Vulnerability Assessment of Twelve Major Aquifers in Oklahoma

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Introduction

PURPOSE

The purpose of this investigation was to provide information on 12 major aquifers in Oklahoma that will enable the state to incorporate groundwater protection for whole-basin planning. The DRASTIC model was used to compute the relative vulnerability of groundwater to contamination from surface sources of pollution. A series of easy-to-understand color maps was produced, which can be used to provide assistance in resource allocation and prioritization of groundwater-related activities.

PARTICIPANTS

This study was prepared under a cooperative agreement with the Oklahoma Office of the Secretary of Environment (OSE) and funded by the U.S. Environmental Protection Agency (EPA). The U.S. Geological Survey (USGS) created, documented, and published digital geospatial data sets that describe the aquifer characteristics and created the grid layers used to calculate the DRASTIC index. The Oklahoma Water Resources Board (OWRB) computed the final DRASTIC indices and produced the aquifer vulnerability maps.

Aquifers

BACKGROUND

Groundwater is water that has percolated downward from the surface, filling voids or open spaces in the rock formations. More than 60 percent of the total water use in Oklahoma, including almost 90 percent of the state's irrigation needs, is from groundwater. Groundwater provides municipal water for more than 300 Oklahoma cities and towns.

An aquifer is a subsurface unit that can yield useful quantities of water. Oklahoma's aquifers may be divided into two general groups: bedrock and alluvium and terrace aquifers. The bedrock aquifers include sandstone aquifers, soluble carbonate and evaporite (limestone, dolomite, and gypsum) aquifers, and the semi-consolidated sand and gravel underlying the High Plains. The alluvium and terrace aquifers consist of unconsolidated deposits of sand and gravel along rivers and streams.

The OWRB considers major aquifers, or groundwater basins, to be those bedrock aquifers that can yield on average at least 50 gallons per minute (gpm), and those alluvium and terrace aquifers that can yield at least 100 gpm. Minor aquifers yield less water. Oklahoma is underlain by 23 major aquifers containing an estimated 320 million acre-feet of water in storage. Many minor aquifers also yield significant amounts of fresh water.

SELECTED AQUIFERS

Twelve major aquifers, for which adequate data were available from previous studies, were selected for the study.

The twelve aquifers included in this study are listed below and are displayed in Figure 1:

Bedrock Aquifers:

- Central Oklahoma
- Vamoosa-Ada
- Rush Springs
- Antlers
- Elk City
- High Plains

Alluvium and Terrace Aquifers:

- Enid Isolated Terrace
- Tillman Terrace
- Cimarron River
- North Canadian River:
  - ------ western reach from the Panhandle to Canton Lake
  - ------ central reach from Canton Lake to Lake Overholser
  - ------ eastern reach from Oklahoma City to Eufaula Lake

The vulnerability was calculated on the surficial, or outcrop, portion of the aquifers. Portions of some bedrock aquifers (Central Oklahoma, Rush Springs, and Antlers) are overlain by less permeable rock and were not included in the final vulnerability determination.

AQUIFER DESCRIPTIONS

The Central Oklahoma aquifer consists of the Permian-age Garber Sandstone, Wellington Formation, and the Chase, Council Grove, and Admire Groups. The Pennsylvanian-age Vamoosa Formation and Ada Group comprise the Vamoosa-Ada aquifer. Both aquifers are in central Oklahoma and consist of fine-grained sandstone interbedded with shale and siltstone. The Rush Springs aquifer, in western Oklahoma, consists of the Permian-age Rush Springs Sandstone, parts of the Permian-age Marlow Formation, and alluvial and terrace deposits. The Rush Springs Sandstone consists of fine-grained sandstone with some interbedded gypsum and dolomite. Wells from these aquifers commonly yield 25 to 400 gpm.

The Cretaceous-age Antlers aquifer, in southeastern Oklahoma, consists of poorly- cemented, fine-grained sand and sandstone with some layers of shale, limestone, conglomerate, and clay. Wells commonly yield 10 to 50 gpm, but can yield as much as 400 gpm. The Elk City aquifer, in southwestern Oklahoma, consists of the Elk City Sandstone and overlying terrace deposits, dune sands, and gravel of the Ogallala Formation. The Permian-age Elk City Sandstone is composed of friable sandstone with minor amounts of silt and clay. Wells in the Elk City aquifer yield 25-300 gpm.

