GROUNDWATER VULNERABILITY TO AGROCHEMICALS: A GIS-BASED DRASTIC MODEL ANALYSIS OF CARROLL, CHARITON, AND SALINE COUNTIES, MISSOURI, USA

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RODNEY CRAIG SOPER

Dr. C. Mark Cowell, Thesis Supervisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled:

GROUNDWATER VULNERABILITY TO AGROCHEMICALS: A GIS-BASED DRASTIC MODEL ANALYSIS OF CARROLL, CHARITON, AND SALINE COUNTIES, MISSOURI, USA

Presented by Rodney Craig Soper

A candidate for the degree of Master of Arts

And hereby certify that in their opinion it is worthy of acceptance.

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C. Mark Cowell
Associate Professor
Department of Geography

____

Gail S. Ludwig
Associate Professor
Department of Geography

____

Anthony A. Prato
Professor
Department of Agricultural Economics

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ABSTRACT

This investigation presents an analysis of groundwater vulnerability in three mid-Missouri counties that represent an agricultural production region that is physiographically and hydrogeologically complex. Anthropogenic activities create a potentially vulnerable environment as groundwater is exposed to contamination from agricultural practices that threaten the sustainability of high-quality groundwater as a natural resource.

The goals of this study are to (1) provide a spatial analysis of the elements and conditions under which groundwater of the study area may become contaminated, and (2) develop a model and decision support process for identifying particular portions of these counties that are vulnerable to agricultural chemical applications. Geospatial analysis is based on hydrogeological elements that are collectively incorporated into the DRASTIC model, a groundwater pollution potential evaluation system. The seven elements that are combined in the model are Depth to Water (**D**), Net Recharge (**R**), Aquifer Media (**A**), Soil Media (**S**), Topography (**T**), Impact of the Vadose Zone (**I**), and Hydraulic Conductivity (**C**). A Geographical Information System (GIS) provides the geoprocessing capability to collect, analyze, display, and disseminate this data.

The culmination of combining the hydrogeological setting elements is a range of numerical values termed the DRASTIC Index. Derived by combining the seven DRASTIC element index values, a range of values are developed that have been classified to represent groundwater vulnerability. Statistical data

grouping is implemented in order to differentiate three categorical index ranges (High, Moderate, Low). Resulting distribution of data in this model indicates that high vulnerability exists at over 32 percent of the study area, primarily in the most intensively farmed Missouri River floodplain. Moderately vulnerable areas comprise nearly 39 percent of the area, and the least vulnerable areas make up the remaining 29 percent of the total area.

A GIS-based groundwater vulnerability map generated by this process provides a decision support mechanism for landowners, agricultural producers, and state and local agencies engaged in investigating the relationship between hydrogeologic-anthropogenic system elements and protective ecosystem planning and management efforts.

CHAPTER 1

INTRODUCTION

Missouri's groundwater resources are abundant yet not infinite. Replenished by precipitation, seven major groundwater provinces and two subprovinces collectively are estimated to store over 500 trillion gallons of water within regional aquifers at varying depths below the land surface. A result of millions of years of geological activity and glaciation, groundwater resources occur in both shallow surficial aquifers and deep bedrock aquifers. A substantial portion of the population depends upon the availability of quality groundwater from public or private sources. Recent anthropogenic activities, though, have created a potentially vulnerable environment as groundwater becomes exposed to contamination from municipal, industrial, and agricultural practices threatening the short and long term sustainability of high-quality groundwater as a natural resource. Both point and non-point sources of pollution can contribute to groundwater contamination. Mining interests, chemical storage facilities, industrial discharge, and waste disposal sites are all examples of point source contamination. Agricultural production practices, specifically the application of pesticides and fertilizers on land used to raise crops, are considered to be one of the most significant non-point sources of groundwater contamination.

Pursuant to this threat, this research investigates groundwater vulnerability to agricultural chemical applications for three mid-state counties: Carroll, Chariton, and Saline Counties, Missouri. The 2000 census found that

42,479 persons reside in these three counties. Estimates of potable groundwater stored within the aquifers supplying the study area are on the order of over 1.5 trillion gallons. Of this, 609 billion gallons are estimated to be stored within the aquifers of Carroll County, 558 billion gallons in Chariton County, and 374 billion gallons in Saline County. In the most recent state water usage report, registered groundwater use for these three counties amounted to approximately 2.3 billion gallons. Self-supplied demands (e.g., private wells) were nearly 100 percent drawn from groundwater resources (Miller and Vandike 1997, MDNR 1998, MDNR 2003a, USCB 2005).

Crop production drives the agroeconomics of the region: on the order of $144 million in sales was recorded in 2002 for Carroll, Chariton, and Saline Counties combined. With a total land area of approximately 1.4 million acres (2,206 square miles), 1.2 million acres (86%) are in farms. Over half of the land area dedicated to crop production was reported as treated with pesticide and fertilizer chemical applications during 2002 (USDA 2005a, AgEBB 2005, MASS 2005).

The goals of this study are to (1) provide a spatial analysis of the elements and conditions under which groundwater of the study area may become contaminated, and (2) develop a model and decision support process for identifying particular portions of these counties that are vulnerable to agricultural chemical applications. The potential users of this project are envisioned to be landowners, agricultural producers, and state and local agencies, such as natural resource and conservation agencies, concerned with the potential contamination of groundwater and ecosystem planning and land management practices necessary to sustain this natural resource.

Geospatial analysis will be based on hydrogeological elements that are collectively incorporated into the DRASTIC model, a groundwater pollution potential evaluation system developed by the National Water Well Association (NWWA) in collaboration with the U.S. Environmental Protection Agency (USEPA; Aller *et al*. 1987). The seven elements that are combined in the model are Depth to Water (**D**), Net Recharge (**R**), Aquifer Media (A), Soil Media (**S**), Topography (**T**), Impact of the Vadose Zone (**I**), and Hydraulic Conductivity (**C**).

Environmental systems are infinitely dynamic. Groundwater contamination in particular depends on many possible combinations of hydrogeologic characteristics within a system along with the political ecology of crop producing practices which impact the agroecosystems being considered. Specific practices that contaminate groundwater fall within three general categories: (1) application of liquids or water soluble products on the land surface, (2) substances buried above the water table, or (3) materials placed in the ground below the water table (Aller *et al*. 1987). This research is concerned with the first category, specifically, the application of agricultural chemicals pursuant to crop production.

In addition to an assessment by DRASTIC modeling, this study incorporates a Geographical Information System (GIS) to manipulate acquired data into a format that will support decision making managers. The concept of a Decision Support System (DSS) incorporating geospatial technologies has found applications in business, government, and academic environments that require locational data to arrive at efficient and effective approaches to decision making. A GIS-based DSS creates a visualization component and adds thematic structure that may not otherwise be incorporated into other DSS methodologies. With the DRASTIC model, a GIS will provide the geoprocessing capability to collect, analyze, display, and disseminate information and aid managers in making decisions that are environmentally ethical and beneficial to stakeholders. Users of the generated data will be able to compare and contrast the potential suitability for the application of agricultural chemicals over a particular county area and make informed decisions as to how to best manage the inputs into the ecosystem based on the potential for groundwater contamination.

As an applied problem, this research answers the following questions: (1) Are there portions of the study area that are vulnerable to groundwater contamination as identified by the application of the DRASTIC model? and, (2) is the DRASTIC model output correlated with measured patterns of contaminant data? The results of this study will provide geospatial information for areas that are sensitive to groundwater contamination from agrochemical applications based on the hydrogeologic profile, and conceivably contribute to future research that is focused on multi-criteria systems analysis and decision support functions for ecosystem management.

CHAPTER 2

LITERATURE REVIEW

The National Research Council (NRC) in its 1993 report defined groundwater vulnerability to contamination as: “The tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer.” This assertion is positioned in reference to “non-point sources or areally distributed point sources of pollution…” In order to build a framework under which groundwater vulnerability can be described and evaluated, fundamental principles are stated in terms of three laws that summarize the difficulties of assessing the relative properties of vulnerability, uncertainty, and subtle characteristics of the hydrogeologic environment.

In the “First Law of Groundwater Vulnerability” it is stated that: “All groundwater is vulnerable.” This is a relative property rather than an absolute measure. The probability of contamination is a function of time and therefore the potential for contamination of groundwater resources must be inferred from surrogate data that is quantifiable (e.g., chemical and physical factors affecting the leaching potential of pesticides; NRC 1993, Shukla *et al*. 1998).

The focus of the “Second Law of Groundwater Vulnerability” is imprecision. Specifically, the law states: “Uncertainty is inherent in all vulnerability assessments.” This is an acknowledgement that scale, spatial resolution, methods, and data uncertainties are realities in a vulnerability assessment and that many parameters are subjectively evaluated. This law points to the need for decision making managers to "become intelligent consumers of vulnerability assessments," recognizing the accuracy constraints inherent in the process.

The final concept is the "Third Law of Groundwater Vulnerability" stated as: "The obvious may be obscured and the subtle indistinguishable." Restated, this law suggests that "extreme differences in vulnerability can be differentiated, but subtle ones cannot." Differences in factors that are "difficult to quantify" are dependent upon the quality and availability of hydrogeologic information. As an example, highly vulnerable areas such as a karst environment are less susceptible to data subtleties as compared to assessing the distinctions between similar soil types. A benefit of implementing processes that incorporate a GIS is the potential for mitigating the difficulties found in quantifying previously indistinguishable data due to the database functions and display capabilities of the technology (NRC 1993).

Dependent upon a collection of environmental factors, an assessment of groundwater vulnerability is a predictive evaluation of processes that are taking place below the earth's surface. Given the relative properties of vulnerability, uncertainty, and subtleties of the process, a groundwater assessment is best approached as an iterative process that is continually modified and improved as new information becomes available (NRC 1993).

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MODELING GROUNDWATER VULNERABILITY

The evaluation of groundwater vulnerability has been undertaken in case studies that have reflected wide ranging circumstances. The global concern for evaluating the conditions under which groundwater may become contaminated is apparent by numerous investigations that include Kaçaroglu's (1999) review of the karst groundwater environment in Turkey and Ibe *et al.* (2001) assessment of groundwater vulnerability in Southeastern Nigeria. Similar studies have been conducted by Secunda *et al*. (1998) in Israel, Thirumalaivasan *et al.* (2003) in India, Murat *et al.* (2004) in Canada, Tovar and Rodriguez (2004) in Mexico, and by Vias *et al.* (2005) in Spain. In the United States, examples of groundwater vulnerability studies accomplished under varying groundwater vulnerability conditions include Evans and Myers (1990) in Delaware, Runquist *et al.* (1991) in Nebraska, Hatchitt and Maddox (1993) in Florida, Merchant (1994) in Kansas, Loague and Corwin (1998) in California, Wade *et al*. (1998) in North Carolina, Stark *et al.* (1999) in Colorado, and Fritch *et al.* (2000) in Texas.

The evaluation of groundwater vulnerability has taken on many forms. Methodologies may focus on very narrow properties of the elements impacting groundwater contamination, such as the Attenuation Factor (AF) screening model discussed by Shukla *et al.* (1998) or the Pesticide Root Zone Model (PRZM), which accounts for pesticide fate in the crop root zone (Eason *et al*. 2004). Although more generic by comparison, the DRASTIC model, produced by the National Ground Water Association (NGWA; formerly the National Well Water Association) and the U.S. Environmental Protection Agency (USEPA), has been widely used including the majority of examples of groundwater vulnerability studies previously cited. In Missouri, Prato and Fulcher (1990) applied the DRASTIC model statewide, arriving at average ratings for each county and classifying the results into three vulnerability categories (low, medium, high). A second study by Barnett (1998) applies the DRASTIC model to Saline County as part of a vulnerability assessment by the Center for Agricultural, Resource and Environmental Systems (CARES) for the Missouri Department of Natural Resources (MDNR). Both studies focus on non-point source (NPS) groundwater contamination from agrochemical applications. The study by Prato and Fulcher (1990) indicates that the three county area investigated in this thesis falls within a low vulnerability category. Barnett (1998), categorizing the Saline County results, finds higher vulnerabilities in alluvial areas (the Missouri River floodplain) and lower vulnerabilities where bedrock is prevalent.

The DRASTIC model provides for systematic evaluation of any hydrogeologic setting with existing information. Intended for non-site specific regional studies Merchant (1994) states that:

> "The design and formulation of DRASTIC was predicated on several assumptions:
> (1) that data required by the model are available;
> (2) that the variables included in the model are critically related to groundwater vulnerability; and
> (3) that the ratings, weightings, and mathematical relationships between variables are adequately set forth in the DRASTIC procedure."

Best applied to areas of 100 acres or more, the seven elements that are combined in the model are Depth to Water (**D**), Net Recharge (**R**), Aquifer Media (**A**), Soil Media (**S**), Topography (**T**), Impact of the Vadose Zone (**I**), and

Hydraulic Conductivity (**C**). These elements are evaluated in reference to a numeric rating system that is weighted according to its relative importance within the model. The rating scales are values that range from 1 to 10 and weights from 1 to 5. For example, a depth to water rating of 5 would correspond to actual depths of 30-50 feet below the surface. The weighting value for this specific parameter is also 5. The product of these two values provides the index value for the depth to water element that will be combined with the remaining elements of the DRASTIC model. The overall equation is provided as:

Pollution Potential = Dr Dw + Rr Rw + Ar Aw + Sr Sw + Tr Tw + Ir Iw + Cr Cw

where: **r** = rating and **w** = weight

When the model is applied specifically to agrochemical applications, a modified Pesticide DRASTIC variation of the model is used, reflecting differing relative weights of four elements within the model (i.e., soil media, topography, impact of the vadose zone media, and conductivity of the aquifer). All other attributes and procedures for implementing the model remain unchanged (Aller *et al.* 1987). As stated by Vias (2005), “The assignment of ratings in the methods involves a certain degree of subjectivity that is difficult to eliminate.” Sound judgment in the application of parameters is therefore required based on the availability of data and the hydrogeologic environment (Aller *et al.* 1987). Merchant (1994) also makes the observation of this model as a relative indicator of pollution potential, dependent upon interpreting the index values of the

DRASTIC elements in reference to their hydrogeological setting. Anastasiadis (2004) also notes that:

> "The DRASTIC method uses subjective scoring as the weighting factors may be identifying the representation of the relative importance in nature but this has no physical basis. The other [factor] is that for the identification of vulnerable areas it does not consider the interactions between the chemicals and physical environment."

