underneath the membrane surface, thereby reflecting the mound shape on the membrane surface (see Figure 4).

A major river with a significant gorge and bluffs nearby can be represented by a ruler underneath the membrane supported by blocks to represent the bluffs and a ruler placed nearby on the membrane to represent the river. Other major topographic features such as quarries, open pit mines, etc. can be represented with combinations of the flexible rulers on top of and underneath the membrane.

For aquifers with tight boundaries such as glacial meltwater channels or alluvial aquifers, the shape can be defined with rulers and blocks placed underneath the membrane. The stream is then placed on top, and pumping stresses can be added as previously described. This makes it possible to see elongated cones of depressions and the effects of geologic boundaries on pumping.

For more complex sites with combinations of the different features previously described, it is best to lay out the boundary features near the edges and add pumping stresses in the center to avoid distortions near the frame. The location of an existing or proposed waste site can be marked with a light thin block of wood, or a piece of masking tape placed on the membrane. For problems with unusually high or low hydraulic conductivity, it may be necessary to tighten or loosen the tension on the membrane. This is easily accomplished with the needlepoint hoop—simply loosen the locking wing nut on the outer of the two hoops, adjust the tightness of the membrane, and then tighten to lock the membrane in place.

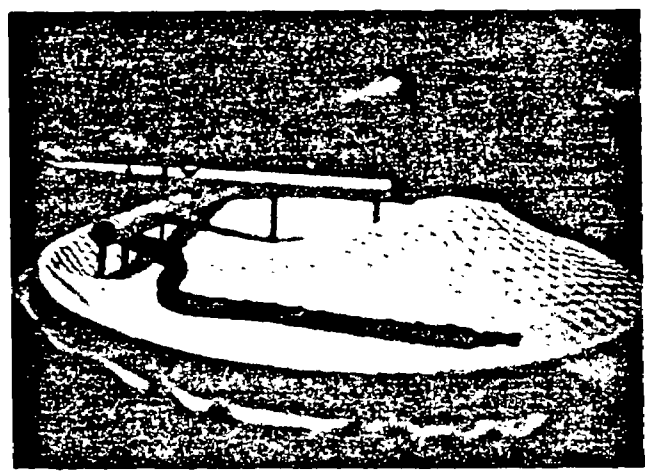


Fig. 4. A simulation of a landfill mound, nearby stream, and multiple pumping wells.

Summary

Use of the membrane analog can enhance the conceptual phase of modeling in trying out initial scenarios of the modeling effort such as cases of multiple stresses near waste sources in complex terrain with nearby surface-water bodies. This type of conceptualization is especially important in wellhead protection, capture well design, and risk assessment.

The membrane analog is also useful in communicating modeling concepts to other colleagues. It makes ground-water mechanics visual, helping others understand your modeling results. By laying out a conceptual model on the membrane analog early in the process, it is possible to match the overall goals of the modeling with the conceptual design of the modeler.

Over time, attention to communicating the conceptual model of different sites will help colleagues to become more comfortable with complex hydrologic concepts. They will be more supportive of modeling efforts in the future. The membrane analog takes the modeling out of the "black box" realm

and puts it into perspective as a useful tool with some limitations.

By using modern materials, some of the drawbacks of the old membrane analogs have been avoided. The revised membrane analog is inexpensive, portable, and compact. It is easy to set up and take down for formal or informal meetings. It does not require preprocessors, postprocessing software, complex configuration files, or supporting hardware like special printers or digitizers. There is no fee for hardware updates. Just make new pieces from inexpensive materials as the need arises.

We are fortunate to be in an era with computerized numerical methods that allow us to go beyond the limitations of simple physical models such as membrane and electrical analogs. The need to carefully conceptualize a site for numerical modeling and the ability to communicate modeling results is still with us, though. The membrane analog, although an older tool, can still be a powerful tool to aid in the newer, modern process of numerical modeling.

Acknowledgments

Special thanks to Otto Strack at the University of Minnesota for explaining the use of membrane analogs initially and for providing references and guidance during development. Also, thanks to Bruce Olson of the Minnesota Department of Health for suggestions which led to refining the representation of complex wells. Thanks to Bob MacNeil of Geraghty and Miller, Inc., Minneapolis, for helpful comments and enthusiasm throughout.

References Cited

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Forest D. Arnold is a Hydrogeologist with Roy F. Weston, Inc. in Lakewood, Colorado. He has 13 years of experience working on surface- and ground-water quality problems. His interests are in the application of ground-water flow and transport models for remediation and exposure assessments of hazardous waste sites.

DENSE, IMMISCIBLE PHASE LIQUID CONTAMINANTS (DNAPLs) IN POROUS AND FRACTURED MEDIA

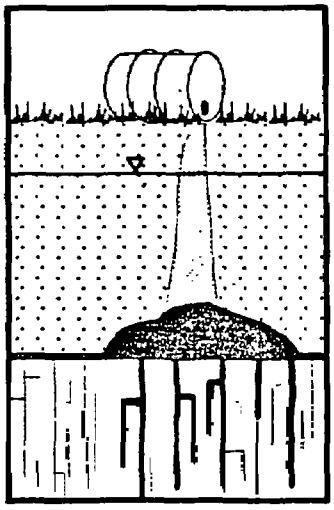
a short course sponsored by:

Waterloo Centre for Groundwater Research

An Ontario Centre of Excellence funded by the Premier's Council on Economic Renewal

October 7 – 10, 1991

Kitchener, Ontario, Canada



This 4 day course is designed for groundwater and environmental professionals who wish to learn about the theory and practice of investigating and remediating groundwater contaminated by DNAPLs such as solvents (TCE), creosotes and PCB oils. The topics addressed will include the physical behaviour of immiscible fluids in the subsurface, the behaviour of contaminant vapours in the unsaturated zone, and the nature of contaminant plumes created below the watertable by the slow dissolution of fluid residuals. Recent research in geophysical methods and remedial technologies will also be discussed. This course is independent of the dissolved organics course offered by the Centre.

To register, or request more information, contact:
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University of Waterloo
Waterloo, Ontario, Canada
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Fax: (519) 888 – 4654