The High Plains aquifer, in western Oklahoma and the Panhandle, consists of the Tertiary-age Ogallala Formation, overlying Quaternary-age alluvial and terrace deposits, and some Triassic, figure 1

Jurassic, and Cretaceous-age rocks that are exposed at the surface. The Ogallala Formation is composed of semi-consolidated layers of sand, silt, clay, and gravel. Wells commonly yield 25 to 1,500 gpm. The depth to water in the High Plains is much deeper than in the other aquifers in this study, with depths generally greater than 100 feet.

The alluvium and terrace aquifers are Quaternary in age, and occur along modern and ancient streams throughout the state. They consist of unconsolidated deposits of sand, silt, clay, and gravel. The alluvium and terrace aquifers typically have shallow water depths and are very permeable. Yields of wells in these aquifers range from 10 to 1,200 gpm.

Vulnerability Assessment

VULNERABILITY

As used in this report, *vulnerability* refers to the sensitivity of groundwater to contamination, and is determined by intrinsic characteristics of the aquifer. It is distinct from *pollution risk*, which depends not only on vulnerability but also on the existence of significant pollutant loading. The seriousness of the impact on water use will depend on the magnitude of the pollution episode and the value of the groundwater resource.

DRASTIC

DRASTIC was developed by the EPA to be a standardized system for evaluating groundwater vulnerability to pollution. The primary purpose of DRASTIC is to provide assistance in resource allocation and prioritization of many types of groundwater-related activities and to provide a practical educational tool. DRASTIC can be used to set priorities for areas to conduct groundwater monitoring. For example, a denser monitoring system might be installed in areas where aquifer vulnerability is higher and land use suggests a potential source of pollution. DRASTIC can also be used with other information (such as land use, potential sources of contamination, and beneficial uses of the aquifer) to identify areas where special attention or protection efforts are warranted.

The model has four assumptions:

1. the contaminant is introduced at the ground surface;
2. the contaminant is flushed into the groundwater by precipitation;
3. the contaminant has the mobility of water;
4. the area being evaluated by DRASTIC is 100 acres or larger.

DRASTIC was not designed to deal with pollutants introduced in the shallow or deep subsurface, by methods such as leaking underground storage tanks, animal waste lagoons, or injection wells. The methodology is not designed to replace on-site investigations or to site any type of facility or practice. For example, DRASTIC does not reflect the suitability of a site for waste disposal. Although DRASTIC may be one of many criteria used in siting decisions, it should not be the sole criterion.

DRASTIC considers seven hydrogeologic factors:

1. ***D***epth to water
2. net ***R***echarge
3. ***A***quifer media
4. ***S***oil media
5. ***T***opography (slope)
6. ***I***mpact of the vadose zone media
7. hydraulic ***C***onductivity of the aquifer

Each of the hydrogeologic factors is assigned a rating from one to 10 based on a range of values. The ratings are then multiplied by a relative weight ranging from one to five (Table 1). The most significant factors have a weight of five; the least significant have a weight of one. The ranges and ratings for each hydrogeologic factor are listed in Appendix A.

Table 1. Assigned weights for DRASTIC hydrogeologic factors

Hydrogeologic Factor	**Weight**
D- Depth to Water	5
R - Net Recharge	4
A - Aquifer Media	3
S - Soil Media	2
T - Topography	1
I - Impact of the Vadose Zone Media	5
C - Aquifer Hydraulic Conductivity	3

The equation for determining the DRASTIC index is:

$$D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w = \text{DRASTIC Index}$$

where D, R, A, S, T, I, C represent the seven hydrogeologic factors, *r* designates the rating, and *w* the weight. An example DRASTIC calculation is shown in Table 2. The smallest possible DRASTIC index rating is 23 and the largest is 226.

The resulting DRASTIC index represents a relative measure of groundwater vulnerability. The higher the DRASTIC index, the greater the vulnerability of the aquifer to contamination. A site with a low DRASTIC index is not free from groundwater contamination, but it is less susceptible to contamination compared with the sites with high DRASTIC indices.

The method used in this study is called DRASTIC. Another DRASTIC method, called Pesticide DRASTIC, is designed to be used in areas where the activity of concern is the application of pesticides. Pesticide DRASTIC differs from DRASTIC in the assignment of relative weights for

Table 2. Example of a DRASTIC index calculation

Factor	**Rating**		**Weight**		**Number**
D	7	*	5	=	35
R	1	*	4	=	4
A	8	*	3	=	24
S	5	*	2	=	10
T	9	*	1	=	9
I	8	*	5	=	40
C	2	*	3	=	6
DRASTIC Index					**128**

the seven hydrogeologic factors. If the user is concerned with groundwater vulnerability to pesticides, then Pesticide DRASTIC should be used.

