

USE OF WHPA AND DRASTIC MODELS IN
VULNERABILITY ASSESSMENT OF AQUIFERS ON
A GIS PLATFORM

By

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CHAPTER I

INTRODUCTION

Groundwater is water that is present below the surface of the earth in underground streams and aquifers. It is one of the most important natural resources in any nation serving as a major source of water to communities, industries and agriculture purposes. As wells are one of the major point source through which groundwater is made accessible for use, protection of these wellheads assumes top priority. Understanding water movement in the aquifers and identifying the sources of contamination in these areas will help in better prevention of their contamination. To facilitate this purpose the use of the Wellhead Protection Area (WHPA) program, a delineation software developed by the US Environmental Protection Agency (EPA) was applied. The area under consideration is Enid and its surroundings, which comprise of about 150 wells, which is a significant source for those communities (Enid, 1995). The work was based on the wellfields in Enid, Cleo Springs, Drummond, Ringwood and Ames. The WHPA was performed for these areas to obtain the flow pattern of water in aquifers and also to obtain the capture zones for the wellfields.

Groundwater vulnerability analysis was performed as some land areas were more vulnerable to groundwater contamination than others. The purpose was to create a map delineating the more vulnerable areas from the less vulnerable ones and based on the possible contaminant sources a management plan was to be devised. Several methods

were available for the assessment of groundwater vulnerability, but for this analysis the DRASTIC method was utilized. DRASTIC stands for the seven governing parameters such as,

Depth of water table from the surface

Retention **R**echarge

Aquifer media

Soil texture

Topography (slope)

Impact on vadose zone

Hydraulic **C**onductivity of aquifer

DRASTIC was developed by the EPA to be a standardized system for evaluating groundwater vulnerability to pollution (EPA, 1987). Except for the Enid well field which lies in the Enid Isolated Terrace Aquifer, all the other wells are located mainly on the Cimarron River Terrace Aquifer. The products of the assessments are vulnerability maps which are created in a GIS platform and can be analyzed in the Arc MAP module of Arc GIS. DRASTIC was not designed to deal with pollutants introduced in the shallow or deep subsurface, such as leaking underground storage tanks, animal waste lagoons, or injection wells. It assumes that the pollutant is introduced at ground level.

Objectives

The purpose of this study was to delineate the wellhead protection areas for the five well fields surrounding the Enid area using semi-analytical groundwater flow models. The objectives were as follows:

- To delineate the particle flow path to each of the wells in the five well fields surrounding Enid region, for a one, ten, twenty and thirty year time of travel.
- To create vulnerability analysis map for the study area using DRASTIC method.
- To locate potential contaminant sources and identify the regions of concern due to pollution by integrating with the results of WHPA and DRASTIC.

CHAPTER II

BACKGROUND

This section provides a description of the location and describes features like the topography, climate, soils, surface water, regional geology and hydrologic settings. The area under consideration is made up of three prominent aquifers, which are the Cimarron River Terrace (CRT) and Alluvium Aquifer, the Enid Isolated Terrace (EIT) Aquifer, and the Cedar Hill Sandstone within the Permian Redbed (PRB) formations.

Location of Study Area

The area of study for this project consists of the wellfields located in and around the City of Enid. Four of the five well fields under consideration lie in the Cimarron River Terrace Aquifer and the underlying Permian Redbed sedimentary formations (Reely, 1992). The Enid well field lays in the Enid isolated terrace aquifer. Geographically the area extends from the 98° 36' W to 97°44' W on the horizontal and 36°10' N to 36°34' N on the vertical. The Cimarron River flows through the area and is connected by a dense network of smaller streams.

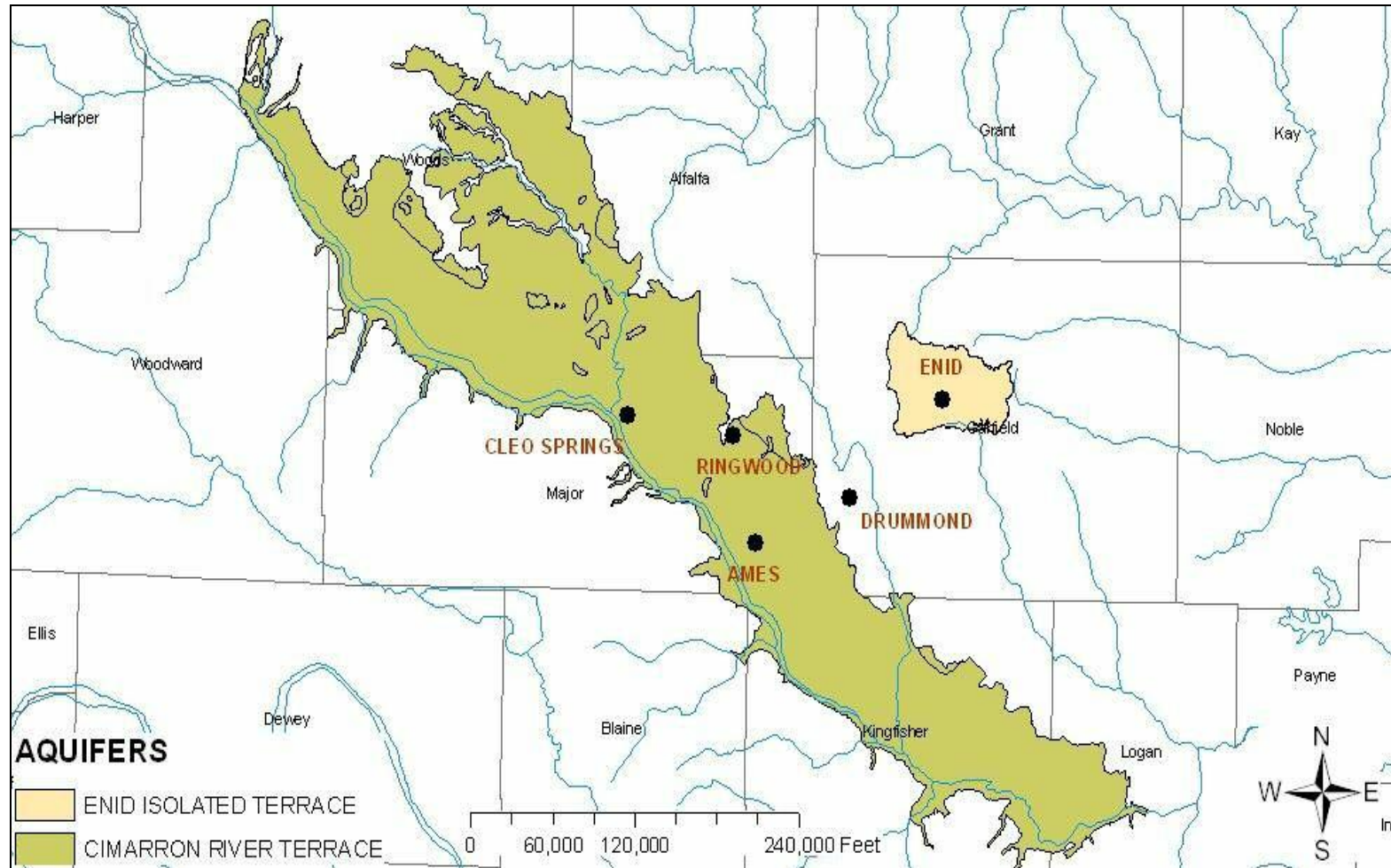


Figure II-1: Location of the study area

Topography

The area under review is present in the north-central Oklahoma region (Figure II-1). The topography where the Cimarron River Terrace Aquifer and the Enid Isolated Terrace Aquifer are exposed is a gentle slope to rolling sand dunes. The elevation in the region ranges from 1,100 feet above mean sea level at the Cimarron River to approximately 1,400 feet in the dune areas (Reely, 1992). The area can generally be classified as rural with Enid having the largest population of 50,000 (US Bureau of Census, 2000). Other towns in the region are Ringwood, Cleo, Ames and Drummond. Basic land use in the region is cultivation, livestock grazing, hog farming, and oil and gas activities. The area is dry and has humid conditions with most of the precipitation occurring in the spring and summer. The soils in the study area are mostly loamy. Land in the study area is primarily used for agricultural purposes and dry land farming (Reely, 1992).

Surface Water

The study area lies in the Cimarron River drainage basin. The Cimarron River flows with its starting point in New Mexico in a south-east ward direction through western Oklahoma and drains in to the Arkansas River drainage at the Keystone Reservoir. The main sources of flow to the river are snow melt from the Rocky Mountains, storm water runoff, and ground water seepage.

Regional Geology

The geologic units exposed in the area are quaternary and Permian in age. The most significant water units include the Quaternary Cimarron River Terrace and the Enid isolated Terrace deposits. Bedrock beneath the study area includes shale, sandstone, siltstone, and mudstone of Permian age (Enid, 1995). The sedimentary sequences extend approximately to the south-southwest and are exposed or overlain by the Cimarron Terrace or Alluvial Deposits. The Cimarron river deposits are located along the north east side of the Cimarron River and extend for approximately 110 miles from near the town of Waynoka southeast to Guthrie (OWRB, 1998). The deposits are Quaternary in age and overlie the Permian red bed formations. The terrace deposits are made up of unconsolidated clay, sandy clay, sand and gravel. These sediments range in color from black to reddish brown. The terrace deposits vary in thickness due to the irregular bedrock surface formed during the erosion periods. In general, the terrace deposits are not found southwest of the Cimarron River and they decrease in thickness to the northeast. The Enid area is covered by unconsolidated deposits of quaternary age, which truncate against Permian formations and are referred to as the Enid Isolated Terrace Deposits. The terrace deposits are derived from the adjacent Permian formations and are made up of discontinuous layers of clay, sandy clay, sand and gravel. The lowest portion of the deposits are typically coarser grained. The colors of the deposits are usually from brown to reddish brown (OWRB, 1998).

Hydrogeologic Settings

The Drummond well field produces water from the Permian aquifers, the depth of which varies from 55ft to 200ft. Well capacities range from 0.05 gallons per minute (GPM) to 0.4 GPM. Cleo Springs, Ringwood, and Ames well fields produce groundwater primarily from the Cimarron River Terrace Aquifer. The depth of these wells range from about 35ft to about 200ft. The Ames well field produces about 2 million gallons per day (MGD). The capacities of the other two wellfields in the Cimarron River Terrace Aquifer range 2.5 to 4 MGD (Tyagi, 2003). The Enid well fields produces groundwater from the Enid Isolated Terrace Aquifer. Most of the water pumped from these well fields is used to supply to the needs of the City of Enid.

In the Permian aquifers the groundwater is under confined conditions and flow direction is extremely variable and controlled by structural characteristics. The orientation and frequency of fractures control groundwater flow in this aquifer. In general the groundwater follows the topography and the slope in the aquifer, from northeast to southwest. The general flow direction in the Cimarron River Terrace Aquifer deposits is from northeast to southwest. The regional groundwater gradient is 0.0035feet/feet. The saturated thickness ranges from 0 to over 80 feet in several locations (Reely, 1992).

These variations in the saturated thickness can be attributed to the irregular surface of the underlying Permian deposits. Based on pumping tests, transmissivity in the Cimarron River Terrace Aquifer ranges from 800 ft²/day to 10,200 ft²/day, with an average value of 2,670 ft²/day (Enid, 1995). The Enid Isolated Terrace Aquifer is an unconfined aquifer with yields ranging from 50 to 300 gpm. Saturated thickness in the well fields range from 10 to 40 feet. The direction of groundwater flow is southeastern and the hydraulic

gradient is 0.0035 feet/feet. The average transmissivity is estimated to be around 1,270 ft²/day (Reely, 1992). Groundwater recharge is primarily from precipitation. Groundwater discharge occurs from seepage into streams, well pumpage, evapotranspiration, and regional discharge.

CHAPTER III

LITERATURE REVIEW

Most of the groundwater resources are stored and move in the aquifers. Aquifers account for a major portion of the much wanted groundwater resource. Flow of groundwater in these aquifers is an important factor in understanding the path and area covered. Thus understanding the flow pattern aids in water management planning and pollution prevention. Flow pattern of groundwater in aquifers depends on a variety of factors which include transmissivity, hydraulic gradient, porosity of the aquifer media and the general direction of flow. Researchers and scientists in the fields of hydrology, environmental engineering, geology, mathematics, physics and chemistry have conducted a broad range of theoretical, numerical, laboratory and field investigations to devise methods and formulations to calculate and trace the flow pattern of groundwater in aquifers.

WHPA/ Particle Tracking

The problem to be solved with this study is to find a capture zone for the wells in the given study area. A capture zone is defined as the area surrounding the pumping wells which will provide as a source of groundwater recharge to the pumping wells. The Wellhead Protection Area (WHPA) model can be used to find three different capture zones; steady state, time-related and hybrid. The steady state capture zone is that area

surrounding a pumping well which will provide as a source of recharge over an infinite period of time (WHPA, EPA, 1993).

The WHPA program was designed specifically for these kinds of purposes, where the analysis of transient movement of groundwater is necessary. The program consists of three main modules which can be used to perform steady state calculations in order to delineate the flow of groundwater over time.

- RESSQC-Delineates time-related capture zones around pumping wells or contaminant fronts around injection wells, for multiple pumping and injection wells in homogeneous aquifers of infinite extent with steady and uniform ambient ground-water flow. Well interference effects are accounted for (WHPA, EPA, 1993).
- MWCAP-Delineates steady-state, time-related or hybrid capture zones for pumping wells in homogeneous aquifers with steady and uniform ambient ground-water flow. The aquifer may be infinite in areal extent or the effects of nearby stream or barrier boundaries can be assessed. If multiple wells are examined the effects of well interference are ignored (WHPA, EPA, 1993).
- GPTRAC-Semi-analytical Option: Delineates time-related capture zones for pumping wells in homogeneous aquifers with steady and uniform ambient ground-water flow. The aquifer may be of infinite areal extent or it may be bounded by one or two (parallel) stream and/or barrier boundaries. The aquifer may be confined, leaky confined or unconfined with areal recharge. Effects of well interference are taken into account. Numerical Option: Delineates time-related capture zones about pumping wells for steady ground-water flow fields.

Since this option performs particle tracking using a head field obtained from a numerical (finite difference or finite element) ground-water flow code, many types of boundary conditions as well as aquifer heterogeneities and anisotropies can be accounted (WHPA, EPA, 1993).

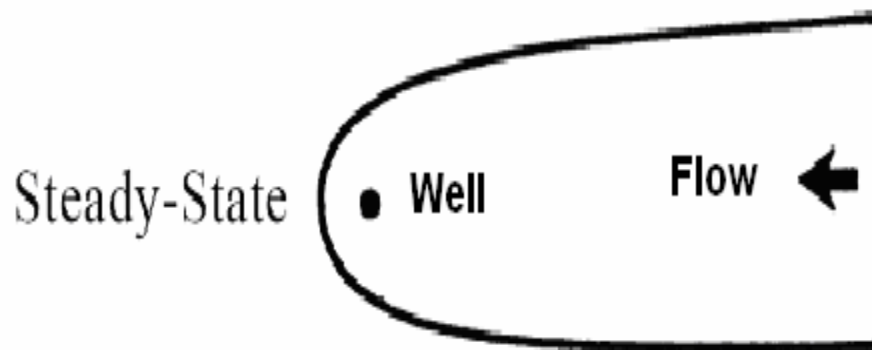


Figure III-1. Steady State Capture Zone using WHPA

A time related capture zone is the area surrounding a pumping well which provides a source of recharge over a specified period of time, for example a capture zone of 5 yrs or 10 yrs. An example of a time related capture is given in Figure III-1.

The WHPA model calculates capture zones around the wells of interest by a method called particle tracking. This method uses a reference stagnation point and the model is programmed to do both forward tracking as well as reverse tracking. Forward tracking involves the tracking of particles in the direction of ground-water flow and is usually used in cases of capture zones for pumping wells. Reverse tracking involves the tracking of particles in the direction opposite to ground-water flow, and is used in cases where a contamination is detected; the contaminant is to be tracked down.

