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Working with WhAEM2000

Source Water Assessment for a Glacial Outwash Wellfield, Vincennes, Indiana

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By

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Abstract

The purpose of this document is to introduce through a case study the use of the ground water geohydrology computer program WhAEM for Microsoft Windows (32-bit), or WhAEM2000. WhAEM2000 is a public domain, ground-water flow model designed to facilitate capture zone delineation and protection area mapping in support of the state's and tribe's Wellhead Protection Programs (WHPP) and Source Water Assessment Planning (SWAP) for public water well supplies in the United States. Program operation and modeling practice is covered in a series of progressively more complex representations of the wellfield tapping a glacial outwash aquifer for the city of Vincennes, Indiana. WhAEM2000 provides an interactive computer environment for design of protection areas based on radius methods, well in uniform flow solutions, and geohydrologic modeling methods. Protection areas are designed and overlaid upon US Geological Survey Digital Line Graph (DLG) or other electronic base maps. Base maps are available for download from the EPA Center for Exposure Assessment Modeling web site. Geohydrologic modeling for steady pumping wells, including the influence of hydrological boundaries, such as rivers, recharge, no-flow boundaries, and inhomogeneity zones, is accomplished using the analytic element method. Reverse gradient tracelines of known residence time emanating from the pumping center are used to delineate the capture zones. WhAEM2000 has on-line help and tutorials.

Foreword

The National Exposure Research Laboratory's Ecosystems Research Division (ERD) in Athens, Georgia, conducts process, modeling, and field research to assess the exposure risks of humans and ecosystems to chemical and non-chemical stressors. This research provides data, modeling tools, and technical support to EPA Program and Regional Offices, state and local governments, and other customers, enabling achievement of Agency and ORD strategic goals in protection of human health and the environment.

ERD research includes studies of the behavior of contaminants, nutrients, and biota in environmental systems, and the development of mathematical models to assess the response of aquatic systems, watersheds, and landscapes to stresses from natural and anthropogenic sources. ERD field and laboratory studies support process research, model development, testing and validation, and characterize variability and prediction uncertainty.

Leading-edge computational technologies are developed to integrate core sciences into multi-media (air, surface water, ground water, soil, sediment, biota), multi-stressor, and multi-scale (organism, population, community, ecosystem; field site, watershed, regional, national, global) modeling systems that provide predictive capabilities for complex environmental exposures.

Exposure models are distributed and supported via the EPA Center for Exposure Assessment Modeling (CEAM).

The development and release of the Wellhead Analytic Element Model (WhAEM2000) is in support of the State's and Tribe's Source Water Assessment and Wellhead Protection Programs as required by the Safe Drinking Water Act. WhAEM2000 is a general purpose ground water hydrology tool based on the innovative modeling technique known as the analytic element method and a standard Windows graphical user interface. WhAEM2000 assists in the delineation of the area contributing source water to public water supply wells. The development of WhAEM2000 has been supported by the EPA Office of Research and Development and the EPA Office of Ground Water and Drinking Water.

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Contents

Acknowledgements

Chapter 1

BACKGROUND

The objective of this document is to introduce the geohydrology computer model WhAEM2000. The presentation will cover both basic model operations and modeling practice. We will use a source water area assessment associated with the wellfield of the city of Vincennes, Indiana, to emphasize a step-wise and progressive modeling strategy. The case study is not an approved component of the Indiana wellhead protection program.

1.1   Source Water Protection Programs

Ground water is a valued source of public drinking water in many parts of the country. Not only is the ground water resource renewable if properly managed, its quality can be excellent, due to the natural cleansing capabilities of biologically active soil cover and aquifer media. It has come to the public attention in the past few decades that ground water wells can be threatened by over-drafting and pollution. Source water protection is based on the idea of protecting public water wells from contamination up front, and working to maintain the quality of the resource. Source water protection means taking positive steps to manage potential sources of contaminants and doing contingency planning for the future by determining alternate sources of drinking water. The Safe Drinking Water Act has required the USEPA to develop a number of programs that involve the source water protection concept for implementation at the State level, such as the Wellhead Protection Program and the Source Water Assessment Program [USEPA,2003].

The main steps of the source water protection process involves the assessment of the area contributing water to the well or wellfield, a survey of potential contaminant sources within this area, and an evaluation of the susceptibility of the well to these contaminants. This includes the possibility of contaminant release and the likelihood of transport through the soil and aquifer to the well screen.

The designation of the wellhead protection area is then a commitment by the community to source area management. Delineation of the wellhead protection area is often a compromise between scientific and technical understanding of geohydrology and contaminant transport, and practical implementation for public safety.

The EPA Office of Ground Water and Drinking Water established guidance on the criteria and methods for delineating protection areas [USEPA,1993], [USEPA,1994]. The criteria include: (1) distance; (2) drawdown; (3) residence time; (4) flow boundaries; and (5) assimilative capacity. The methods applying the criteria range from the simple to the complex, including setback mapping, calculated radius, and geohydrologic modeling (see Table 1.1). This document will review selected criteria and their methods using WhAEM2000

Table 1.1: **Wellhead protection area delineation criteria and methods.**

METHODS CRITERIA	arbitrary fixed radius	calc. fixed radius	well in uniform flow field	geo-hydro-logic mapping	geo-hydrologic modeling	transport/transfor-mation modeling
distance	x	x				
drawdown		x	x		x	x
residence time		x	x		x	x
geohydrologic boundaries				x	x	x
assimilative capability						x

through examination of the Vincennes, IN case study. The emphasis will be on the residence time criteria and its methods. The evaluation of assimilative capability is an active area of research and will not be discussed in detail in this document.

1.2   Modeling Philosophy

The philosophy presented below is for deterministic mathematical modeling, and a more complete discussion can be found in [Konikow and Bredehoeft, 1992]. The reader is encouraged to explore an alternative modeling approach based on stochastic theory [Vassolo et al., 1998] , [Feyen et al., 2001].

Modeling of flow and transport through geohydrologic systems is a complex undertaking. Our definition of good modeling practice revolves around step-wise problem solving. The mathematical model is an abstraction of the real world, and all abstractions are simplifications. The challenge is to make the abstraction represent the essence of the natural system as required by the problem at hand. Representation of the advective flow system is understood to be prerequisite to modeling transport and transformations.

Formally speaking, mathematical modeling of ground-water flow is concerned with finding solutions to a governing differential equation subject to a set of boundary conditions. This procedure can be simple or complex depending on the ground-water flow processes included in the differential equation and the complexity of the boundary conditions. That combination of processes and boundary conditions is referred to as the "conceptual model". An example of a very simple conceptual model is a single well in a homogeneous confined aquifer near a straight infinitely long "equipotential" (line of constant head). Such a conceptual model is a severe abstraction of a well near a stream or lake boundary. The actual meandering surface water boundary is replaced by an infinitely long straight line, heads underneath it are assumed equal to the surface water elevation, aquifer properties are assumed uniform and homogeneous throughout the flow domain, and lastly the ground-water flow is assumed to be purely horizontal. The virtue of this conceptual model is the ease with which a solution can be obtained (Thiem's solution for a well with an image recharge well across from the equipotential line). Of course, the price paid is the lack of realism of this conceptual model when compared to the complex reality of a partially penetrating well near a meandering stream with a silty stream bottom in a heterogeneous aquifer of varying thickness.

A realistic conceptual model is often thought of as a representation of reality that includes most if not all of the geologic and hydrologic complexities of an aquifer or aquifer system. The more realistic (read

complex) a conceptual model is the more involved the modeling becomes, mostly for the following reasons:

1. Field data requirements may escalate when striving for maximum realism.

2. Computer codes needed to solve complex conceptual models are difficult to operate.

3. Non uniqueness invades the modeling process — many different sets of parameters and boundary conditions can represent the same observed water levels and fluxes.

While incorporation of more and more "realism" in the conceptual model may suggest an increasingly accurate representation of the ground-water flow regime, the *reality* may well be different. Increased data requirements and the associated data uncertainty, as well as the difficulty to interpret the results of complex (multi-parameter models) can defeat the theoretical improvement in model realism. This is not only true for ground-water flow modeling. Albert Einstein is known to have offered the following advice when talking about models of the universe: "Things should be made as simple as possible ... but not simpler". In other words, good modeling practice requires a balance between the realism of the conceptual model and the practical constraint of parameterizing the resulting ground-water flow model.

When deciding on an appropriate conceptual model it is important to not only take the complexity of the geohydrology into account, but also the objective of the modeling exercise. In the context of wellhead protection the purpose of the modeling is often the delineation of a "time-of-travel capture zone" for one or more drinking water production wells. The delineation of the time-of-travel capture zone, for the purpose of wellhead protection, is based on the assumption of steady state ground-water flow and average ground water travel times. A time-of-travel capture zone, defined in this manner, is arguably not the most relevant entity when it comes to protecting drinking water wells from potential toxic substances. The movement of contaminants toward a drinking water well is a complex contaminant transport problem where such processes as dispersion, adsorption and (bio)chemical reactions strongly influence the degree to which a well is actually exposed to contaminants in the aquifer. Incorporation of all these aspects in the definition of a wellhead protection zone would require sophisticated transport modeling for a whole series of different contaminants. The field data requirements for such an endeavor are staggering, while the technology to reliably describe these contaminant transport processes is not completely developed. In any case, the definition of multiple wellhead protection areas, one for each potential contaminant, is impractical to say the least. Consequently, many States base their wellhead protection areas on time-of-travel capture zones that result from considering average ground water travel times and steady state (average) flow conditions.

The essence of good ground-water flow modeling is to find a proper balance between a simple conceptual model and a realistic one. The most economical way to judge whether or not a conceptual model is not too simple, is to gradually increase its complexity and investigate the effect on the purpose of the modeling; the time of travel capture zone in this case. A very good example is the classical dilemma of modeling two-dimensional flow or three-dimensional flow. Most modelers feel inadequate when using a horizontal flow model (based on the Dupuit assumption), when realizing that the actual world is clearly three-dimensional. Intuition, however, offers poor guidance here. Only a comparison between a three-dimensional solution and two-dimensional one can answer this question. This is true for all aspects of conceptual model design. The need to include aquifer heterogeneities, varying recharge rates, resistance to flow in or out of surface water features, etc. can only be assessed by comparing ground-water flow solutions with and without these features. In all cases it is important to look at the impact on the time-of-travel capture zone, since that is what we are modeling for. Once progressively more complex conceptual models do not change the time-of-travel capture zone in a meaningful way, the modeling may be considered complete. Sometimes, it may be preferable to

trade data acquisition and model complexity for a larger, thus more protective, wellhead protection zone. Such a conservative time of travel capture zone may be obtained by making some assumptions that are known to lead to a larger capture zone than the one that may result from a more detailed conceptual model — trading uncertainty into conservative/protective assumptions. Also, modeling experience will lead to general "rules-of-thumb" in formulation of the conceptual model. These topics will be visited in the discussion in the final chapter.

1.3   The Emergence of the WHPA Model

Nearly all ground water modeling projects are constrained by a finite budget and a finite amount of time. This is particularly true for time-of-travel capture zone delineation in the context of wellhead protection. Most States are confronted with the task of developing wellhead protection programs for thousands of public drinking water supply systems in only a few years time. Conducting an extensive ground water modeling campaign for each individual drinking water well (or well field) is out the question, both in view of the time involved and the cost. The EPA recognized this reality from the start and proposed a series of simplified capture zone delineation methods to facilitate a timely implementation of the States wellhead protection programs:

1. arbitrary fixed radius method.

2. calculated fixed radius method.

3. simplified variable shapes.

4. well in a uniform flow method.

5. geologic mapping.

6. ground-water flow modeling based on a simple conceptual model.

7. ground-water flow modeling based on a sophisticated conceptual model.

While only the latter (#7) all-out modeling exercise may completely satisfy the groundwater hydrologist, the more approximate approaches are offered to get the job done. The rationale behind this thinking is that it is better to define a less then perfect wellhead protection zone than none at all. The task of the ground water hydrologist is to select the best possible approach within the time and budget constraint of the wellhead protection program.

The first two methods lead to circular wellhead protection zones and often over-protect some areas and not protect other areas near the well.

The well in uniform flow method takes ambient ground-water flow into account (approximately) and offers a significantly better approximation of the actual time-of-travel capture zone. That approach has been implemented in a computer code WHPA, made public by the USEPA [Blanford and Huyakorn,1993]. In addition, WHPA allows for wells in flow fields generated by enclosed (rectangular) boundaries, such as provided by combinations of canals (constant head) or geologic contacts (no flow). WHPA uses particle tracking to draw bundles of streamlines toward the well, including the boundary streamlines that define the capture zone for the well. By drawing streamlines with a constant ground water residence time, from starting point to the well, a *time-of-travel* capture zone is delineated. WHPA is menu driven, has a windows-like graphical user interface under DOS, and requires minimal computer resources.

1.4 The Evolution of W*h*AEM

W*h*AEM (pronounced wăm) offers an evolutionary but significant step. In addition to facilitating the simplified techniques (e.g., fixed radius and uniform flow), the modeling environment allows the incorporation of the principal hydrologic boundaries (surface waters) in the regional ground-water flow domain and calculates ambient ground-water flow patterns based on aquifer recharge due to precipitation in the presence of these surface waters. Consequently, the ambient flow does not have to be specified a priori and will not be limited to a uniform flow field. Also, surface water features and geologic boundaries are not limited to infinitely long straight lines (WHPA), but can be of arbitrary shape, further improving the realism of the conceptual model. On the other hand, W*h*AEM currently lacks varying aquifer bottom elevations, three-dimensional elements, multi-aquifer flow, transient flow, etc., which are supported in full-feature ground water models. While this limits the applicability of W*h*AEM2000, it also makes the code easier to operate and thus easier to learn. In addition, the relatively simple conceptual model of W*h*AEM requires less input data, thus further simplifying its use. Taken together, time-of-travel capture zone delineation with W*h*AEM is considerably cheaper than when using a full feature ground water flow model such as e.g. , MODFLOW [McDonald and Harbaugh, 1988]. Obviously, the price for this is a less sophisticated (potentially less accurate) definition of the time-of-travel capture zone. W*h*AEM clearly offers more realism than the first three approaches in the list, but also requires more work (more time and more money). In some cases this may be justified, in some cases one of the simpler methods may be adequate, and in some other cases a more powerful ground water model must be employed. It is the responsibility of the hydrologist to determine whether or not W*h*AEM is an adequate tool for the delineation of a time-of-travel capture zone for a particular public water supply system. That decision, as explained, should be based on technical merits, while taking into account the practical limitations associated with the timely implementation of the entire wellhead protection program.

The release of the Capture Zone Analytic Element Model (CZAEM) [Strack et al.,1994] introduced a new analytical solution technique to the wellhead community – the analytic element method. This method is based on the principle of superposition of many closed-form analytic functions, each representing a hydrological feature, such as point-sinks for wells, line-sinks for rivers, area elements for zones of effective recharge, line doublets (double layers) for geologic contacts [Strack,1989], [Haitjema,1995]. The two-dimensional analytic element models invoke the Dupuit assumption [Dupuit, 1863], meaning that resistance to vertical flow is negligible and that the head is constant with depth (zero vertical head gradients). The Dupuit assmumption has been shown to be very powerful for modeling flow in shallow aquifers. The Dupuit assumption is reasonable for capture zone delineation when the capture zone is an order of magnitude wider than the saturated thickness of the aquifer. The significance of the Dupuit assumption is to approximate a three-dimensional flow field by a two-dimensional one. Implementation of the analytic element method in CZAEM includes wells, line-sinks, uniform flow, and circular recharge elements, and is operated from a DOS command line. CZAEM has sophisticated routines for drawing time-of-travel based capture zone envelopes and time and source water sub-zones [Bakker and Strack,1996].

A graphical user interface (GUI) and geographic analytic element preprocessor, GAEP [Kelson et al., 1993], was added to solution engine CZAEM in the first release of W*h*AEM [Haitjema et. al, 1995], [Haitjema et. al, 1994]. This version ran under Windows 3.1. The development of GAEP opened the door for conceptual modeling, where the model elements (e.g. wells, line-sinks) are superimposed on top of binary base maps showing hydrography and roads. It is interesting to note that the conceptual modeling approach pioneered by GAEP is now being implemented in advanced modeling packages, such as the Groundwater Modeling System [USACOE,2002].

WhAEM for Windows 95 was released in 1997.

The release of WhAEM version 1 (April 2000) included an improved windows graphical user interface, the use of U.S. Geological Survey (USGS) digital line graphs (DLGs) as the base map, a new solution engine ModAEM [Kelson,1998] that included arbitrarily shaped no-flow boundaries. The release of WhAEM version 1 supported delineation by fixed radius, calculated radius, well in uniform flow, and steady flow in confined/unconfined aquifers with constant aquifer properties and recharge.

The most recent release, WhAEM2000 version 2, uses the GFLOW1 solution engine [Haitjema, 1995], and includes new elements: inhomogeneities and resistance linesinks. WhAEM2000 runs under Windows 98/NT/2000/XP.

1.5   The Base Map

Ground-water models are applied to regular Cartesian coordinate systems, even though the surface of the Earth is curved. Cartographers have solved the problem by projecting the surface of a spheroid, where position is measured in latitude and longitude, to a rectangular coordinate system on a flat piece of paper. In addition, we need to define the origin of our ground-water model coordinate system in a standard way so that we can overlap maps and spatial data from different sources.

WhAEM2000 can use any Cartesian coordinate system, including universal transverse mercator (UTM), State Plane, local site coordinates, etc. The graphical user interface (GUI) for WhAEM2000 provides both pre- and post- processing in the base map coordinates, while the computational engine operates in local rectangular coordinates for reasons of numerical accuracy, but this is hidden from the user.

We will build our base maps using the USGS Digital Line Graph series. DLG maps include lines for hydrography (rivers, lakes, etc), roads, hypsography (topography), and other line features. DLG maps are available at convenient scales for ground water modeling, including the intermediate scale (1:100,000) and the large scale (1:24,000). DLG maps are available for download on the Web (See Appendix B.2).

The DLG maps use the UTM projection [USGS,1997]. In this grid system, the globe is divided into 60 north-south zones, each covering a strip 6 degrees wide in longitude. The zones are numbered from 1 to 60, where by zones 10 to 19 cover the conterminous U.S. Figure 1.1. In each zone, coordinates are measured north and east in meters. The northing values are measured continuously from zero at the Equator, in a northerly direction. A central meridian through the middle of each 6 degree zone is assigned an easting value of 500,000 meters. Grid values to the west of this central meridian are less than 500,000 meters; to the east they are more than 500,000 meters. Caution: Base maps do not smoothly join across UTM zones!

For performance reasons, we have developed a compressed binary form of the DLG called BBM (binary base map). WhAEM2000 reads BBM files from the disk each time it redraws a map on the screen. WhAEM2000 has tools to convert DLG to BBM. The EPA Center for Exposure Assessment (CEAM) operates a web server for download of BBMs. The CEAM web server has a graphical index, and when accessed with a browser, you can select specific maps for your project. This procedure is described in Appendix B.

Another important projection is the state plane coordinate system (SPCS), wherein each state has its own zone(s). The number of zones in a state is determined by the area the state covers and ranges from one for a small state such as Rhode Island to as many as five. The projection used for each state is also variable; states that are elongate from east to west, such as New York, use a transverse Mercator projection, while states that are elongate from north to south, such as California, use a Lambert conformal projection. Maps in any projection stored in digital exchange format (DXF) may be translated to BBM format using the **Tools** .
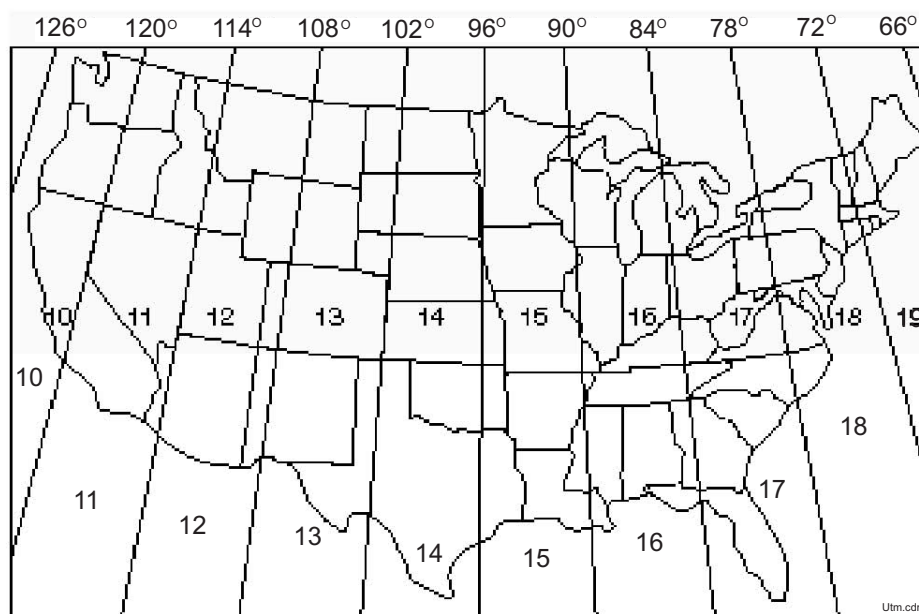
Figure 1.1: UTM zones of the conterminous U.S.

1.6 Exercise: Exploring the USGS quad map Vincennes, Indiana

We will use a source water area delineation for the well field of Vincennes, Indiana, as a case study throughout this document. The case study will be used to: (1) familiarize the reader with the basic operations of WhAEM2000; and (2) illustrate some basic ground-water modeling concepts.