For a complete discussion of the DRASTIC method, refer to the EPA publication *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings* by Aller and others, 1987.

METHODOLOGY

The ARC/INFO Geographic Information System (GIS) was used to compile the geospatial data, to compute the DRASTIC indices, and to generate the final vulnerability maps (ESRI, 1997).

The USGS created digital geospatial data sets that describe aquifer characteristics of the 12 aquifers (Abbott and others, 1997a,b; Adams and others, 1997; Becker and others, 1997a,b,c,d; Runkle and Rea, 1997a,b). Included in the data sets are the aquifer boundaries, hydraulic conductivity, recharge, and water-level elevations. The data sets are available in nonproprietary and ARC/INFO formats on the Internet at: http://wwwok.cr.usgs.gov/gis/aquifers/index.html. The USGS also created digital surficial geology sets from the hydrologic atlases of Oklahoma (Cederstrand, 1996a,b,c,d,e,f,g,h,i,j,k,l). The surficial geology data sets are available on the Internet at http://wwwok.cr.usgs.gov/gis/geology/index.html.

The USGS then overlaid a model grid over the aquifers, and assigned DRASTIC ratings to the grid cells for each of the seven hydrogeologic factors. The cell size is 960 x 960 meters, which is about 228 acres.

The OWRB used the grid layers created by the USGS to compute the final DRASTIC indices and to produce the aquifer vulnerability maps. The OWRB created an aquifer zone grid to group grid cells by aquifer for the statistical analysis.

HYDROGEOLOGIC FACTORS

The hydrogeologic factors are described 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.

The grid layers for depth to water were generated by computer subtraction of water-level elevation data sets from land surface elevation. Land surface elevations were derived from a digital elevation model (DEM) for Oklahoma from 1:100,000-scale maps (Cederstrand and Rea, 1996). The water-level elevation data sets were developed from maps published in aquifer reports. Depth to water ranged from less than 5 feet in some alluvium and terrace aquifers to greater than 100 feet in the High Plains aquifer.

Net Recharge (R): The primary source of recharge is precipitation, which infiltrates through the ground surface and percolates to the water table. Net recharge is the total quantity of water per unit area, in inches per year, which reaches the water table. Recharge is the principal vehicle for leaching and transporting contaminants to the water table. The more the recharge, the greater the chance for contaminants to reach the water table.

The grid layers for net recharge were developed from the recharge data sets. Recharge rates for the aquifers were usually derived from groundwater flow models and represent averages over large areas. All of the values in this study were in the ranges of 0-2 or 2-4 inches per year.

Aquifer Media (A): Aquifer media refers to the consolidated or unconsolidated rock that serves as an aquifer. The larger the grain size and the more fractures or openings within the aquifer, the higher the permeability, and thus vulnerability, of the aquifer. In unconsolidated aquifers, the rating is based on the sorting and amount of fine material within the aquifer. In consolidated aquifers, the rating is based on the amount of primary porosity and secondary porosity along fractures and bedding planes.

Information on aquifer media was obtained from the aquifer studies and the hydrologic atlases of Oklahoma. The grid layers for aquifer media consist of one number for each aquifer. Ratings for the aquifers in this study range from six for the Vamoosa-Ada and Central Oklahoma aquifers, to eight for the High Plains and the alluvium and terrace aquifers.

Soil Media (S): Soil media is the upper weathered zone of the earth, which averages a depth of six feet or less from the ground surface. Soil has a significant impact on the amount of recharge that can infiltrate into the ground. In general, the less the clay shrinks and swells and the smaller the grain size of the soil, the less likely contaminants will reach the water table.

The general soil associations for an area were determined from soil survey maps. The soil horizons were then evaluated to determine which will most significantly affect groundwater vulnerability, based on texture and thickness of each layer. The USGS used the U.S. Department of Agriculture's State Soil geographic Database (STATSGO) to develop the grid layers for soil. Soils in this study varied greatly from clay to sand.

Topography (T): Topography refers to the slope of the land surface. Topography helps control the likelihood that a pollutant will run off or remain long enough to infiltrate through the ground surface. Where slopes are low, there is little runoff, and the potential for pollution is greater. Conversely, where slopes are steep, runoff capacity is high and the potential for pollution to groundwater is lower. The USGS used a digital elevation model (DEM) to calculate percent slopes. Most of the slopes in this study were in the ranges of 0-2 and 2-6 percent.