The first major requirement for particle tracking is the velocity of groundwater at any point in the aquifer. The velocity in the aquifer is expressed in terms of Darcy's law.

It is given as, (WHPA, EPA, 1993)

$$Q=KiA \quad (III-1)$$

Where

Q = volumetric flow rate

K = hydraulic conductivity of the porous medium

i = hydraulic gradient. A is the cross sectional area of flow. The Darcy

Velocity is given by

$$q = Q/A = Ki \quad (III-2)$$

the x and y components of seepage velocity for two dimensional horizontal flow can be expressed as, (WHPA, EPA, 1993)

$$v_x=q_x/\theta \quad (III-3)$$

$$v_y=q_y/\theta \quad (III-4)$$

Where

θ = effective porosity of the medium

At this point the different modules have different sets of mathematical equations to solve for the parameters required to do particle tracking. Once the velocities are known the pathlines can be delineated hence aiding in the particle tracking. The major fundamental for the next step in particle tracking is to find the distance covered, dl, in the given time, dt. Now dl can be defined as, (WHPA, EPA, 1993)

$$dl=(dx^2+dy^2)^{1/2} \quad (III-5)$$

where,

$$dx=v_x dt \quad (III-6)$$

$$dy=v_y dt \quad (III-7)$$

dx and dy are the projections of dl on the x and y directions respectively. So the next position of the particle with time will be x_{i+1} , y_{i+1} . Forward tracking as mentioned before is a method to track particles along with the flow of groundwater in the aquifer. By this we can determine whether a pumping well will be contaminated by a definite contaminant source. Also by using reverse tracking, if a well is found to be contaminated can be traced backwards to the source of contamination.

RESSQC Module

This module can be used to delineate time related capture zones for one or more pumping or injection wells in a well field. Particle tracking by this module assumes that there is steady ground water flow in the aquifer. The previous sections provided a general idea to the methodology of particle tracking. In this section the specific equations used in pathline delineation for the RESSQC module are explained. The basic assumptions used in developing the analytical solutions in RESSQC are as follows:

- The aquifer is homogeneous, isotropic, and of constant saturated thickness.
- The flow of ground water in the aquifer is two-dimensional in a horizontal plane and is at a steady state.

Let Φ represents the velocity potential function which satisfies the Laplace equation, (WHPA, EPA, 1993)

$$\delta^2\Phi/\delta x^2 + \delta^2\Phi/\delta y^2=0 \quad (III-8)$$

Where

x and y = Cartesian coordinates in a horizontal areal plane.

Now the Darcy velocity x and y components are given as,

$$q_x = -\delta\Phi/\delta x \quad (\text{III-9})$$

$$q_y = -\delta\Phi/\delta y \quad (\text{III-10})$$

from the analytical solution to the equation involving Φ and ψ the stream function, the solution for Φ is obtained as, (WHPA, EPA, 1993)

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

hence solving for Darcy velocity with the value of Φ we obtain

$$q_x = -\delta\Phi/\delta x = U\cos\alpha \quad (\text{III-11})$$

$$q_y = -\delta\Phi/\delta y = U\sin\alpha \quad (\text{III-12})$$

Where

α = angle or direction of flow

So by the knowledge of direction of flow and the Darcy velocity the path line can be delineated.

MWCAP Module

The MWCAP module is specifically designed for efficient delineation of individual capture zones for multiple wells. The module uses potential function analytical solutions to determine the control points to use in the zone capture technique. The three types of flow can be modeled using this module are, the steady state, time related and hybrid functions. The computational procedure is based on the fundamental analytical assumption of steady-state two-dimensional flow in a homogeneous aquifer of constant

saturated thickness. In addition, MWCAP assumes that well interferences due to simultaneous pumping have negligible effects on capture zones of the individual wells. For this study analytical solutions are solved for an aquifer with lateral boundary or infinite boundary. In this case the potential function is described as, (WHPA, EPA, 1993)

$$\Phi = -U(x \cos \alpha + y \sin \alpha) + (Q/4\pi b) \ln[(x-x_0)^2 + (y-y_0)^2] \quad (\text{III-13})$$

Where

U = Darcy velocity of ambient flow

α = angle of ambient flow

Q = discharge

x_0 and y_0 = x and y components of the well

b = aquifer thickness

It is then assumed that the origin is at the well and x axis is parallel to the flow, the above equation simplifies to

$$Q = -Ux + (Q/4\pi b) \ln[x^2 + y^2] \quad (\text{III-14})$$

from this value of the potential function, the Darcy velocity x and y components can be derived as,

$$q_x = -\delta\Phi/\delta x = U - (Q/4\pi b) [x/(x^2 + y^2)] \quad (\text{III-15})$$

$$q_y = -\delta\Phi/\delta y = - (Q/4\pi b) [y/(x^2 + y^2)] \quad (\text{III-16})$$

using the above equations in the solutions for determining the pathline computation, delineation of pathlines is made possible in the MWCAP module.

GPTRAC Module

The GPTRAC module is like a supplement to the RESSQC and MWCAP modules. It is an all purpose module used for particle tracking. Some of the advantages with this module are, it can handle site specific data such as confined, unconfined or leaky aquifers. The two types of solution offered by the GPTRAC module are analytical and the numerical solution. The module is not suitable where a large number of wells are involved. The solutions to the GPTRAC confined aquifer conditions are the same as those for the other two modules discussed. The different conditions for which the solutions are discussed are

- well flow in an unconfined aquifer with areal recharge
- well flow in a leaky semi-confined aquifer
- well flow in strip aquifers with two parallel boundaries

The scope of this study is restricted to flow in unconfined aquifer with areal recharge alone. The potential equation for this module is;

$$\Phi = Kh^2/2 \quad \text{(III-17)}$$

Where K is the hydraulic conductivity and h is the hydraulic head above the base of the aquifer.

Overview of DRASTIC

DRASTIC is an assessment method to determine the vulnerability of groundwater. Since the main purpose of DRASTIC is to provide assistance in locating the vulnerable zones, which in turn aids with prioritization of resources, the efficiency of the analysis increases with the number of pertinent factors taken into account.

The various hydrogeologic factors in the analysis are given below:

Depth to Water (D): The depth to water is the distance, in feet, from the ground surface to the water table. It determines the depth of material through which a contaminant must travel before reaching the aquifer. Thus, the shallower the water depth, the more vulnerable the aquifer is to pollution.

Net Recharge (R): The primary source of recharge is precipitation; it is the principal vehicle for leaching and transporting contaminants to the water table. The more the recharge, the greater the amount of that could contaminants reach the water table.

Aquifer Media (A): The aquifer media refers to the type of the rocks and material surrounding the aquifers. This factor depends on the amount of cracks and fissures which controls the permeability into the aquifer. The more the permeability the higher the pollution potential.

Soil (S): This is the uppermost layer of ground material which affects the seepage of precipitation and also the runoff.

Impact of the Vadose Zone Media (I): The vadose zone is the unsaturated zone above the water table. The texture of the vadose zone determines the time of travel of the contaminant through it. Information on vadose zone geology was obtained from the previous work on vulnerability assessment of Oklahoma aquifers by the OWRB.

Hydraulic Conductivity (C.): Hydraulic conductivity is rate at which water moves horizontally in an aquifer. The faster the rate of transport the higher the risk of contamination.

These seven parameters form the basis of the analysis, and are used in calculating the DRASTIC index by assigning 'ratings' and 'weights' for each of them.

The ratings are a set of values between 1 and 10, representing the relative potential to contamination of the area for which it has been assigned. The weights are again numerical values between 1 and 5, which are used to rank the seven parameters based on how important a role they play in contaminant transport. In both the cases the higher end of the range represents a higher potential to contamination.

The final DRASTIC index is calculated using the following formula:

$$\text{DRASTIC Index} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

Where

‘r’ = the rating assigned to a particular cell for each of the hydrologic factors

‘w’ = weight for the same

Based on the resulting DRASTIC indices, a greater value means higher susceptibility to contamination compared to a lower DRASTIC index. According to the US EPA (1991), aquifers with a DRASTIC rating greater than 150 are considered to be highly vulnerable. Representation of these values on a map is with the help of various colors. In most DRASTIC assessments red is used to represent the values with maximum contamination potential.

DRASTIC Worksheet (Circle appropriate range and rating).

County: _____ State: _____

General Soil Map Unit Number: _____

General Description:

1. Depth to Water (ft)

Range	Rating
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1

2. Net Recharge (in)

Range	Rating
0-2	1
2-4	3
4-7	6
7-10	8
10+	9

3. Aquifer Media

Type	Rating		Typical Actual
	Range	Typical Actual	
Massive Shale	1-3	2	_____
Metamorphic/Igneous	2-5	3	_____
Weathered MT	3-5	4	_____
Glacial Till	4-6	5	_____
Bedded SS/LS/Shale	5-9	6	_____
Massive Sandstone	4-9	6	_____
Massive Limestone	4-9	6	_____
Sand and Gravel	4-9	8	_____
Basalt	2-10	9	_____
Karst Limestone	9-10	10	_____

4. Soil Media

Type	Rating
Thin/ Absent	10
Gravel	10
Sand	9
Peat	8
Structured Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Muck	2
Massive Clay	1

5. Topography (%)

Range	Rating
0-2	10
2-6	9
6-12	5
12-18	3
18+	1

6. Vadose Zone Media

Type	Rating		Typical Actual
	Range	Typical Actual	
Confining Layer	1	1	_____
Silt/Clay	2-6	3	_____
Shale	2-5	3	_____
Limestone	2-7	6	_____
Sandstone	4-8	6	_____
Bedded LS/SS/Shale	4-8	6	_____
Sand and Gravel with Sig. Silt and Clay	4-8	6	_____
Metamorphic/Igneous	2-8	4	_____
Sand and Gravel	6-9	8	_____
Basalt	2-10	9	_____
Karst Limestone	8-10	10	_____

7. Hydraulic Conductivity (gpd/sq. ft.)

Range	Rating
1-100	1
100-300	2
300-700	4
700-1,000	6
1,000-2,000	8
2,000+	10

DRASTIC Index

Rating x Weight = _____

1. _____ x 5 = _____
2. _____ x 4 = _____
3. _____ x 3 = _____
4. _____ x 3 = _____
5. _____ x 1 = _____
6. _____ x 5 = _____
7. _____ x 3 = _____

Total _____ *

Pesticide Rating x Weight = _____

1. _____ x 5 = _____
2. _____ x 4 = _____
3. _____ x 3 = _____
4. _____ x 5 = _____
5. _____ x 3 = _____
6. _____ x 4 = _____
7. _____ x 2 = _____

Total _____

* Aquifers with DRASTIC ratings > 150 are considered to be "highly vulnerable" by EPA.

Figure III-2: DRASTIC Worksheet

CHAPTER IV

MODEL APPLICATION AND METHODOLOGY

The RESSQC semi-analytical module was used in this study to delineate the capture zones for the 5 well fields in the Enid region. The five well fields comprise of about 150 wells, with each well field being separately considered. The purpose of this experiment was to delineate the capture zones for each of the 150 wells with 1, 10, 20 and 30 year time of travels. The analytical solutions of the module given in Chapter IV were the base equations used in the delineation procedure. There are certain values which are generated by the models themselves. But input parameters such as the direction of flow, hydraulic conductivities, hydraulic gradient and aquifer thickness are to be manually fed into the models.

Site specific data were obtained from the City of Enid, giving precise locations of the wells as X and Y coordinates in their respective wellfields and also the other geologic data such as

- transmissivity in ft²/day
- hydraulic gradient ft/ft
- the saturated thickness of the aquifers in feet
- aquifer porosity in percentage porosity
- angle or direction of flow in degrees (Appendices A, B, C, D, E)

In addition to this the maximum pumping rate for each well was also obtained in ft³/day. The well diameters were more or less the same all throughout the well fields. Each well field was considered separately to create a separate databases and the model was run with different times of travel (1, 10, 20 and 30yr). With each run a map giving the delineated capture zone for that specific well field was obtained. An example output of the capture zone for one well using the MWCAP module is given in the Figure IV-1.

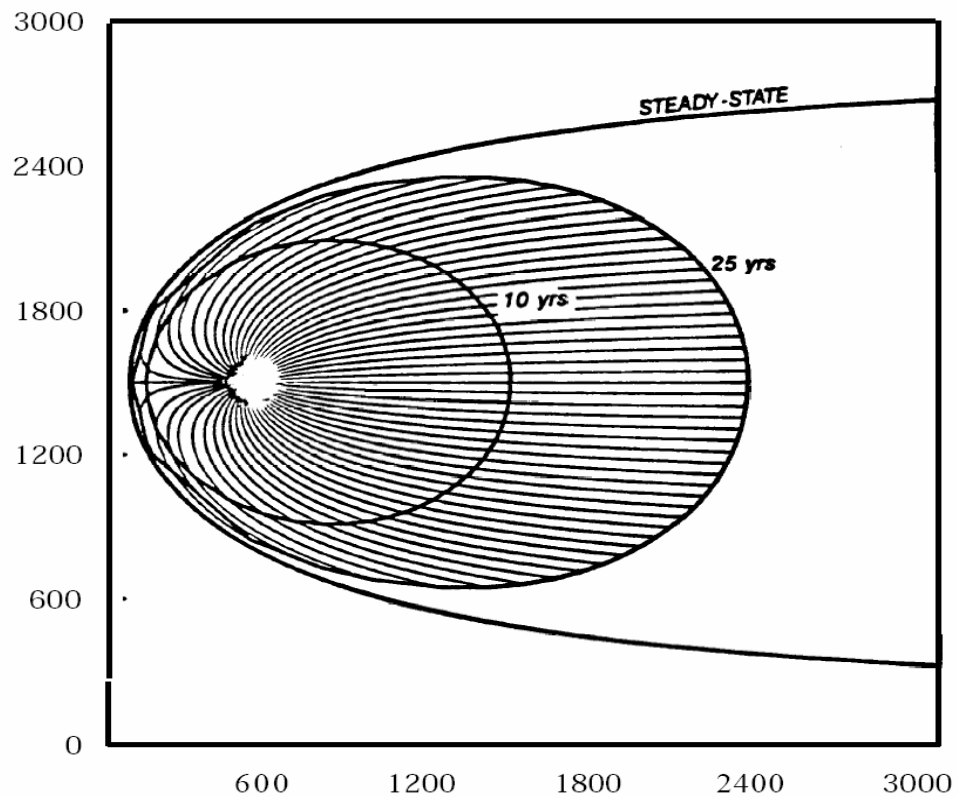


Figure IV-1. Capture zones obtained from MWCAP module

Selection of Model

Amongst the three modules used in the analysis the results of only one module can be used, which is best suited to the current situation. To eliminate two of the modules it is necessary to analyze the capabilities and limitations of each, so that the site specific module can be identified.

The common capabilities of the three modules are (WHPA, EPA, 1993):

- Ability to delineate time related capture zones for homogeneous aquifers.
- Potential to be utilized for a cluster of up to 50 wells at a time ward and capability for reverse tracking.

Under perfect conditions all three modules could be used to delineate the required area, but the conditions present in the study area bring out a few limitations in the given modules:

- MWCAP module does not take into account well interference from neighboring wells. Since most of the wellfields in the region are a dense cluster of pumping wells, not taking into account interference would result in incorrect delineations (WHPA, EPA, 1993).
- Also the study area is made of dense network of streams, which could result in a stream or barrier boundary. As mentioned above the MWCAP module does not take these interferences into account. The GPTRAC on the other hand is usually used as a post processor, once the capture zones have been created (Vieux et. al, 1998).
- The RESSQC module, unlike the other two modules, accounts aptly for such interferences. Especially in this study where the wells are not evenly spaced, this

model is more suitable than the others. Also in the case of a stream barrier, the module assumes image wells in such locations and counters for the barriers, to give much better delineations than the other modules.