Regional - Shallow - Dupuit - Forchheimer
Ground water Flow

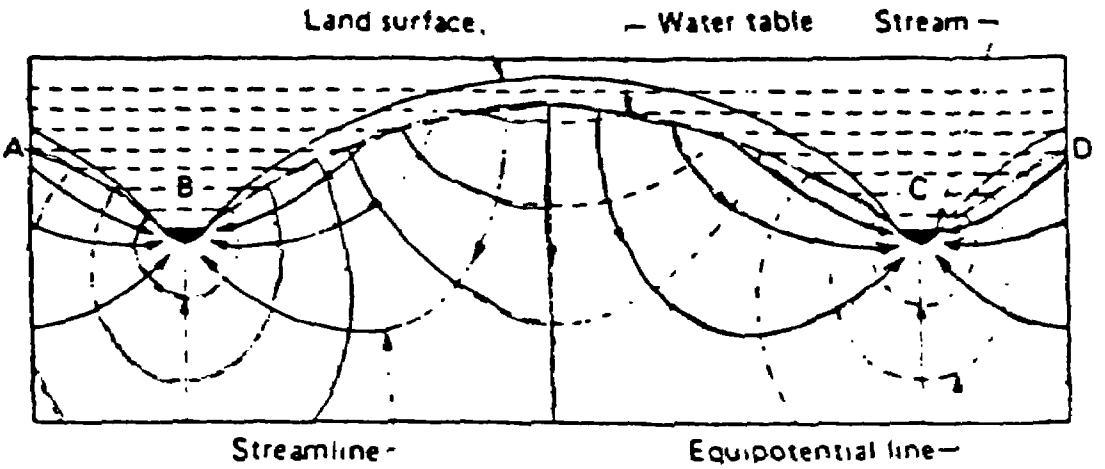
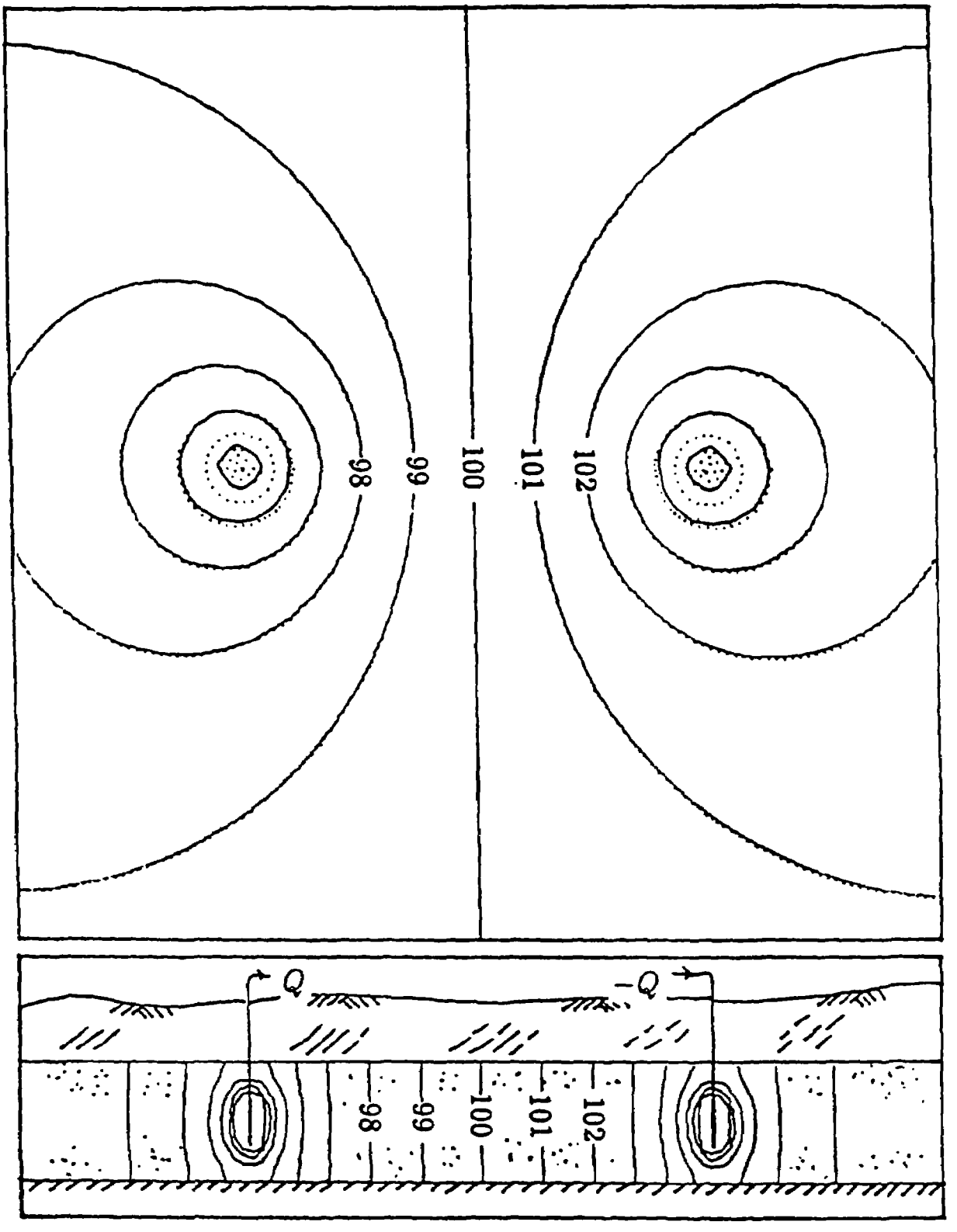


Figure 3.—Flow pattern in uniformly permeable material with constant areal recharge and discharge to symmetrically placed streams. (Modified from Hubbert, 1940.)



Partially Penetrating Well (3D)

DRAFT

United States
Environmental Protection
Agency

Robert S. Kerr Environmental
Research Laboratory
Ada OK 74820

Research and Development

EPA/600/SR-94/210 December 1994

EPA

Project Summary

Demonstration of the Analytic Element Method for Wellhead Protection

Hendrik M. Haitjema, Otto D.L. Strack, and Stephen R. Kraemer

Abstract

A new computer program has been developed to determine time-of-travel capture zones in relatively simple geohydrological settings. The WhAEM package contains an analytic element model that uses superposition of (many) closed form analytical solutions to generate a ground-water flow solution. WhAEM consists of two executables: the preprocessor GAEP, and the flow model CZAEM. WhAEM differs from existing analytical models in that it can handle fairly realistic boundary conditions such as streams, lakes, and aquifer recharge due to precipitation.

The preprocessor GAEP is designed to simplify the procedures for getting data into a ground-water model; specifically it facilitates the interactive process of ground-water flow modeling that precedes capture zone delineation. The flow model CZAEM is equipped with a novel algorithm to accurately define capture zone boundaries by first determining all stagnation points and dividing streamlines in the flow domain. No models currently in use for wellhead protection contain such an algorithm.

This Project Summary was developed by USEPA's Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, to announce key findings of the Research Project that is fully documented in separate reports and supporting software (See Project Report ordering information at the back).

Introduction

The delineation of capture zones requires precise determination of streamlines. In most numerical methods, such accurate determin-ation is difficult because the velocities are computed on the basis of values of piezometric heads that are known only at the nodes of a mesh. This deficiency stimulated the development of a number of computer models which implement elementary analytic solutions for ground-water flow problems. The analytic are capable of producing more or less approximate shapes of the boundaries of capture zones for any given time; e.g., the USEPA's original wellhead protection model WHPA. However, even when the velocity components are known precisely, accurate determination of the boundaries of capture zones still requires that both stagnation points and dividing streamlines are known.

The delineation of capture zones in complex settings is currently done either by the use of discrete numerical models or analytic element models. The discrete numerical models, such as MODFLOW/MODPATH of the US Geological Survey, and analytic element models, such as Strack's MLAEM, require detailed knowledge of the setting and advanced modeling expertise to run; and they do not currently have advanced algorithms for delineation of capture zones.

The Wellhead Analytic Element Model (WhAEM) falls between the two aforementioned technologies. It does contain an advanced algorithm for determining capture zones for any well at any time based on precise knowledge of the locations of all stagnation points and dividing streamlines. It has features that make the inclusion of open or closed, head-specified boundaries possible (for example to model streams), but lacks the power of

advanced discrete numerical or analytic element models. The authors believe that the newly developed model will serve ground-water professionals who wish to determine capture zones in relatively simple geohydrological settings.