Vincennes is the seat of Knox County and home to about 40,000 people. The city is located in the alluvial flood plain of the Wabash River in the southwestern quadrant of Indiana. See Figure 1.2. The floodplain of the Wabash River is characterized by valley fill from glacial outwash, and consists of coarse sand and fine gravel on top of underlying bedrock. The area receives about 40 inches per year of precipitation. The areal recharge to the aquifer is estimated to be 12.1 inches per year, and the average hydraulic conductivity of the local aquifer is 350 feet per day, and an effective porosity is 0.2 [Shedlock, 1980]. The wellfield pumped about 2.75 MGD (million gallons per day) in 1977, and about 3.5 MGD in 1999. You will learn more details about the wellfield as you progress through the case study.

In this exercise, we will place the Vincennes wellfield in its geographic context. You will locate the wellfield on the digital U.S. Geological Survey 7.5 minute topographic map (vincenne.tif) using the DLG-Viewer [USGS,2002]. The DLGV32 Pro program is available for download from the USGS webpage (http://mcmcweb.er.usgs.gov/drc/dlgv32pro/). The 7.5 minute digital raster graphic (DRG) for the Vincennes quad (vincenne.tif) is available at the CEAM web download area (http://www.epa.gov/ceampubl/gwater/whaem/index.htm).

We will assume basic familiarity with the Microsoft Windows operating system, and basic mouse operation.

Step 1   Start the USGS DLG-View program and open the file `vincenne.tif`.

How is this accomplished? From Windows, use the mouse to **Start**, **Programs**, **US Geological Survey**,**dlgv32**. From the Menu bar, click on **File**, **Open as New**, look in the WhAEM folder for the file

Figure 1.2: Location of Vincennes, Indiana

`vincenne.tif`, click to select, and **Open**.

Size your view to fill the monitor screen. Figure 1.3.

<div style="border:1px solid black; display:inline-block; padding:2px">**Step 2**</div> Test out the Smart Icons buttons: **Zoom In, Zoom Out, Full View, Zoom Tool, Pan**.

You will use the smart icons (see Figure 1.4) of the USGS DLG-View program to reposition the view.

Zoom In to the City of Vincennes, and find the city wellfield, Figure 1.5. Note the UTM coordinates of the pumping center reported in the Status Message bar in the lower right corner of the Workspace (452650 m, 4280665 m). **Pan** up the Wabash River to the north and locate where the 400 foot topographic line crosses the river.

Minimize the view to continue to the next chapter, or exit the program by clicking **File** and **Exit**.
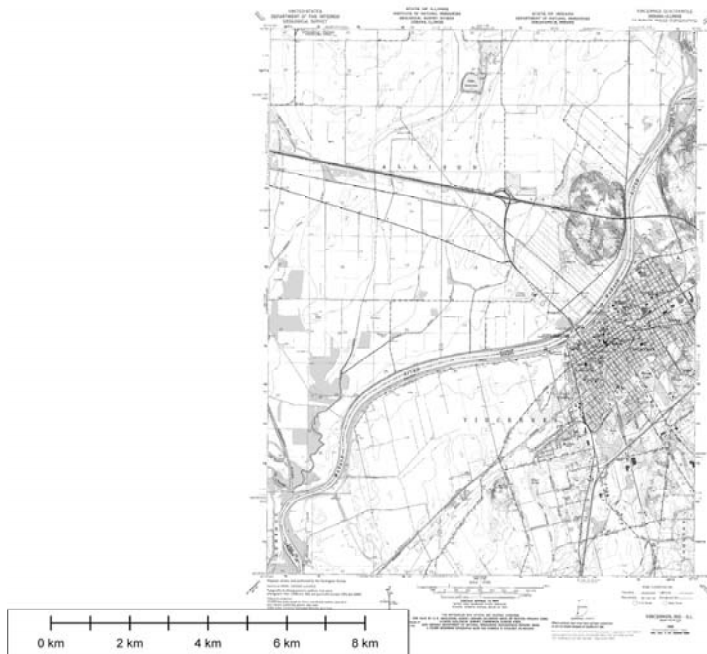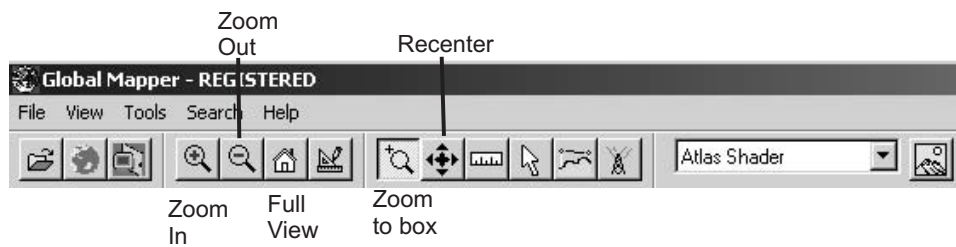
Figure 1.3: USGS DLG-View of Vincennes, Indiana.

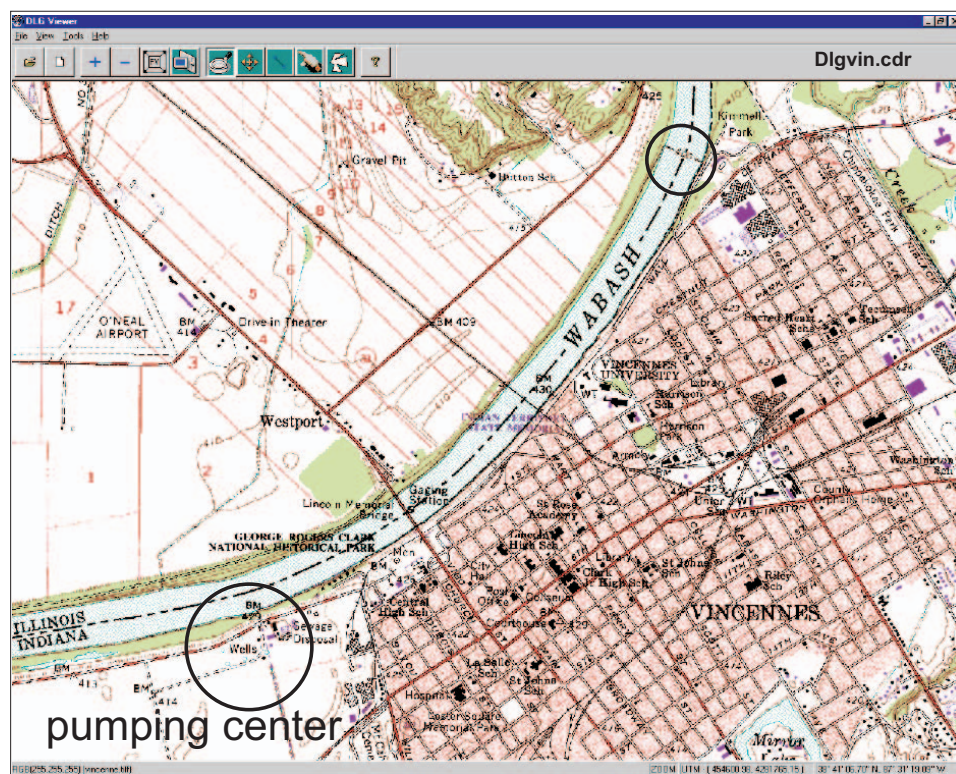
Figure 1.4: USGS DLG-View icons.

Figure 1.5: Zoom in view of Vincennes wellfield.

Chapter 2

PROTECTION ZONES I – DISTANCE CRITERIA

2.1 Setbacks

One of the basic criteria for defining a protection zone surrounding a pumping well or wellfield is distance. The method of designating a setback based on a fixed radius is commonly used by the States [Merkle et al.,1996]. For example, at this time, Indiana has a setback distance of 200 feet between potential sources and public drinking water wells. The fixed radius is the first line of defense against surface contaminants that could reach the wellhead and travel down an improperly sealed borehole into the ground water near the well screen. A fixed radius wellhead protection zone is also used as a setback for potential sources of microbial pathogens. The assumption is that pathogens entering ground water outside the setback area will become inactive before entering the well. The actual survival time of pathogens in ground water, however, is still the topic of ongoing research. And the setback is not likely protective from a gasoline spill containing the additive MTBE (methy tertiary butyl ether). MTBE resists degradation in many subsurface environments.

2.1.1 Exercise: Vincennes, Indiana

Step 1 Start WhAEM2000 and familiarize yourself with the graphical user interface (GUI).

From the **Start** button, go to **Programs**, start **WhAEM2000** for Windows. The "About WhAEM2000 for Windows" splash screen will appear briefly, and credits are given. Figure 2.1. Select the "Start WhAEM" option on the welcome screen. Figure 2.2.

The workspace for WhAEM2000 has standard windows features: a Menu bar on top; smart icons bar underneath the menu bar; status bar on the bottom of the window. Figure 2.3.

Step 2 Create a new project database.

From the Menu Bar, drop down the **Project** options. Select **New Database**, and select your project folder (e.g., where you stored your bbms) on the hard drive, and type `vinbase` into the dialog box for the file. Figure 2.4. Click **Open**.

The "New Database Wizard" will prompt you for a project description and the units associated with the input data. 2.5. WhAEM2000 requires consistent units, either meters and days or feet and days. The
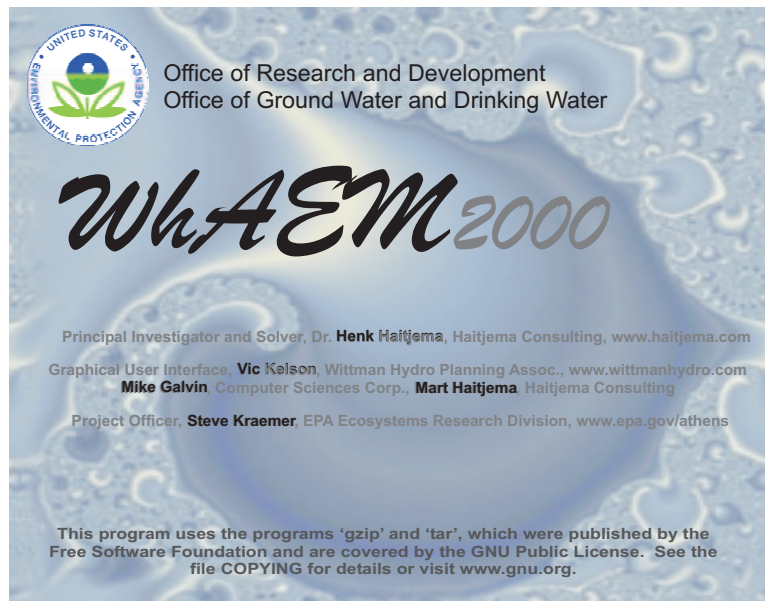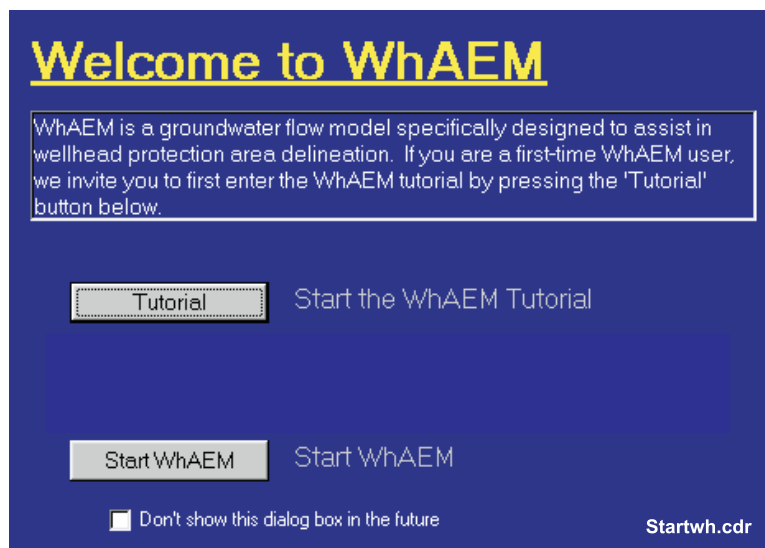
Figure 2.1: W*h*AEM2000 splash screen.

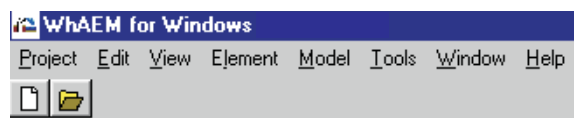Figure 2.2: Start W*h*AEM2000.
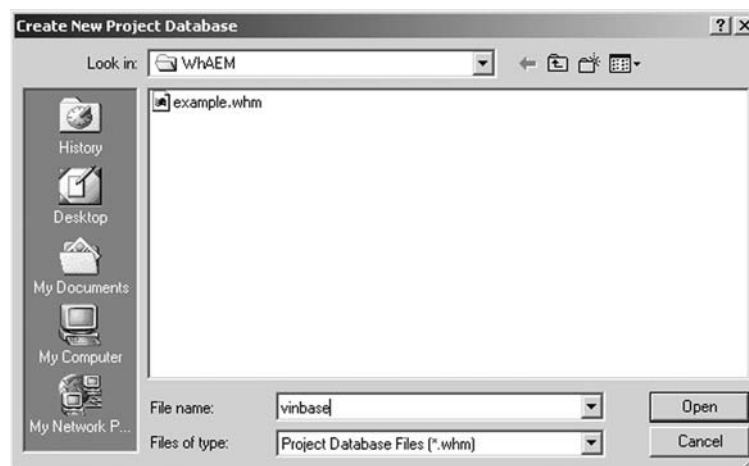

Figure 2.3: W*h*AEM2000 menu bar.

Figure 2.4: Create new database.

"Distance Units in the Basemap Files" will be dictated by your source files. Select **meters** for the "Distance Units in Basemaps Files" by clicking on the radial button. The provided basemaps are in UTM coordinates so you must select **meters**. You are free to select the "Units for Computations"; the computer program will enforce consistent units for future data entry. Select **feet and days** for this exercise. After you have made these selections, click on **Create Database**.

Note: Your base map units are actually not a choice, but are dictated by the units of your electronic source. The coordinates displayed on-screen will match your map units. The units for computation are your choice. For instance, if you select feet and days for your units for computations, the hydraulic conductivity must be entered in feet per day and a well pumping rate must be entered in cubic feet per day. The GUI will convert the base map units to the computational units when forwarding data to the solver, which works in consistent units.

The next window facilitates the definition of base maps (in binary format). Figure 2.6. The window "Currently Used Base maps" will be empty at this point. Click on **Add BBM** to display the available *.bbm files. Do a shift click to select all of the bbm files. Then click **Open**. The list of bbm files will be displayed in the box "Currently Used Basemaps". Click **OK** and wait a few seconds. The maps will be loaded and plotted on the project workspace. Figure 2.7. See Appendix B.1 for information about the USGS naming convention for these files.

From the Menu Bar, drop down the **View** options. Go to Basemap to view the available layers. Play with toggling these layers on and off and observe the change in the view.

From the smart icons bar, test the zoom in, zoom out, zoom to extents, zoom to window icons, scrolling, and re-centering. Figure 2.8.

Step 3 In this step you will locate a well in the center of the Vincennes wellfield, and draw setback protection area.

Make a duplicate database "setback1". (**Project** , **Make Duplicate Database**, `setback1`). WhAEM2000 stores project information as it is entered, as is common in database programs. This is in contrast to word processing programs, where you are required to enter information, and then save to the file. So it is useful to make a new project database anytime you start a new exercise.

Minimize the WhAEM2000 window. Restore (or open) the **dlgv32** program and explore the Vincennes
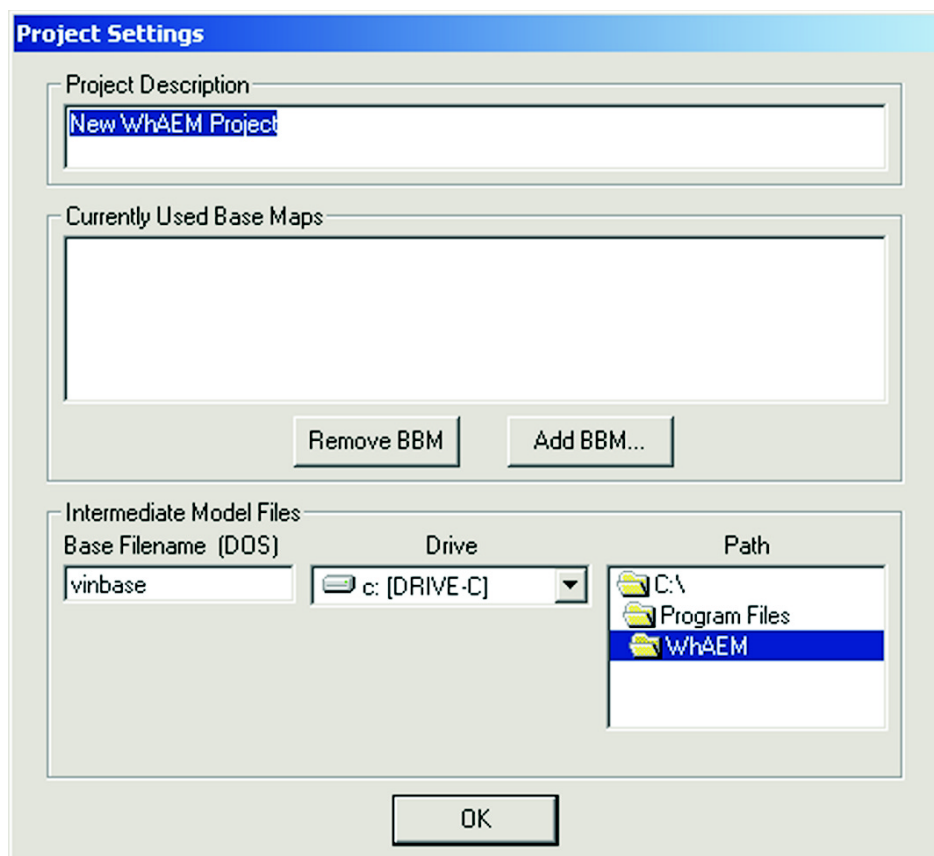
Figure 2.5: New database wizard.

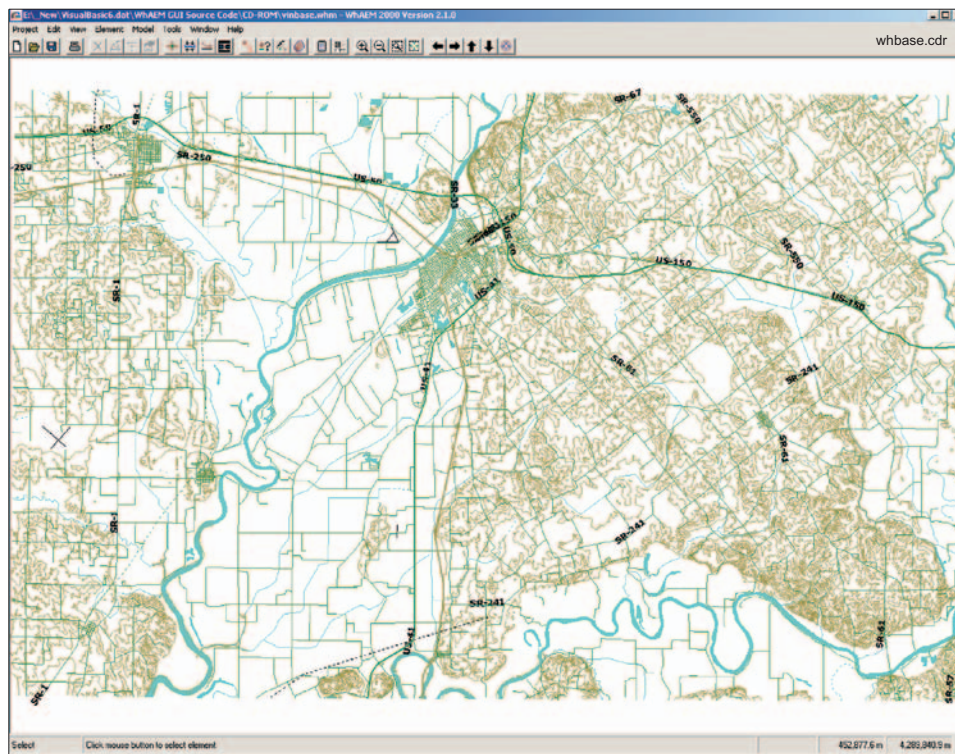Figure 2.6: Project settings.

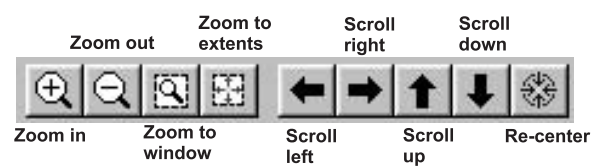Figure 2.7: The base map view.
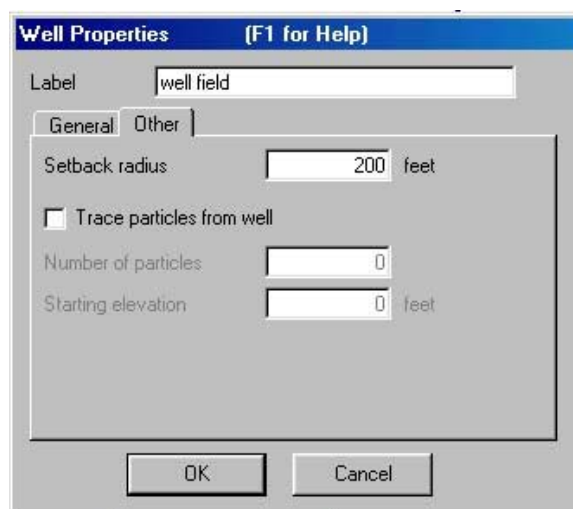

Figure 2.8: The View smart icons.