Based on the above considerations, it would be appropriate to select the RESSQC module for further analysis.

Integration of WHPA output and GIS

The output from the various modules of the WHPA semi analytical solution RESSQC was obtained on screen showing the pathlines delineated. Using an inbuilt feature of the WHPA model, these WHPA output maps were converted to text files, suitable for input into the Arc GIS program. The output text files were sets of rows and columns representing the coordinates of the points constituting the path delineated by the program. A snapshot of the resultant text file is shown in Figure IV-2.

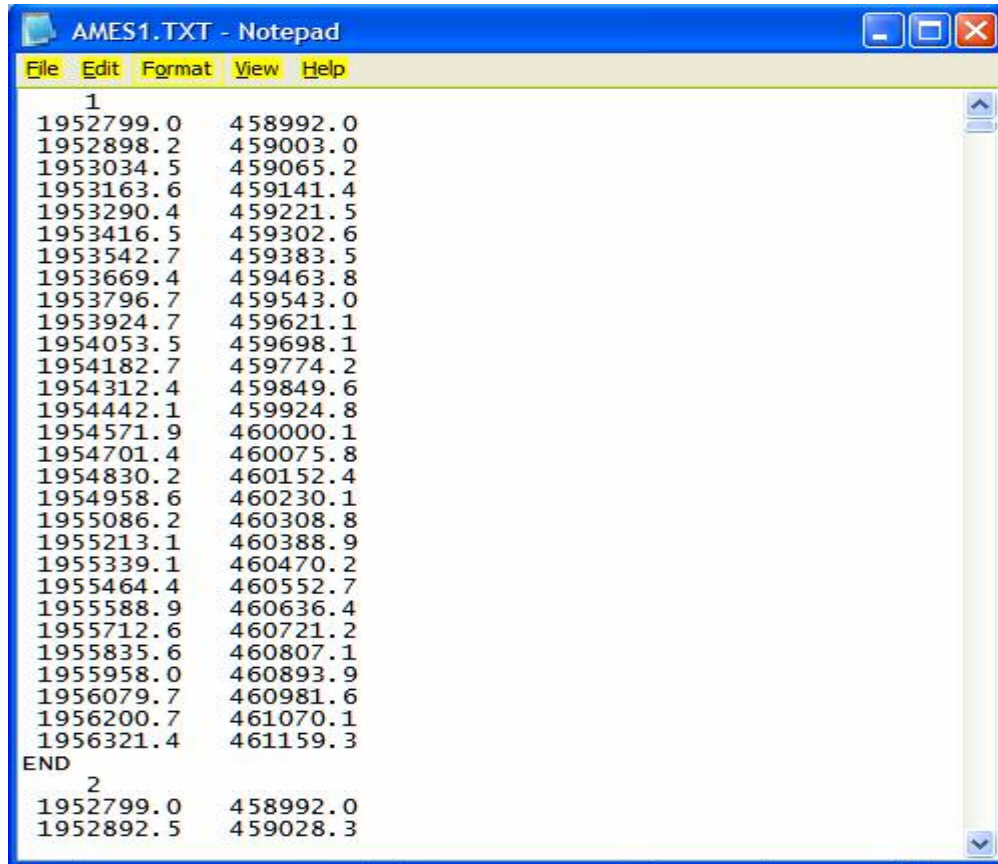


Figure IV-2. Output text file from WHPA model

These text files were converted into database files in the Microsoft Excel. In the Arc GIS model an option to input data in the form of database tables is available. The import X,Y data in the Arc GIS considers each set of values in these tables as points and plots them on the map for the specified coordinate system. The coordinate system used in this case is the State Plane Projection (OKLAHOMA); NAD 1927 system. Using this method of input into Arc GIS, maps were created for each of the four times of travel for the results obtained from the RESSQC module. These maps were then integrated with a political boundary map of the U.S. showing the state and county boundaries, major aquifer boundaries, the local stream network and also locating important cities. This is done to

obtain an extent of the delineations on the maps for various time periods. This gives us an idea of path of travel of water to the wells from inside the aquifers.

Figures IV-3 TO IV-6 represent the results obtained from the WHPA delineations using the RESSQC module. The shaded areas represent the capture zones for each of the five wellfields. This implies that a particle at the end of a 10 year capture zone would reach the well in same time. This area can be used as the basis or the region of analysis.