WhAEM consists of two executables: the preprocessor GAEP and the flow model CZAEM (see Figure 1). In order to facilitate data entry in the computer program CZAEM (Capture Zone Analytic Element Model), a separate computer program was developed called GAEP, (Geographic Analytic Element Preprocessor). This program makes it possible for most users not familiar with the input structure of analytic element models to concentrate on modeling aspects, rather than on the intricacies of preparing input data files.

WhAEM was developed under a cooperative agreement between EPA and Indiana University and the University of Minnesota.

The Analytic Element Method

The analytic element method was developed at the end of the seventies by Otto Strack at the University of Minnesota. For a detailed description of the method, the reader is referred to Groundwater Mechanics, O.D.L. Strack, 1989, Prentice Hall, while a brief review follows.

This new method avoids the discretization of a ground-water flow domain by grids or element networks. Instead, only the boundaries of the surface water and aquifer features in the domain are discretized and entered into the model. Each of these boundary segments are represented by closed form analytic solutions — the analytic elements. The comprehensive solution to a complex, regional ground-water flow problem is obtained by superposition of all analytic elements in the model, from a few hundred to thousands.

Traditionally, modeling ground-water flow by use of analytic functions was considered to be limited to homogeneous aquifers of constant transmissivity. However, by formulating the ground-water flow problem in terms of appropriately chosen discharge potentials rather than piezometric heads, the analytic element method becomes applicable to both confined and unconfined flow conditions as well as to heterogeneous aquifers.

The analytic elements are chosen to best represent certain hydrologic features. For instance, stream sections are represented by line-sinks; lakes or wetlands may be represented by areal sink distributions. Streams and lakes that are not fully connected to the aquifer are modeled by area sinks with resistance to flow between surface water and the aquifer. Discontinuities in aquifer thickness or hydraulic conductivity are modeled by use of line doublets (double layers). Other analytic elements may be used for special features, such as drains, fractures, and slurry walls.

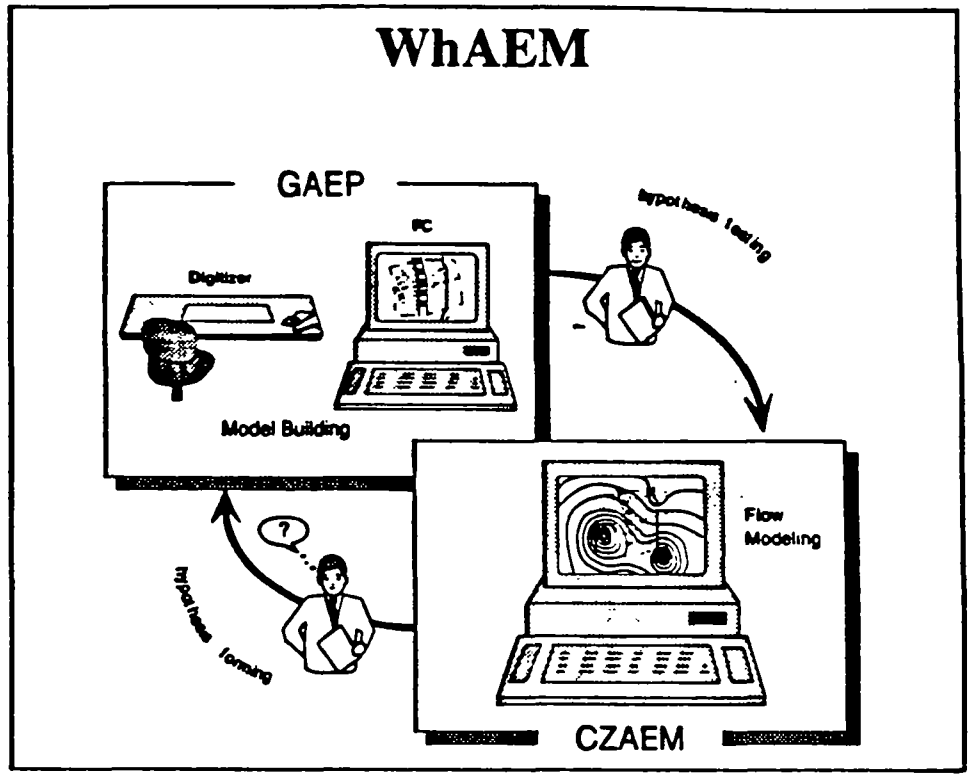


Figure 1. The modeling process using WhAEM.

The analytic element method differs fundamentally from most classical numerical models, for instance:

1. The solution is analytical; no interpolation is required to compute heads or velocities at any point in the domain. This makes the method insensitive to scale, allowing contour plots and streamlines to be produced in areas varying in size from several square feet to hundreds of square miles.

2. Since the velocity field is calculated analytically, inaccuracies in capture zone boundaries and isochrones of travel times are due solely to approximations made in the conceptual model and its implementation in the program; they are not the consequence of a model grid resolution and the associated numerical (approximate) differentiation process.

3. The aquifer is unbounded in the horizontal plane; there are no artificial model boundaries that may influence the solution.

WhAEM

Time-of-travel capture zone delineation is conducted by ground-water flow modeling. Modeling in this context is an interactive process of data acquisition, data analysis, and running a computer model. Initial modeling results prompt changes in the conceptual model, which in turn will lead to new modeling results. In the absence of definite data, hypothesis testing and sensitivity analysis will be important aspects of the modeling process. As a result, the modeler will usually make frequent changes to the input data file (an ASCII file of program instructions) during the modeling process.

WhAEM was designed to facilitate this process. GAEP greatly improves the process of data entry, especially when used

in combination with USGS topographic maps and a digitizer (optional). The GAEP generated electronic background map becomes the template for "on-screen" design of the ground-water flow model. GAEP communicates with the flow solver CZAEM through an ASCII file that contains the command script for delineating capture zones.

Program CZAEM

CZAEM is a single layer model for simulating steady flow in homogeneous aquifers. The mathematical framework underlying the model is based on the Dupuit-Forchheimer assumption, where the vertical resistance to flow is negligible, such as for shallow aquifer flow. The implementation of the analytic element method in CZAEM is elementary, supporting only a few basic analytic elements. These elements can be used to simulate river boundaries, streams, lakes, wells, uniform flow, and uniform infiltration over a circular area.

Line-sinks are used to model river boundaries, streams, and lakes. Line-sinks are mathematical functions that simulate a constant rate of extraction along a line. The sink densities (strengths) of the line-sinks in the model are determined such that the heads at the center of the line-sinks are equal to specified values (usually chosen to equal the water levels in the streams or lakes). The accuracy with which the ground-water inflow (or outflow) along a stream can be modeled improves with a finer subdivision of the stream in line-sink segments.

The well function (Thiem equation) is used to model wells with given discharge (pumping rate). Unlike numerical models, the piezometric head distribution and the velocity field near a well remain accurate, since there is no discretization of the aquifer by a grid or element network.

A special function, the "pond" function, is used to model areal recharge due to precipitation. Since CZAEM models steady state flow, this recharge rate is a yearly average. The "pond" function is a circular element with an areal "source" density equal to the recharge rate. The circular pond overlays the domain of interest, the well field and surrounding surface waters, to simulate the desired aquifer recharge.

