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CAPTURE ZONE MODELING USING THE WELLHEAD ANALYTIC ELEMENT MODEL (WhAEM)

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Introduction

A new computer modeling package has been developed through cooperative agreement between Indiana University, the University of Minnesota, and the U.S. Environmental Protection Agency for the determination of time-of-travel capture zones in relatively simple geohydrological settings. The WhAEM package includes 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 distinguishes itself from existing analytical models in that it can handle fairly realistic boundary conditions such as streams, lakes, and aquifer recharge due to precipitation.

The Geographical Analytic Element Preprocessor (GAEP) was developed by the research group at the School of Public & Environmental Affairs, Indiana University, Bloomington. GAEP is designed to simplify input data preparation, specifically to facilitate the interactive process of ground-water flow modeling that supports capture zone delineation. The Capture Zone Analytic Element Model (CZAEM) was developed by the research group at the Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis. CZAEM is equipped with a novel

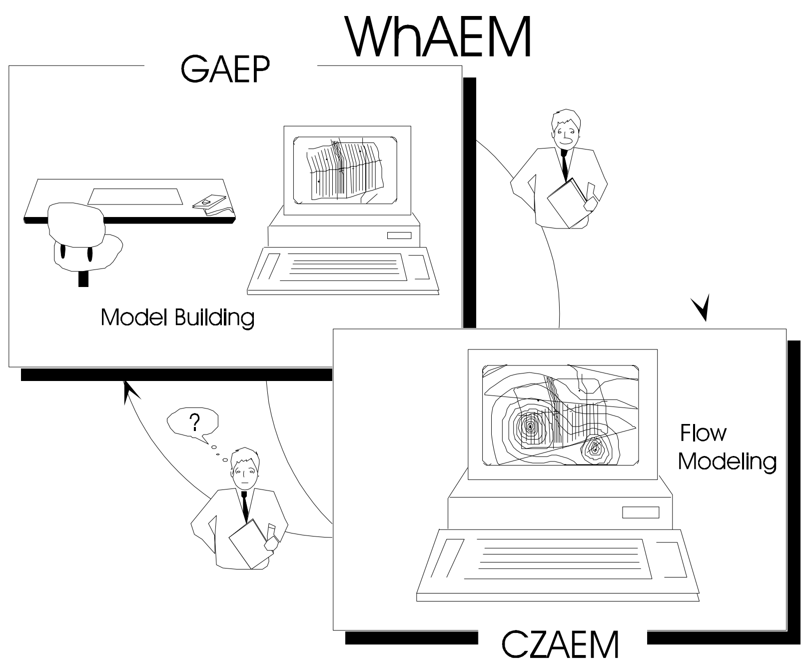

Figure 1 The modeling process using WhAEM.

[1]Respectively, USEPA (Ada,OK), Indiana University (Bloomington), University of Minnesota (Minneapolis)

algorithm to accurately define capture zone boundaries by first determining all stagnation points and dividing streamlines in the flow domain. Figure 1 shows a cartoon of the modeling procedure using GAEP and CZAEM.

The selection of the appropriate tool to assist capture zone delineation will depend on many factors, including site complexity, data availability, modeling experience, time, and money. The simplest analytical models can represent wells in uniform flow fields, are easy to use, and have modest data and implementation costs. An example is the WHPA model (USEPA,1991,1993). On the other hand, numerical models can represent more complex settings (eg. three dimensional flow, heterogeneous geology), but at greater data and implementation costs. An example is the finite difference model MODFLOW (McDonald,Harbaugh,1988). The WhAEM package and documentation is intended to provide intermediate conceptual modeling capabilities for water resource scientists and engineers responsible for capture zone delineation.

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 --- that vertical resistance to flow is negligible. 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 (rainfall). For a complete description of the method and other analytic elements the reader is referred to Strack (1989).

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 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 into line sink segments.

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

A special pond function is used to model areal recharge due to precipitation. 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 wellfield and surrounding surface waters, to simulate the desired aquifer recharge. The uniform flow function may be used to approximate the combined effects of areal recharge and surface water boundaries.

Data is input into CZAEM by direct command line entry from the keyboard, or from a prepared ASCII command "script" file. Figure 2 shows an example of the CZAEM commands needed to represent two wells in a uniform flow field. At the simplest level, the capture zone routines of CZAEM support backward stream line tracing from the wells, with tic marks to indicate time-of-travel. The more sophisticated routines define the capture zone boundaries, as well as the travel time isochrones inside the capture zone boundaries for arbitrary arrangements of wells and line sinks (stream boundaries).