Figure 2.9: Well properties dialog box.

Figure 2.10: Well properties dialog box.

DRG map. Zoom to the Vincennes wellfield. Position the cursor near the pumping center and read off the UTM coordinates. Note that $452650m, 4280665m$ is about the pumping center. Minimize or exit the program dlgv32.

Restore the WhAEM2000 window. Zoom in to the city of Vincennes.

To create a well, from the Menu select **Element** , then select **New** and click on **Well**. Move the cursor to the approximate location of the well, based on your exploration of the Vincennes DRG map, and click the left mouse button. A marker for the location of the well is added to the base map and a dialog box appears. Type in a name for a label, e.g. ``well field''. Under the Other folder enter the "Setback radius" of $200 feet$. Figure 2.9.

Under the General folder, re-adjust the well location to be utm location $x = 452650m, y = 4280665m$ by typing into the X and Y boxes. Figure 2.10.

Click *OK* to add the well to the database.

Zoom in on the well and note the setback is plotted as a dashed circle around the well. Figure 2.11.
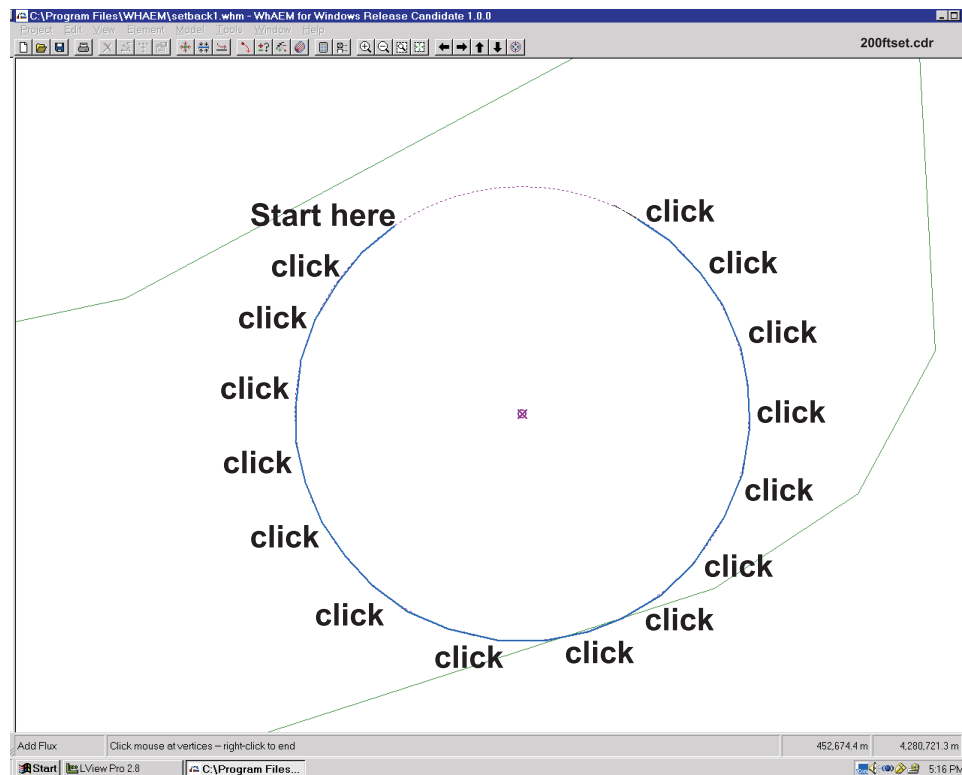
Figure 2.11: 200 foot setback.

Draw the wellhead protection area (**Edit** , **Draw wellhead protection area**). Name the protection area "200 ft setback". With the left mouse button, click a series of short segments along the dotted outline; click with the right mouse to close the final segment.

The purpose of drawing this area by hand is separate the delineation of the capture zone (based on hydraulics/hydrology) from the definition of the wellhead protection area (based on other considerations, such as parcel or zoning boundaries). The draw utility allows the wellhead manager to fine tune the shape of the wellhead protection area to correspond with on-the-ground realities. Also, if multiple capture zones are generated using various conceptual models, a "wellhead protection area" may be drawn that envelops the various capture zones for maximum protection. More on this later.

Chapter 3

PROTECTION ZONES II — RESIDENCE TIME CRITERIA

The justification of the residence time criteria as protective of ground water source water protection is based on the assumption that: (1) non-conservative contaminants (open to sorption or transformation processes) will have an opportunity to be assimilated after a given mean time in the subsurface; or (2) that detection of conservative contaminants (no sorption or transformation) entering the protection area will give enough lead time for the drinking water community to develop a new water supply or take immediate remedial action. In this chapter we will examine two simple methods involving the residence time criteria as applied to our Vincennes case study: (1) calculated fixed radius; and (2) well in uniform flow.

3.1 Calculated Fixed Radius

The fixed radius can be calculated based on a simple two dimensional static water balance analysis, assuming negligible ambient flow in the aquifer. If we assume radial flow toward a well in an aquifer with a constant saturated thickness $H(m)$, the cylindrical boundary of radius $R(m)$ is delineated by an isochrone of residence time $t(days)$, which means that any water particle that enters the cylinder or is present in the cylinder will travel no longer than t days before being pumped up by the well (See Figure 3.1). The pumping rate of the well is $Q(m^3/day)$, the areal recharge to the water table rate due to precipitation is $N(m/day)$, and the aquifer porosity is $n(-)$. A water balance for the period t yields:

$$N\pi R^2 t + n\pi R^2 H = Qt \tag{3.1}$$

The first term represents the inflow due to aquifer recharge, the second term represents the amount of water contained inside the cylindrical aquifer, and the term of the right hand side is the total amount of water removed by the well for the pumping period. The radius R can be expressed as:

$$R = \sqrt{\frac{Qt}{N\pi t + n\pi H}} \tag{3.2}$$

When t becomes infinitely large, the radius R represents the complete capture zone:
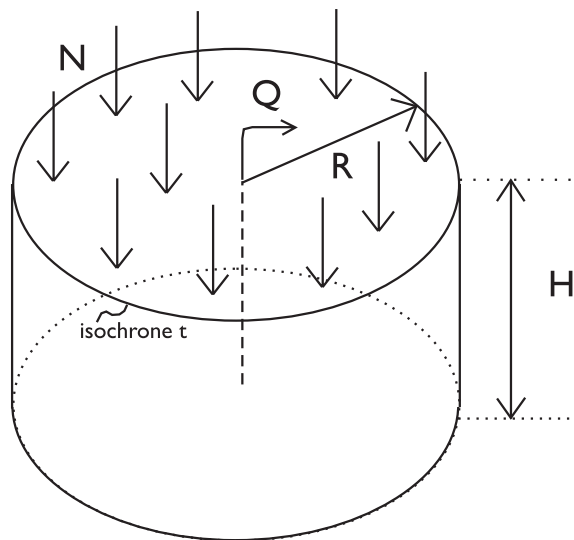
$$R \approx \sqrt{\frac{Q}{\pi N}} \tag{3.3}$$

Figure 3.1: Water balance for radial flow to a well in a domain bounded by an isochrone of residence time t.

Use of this equation is called the "recharge method" [USEPA,1993].

If the term $N\pi t$ becomes small, due to a small value of t or N or both, equation 3.2 reduces to:

$$R \approx \sqrt{\frac{Qt}{n\pi H}} \tag{3.4}$$

Use of this equation is called the "volumetric method" [USEPA,1993].

The equations 3.2 through 3.4 only apply if the Dupuit assumption applies, that is shallow, horizontal flow. If the capture zone or isochrone radius is smaller than say twice the saturated aquifer thickness, and the well is partially penetrating, then three-dimensional effects may become important, and the approximation may lead to an underestimation of the capture zone isochrone radius R. Such a non-conservative result may be avoided by replacing the saturated thickness H in Equation 3.4 by the length of the well screen.

The radially symmetric isochrone in Figure 3.1 will only occur in the absence of ambient flow or if the well dominates the flow inside the isochrone. For an isochrone with t as 1 or 2 years and a high capacity well, the assumption of radial flow is often reasonable. However, a low capacity well in a strong ambient flow field will exhibit an elongated isochrone which extends in the upgradient direction well beyond the circular representation of that isochrone, as follows from Equation 3.2. Under these conditions the direction and magnitude of the ambient flow must be determined and isochrones should be constructed using the solution for a well in a uniform flow field.

The discussion so far assumed a constant saturated thickness H, as might occur in a confined aquifer of constant thickness. The saturated thickness of an unconfined aquifer will not be constant, even assuming a horizontal base, due to drawdown of the water table. A conservative (protective) capture zone will be obtained by using the smallest saturated thickness as H in Equation 3.4.

3.1.1   Exercise: Vincennes, Indiana

 Step 1 Use WhAEM2000 to plot the Calculated Fixed Radius protection areas based on the recharge method and the volumetric method.
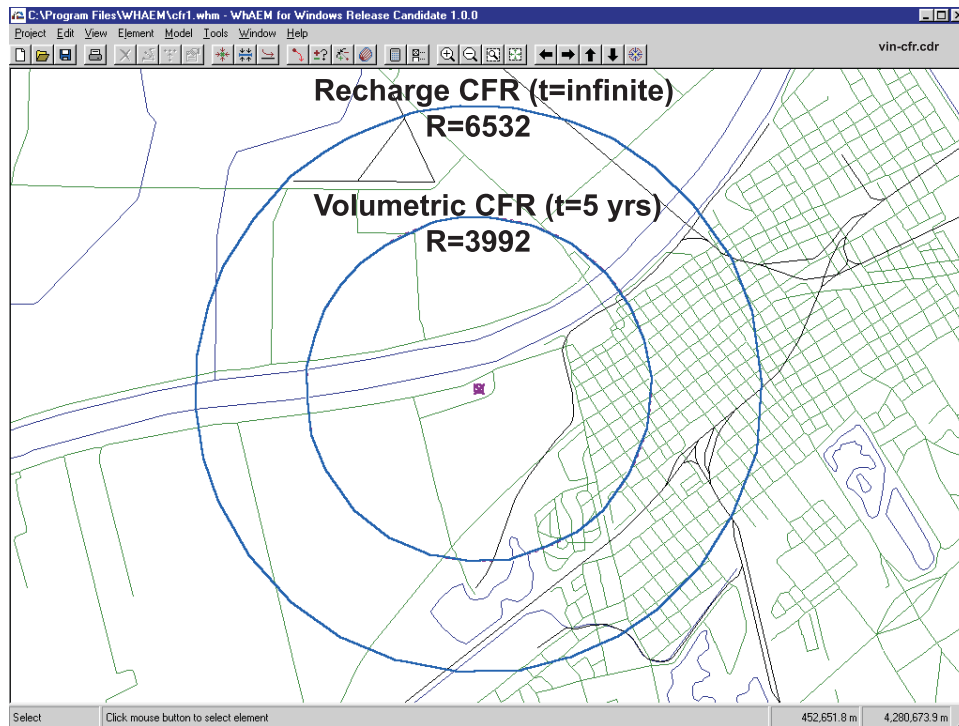
Figure 3.2: Calculated fixed radii for Vincennes wellfield based on recharge and volumetric methods.

We will continue to build on the previous exercise. **Open** the `setback1.whm` project. You may get a warning about no specified head condition set yet. Acknowledge, and carry on. From the menu, select **<u>P</u>roject** , then **Make Duplicate Database** and type `vincfr1` in the File Name box. Click **open**.

For the recharge method, use equation 3.3, and assume the well field pumps $Q = 370,000 ft^3/day$, and the areal recharge to the water table is $N = 0.00276 ft/day(12.1 in/yr)$, and calculate R. If you do not have a portable calculator handy, we suggest you use the Microsoft Windows calculator (Start > Programs > Accessories > Calculator). Recall $\pi = 3.14$. To draw the new radius on the screen, double click on the well, and edit the setback box and type in the new radius. After clicking **OK**, drop down the **<u>V</u>iew** menu and click on **Refresh**. You may have to zoom out to see the circle (setback zone). Draw the wellhead protection area (recall the exercise in previous chapter).

For the volumetric method, use equation 3.4, assume $Q = 370,000 ft^3/day$, aquifer saturated thickness $H = 67.5 ft$, the aquifer porosity is $n = 0.2$, and the pumping period is five years (1826.25 days). Draw the wellhead protection area.

Compare your results to Figure 3.1.1.

3.2   Well in Uniform Flow

Ambient flow, resulting from far field aquifer recharge due to precipitation and ground water exchanges with streams and lakes, may be approximated by a uniform flow field (straight streamlines) in the immediate vicinity of the well. The capture zone for the well in a uniform flow field will no longer be circular and centered about the well, but will be a somewhat elongated oval-shaped domain into the direction of uniform flow.

To determine this capture zone (e.g. by use of WhAEM2000) it is necessary to determine:

- direction of the ambient flow.

- the hydraulic gradient.

- the aquifer transmissivity.

- the pumping rate of the well.

- the desired maximum residence time.

Given three water levels (average, static), it is possible to estimate the direction of the ambient flow and the hydraulic gradient [Heath,1983]:

1. Identify the well that has the intermediate water level.

2. Calculate the position between the well having the highest head and the well having the lowest head at which the head is the same as that in the intermediate well.

3. Draw a straight line between the intermediate well and the point identified in step 2. This line represents a segment of the water level contour along which the total head is the same as that in the intermediate well.

4. Draw a line perpendicular to the water level contour and through the well with the lowest (or highest) head. This indicates the direction of ground water movement in an isotropic aquifer.

5. Divide the difference between the head of the well and that of the contour by the distance between the well and the contour. This gives the hydraulic gradient.

The reader is referred to EPA's on-line three-point gradient calculator created by Dr. Jim Weaver at http://www.epa.gov/athens/learn2model/part-two/onsite/gradient3.htm.

A 3-point method based on the squared heads (water levels) has been shown to reduce bias in the estimate of the magnitude and direction of the uniform flow vector in heterogeneous unconfined aquifers, provided the monitoring wells have a significant separation distance, and that there are no sources and sinks in between [Cole, Silliman, 1996].

Be sure to do a search of the scientific literature (US Geological Survey, State Geological Survey) to find any studies of the regional aquifer system and the regional hydraulic gradient.

The aquifer transmissivity should be determined by a pumping test. This is an expensive procedure, and transmissivity is known to be scale dependent. Perhaps transmissivity measurements are available from locations not too far from the well.

The well in uniform flow solution is difficult to parameterize in practice. It is difficult to anticipate the average hydraulic gradient and direction of flow given limited synoptic observations of a transient phenomenon. It is difficult to separate out the local effects of the well, unless it is out of production for a period of time. For these reasons, caution is advised to the use of the well in uniform flow solution. The modeler is encouraged to respond to the uncertainty by generating a number of reasonable solutions, and encapsulating the union of solutions into a protective area. In other words, use the "wellhead area" drawing tool to draw an envelope around the set of capture zone realizations.
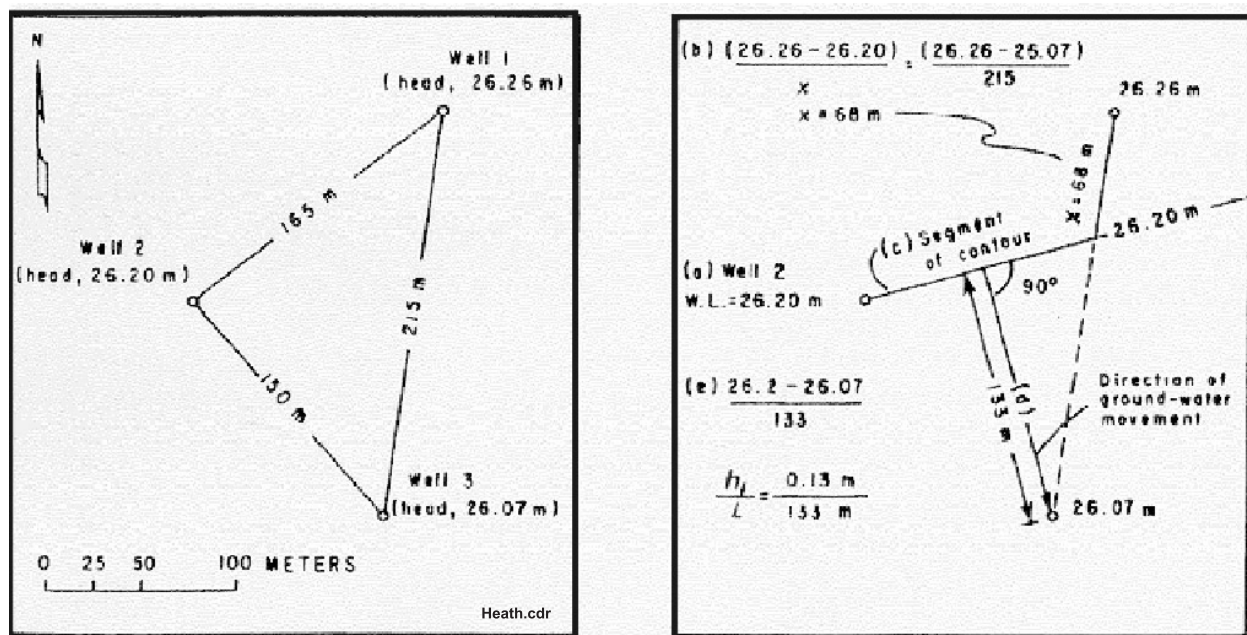
Figure 3.3: Procedure A for determination of an equipotential contour and direction of ground water flow in homogeneous,isotropic aquifer (after [Heath,1983]).

3.2.1 Exercise: Well in Uniform Flow, Vincennes, Indiana

Step 1 Determine the magnitude and direction of a uniform flow field near the Vincennes pumping center.

First we will give our project a new name. Open the database from the previous exercise. From the Menu, **Project** , **Make Duplicate Database**, and enter `vinuni1`.

As a first estimate, we will attempt to characterize the uniform flow field by using the USGS topographic map and the USGS DLGV32 software and the Vincennes DRG. The "lakes and ponds" in this area are actually abandoned quarries, and the removed overburden gives a window into the elevation of the water table. We assume these pits act like large piezometers, and field observations confirm that their water levels do in fact respond to recharge events.

A note of caution is deserved regarding extracting water elevations from USGS topographic maps. These elevations reflect a snapshot in time (check the date of publication of the map), and may not reflect conditions related to your study. The Vincennes maps was photo-revised in 1989. The elevation values are accurate say plus or minus a foot. The spatial accuracy of the topographic lines are accurate say plus or minus 5 feet. These uncertainties are acceptable for this level of analysis.

Use the method of Heath or the OnSite Calculator discussed in the previous section,with the following three points of known head: (1) Mirror Lake (407 feet); (2) Otter Pond (403 feet); and (3) the 400 foot topographic line crossing of the Wabash River.

Step 2 Use the uniform flow element in WhAEM2000 to fit the estimated uniform flow.

Zoom to approximately the view shown in Figure 3.4, which includes Mirror Lake and Otter Pond. From the Menu, select **Element** , then **Uniform Flow**. Acknowledge the warning. Click the cursor over Mirror
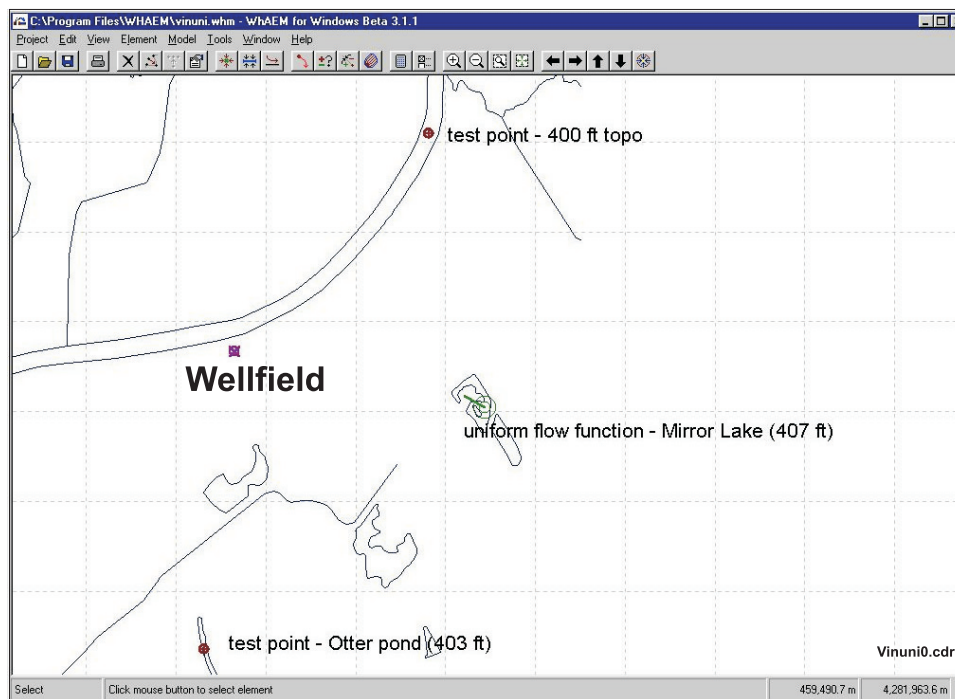
Figure 3.4: WhAEM2000 view of test points used to calculate uniform flow vector.