These points are significant, particularly with respect to the complexity of the surficial and bedrock aquifer systems and soil profiles present in Carroll, Chariton, and Saline counties. Further adaptability of the DRASTIC model has been demonstrated by Hatchitt and Maddox (1993) who created additional hydrogeologic layer properties to account for swamp, wetland, beach, and sandbar settings in Florida. Piscopo (2001) and Al-Adamat *et al*. (2003) also demonstrate model flexibility by integrating slope and soil permeability with rainfall into the recharge model element. A realistic DRASTIC index necessitates coupling of the best hydrogeologic information available with the application of procedural discipline (Aller *et al.* 1987).

GEOGRAPHIC INFORMATION SYSTEMS BASED DECISION SUPPORT

Decision Support Systems (DSS) integrate a multitude of available technologies that collect, analyze, display, and disseminate information to a broad range of user communities. Fundamental to these technologies are data, models, knowledge, and user interface as the basic components that are intended to serve decision-makers under semi-structured decision making situations (Turban and Aronson 2001). Dependent upon specific goals, these basic components become useful information and readily available to decision-making managers, when appropriately communicated.

Decision Support Systems that incorporate an analysis based on location have been characterized by various naming conventions to include Environmental Decision Support Systems (EDSS), Spatial Decision Support Systems (SDSS), and Geospatial Decision Support Systems (GDSS) depending upon the application. As with a traditional DSS, several definitions have been formulated. As an example, Sengupta and Bennett (2003) have referred to definitions that describe a DSS and SDSS in the following manner:

> "…Decision Support Systems (DSS) are computer systems that are: *(i)* designed to solve semi- and un-structured problems that upper level managers often face; *(ii)* able to combine analytical models with traditional data storage and retrieval functions; *(iii)* use-friendly and accessible by decision-makers with minimal computer experience; and *(iv)* flexible and adaptable to different decision-making approaches. Extending this definition… Spatial Decision Support Systems (SDSS) refer to computer programs that assist decision-makers generate and evaluate alternative solutions to semi-structured spatial problems through the integration of analytical models, spatial data and traditional geoprocessing software (such as GIS)."

The array of spatial decision-making problems that can be supported by a DSS are being broadened by researchers in a variety of disciplines. Mineral vein identification, severe pollution occurrences or land use scenarios such as highly suitable soils for crops are some of the applications that have been investigated (Stein *et al*. 1998, Schnug *et al*. 1998). In particular, Geographical Information Systems (GIS), when integrated with other computing and communication technologies, facilitate collaboration and problem solving. Leveraging a GIS by capturing, storing, integrating, manipulating, and displaying spatially oriented features adheres to the definition of a DSS. GIS-based models have enabled data layering and serve to integrate hydrogeological elements, data structures, and cartographic functions that link the characteristics of place with its geospatial location. The intelligent organization of data within a GIS supports and enhances the decision-making process to a wide variety of users (Loague and Corwin 1998, Stein *et al*. 1998, Jankowski and Nyerges 2001, Turban and Aronson 2001).

Well-suited to an analysis of groundwater vulnerability, the exploitation of the capabilities of a GIS for water resource assessment programs have found practical applications by federal, state, and county governmental agencies in assembling and creating data for display as maps and tables in various forms. Stark *et al*. (1999) find that a GIS “provides resources for evaluating regulatory policies and management practices, economic feasibility, suitability of specific practices, and long term impacts at a site.” The Environmental Protection Agency’s Source Water Assessment Program (Bice *et al.* 2000), Missouri’s Source Water Assessment Plan (MDNR 2000a) and Source Water Inventory Project (MDNR 2000b) developed by the Department of Natural Resources in collaboration with the Center for Agricultural, Resource and Environmental Systems (CARES) demonstrate how government is applying these principles.

Published studies from individual investigators worldwide have proliferated as GIS applications have matured, and combining the analysis of the DRASTIC model with a GIS has proven to add analytical depth to existing groundwater resource data. Using a GIS to quantitatively assess non-point sources (NPS) of contamination (e.g., agricultural chemical applications) is an especially useful analytical tool in evaluating the potential risks to groundwater resources.

Digital data enhance the evaluation of impacting elements and the potential for contamination from agricultural chemicals. The display of data derived from Pesticide DRASTIC indices provides decision-makers with a tool for an analysis of groundwater vulnerability to contamination. The interaction of users and data can provide a powerful means by which groundwater vulnerability to contamination can be assessed and informative decisions made as to the potential impact of agricultural chemical applications.

GROUNDWATER VULNERABILITY AND THE LAW

A vast body of work concerned with the investigation of groundwater systems has been undertaken by all levels of government based upon legislation enacted at the Federal level. Knowledge of the programs designed to fulfill the directives embodied within the law provides an avenue for accessing a network of quantifiable information useful in evaluating the relationship of groundwater vulnerability to agricultural chemicals and water quality. In Appendix A, a focused analysis of Federal and State legislative mandates for those programs that impact the study area is provided. Summarization of the guiding legislation, programs, and plans are highlighted in the following paragraphs.

Federal Legislation, Programs, and Plans

National policy for the protection of groundwater exists within the U.S. Code embodied under three major statutes: 1) the National Environmental Policy Act (NEPA) of 1969, 2) the Federal Water Pollution Control Act Amendments of 1972, and 3) the Safe Drinking Water Act of 1974. Based on this foundation, federal, state, and local programs have been developed to manage groundwater resources for the most efficient and effective benefit of current and future generations. Enforcement authority, scientific expertise, and administrative responsibilities are executed by the U.S. Environmental Protection Agency (USEPA), the U.S. Geological Survey (USGS), and the U.S. Department of Agriculture (USDA).

State Legislation, Programs, and Plans

Pursuant to Federal mandates and guidelines, the State of Missouri through the legislative process has created an infrastructure designed to meet the requirement of its citizenry for clean water and effective water resource management. The statutes that direct the water policy for the State of Missouri are to be found in the Clean Water Law (RSMo 644.006-644-141) and the Water Resources Law (RSMO 640.400-640.435). The Missouri Department of Natural Resources' Environmental Quality and Geology and Land Survey divisions manage the state's Water Protection and Water Resources Programs (MDNR 2005a, MDNR 2005b). Discussions pertaining to source water resources, public drinking water, and water pollution control are contained throughout the body of literature.

Local Legislation, Programs, and Plans

Examples of organizations that bring groundwater resource management to the county level include Soil and Water Conservation districts, the Natural Resources Conservation Service and local Farm Service Agency offices. Additionally, Consumer Confidence Reports as required by the USEPA to address issues regarding source water, aquifer, and contaminant levels for drinking water involve local communities in public water supply systems. (NRCS 2002b, MDNR 2005k , MDNR 2005l, USEPA 2005h).

Policy and standards are the cornerstone of groundwater protection. As exhibited by agencies such as the USEPA and others, relationships are forged and strategies enacted to include all levels of government and associated agencies. A comprehensive groundwater protection program that includes agricultural Best Management Practices (BMPs) that have been determined to provide the most effective control in preventing pollution, serves to enhance the decision making process and ensures that water quality standards are maintained (MDNR 2004a, Neill *et al.* 2004, USEPA 2006b).

GROUNDWATER VULNERABILITY AND AGROCHEMICALS

With the objective of improving crop yields, fertilizer and pesticide applications are routine for today's agricultural producer. The application of agricultural chemicals to improve crop yields, however, has contributed to the contamination of the groundwater resources, and nationally is one of the most important environmental quality concerns. It was not until the 1970s that groundwater contamination from pesticides was detected, and by 1988, 26 states had detected pesticides in groundwater. It is estimated that in excess of 660 million pounds of pesticides are used in agriculture each year. In addition to pesticides, the most pervasive type of groundwater contamination, resulting from agricultural production, has come from nitrates in fertilizer. In 2003, an estimated 21 million tons of fertilizer was applied to agricultural lands (Aller *et al.* 1987, NRC 1993, Loague and Corwin 1998, Wade *et al.* 1998, Murray and McCray 2005, USDA 2005d).

The USEPA defines pesticides as substances or mixtures of substances that are intended for the prevention, destruction, repelling, or mitigation of any pest. This terminology is inclusive of insecticides, herbicides, fungicides, and other substances used to control pests that are unwanted and cause damage to crops, humans or other animals. This definition can be extended further to include substances that are intended for use as a plant regulator, defoliant, or desiccant. The risk of using pesticides is that they can adversely affect living organisms. Intended to kill potential disease-causing organisms, insects, weeds, and other pests, pesticides also can potentially harm humans, animals, or the environment (USEPA 2006).

Inorganic fertilizers, like pesticides, have contributed to increased groundwater contamination in recent years. Both organic and inorganic fertilizers are combined to provide optimum growth conditions for agricultural crops. Inorganic fertilizers contain in large part the nutrients nitrogen, potash, and phosphate. The impact to groundwater from fertilizers becomes problematic when the concentration of inorganic nitrogen in soils exceeds the ability of the crop root zone to absorb the available nutrients. Nitrogen fertilizers are very soluble and therefore do not bind to soils, creating a high probability for migrating into groundwater. Data indicate that crop recovery of nitrogen rarely exceeds 50 percent of the available nitrogen and approximates more closely a value of 35 percent for grain crops with the excess nitrogen directly impacting concentrations in groundwater (Aller *et al*. 1987, Nolan 2005, USEPA 2006b).

Although the Pesticide DRASTIC model terminology adjusts parameters in terms of generic pesticide applications, the application of fertilizers also are considered as contributing to the potential for groundwater contamination as related to agricultural land use practices (Aller e*t al.* 1987, MDNR 2000b, Anastasiadis 2004). The adjustment in weighting assignments from the regular DRASTIC model to the Pesticide DRASTIC model, specifically soil media and topography, would be just as appropriate in the agricultural chemical application setting for both fertilizers and pesticides as opposed to the non-agricultural setting. According to Gogu and Dassargues (2000) “one weight classification should be selected for the whole area.” Terminology suggesting a modified DRASTIC model including all agrochemicals would more appropriately reflect non-point source (NPS) contamination from agricultural production.

In the 2004 Missouri Water Quality Report, pesticide and fertilizer applications are listed as major sources of groundwater contamination (MDNR 2004b). Statewide, the most recent agricultural census data (2002) reflect that pesticides were applied to approximately 8.7 million acres and fertilizers were applied to approximately 10.7 million acres. Within the area under investigation, the area dedicated to crop production in Carroll, Chariton, and Saline counties in 2002 amounted to 540,281 acres treated with pesticides and 559,582 acres treated with fertilizers (USDA 2002). Table 2.1 includes chemicals detected within the study area and the common sources of contamination. These data are a subset of Appendix B which provides alternative trade name details and definitions for each chemical listed.

Table 2.1. Common chemical name, county where detected, and source of contamination.

Common Name	County	Common sources of contaminant
2,4-D	Carroll	Runoff from herbicide used on row crops
Alachlor	Carroll	Runoff from herbicide used on row crops
Atrazine	Carroll, Saline	Runoff from herbicide used on row crops
Carbaryl	Carroll, Chariton, Saline	Insecticide
Carborfuran	Carroll	Leaching of soil fumigant used on rice and alfalfa
Metribuzen	Carroll, Chariton	Herbicide runoff
Nitrate	Carroll, Chariton, Saline	Runoff from fertilizer use
Simazine	Carroll	Herbicide runoff
2,4,5-TP Silvex	Carroll, Chariton	Residue of banned herbicides
Heptachlor	Carroll	Residue of banned termiticide
Heptachlor epoxide (HCE)	Carroll	Breakdown of heptachlor
3-Hydrocarbofuran	Carroll	Degrade form of Carbuforan
Cyanazine	Carroll, Chariton, Saline	Herbicide runoff. USEPA accepted cancellation end use pesticide products pursuant to agreements by registrants.

Source: CARES, MDNR, USEPA.

The potential impact of agrochemical contamination to groundwater resources are particularly noteworthy when compared with recent (2005) Missouri Public Water Systems census data. A community public water system is defined as serving “at least 15 service connections and is operated on a year-round basis or regularly serves at least 25 residents on a year-round basis.” Inclusive in this definition are 20 city water systems within the study area, 84 percent of which draw upon groundwater resources. Similarly, 100 percent of the water district systems in the three county area source their water from groundwater resources (MDNR 2005m).