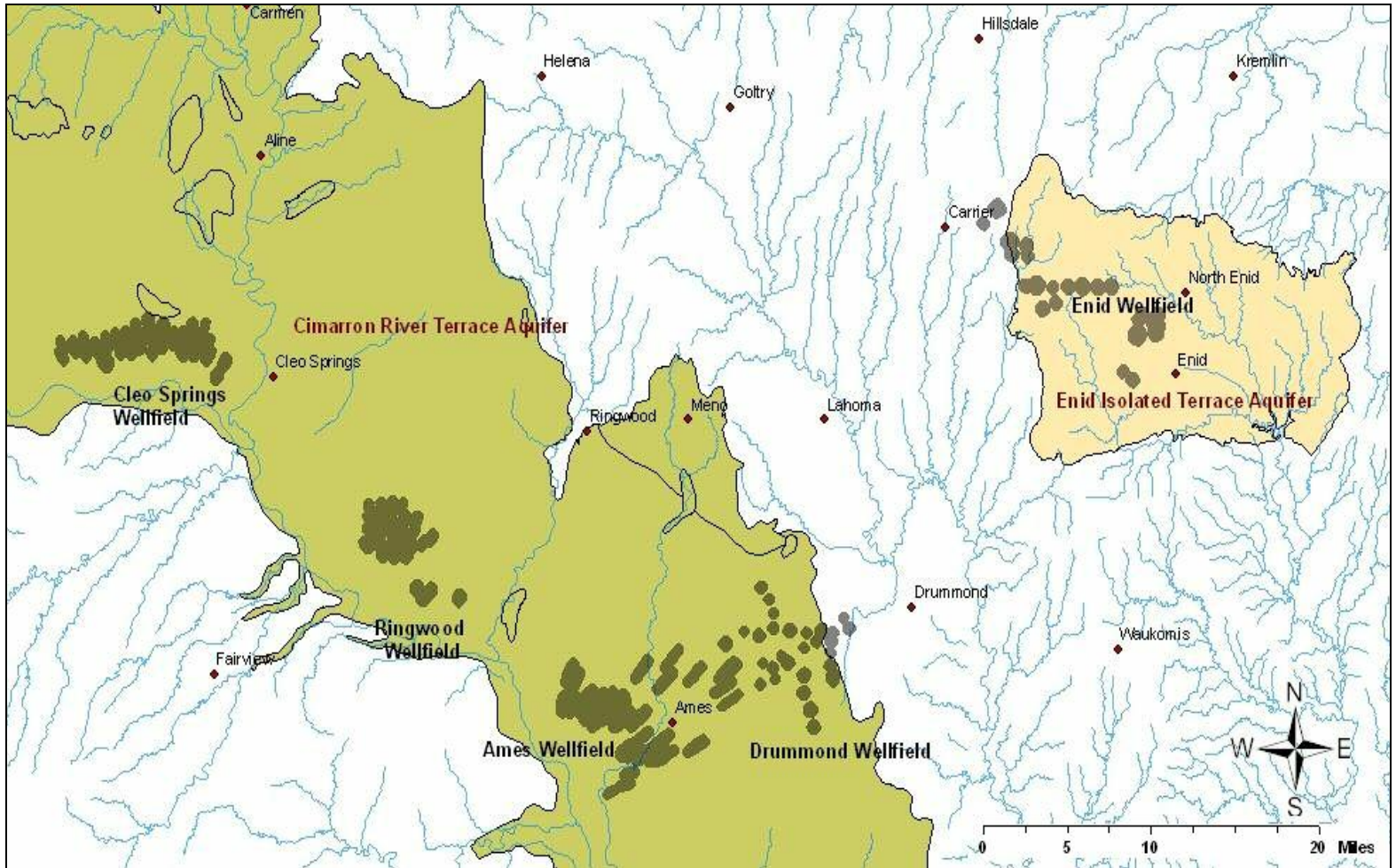


Figure IV-3: RESSQC module 1 year time of travel

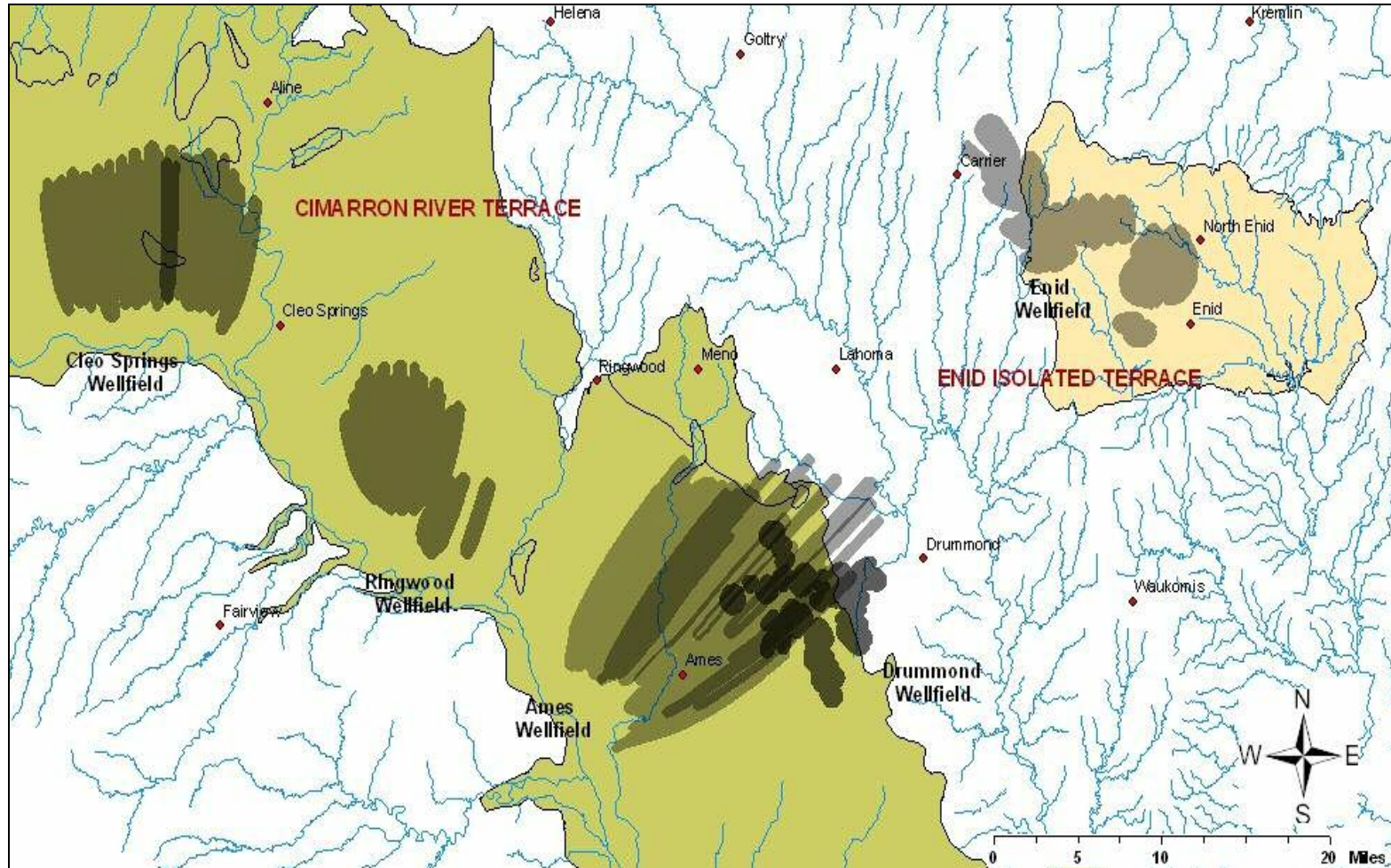


Figure IV-4: RESSQC module 10 year time of travel

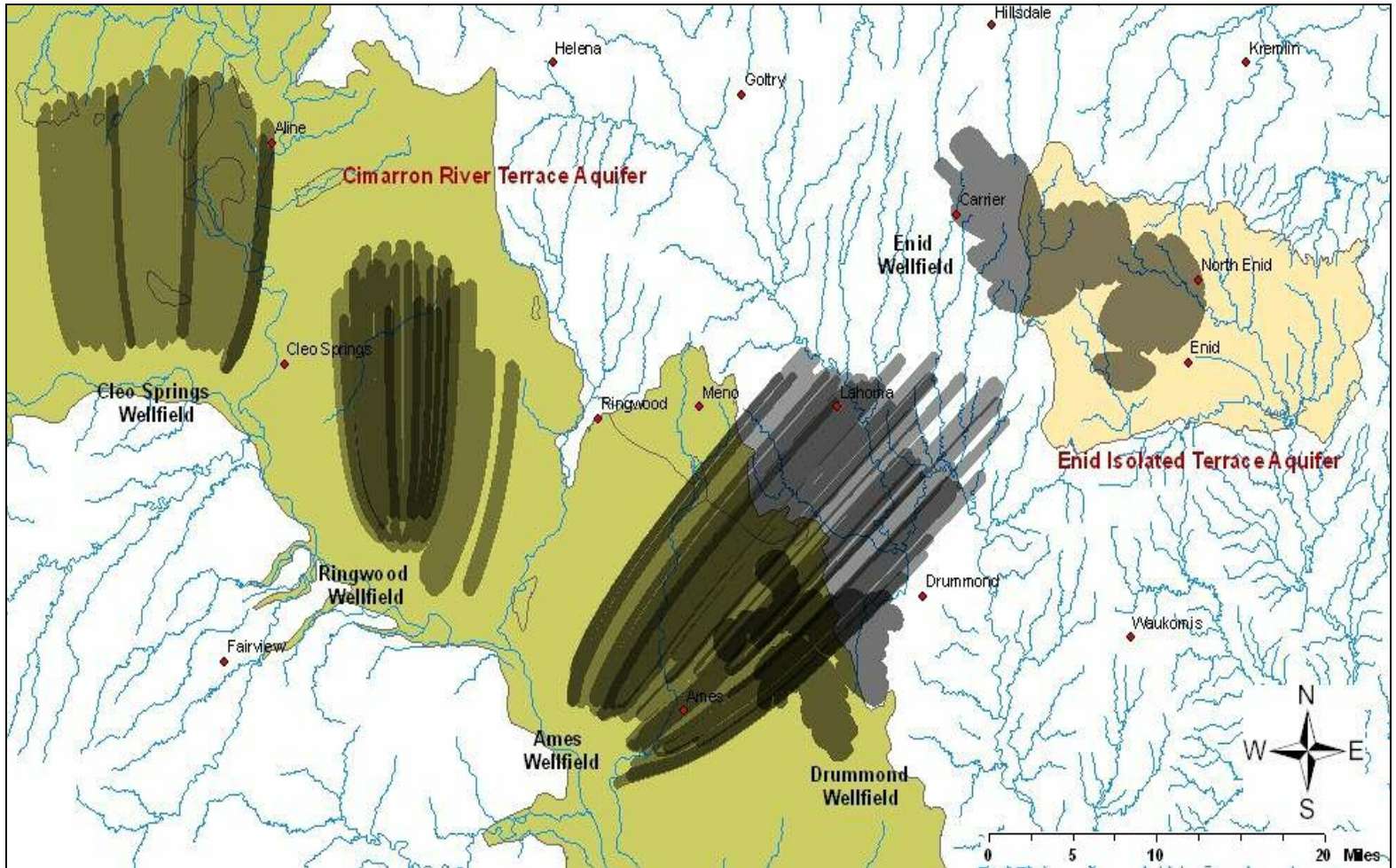


Figure IV-5: RESSQC module 20 year time of travel

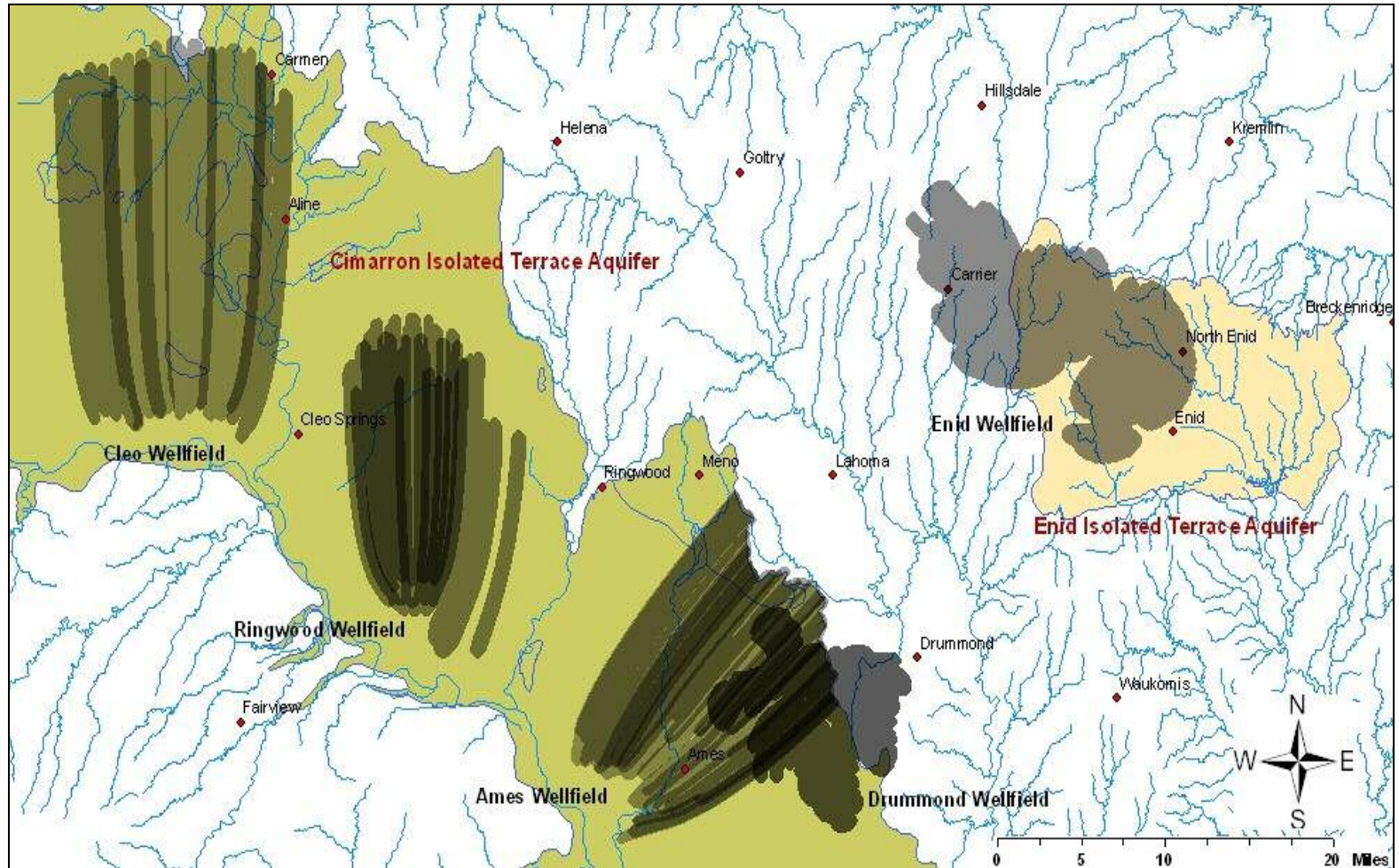


Figure IV-6: RESSQC module 30 year time of travel

DRASTIC Methodology:

Maps were created with the help of the Arc Geographic Information Systems (GIS).

Based on the data obtained for each of the seven parameters, the ratings and the weights were assigned to calculate the DRASTIC index. Previous studies confirm the depth to groundwater and the impact on vadose zone to be the most important factors (OWRB, 1998; Barry et. al, 1990; Babiker et. al, 2005). Recharge is the next most important with a weight of 4 followed by aquifer media and hydraulic conductivity at 3 and soil media at 2. The least important factor being the topography of the region is given a weight of 1.

One of the previous studies by the Oklahoma Water Resources Board (OWRB) conducted a vulnerability analysis for all major aquifers in Oklahoma. Since the same prevailing conditions are being used in this study as well, some data has been retained from that study. The sources from which data on the governing parameters were obtained are:

- The OWRB well log data
- USGS data for annual precipitation and recharge
- USGS data for hydraulic conductivity through the aquifers
- The Hydrologic atlases of Oklahoma
- Natural Resource Conservation Board (NRCS), soil data

The related tables giving the weights and ranges for the seven parameters are given below.

Table IV-1: Depth to Groundwater

Range (ft)	Rating	Weight	DRASTIC Index
0 to 5	10	5	50
5 to 15	9	5	45
15 to 30	7	5	35
30 to 50	5	5	25
50 to 75	3	5	15
75 to 100	2	5	10
Greater than 100	1	5	5

Table IV-2: Recharge to Groundwater

Range (in.)	Rating	Weight	DRASTIC Index
0 to 2	1	4	4
2 to 4	3	4	12
4 to 7	6	4	24

Table IV-3: Aquifer Media

Media	Rating	Weight	DRASTIC Index
Cimarron river terrace – sand and gravel	8	3	24
Enid isolated terrace – sand gravel	8	3	24
Permian aquifers	7	3	21
Cedar hills – sandstone and siltstone	6	3	18

Table IV-4: Soil Type

Media	Rating	Weight	DRASTIC Index
Thin or absent	10	2	20
Gravel	10	2	20
Sand	9	2	18
Sandy loam	6	2	12
Clay loam	3	2	6

Table IV-5: Topography

Percent slope	Range	Weight	DRASTIC Index
0 to 2	10	1	10
2 to 6	9	1	9

Table IV-6: Impact on Vadose Zone

Media	Rating	Weight	DRASTIC Index
Cimarron river terrace – sand and gravel	8	5	40
Enid isolated terrace – sand gravel	8	5	40
Permian aquifers	5	5	25
Cedar hills – sandstone and siltstone	6	5	30

Table IV-7: Hydraulic Conductivity

Range (gpd/ft ²)	Rating	Weight	DRASTIC Index
1 to 100	1	3	3
300 to 700	4	3	12
700 to 1000	6	3	18

The layers obtained from the various sources were used as the base maps to input the ratings and weights. Using the extent of the base map a grid or a raster of 50 X 50 cells was created over the coverage area. The NPS grid tool extension was used to create the grid. Using this extension enabled specifying the number of cells making up the raster and also the cell size. A raster is an area containing cells or rectangles of equal size. Simple mathematical and logical operation can be carried out on rasters. The pixel size used in these grids came up to 4265ft x 4265ft. Seven different grids were created for each of the governing parameters. To give the cells the ratings, a method in ARC GIS called ‘reclassify’ was used. Reclassify is a simple process by which individual values or ranges are changed to new user defined values. A simple reclassification operation is given in Figure IV-7.

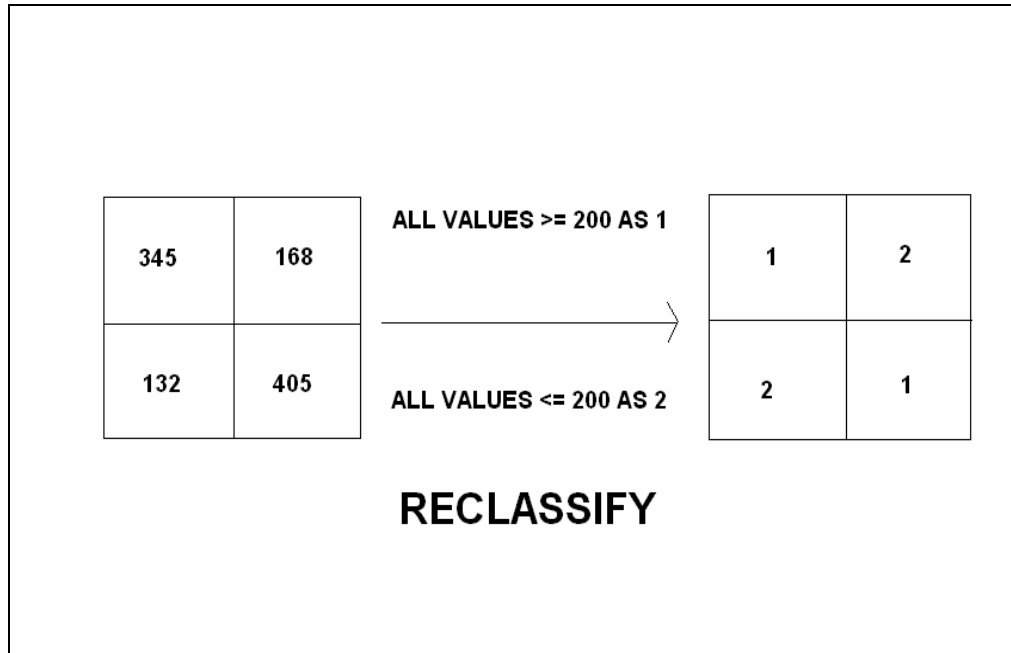


Figure IV-7: Example of a raster reclassification operation

Based on this operation the ranges of values in the different parameter maps were converted into the ratings given in Tables IV-1 to IV-7. The result is a raster data set containing the ratings for the seven parameters. Using a simple mathematical operation, the ratings were multiplied by the weights previously assigned for each of the parameters. This transformed the values of the cells into the DRASTIC index for all the maps. In GIS it is possible to add the values of the cells of different rasters, if the layers are of the same size. Same size means that the number of cells constituting the raster map and the dimensions of each of these cells are the same. This methodology is called Raster Addition. Since the grids or rasters created were all of the same size, the final DRASTIC groundwater vulnerability map was obtained by the additive overlay of the seven individual maps. Standard DRASTIC colors ranging from grey being the least vulnerable

to red the most vulnerable were used to represent the vulnerability map. The final DRASTIC vulnerability map is given in Figure IV-8.

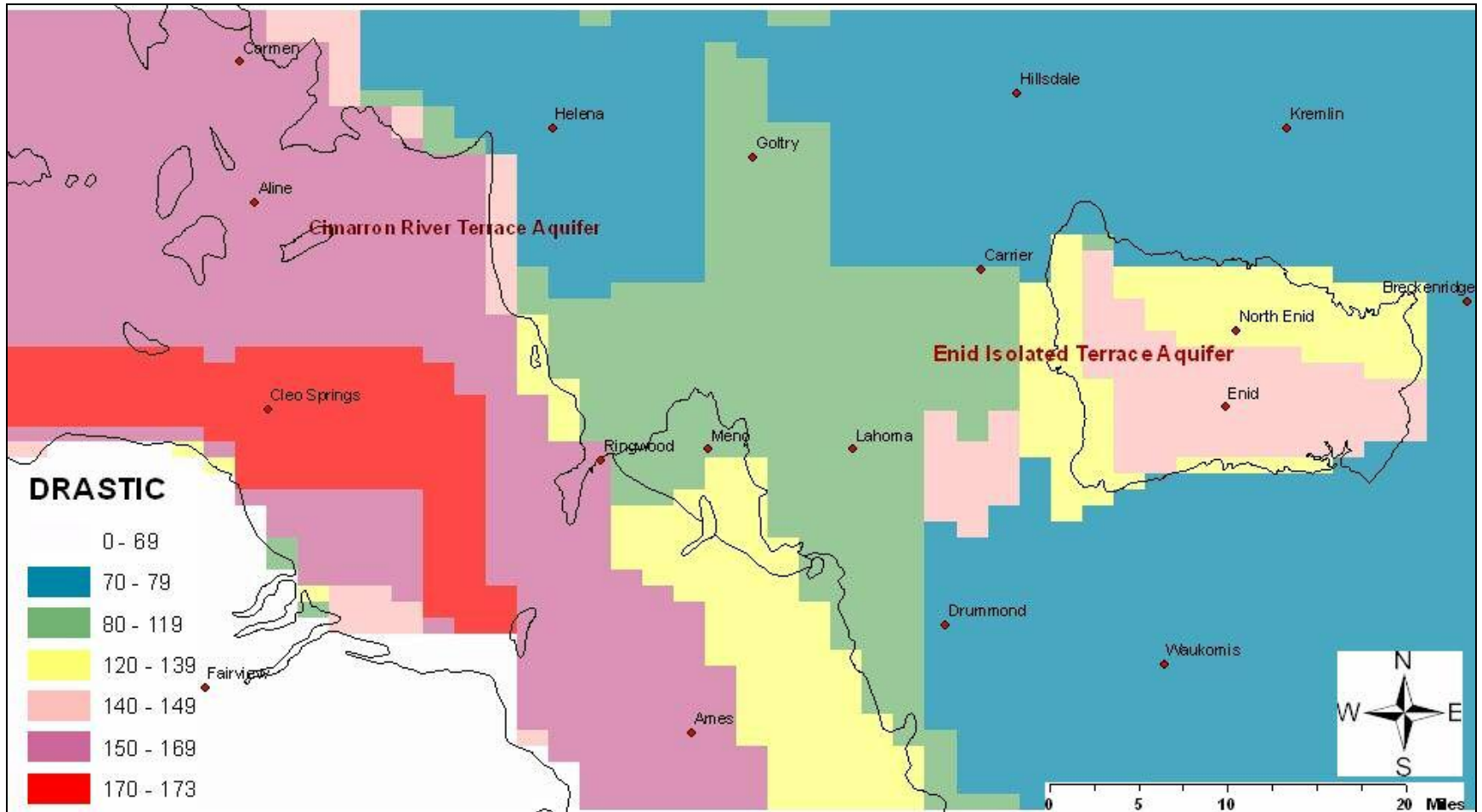


Figure IV-8: Overall vulnerability map for the study area. A greater value indicates a higher potential to contamination

CHAPTER V

CONTAMINANT INVENTORY

Land Use

One of the major factors influencing how the results obtained from the vulnerability assessment can be interpreted is, by analyzing the contaminants present in the study area.

The reasons for analyzing the land use are:

- The type and severity of groundwater contamination can be in some cases directly related to human activity. An analysis of the land use and population gives an idea as to the types of possible contaminants in the study area.
- In analyzing the effect of land use on groundwater contamination, it can be assumed that the recharge wasn't already contaminated and the contaminant lies in the path delineated for the well.

Some of the common groundwater contaminants related to land use patterns are:

- High concentrations of nitrate can be connected with domestic sewage and lawn fertilizers in residential areas, from crop fertilizers and manure in agricultural areas. Nitrate bearing fertilizers can readily leach through the soil in to the groundwater after irrigation or heavy rains (Wellhead Protection, EPA, 1994).
- Human sewage and animal waste can be a major source of bacteria. It evolves from septic tanks and animal activities. Data on the denseness of septic tanks in the area gives an idea of bacteria contamination of wells.

- VOC's have been another major groundwater contaminate. Usual suspects for release of VOC's are leaky petroleum tanks and industrial activities. Commonly the population density near wells is directly related to presence of organic compounds in groundwater (Wellhead Protection, EPA, 1994).

The study area consists of a mixed utilization pattern in the forms of agriculture lands, forests, residential and a small number of commercial and industrial activities. From the land use land cover map obtained from the ESRI GIS database (Figure V-1), it is observed that the regions represented in pink to red denote residential, commercial or industrial occupation. Such regions are found mainly around the City of Enid and sparsely in other parts of the study area. The regions represented by the green patches represent agricultural activity and the brown to yellow regions represent rangeland or forested areas. Drummond well field lies amidst vast areas of non irrigated pasture and agricultural fields. Ames well field again lies completely on agricultural and forested region, with the exception of a few residential spaces. The other two wellfields, Cleo Springs and Ringwood lie in region of high agricultural activity. Except for agriculture no other major commercial activity is observed in that region. To further analyze possible contaminants, a study of the hazardous waste sites and the oil and gas activities in the region would be substantial.