Lake. Enter in the elevation $407feet$. Enter the gradient (for our case about 0.001). Enter the angle (for our case about 150 degrees).

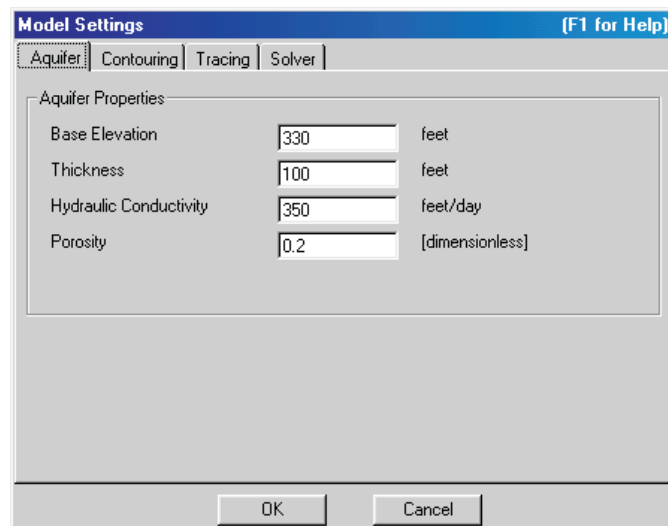Step 3   Enter the aquifer and contouring properties and test points.

From the Menu, select **Model** , then **Settings**, and then select the **Aquifer** tab. Set the **base elevation** to $330ft$, the **thickness** to $100ft$, the **hydraulic conductivity** to $350ft/day$, and leave the **porosity** as 0.2. Figure 3.5.

Now set the **Contouring** properties. Select the Contouring tab. Check the **Show Contours** box and select the radial button for **coarse** (resolution). Enter the **minimum contour** elevation of $390ft$, the **maximum elevation** of $430ft$, and a **contour interval** of $1ft$.

Click on **OK**.

To test our conceptual solution, we may introduce so-called "test points" at locations of *known* head, e.g. Otter Pond ($403ft$ and utm 452325, 4277311) and the $400ft$ topographic intersection (utm 454815, 4283085) with the Wabash River, by selecting **Model** , then **add test points**, locate on the screen with a click of the left mouse button, and enter the elevations. The test points will store the difference between the model head and the observed head. The head differences at the test points are visually displayed after the solve with a scaled triangle, or can be queried by clicking on the test point (look at the status bar at the bottom of the screen when clicking a test point).
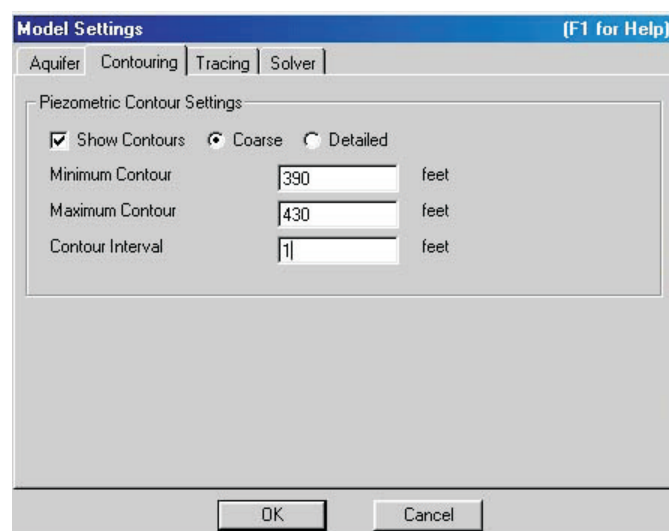
Next we will set some options for the solution process. Select the Solver tab. Make sure that the options: View error log file after solve and View message log file after solve are both checked. While our uniform flow model has only linear equations (see comment on the dialog box) you may set the number of iterations to 2 in order to achieve some "iterative refinement" of the solution.

Figure 3.5: Aquifer settings dialog box.

Figure 3.6: Contouring settings dialog box.
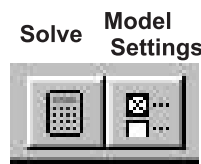
Figure 3.7: Solve icons.
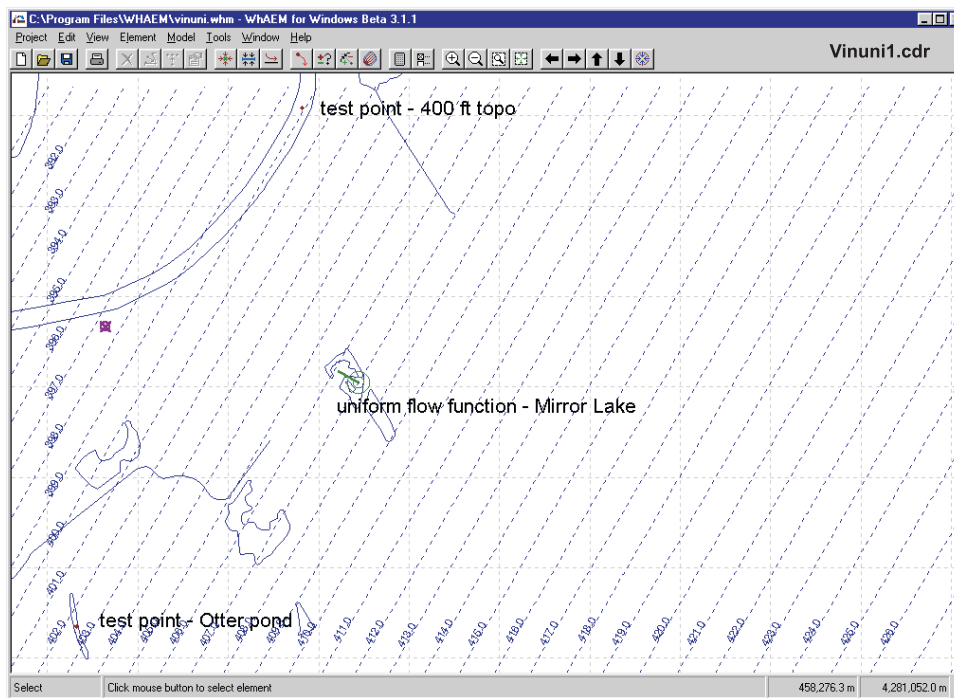
Figure 3.8: Hydraulic head contours of uniform flow field with test points.

Step 4 | Solve the model and plot the contour map.

From the menu select **Model**, then **Solve** (Alternatively, use the F9 mapped function key, or the smart icon Figure 3.7). A black box appears with some progress indicators for the solution process. When the solver is done the base map reappears with an overlay of piezometric contours (blue lines) that are labeled with their piezometric head elevations. On top of the base map the two log files, specified on the Solver tab, are opened in Notepad. The file Error.log should have only an asterix on the start of the first line and be empty otherwise. The file is used by the Solver to report problems (errors or warnings) with the input data. Close the file after reviewing its contents.

The file Message.log contains Solver activity messages and a report of maximum errors in boundary conditions. In general, errors should be less than 1%. Close the file after reviewing its contents.

The hydraulic head contour map of this solution is shown in Figure 3.8.

Note: since our model heads will be close to the test point heads, the triangles designating the head difference will be too small to see. Change the direction or magnitude of the uniform flow field and you will see the triangles grow in size. You may modify the test point appearance by selecting **Test Points** on the **View** menu.

Step 5 | Enter the pumping rate and radius of the pumping center.
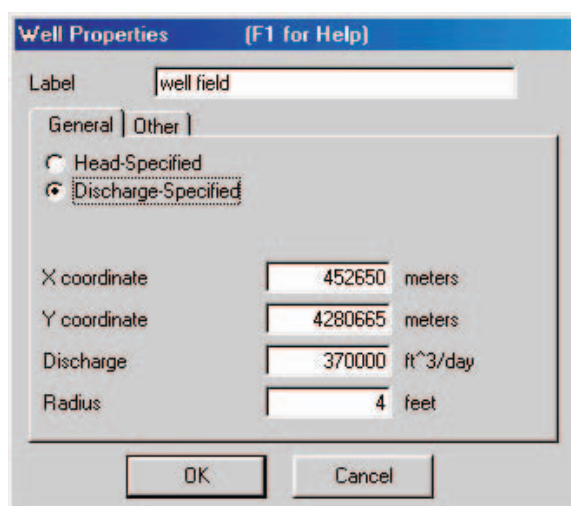
Figure 3.9: Well dialog box.

Locate the Vincennes pumping center either by double clicking on the existing well or creating a new one (**Element** > **New** > **Well**). Enter in the well **pumping rate** of $370,000 ft^3/day$. Enter a **radius** of $4ft$ to represent our pumping center. The Vincennes wellfield consists of a local cluster of at least 5 wells; we will represent with a single pumping center. Too small an effective radius and the pumping center will draw the water table below the aquifer base. The radius value does not effect the flow solution, but will provide the starting point for particle of particles during capture zone delineation. A radius of 4 feet will work fine. Figure 3.9.

Enter **OK**.

Step 6   Plot a capture zone based on 5 years of residence time.

From the well properties box, click on the "Other" tab, on the well, and check the box **Trace particles from Well** in the Other tab, and set the **Number of pathlines** to 20. The well is assumed fully penetrating so we have an option to set the starting elevation of the trace particles. Set the **Starting elevaton** to $335 feet$ (that is $5 feet$ above the aquifer base). Click on **OK**. Go back into the **Model** , **Settings**, and select the **Tracing** tab. Check the box **Compute particle paths**. Accept the default **Step size**, and change the **Maximum travel time** to 1826.25 days (5 years). In the Contouring tab, click off the show contours box. Click **OK** and click the calculator button on the tool bar (re-solve). You can add the tic marks by going to **View** , and select **Pathlines**, then **Show Time Tics**, and check **Every 1 years**. Draw the wellhead protection area around the trace lines. The graphics should look similar to Figure 3.10. You are encouraged to try a number of equally valid uniform flow field solutions, and vary the **Model** setting parameters to get insight into the sensitivity of the solution to the parameterization.

The solution is becoming more realistic. However, we still do not account for the presence of the Wabash River and other hydrological features in the area! We shall do that in the next chapter.

Step 7   Compare solutions.

It is interesting to do a verification of the well in uniform flow solution in comparison to the CFR volumetric. Click on the well, enter the 5 year CFR volumetric previously calculated (R=3992 ft). Change

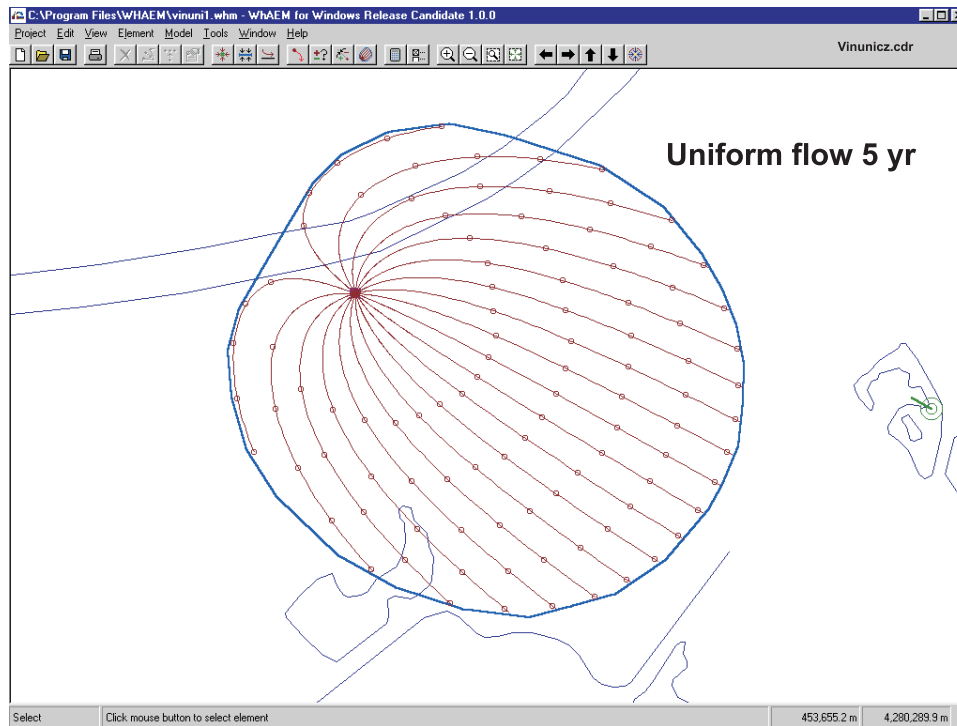Figure 3.10: Capture zone based on 5 years residence time in uniform flow field.

the uniform flow gradient to a very small number, say 0.00001, and plot the 5 yr capture zone. Notice that the uniform flow and the CFR capture zones become essentially equivalent, as expected. Figure 3.11.
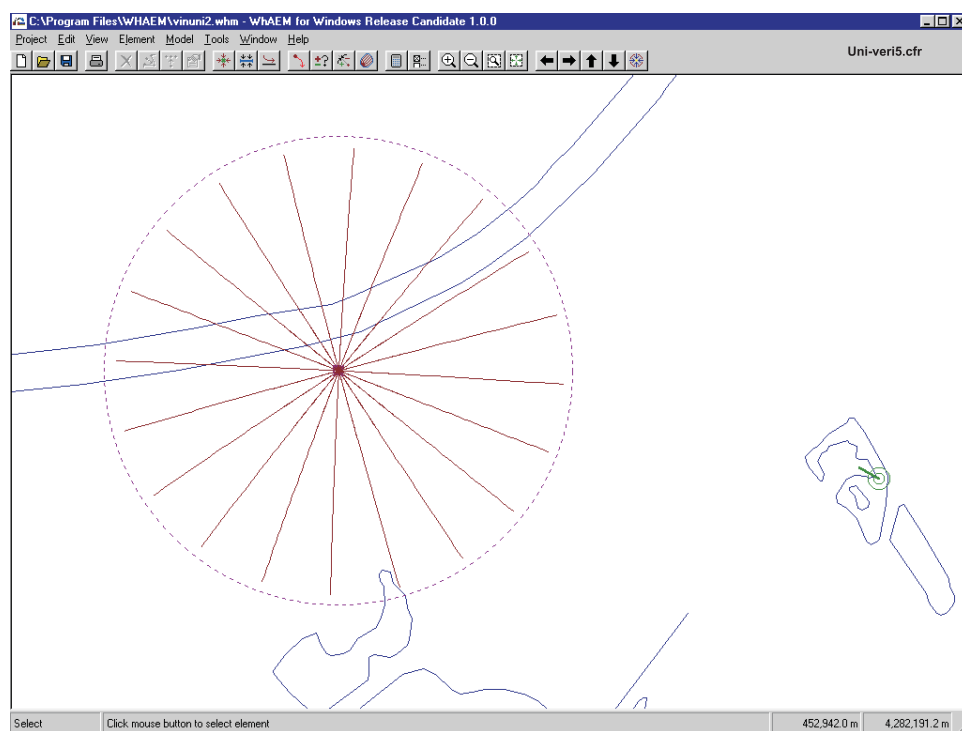
Figure 3.11: Capture zone based on 5 years residence time based on CFR volumetric and tracelines for well in uniform flow field (zero gradient).

Chapter 4

PROTECTION ZONES III — FLOW BOUNDARIES CRITERIA

In the previous analyses we have ignored the presence of hydrological boundaries. Instead, we lumped their effects near the well into a uniform flow field. Our geology might also have been oversimplified. In this chapter we will examine the influence of hydrological and geological boundaries on the capture zone. To do so we will use the full power of WhAEM2000. We will progressively refine the complexity of our hydrogeological conceptual model using the Vincennes example. But before doing so we will explain briefly how the analytic element methods work. The reader is encouraged to explore in more depth the topic of system and boundary conceptualization outside of this tutorial [Reilly, 2001].

4.1 Introduction to the Analytic Element Method

WhAEM2000 uses the analytical element method to solve ground-water flow subject to hydrological boundary conditions. Analytic elements are mathematical functions that represent hydrogeologic features in a ground-water flow model. For instance, a meandering creek or river may be represented by a string of straight line elements, which approximates the geometry of the stream. In WhAEM2000, each of these line elements is associated with a "line-sink function", which represents mathematically the ground-water inflow, or outflow, into the stream section. The sink density of the line-sink equals the ground-water inflow into the stream section. Each stream section is likely to have a different ground-water inflow rate and thus a different sink density. These sink densities are not known in advance. What is considered known are the heads underneath the stream sections. For instance, in WhAEM2000 it is assumed that the head underneath the center of each line-sink is equal to the average water level in the stream section it represents. WhAEM2000 has as many known heads at line-sink centers as it has unknown sink densities for the line-sinks. The unknown sink densities can then be calculated by solving a system of (linear) algebraic equations, see [Strack,1989] and [Haitjema,1995].

Other examples of analytic elements in WhAEM2000 are wells (point sinks in two-dimensions), line doublets or "double layers" to represent aquifer inhomogeneities, and area elements to model area recharge due to precipitation (using a negative sink density to create infiltration). Once all sink densities and doublet densities are calculated — the solution procedure in WhAEM2000 — the head and average ground-water flow rate can be calculated at any point by adding the influence of all the line-sinks, point-sinks, line doublets, and areal elements. This is the principle of superposition.

Note: the ground-water velocity is calculated by adding "derivative functions" for the analytic elements, which have been obtained analytically and are programmed into W*h*AEM2000. For details on the mathematical functions and on the mathematical procedures to enable the superposition of solutions of both confined and unconfined flow, the reader is referred to [Strack,1989] and [Haitjema,1995].

Analytic elements are defined in W*h*AEM2000 by clicking the **El̲ement** menu, and selecting **New**.

4.2   Rivers and Line-sinks

Line-sinks are used to represent streams (creeks, ditches, and rivers) and lake and coastal boundaries. A line-sink in W*h*AEM2000 has a constant sink density (constant groundwater extraction rate along the line element). The sink density or "strength" of a line-sink that represents a stream section or a section of a lake boundary is in general not known. In W*h*AEM2000 this is handled by specifying a piezometric head at the center of the line-sink, which is selected equal to the average water level in the stream section or lake that is represented by the line-sink. For every unknown line-sink strength there exists one known head. This leads to a system of equations that is solved for the unknown strength parameters of the line-sinks. Every change in data in the W*h*AEM2000 model, therefore, requires a new solution procedure to recalculate the strength parameters. The line-sink strengths represent the ground-water extraction rates of the line-sinks, in volume per time per unit length of the line-sink (stream or lake boundary).

The use of line-sinks along lake boundaries implies that in W*h*AEM2000 a lake receives or loses ground water along its boundary only. This appears to be a good approximation of reality when the size of the lake is large compared to the saturated thickness of the aquifer. For streams that have a width that is large compared to the aquifer thickness, the realism of the line-sink representation may be improved by positioning line-sinks along both sides of the river.

The number of line-sinks required to represent a stream or lake depends on two factors: (1) the need to follow detailed stream geometry, and (2) the need to allow for variations in the ground-water discharge or recharge along the stream or lake boundary. Representing stream geometry is more important in the near field (immediate area of interest) than in the far field. Similarly, the need to use many small line-sinks to follow discharge or recharge variations along the stream is most pressing in the near field, particularly near a high capacity well which may draw water from the stream. Consequently, surface water features in the area of interest (near field) should be represented with more and smaller line-sinks than surface waters in the far field, remote from the area of interest.

Line-sinks are defined in W*h*AEM2000 by selecting the **El̲ement** menu, and selecting **New** and then **Line-sinks**.

4.2.1   Exercise: Vincennes and Line-sinks

Step 1   Annotate the basemap with elevations.

It is useful to annotate your basemap with estimated surface water elevations at those streams that you intend to include in the model (represent by line-sinks).

Open the database file `vinbase.whm`. Create a duplicate database `hydro1`. Minimize the W*h*AEM2000 window. Open the USGS 7.5 minute topographic map for Vincennes with the dlgv32 program. Find the location where the $400ft$ topographic contour crosses the Wabash River north of the city. Note below the

UTM location of the $400ft$ contour:

$$utm - x(easting) = \underline{\hspace{3cm}} \tag{4.1}$$

$$utm - y(northing) = \underline{\hspace{3cm}} \tag{4.2}$$

Now minimize the dlgv32 window, and restore the W*h*AEM2000 window. **Zoom In** to the location of the $400ft$ contour. From the Menu, select **Edit**, and then **Add text**, move the text cursor to the proper location (using feedback on the UTM location of the cursor from the bottom status line) on the stream and click the left mouse button. Type the contour elevation 400 feet in the dialog box, check the **Hydrography Label** option, and click **OK**. The label appears in the map and the text cursor reappears. You would need to repeat this procedure to add all the rest of the hydrography elevations, i.e. elevations where topography contour lines cross the surface water features.

Note: You could also *eyeball* the location of the hydro label on the W*h*AEM2000 basemap by either having a paper topo sheet in hand, or have the W*h*AEM2000 and dlgv32 windows open at the same time on your computer screen. Another option is to use a digitizing tablet and a paper topographic map, and saving the hydro labels to an ASCII text file, as described below.

It is often sufficient to add hydrography labels near the map boundaries and near confluences of streams. When creating line-sink strings you will only be prompted for a head at the start of the string and at the end of the string. It is good practice to start a linesink string at the higher elevation and work down. This will ensure more meaningful data reporting in the graphical user interface (GUI). The W*h*AEM2000 program linearly interpolates between the starting head and ending head for the heads at vertices of the linesink stream.