The uniform flow function may be used to replace the combined effects of areal recharge and surface water boundaries, similar to the WHPA program. Since WhAEM allows the explicit representation of these boundary conditions, the uniform flow approximation is less often used in applications to field problems.

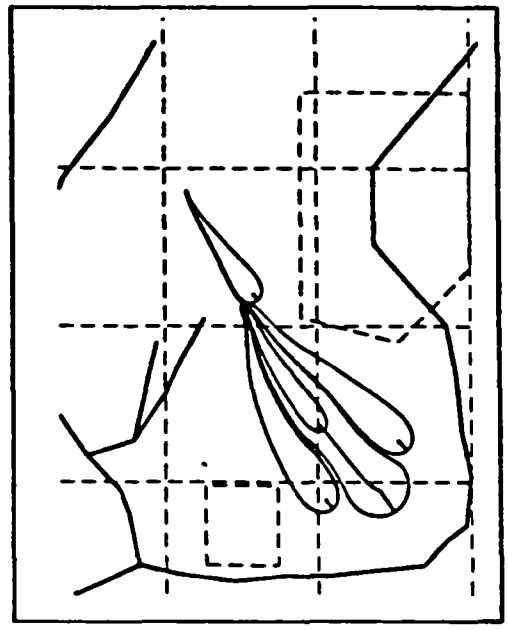


Figure 2. Capture zone envelopes for five wells in a regional setting defined by streams and areal recharge.

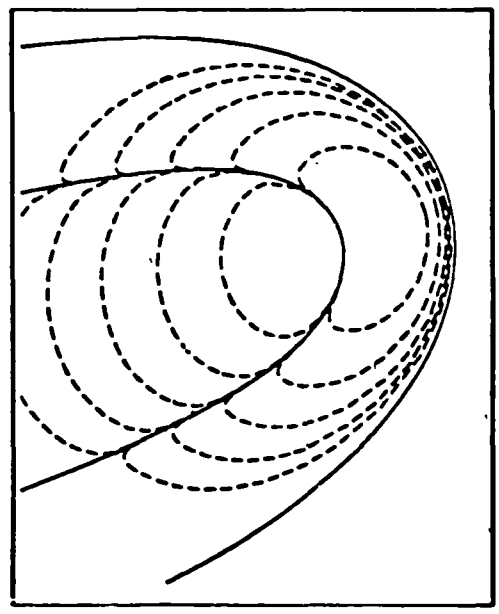


Figure 3. Travel time isochrones for two wells in a uniform flow field.

The computer program CZAEM is an elementary analytic element model with the capability to generate capture zones of wells. The program has the following modules:

1. AQUIFER, for the input of aquifer data.
2. GIVEN, for the input of uniform flow and areal recharge.
3. REFERENCE, for the input of the head at one point in the aquifer.
4. WELL, for the input and implementation of wells.
5. LINE-SINK, for the input and implementation of line-sinks.
6. GRID, for the generation of a grid of piezometric heads to be contoured.
7. PLOT, for piezometric contour plotting.
8. TRACE, for streamline tracing.
9. CAPZONE, for the generation of time-of-travel capture zones.
10. CURSOR, for cursor controlled interaction with elements.
11. CHECK, for monitoring the values of parameters.
12. IO, for binary write and save of solutions.
13. PSET, for sending graphics to output devices.

Capzone Module

The capzone module has been designed to define the capture zone boundaries as well as the travel time isochrones inside these capture zone boundaries, called timezones for arbitrary arrangements of wells and line-sinks (stream boundaries). Rather than merely tracing a number of streamlines from the well, the capzone module logic first determines all stagnation points in the flow domain, determines whether they are connected to the wells by streamlines, and uses them as the basis for defining the capture zone boundaries. Under multiple well scenarios, one well may have several different capture zones, termed subzones, which have their own travel time isochrones.

Figure 2 illustrates capture zones for five different wells surrounded by two stream branches and a tributary (solid lines). The dashed lines are background map features for orientation purposes. The capture zones are pear shaped and of finite extent: the wells receive all their water from areal recharge.

In Figure 3, travel time isochrones are presented for two wells in a uniform flow field. Notice that the isochrones wrap all the way around the well; between the well and

its stagnation point, all travel times between zero and infinity occur. Also notice that the capture zone of the right-hand well wraps around the capture zone of the other well, causing a discontinuity in the residence times across the latter capture zone envelope.

Figure 4 shows capture subzones for a well near a river. The well is receiving 80% of its discharge from the far-field and 20% from the river.

The module CAPZONE has been written specifically for this project. The source code (FORTRAN) of this module is available from USEPA and contains documentation to facilitate its inclusion in other groundwater models.

Preprocessor GAEP

The absence of a grid or element network in analytic element models makes it unnecessary to translate hydrography data (stream locations and associated stream levels) into cell specific data, which is the main function of preprocessors for numerical models. In contrast, the stream levels and geometry are entered into the analytic element model, through simple commands which are in an ASCII file. These commands can be input directly from the keyboard (command line mode) or read in from an ASCII file (batch mode) (see Figure 5). The line-sinks representing streams and lakes are represented in the file by their end coordinates and a specified head at the center (stream level). The traditional procedure for creating such an input data file is to sketch the line-sink layout on a map, write the stream elevations near these line-sinks, and use a digitizer to produce the coordinate pairs listed in Figure 5. The syntax of the various commands in Figure 5 must be consistent with the requirements of CZAEM, or one or more errors occur when the file is read by CZAEM. Any change in the input data, as part of the interactive modeling procedure requires editing of the input file, whereby it is often necessary to revisit the topographical map and digitize new line-sinks.

To facilitate this process, the preprocessor GAEP separates the digitizing activities from the creation of analytic elements (e.g. line-sinks) to be included in the input data file for CZAEM. GAEP, therefore, has two functions:

1. Creation of a digital map of all streams, lakes, wetlands, well locations, and background map information (roads, city boundaries, outlines of surface geological features, etc.). The surface water features have associated with them the water levels as reported on the topographical map (intersections of elevation contours with the stream beds).

2. Creation of an input data file for CZAEM with all aquifer data and all analytic elements (line-sinks and wells) needed for the model.

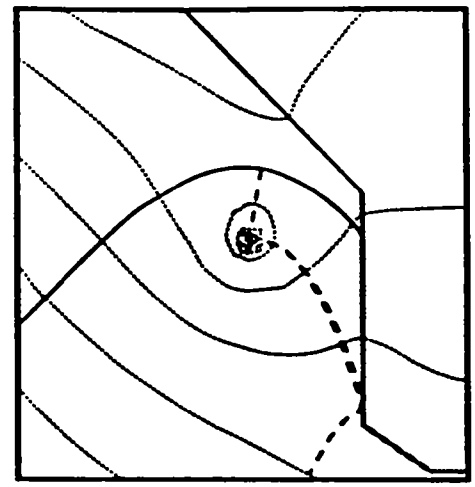


Figure 4. Subzones for a well near a river. The dotted lines represent hydraulic head contours.

```
AQUIFER
BOTTOM 330
THICKNESS 100
PERMEABILITY 350
POROSITY 0.20
RETURN
AQUIFER
REFERENCE    0   656160   410
RETURN
*RainElement
SINKDISK
DISCHARGE
   21983   -6193   43881   -24755   -0.00411
RETURN
*TabletItemID:        wabash east
LINESINK
HEAD
   -13409   -18389   -12778   -10574   395.2  [we1]
   -12778   -10574    -8046    -5825   396.1  [we2]
    -8046    -5825    -5927    -1257   396.8  [we3]
    -5927    -1257    -2322      367   397.2  [we4]
```

Figure 5. Part of a CZAEM input data file.