Loague and Corwin (1998) remind us that large-scale agricultural production is the fundamental cause of non-point source (NPS) groundwater contamination. Furthermore,

> “The goal of sustainable agriculture is to meet the needs of the present without compromising the ability to meet the needs of the future. Ideally, it strives to optimize food production while maintaining economic stability, minimizing the use of finite natural resources and minimizing environmental effects. This presents a formidable dilemma because agriculture remains as the single greatest contributor of NPS pollutants to soil and water resources.” (Loague and Corwin 1998)

To understand the impact of agricultural chemical applications, researchers and managers must consider the complex interactions of the hydrogeologic setting, crop management practices, and climatic conditions (Aller *et al.* 1987, Loague and Corwin 1998, Merchant 1994). A study of groundwater considers vulnerability as a potential and characterizes hydrogeologic factors as receptors of pollutants (Aller *et al.* 1987). Contrastingly, a study of water quality is dependent upon usage concerns (e.g., irrigation vs. drinking; MDNR 2005C). NPS contamination is where groundwater vulnerability and groundwater quality intersect. Monitoring chemical detections and degraded water quality substantiate the concept of vulnerability modeling and provide data for effective land use decisions and water quality management planning.

CHAPTER 3

STUDY AREA

This study focuses on the complex hydrogeologic profile of Carroll, Chariton, and Saline Counties, Missouri, centrally located in the state of Missouri and adjacent to the Missouri River (Figure 3.1). These three counties have a population of 42,479, as determined by the 2000 U.S. Census, and a total land area of 1.4 million acres. Of this total, 1.2 million acres (86%) are in farms of which 78 percent are used as cropland (USDA 2005a, AgEBB 2005, MASS 2005). Selection of this area provides for analysis of an agricultural landscape that has been in production since the early 1800s.

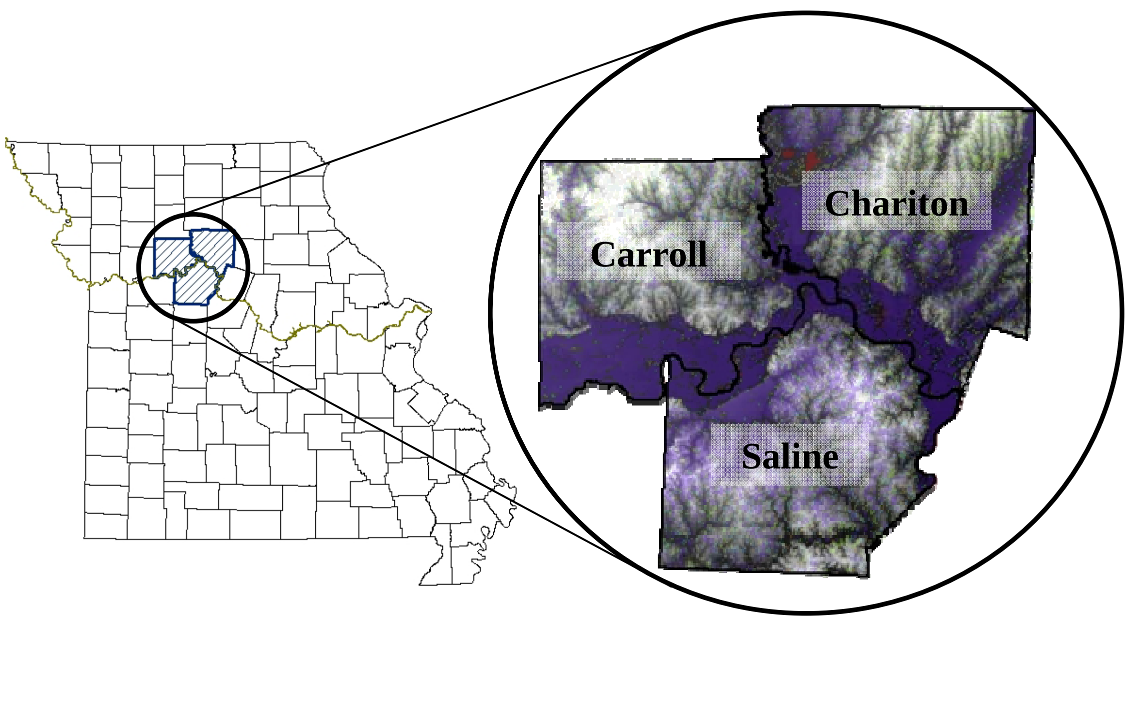


Figure 3.1. Study area: Carroll, Chariton, and Saline Counties, Missouri.

HISTORY

The French were the first settlers in the Missouri region, seeking mineral wealth, salt springs, and the fur trade beginning in the early 1700s (Sauer 1920). Until about 1806 or 1808, fur traders were the only settlers in the area now recognized as Chariton County, and by 1808 trading posts were established in what is now Saline County. In Carroll County the first permanent settlement was established by 1819 (USDA 1993, USDA 1994, USDA 1997). Settlers continued to arrive from Virginia, Kentucky, Tennessee, and Indiana and by the first half of the 19th century the existing county boundaries were established. Chariton County was organized in 1820, Saline County in 1825, and Carroll County in 1833.

As early as 1819, farming practices began to yield returns that convinced settlers of the fertility of the prairie soils. Early crops consisted of grains and tobacco and since that time, farming and agribusiness have remained mainstays of the local economies. Much of the study area is tillable and is used for row crops, mainly corn, wheat, and soybeans (USDA 1993, USDA 1994, USDA 1997). Appendix C provides historical farmland values and acreage statistics from 1850 through 2002.

PHYSIOGRAPHY

Common to the three counties in this study is the Missouri River. The Missouri River floodplain at its widest point in Carroll County is about nine miles, six miles in Saline County, and five miles in Chariton County. Elevation varies from about 590 feet in Saline County to 990 feet in Carroll County. The main streams that drain the area are the Missouri, Grand, and Chariton Rivers. Stream-dissected deposits of loess and glacial drift are the primary surface material in all counties (Appendix D provides the physiography of Missouri).

PRECIPITATION

For the period of 1971 to 2000, the mean annual precipitation normals for the study area were 39.05 inches. Most of this precipitation, approximately 65 percent, falls during the growing season in April through September with the heaviest rainfall occurring in spring and early summer. Rainfall accumulation is normally adequate for corn, soybeans, and most grain crops. During the winter months, snowfall averages 18.13 inches for the three county area. Much of the precipitation is lost through runoff, or to plants and the atmosphere through evapotranspiration, therefore only a portion of annual precipitation is available for groundwater recharge (USDA 1993, USDA 1994, Miller and Vandike 1997, USDA 1997, HPRCC 2005). Annual precipitation normals and contributing watersheds are provided in Appendices E and F.

GEOLOGY

The generalized geology of Missouri is represented in Figure 3.2, which identifies rock types that range from the Precambrian igneous rocks of the St. Francois Mountains of Southeastern Missouri (approximately 2.5 billion years old) to the Quaternary alluvium common to the Missouri River floodplain deposited in the relatively recent past (0 – 2 million years ago). Pleistocene aged glacial deposits also overly bedrock formations within the area (Miller and Vandike 1997).

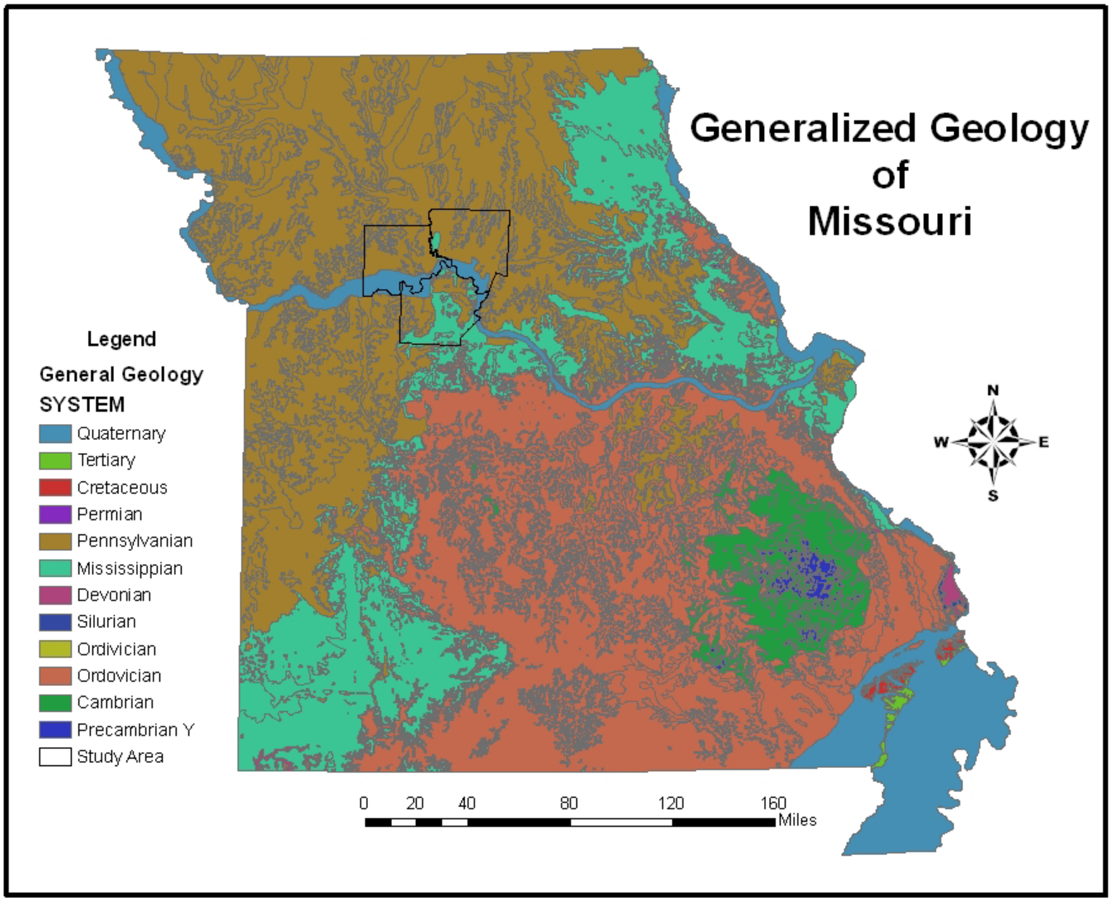
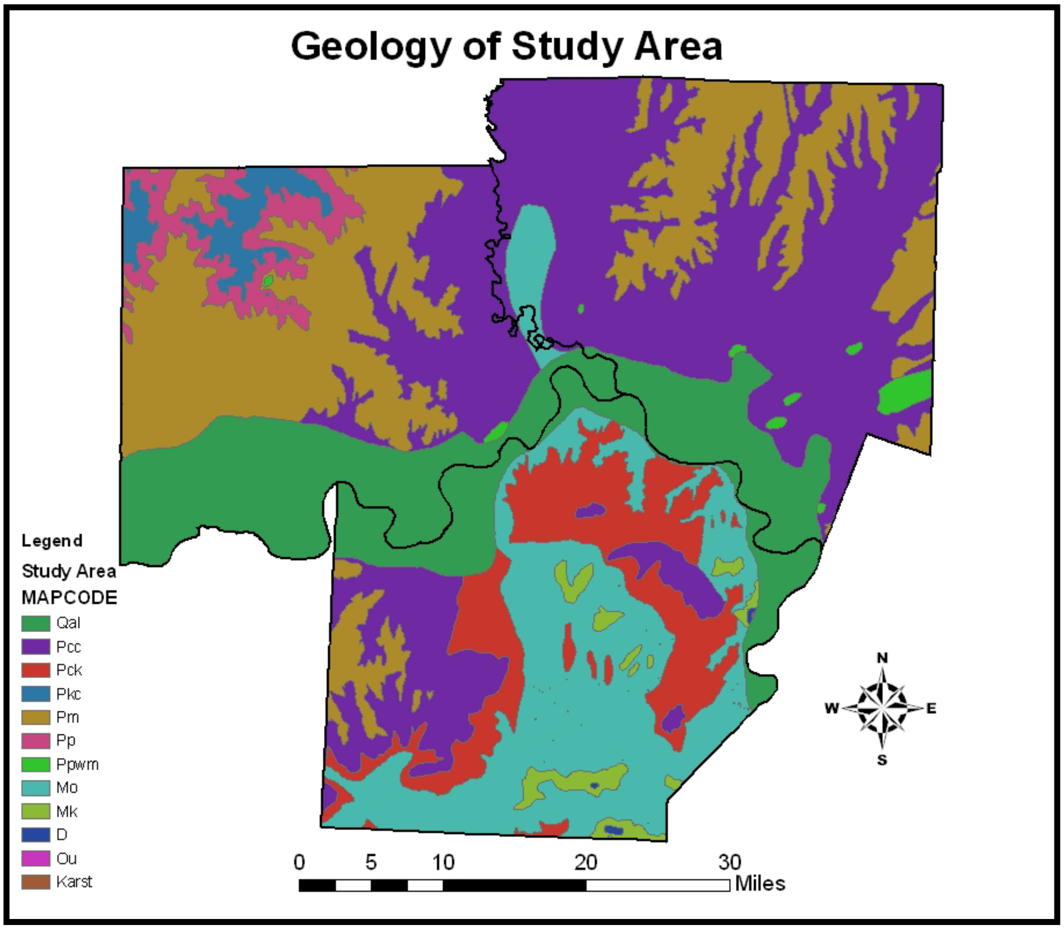


Figure 3.2. Generalized geology of Missouri. The surface area is comprised of Quaternary, Pennsylvanian, and Mississippian aged formations. Source: Missouri Spatial Data Information Service (MSDIS) and Missouri Department of Natural Resources (MDNR)

Sedimentary formations that make up the three county study area (Figure 3.3) consist of the Ordovician, Devonian, Mississippian, Pennsylvanian and Quaternary systems. Appendix G provides a stratigraphic column and description of systems, series, groups, and formations present. The dominant rock types within the study area are limestone and sandstone with shale and clay. Glacial drift, alluvium, and loess sequences also are present (Miller 1968, Imes 1985, Umklesbay and Vineyard 1992, Imes and Emmett 1994, Miller and Vandike 1997).