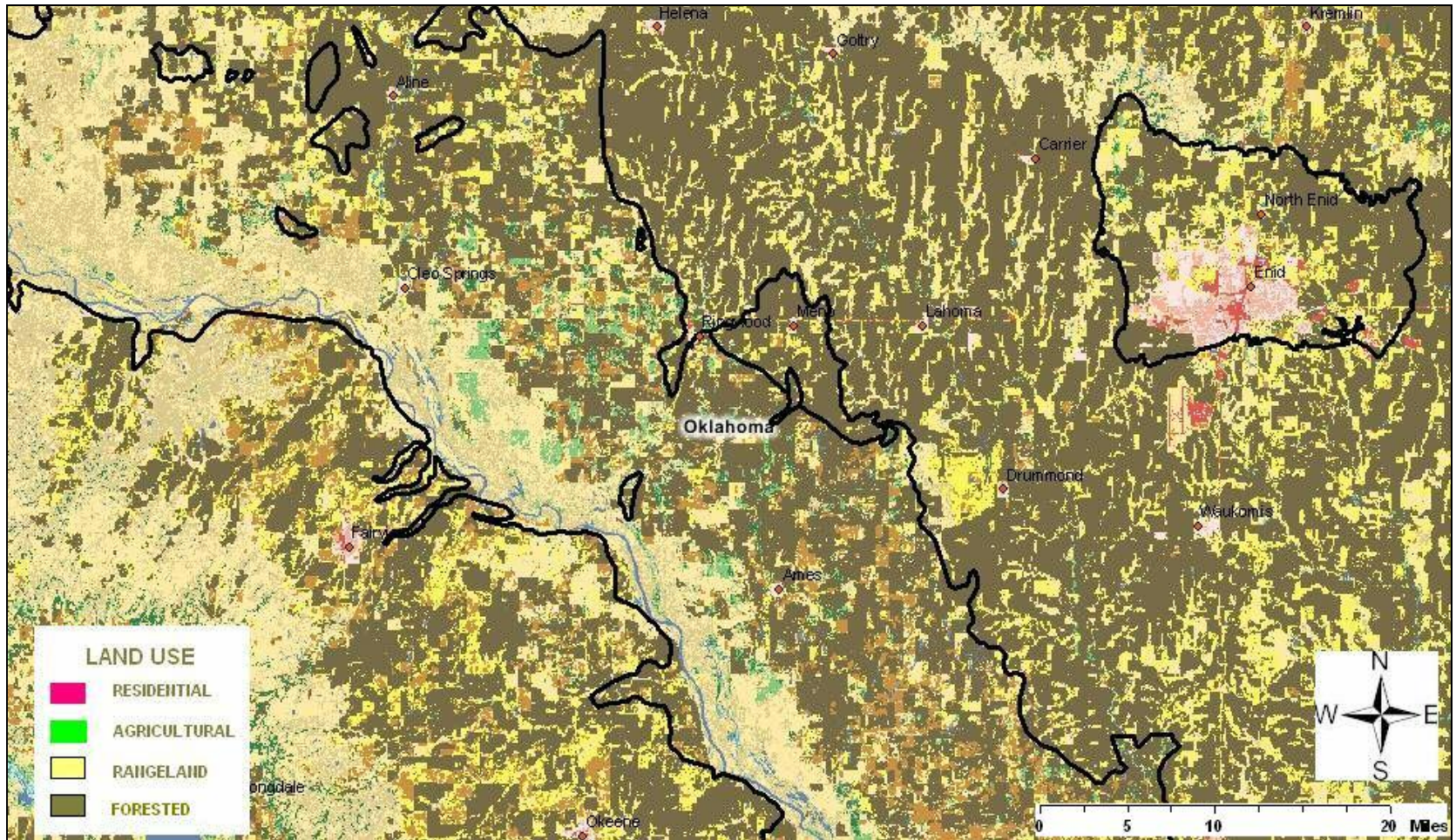


Figure V-1: Land Use Land Cover for the study area

Chemical Contamination in Groundwater Wells

Nitrates are a major concern and result in groundwater due to common processes like application of agricultural fertilizers and domestic sewage. It is important to monitor and thereby identify locations which are most susceptible to nitrate contamination, as it can easily leach through the soil during heavy rainfall and reach groundwater. In this context a probability map for groundwater contamination to nitrates, developed by the USGS was used. The model predicts the probability of nitrate contamination of shallow ground waters based on several factors:

- Nitrogen (N) fertilizer loading
- Percent cropland-pasture
- Natural log of human population density
- Depth to the seasonally high water table
- Presence or absence of unconsolidated sand and gravel aquifers

The model predicts the probability of recently recharged ground waters with a nitrate contamination of over 4 mg/L. Since the maximum allowable contaminant levels (MCL) set by the US EPA is 10 mg/L, from the map given in Figure V-2 the probabilities for nitrate contamination over 65% were chosen as vulnerable areas.

Also the Department of Environmental Quality (DEQ) in Oklahoma monitored the testing of each of the wells in the study area. The data was available from 1995 till 2005. For this analysis only the data from 2004 and 2005 was used to identify wells with high nitrate concentrations. From the results, the data for amount of nitrates present was taken to find any contaminated wells. The wells exceeding the DEQ limits for safe drinking

water standards are presented in Table V-1 and the location of the wells are given in Figure V-3.

Table V-1: 2004-2005 DEQ Test Results

Maximum Allowable Contaminant Level for nitrate = 10 mg/L

WELLNAME/NUMBER	AMOUNT OF NITRATE (mg/L)
AMES 1	11.8
AMES 11	13.6
AMES 13, AMES 15	14.0
AMES 14	13.0
AMES 17	15.6
AMES 18, AMES 19	14.8
ENID 4, ENID 20	15.4
ENID 9, ENID 14	12.8
ENID 13	15.6
RINGWOOD 14, 22	13.6
RINGWOOD 21, 26	12.0
RINGWOOD 28	16.2
CLEO SPRINGS 18	15.4
CLEO SPRINGS 20	13.4
CLEO SPRINGS 21	13.7

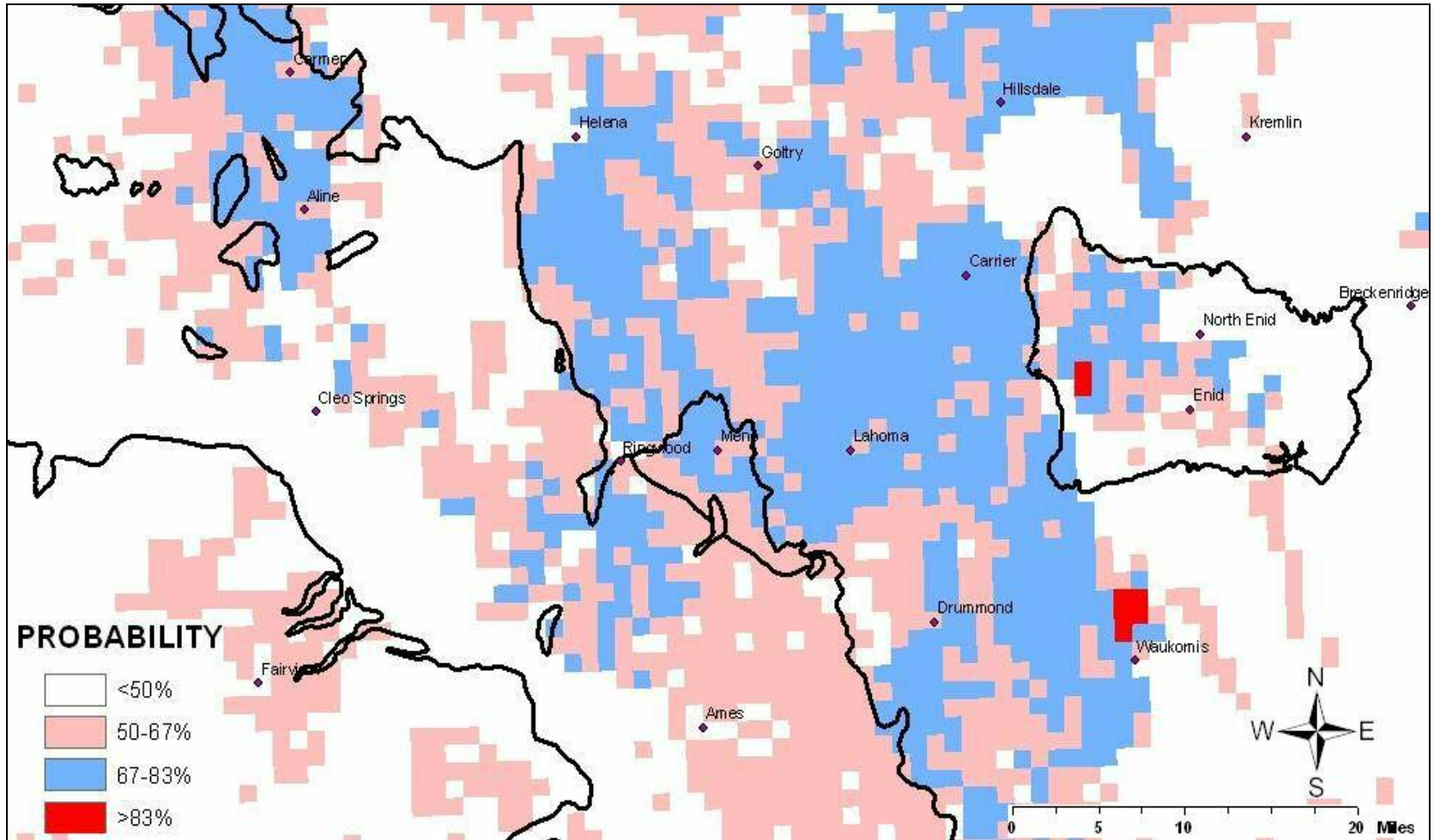


Figure V-2: Probability map of groundwater contamination by nitrates

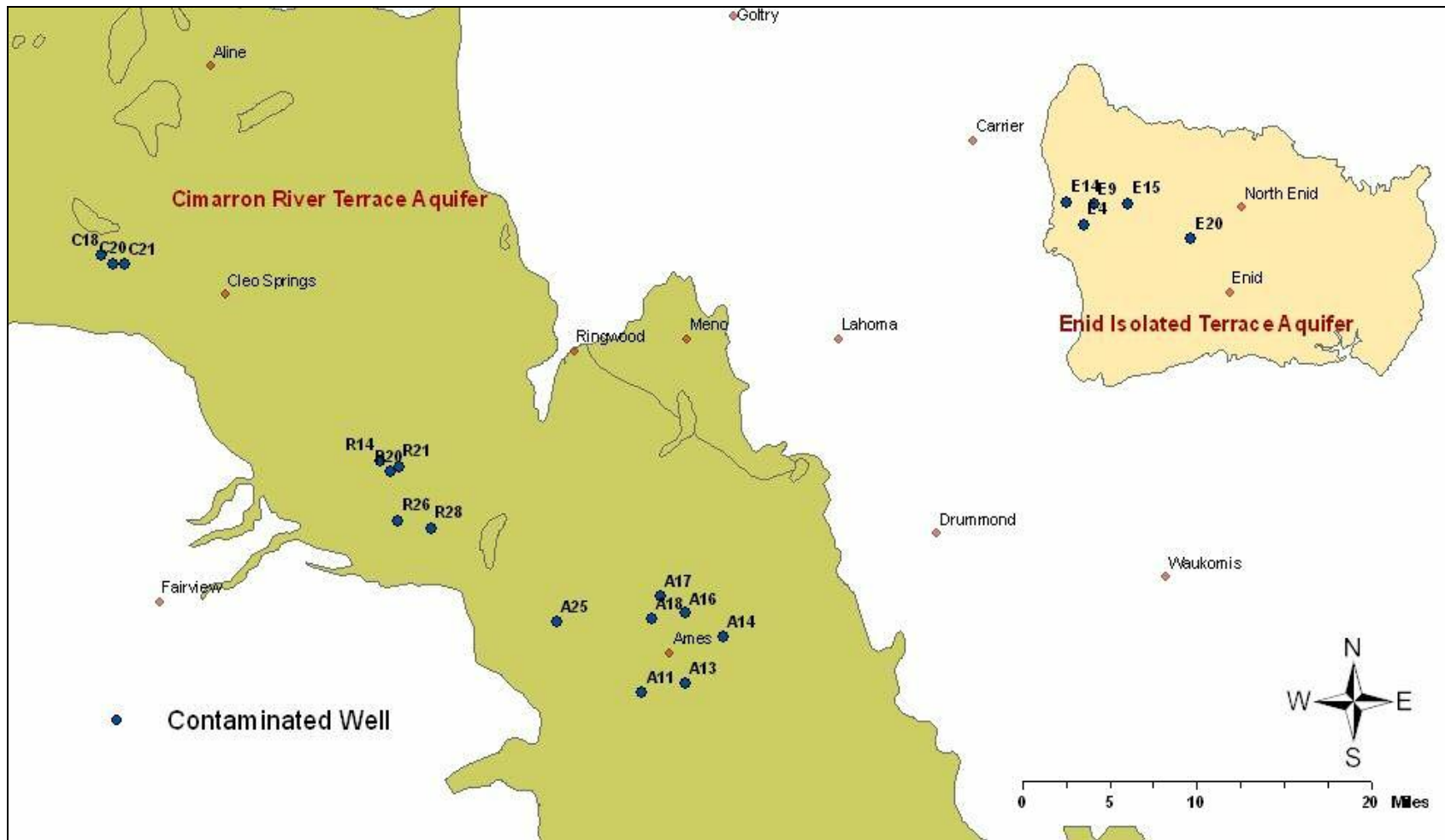


Figure V-3: Location of wells contaminated with nitrates

Hazardous Waste Storage and Handling

From the ESRI GIS and USGS database the location of the major hazardous waste sources were identified and are shown in Figure V-4. Since dealing with groundwater protection is the major concern, sources that could reach groundwater through percolation, leakage and spills, such as toxic release sites, hazardous waste generation and handling sites and landfill sites have been considered here. Most of the subjects under the above stated categories lie in and around the Enid region. A total of 8 toxic release sites, were identified. This could be a major source of contamination, but still depends on how close it is to the pumping wells. Two landfill sites one inside the city limits and another near Ringwood were identified. A major source of hazardous waste generation was identified to be the USAF Vance Air force Base located a few miles from the city. Also one hazardous waste handling facility was identified inside the city limits. Though the processes here are taking place in a controlled environment, due to the nature of the substances handled it has to be categorized as a contaminant source.