The first activity, creation of the digital map, is a routine procedure that does not require any modeling expertise or hydrological knowledge. The digital map is saved on disk for future use by the modeler. A digital map, as displayed on screen by GAEP, is reproduced in Figure 6. By pointing at a feature with the mouse, its name is displayed for easy identification.

The modeler will use GAEP and a digital map previously saved on disk to create a CZAEM input data file. To represent a stream by line-sinks, the modeler merely points at the stream with the mouse and selects it by "clicking" the mouse button. By moving the pointer over the stream and "clicking" on intended line-sink end points, a string of line-sinks is created with heads computed at their centers using the stream elevations stored with the digital map. In Figure 7, a string of line-sinks is illustrated. The numbers printed near the line-sinks represent the average stream elevations (heads at the center of the line-sinks). GAEP will also prompt for aquifer data; and when instructed to create the CZAEM input data file, write an ASCII file to disk that can be read directly by CZAEM. In fact, the GAEP generated input data file will introduce the data, solve the problem, and create a grid with piezometric heads. The modeler then enters the TRACE and CAPZONE modules in CZAEM to generate capture zone boundaries.

Conclusions and Recommendations

The deliverable of this project consists of an analytic element modeling package for simulating steady flow in homogeneous aquifers, with the primary objective to delineate capture zones in settings with streams, rivers, lakes, infiltration and wells. New algorithms have been developed for the accurate delineation of capture zone boundaries. These algorithms are implemented in the computer code CZAEM. The algorithms make accurate delineation of capture zone boundaries possible. A preprocessor program, GAEP, has been developed to facilitate the entry of field data into CZAEM. GAEP simplifies the process of modeling considerably. Specifically, GAEP separates the time consuming (but routine) task of digitizing hydrography data from the creation of conceptual models and subsequent analytic element input data files. With GAEP, the modeler is free to concentrate on interpretation of modeling results rather than the details of data modification and entry into CZAEM.

The WhAEM package is documented in various ways. The primary documentation is contained in a program manual, which includes installation instructions, program descriptions and a tutorial for the integrated use of GAEP and CZAEM. Reference manuals for both GAEP and CZAEM are

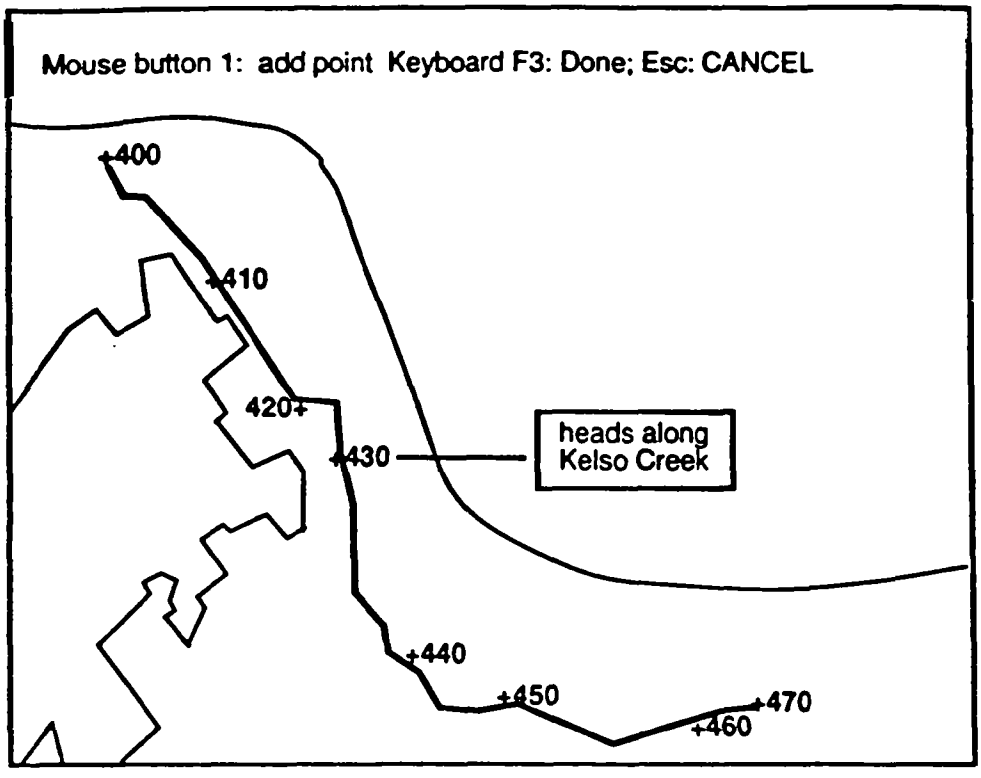


Figure 6: Kelso Creek with elevation marks where contours cross the stream.

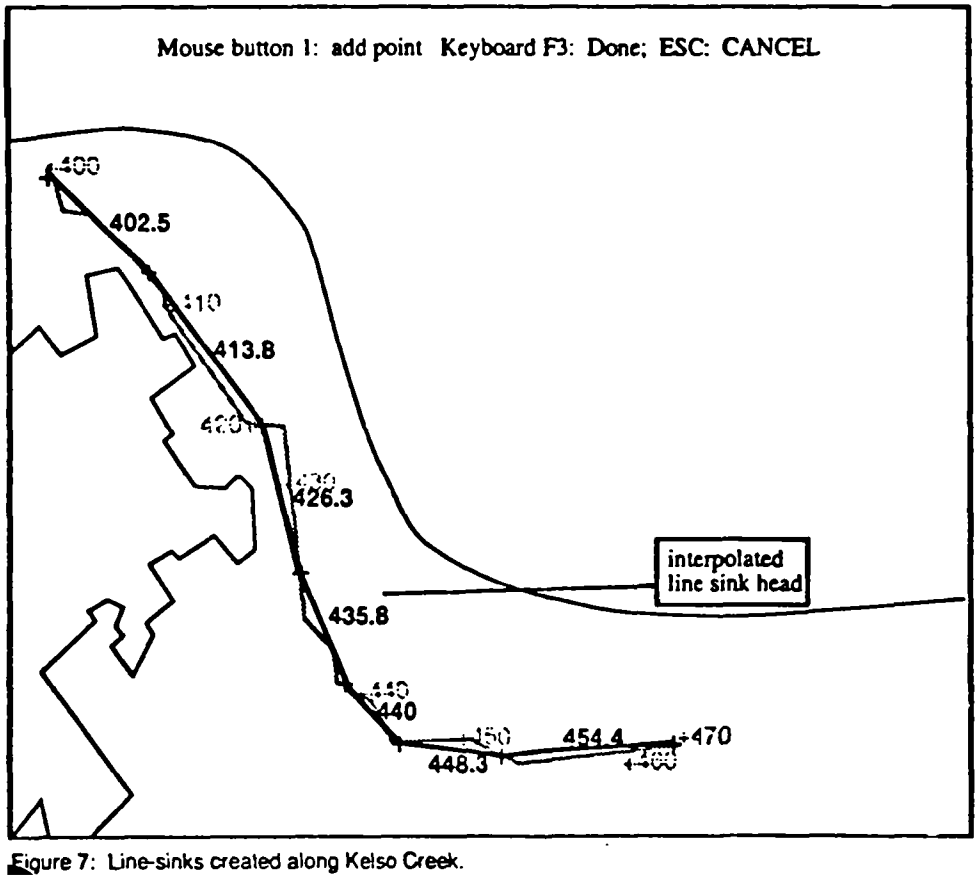


Figure 7: Line-sinks created along Kelso Creek.

provided in the WhAEM manual. A tutorial for stand-alone use of the program CZAEM is available as a separate document. Finally, both GAEP and CZAEM codes support on-line help.