MAP CODE	ERA	SYSTEM	SERIES	GENERAL TYPE
Qal	Cenozoic	Quaternary	Holocene	Alluvium
Pcc	Paleozoic	Pennsylvanian	Desmoinesian	Limestone
Pck	Paleozoic	Pennsylvanian	Atokan/Desmoinesian	Limestone
Pkc	Paleozoic	Pennsylvanian	Missourian	Limestone
Pm	Paleozoic	Pennsylvanian	Desmoinesian	Limestone
Pp	Paleozoic	Pennsylvanian	Missourian	Sandstone
Ppwm	Paleozoic	Pennsylvanian	Missourian	Clay
Mo	Paleozoic	Mississippian	Osagean	Limestone
Mk	Paleozoic	Mississippian	Kinderhookian	Limestone/Shale
D	Paleozoic	Devonian	Lower/Middle/Upper	Limestone/Sandstone/Shale
Ou	Paleozoic	Ordovician	Cincinnatian/Champ	Dolomite/Limestone

Figure 3.3. Geology of the study area consisting of limestone, sandstone, shale, clay, and alluvium sequences. Appendix G provides group/formation sequences. Data source: Missouri Spatial Data Information Service (MSDIS) and Missouri Department of Natural Resources (MDNR)

The rock types and their occurrences are significant in determining the DRASTIC index values for the Aquifer Media, Impact of the Vadose Zone, and

Hydraulic Conductivity DRASTIC elements. The rock types, whether consolidated or unconsolidated define whether there will be sufficient quantities of water for use. The aquifer medium and the flow of water within the aquifer are dependent upon the porosity, fracturing, and solution openings (e.g., karst areas) of the rock units present. The vadose zone, described as the zone above the water table that is saturated or discontinuously saturated and below the soil horizon, is also influenced by the geological formations present. Processes such as biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization, and dispersion all contribute to the attenuation characteristics of the rock media. The path length and routing also are contributing factors for the attenuation of material passing through this zone with fracturing of the media strongly influencing routing. Finally, the uppermost units within the stratigraphic column will have an impact on soil development (Aller *et al*. 1987).

AQUIFERS

The Missouri aquifer systems are numerous and complex consisting of unconsolidated, semi-consolidated and consolidated material ranging from sand and gravel to clay, silt, shale, sandstone, limestone, or dolomite. For the three county study area, there are three main aquifer systems that are significant to evaluating groundwater vulnerability to agricultural chemical applications. These include the Surficial Aquifer systems consisting of stream valley and glacial drift aquifers, the Cambrian-Ordovician and Mississippian aquifers of northern Missouri, and the Ozark Plateau Aquifer System in southern Missouri. The U.S.

Geological Survey, Hydrologic Atlas 730-D for Kansas, Missouri and Nebraska in

Figure 3.4 depicts these aquifer systems (Miller and Appel 1997).

Figure 3.4a. The surficial aquifer system consists of stream-valley aquifers along major drainages, the Mississippi River Valley alluvial aquifer in the Missouri bootheel, and glacial-drift aquifers in northern Missouri, eastern Nebraska, and northeastern Kansas. All three aquifers consist of unconsolidated deposits of sand and gravel.

Figure 3.4b. The High Plains aquifer primarily consists of unconsolidated sand and gravel of the Ogallala Formation in Nebraska and western Kansas and of Quaternary beds in south-central Kansas. The aquifer underlies and is hydraulically connected to parts of the surficial aquifer system in Kansas and Nebraska.

Figure 3.4c. The Mississippi embayment aquifer system directly underlies and is hydraulically connected to the surficial aquifer system in southeastern Missouri. The Great Plains aquifer system in Kansas and Nebraska underlies much of the High Plains aquifer and is separate from parts of it by a thick confining unit of shale.

Figure 3.4d. The Ozark Plateau aquifer system in southern Missouri is a large freshwater system in Paleozoic rocks. Equivalent rocks of the Western Interior Plains aquifer system, however, contain no fresh-water. The Mississippian aquifer of northern Missouri is in rocks equivalent to those of the upper part of the Ozark Plateaus aquifer system but has little or no hydraulic connection to that system.

Figure 3.4e. The Cambrian-Ordovician aquifer consists of dolomite and sandstone beds equivalent to part of the Ozark Plateau aquifer system but is hydraulically separate from that system in some places. The aquifer is overlain and underlain by confining units.

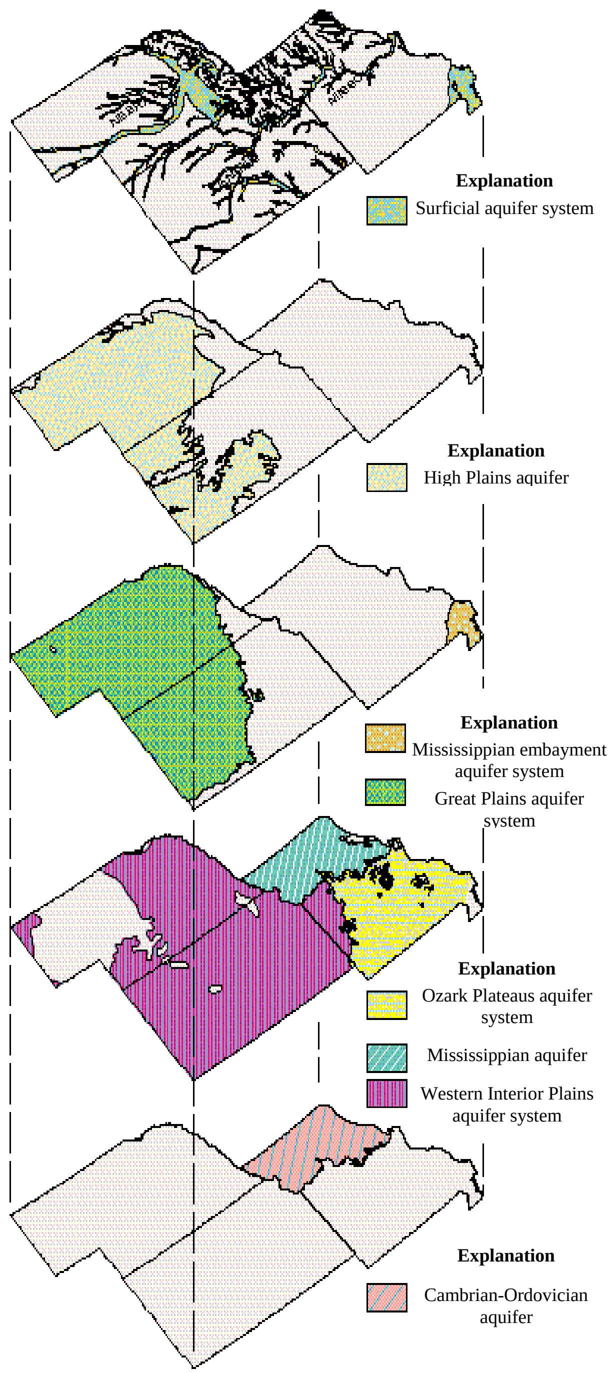


Figure 3.4 Regional aquifer systems. Figure II-4a, II-4d., and II-4e depict the surficial aquifer system, the Ozark Plateau aquifer system, and the Cambrian-Ordovician aquifer significant to the study area. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

Surficial Aquifers

The Surficial aquifers of importance to this study are the Stream Valley aquifers that occur along major drainages and the Glacial Drift Aquifers that occur in northern Missouri. Existing mostly as unconsolidated and unconfined aquifer systems, these systems are likely to be hydraulically connected and the primary sources of freshwater for domestic and farm uses (Figures 3.5 and 3.10; Miller and Appel 1997, Imes 1985).

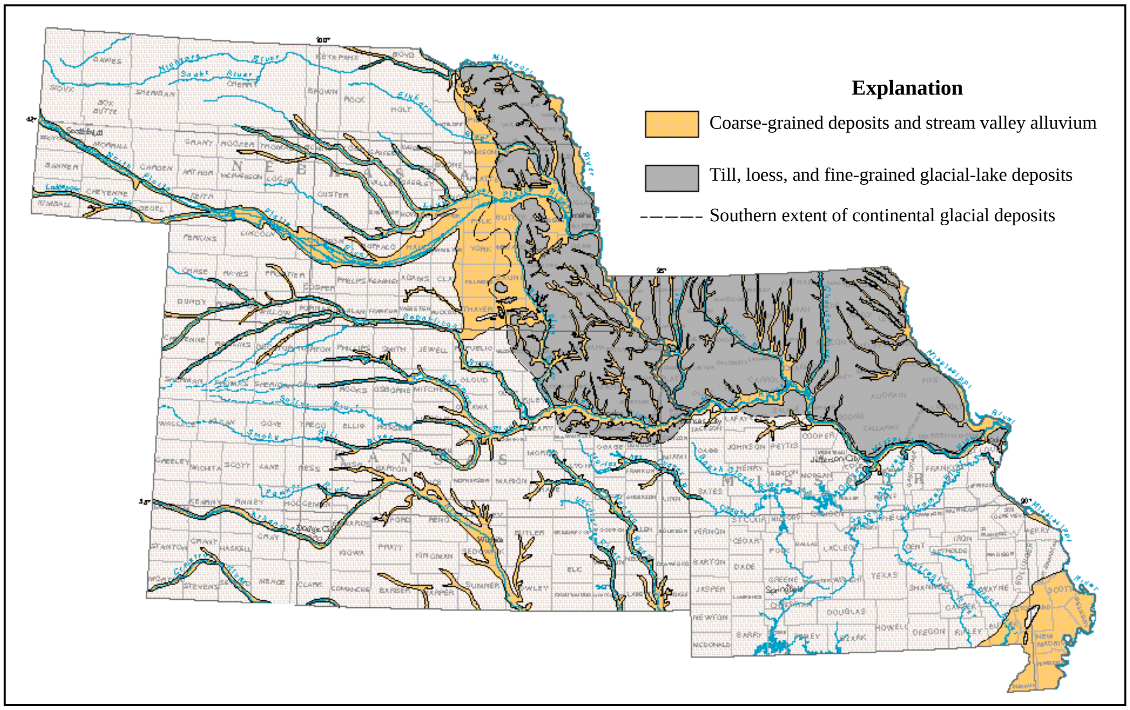


Figure 3.5. Surficial aquifer system. Coarse-grained, unconsolidated deposits, mostly Quaternary age, compose the surficial aquifer system and provide water for many shallow wells. Alluvium along major stream valleys, a broad blanket of alluvium in southeastern Missouri, and glacial outwash (buried in some places beneath fine-grained sediments) form productive aquifers. Till, loess, and fine-grained glacial-lake deposits are widespread in areas of the segment that were covered by continental glaciers; these deposits generally yield only small amounts of water and are not considered to be principal aquifers. Scale of figure is 1:2,000,000. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

1) Stream Valley Aquifer

Fluvial and alluvial processes have provided unconsolidated clay, sand and gravel deposits of Holocene and Pleistocene age. Average thicknesses can range from 90 to 100 feet, with some areas having thicknesses to 160 feet. Saturated alluvial material generally ranges in thickness from 50 to 80 feet. The Missouri River Valley deposits fill an entrenched bedrock valley of Pennsylvanian and Mississippian age formations that ranges from 2 to 10 miles wide forming an important stream-valley aquifer. Because much of the bedrock in northern Missouri contains saline water, the stream-valley aquifers provide an important source of fresh water (Figures 3.6, 3.7 and 3.8; Miller and Appel 1997, Imes 1985, Miller 1968).

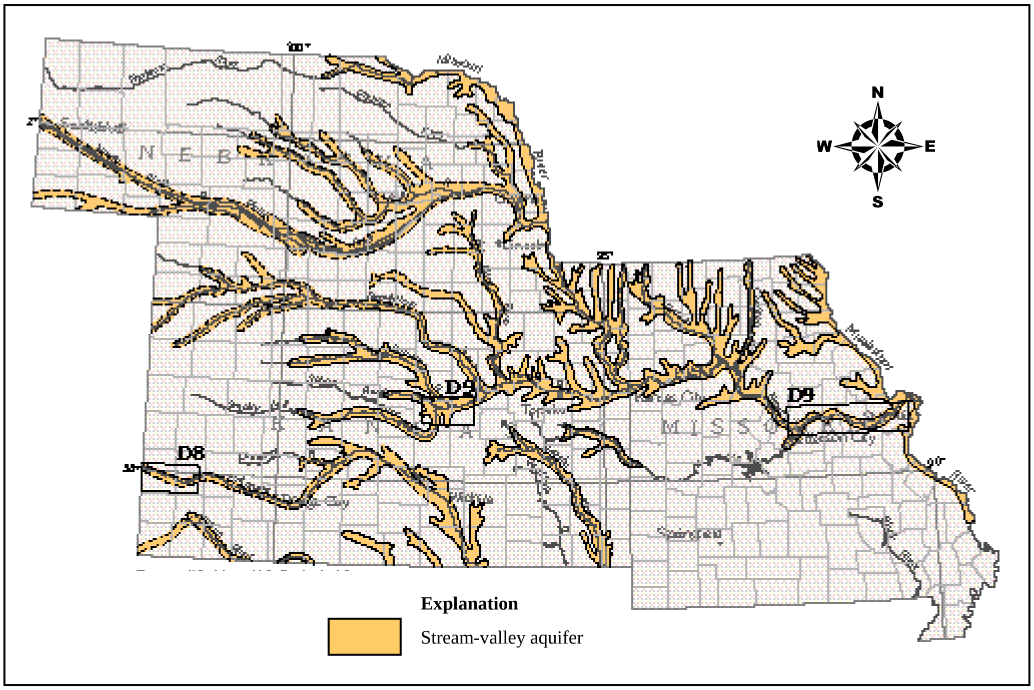


Figure 3.6. Stream-valley aquifer system. Stream-valley aquifers are a source of water along several major rivers and their tributaries. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