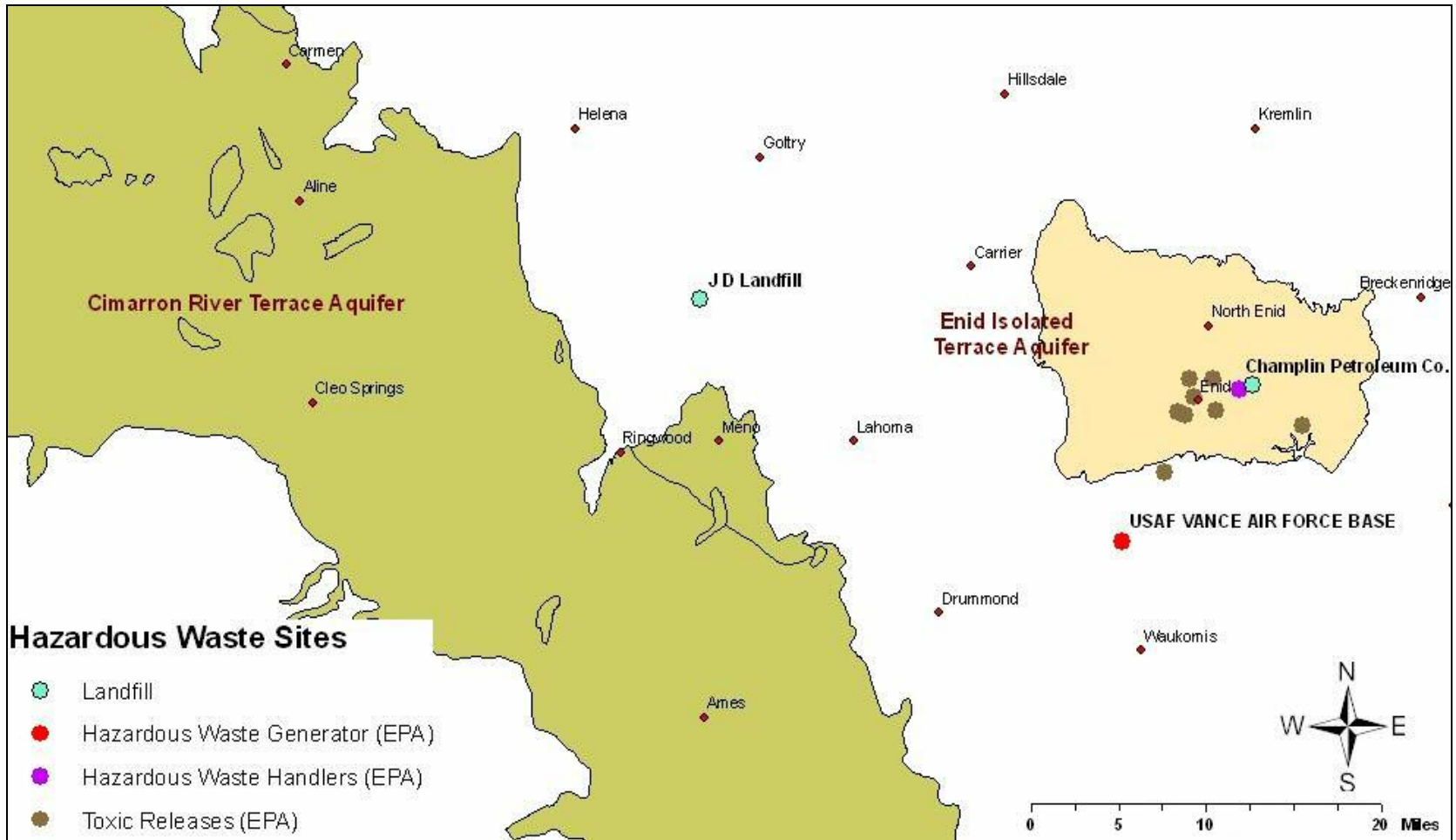


Figure V-4: Hazardous waste sites in the study area

Oil and Gas Wells

The data on oil and gas wells location was obtained from the Natural Resource Conservation Society (NRCS) database maintained by Department of Geology at the University of Oklahoma. The data set contains the locations oil and gas wells in the region, both active and abandoned (Figure V-5). Both active and inactive wells have to be considered as a source of contamination due to various reasons:

- Improperly cased or drilled wells or when casing of the well has corroded, serves as a path for contamination of the underlying aquifer.
- Abandoned oil wells act as channels for upward movement of brine and contaminated water found in oil bearing zones. Plugging of these wells is essential to prevent contamination of the underlying aquifer.
- Abandoned or improperly sealed wells are a hazard to groundwater aquifers because contaminated surface water can enter a well when the well cap is damaged or removed. Contamination can occur if there are holes in the well casing due to damage or deterioration with age.
- Contaminated surface water can seep down along the casing of an improperly constructed well.
- Well covers in flood-prone and low areas can also allow contamination to enter the aquifer during heavy rainfall.

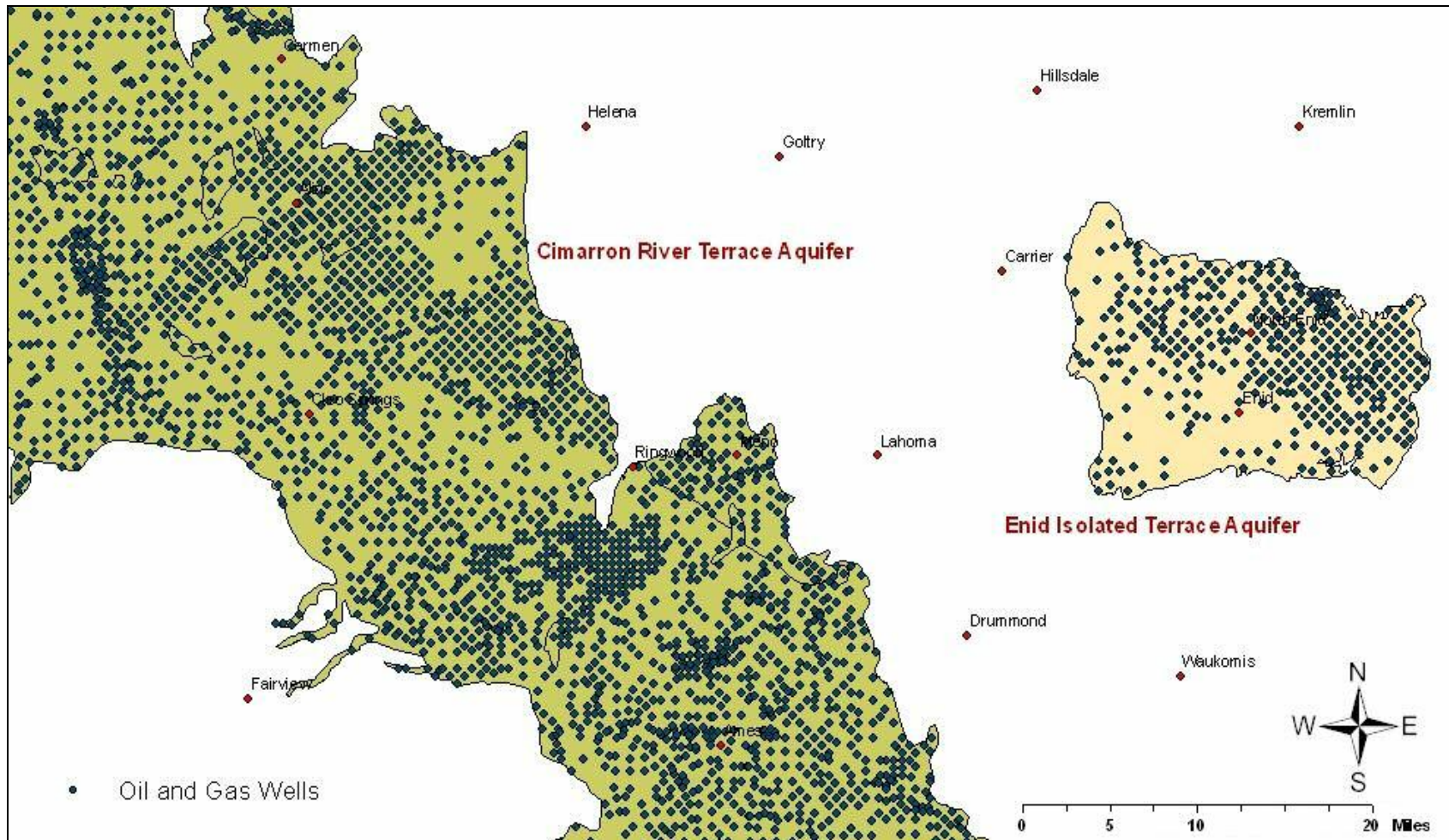


Figure V-5: Location of oil and gas wells, both active and abandoned

CHAPTER VI

RESULTS AND DISCUSSIONS

WHPA and DRASTIC

The areas delineated using the WHPA program would get a better meaning when used in conjunction with the vulnerability analysis. The results of the 30 year WHPA obtained from the RESSQC overlaid on the DRASTIC vulnerability analysis map. The result of the overlay is shown in Figure VI-1.

As represented by the DRASTIC color schemes, the regions in red represent maximum vulnerability. Any well in this region can be considered to have the shortest and easiest path for contaminant transport. On the outlook, the wellfields of major concern would be Ringwood and Cleo Springs.

The 30 year WHPA's for the Cleo Springs and Ringwood wellfields are in the zone of maximum vulnerability. This zone is present along the Cimarron River in the Cimarron River Terrace Aquifer. Ames well field also finds itself in a region of high vulnerability. Also as these three wellfields have a high yield and contribute as a majority to the water supply, monitoring is essential. Since Drummond well field is in a confined aquifer, the results of DRASTIC do not affect the groundwater in this wellfields. Though the Enid Wellfield finds itself in a region moderate vulnerability, taking other contamination factors into consideration, it can be considered to fall in a highly vulnerable zone.

Verification of the DRASTIC Model

Verification of the DRASTIC model would be important in identifying the regions of concern with utmost accuracy. In order to facilitate that, the results of the Oklahoma DEQ well test results were used. The location of the contaminated wells on the DRASTIC analysis is shown in Figure VI-2. The integration identified that 8 out of the 20 contaminated wells were in the maximum vulnerability zone or the region having a DRASTIC index over 170. There were 7 other wells in the Ames well field on a very high vulnerable region. The 8 wells in the maximum vulnerability region came from the Ringwood and Cleo Springs wellfields. This further ascertained the high potential to contamination of groundwater in the Ringwood and Cleo Springs wellfields.