We have created a text file for you with elevations to assist in the completion of your basemap. The label file must be a comma delimited ASCII text file (`filename.TX`) in which each line has the following format:

$$utm - x, \qquad utm - y, \qquad h, \qquad label \tag{4.3}$$

where x and y are the (basemap) coordinates of the lower left corner of the text, where $h = 1$ for hydrography labels (water levels in surface waters) and $h = 0$ for any other text label. The label is the water level or text to be printed on the map. The text labels will be added to the current project database file. To import the file containing text labels select the **Tools** menu, then **Import**, and then **Text Label File**. Select the file `Hydro_Example.tx`. In order to view the hydrography labels on the basemap, you may need to toggle them on (**View > show hydrography labels**).

Step 2 | Represent the Wabash River with a string of Line-sinks.

At this point, it is recommended that you set your window to frame the region including the 395 foot elevation and 400 foot elevation of the Wabash River. Then, from the menu select **Element** , and then **New**, and then **Linesink**, or alternatively, click on the Line-sink smart icon Figure 4.1. You will be prompted for the name of the line-sink string about to be entered. Let's start with Wabash River, hence type `Wabash River`. Treat the linesinks as far field. Next fill in the **Starting Head** of 400 ft and ending head of 395 ft. Figure 4.2. Click OK. Move the cursor to the east bank of the Wabash at the 400 ft text label north of the city and click the left mouse button. Now move the cursor down stream, clicking the left mouse button to enter linesink vertices. You may elect to use shorter segments close to the wellfield. After clicking on the 395 ft location, click the right mouse button to end the linesink entry. Click OK.
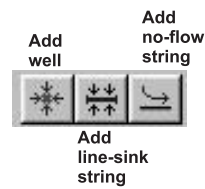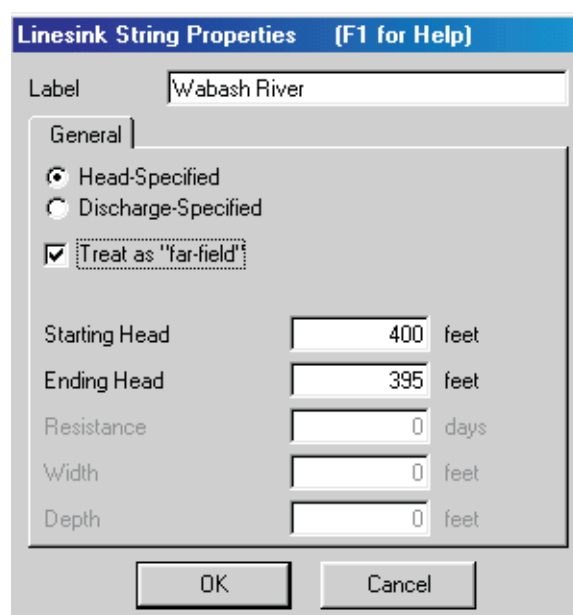
Figure 4.1: Elements smart icons.

Figure 4.2: Linesink properties dialog box.

Note: It is recommended to enter line-sink strings along streams going down-stream (into the direction of the stream flow). This is particularly important when querying line-sinks that are part of stream networks, as it will assure that the stream flow reported actually occurs at the vertex that is highlighted.

That completes your first line-sink string. At the center of each line-sink in the string a head will be specified by W*h*AEM2000 based on a linear interpolation of the starting head and ending head along the line-sink string.

We recommend you represent the other side of the Wabash River with a string of line-sinks, particularly near the wellfield. Start again at the of 400 foot contour, and continue to an estimated location of 397.5 feet (halfway between 400 and 395 ft.

<hr>

Step 3 Surround the wellfield with hydrologic (line-sink) boundaries and solve.

Position the pumping center as described in the previous Chapter, and create the discharge specified well ($Q_w = 370,000\,ft^3/d, radius = 4ft$).

You should attempt to locate head specified boundaries (line-sinks) in all directions projected out from the well-field, putting more detail (i.e. using more line-sinks) in the near field and less detail in the far field. In our steady state model, we will include the perennial streams, or streams that are flowing all year round. In the Vincennes wellfield area, those include City Ditch, Mantle Ditch, Kelso Creek, Ditch 2, Ditch 3, and the Wabash River, of course [Shedlock, 1980]. See Figure 4.3. Perennial streams show up as solid blue lines in USGS topographic maps, and dashed if ephemeral.

Create line-sinks representation of the perennial streams. Add the Vincennes well-field with the same properties as before.

Try to use short length line-sinks in the near field and longer length line-sinks in the far field. Try to keep the total amount of line-sinks below 200 for efficient model operation. You can check this by clicking **Model** and **Model size**.

You may change the location or properties of wells and line-sinks as follows. Click on the well or a line-sink vertex in the string you want to edit. The well or line-sink string will become highlighted (red). Click on the **Edit** menu and select **Properties, Move, Delete**, or **Refine**. For line-sinks you will be asked whether you want to delete only the selected vertex or the entire string. When selecting **Refine**, a vertex is added midway in the line-sink on either side of the vertex that was selected (highlighted in red).

Let's refine the line-sink distribution of the Wabash River near the wellfield. This is the area of induced recharge from the river to the well, and the solution will be improved with refinement. Click on a vertex of the line-sink string. Next click on *Refine* on the **Edit** menu. You may also click on the refine icon (the third to the right of the printer icon). Acknowledge the warning. Notice the two added vertices (dots) on either side of the vertex you clicked on. Repeat this for one or two other vertices of the Wabash River line-sink string near the well.

Now let's add areal recharge based on the USGS suggested value of 12.1 inches per year (0.00276 ft/day) [Shedlock, 1980]. To do this, from the Menu, select **Element** , **New**, **Inhomogeneity**. Type in the recharge rate of 0.00276 ft/day. Click OK. Use the mouse and click to define the boundary vertices. Surround the linesink elements with an inhomogeneity polygon. We will further the discussion of the inhomogeneity elements later in this chapter.

Your model space should look something like Figure 4.5.

From the Menu, select **Model** , and reset your **Settings**, including **Aquifer** and **Contouring** parameters as in previous exercises.
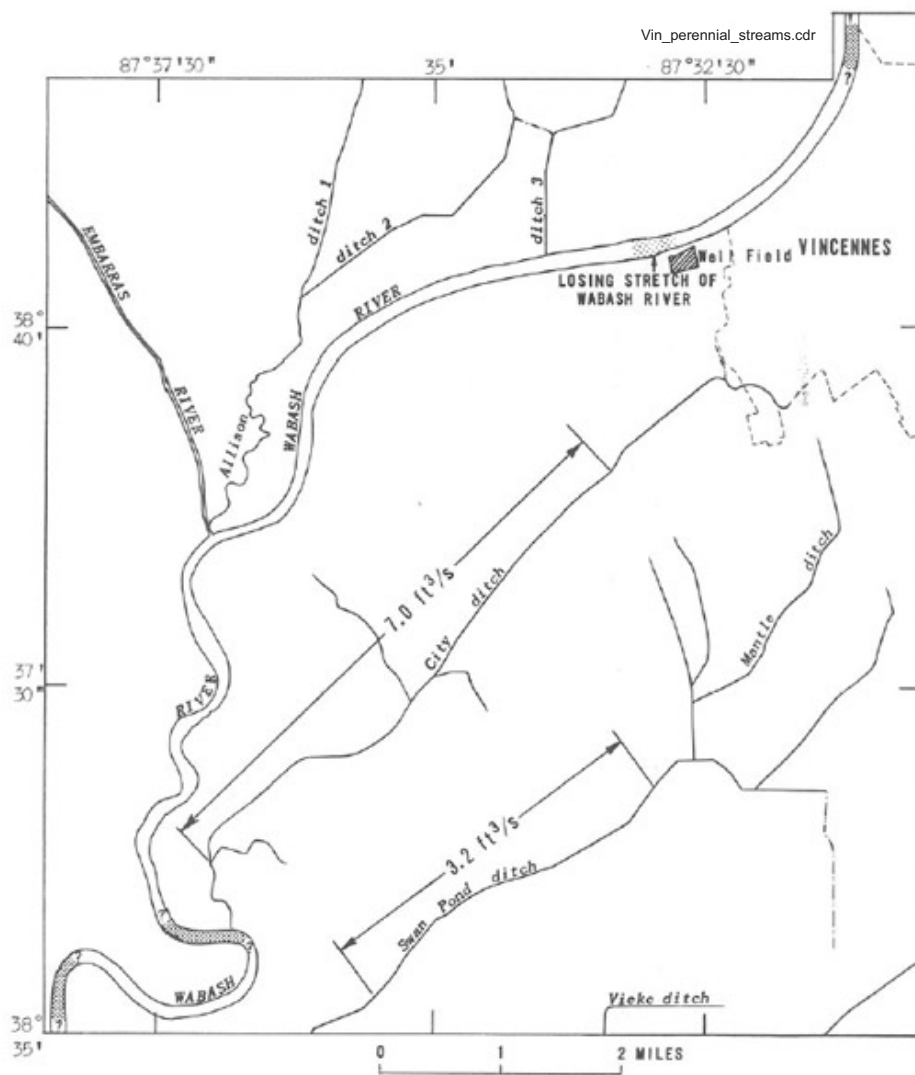
Figure 4.3: Perennial streams in the Vincennes area, after [Shedlock, 1980].

Figure 4.4: Inhomogeneity element properties box.

Step 4 | Solve and plot the 5 year capture zone for the well field.

In **Model** , **Settings**, select the **Tracing** tab and check the **Compute Particle Paths**. Double click on the well and check the box **Trace Pathlines Emanating From Well**. Select **Number of Pathlines** 20. Click **OK** and then **Solve**. Draw the wellhead protection area. Figure 4.6.

Note: if no pathlines appear, ensure they are turned on under the **View** menu and that your aquifer parameters are correct; if heads are drawn down to the aquifer bottom no pathlines will appear!

Step 5 | Check the solution for integrity.

Select **View Results Table** from the **Model** menu, click on **View** and on **Linesinks**. You are looking at the vertices of the line-sink strings. Look further to the right in the table to ensure that the "Specified Head" and "Modeled Head" for all line-sinks are nearly the same (less than one percent error). This ensures a solution that meets the boundary conditions, at least at the line-sink centers.

It is sometimes possible to compare the cumulative "discharge" of a linesink string to the observed base flow of a stream. The observation may be based on the difference between base flow separation estimates at two USGS gauging stations, or a base flow separation at a USGS gauge on a head waters reach. This would provide an additional test of the reasonableness of the model water balance (which is insured in the analytic element method) in comparison to the field.

It is useful to compare the model predicted heads to observations of heads at monitoring wells. Fortunately, the USGS has reported a series of measured water levels in the Vincennes area for the period January 23-25, 1978 [Shedlock, 1980]. These water levels have been stored in a Test Point file. To import this file, select **Tools** and then **Import** the file `vin-mw.tp`. The view will show the test point locations as triangles, with the size and direction related to the difference between model head and observed head. Figure 4.7. Click on the triangle to report the error on the bottom status bar. Notice we have some large errors in the model to the south. The conceptual model will be refined in the next section.
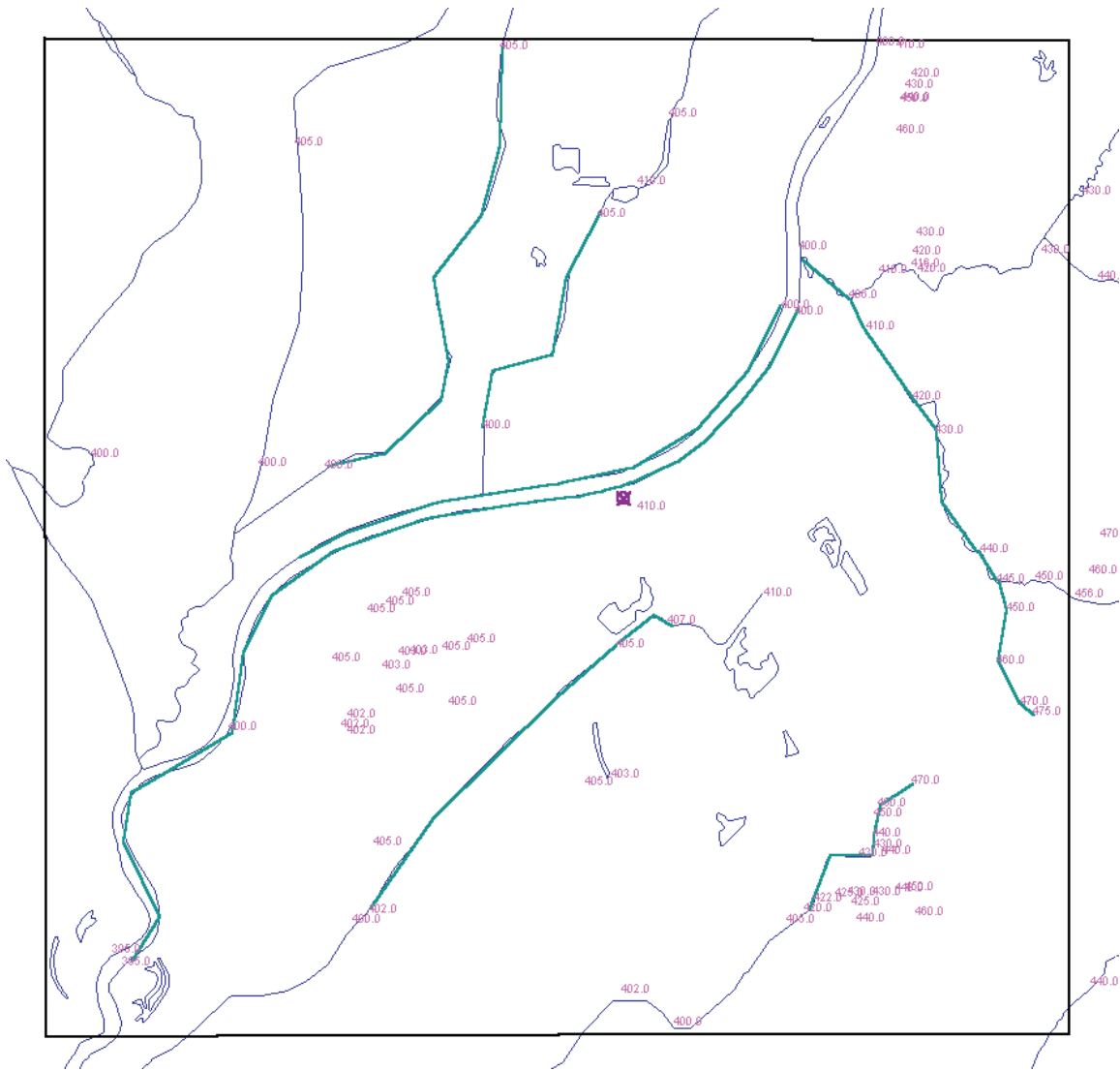
Figure 4.5: Hydrography labels, recharge element, and line-sinks representing the Wabash River between elevations $395\,ft$ and $400\,ft$ and perennial streams and ditches.
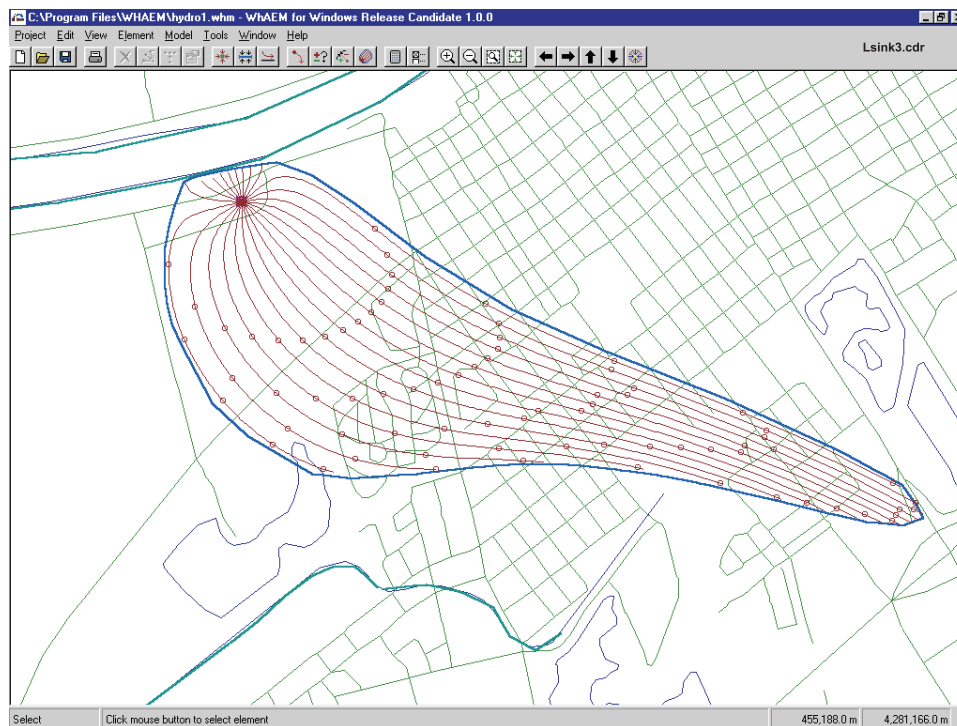
Figure 4.6: 5 year capture zones including the influence of hydrologic boundaries.
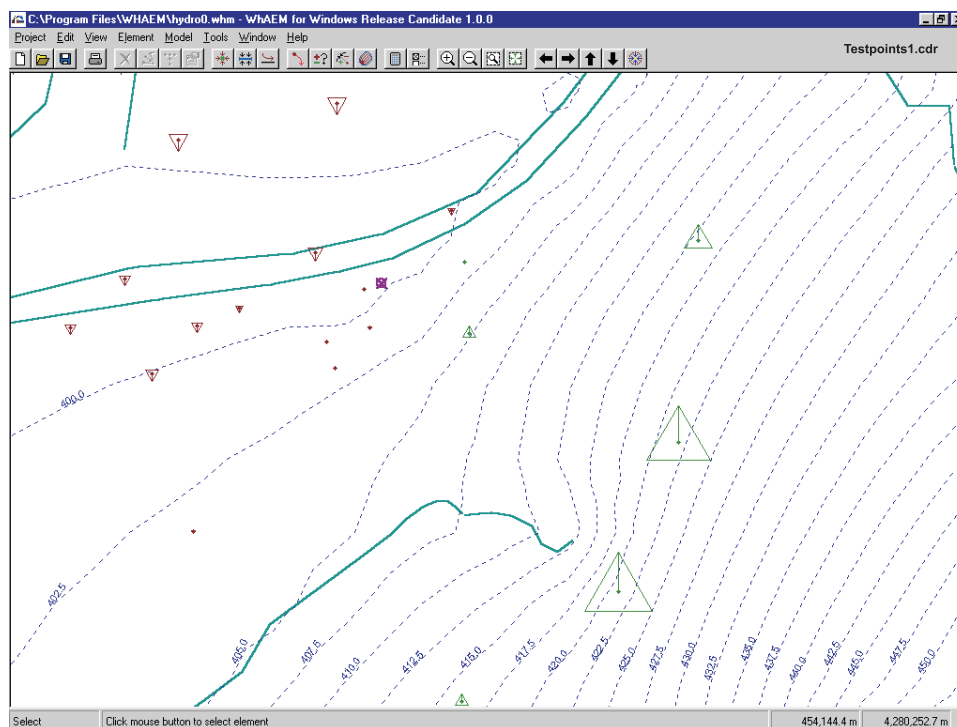

Figure 4.7: Model head contours compared to field observations at monitoring wells.

It is good practice to keep separate test point files to distinguish between differences in water level observations, such as differences in dates of observations, differences in well screen elevations, differences in quality of the measurements, etc. There is an **Edit** > **Delete All** > **Test Points** sequence to assist bringing different sets of test points to the view.

Calculated heads are expected to differ from observed heads for many reasons, most importantly because the model aquifer is merely an abstraction of the real aquifer system. A good model will show test point triangles that point both up and down, whereby the differences between model head and observed head are not too large. A good model will also show a rather random distribution of up and down arrows, instead of having all up arrows clustered in one area and all down arrows in another.

In an ideal homogeneous single aquifer some general rules apply for heads that are too high or too low. Heads that are consistently too low close to the well field suggest too low a transmissivity in the model. Heads that are consistently too high in areas of ground water mounding may also indicate too low a model transmissivity or too high an areal recharge rate (or both). When the actual aquifer is significantly stratified or, in fact, consists of several vertically stacked interconnected aquifers, discrepancies between observed and calculated heads may also be explained based on the relative depth of the piezometers (wells) in the field. In most cases, shallow piezometers in a stratified aquifer tend to show higher heads than predicted in a homogeneous aquifer, while deep piezometers tend to show lower heads. Only close to discharge areas, such as streams or lakes, may this trend be reversed.

Heads that are too high or too low may also be the result of improper representation of surface waters. For instance, the headwaters of a creek may artificially raise the ground water table in W*h*AEM2000 by infiltrating large amounts of water (which these headwaters don't have to give). Such stream sections and their line-sinks should be removed from the W*h*AEM2000 model particularly if they show up as ephemeral or intermittent steams on USGS topo maps.