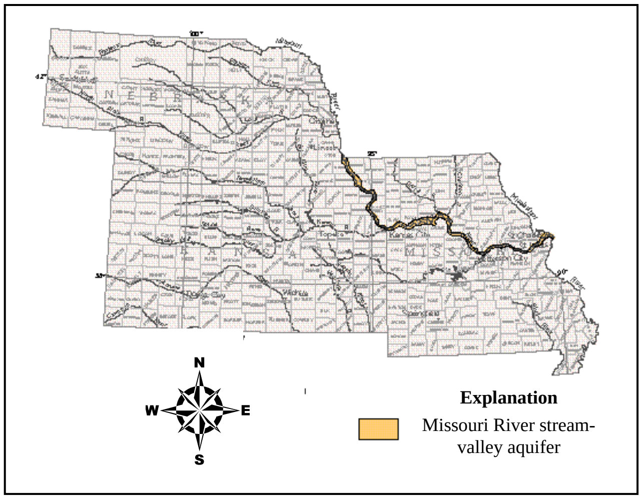


Figure 3.7. Missouri River stream-valley aquifer. The stream-valley aquifer along the Missouri River is an important source of water for industries and several cities in northwestern and central Missouri. Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

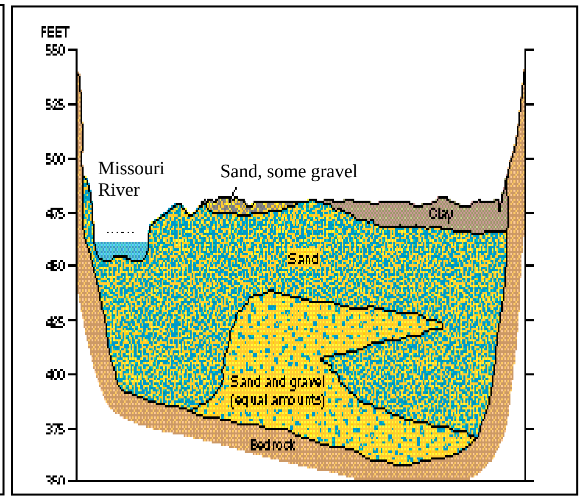


Figure 3.8. Stream-valley aquifer cross-section. The stream-valley aquifer consists of coarse-grained alluvium in the lower part, overlain by finer grained sediments that locally are confining units. The aquifer partially fills a channel that has been incised into bedrock and averages about 90 feet in thickness. Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

2) Glacial Drift Aquifer

The current location of the Missouri River provides a rough boundary for the extent of glacial ice and glacial drift deposits in Missouri. This boundary extends south of the Missouri River within the study area to include a portion of northern Saline County (Figure 3.5). Like alluvial valley deposits, glacial drift deposits, consisting of silt, clay, or till, are a source of water for domestic and non-irrigation farm uses. Generally, these deposits are poorly sorted and predominantly fine grained with some coarse grained basal deposits that fill glacial stream channels. Some glacial deposits areas exhibit a more complex interbedding of fine and coarse grained material. Meandering meltwater streams in advance of the glacier and the periodic change of stream location provided an environment for interbedding and lenslike formations across the valley floor. Because of this interbedding, permeable and poorly permeable sediments are the result, leading to locally confined and unconfined conditions.

Glacial drift deposits extend over wide areas having been lain down by glacial ice during the late Pliocene and Pleistocene age. These deposits vary in thickness, but are generally 100 to 200 feet thick with local occurrences of 300 to 400 feet thick. Many glacial drift aquifers, such as the Grand River Valley aquifer are known as buried channel or buried valley aquifers (Figure 3.9). The Grand River forms part of the border between Carroll and Chariton Counties. Overall, glacial drift aquifers usually yield only small amounts of water to wells due to the presence of relatively impermeable silt and clay. The exception to this is in areas that have deposits of well sorted sand bodies that are 20 to 40 feet thick which may yield enough water to supply smaller townships (Miller and Appel 1997, Imes 1985, Miller 1968).

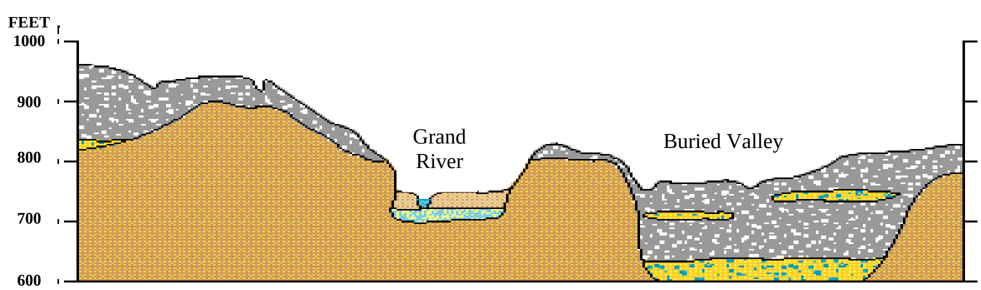
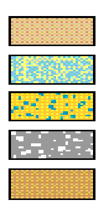


Figure 3.9. Grand River buried-channel aquifer. In Missouri, sand and gravel commonly are at the base of the glacial channel-fill deposits and are covered by clay and silt. The cover of fine-grained material creates confined conditions for the water in the coarse-grained sediments. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

Explanation



Clay, silt, and fine-grained sand
Coarse-grained sand and gravel
Sand, gravel, and boulders
Till
Bedrock

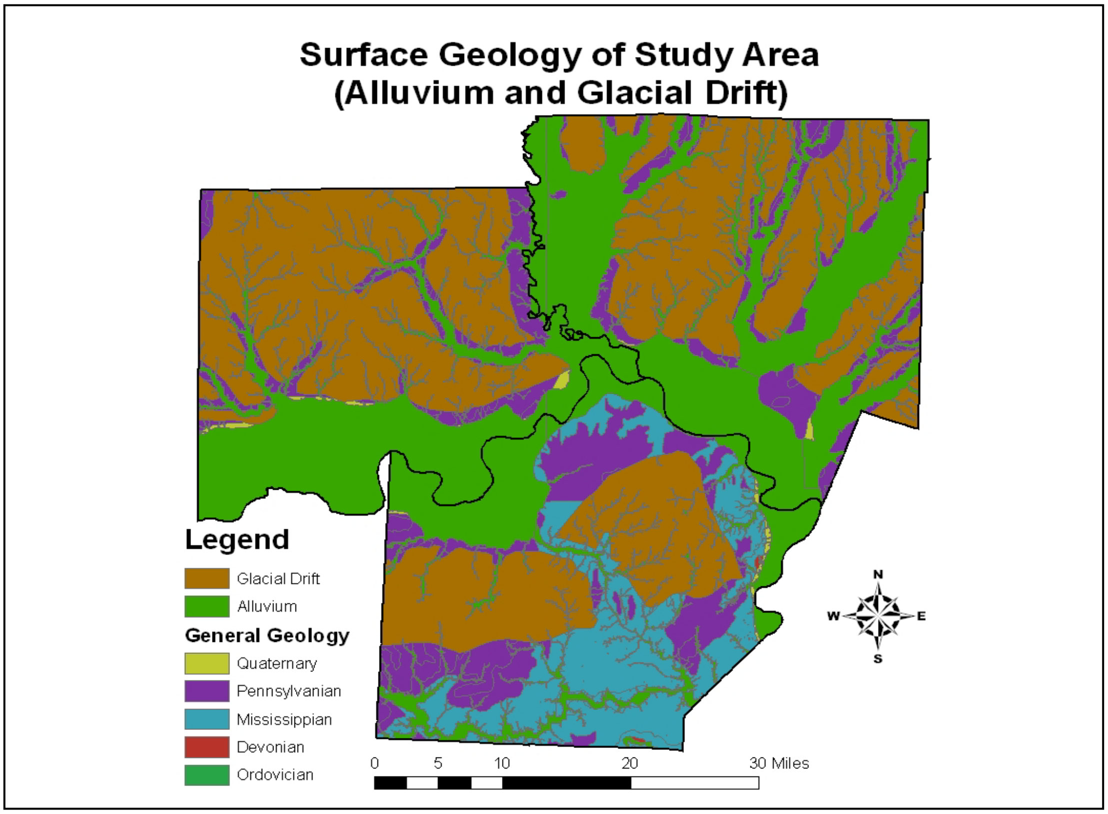


Figure 3.10. General geology of the study area with alluvium and glacial drift layers. Data source: Missouri Spatial Data Information Service (MSDIS) and Missouri Department of Natural Resources (MDNR)

Northern Missouri Bedrock Aquifers (Carroll and Chariton Counties)

1) Mississippian Aquifer

Named for the Mississippian age limestone that makes up the aquifer, this aquifer extends throughout the study area north of the Missouri River and is the uppermost aquifer in northern Missouri (Figure 3.4d and Figure 3.11a). The Mississippian aquifer is comprised of Osagean and Kinderhookian Series strata. The principal water yielding formations are the Keokuk and Burlington limestone of the Osagean Series. Because the contact between the Burlington-Keokuk limestone formations is difficult to ascertain, these formations are generally treated as a combined geologic unit. Both sequences are stratigraphically equivalent to rocks in the Springfield Plateau aquifer south of the Missouri River. The Mississippian and Springfield Plateau aquifers may be hydraulically connected in the Saline and Chariton County areas, however, the connection is poorly known and therefore treated as separate groundwater flow systems. The aquifer rests on a confining layer of shale within the Kinderhookian Series and is recharged by leakage from the overlying confining Pennsylvanian strata. The thickness of this aquifer averages about 200 feet within the study area (Figure 3.11b). It is thinnest near the Missouri River where it has become dissected or removed by erosion. Water quality varies within the Mississippian aquifer but within Carroll and Chariton Counties it is generally known for its salinity caused either by the upward leakage of the underlying Cambrian-Ordovician aquifer or the eastward-moving discharge of the Western Interior Plains aquifer system (Figure 3.4d and Figure 3.11; Miller and Appel 1997, Imes 1985).

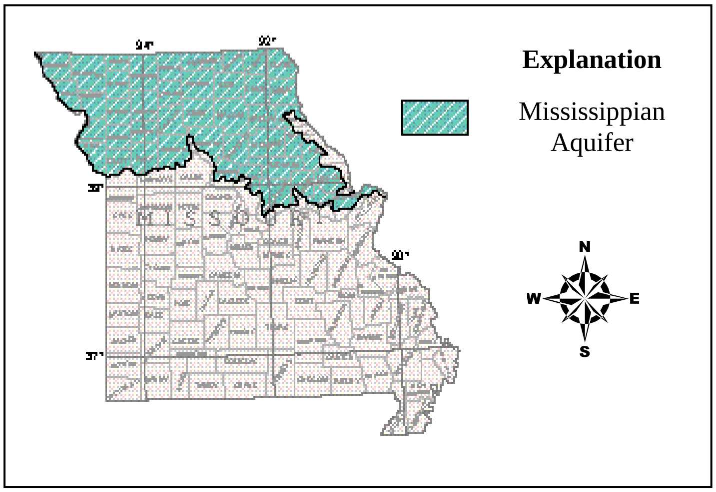


Figure 3.11a. Mississippian aquifer. The Mississippian aquifer underlies most of northern Missouri except where it has been locally removed by erosion. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

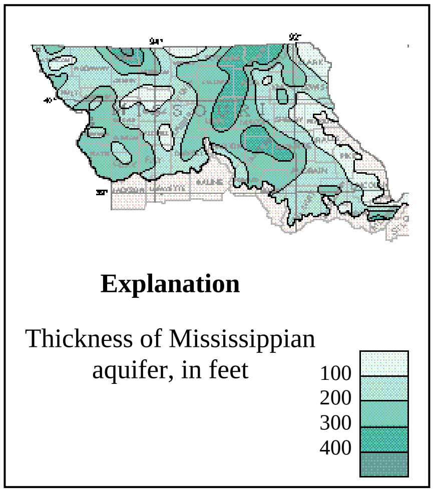


Figure 3.11b. The Mississippian aquifer generally is less than 300 feet thick except in local geologic downwarps where it is thicker. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

The Cambrian-Ordovician aquifer, which underlies the Mississippian aquifer, consists mainly of carbonates in the form of limestone and dolomite with some strata of sandstone and shale existing to a lesser degree (Figure 3.4e). With the exception of the Missouri River alluvium, this is the most important aquifer in northern Missouri in terms of the amount of water volume withdrawn. The important water-yielding beds of this aquifer are to be found in the Middle and Lower Ordovician and Upper Cambrian dolomites and sandstones. This use is limited, however, to eastern portions of the state since elsewhere, including the study area, the aquifer water is saline. The average thickness of the Cambrian-Ordovician aquifer is about 1200 feet. Confining units exist both above and below this aquifer, although not exposed within the study area, these rocks are stratigraphically equivalent to the Ozark Aquifer south of the Missouri River (Figure 3.12; Miller and Appel 1997, Imes 1985).