Program GAEP

The GAEP program facilitates the creation of the CZAEM script file in three steps: first, by building an electronic background map; second, by assisting in the interactive "designing" of the analytic elements; and third, by storing the analytic elements and aquifer data in a script file that canbe read by CZAEM. Typically, the electronic background map is created by extracting the hydrologic features from paper copy of USGS topographic maps using a digitizer. This electronic map becomes the template for the on-screen creation of the analytic elements. For example, to represent a stream by line sinks, the modeler merely selects a stream with the mouse, and by moving the pointer over the stream and "clicking" on intended line sink end points, creates a string of line sink analytic elements. These line sinks will have heads assigned at their centers that are computed using the stream elevations stored within the digital map. GAEP will also prompt and process the basic aquifer data. A script file can be saved that will introduce the data to the

CZAEM model, solve the flow problem, and create a grid with piezometric heads. The modeler then enters the TRACE module in CZAEM to generate the capture zone boundaries. GAEP also allows the modeler to return to and edit the script file "on-screen" and refine the analytic element representation, as implied by the return cycle in Figure 1. The reader is referred to Kelson et al. (1993) for a more complete discussion of GAEP.

```
WINDOW -2027 -2205 3039 2989 * window defines the screen
*                                lower left (x,y) and upper
*                                right (x,y) corners in (ft)
*                                model space
AQUIFER
 BASE 0 * ft
 THICKNESS 26 * ft
 PERMEABILITY 609.2 * ft/day
 POROSITY 0.3
RETURN
GIVEN
 UNIFLOW   11.879  -65  *   discharge vector (ft^2/day),
*                            angle (degrees from horizontal)
RETURN
REFERENCE
 2838  -639  37.15   *  location (x,y) , head (ft)
WELL
 GIVEN
  325  647  25669  1  *  location (x,y), discharge (ft^3/day),
*                          radius (ft)
  703  535  12834  0.67
RETURN
```

Figure 2 Example CZAEM commands for 2 wells in a uniform flow field.

Benchmark Experiment

Figure 3 shows the superposition of WHPA and MODFLOW generated capture zones upon a CZAEM solution for two pumping wells in a uniform flow field. The parameterization of the problem is the same data set of Figure 2. The capture zones for the MODFLOW solution were created using the code MODPATH (Pollock, 1989). Notice that CZAEM draws the capture zone envelope for each well. The CZAEM and WHPA capture zones are very similar, while the shape of the MODFLOW zones are slightly different. MODFLOW approximates the far-field (infinite) uniform flow field of the analytical models with a finite difference grid.

Summary

An important objective of the WhAEM project was to demonstrate a promising new technology to the ground-water modeling community, and to stimulate further development of analytic element applications. The WhAEM package is intended to assist municipal water supplies in the design of wellhead protection zones. Capture zone modeling is also needed in the design of pump-and-treat systems during aquifer clean-up.

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. A separate users guide exists for the stand alone use of CZAEM, including a suite of directed modeling exercises. The WhAEM package is distributed by the USEPA Center for Subsurface Modeling Support (CSMoS), POB 1198, Ada, OK, 74820, ph. (405) 436-8500.

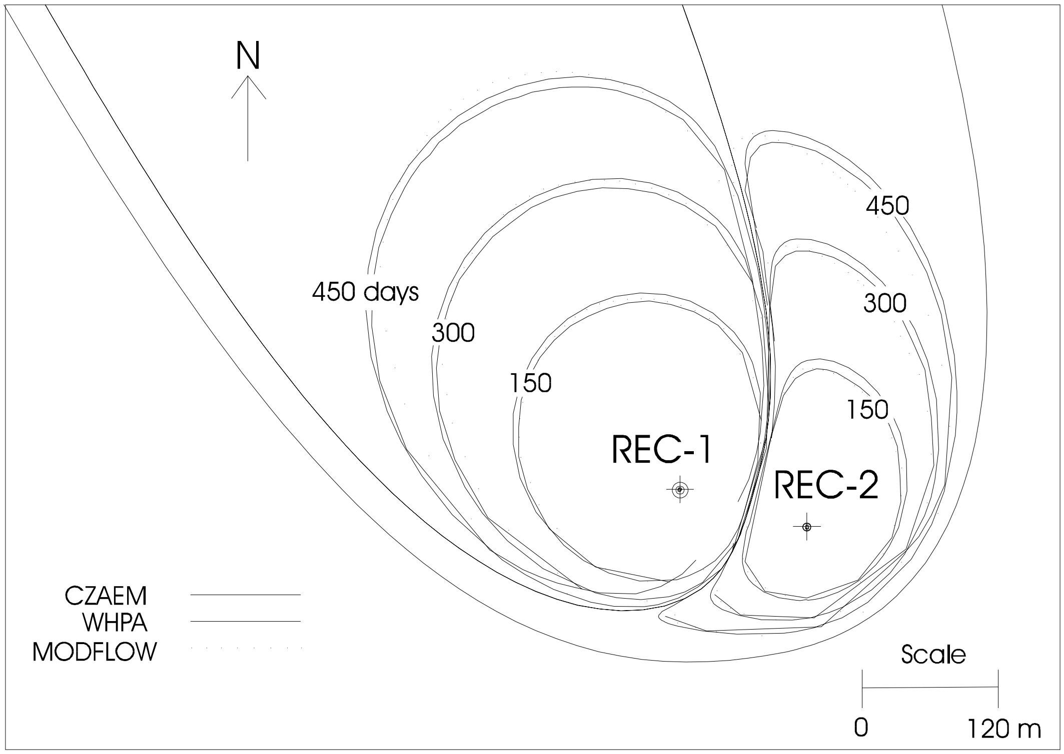

Figure 3 Benchmark experiment comparing capture zones for CZAEM, WHPA, and MODFLOW.

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