The WhAEM package should only be used by ground-water hydrologists qualified to address wellhead protection delineation problems. WhAEM is designed to assist hydrologists in learning as much as possible about the geohydrological problems they face. Model predictions must always be interpreted critically, with the simplifying assumptions in mind. For complex geohydrological settings, it may be necessary to apply a more powerful model than WhAEM, requiring more experience from the ground-water flow modeler.

Hardware requirements:
- 386 or 486 PC
- 2.5 MB RAM
- 2 MB hard disk space
- MS compatible mouse
- digitizer (optional)
- printer (optional)

Software requirements:
- MS DOS version 5.0 or higher
- Windows 3.1 (optional)

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Stephen R. Kraemer, Ph.D., is a Research Hydrologist for the USEPA, Robert S. Kerr Environmental Research Laboratory, Ada, OK 74820. Dr. Kraemer served as the USEPA Project Officer for the cooperative agreement.

The complete reports are:

CZAEM User's Guide: Modeling Capture Zones of Ground Water Wells Using the Analytic Element Method, EPA/600/R-94/174.

WhAEM: Program Documentation for the Wellhead Analytic Element Model, EPA/600/R-94/210.

For a copy of the reports and associated software, please send a letter of request and one formatted 3.5 inch high density PC diskette (please specify whether DOS or Windows) to:

Center for Subsurface Modeling Support (CSMoS)
Robert S. Kerr Environmental Research Laboratory
P.O. Box 1198
Ada, OK 74821

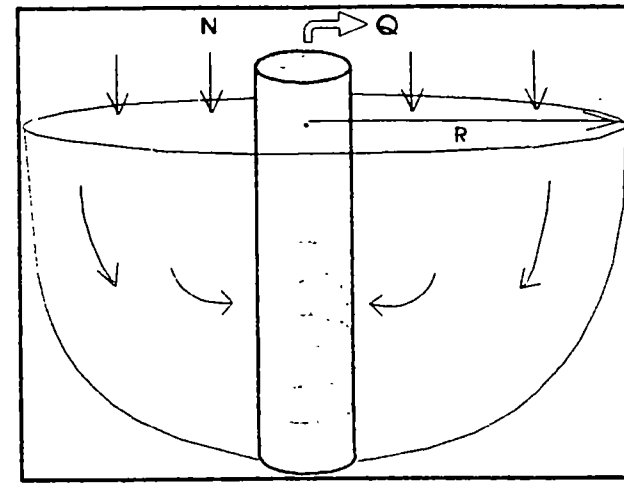
The reports are also available from:

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

CALCULATED FIXED RADIUS

- RECHARGE METHOD

$$R = \sqrt{\frac{Q}{\pi N}}$$



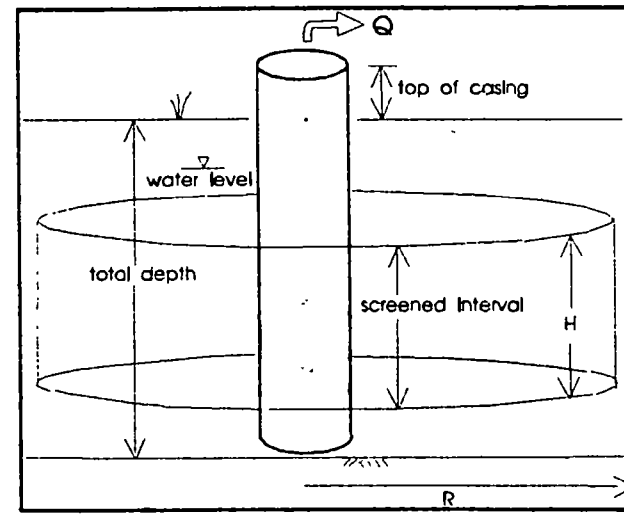
Vincennes, IN

Q = 370,000 ft3/day
N = 0.0032 ft/day (14 in/yr)

R = 6067 ft (1849m)

- VOLUMETRIC METHOD

$$R_t = \sqrt{\frac{Q\ t}{\pi\ n\ H}}$$



Vincennes, IN

Q=370,000 ft^3/day

H = 30 ft screen
n = 0.2
t = 1825 days (5 yrs)
t = 3650 days (10 yrs)

R_5 = 5985 ft (1824 m)
R_{10} = 8464 ft (2580m)

CALCULATED FIXED RADIUS (CFR) WORKSHEET

What is the average pumping rate at the well
(in m^3 per year)? ..... A._____

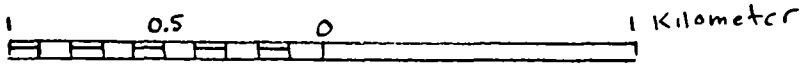
What is the estimate for effective porosity?
(porosity ranges: gravel 0.20-0.40, sand 0.20-0.50,
silt 0.30-0.50, clay 0.30-0.70) ..... B._____

What is the average saturated thickness of the aquifer
(in meters)?..... C._____

What average residence time for the contaminant do
you want to calculate (in years)? ..... D._____

Multiply	A x D =	E._____
Multiply	B x C x 3.14 =	F._____
Divide	E / F =	G._____
Square root	G =	_____ = CFR (m)

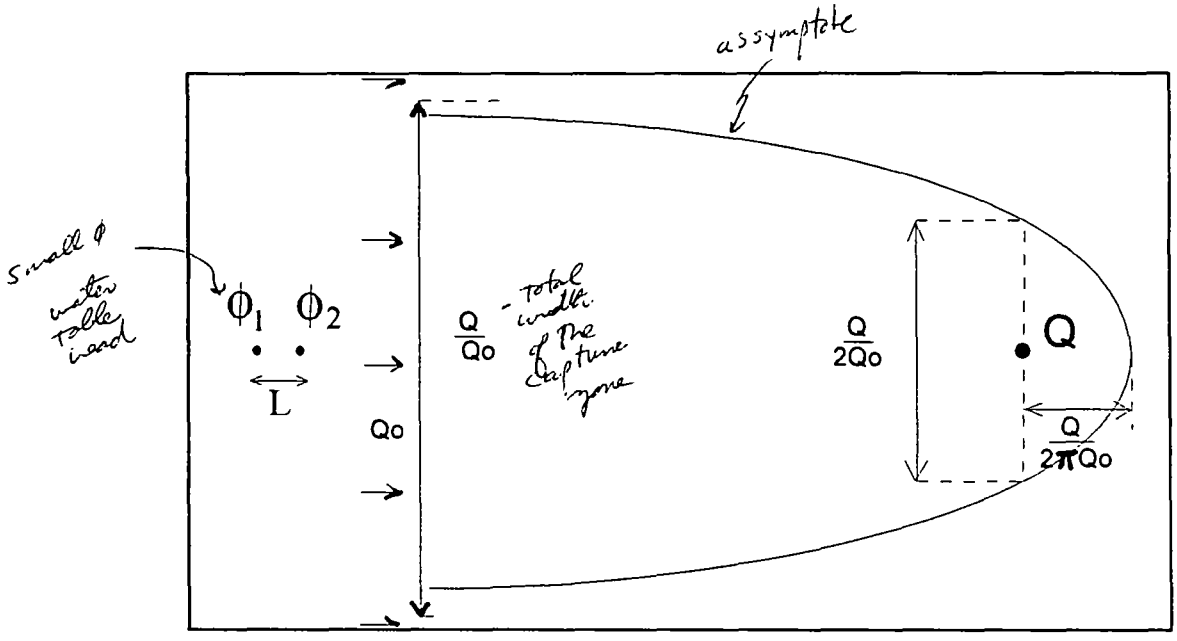
Locate your well on a USGS 7.5 minute map. Set your compass spread to the calculated radius (CFR) using the scale below. Draw your CFR on the map.