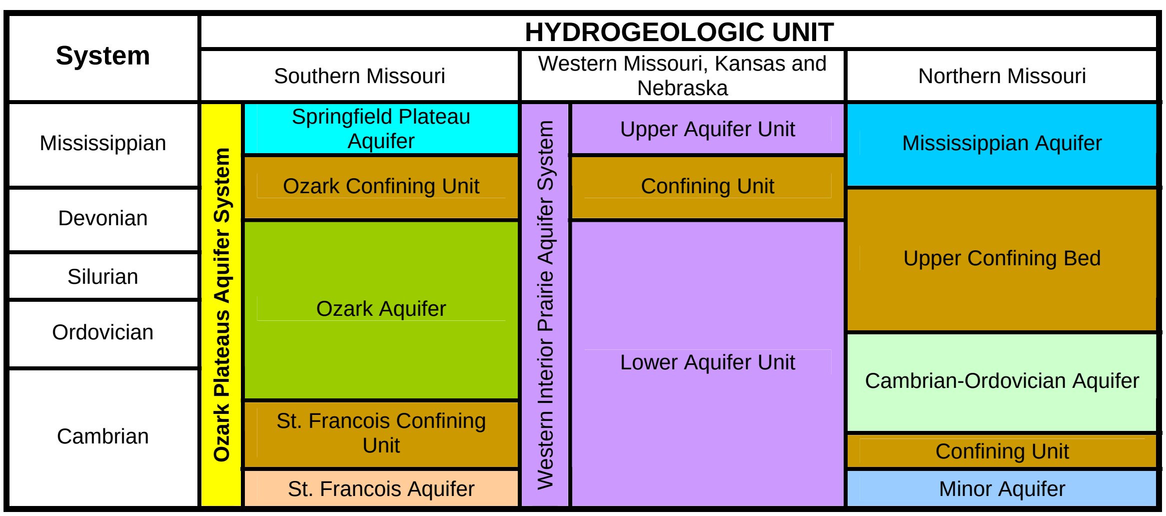


Figure 3.12. The major aquifers and confining units of the Ozark Plateau aquifer system grade westward into equivalent hydrogeologic units of the Western Interior Plains aquifer system and have stratigraphic equivalents in northern Missouri. The Mississippian aquifer in northern Missouri has little hydraulic connection with the Springfield aquifer. By contrast, the Ozark aquifer and the Cambrian-Ordovician aquifer appear to be hydraulically connected, at least in part. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

Southern Missouri Bedrock Aquifers (Saline County)

1) Ozark Plateaus Aquifer System

Underlying most of southern Missouri is the Ozark Plateaus aquifer system (Figure 3.13). This system is comprised of the Springfield Plateau aquifer, the Ozark aquifer, and the St. Francois aquifer (not present in the study area; Figure 3.4d). Water yielding units in this system are predominantly limestone, dolomite, and some sandstone that are Mississippian and older in age. The confining units that separate the aquifers are made up primarily of shale. The Springfield Plateau aquifer is stratigraphically the equivalent of the Mississippian aquifer north of the Missouri River but with only limited hydraulic connectivity. Equivalency also exists between the Ozark aquifer and the Cambrian – Ordovician aquifer which are considered partially hydraulically connected (Figure 3.12; Miller and Appel 1997, Imes and Emmett 1994).

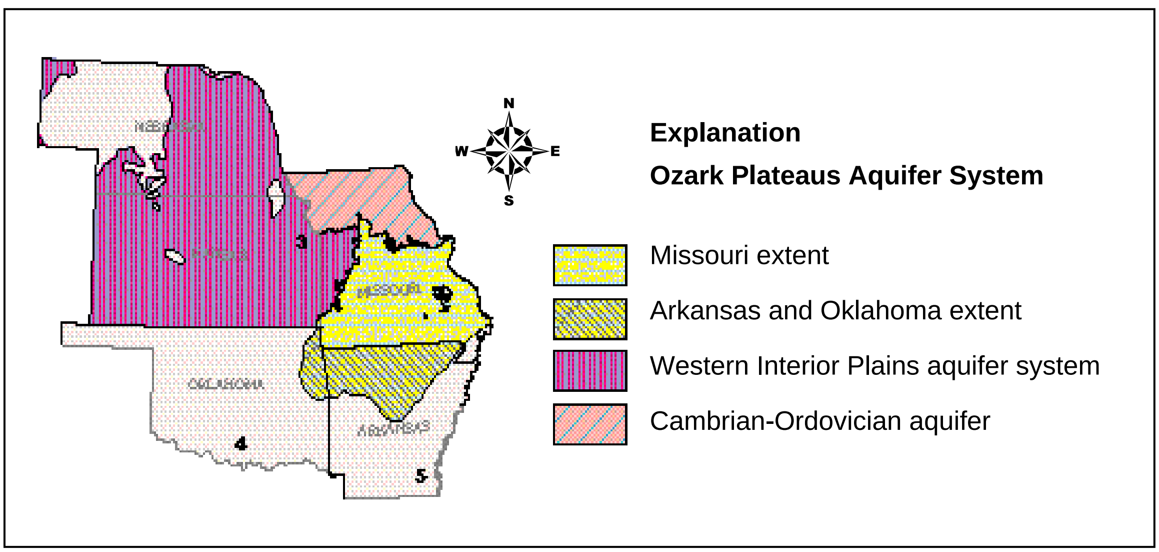


Figure 3.13. Ozark Plateaus Aquifer System. The Ozark Plateaus aquifer system extends over most of southern Missouri and smaller parts of adjacent States. An equivalent aquifer system to the west, the Western Interior Plains aquifer system, contains saline water or brine. The Cambrian-Ordovician aquifer in northern Missouri partly contains fresh water and is equivalent to part of the Ozark Plateaus aquifer system. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

1a) Springfield Plateau Aquifer

Consisting of Mississippian age limestone, the Springfield Plateau aquifer is the uppermost aquifer in the Ozark Plateau aquifer system. As with the Mississippian aquifer north of the Missouri River, the most significant water-yielding formation within the Springfield Plateau aquifer are the Burlington and Keokuk limestones of the Osagean Series. Fracturing and bedding planes provide openings for the movement of water that in the southeastern portion of Saline County have contributed to the formation of karst topography. Underlying the Springfield aquifer is the Ozark Confining Unit, consisting mostly of shale, separating this aquifer from the Ozark aquifer (Figure 3.12; Miller and Appel 1997, Imes and Emmett 1994).

1b) Ozark Aquifer

Lying beneath the Springfield aquifer and Ozark confining unit and above the St. Francois aquifer, the Ozark aquifer consists of rocks of Devonian to Cambrian in age. In Saline County minor outcrops of Devonian and Ordovician rocks occur in the south and southeastern portions of the county. This Ozark aquifer is the primary source of water within the Ozark Plateaus aquifer system. The main water-yielding formations are the Upper Cambrian and Lower Ordovician Series which consist predominantly of dolomite and some sandstone. The equivalent rocks north of the Missouri River are in the Cambrian-Ordovician aquifer. Thickness of the Ozark aquifer is approximated at 1500 feet in the area of Saline County (Figure 3.12; Miller and Appel 1997, Imes and Emmett 1994, Miller 1968).

2) Western Plains Aquifer System

A small portion of western Saline County lies within the boundary of the Western Interior Plains aquifer system (Figure 3.4d and 3.13). Stratigraphically equivalent to aquifers of the Ozark Plateaus aquifer system, this aquifer system also consists of water-yielding dolomite, limestone, and sandstone. The significant aspect of the Western Interior Plains aquifer system is that it contains saline water or brine and no freshwater (Miller and Appel 1997).

CONFINING UNITS

A confining bed as defined by Imes (1985) is “A body of relatively impermeable material stratigraphically adjacent to one or more aquifers.” Confining units are evaluated as part of the Vadose Zone element within the DRASTIC model.

Pennsylvanian Unit

The most predominant confining unit within the study area is the layer of Pennsylvanian rocks that completely overly the Mississippian aquifer north of the Missouri River in Carroll and Chariton Counties and partially overly the Springfield aquifer south of the Missouri River in Saline County. Reaching a thickness of approximately 700 feet north of the Missouri River to less than 100 feet south of the Missouri River, this layer is composed of shale and sandstone and is interbedded with shaley limestone and coal. It is the large shale content that impedes the flow of groundwater into the underlying aquifer systems. This unit is the primary consideration when evaluating the impact of the Vadose Zone in terms of the vulnerability and recharge to the underlying aquifer systems (Figure 3.14; Miller and Appel 1997, Imes 1985, Imes and Emmett 1994).

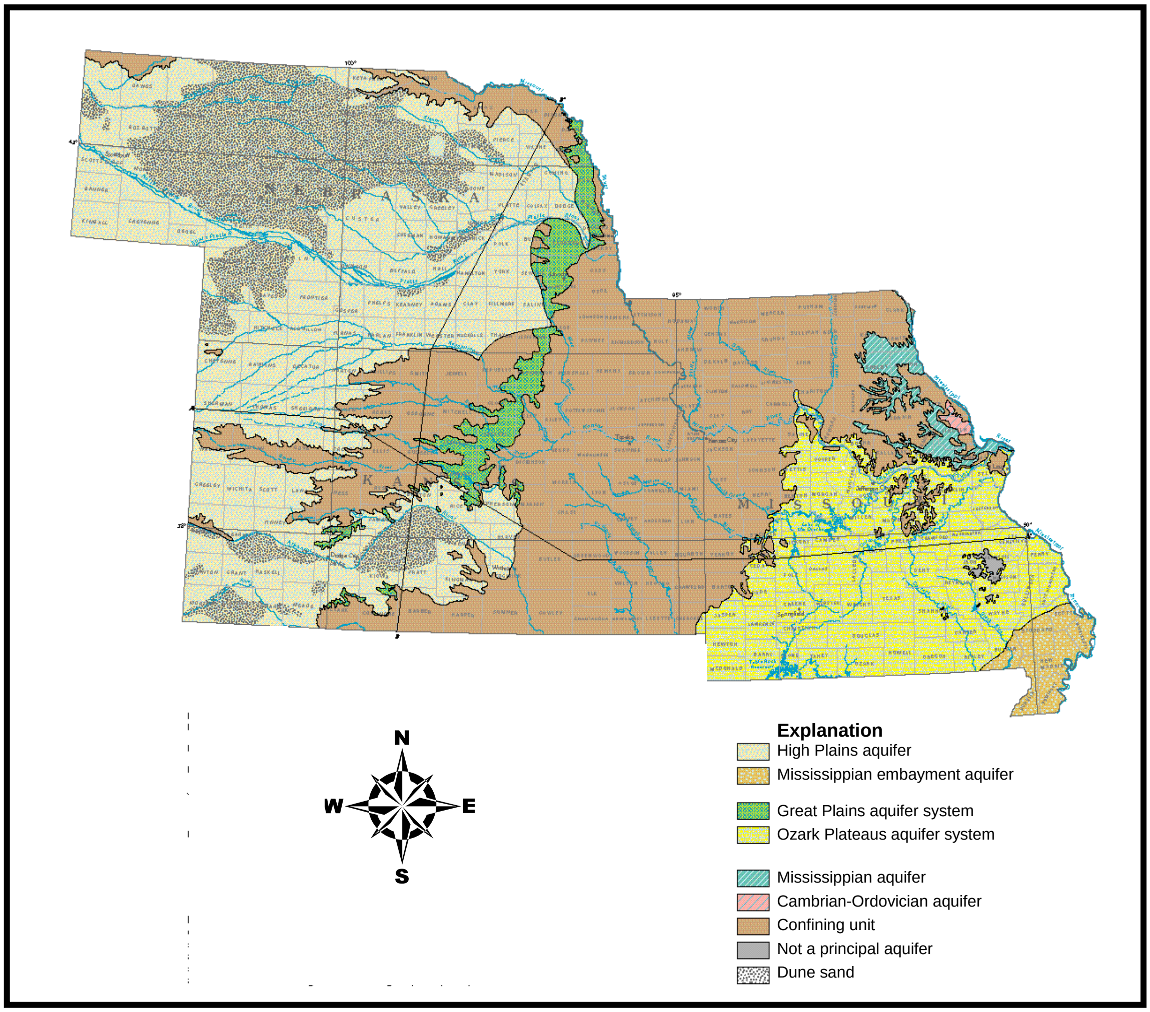


Figure 3.14. Principal Aquifers. The extent of six principal aquifers or aquifer systems, which are either exposed at the land surface or underlie parts of the surficial aquifer system and associated poorly permeable sediments, is mapped. A seventh aquifer system, the Western Interior Plains, is entirely in the subsurface. Only small to moderate amounts of water can be obtained from wells completed in areas shown as confining units or have no principal aquifer. Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997).

SECONDARY CONFINING UNITS

Other confining units exist within the aquifer systems as identified in Figure 3.12. These units occur north of the Missouri River as the upper confining bed underlying the Mississippian aquifer and the lower confining bed underlying the Cambrian – Ordovician aquifer. South of the Missouri River these occur as the Ozark confining unit underlying the Springfield Plateau aquifer and the St. Francois confining unit underlying the Ozark aquifer (Miller and Appel 1997, Imes and Emmett 1994, Imes 1985).

SOILS

The soil profiles for Carroll, Chariton and Saline Counties are a result of Pennsylvanian and Mississippian bedrock formations and Cenozoic Era processes that have left varying thicknesses of glacial drift and loess over the area. In general terms, Table 3.1 provides the U.S. Department of Agriculture (USDA) Soil Survey data for each county.

Table 3.1a. Carroll County general soil description.