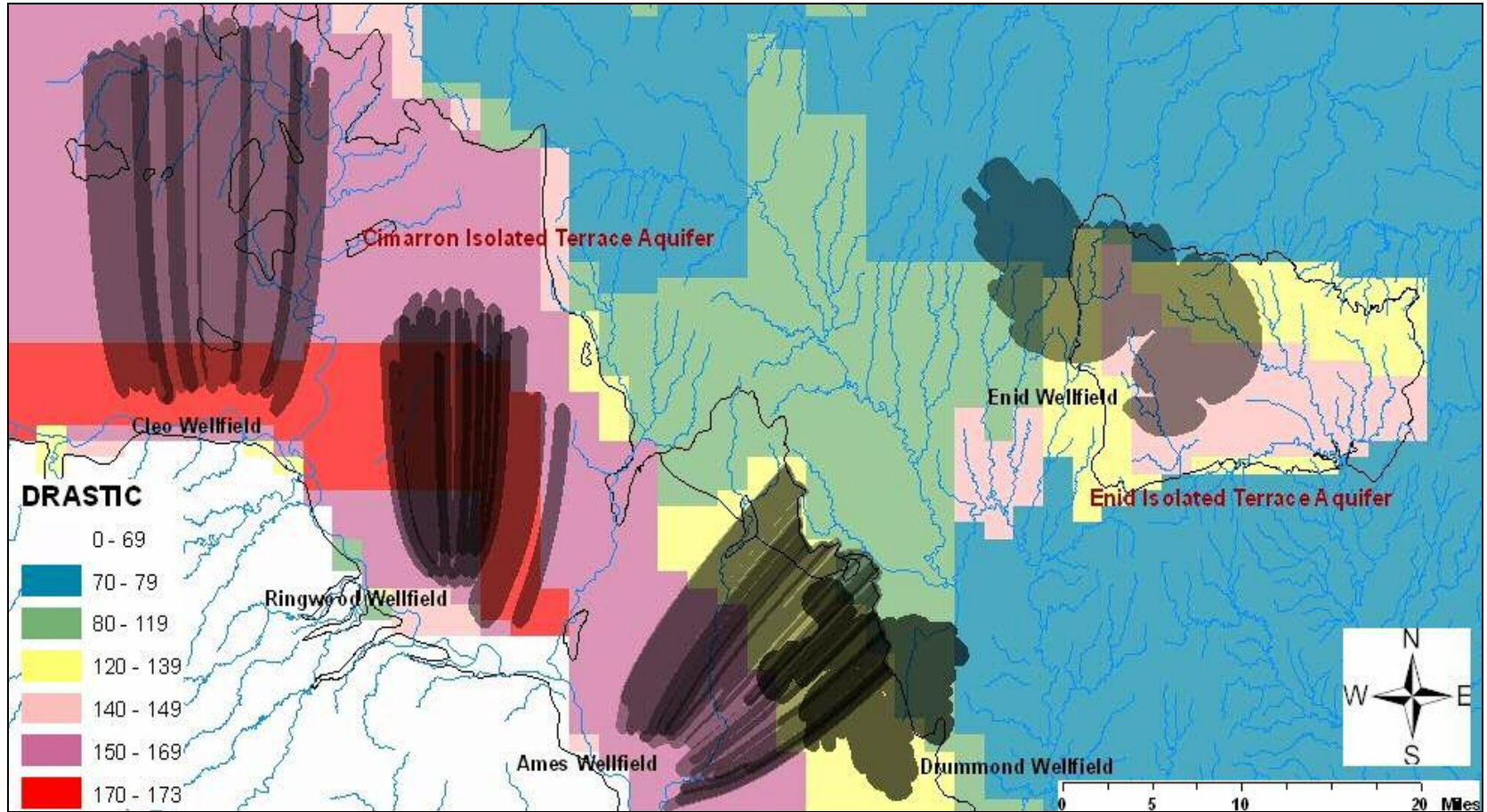


Figure VI-1: RESSQC module 30 year time of travel on the DRASTIC map

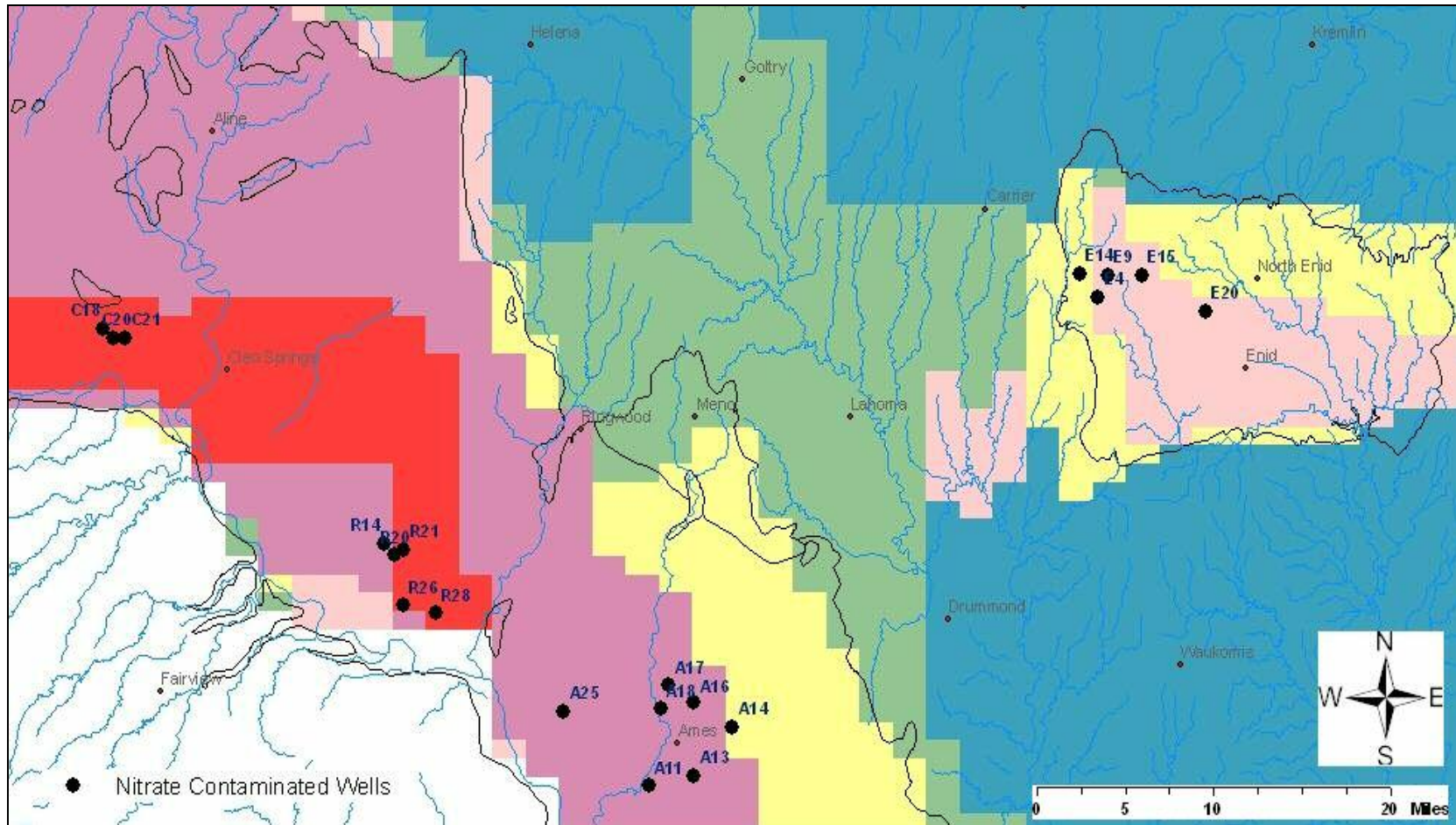


Figure VI-2: Wells exceeding MCL for nitrates on the DRASTIC map

Contaminants from Land Use

From the contaminant inventory, the presence of landfills, hazardous waste sites and nitrate application were identified. The map representing the location of hazardous waste sites on the nitrate contamination probability map is given in Figure VI-3. From the inventory of the hazardous waste sites it is observed that most of the locations lay in the surroundings of the Enid wells to the south of the city. From Figure VI-4 giving a close up view on the locations of the sites along with the 30 year time of travel delineation, it was observed that most of the wells lie in a zone of 67 – 83% probability to nitrate contamination. A well in the bottom of the Enid well field has paths delineated, which cross with the location of a toxic waste producing site. Around 5 wells are in close proximity with a landfill site and a hazardous waste handling facility. Apart from these all the wells in the other wellfields lie in a zone free from any of the major land use contamination sources mentioned above. Also due to the fact that the City of Enid has the maximum population density in the study area, the presence of septic tanks can be assumed to be abundant in the residential areas. Septic tanks could prove as a major source for nitrate contamination. From the above analysis it can be concluded that the attention in the case of contamination due to land use patterns has to be focused more on the region surrounding the wells in the Enid well field and inside the city limits of Enid.

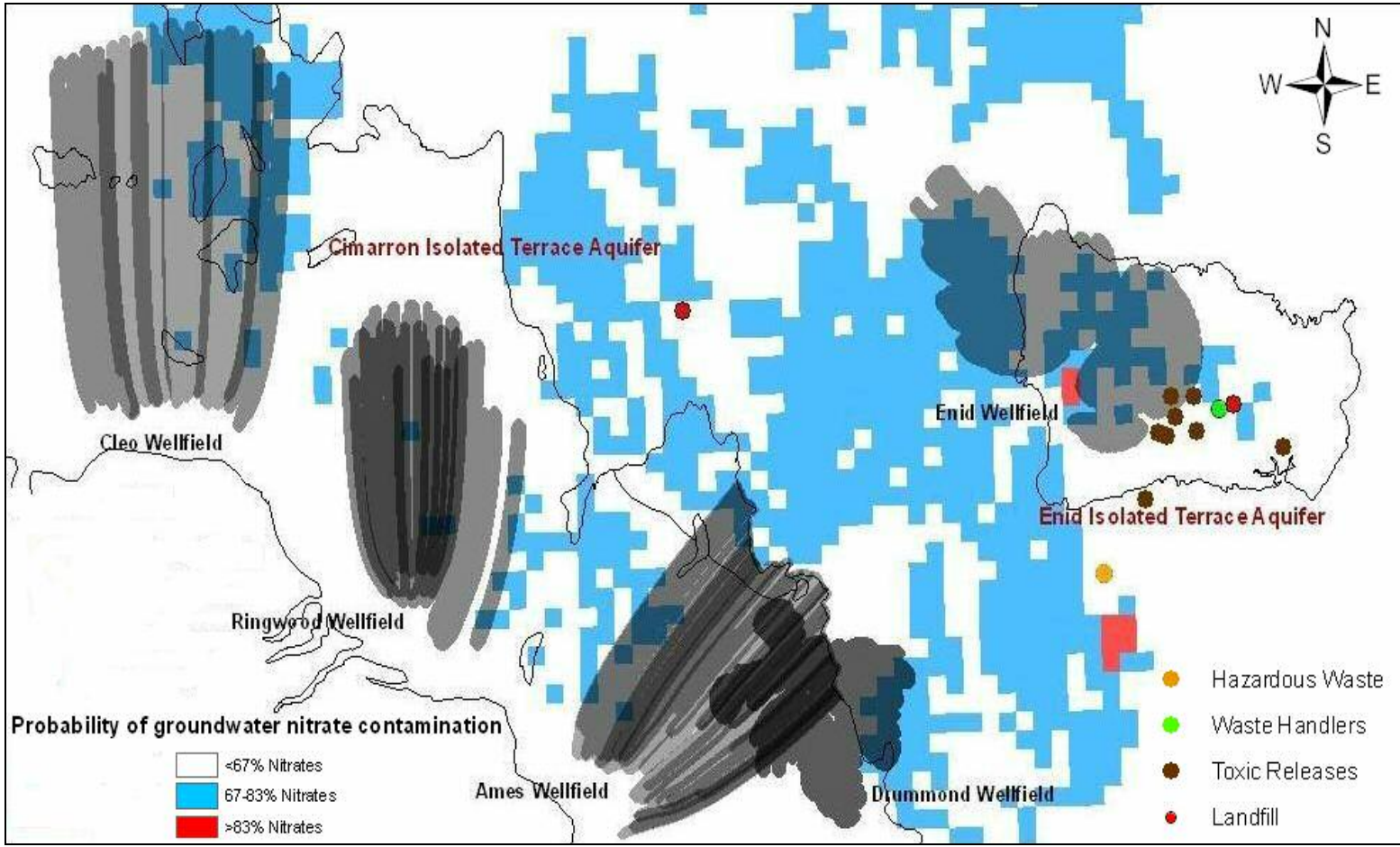


Figure VI-3: Location of hazardous waste sites on the nitrate probability map

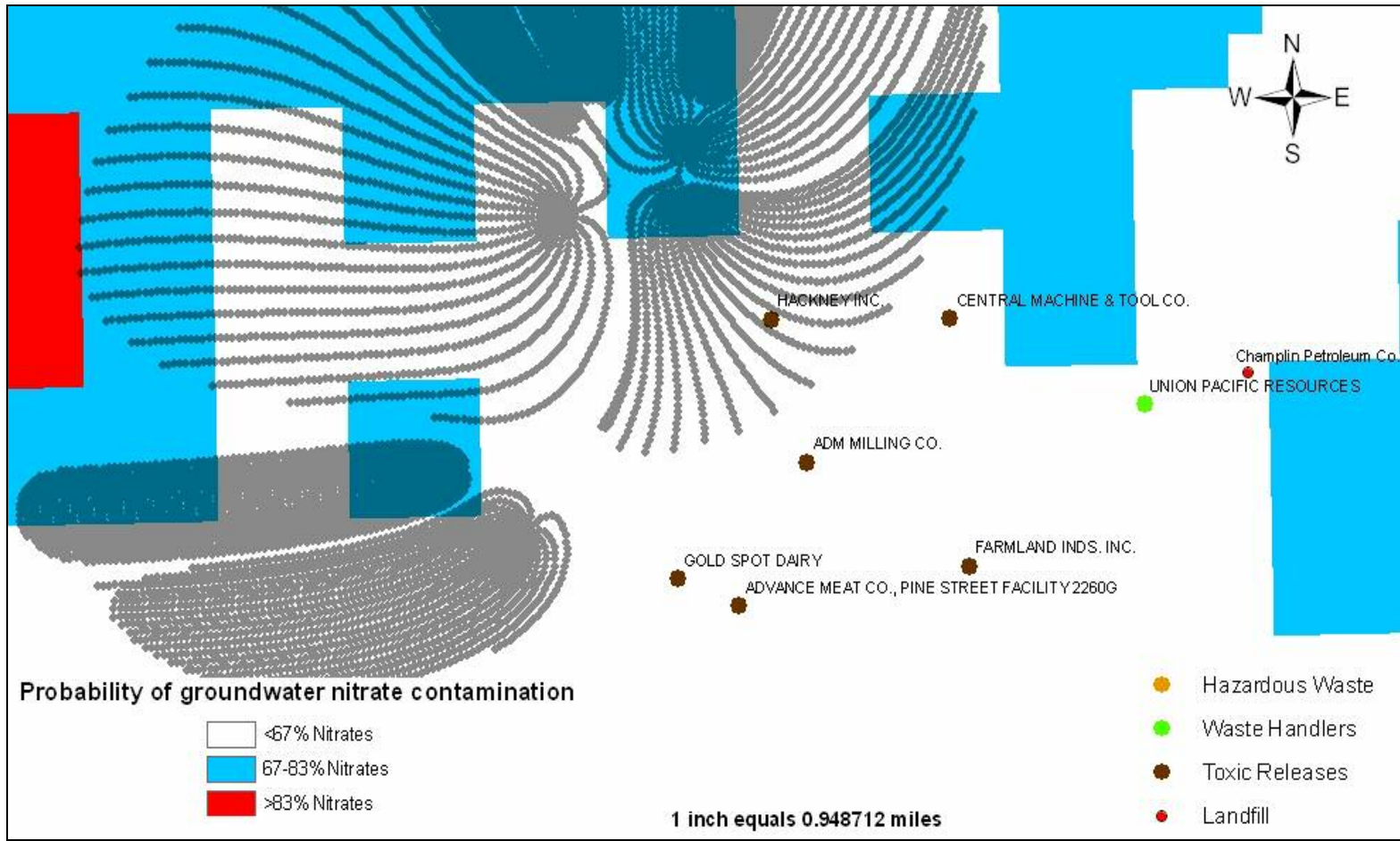


Figure VI-4: Location of hazardous waste sites around the City of Enid

Oil and Gas Wells

The oil and gas wells that fall in the WHPAs of the five well fields under consideration are shown in Figure VI-5. Due to presence of an abundant number of oil and gas wells, both active and abandoned, this is considered as the single most major source for possible contamination of groundwater. Wellfields, Cleo Springs and Ringwood are found to lie in an area of high vulnerability in addition to which hold residence to about 900 oil and gas wells between them. Though all the other wellfields require monitoring and preventive measures from oil well contamination, special interest has to be given to the WHPAs of the Cleo Springs and the Ringwood wellfields. Some of the measures to be taken in these areas:

- Establish task force to verify if abandoned wells have been sealed off properly.
- All the oil and well facilities within the 30 year WHPA have to be regulated with special provisions which entitle them to develop a monitoring and reporting system.
- Existing spills and accidents in the present 30 year WHPA has to be investigated for any kind of groundwater damage.
- Special rules for prevention in the more vulnerable regions.
- Prevent the establishment of disposal wells within the WHPAs.
- Establishment of financial agreements with oil and gas well owners for clean up in case of any contamination detected.

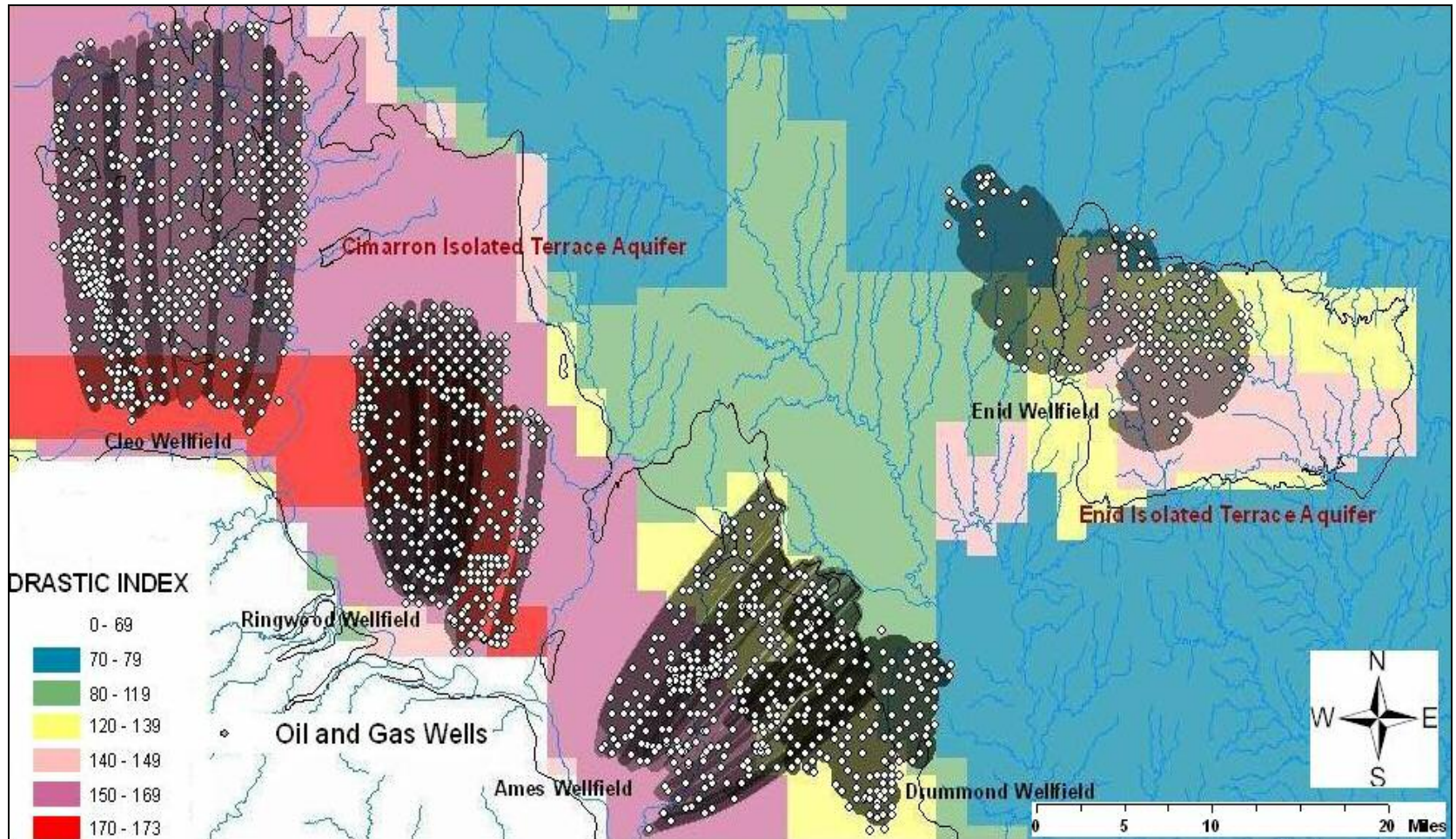


Figure VI-5: Location of oil and gas wells on the 30 years WHPA's for the five wellfields

CHAPTER VII

CONCLUSIONS

WHPAs play an important role in the prevention of groundwater detection and prevention of contaminant sources. The five wellfields under consideration serve as an important source of drinking water for Enid and few other smaller communities. They are an important alternative source of water to Enid and the other communities in the surrounding region.

The Wellhead Protection Area program developed by the EPA was used in this study to delineate the areas for the five well fields for a 1, 10, 20 and 30 year time of travel. In addition to this a hydro geologic vulnerability assessment of the study area was conducted to locate the areas more vulnerable to contamination. Using this in conjunction with the possible contaminant sources in the area, the following conclusions were arrived upon:

- Cleo Springs Wellfield

The results of the DRASTIC vulnerability assessment show that all the 30 wells fall in the region of maximum vulnerability. Monitoring is needed for checking on levels of nitrates on a regular basis due to the presence of agricultural activity around the region. Though no contamination which can be directly related to oil and gas well activity has been recorded, due to the large number of wells present in the 30 year WHPA monitoring and proper sealing of abandoned wells is

required. Further drilling for oil has to be prohibited within the 30 year WHPA, taking into account the high vulnerability of the region.