scale 1:24000

"Back of envelope" calculation - how to do w/o a

CAPTURE ZONE
WELL IN UNIFORM FLOW



$$Q_o = -\frac{\delta\Phi}{\delta x} \approx -\frac{\Delta\Phi}{\Delta x} = \underbrace{\frac{\Phi_1 - \Phi_2}{L}}_{\text{approximation for the gradient}}$$

differential approximation in the x direction

The discharge vector

mult. by a width, gives the total discharge

Strack's discharge potential

potential

$$\Phi = k\,H\,\phi - \frac{1}{2}\,k\,H^2 \qquad \textit{confined flow}$$

$\frac{L^2}{t}$

derivative of the potential yields the discharge vector

$$\Phi = \frac{1}{2}\,k\,\phi^2 \qquad \textit{unconfined flow}$$

where Q (m3/day) is the well pumping rate, k is the hydraulic conductivity (m/day), H is the aquifer thickness (m), x is the cartesian coordinate in direction of flow (m), and ϕ_1 (m) is the hydraulic head at x_1. See the CZAEM Users Guide, page 7, for an example of computing Qo given head observations in the field.

WhAEM Tutorial Script

Load and Start the GAEP Program

1. C:\WHAEM> gaep <Enter>
   press any key to continue

An Example Digital Map

1.	<F>	select File module
2.	<R>	read digital map
3.	vincenne<Enter>	import file vincenne.dm
4.	<Q>	return to the Main module
5.	<D>	enter the Digitize module
6.	<V>	view the vincennes digital map
7.	<PgDn>	zoom in
8.	<PgUp>	zoom out
9.	<= =>	cursor controlled pan and scan
10.	<Q>	quit the Digitize module
11.	<Q>	exit the program

Create and Input File for CZAEM

1.	C:\WHAEM> gaep <Enter>	
2.	<F>	select File module
3.	<R>	read digital map
4.	vincenne<Enter>	import file vincenne.dm
5.	<Q>	return to the Main module
6.	<E>	enter the Element module
7.	<L>	select the Linesink command
8.	<PgDn> <= =>	page down, pan, scan to set window for Kelson Creek
9.	"mouse"	select Kelso Creek with left mouse button
10.	"mouse"	build line-sinks by clicking left mouse button for end points
11.	<F3>	save, return to Element menu
12.	<W>	select the Well command
13.	<PgDn> <= =>	zoom down, pan & scan to set window for wellfield
14.	"mouse"	select wellfield
15.	"mouse"	position cursor in center of wellfield, click left button
16.	~~467000~~ 370000 <Enter>	set the well discharge in ft^3/day
17.	1 <Enter>	set the well radius in ft
18.	<F3>	save, return to Element menu
19.	<Q>	quit, return to Main module
20.	<A>	enter the Aquifer module
21.	<B>	select the Base command
22.	330 <Enter>	set the base in ft above mean sea level
23.	<T>	select the Thickness command
24.	100 <Enter>	set the thickness of aquifer in ft above base
25.	<P>	select the Permeability command
26.	350 <Enter>	set the hydraulic conductivity in ft/day
27.	<O>	select the Porosity command
28.	0.2 <Enter>	set the porosity
29.	<F>	select the Reference command
30.	0 <Enter>	reference point x coordinate (world coordinates)
31.	656160 <Enter>	reference point y coordinate (world coordinates)
32.	410 <Enter>	reference head in ft above mean sea level
33.	<R>	select the Rain command
34.	"mouse"	click the left mouse button at the center of the near field
35.	"mouse"	click the left mouse button to define the rain circle
36.	yes <Enter>	accept the rain circle
37.	0.0032 <Enter>	set the recharge rate in ft/day
38.	<Q>	quit, return to the Main

Saving the CZAEM Input Data on Disk

1.	<F>	enter the File module
2.	<S>	select the SaveElement command
3.	tutorial <Enter>	save the file tutorial.dat to disk
[illegible]	450000 4280000 <Enter>	define the model origin in world coordinates
[illegible]	<Q>	quit, return to Main module
[illegible]	<Q>	exit the program

Model the Site with CZAEM

1.	C:\WHAEM> cz <Enter>	activate the CZAEM program
2.	<Enter>	clear the intro screen, display COMMAND module
3.	swi vincenne.dat <Enter>	switch in the script file
4.	window push <Enter>	push the current window coordinates into the buffer
5.	window all <Enter>	define the new window to include all elements
6.	lay <Enter>	display the layout of elements
7.	<Enter>	return to the COMMAND module
8.	window pop <Enter>	retrieve the last window in buffer
9.	win	display the window coordinates
10.	lay	display the layout of the wellfield
11.	<Enter>	return to the COMMAND module
12.	plot	enter the PLOT module
13.	d <Enter>	select default contour settings
14.	<Enter>	accept levels, view head contours
15.	<Enter>	return to COMMAND module
16.	trace <Enter>	enter the TRACE module
17.	lay <Enter>	view the layout
18.	"mouse"	set the cursor with the mouse to define initial position of traceline
19.	trace 380	start trace at elevation 380 ft
[illegible]	menu <Enter>	return to TRACE menu
[illegible]	set <Enter>	enter the SET submodule
22.	back on <Enter>	set backward tracing on
23.	maxstep 100 <Enter>	set the step size to 100 days
24.	mark time 730 <Enter>	mark time on tracelines to 730 days
25.	term time 3650 <Enter>	terminate tracelines after 3650 days
26.	ret <Enter>	return to the TRACE menu
27.	lay <Enter>	view the layout
28.	"mouse"	move the cursor to the well
29.	wgen 16 <Enter>	release 16 reverse tracelines from well casing
30.	menu <Enter>	return to the TRACE menu

Hypothesis Testing with GAEP

1.	C:>\WHAEM> gaep <Enter>	initiage the GAEP program
2.	<F>	enter the File Module
3.	<R>	select ReadNew command
4.	vincenne <Enter>	read in the digital map vincenne.dm
5.	<Q>	quit, return to Main Module
6.	<E>	enter the Element Module
7.	<V>	view and identify Mantle Ditch
8.	<I>	select the Image command
9.	"mouse"	position cursor, click to define image origin
10.	"mouse"	select the image second point, click and define axis of symmetry
11.	yes <Enter>	accept image line
12.	"mouse"	use mouse to open recharge circle, click to set
13.	yes <Enter>	accept recharge circle
14.	0.0032 <Enter>	enter recharge rate in ft/day
15.	405 <Enter>	enter the reference head
16.	<V>	view the image and real linesinks
17.	<Esc>	return to Element menu
18.	<Q>	return to Main Module