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. In surficial aquifers, the ratings for the vadose zone are generally the same as the aquifer media. Sometimes a lower rating is assigned if the aquifer media is overlain by a less permeable layer such as clay.

As in the aquifer media (A) factor, this information was obtained from the aquifer studies and the hydrologic atlases of Oklahoma. The grid layers for vadose zone media consist of one number for each aquifer.

Hydraulic Conductivity of the Aquifer (C): Hydraulic conductivity refers to the rate at which water flows horizontally through an aquifer. The higher the conductivity, the more vulnerable the aquifer.

Conductivity values for the aquifers were usually derived from groundwater flow models and represent averages over large areas. Most of the bedrock aquifers in this study have hydraulic conductivity values in the range of 10-100 gpd/ft^2. The alluvium and terrace aquifers have higher hydraulic conductivity values, ranging from 100 to greater than 2,000 gpd/ft^2.

Results and Discussion

RESULTS

The vulnerability maps are displayed in Appendix B. Standard DRASTIC colors were used for the maps. These standard colors range from purple for the least vulnerable to yellow for the most vulnerable. The large state-wide map is useful for comparing the relative vulnerability of the 12 aquifers. Ten smaller maps display the DRASTIC results by aquifer. These are useful in viewing smaller areas within an aquifer.

A statistical summary of the DRASTIC indices, by aquifer, is listed is Table 3. The mean DRASTIC indices range from 96 (least vulnerable) for the Central Oklahoma aquifer to 156 (most vulnerable) for the eastern reach of the North Canadian Alluvium and Terrace aquifer. Table 4 lists the mean DRASTIC numbers, by aquifer, for each of the hydrogeologic factors.

Table 3. Summary statistics of the DRASTIC indices by aquifer

Aquifer Type	Aquifer	Minimum	Maximum	Mean	Median	Standard Deviation
Bedrock	Central Oklahoma	75	133	96	95	13.31
	Vamoosa-Ada	71	132	96	95	15.47
	Rush Springs	74	136	98	98	13.53
	High Plains	91	152	104	98	13.41
	Antlers	70	136	111	114	15.03
	Elk City	95	151	129	126	10.41
Alluvium and Terrace	N. Canadian River (west)	95	164	134	133	14.19
	N. Canadian River (central)	107	177	134	137	10.93
	Tillman Terrace	110	166	142	141	11.80
	Cimarron River	81	172	151	151	13.07
	Enid Isolated Terrace	131	166	152	151	7.65
	N. Canadian River (east)	122	178	156	156	15.64

Table 4. Mean values for DRASTIC indices and hydrogeologic factors by aquifer

Aquifer	DRASTIC Index	D	R	A	S	T	I	C
Central Oklahoma	95.8	25.6	4.0	18.0	6.1	9.1	30.0	3.0
Vamoosa-Ada	95.9	26.1	4.0	18.0	6.1	8.6	30.0	3.0
Rush Springs	98.5	23.8	4.2	21.0	7.4	9.1	30.0	3.0
High Plains	104.0	11.6	4.0	24.0	9.0	9.6	40.0	5.7
Antlers	110.9	35.8	4.0	21.0	7.7	9.4	30.0	3.0
Elk City	129.1	36.8	12.0	21.0	9.7	9.7	35.0	4.8
N. Canadian River (West)	133.5	29.3	4.0	24.0	16.1	9.9	40.0	10.3
N. Canadian River (Central)	134.2	37.6	4.1	24.0	12.4	9.9	40.0	6.2
Tillman Isolated Terrace	142.2	34.6	12.0	24.0	9.6	10.0	40.0	12.0
Cimarron River	150.9	37.3	11.9	23.9	15.1	9.9	39.9	12.8
Enid Isolated Terrace	152.0	41.0	12.0	24.0	7.0	10.0	40.0	18.0
N. Canadian River (East)	155.5	30.2	12.0	24.0	9.6	9.5	40.0	30.0

There is a correlation between the mean DRASTIC indices and the type of aquifer material. The three bedrock aquifers that consist of sandstones with interbedded shales (Central Oklahoma, Vamoosa-Ada, and Rush Springs) have low mean DRASTIC indices of less than 100. The Antlers and Elk City aquifers, composed of loosely-cemented sandstones, have mean DRASTIC indices of 111 and 129. All of the alluvium and terrace aquifers, composed of unconsolidated sands and gravels, have mean indices above 130.

Because DRASTIC indices were calculated only for the areas where the aquifers outcrop, the ratings for aquifer media (A) and the impact of the vadose zone media (I) factors are usually the same. These factors have weights of five and three respectively, and together they have a strong influence on the final DRASTIC index.