CARROLL COUNTY	
Association	**Description**
Gosport-Greenton-Sharpsburg	Moderately deep and deep, gently sloping to steep, moderately well drained and somewhat poorly drained soils that formed in shale residuum and in loess; on uplands
Lagonda-Armster-Grundy	Deep, gently sloping to strongly sloping, somewhat poorly drained and moderately well drained soils that formed in loess, pedisediment, and glacial till; on uplands
Colo-Nodaway	Deep, nearly level, poorly drained and moderately well drained soils that formed in alluvium; on flood plains
Knox-Higginsville-Wakend	Deep, gently sloping to steep, well drained and somewhat poorly drained soils that formed in a thick layer of loess; on uplands
Bremer-Cotter-Booker	Deep, nearly level, well drained, poorly drained, and very poorly drained soils that formed in alluvium; on flood plains
Leta-Haynie-Waldron	Deep, nearly level, somewhat poorly drained and moderately well drained soils that formed in calcareous alluvium; on flood plains

Source: Soil Survey of Carroll County, Missouri.

Table 3.1b. Chariton County general soil description.

CHARITON COU NTY	
Association	**Description**
Armstrong	Very deep, gently sloping to strongly sloping, somewhat poorly drained soils that formed in loess, pedisediments, and glacial till; on uplands
Lagonda-Grundy-Armstrong	Very deep, gently sloping to strongly sloping, somewhat poorly drained soils that formed in loess over pedisediment, loess, and pedisediment and in the underlying paleosol derived from glacial till; on uplands
Menfro-Higginsville-Wakenda	Very deep, gently sloping to steep, well drained and somewhat poorly drained soils that formed in a thick layer of loess; on uplands
Tina-Triplett-Shannondale	Very deep, nearly level to moderately sloping, somewhat poorly drained and moderately well drained soils that formed in loess, alluvium, or loess over alluvium; on lowstream terraces
Carlow-Tice-Dockery	Very deep, nearly level, poorly drained and somewhat poorly drained soils that formed in alluvium; on flood plains
Haynie-Waldron-Booke	Very deep, nearly level, moderately well drained, somewhat poorly drained, and very poorly drained soils that formed in calcareous alluvium; on flood plains along the Missouri River

Source: Soil Survey of Chariton County, Missouri.

Table 3.1c. Saline county general soil description.

SALINE COUNTY	
Association	**Description**
Haynie-Waldron-Leta	Deep, nearly level, moderately well drained and somewhat poorly drained soils formed in alluvium; on flood plains
Knox-Menfro-Sibley	Deep, gently sloping to steep, well drained soils formed in loess; on uplands
Monona-Joy-Winterset	Deep, nearly level to moderately sloping, well drained, somewhat poorly drained, and poorly drained soils formed in loess; on high stream terraces
Dockery-Colo	Deep, nearly level, somewhat poorly drained and poorly drained soils formed in alluvium; on flood plains
Macksburg-Arispe	Deep, very gently sloping to strongly sloping, somewhat poorly drained soils formed in loess; on uplands
Sibley-Higginsville	Deep, gently sloping to strongly sloping, well drained and somewhat poorly drained soils formed in loess; on uplands
Weller-Winfield-Goss	Deep, gently sloping to steep, moderately well drained and well drained soils formed in loess or cherty limestone residuum; on uplands

Source: Soil Survey of Saline County, Missouri.

Soil characteristics, especially texture and permeability, play an important part within the DRASTIC model. Appendix H provides soil map unit descriptors from which model ratings were based (USDA 1993, USDA 1994, USDA 1997).

GROUNDWATER PROVINCES

Because of the diverse geology and hydrology of Missouri, seven major groundwater provinces have been identified by the Missouri Department of Natural Resources, Division of Geology and Land Survey to assess aquifer characteristics, availability, and quality of groundwater resources specific to Missouri. These include the Northwestern Missouri, West-Central Missouri, Northeastern Missouri, Southeastern Lowlands, Springfield Plateau, Salem Plateau, and St. Francois Mountains provinces. Two other areas are also identified as the Missouri and Mississippi River alluvium subprovinces (Figure 3.15; Miller and Vandike 1997).

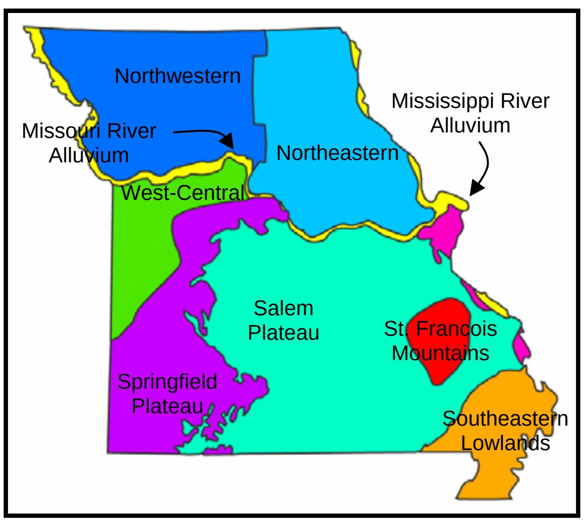


Figure 3.15. Missouri Groundwater Provinces : Northwestern Missouri, West-Central Missouri, Northeastern Missouri, Southeastern Lowlands, Springfield Plateau, Salem Plateau, and St. Francois Mountains provinces.

Missouri Groundwater Subprovinces: Missouri and Mississippi River alluvium

Source: Modified from the Missouri Department of Natural Resources (MDNR)

Of interest to this study are the Northwestern Missouri province which includes Carroll and Chariton Counties and the West-Central Missouri province which includes Saline County. The Missouri River alluvium subprovince borders all three counties and is therefore also evaluated (Miller and Vandike 1997).

In much of the Northwestern province, the availability of groundwater from bedrock aquifers, with the exception of locally available pockets, is typically highly mineralized and therefore unusable. Glacial deposits are somewhat better in quality depending upon the thickness and texture of the layer. These are the most widely used groundwater resources in the province where sufficient yields exist. Alluvial sources of groundwater are usually minimal with the exception of the lower sections of the Grand and Chariton River alluvium, and the Missouri River alluvium. These are the most favored aquifers in northwest Missouri in terms of volume and yield of stored groundwater (Miller and Vandike 1997).

In the West-Central province a freshwater-salinewater transition zone generally follows the southern and eastern boundary, and like the Northwestern province, the deeper aquifers within this zone are highly mineralized with occasional occurrences of quality groundwater. The Missouri River alluvium is the most significant alluvial aquifer in the Saline County area, however, glacial-fluvial deposits along a southeast trending buried glacial channel resulting from probable glacial damming and subsequent ponding can yield varying amounts of groundwater. In particular, an area known as Teteseau Flats, which is a thick deposit of course sand and gravels accumulated within a buried pre-glacial valley, provides a substantial yield of good quality groundwater (Miller and Vandike 1997).

The Pleistocene epoch is credited with the formation of the Missouri River alluvial aquifer, resulting from glacial process that deposited considerable thicknesses of sediment within the river valley. Each county within this study area benefits from the water resources available from this aquifer which yields a significant volume of water and supplies both rural water districts and city municipalities (Miller and Vandike 1997).

The combined potable water resources from predominantly stream valley and glacial drift aquifers are estimated at over 1.5 trillion gallons for the three county area under investigation. Of this, 609 billion gallons are estimated to be stored within the aquifers of Carroll County, 558 billion gallons in Chariton County, and 374 billion gallons in Saline County (Table 3.2). In 2000, nearly 2.3 billion gallons of registered groundwater use was reported in the state water usage report for these three counties (Miller and Vandike 1997, MDNR 2003a).

Table 3.2. Potable water resources for Carroll, Chariton, and Saline Counties, Missouri.

County	Glacial Drift Aquifer [North of Missouri River]	Missouri River Alluvial Aquifer	Other Aquifers [Bedrock & Glacial Drift South of the Missouri River]	Total
Carroll	199	410	-	609
Chariton	384	174	-	558
Saline	-	180	194.4	374.4

Source: Groundwater Resources of Missouri (Miller and Vandike 1997)

The groundwater resources that are available to support the agroeconomic base of Carroll, Chariton, and Saline Counties are relatively modest compared to the more substantial volume in the southern part of the state. However, storage estimates and replenishment rates for the study area are currently within usage demands of the resident population. With agriculture as the major land use, agrochemical usage presents a challenge to the protection of groundwater quality affecting a complex hydrogeologic profile that once contaminated, will take generations to repair.

CHAPTER 4

METHODS

The DRASTIC index based model provides for a decision support mechanism that will identify land use areas that potentially are vulnerable to groundwater contamination. This model was not originally designed for use in a GIS, although it has been shown that such an implementation provides substantial benefits (Merchant 1994). By using the spatial analysis tools available within a GIS, data layers are developed based on the seven DRASTIC components. This methodology creates a spatial database which is divided into contamination vulnerability categories for evaluation over the selected area. When the DRASTIC score is displayed via a GIS, the spatial relationship between land management practices and groundwater vulnerability is illustrated.

MODIFIED PESTICIDE DRASTIC MODEL

The method used to evaluate groundwater vulnerability to agricultural chemical applications is a relative rating system defined by the acronym DRASTIC (Table 4.1). The DRASTIC model consists of seven hydrogeological elements that have weighted averages assigned. These weights have been allocated using a Delphi (consensus) approach and are constant across the study area (Aller *et al*. 1987). The seven elements evaluated in the model are Depth to Water (**D**), Net Recharge (**R**), Aquifer Media (**A**), Soil Media (**S**), Topography (**T**), Impact of the Vadose Zone (**I**), and Hydraulic Conductivity (**C**).

The Pesticide DRASTIC methodology is identical to the DRASTIC methodology with the exception of the assignment of weighting values. This is a specific case analysis for evaluating groundwater vulnerability to agrochemical applications. Specifically, the modified Pesticide DRASTIC weights for soil media and topography are elevated over the unmodified DRASTIC values, and the Pesticide DRASTIC weights for impact of the vadose zone media and hydraulic conductivity are less than the DRASTIC values, indicating the differences in relative importance of pesticides (agrochemicals) in the Pesticide DRASTIC model (Table 4.1). The modifications for the Pesticide DRASTIC index are meant to reflect the mobility of pesticides and therefore should not be used as a comparison to the general DRASTIC index (Aller *et al*. 1987). Aller *et al.* (1987) describe in detail each of the elements and their function in determining the values in the DRASTIC model. A concise description of each follows along with the methods for deriving an integrated model.

Table 4.1. DRASTIC acronym, model elements and weights

	Element	**DRASTIC Weight**	**Pesticide DRASTIC Weight**
D	Depth to Water	5	5
R	Net Recharge Rate of Aquifer	4	4
A	Aquifer Media (geologic characteristics)	3	3
S	Soil Media (texture)	2	5
T	Topography (Slope)	1	3
I	Impact of the Vadose Zone (unsaturated zone above the water table)	5	4
C	Hydraulic Conductivity of the Aquifer	3	2

Source: Aller *et al*. 1987

Using the seven DRASTIC elements, a numerical ranking system of weights, ranges, and ratings have been devised to evaluate the potential of groundwater contamination (Aller *et al*. 1987). These elements are defined as:

Weights: A relative value ranging from 1 to 5.

Ranges: A division of values for each DRASTIC factor.

Rating: A relative value in terms of range with respect to pollution potential. Values range from 1 to 10.

The relative pollution potential can be defined and evaluated by the following equation (Aller *et al*. 1987, Hopkins 1977):

Pollution Potential = Dr Dw + Rr Rw + Ar Aw + Sr Sw + Tr Tw + Ir Iw + Cr Cw

where: **r** = rating and **w** = weight

Calculating each individual element based on the rating and weight results in an index that provides a basis for classifying the vulnerability to contamination from agricultural chemical applications.

DRASTIC MODEL - GIS INTEGRATION

All DRASTIC data elements are incorporated, manipulated, interpreted, and displayed using a GIS. The resulting output is a spatially-oriented dataset showing the hydrogeologic setting and areas of groundwater vulnerability to contamination. The particular GIS software tool used in this analysis is the Environmental Systems Research Institute (ESRI) ArcGIS 9.0 software package.

APPROACH

The process for implementing the GIS-based DRASTIC model consists of an integrated three phased approach that includes: 1) Data Collection, 2) Analysis and Development, and 3) Implementation (Figure 4.1). Each phase is outlined as an independent vertical process flow with a concurrent horizontal process between the DRASTIC model and the GIS application creating an opportunity for constant feedback and a quality assurance evaluation.