4.3   Geologic Contacts and No-Flow Elements

The geology of the Vincennes study area deserves a closer look at this point as we refine the conceptual model. The area is underlain by unconsolidated sediments shown in Figure 4.8. The sediments were deposited by glacial processes in the Wabash River valley during the Pleistocene Epoch and were reworked by wind and water. The outwash pinches out a the margins or the river valley and generally rests directly on the underlying bedrock, as shown in Figure 4.9. A couple of rock "islands" outcrop just south of the wellfield.

Ideally, we should represent the high permeable rock and till explicitly in our model. As a first step, we will represent in W*h*AEM2000 open strings of line elements to create a no-flow boundary positioned along the boundary of the outwash or channel deposits to approximate the effect of an absolute reduction in permeability. This no-flow boundaries should be extended into the far field to ensure complete effect in the near field.

W*h*AEM2000 conceptual models with and without these no-flow boundaries may be seen as bounding cases of the real situation, at least for the property of heterogeneous hydraulic conductivity distributions. If these two extreme models do not significantly affect the time of travel capture zones, no further (more sophisticated) modeling seems necessary. On the other hand, if the two extreme models lead to drastically different time of travel capture zones, then further refinement of the model is justified.

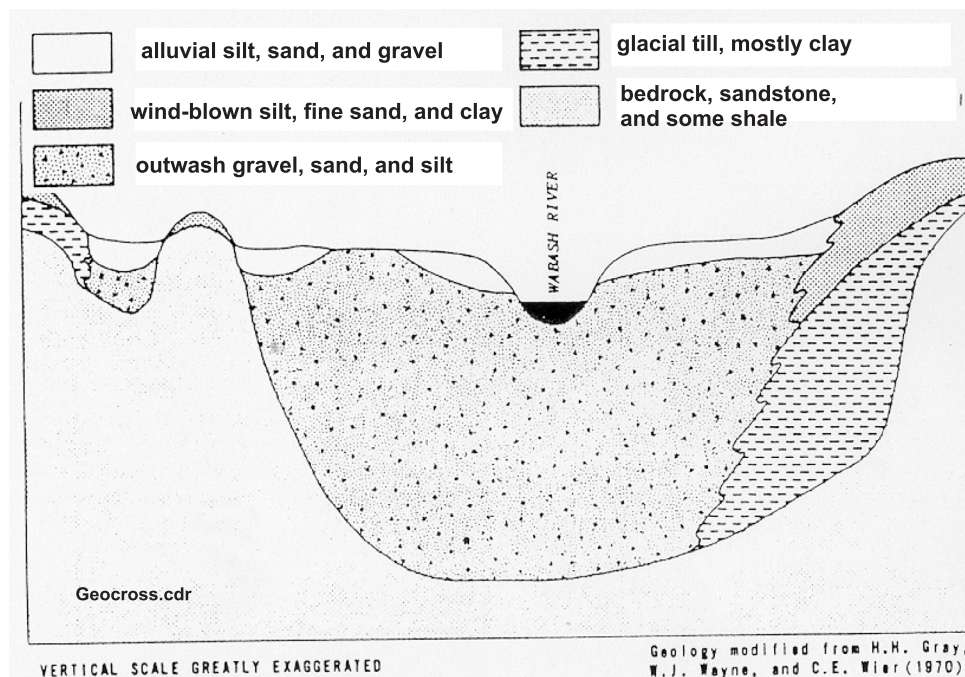Figure 4.8: Surficial geology near Vincennes, Indiana. [Shedlock,1980]

Figure 4.9: Generalized geologic cross section of the Wabash River Valley near Vincennes, Indiana [Shedlock,1980]

4.3.1 Exercise: Vincennes and no flow boundaries)

| Step 1 | Create the no-flow boundary at the topographic contact between outwash and rock.

First, create a duplicate database as `noflow1`. From the menu, select **E̲lement** , **New**, and **Horizontal Barrier**. Name the feature "Outcrop" and click **OK**. Use the mouse create vertices along the boundary (left click) and end (right click). Do the same for the island outcrops south of the wellfield. See Figure 4.10.

Remove the line-sinks that intersect or are to the east of the no-flow elements (click on string, then press delete key). The link-sink elements to the east of the no-flow elements are now hydrologically separated from the wellfield and are irrelevant to the local capture zone solution. You should avoid crossing line-sink elements and no-flow elements to avoid numerical difficulties.

| Step 2 | Solve and check the calibration.

| Step 3 | Plot the 5 year capture zone.

Double click on the wellfield, and release around 20 pathlines. Check the **Model Settings**, and **Solve**. In **V̲iew** set the **Pathlines** to **Show time tics** to **every 1 year**. Draw the wellhead protection area.

Apparently, the presence of a no-flow boundary has a significant effect on the flow patterns in the outwash, particularly on the capture zone for our wellfield (compare Figure 4.6 and Figure 4.12). If in reality some water enters the outwash from the till and rock formations to the east, the capture zone will tend to extend further to the east than for the case the rock and till are considered impermeable. This makes it reasonable to explore solutions for the problem where the till and rock formations are given a finite hydraulic conductivity,
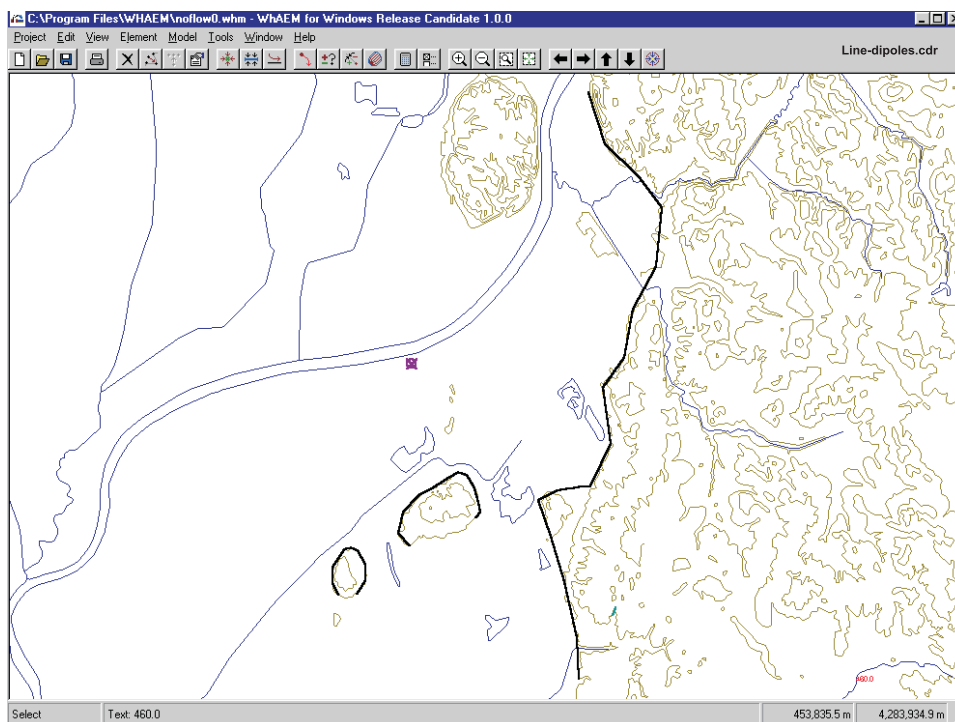
Figure 4.10: Superposition of no-flow elements along the geologic contact inferred from the topographic contours.
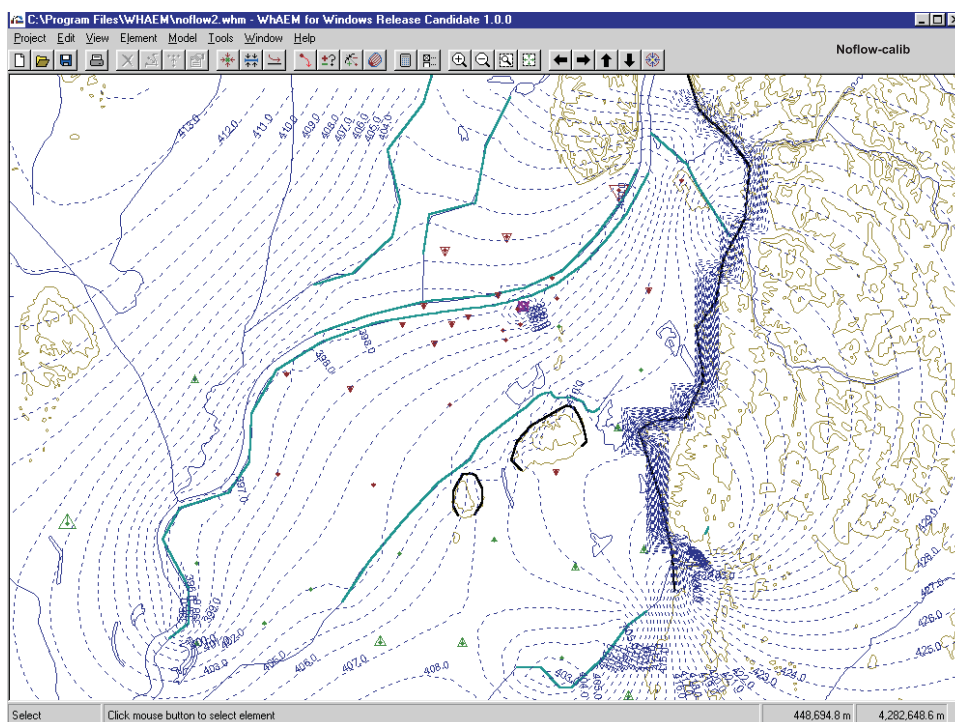

Figure 4.11: Hydraulic head contours and test points, including the no-flow elements.
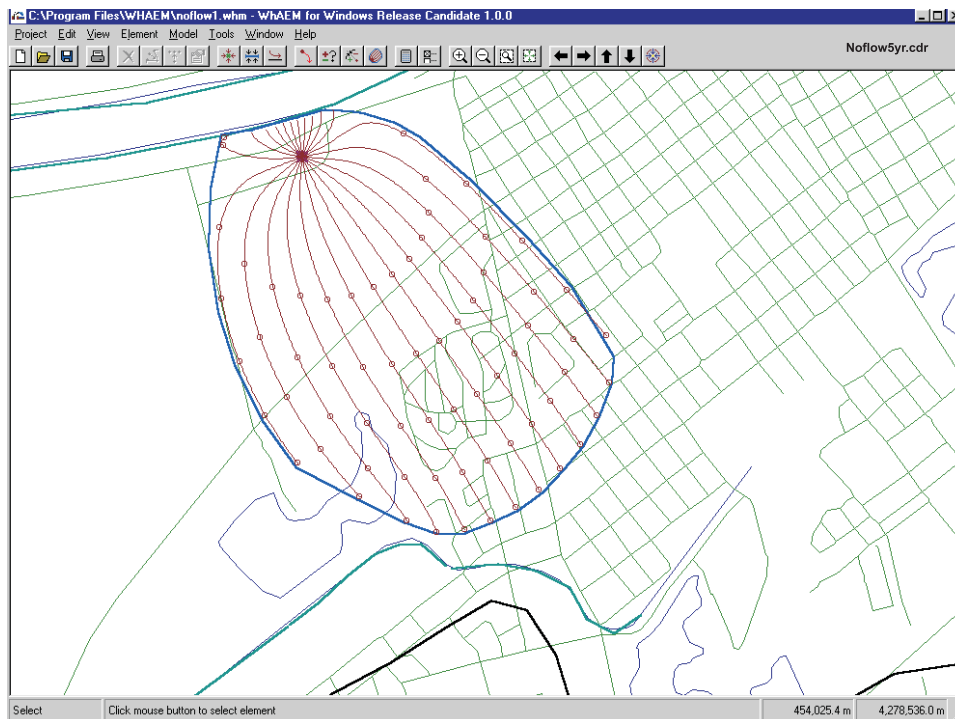
Figure 4.12: 5 year capture zone solution including the influence of hydrologic and no-flow boundaries.

as we shall see in the next section.

4.4   Aquifer Inhomogeneities

Domains with differing properties are enclosed within polygons defining the inhomogeneity using the W*h*AEM2000 interface. These domains may have a different hydraulic conductivity, aquifer bottom elevation, effective porosity, and/or areal recharge due to precipitation. W*h*AEM2000 uses mathematical features called line-doublets to simulate the polygon segments. Domains may be nested, but should not overlap. You should avoid sharp corners when designing the domains. A line-sink should be either inside or outside the inhomo-geneity domain. Extra vertices are needed near high capacity wells. See Figure 4.13.

4.4.1   Exercise: Vincennes and Inhomogeneities

Step 1 | Create inhomogeneities using W*h*AEM2000 to represent the outwash and rock outcrops.

We will build an inhomogeneity domain to represent the outwash of the Wabash River of hydraulic conductivity 350 ft/d, in contrast to the rock uplands area of finite hydraulic conductivity, say 10 ft/d.

The first thing to do is to open the `vinbase` project database, and make duplicate database `inhomo1`. Now go to **Model** , then **Settings**, and re-enter the aquifer properties (Figure 3.5), but enter a new hydraulic conductivity to a background value of 10 ft/d. You should also re-enter the data on the wellfield (Figure 3.9).

To build the outwash inhomogeneity, select **Element** , **New**, then **Inhomogeneity**. You will be presented with the opportunity to parameterize the inhomogeneity. Figure 4.14. Click the box to change hydraulic condutivity from the default. Enter the new hydraulic conductivity for the outwash domain

Drawing the inhomogeneity

Enter vertices.

Right-click on
last vertex closes
the domain.

Added
vertices

Do not create sharp
corners!

Incorrect: line-sink
should not intersect
line-doublet.

Correct: line-sink vertex is
on line-doublet.
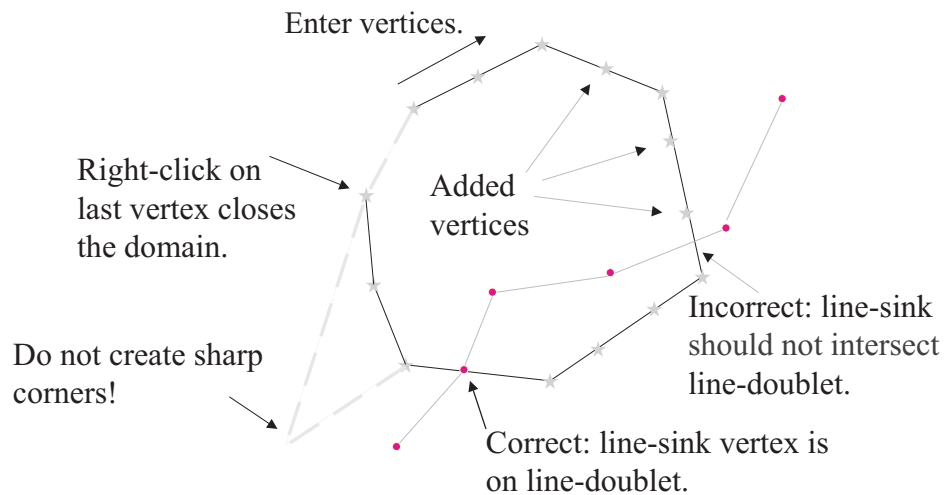
Figure 4.13: Drawing inhomogeneities using the mouse.

Inhomogeneity Properties   (F1 for Help)

Label   outwash

General

☑ Change hydraulic conductivity from default

Conductivity   350   ft/day
Added Recharge Rate   0.00276   ft/day
Porosity   0.2
Color...

☐ Change base elevation from default

Base Elevation   330   feet

☐ Provide estimate of average head

Average Head   430   feet

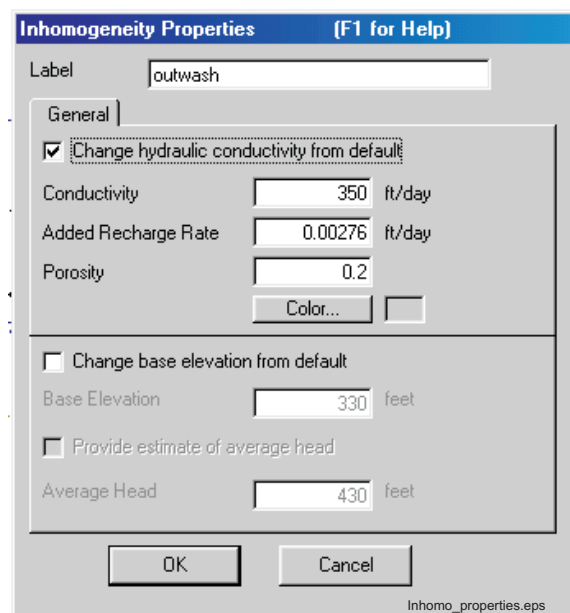OK   Cancel

Inhomo_properties.eps

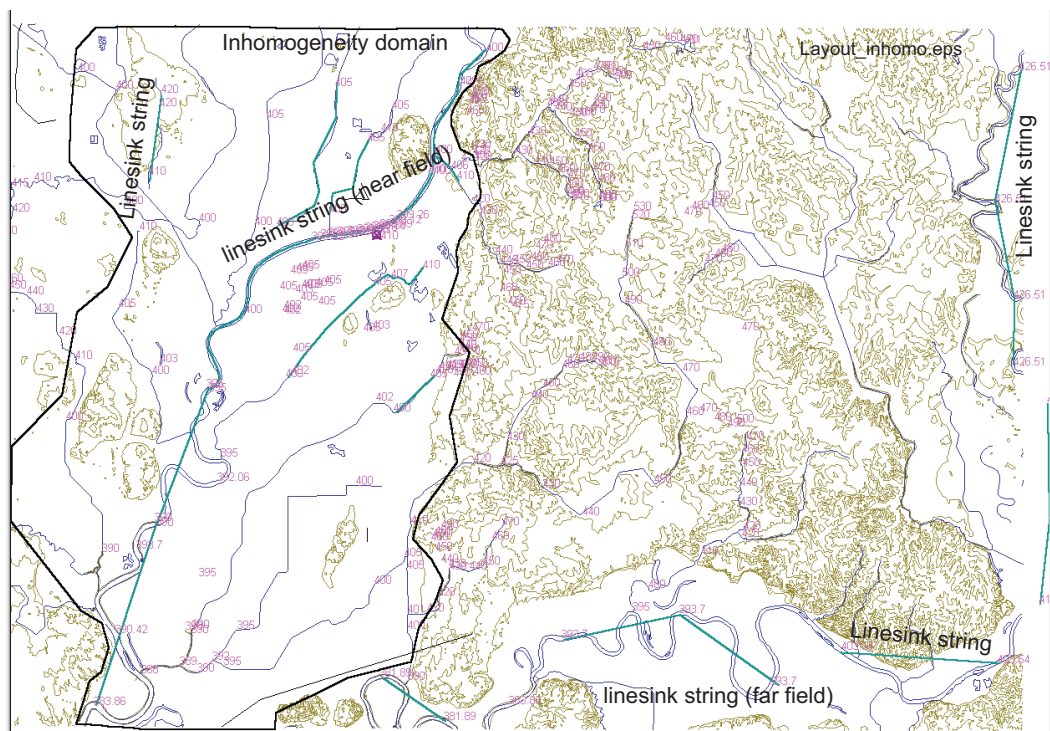Figure 4.14: Dialog window for entering inhomogeneity properties.

Figure 4.15: Layout of linesinks, wellfield, and aquifer inhomogeneity domain.

$k = 350$ ft/d. Label the inhomogeneity. Check that the recharge rate is correct. Click OK. Use the hypsography basemaps (vi1hpf06, vi1hpf07) to guide your drawing the polygon, following the sharp transition from outwash to rock. Figure 4.15.

Step 2 | Enter the linesinks representing the near field and far field.

We will want to re-enter the linesinks to represent the Wabash River, and in addition, represent the White River to the east and south. As before, bring in the already prepared text label file by **Tools** > **Import** > **Text label file** > Hydro_Example.tx. The far field linesinks are entered in a very coarse representation of the rivers. The elevations in the text label file were acquired using a USGS digital elevation model (DEM) and ArcView. The near field linesinks representing the center channel of the Wabash River between elevations 400 ft and 395 ft should be entered as in a previous exercise. See Figure 4.15.

Step 3 | Solve the model and plot the 5 year capture zones.

You are encouraged to check for improvement of the model solution by comparing the model predicted heads to the test points **Tools** > **Import** > **Test Point File** > vin_mw.tp. A capture zone solution is shown in Figure 4.16. Notice that the tracelines now extend to the north under the Wabash River. The interactions of the aquifer and the river deems further examination, as we shall do in the next section.
Advanced Use: When only the recharge differs, inhomogeneity domains may have arbitrarily large line-doublet sides, the domain may overlap any other feature, including inhomogeneity domains and linesinks, and the domain may have any shape, including sharp corners. When only porosity jumps, but not hydraulic conductivity or base elevation, the inhomogeneity domains may not overlap other inhomogeneity domains, but the domains can take any shape, including sharp corners and large sides, and the domains may intersect linesinks.
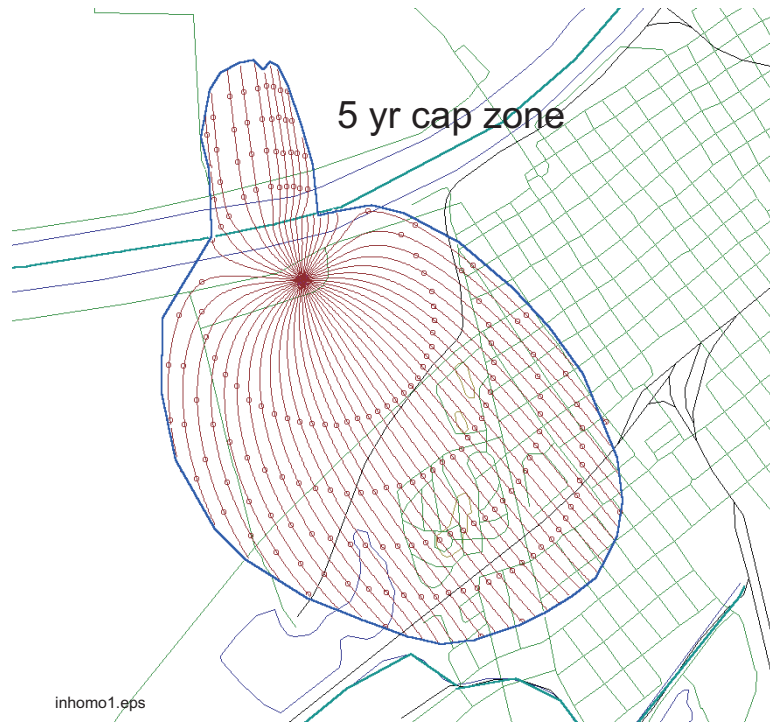
Figure 4.16: 5 year capture zone solution including the influence of aquifer inhomogeneities.