Depth to water (D) is also heavily weighted, with a weighting factor of five, and therefore has a significant influence on the index. The Central Oklahoma, Vamoosa-Ada, and Rush Springs Sandstone aquifers have the lowest ratings for depth to water, and the alluvium and terrace aquifers have the highest ratings. The impact of water depth is most apparent in the High Plains aquifer. Although the High Plains aquifer has a high DRASTIC rating for aquifer media (A) and impact of the vadose zone media (I), similar to the alluvium and terrace deposits, its great depth to water lowers its mean DRASTIC index.

MAP LIMITATIONS

The twelve aquifers included in this study represent only a portion of the groundwater in the state. Several major and all of the minor aquifers were excluded. None of the carbonate or evaporite aquifers, which are typically very vulnerable, were included in this investigation. Therefore, caution should be used in making conclusions about which aquifers in the state are the most or least vulnerable. Additional work is needed to produce hydrologic studies and vulnerability maps of the other major and minor aquifers in Oklahoma.

The aquifer data used in these analyses were taken from various studies, which were conducted by different authors. Values for some factors, such as recharge (R), were determined by different methodologies. Thus, apparent differences in vulnerability may be due to differences in methodology or interpretation.

Another limitation is the accuracy of the depth to water. The accuracy of depth to water is a function of the contour interval of the water-level elevations. The larger the contour interval, the less accurate were the depths to water.

These maps describe the relative vulnerability of the aquifers based on available data of different levels of precision and resolution. Resolution depends on the number and proximity of data points. For example, the grid layer for topography (T) was derived from a high resolution, 60-meter DEM grid, while other layers, such as net recharge (R) and hydraulic conductivity (C), were derived from groundwater flow models and represent averages over large areas. The mixed resolution is acceptable for evaluating relative vulnerability of aquifers, but is not adequate to determine site-specific vulnerability. No attempt has been made to calibrate the DRASTIC results to field data.

Conclusions

The relative vulnerability of 12 major Oklahoma aquifers was determined using the EPA's DRASTIC method. Of the aquifers included in this investigation, the bedrock aquifers have the lowest DRASTIC indices and are the least vulnerable to contamination from pollutants introduced at the ground surface. The alluvium and terrace aquifers have the highest DRASTIC indices and are the most vulnerable. The High Plains aquifer has a moderate DRASTIC index, largely due to its great depth to water.

The vulnerability maps can assist in the implementation of groundwater management strategies to prevent degradation of groundwater quality. The DRASTIC vulnerability maps are useful in identifying areas where certain activities may pose a higher risk, but they do not replace the need for site-specific investigations.

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APPENDIX A

DRASTIC Ranges and Ratings

Table A-1. Ranges and ratings for depth to water

D - Depth to Water (Feet)	
Range	Rating
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1
Weight: 5	

Table A-2. Ranges and ratings for net recharge

R - Net Recharge (Inches)	
Range	Rating
0-2	1
2-4	3
4-7	6
7-10	8
10+	9
Weight: 4	

Table A-3. Ranges and ratings for aquifer media

A - Aquifer Media		
Range	Rating	Typical Rating
Massive Shale	1-3	2
Metamorphic/Igneous	2-5	3
Weathered Metamorphic/Igneous	3-5	4
Glacial Till	4-6	5
Bedded Sandstone, Limestone and Shale Sequence	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
Weight: 3		

Table A-4. Ranges and ratings for soil media

S - Soil Media	
Range	Rating
Thin or Absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Muck	2
Nonshrinking and Nonaggregated Clay	1
Weight: 2	

Table A-5. Ranges and ratings for topography

T- Topography (Percent Slope)	
Range	Rating
0-2	10
2-6	9
6-12	5
12-18	3
18+	1
Weight: 1	

Table A-6. Ranges and ratings for impact of the vadose zone media

I - Impact of The Vadose Zone Media		
	Range Rating	
Confining Layer	1	1
Silt/clay	2-6	3
Shale	2-5	3
Limestone	2-7	6
Sandstone	4-8	6
Bedded Limestone, Sandstone, Shale	4-8	6
Sand and Gravel with significant 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
Weight: 5		

Table A-7. Ranges and ratings for aquifer hydraulic conductivity

C- Hydraulic Conductivity (GPD/Ft^2)	
Range	Rating
1-100	1
100-300	2
300-700	4
700-1000	6
1000-2000	8
2000+	10
Weight: 3	

APPENDIX B

Vulnerability Maps