- Ringwood Wellfield

Oil and gas activities have been found to be the major cause of concern in this region. Like Cleo Springs, all the wells in this well field fall in a region of maximum vulnerability. The DEQ monitoring results show high levels of nitrates in five wells. This can be attributed to the agricultural activity in the area and requires remediation to bring excess nitrates in soil to acceptable levels.

Educating fertilizer users about proper and calculated application techniques would help with this problem.

- Ames Wellfield

Ames happens to be the well field with maximum pumping statistics. Fortunately it lies on a relatively less vulnerable region. Only major concern would be the oil and gas well activity in the region. The excessive nitrate in the seven wells recorded in this region can be attributed to the sewage systems in Ames and also the agricultural activity around the region.

- Drummond Wellfield

Since this well field is of a confined type, the pumping capacity is not very high and the thirty year WHPA does not cover a large area. Some oil and gas activity has been identified in this region, which requires monitoring. From the DRASTIC analysis, it is noted that it does not occur on a high vulnerable zone either.

- Enid Wellfield

Though the Enid well field does not fall in a highly vulnerable region, wells present in the City of Enid and its surroundings are in close proximity to toxic release sites, landfill location and a waste handling facility. Monitoring has to be set up to make sure the toxic wastes are treated well beyond contaminable levels before release to open water systems. Also due to the presence of densely populated residential areas within the city limits of Enid, the probability due to contamination from septic systems is high. Arrangements have to be carried out to remove septic systems and replace them with a connection to the local sewer system.

- Zoning ordinances are required for the region surrounding the City of Enid. A zoning ordinance would be defined by the authorities specifying the type of commercial activity that can be conducted in selected locations. This can be based on the 30 year WHPA for the Enid well field, thereby planning well in advance to prevent future contamination.
- The oil and gas wells and the agricultural activity in the study area have been found to be the most threatening sources of contaminants in all five wellfields. Regulations have to be imposed in WHPAs regarding groundwater remediation techniques and prohibit any kind of disposal in these areas.

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APPENDICES

APPENDIX A: Location of wells in the Ames Wellfield

Table A-1 Ames Well Field WHPA Parameters								
Number of Wells – 29								
Transmissivity – 10,650 ft ² /day (average all Cimarron River Aquifer pumping tests)								
Hydraulic Gradient – 0.0035 (Reed, 1952)								
Thickness – 30 feet								
Porosity – 15 percent								
Ambient Flow Direction – 225 degrees								
Well No.	X-cor.	Y-cor.	Well Depth (ft)	Well Diam. (in.)	Pump Capacity (gpm)	Max. Pump Rate (ft ³ /day)	Formation	Thick (ft)
A-1	1952799	458992	62	12	200	38,500	CRT	59
A-2	1941131	449871	67	12	250	48,125	CRT	64
A-3	1937998	447792	60	12	200	38,500	CRT	57
A-4	1935882	445262	54	12	100	19,250	CRT	50
A-5	1935078	443314	52	12	100	19,250	CRT	49
A-6	1935367	448561	145	12	300	57,750	PRB	145
A-7	1936440	448228	51	12	150	28,875	CRT	46
A-8	1937618	450372	144	12	200	38,500	PRB	144
A-9	1937014	453397	160	12	300	57,750	PRB	160
A-10	1932643	441980	38	12	42	8,085	CRT	35
A-11	1940299	447681	65	12	386	74,305	CRT	60
A-12	1941968	447913	60	12	108	20,790	CRT	55
A-13	1947706	449179	49	12	221	42,542	CRT	45
A-14	1954076	456792	72	12	95	18,287	CRT	66
A-15	1953624	461243	170	12	412	79,310	PRB	170
A-16	1947716	460785	59	12	187	35,997	CRT	55
A-17	1943547	463319	53	12	158	30,415	CRT	50
A-18	1942132	459641	57	12	247	47,547	CRT	47
A-19	1938042	461407	58	12	202	38,885	CRT	53
A-20	1933141	454756	87	12	288	55,440	CRT	85
A-21	1933951	453412	75	12	309	59,482	CRT	70
A-22	1931595	454476	83	12	212	40,810	CRT	83
A-23	1929821	453463	65	12	119	22,907	CRT	63
A-24	1928519	454311	83	12	76	14,630	CRT	80
A-25	1926120	459238	50	12	179	34,457	CRT	44
A-26	1925125	460679	61	12	213	41,002	CRT	57
A-27	1928262	455388	75	12	246	47,355	CRT	69
A-28	1925805	455680	57	12	261	50,242	CRT	56
A-29	1924394	455783	53	12	211	40,617	CRT	48
A-30	1928595	455791	68	12	375	72,187	CRT	67
A-31	1930255	455417	76	12	199	38,307	CRT	74
A-32	1931755	455421	77	12	293	56,402	CRT	75
A-33	1933203	455400	79	12	267	51,397	CRT	77

Appendix B: Location of Wells in the Cleo Springs Wellfield

Table A-2 Cleo Springs Well Field Input Parameters								
Number of Wells—31 Transmissivity—6,050 ft ² /day Hydraulic Gradient—0.0035 Thickness—30 feet Porosity—15 percent Ambient Flow Direction—90 degrees								
Well No.	X-cor.	Y-cor.	Well Depth (ft)	Well Diam (in.)	Pump Capacity (gpm)	Max. Pump Rate (ft ² /day)	Formation	Thick (ft)
CS-1	1831546	516497	63	16	55	10,587	CRT	57
CS-2	1831639	514918	53	16	90	17,325	CRT	47
CS-3	1835597	517099	64	16	85	16,362	CRT	57
CS-4	1833818	516174	70	16	140	26,950	CRT	66
CS-5	1835751	515450	47	16	67	12,897	CRT	41
CS-6	1837803	516186	48	16	110	21,175	CRT	42
CS-7	1839575	514008	21	16	230	44,275	CRT	
CS-8	1839796	516908	55	16	100	19,250	CRT	48
CS-9	1841576	517544	52	16	50	9,625	CRT	46
CS-10	1842185	515804	48	16	60	11,550	CRT	41
CS-11	1845291	518697	77	16	120	23,100	CRT	70
CS-12	1843525	517821	78	16	70	13,475	CRT	72
CS-13	1845734	516895	67	16	160	30,800	CRT	61
CS-14	1844143	515923	52	16	145	27,912	CRT	45
CS-15	1847435	519566	84	16	160	30,800	CRT	78
CS-16	1847968	517991	72	16	135	25,987	CRT	65
CS-17	1847999	515723	58	16	50	9,625	CRT	51
CS-18	1850023	518887	68	16	160	30,800	CRT	61
CS-19	1849783	516929	74	16	125	24,062	CRT	67
CS-20	1851861	517479	68	16	150	28,875	CRT	61
CS-21	1853769	517448	77	16	160	30,800	CRT	71
CS-22	1853789	515741	63	16	150	28,875	CRT	56
CS-23	1855117	518750	76	16	160	30,800	CRT	69
CS-24	1857269	518985	64	16	50	9,625	CRT	57
CS-25	1855756	516964	63	16	160	30,800	CRT	56
CS-26	1855709	515007	56	16	160	30,800	CRT	49
CS-27	1857804	516651	58	16	90	17,325	CRT	51
CS-28	1857961	514935	52	16	105	20,212	CRT	46
CS-29	1859758	511725	21	16	105	20,212	CRT	
CS-30	1861005	513671	56	16	140	26,950	CRT	49

Appendix C: Location of wells in the Drummond Wellfield

Table A-3 Drummond Well Field WHPA Input Parameters								
Number of Wells-30								
Transmissivity-1,600 ft ² /day (Average from pumping tests in Permian wells)								
Hydraulic Gradient-0.0035								
Thickness-100 feet (well logs)								
Porosity-15 percent								
Ambient Flow Direction-135 degrees (Reed, 1952)								
Well No.	X-cor.	Y-cor.	Well Depth (ft)	Well Diam (in.)	Pump Capacity (gpm)	Max. Pump Rate (ft ³ /day)	Formation	Thick (ft)
D-1	1974791	462170	210	15.5	200	38,500	PRB	210
D-2	1963823	463421	178	15.5	128	24,640	PRB	178
D-3	1965510	465325	120	12	76	14,630	PRB	120
D-4	1966560	464289	200	12	250	48,125	PRB	200
D-5	1969460	466757	130	12	60	11,550	PRB	130
D-6	1969938	469130	130	12	75	14,437	PRB	130
D-7	1972613	469514	81	12	180	34,650	PRB	81
D-8	1971805	467860	130	12	120	23,100	PRB	130
D-9	1974300	466069	61	12	48	9,240	PRB	61
D-10	1974350	467886	130	12	228	43,890	PRB	130
D-11	1974673	469174	130	12	125	24,062	PRB	130
D-12	1961538	460790	146	12	80	15,400	PRB	146
D-13	1977731	469970	55	12	200	38,500	PRB	55
D-14	1961990	464229	209	15.5	40	7,700	PRB	209
D-15	1964238	461670	210	12	70	13,475	PRB	210
D-17	1976799	471697	68	12	53	10,202	PRB	68
D-18	1974716	461602	84	12	125	24,062	PRB	84
D-19	1974247	463811	108	15.5	132	25,410	PRB	108
D-20	1969452	462226	110	12	250	48,125	PRB	110
D-21	1969454	459327	120	12	218	41,965	PRB	120
D-22	1970659	456497	105	12	340	65,450	PRB	105
D-23	1971277	453708	105	12	225	43,312	PRB	105
D-25	1966890	469541	120	12	280	53,900	PRB	120
D-26	1963859	469955	209	15.5	125	24,062	PRB	209
D-27	1963847	472428	150	12	72	13,860	PRB	150
D-28	1963057	474768	242	15.5	90	17,325	PRB	242
D-29	1961587	476780	203	15.5	200	38,500	PRB	203
D-31	1961282	468757	209	15.5	180	34,650	PRB	209
D-32	1954997	469479	220	15.5	240	46,200	PRB	220
D-33	1958368	469463	262	15.5	50	9,625	PRB	262

Appendix D: Location of wells in the Ringwood Wellfield

Table A-4 Ringwood Well Field WHPA Input Parameters								
Number of Wells—28								
Transmissivity—5,400 ft ² /day (average from pumping tests)								
Hydraulic Gradient—0.0035								
Thickness—40 (logs and regional map)								
Porosity—15 percent								
Ambient Flow Direction—135 degrees								
Well No.	X-cor.	Y-cor.	Well Depth (ft)	Well Diam (in.)	Pump Capacity (gpm)	Max. Pump Rate (ft ³ /day)	Formation	Thick (ft)
R-1	1888847	489262	63.5	16	100	19,250	CRT	57
R-2	1890933	489176	72	16	108	20,790	CRT	66
R-3	1892769	489315	78	16	150	28,875	CRT	72
R-4	1894497	489478	85	16	57	10,972	CRT	78
R-5	1889033	487299	56	16	110	21,175	CRT	50
R-6	1890804	487450	67	16	63	12,127	CRT	61
R-7	1892681	486878	73.5	16	105	20,212	CRT	67
R-8	1894710	487235	79	16	160	30,800	CRT	73
R-9	1896857	487121	78	16	115	22,137	CRT	72
R-10	1889138	485582	63	16	160	30,800	CRT	58
R-11	1890753	485609	68	16	160	30,800	CRT	62
R-12	1893005	484914	69	16	160	30,800	CRT	63
R-13	1894782	484878	64	16	127	24,447	CRT	58
R-14	1896526	485511	62	16	53	10,202	CRT	56
R-15	1888541	483479		16	160	30,800	CRT	
R-16	1890633	483657	54	16	160	30,800	CRT	48
R-17	1892695	483256	66	16	160	30,800	CRT	61
R-18	1895047	483453	62	16	81	15,592	CRT	56
R-19	1896403	483093	54	16	51	9,817	CRT	48
R-20	1898210	483618	59	16	83	15,977	CRT	53
R-21	1899784	484490	65	16	93	17,902	CRT	59
R-22	1891245	481806	57	16	56	10,780	CRT	51
R-23	1893161	481718	79	16	79	15,207	CRT	72
R-24	1895148	481795	58	16	127	24,447	CRT	51
R-25	1897394	476180	101	16	150	28,875	CRT	95
R-26	1899642	475736	83	16	150	28,875	CRT	76
R-27	1898529	474643	85	16	160	30,800	CRT	79
R-28	1905033	474520	55	16	160	30,800	CRT	49

Appendix E: Location of wells in the Enid Wellfield

Table A-5 Enid Well Fields WHPA Input Parameters								
Number of Wells—7 in Carrier, 8 in Northwest, 3 in Plant, and 6 in Van Buren								
Transmissivity—1,270 ft ² /day (Kent and Beausoleil, 1982)								
Hydraulic Gradient—0.0035								
Thickness—30 feet								
Well No.	X-cor.	Y-cor.	Well Depth (ft)	Well Diam. (in.)	Pump Capacity (gpm)	Max. Pump Rate (ft ³ /day)	Formation	Thick (ft)
C-2	2005863	540232	78	12	200	38,500	EIT	73
C-3	2003398	537840	80	12	50	9,625	EIT	75
C-11	2008743	532826	35.5	12	100	19,250	EIT	30.5
C-12	2014375	523839	49	12	100	19,250	EIT	44
C-13	2011374	532448	35	12	50	9,625	EIT	30
C-15	2008268	534733	47	12	200	38,500	EIT	42
C-16	2011139	533983	79	12	100	19,250	EIT	74
NW-	2016704	524707	62	12	75	14,437	EIT	57
NW-	2016068	527158	65	12	50	9,625	EIT	60
NW-	2018978	527224	73	12	100	19,250	EIT	68
NW-	2026855	527211	51.1	12	100	19,250	EIT	47
NW-	2024459	527175	65.5	12	100	19,250	EIT	60.5
NW-	2013223	527509	74.5	12	200	38,500	EIT	69.5
NW-	2011435	527540	52	12	75	14,437	EIT	47
NW-	2021621	527228	73.5	12	150	28,875	EIT	68.5
PL-1	2029297	513236	50	12	50	9,625	EIT	45
PL-3	2030257	512419	49	12		0	EIT	44
PL-4	2030967	511832	48	12	75	14,437	EIT	43
V-1	2031911	519304	66	12	250	48,125	EIT	61
V-3	2032162	521569	55	12	50	9,625	EIT	50
V-4	2035037	519708	53	12	100	19,250	EIT	48
V-5	2032800	522274	57	12	100	19,250	EIT	52
V-7	2035042	520915	58	12	200	38,500	EIT	53
V-8	2035417	522282	54	12	100	19,250	EIT	49

VITA

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Scope and Method of Study: This research uses the EPA developed wellhead protection area (WHPA) model, to delineate the wellhead protection area for different times of travel through the major aquifers surrounding Enid, Oklahoma. The methodology involves the tracking of flow movement within the aquifers for 30 years in different well fields. Furthermore, this research involves the integration of the output from the WHPA model to a GIS platform. This research also uses the DRASTIC model of the EPA to evaluate vulnerability of aquifers from nitrate contamination, resulting from agricultural activities. This model also is integrated on to a GIS platform. Other potential sources of contamination include oil and gas wells and hazardous waste sites and municipal landfills in the Enid area.

Findings and Conclusions: The RESSQC module of the WHPA program was used to delineate the capture zones for the five wellfields under consideration. The vulnerability assessment was carried out using the DRASTIC methodology. Combining the results with the contaminant inventory on a GIS interface, gave the areas of high vulnerability and the possible contaminant sources in that area. This further helped in devising a management plan for the affected regions.

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