4.5 Riverbed Resistance

How do you know if riverbed resistance is important in your field study? You have resistance if there is a significant difference between water levels in the stream and heads below the stream. What causes resistance? Resistance may be caused by vertical flow near a stream/lake, silt and muck on the stream/lake bottom, a clay or till layer underneath the stream/lake, or an aquitard between aquifers (multi-aquifers).

A conceptual model of stream/lake resistance is shown in Figure 4.17. Resistance $c[T]$ is equal to the thickness of the layer divided by the hydraulic conductivity of the layer.

$$c = \frac{\delta}{k_c} \tag{4.4}$$

The vertical specific discharge $q_z[L/T]$ is equal to the head in the aquifer minus the head in the stream divided by the resistance.

$$q_z = \frac{\phi_a - \phi_s}{c} \tag{4.5}$$

The discharge of the stream segment $\sigma[L^3/T]$ is equal to the specific discharge times the width.

$$\sigma = wq_z \tag{4.6}$$

What values might one expect of the resistance parameter? Major rivers with sandy bottoms might have resistance between 0 and 1 day. Small streams with silty bottoms might have resistance in the range between 1 and 10 days. Stream or lakes in till formations (overlying a deeper aquifer) might have resistance up to 100 days. Resistance greater than 100 days means almost no interaction with the aquifer. Resistance for a specific site is dependent on both the hydraulic conductivity of the riverbed and the thickness of the unit.
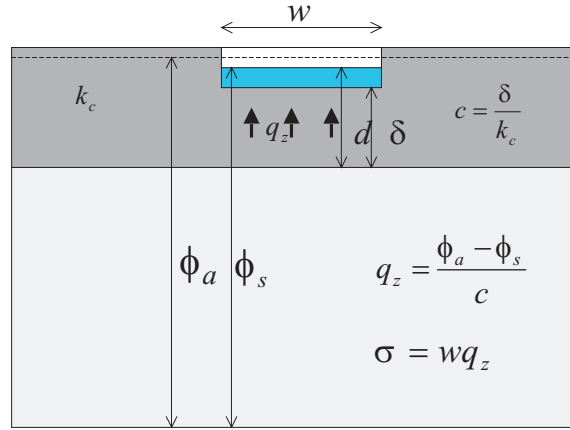
Figure 4.17: Conceptual model of stream/lake resistance.

Discharge to resistance line-sinks in WhAEM2000 is calculated given a layer of given resistance and thickness, and effective width. Line-sink effective width $w[L]$ is calculated based on a characteristic leakage length $\lambda[L]$ and the stream width $B[L]$. The characteristic leakage length is equal to the square root of the product of aquifer transmissivity (hydraulic conductivity times thickness) times resistance:

$$\lambda = \sqrt{kHc} \tag{4.7}$$

There are some rules of thumb on setting the effective line-sink width parameter, given the stream width and the leakage length.

Put line-sinks along both sides
of the stream of width w:

$w = \lambda$	$\lambda \leq 0.1B$
$w = \lambda \tanh(B/2\lambda)$	$0.1B < \lambda < 2B$
$w = B/2$	$\lambda \geq 2B$

Put line-sinks along the center
of the stream of width w:

$w = B$	$\lambda \geq 2B$

4.5.1   Exercise: Vincennes and Resistance Linesinks

Step 1   Calculate the resistance of the bottom materials in the Wabash River.

The USGS report [Shedlock, 1980] includes a discussion of the leakage from the Wabash River to the outwash aquifer in the vicinity of the Vincennes pumping center. They report a leakage layer of average hydraulic conductivity 0.03 ft/d, and of local values of 0.07 and 0.7 ft/d, and of average thickness of 1 foot. Let's work with the value of $k_c = 0.07 ft/d$ and $\delta = 1 ft$, and calculate the resistance using equation 4.4.

Step 2   Calculate the characteristic leakage length for the Wabash River.

Assume an aquifer thickness of $H = 70ft$ and aquifer hydraulic conductivity of $350ft/d$. Use equation 4.7 to calculate the characteristic length.

| Step 3 | Calculate the effective stream width for line-sink representation of the Wabash River.

Estimate the width $B(ft)$ of the Wabash River near the pumping center using the USGS dlgv32 software and the digital map `vincennes.tif`. Calculate an effective width w based on the table knowing B and λ. The Microsoft Windows calulator, under Accessories, can be set to scientific mode in the View options, giving access to the hyperbolic tangent.

| Step 4 | Enter resistance linesinks to represent the Wabash River near field.

Let's build off of the previous database. Open the project database `inhomo1.whm`. Create a duplicate database `resist1`. In the view, toggle on the hydrography labels. We are going to want to create resistance linesinks on both sides of the Wabash river in the near field (the area of influence of the pumping well), and we want to represent the far field Wabash on either side of the near field with single linesinks down the center. In order to parameterize the heads in the near field, we suggest you query the vertices of the Wabash river linesink for the elevations in the near field after a solve, and add those elevations to the basemap as hydro text labels. You can then delete the Wabash river linesinks and build the new ones. We suggest you create individual linesinks between each of the near field elevation labels, on both sides of the river channel, starting from highest elevation to lowest. Enter the resistance, thickness, and width parameters as calculated above. See Figure 4.18. Enter a string of far field (no resistance) linesinks down the center of the Wabash River channel from elevation label 400 ft to the start of the near field linesinks. Do the same for the the Wabash River to the west of the near field linesinks to the 395 ft contour.

| Step 5 | Solve the model and plot the 5 year capture zone.

4.6 Discussion

In the face of uncertainty, it is prudent to present more than one piezometric contour map and more than one time-of-travel capture zone. The impact of the most sensitive parameters on the capture zone should be illustrated by presenting the different capture zones and clearly explaining the different parameter choices that lead to them. It is much more convincing to show that, for instance, a fifty foot per day difference in hydraulic conductivity does not noticeably change the capture zone than argue at length why the particular value chosen for the model is the right one. You may annotate the graphics (piezometric contour maps or capture zones) directly on the screen by use of the **Add Text** option on the **Edit** menu. The maps may be printed using the Printer setup and **Print** options on the **Project** menu. You may also export the graphics in DXF format or export the piezometric contour and path line data in SURFER format for further post processing. DXF maps can then be converted to binary base map format using the **Tools** and **Convert** sequence.

Haitjema and Kelson investigated the influence of complexity of the conceptual model on the capture zones for Vincennes [Haitjema,1995]. They used the analytic element code GFLOW [Haitjema,1995] to include the influence of the low hydraulic conductivity of the rock outcrops. They used the finite difference code MODFLOW [McDonald and Harbaugh, 1988] to represent localized three-dimensional flow, anisotropy,
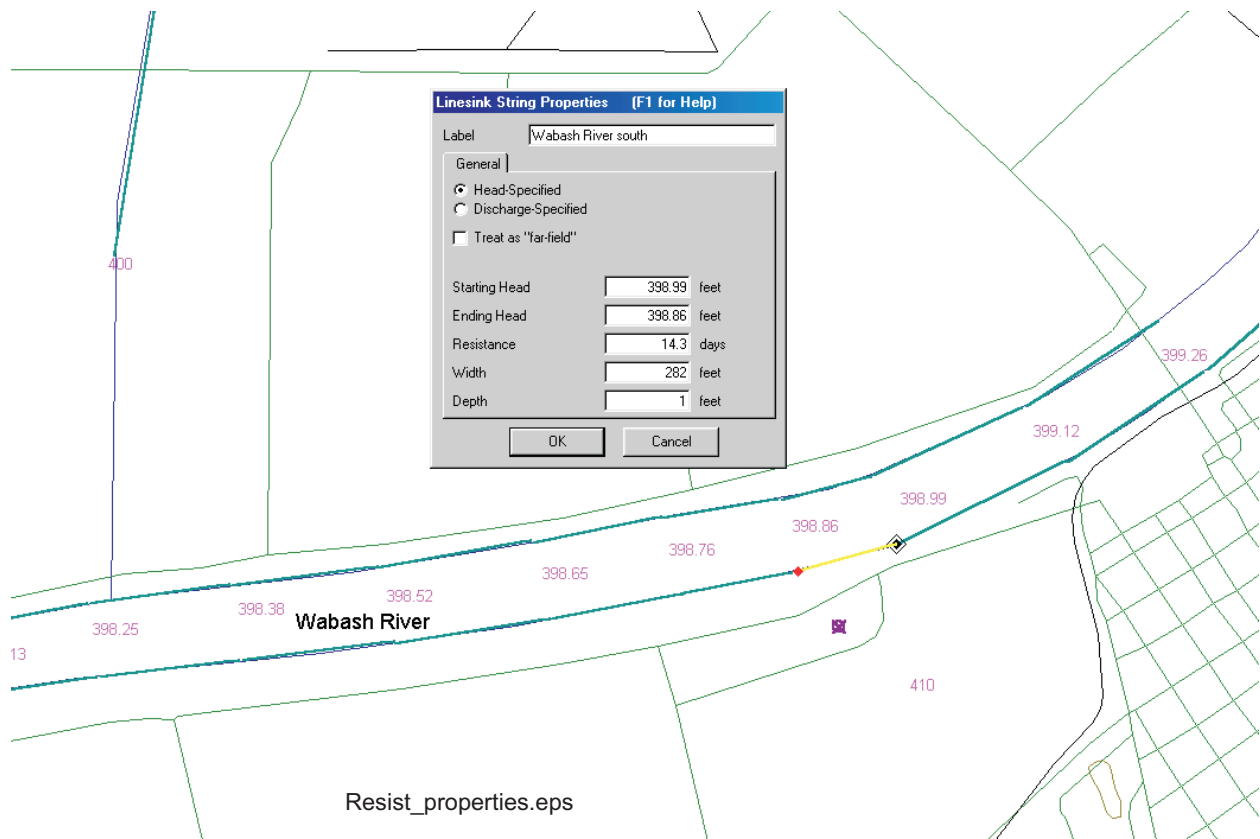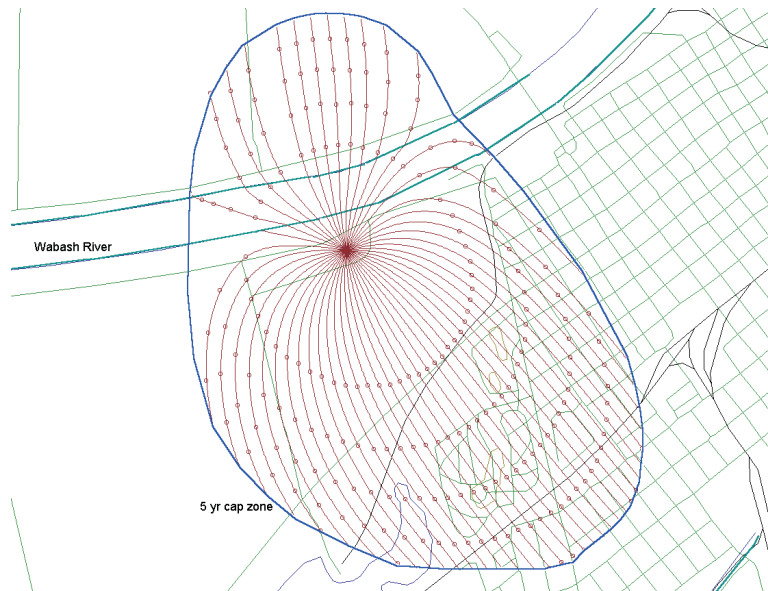
Figure 4.18: Dialog box for entry of resistance linesinks.

Figure 4.19: 5-year capture zones including resistance of Wabash River ($c = 14.3$ days, $\delta = 1$ ft, $\lambda = 592$ ft, $B = 615$ ft, and $w = 282$ ft

.

and resistance between the river and the aquifer. In carrying out this modeling, progressively more complex conceptual models were tested. It appeared that three-dimensional effects did not impact the capture zones, but different values for the resistance of the Wabash River bottom did. The reader is directed to Chapter 6.1 in [Haitjema, 1995] for a full discussion. In Figure 4.20, "composite capture zones" are depicted, based on the many capture zones generated by Haitjema and Kelson. The capture zones were produced in GFLOW using only 2D flow, but including resistance to flow from or into Wabash River.

Based on the exercises in this guide for the Vincennes wellfield, it appears that the 5 year capture zone solution is insensitive to the exact value of the hydraulic conductivity of the rock outcrops — a no-flow boundary (assuming the rock is impermeable) captures the essence. However, we did learn that the 5 year capture zone is very sensitive to the resistance of the Wabash River channel — our capture zone extended all the way to the north side of the river when resistance was given a conservative (high end) value. More investment in characterizing the riverbed resistance through field observations and modeling simulations might be justified. Alternatively, one may assume the worst and accept the capture zone to the north side of the river as realistic.

Remember, the case study for the Vincennes wellfield was for illustration purposes, and is not to be misunderstood as the approved State source water assessment.

Now some other complexities. We have not introduced the concept of horizontal anisotropy in the hydraulic conductivity distribution. Horizontal anisotropy is known to influence the capture zone [Cole, Silliman, 1997]. There is the temptation to represent a highly fractured rock aquifer as an equivalent porous medium with anisotropic hydraulic conductivity, at least at the regional scale; this should be done with caution in fractured carbonate rock aquifers, [Kraemer, 1990],[Podgorney, Ritzi, 1997]. WhAEM2000 should not be used in aquifers with a highly anisotropic hydraulic conductivity distribution.

We have not introduced the concept of dispersion to this point. The capture zones presented in this document represent average water residence times in the subsurface. These residence times more closely represent the breakthrough time of the mean concentration of a conservative tracer at the well. If you wanted to represent the first arrival of the tracer in your delineations, and thus capture the initial breakthrough of a potential contaminant, you would need to incorporate macroscale dispersion (http://www.epa.gov/athens/learn2model/part-two/onsite/conc.htm). Characterizing dispersion in capture zone models is a topic of active research [Maas, 1999].

We have limited our guidance to manual model calibration. The reader is referred to [Hill, 1998] for a discussion of automated methods of parameter estimation and model calibration. Automated non-linear parameter estimation is implemented in UCODE (http://water.usgs.gov/software/ucode.html) and PEST (http://members.ozemail.com.au/~wcomp/).

There are other professional analytic element modeling packages, including WINFLOW, TWODAN, GFLOW, and MLAEM. The reader is encouraged to follow developments of ArcFlow which is based on the solution engine SPLIT by Igor Jankovic, State University of New York-Buffalo, and the ARCVIEW interface by the Minnesota Department of Health [Blum, 2000]. Three-dimensional flow AE models include PhreFlow by Randal Barnes of the University of Minnesota and 3DFlow by David Steward at Kansas State University. EPA maintains a web page with links to the above analytic element ground water models (www.epa.gov/athens/software/whaem/press.html).

Figure 4.20: Composite time of travel capture zones with 2-,5-, and 10-year isochrones for the Vincennes well field using the full-feature analytic element model GFLOW (after [Haitjema,1995]).

Chapter 5

SUMMARY

5.1 Good Modeling Practice

Fortunately, we do not always have to repeat the procedure of hypothesis testing with increasingly complex conceptual models for each individual modeling project. After a while some general conclusions may be drawn from comparing simple and complex conceptual models. In many cases the validity of certain assumptions have already been investigated by others and are published in the literature. It is not practical to present here a complete list of valid and invalid conceptual models, covering all possible geohydrological circumstances. It is the responsibility of the modeler to refer to the ground water literature and make these choices on a case by case basis. We will, however, provide a few general rules of thumb that may be of help in making some initial decisions regarding conceptual models, Figure 5.1 [Haitjema,2002].

5.1.1 Rules of Thumb

1. **River Proximity.** The residence time based protection zone, or capture zone, is not likely influenced by surface water when the distance of the well to the feature is greater than $4\sqrt{QT/(\pi Hn)}$, where Q is the pumping rate of the well, H is the aquifer saturated thickness, n is the aquifer porosity, and T is the residence time associated with the well capture.

2. **Three-Dimensional Flow.** Three-dimensional flow modeling may be necessary when one of the following circumstances apply:

   (a) The well or well field is within a distance of $2\sqrt{k_h/k_v}H$ from a hydrological boundary, where k_h and k_v are the horizontal and vertical hydraulic conductivity, respectively, and where H is the average saturated aquifer thickness.

   (b) The width of the capture zone in a two-dimensional model is less than $2\sqrt{k_h/k_v}H$, where k_h and k_v are the horizontal and vertical hydraulic conductivity, respectively, and where H is the average saturated aquifer thickness.

   Note that in the event that the (2D) capture zone width is in the same order than the aquifer thickness, the three-dimensional capture zone is likely a slender three-dimensional stream tube that may occur at some depth below the water table. A conservative (protective) time-of-travel capture zone may be obtained by using a wellhead protection zone that is obtained from a horizontal flow model with a confined aquifer of the same thickness as the length of the well screen.
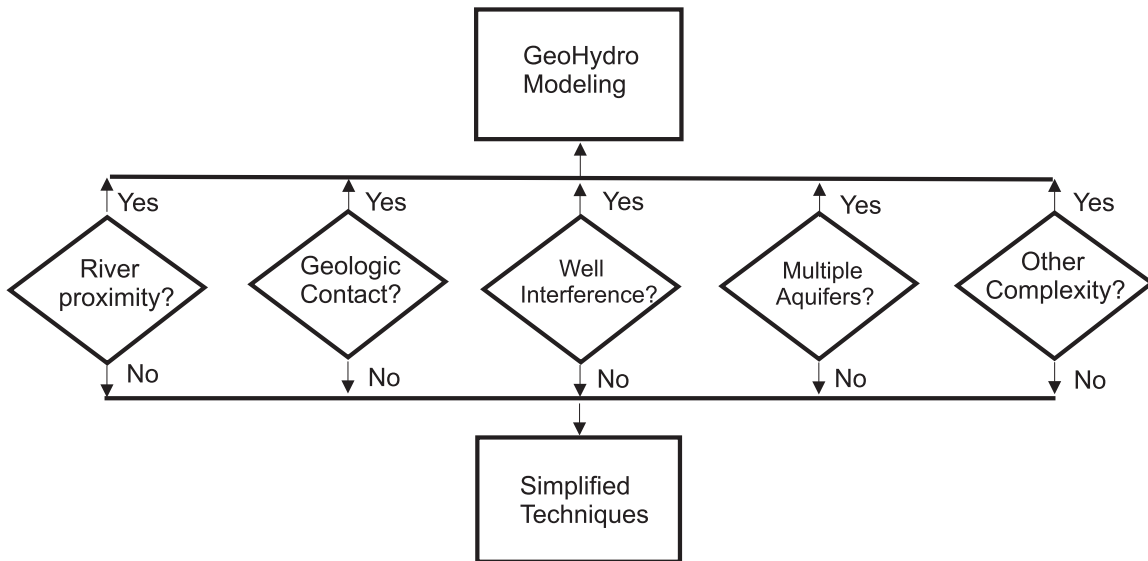
Figure 5.1: Decision tree for complexity of capture zone delineation method, after [Haitjema,2002]. The simplified techniques are discussed in section 5.1.2. Geohydro modeling involves solving the regional ground water flow differential equations, including boundary conditions.

3. **Multi-Aquifer Flow.** The subsurface is usually stratified (layered) with each layer having its own hydraulic conductivity. If the hydraulic conductivities of the various formations are all within the same order of magnitude, the layers form one *stratified* aquifer, see item 4 in this list. If on the other hand one or more layers have a hydraulic conductivity that is more than an order of magnitude lower than the more permeable layers they are referred to as aquitards. Aquitards divide the subsurface into more than one aquifer, forming multi-aquifer systems. In case of a multi-aquifer system a multi-aquifer model (quasi three-dimensional model) may be necessary if all of the following circumstances apply:

    (a) The well occurs in a multi-aquifer zone and is not screened in all aquifers.

    (b) The length of the capture zone, based on flow in the aquifer(s) accessed by the well, is in the order of (or smaller) than $4\sqrt{Tc}$, where T (ft^2/day) is the transmissivity of the aquifer and c ($days$) is the largest resistance of one of the adjacent aquitards. Resistance is equal to the aquitard thickness divided by its hydraulic conductivity $c = b/k$.

    (c) A hydrological boundary (stream or lake)is present within a distance of $4\sqrt{Tc}$ from the well, where T (ft^2/day) is the transmissivity of the aquifer and c ($days$) is the largest resistance of one of the adjacent aquitards.