19.	<F>	enter File Module
20.	<S>	select the SaveElement command
21.	tu_image <Enter>	save element file to hard disk
22.	<Q>	return to Main Module
23.	<Q>	exit program

pothesis Testing with CZAEM

1.	C:\WHAEM> cz <Enter>	activate the CZAEM program
2.	<Enter>	clear intro screen
3.	swi vinimage.dat <Enter>	switch in script file for images solution
4.	capzone <Enter>	enter the CAPZONE module
5.	400 5 <Enter>	select contour levels for viewing
6.	<Enter>	view contours
7.	"mouse"	position the cursor on the well
8.	subzone <Enter>	wait for subzones to be drawn
9.	time <Enter>	select for time zones
10.	730 730 3650 <Enter>	wait for timezones to be drawn
11.	ret <Enter>	return to CAPZONE menu
12.	ret <Enter>	return to COMMAND menu

CZAEM Tutorial Script

Example 1. Uniform Flow with a Well

```
      C:\WHAEM> cz <Enter>     activate the CZAEM program
      <Enter>                  clear intro menu
3.    aquifer <Enter>          enter the AQUIFER module
4.    perm 6 <Enter>           define hydraulic conductivity in m/day
5.    poro 0.3 <Enter>         define porosity
6.    thick 100 <Enter>        define aquifer thickness in m
7.    base 150 <Enter>         define base in m
8.    ret <Enter>              return to COMMAND module
9.    given <Enter>            enter GIVEN module
10.   uni 0.3015 0             define uniform flow discharge vector in
                               m^2/day and angle in degrees from x-axis
11.   ret <Enter>              return to COMMAND module
12.   ref                      enter REFERENCE module
13.   -250 -250 200.5<Enter>   define reference coordinates
14.   solve <Enter>            solve for the unknowns
15.   win -2000 -2000 2000 2000 <Enter> define the lower left and upper
                               right coordinates  of the window
16.   grid 50 <Enter>          fill a grid 50 x 50 with heads
17.   plot <Enter>             enter the PLOT module
18.   d 20 <Enter>             select default levels and plot 20 contours
19.   <Enter>                  view head contours
20.   <Enter>                  return to the COMMAND module
21.   well <Enter>             enter the WELL module
22.   given <Enter>            select for given discharge wells
23.   0 0 60 0.15 <Enter>      x,y,discharge,radius
24.   ret <Enter>              return to COMMAND module
25.   solve <Enter>            solve for the new unknowns
26.   win -500 -500 500 500 <Enter> zoom in with new window
27.   grid 50 <Enter>          fill 50x50 grid with heads
28.   plot <Enter>             enter the PLOT module
29.   d 20 <Enter>             select default levels for 20 contours
30.   <Enter>                  view head contours
31.   <Enter>                  return to COMMAND module
32.   trace <Enter>            enter the TRACE module
33.   plot <Enter>             prepare for plot of head contours in background
34.   d 20 <Enter>
35.   <Enter>
36.   "mouse"                  position cursor for beginning of streamline
37.   trace <Enter>            start streamline
38.   ret <Enter>              return to COMMAND module
39.   map <Enter>              enter MAP module
40.   plot on <Enter>          turn of map features on
41.   curve <Enter>            activate curve definition
42.   -350 150 <Enter>         x,y
43.   -350 350 <Enter>
44.   -150 350 <Enter>
45.   -150 150 <Enter>
46.   -350 150 <Enter>
47.   ret <Enter>              finish curve
48.   ret <Enter>              return to COMMAND module
49.   trace <Enter>            enter the TRACE module
50.   plot <Enter>
51.   d 20 <Enter>
52.   <Enter>
53.   "mouse"                  position cursor for beginning of streamline
54.   trace <Enter>            start streamline
55.   ret <Enter>              return to COMMAND module
56.   stop <Enter>             exit the program
```

Example 2. Well Near A River

```
1.    C:\WHAEM> cz <Enter>
```

```
2.    <Enter>
3.    aquifer <Enter>
4.    perm 5 <Enter>
5.    thick 50 <Enter>
6.    base 0 <Enter>
7.    poro 0.25 <Enter>
8.    ret <Enter>
9.    given <Enter>
10.   uni 0.5 30 <Enter>
11.   ret <Enter>
12.   linesink <Enter>          enter the LINESINK module
13.   head <Enter>              select head specified line-sinks
14.   -1500 1500 -600 1300 32 <Enter> x1,y1, x2, y2, head
15.   -600 1300 -200 900 33 <Enter>
16.   -200 900 200 500 34 <Enter>
17.   200 500 500 200 35 <Enter>
18.   500 200 500 -800 37.5 <Enter>
19.   500 -800 800 -1000 38 <Enter>
20.   800 -1000 1100 -1000 39 <Enter>
21.   1100 -1000 1500 -1800 40 <Enter>
22.   ret <Enter>
23.   win -1500 -1500 1500 1500 <Enter>
24.   layout <Enter>            view the layout
25.   <Enter>                   return to the COMMAND module
26.   ref <Enter>
27.   -2000 4000 40 <Enter>
28.   solve <Enter>
29.   grid 50 <Enter>
30.   plot <Enter>
31.   d <Enter>
32.   <Enter>
33.   <Enter>                   return to the COMMAND module
34.   check <Enter>             enter the CHECK module
35.   head 1 1 <Enter>          display head at point (1,1)
36.   head -2000 5000 <Enter> display head at point (-2000,5000)
37.   ret <Enter>
38.   win -1000 -1000 1000 1000 <Enter>
39.   well <Enter>
40.   given <Enter>
41.   0 0 1500 0.3 <Enter>
42.   ret <Enter>
43.   solve <Enter>
44.   save <Enter>              enter the SAVE module
45.   sol <Enter>
46.   ex2.sol <Enter>
47.   grid 50 <Enter>
48.   plot <Enter>
49.   d <Enter>
50.   <Enter>                   view the head contours
51.   <Enter>                   return to COMMAND module
52.   ref <Enter>
53.   1 1 37.1828 <Enter>
54.   solve <Enter>
55.   grid 50 <Enter>
56.   plot <Enter>
57.   34 4 <Enter>
58.   <Enter>                   view the head contours
59.   <Enter>                   return to COMMAND module
60.   ref <Enter>
61.   -2000 5000 39.7540 <Enter>
62.   solve <Enter>
63.   grid 50 <Enter>
64.   plot <Enter>
65.   26 2 <Enter>
66.   <Enter>                   view the head contours
67.   <Enter>                   return to COMMAND module
```

```
68.   read <Enter>              enter READ module
69.   sol <Enter>
70.   ex2.sol <Enter>
71.   trace <Enter>
      plot <Enter>
      d <Enter>
      <Enter>
75.   backward on <Enter>       set backward tracing on
76.   wgen 20 <Enter>           well generate 20 streamlines
77.   ret <Enter>               return to COMMAND module
78.   stop <Enter>              exit the program

?
```