    Multi-aquifer flow often greatly complicates the delineation process due to uncertainties in aquifer interaction. In many cases, aquifers do not interact through a homogeneous leaky aquitard, but through discrete openings in clay layers, whose presence and location may or may not be known. If a well is screened in only one aquifer, the largest time-of-travel capture zone will occur if interaction with adjacent aquifers is ignored. If the direction of flow in the various aquifers are expected to be not too different, the single aquifer capture zone may offer a conservative time-of-travel capture zone.

4. **Aquifer Stratification.** An aquifer is considered stratified if the hydraulic conductivities of the various geological formations (layers) are within the same order of magnitude. Aquifer stratification

will not affect the capture zone width, but may significantly affect the capture zone length. The groundwater flow velocities in the various aquifer layers are proportional to their hydraulic conductivity and inversely proportional to their porosity. This can lead to substantially different time-of-travel capture zone lengths in the various layers. If it is considered important to include this in the definition of a wellhead protection zone, a time-of-travel capture zone may be produced using a porosity value for the aquifer that incorporates both the effect of the highest conductivity and the associated porosity. For instance, for an aquifer layer with five times the average hydraulic conductivity the model should be given a porosity that is five times smaller than the average porosity in order to get the correct time-of-travel capture zone length in that layer. This is assuming that the porosity is the same in all layers.

5. **Aquifer Heterogeneities.** Small inclusions of clay or gravel with different hydraulic conductivities than the average regional value are inconsequential, except if their size is on the order of the capture zone width or larger.

6. **Transient Flow.** Highly permeable unconfined aquifers, and most confined aquifers, will exhibit "summer conditions" and "winter conditions" that may be approximated by steady-state solutions using recharge rates and surface water levels observed in the summer and winter, respectively. When delineating capture zones for wells based on residence times greater than say 5 years, the detailed day-to-day pumping records can safely be averaged over the observation period, provided there is no long term trend. Accurate delineation for transient non-community wells may require special attention. And projections into the future should include additional safety factors.

5.1.2 Simplified methods

The material presented in this section was sponsored by the Indiana Department of Environmental Management [Ceric, 2000], [Haitjema,2002].

How does one choose a simplified method? This decision depends on several parameters, including the magnitude and direction of the ambient flow near the well or well field, which while important, is challenging to characterize. The magnitude of the uniform flow is denoted by Q_o and may be estimated from the hydraulic gradient i and the aquifer transmissivity kH (hydraulic conductivity k times saturated aquifer thickness H) Figure 5.2. The magnitude of the uniform flow rate is $Q_o = kHi$. The flow Q_o is defined as the total amount of water that flows in the aquifer per unit time per unit width. Techniques for estimating the direction of the uniform flow field were discussed in Chapter 2.

The shape and size of a simplified time of travel capture zone may be related to a dimensionless travel time parameter $T/\tilde{T}$, knowing the time of travel T for the capture zone, the uniform flow Q_o, the saturated aquifer thickness H, the aquifer porosity n, and the pumping rate of the well Q, Figure 5.3.

$$\tilde{T} = \frac{nHQ}{2\pi Q_o{}^2} \tag{5.1}$$

When $T/\tilde{T} \leq 0.1$, the calculated fixed radius (CFR) centered on the well, including a safety factor for a non-zero ambient flow field, is

$$R = 1.1543\sqrt{(QT)/(\pi Hn)} \tag{5.2}$$

When $0.1 < T/\tilde{T} \leq 1$, the CFR is

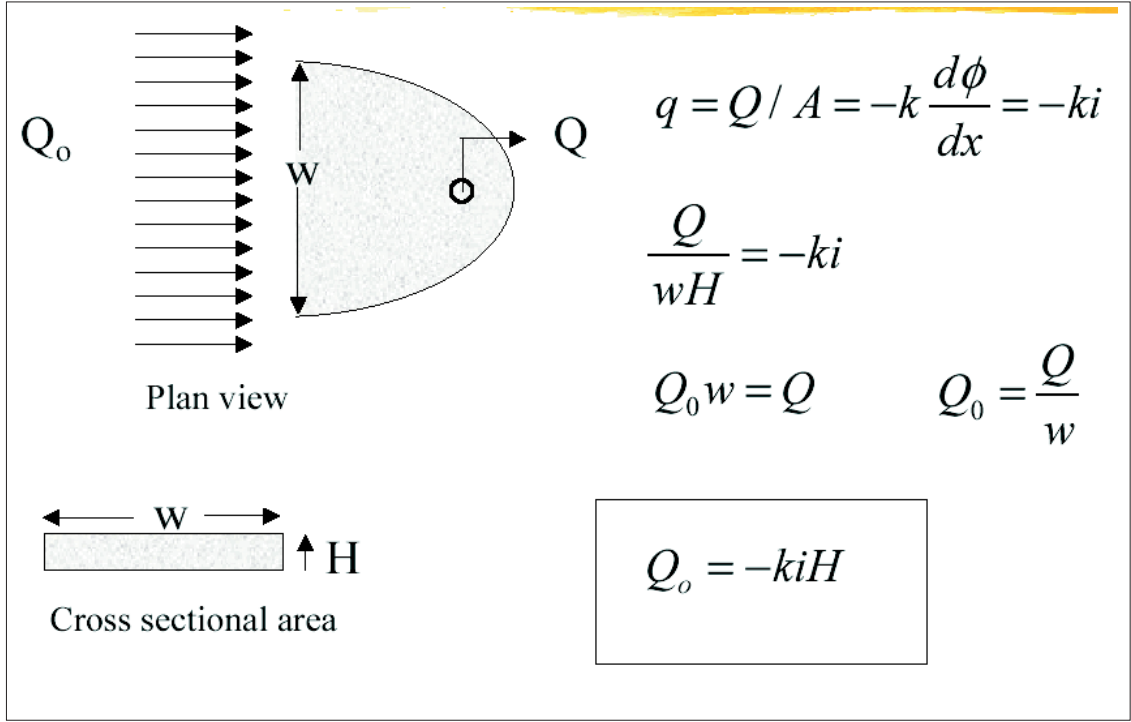$$R = L_s[1.161 + ln(0.39 + \frac{T}{\tilde{T}})] \tag{5.3}$$

Figure 5.2: The magnitude of the discharge vector.

where the eccentricity is

$$\delta = L_s[0.00278 + 0.652\frac{T}{\tilde{T}}] \tag{5.4}$$

given the distance from the well to the stagnation point downgradient from the well is

$$L_s = Q/(2\pi Q_o) \tag{5.5}$$

When $T/\tilde{T} > 1$, a uniform flow envelope can be defined as

$$x = y/tan(y/L_s) \tag{5.6}$$

given

$$-Q/2Q_o < y < +Q/2Q_o \tag{5.7}$$

and clipped at upgradient distance

$$L_u = L_s[\frac{T}{\tilde{T}} + ln(e + \frac{T}{\tilde{T}})] \tag{5.8}$$

The reader is referred to [Ceric, 2000] details on the above analysis.

5.2   Conclusion

WhAEM2000 is a computer tool to support step-wise and progressive modeling and delineation of source water areas for pumping wells. Our case study moved from arbitrary fixed radius, to calculated fixed radius, to well in uniform flow, to modeling with hydrologic boundary conditions only, to modeling with hydrologic and geologic boundary conditions. Each solution was conceptually more sophisticated, and we assume that
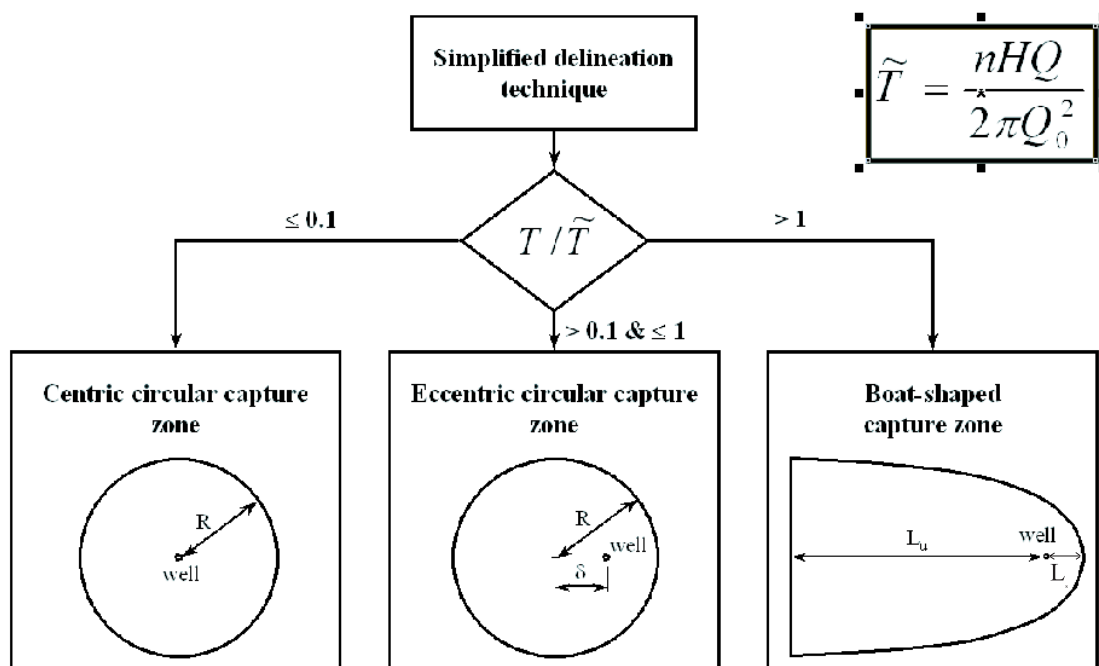
Figure 5.3: Simplified delineation techniques for a well pumping at rate Q, in an ambient flow field Q_o, with aquifer saturated thickness H and porosity n, and time of travel capture zones of time T, after [Haitjema,2002].

the corresponding capture zones were progressively more realistic. The emphasis of the W*h*AEM2000 project on "ease-of-use" and computational efficiency does not release you, the modeler, from responsibilities in justifying the conceptual models, and defending the reasonableness of the solutions. We emphasized uncertainties in conceptualization of boundary conditions in our case study, but uncertainties in parameterizations are also important. W*h*AEM2000 is public domain and no cost software, and while it is intended to capture the basics of ground water modeling in support of State efforts in source water assessments and wellhead protection, it is also intended to stimulate innovation in software design and modeling practice in the private sector.

One more time, "Ground water models should be as simple as possible, but not simpler." Good modeling!

Appendix A

Conversion Factors

	Multiply	**By**	**To obtain**
Length	ft	0.3048	m
	$miles$	5280	ft
	$miles$	1609.344	m
	yd	0.9144	m
Area	ft^2	0.092903	m^2
	$acre$	4046.8564	m^2
	mi^2	2.589988 x 10^6	m^2
	$hectare$	$10,000$	m^2
Rate	$inches/yr$	2.2815 x 10^{-4}	ft/day
	$inches/yr$	6.9541 x 10^{-5}	m/day
	ft/day	0.3048	m/day
	gpd/ft^2	0.0407	m/day
Volume rate	ft^3/s	$2,446.5754$	m^3/day
	ft^3/s	86400	ft^3/day
	gal/min	5.4510	m^3/day
	gal/day	0.0038	m^3/day

Appendix B

W*h*AEM₂₀₀₀ Binary Base Maps and the Internet

B.1 Getting BBMs from the EPA Web Server

A Binary Base Map server is supported by the EPA Center for Exposure Assessment Modeling (CEAM). To access the server from within W*h*AEM2000, go to **<u>T</u>ools** select **Base Map Browser**, and select **Use Web**. (Alternatively, from outside of the program you can point your web browser to www.epa.gov/ceampubl/gwater/whaem/us.htm). Figure B.1. Left click on the State, then the 30x60 minute map, then the 15 minute series. Save the self extracting file to your local drive, and uncompress (by double clicking the file) to your workspace. The binary basemaps (bbm) are now loaded into your project database by using the **<u>P</u>roject** and **Project Settings**, and **Add BBM** commands.

The EPA supplied BBMs are a binary form of the USGS DLG maps. The BBMs are saved in files associated with their location and category, and the name reflects this information. The 1:100,000 scale quad is divided in eight 15-minute quads. Table B.1. Each of these quads contains the DLG for the associated category: hypsography, hydrography, roads, railroads, and miscellaneous. Table B.2. Therefore, the hydrography quad for Vincennes, IN, is **VI1HYF06**, which refers to the sixth quadrant (**F06**) of the Vincennes 1:100,000 map (**VI1**), containing hydrography (**HY**).

Table B.1:

F01	F02	F03	F04
F05	F06	F07	F08

B.2 Creating BBMs from USGS DLGs maps from the USGS Web Server

W*h*AEM2000 has utilities to convert the USGS digital line graph (DLG) maps into the binary base map format (BBM).

The USGS DLGs are available for download on the Internet at their GeoData webpage. Point your web browser to edc.usgs.gov/geodata/. Figure B.2.

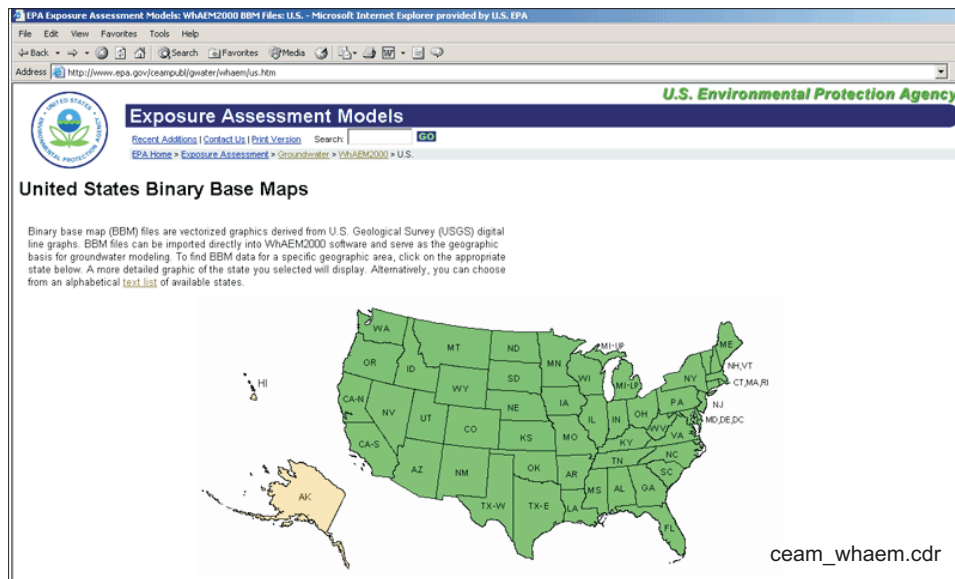The DLG maps are available at two scales: 7.5 minute (or 1:24,000) and 30 x 60 minute (or 1:100,000).

Figure B.1:

Table B.2:

Category Name	Abbreviation
hypsography	hp
hydrography	hy
boundaries	bd
roads and trails	rd
railroads	rr
miscellaneous transportation	mt

The 30 x 60 minute maps are stored in optional format and SDTS format, while the 7.5 minute maps are stored in SDTS format. Complete coverage is available of the USA at the 30 x 60 minute scale, while coverage at the 7.5 minute scale is not complete — you can check the status of maps for your state by going to the web page

mcmcweb.er.usgs.gov/status/dlg_stat.html.

We will demonstrate the procedures for downloading the 7.5 minute (1:24K scale) DLGs for Vincennes, Indiana from the USGS website, and convert to BBMs. The 30x60 minute BBMs are available from the EPA web server as described above.

From the Eros Data center webpage, select 1:24K DLG. You can select the DLG maps by alphabetical List, by State, or by Graphics. Select "FTP by Graphics", then select conterminous 48 states, you will be presented with a map of the USA. Locate your mouse and click on the point on the map near west-central Indiana that you want to zoom in to. Continue to point and click until the quads are displayed as shown in Figure B.3.

As an example, select the Frichton quad, and download the hypsography DLG (1669820.HP.sdts.tar.gz) to your project directory.

From the WhAEM2000 menu, select **Tools** , then Convert. For the Frichton hypsography DLG, which is 1:24K SDTS format, select **SDTS to Basemap**. (If you were working with the USGS 1:100K optional
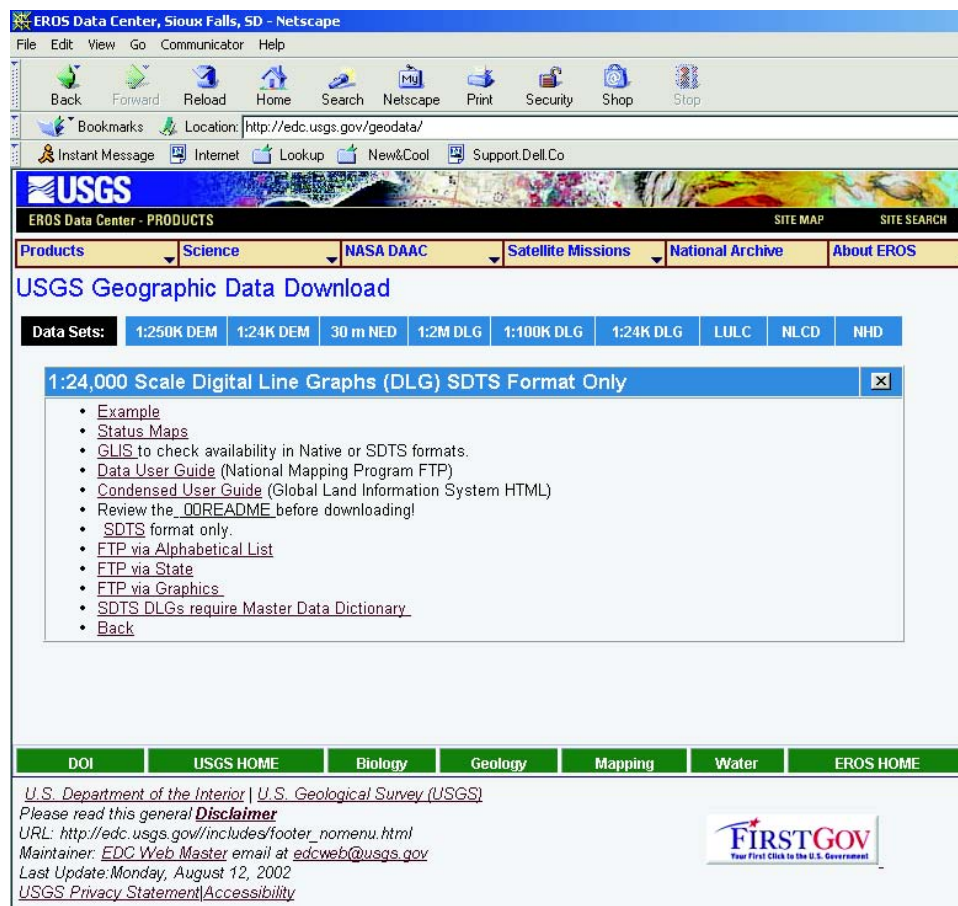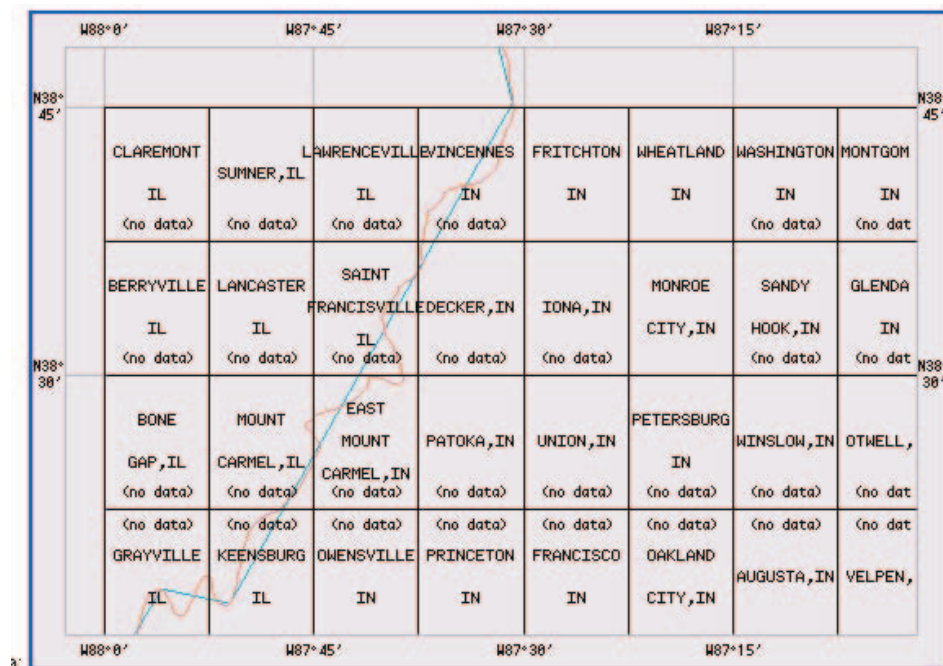
Figure B.2:

Figure B.3:

format DLG, you would select **DLG to Basemap**). Select the compressed file (*.gz) you downloaded from the Internet. Provide a name for the BBM. Be sure to limit yourself to 8 characters. W*h*AEM2000 will automatically call a sequence of utilities (e.g., gzunzip, chop). The final utility will do the conversion from DLG to BBM, and store the file in your workspace. You can now use this BBM in a new database, or add it to an existing project with the **Project** , **Base Map Settings**, **Add BBM** sequence.

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