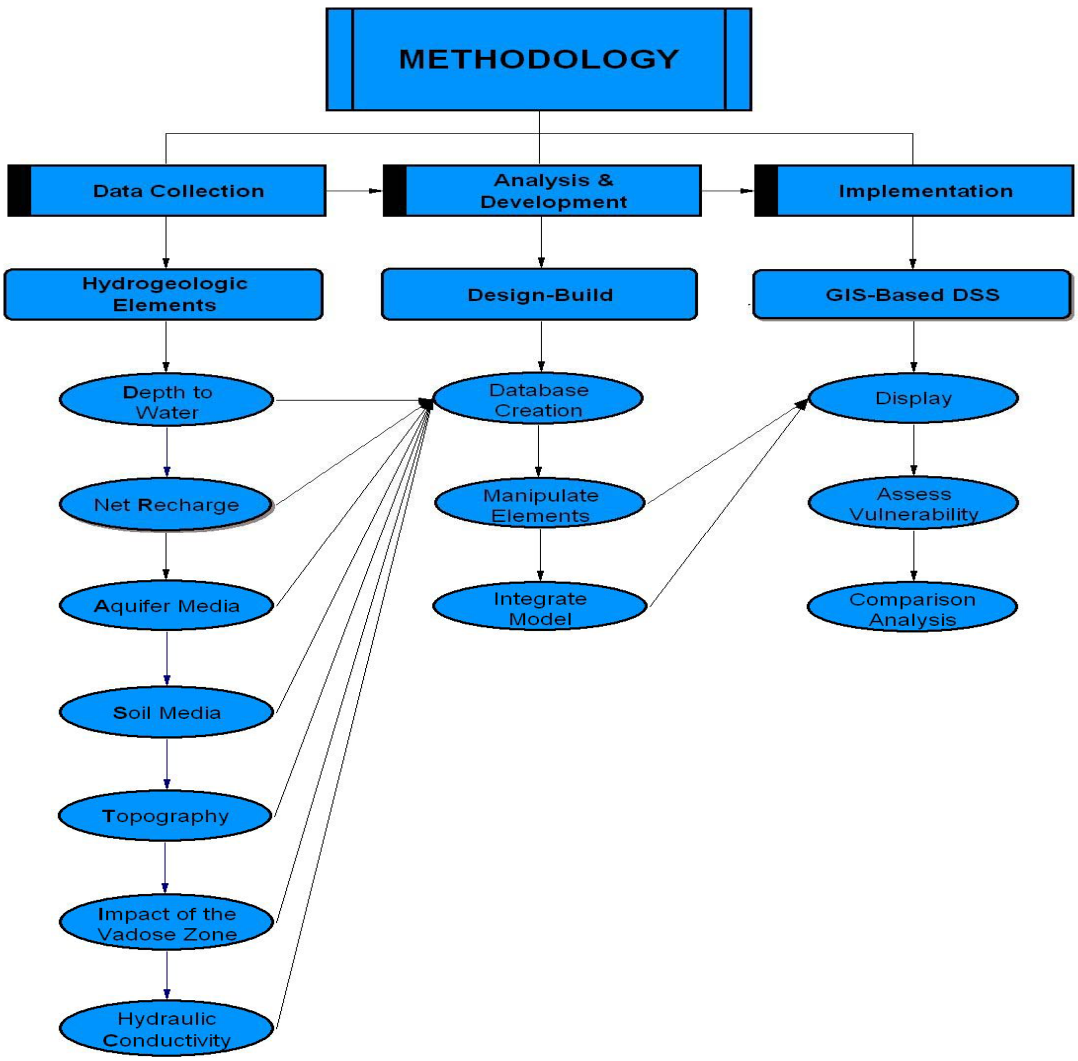


Figure 4.1. Diagram of approach for conducting a vulnerability assessment using the DRASTIC model and a GIS.

An illustration of this conceptual framework is provided with the depth to water hydrogeologic element. These data are collected from federal and state sources and a database created as part of the design-build criteria. In the case of this particular element, a continuous surface is created and manipulated from individual water well point data using the Inverse Distance Weighting (IDW) function within the GIS Spatial Analyst extension. The results, which are integrated into the final model, are displayed and critiqued for accuracy.

Each element follows a similar pattern resulting in the integration of all seven hydrogeologic elements. Display of the integrated model allows for a decision support process of vulnerability assessment and a comparison against existing ecosystem planning and management practices such as agricultural land use decisions.

DATA COLLECTION

The hydrogeologic parameters described are interdependent in determining the potential for contamination in groundwater. Concurrently, variation within each parameter can also affect the overall values and how a contaminant may act. Rather than rigorously applied datasets, these parameters are subjectively based upon the conditions at a particular site as evaluated by the researcher. The value in this type of evaluation is in determining a comparative analysis based upon readily available data that can be mapped and presented with relatively low cost and time commitments as compared to extensive data collection in the field (Aller *et al*. 1987). The sources for the hydrogeologic data in this study are identified in Table 4.2.

Table 4.2. Sources of hydrogeologic data.

DRASTIC Elements	Data Type	Format	Scale	Source
Depth to Water	Well Location / Depth	GIS Point	1:24,000	MDNR[a]*/CARES[b] /USGS[c]*/MSDIS[d]*
Net Recharge	Precipitation / Soil / %slope	State database / SSURGO / GIS DEM	Inches per year/ 1:24,000/30m DEM	MCC[e]*/NRCS[f]*/ MSDIS*
Aquifer Media	Geology	GIS Vector	1:24,000 to 1:500,000	MDNR/GSRAD[g] /MSDIS*
Soil Media	Soil Mart (SSURGO)/ County Soil Surveys	Tabular/GIS Vector	1:24,000	NRCS*/MSDIS*
Topography	Slope	GIS DEM	1:24:000 / 30m	USGS/MSDIS*
Impact of the Vadose Zone	Geology	GIS Vector	1:24,000 to 1:500,000	MDNR/GSRAD/ USGS/MSDIS*
Hydraulic Conductivity	Glaciated/Non-glaciated regions	Tabular / Text	Regional	NWWA[h] / USEPA[i] Series* / USGS Professional Papers 1414-D and 1305
	Land Use / Land Cover	GIS Grid	30m	MoRAP[j]/MSDIS*
	Wellhead	GIS Point	1:24,000	MDNR/CARES /MSDIS*

a Missouri Department of Natural Resources

b Center for Agricultural, Resource and Environmental Systems

c U.S. Geological Survey

*d Missouri Spatial Data Information Center**

e Missouri Climate Center

f Natural Resources Conservation Service

g Geological Survey and Resource Assessment Division

h National Water Well Association

i Environmental Protection Agency

j Missouri Resource Assessment Partnership

Note: An asterisk (*) indicates where the data has been published.

HYDROGEOLOGIC ELEMENTS

Depth to Water (D)

The depth to water element of the DRASTIC model determines the depth of material a contaminant travels enroute to the aquifer. As the depth to water implies, an increased travel time for deeper water levels, factors such as contact time with surrounding media, oxidation, layer permeability, and attenuation become pertinent within the DRASTIC system (Aller *et al*. 1987). Range values are divided into seven depth to water levels from 0 (water occurring at the surface) to depths of 100+ feet. The highest rating values are assigned to depth to water levels that are nearer to the surface and more vulnerable to contamination. The depth to water index (Dr x Dw) is weighted at a value of 5 indicating the relative importance of this model element (Table 4.3).

Table 4.3. Range, rating, and weight values for Depth to Water.

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
DRASTIC Weight: 5	Pesticide DRASTIC Weight: 5

Source: Aller *et al*. 1987

Depth to water data are derived from published research and professional reports (Miller 1968, Imes 1985, Imes and Emmett 1994) in conjunction with publicly available water well databases that document water level and location. The point data for determining depth to water from water wells are incorporated from several sources. The USGS in cooperation with the MDNR operates a network of monitoring wells that collect depth to water data throughout Missouri. Additionally, the MDNR, USGS, and CARES provide data for public drinking water wells, private and certified wells, and other well log information (Table 4.4).

Table 4.4. Sources, type of data, format and availability of data for determining depth to water for the study area.

Source	Type of Data	Format	Available from:
USGS	Monitoring Well	Tabular	http://waterdata.usgs.gov/mo/nwis/gw
MDNR	Certified Wells	GIS Point File	ftp://msdis.missouri.edu/pub/state/
MDNR/USGS	Well Logs	GIS Point File	ftp://msdis.missouri.edu/pub/state/
MDNR/CARES	Public Drinking Water Wells	GIS Point File	http://drinkingwater.missouri.edu/
MDNR/CARES	Private Wells	GIS Point File	http://drinkingwater.missouri.edu/
USGS	Mapped Units	Document	USGS Professional Papers 1414-D and 1305
USGS	Mapped Units	Document	USGS HA730-D
Master's Thesis (Miller 1968)	Mapped Units	Document	UMC Library

In order to create a continuous depth to water surface layer from point data information, the Inverse Distance Weighting (IDW) function within the GIS Spatial Analyst extension is used. Location and water depth are of primary importance for this element. When available, geologic formation and aquifer media data from well logs also contribute to the analysis and assignment of rating values for other hydrogeologic elements.

Net Recharge (R)

Precipitation is the primary source of groundwater. Net recharge is described as the total quantity of water which is applied to the ground surface and infiltrates to reach the aquifer (Aller *et al*. 1987). Miller and Vandike (1997) account for runoff and evapotranspiration as impacting net recharge and Piscopo (2001) and Al-Adamat (2003) apply percent slope and soil permeability to further refine the net recharge value in the form of the equation:

Recharge = Slope(%) + Precipitation + Soil Permeability (Table 4.5)

1) Percent Slope

To calculate percent slope, a 30m digital elevation model (DEM) of the study area is used and classified according to the range criteria in Table 4.5 via the GIS Spatial Analyst extension application. A factor of 1 to 5 is assigned with 1 corresponding to 18+ percent slope and 5 corresponding to a 0 to 2 percent slope. Data for percent slope is acquired from the USGS and Missouri Spatial Data Information Center (MSDIS; Table 4.2).

2) Precipitation

The range of precipitation values are in inches per year. A factor of 1 to 5 is assigned with 1 corresponding to 0 to 2 inches per year and a value of 5 for 10+ inches per year (Table 4.5). Precipitation data is derived from the Missouri Climate Center (MCC), a section of the Atmospheric Science program of the Department of Soil and Atmospheric Sciences, University of Missouri-Columbia.

3) Soil Permeability

Ranges for soil permeability are determined from soil surveys for each county within the study area based on soil type (USDA 1993, USDA 1994, USDA 1997). A factor of 1 to 7 is assigned with 1 corresponding to soil types having very slow infiltration (less than 0.06 inches per hour) and 7 representing soil types with a very rapid rate of infiltration (more than 20 inches per hour; Table 4.5). Comparing these modified variables using the Recharge equation, yield factors for the Net Recharge element that range from a minimum value of 3 to a maximum value of 17.

Table 4.5. Net Recharge Range Variables and Factors. Recharge = %Slope + Precipitation + Soil Permeability. Variables added in terms of factor values (no units).

% Slope		**Precipitation**		**Soil Permeability**		
Range	Factor	Range (inches)	Factor	Range		Factor
18+	1	0 – 2	1	Very slow	less than 0.06 inch	1
12 - 18	2	2 – 4	2	Slow	0.06 to 0.2 inch	2
6 - 12	3	4 – 7	3	Moderately slow	0.2 to 0.6 inches	3
2 - 6	4	7 – 10	4	Moderately	0.6 to 2.0 inches	4
0 - 2	5	10+	5	Moderately Rapid	2.0 to 6.0 inches	5
				Rapid	6.0 to 20 inches	6
				Very Rapid	more than 20 inches	7
Minimum Recharge = 3				Maximum Recharge = 17		

Source: modified from Piscopo 2001
* Slope (%) range criteria taken from DRASTIC model parameters
** Precipitation range criteria taken from DRASTIC model parameters
*** Soil permeability range criteria taken from county soil surveys

The final step is to create ranges for the recharge values and assign ratings to ranges consistent with the DRASTIC model (Table 4.6). The rating value can then be multiplied by the Pesticide DRASTIC weight value resulting in the net recharge index (Rr x Rw). Specific data sources are included in Table 4.7.

Table 4.6. Range, rating and weight values for Net Recharge.

Net Recharge	
Range	**Rating**
3 - 5	1
5 - 7	3
7 - 9	5
9 - 11	7
11 - 13	8
13 - 15	9
15 - 17	10
DRASTIC Weight: 4	Pesticide DRASTIC Weight: 4

Source: modified from Aller *et al*. 1987

Table 4.7. Sources, type of data, format and availability of data for determining Net Recharge for the study area.

Source	Type of Data	Format	Available from:
USGS/MSDIS	Slope	30m DEM	http://msdisweb.missouri.edu/datasearch/VectDisplayResults.jsp?currDispPageNum=1
MCC	Precipitation	Tabular	http://www.hprcc.unl.edu/wrcc/states/mo.html
NRCS/County Soil Surveys	Soil Permeability	Tabular	http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/index.html

Aquifer Media (A)

An aquifer is defined as “a subsurface rock unit which will yield sufficient quantities of water for use.” Aquifer media describes consolidated and unconsolidated rock where water is contained. This will include the pore spaces and fractures of the media where water is held. The aquifer media therefore affect the flow within the aquifer. This flow path controls the rate of contaminant contact within the aquifer (Aller *et al*. 1987).

This element of the DRASTIC model is constructed from geological data created by the MDNR and GSRAD and published by MSDIS as a GIS vector file. The rating values are based on the subjective interpretation of the geologic formations present. Unless specific field determinations dictate, a typical rating value may be used. For example, a rating value of 5 would indicate the aquifer media are made up of glacial till. This value and the Pesticide DRASTIC weight of 3 are used to determine the final index value (Ar x Aw; Table 4.8).

Table 4.8. Ranges and rating values for Aquifer Media

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 Sequences	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
DRASTIC Weight: 3	Pesticide DRASTIC Weight: 3	

Source: Aller *et al*. 1987

Soil Media (S)

Soil media represents a significant factor for influencing groundwater pollution potential, particularly from agrochemical applications. Commonly taken to mean the upper weathered zone of the earth's surface, the six feet (on average) of the uppermost portion of the vadose zone is where the most significant biological activity occurs. The makeup of soil media on groundwater vulnerability directly impacts the amount of recharge and the ability of contaminants to infiltrate the vadose zone. Soil permeabilities and contaminant migration then is directly linked to soil type, shrink and swell potential, and grain size of the soil (Aller *et al*. 1987)

The soil data used in this study are the NRCS Soil Survey Geographic (SSURGO) database (available as tabular and GIS vector files). By referring to the soil series description in the engineering and physical properties indexes, the most significant portion of the soil profile is considered. Textural classification

(Figure 4.2) and thickness of a soil type provide the necessary information for evaluating the rating value (Table 4.9) that is assigned for the range of soil media, reflecting the greatest impact to vulnerability. The ratings and Pesticide DRASTIC weight are used to determine the final index value (Sr x Sw). The significance of this hydrogeologic element is reflected in a weight value of 5 as compared to a weight value of 2 used in non-agricultural environments.

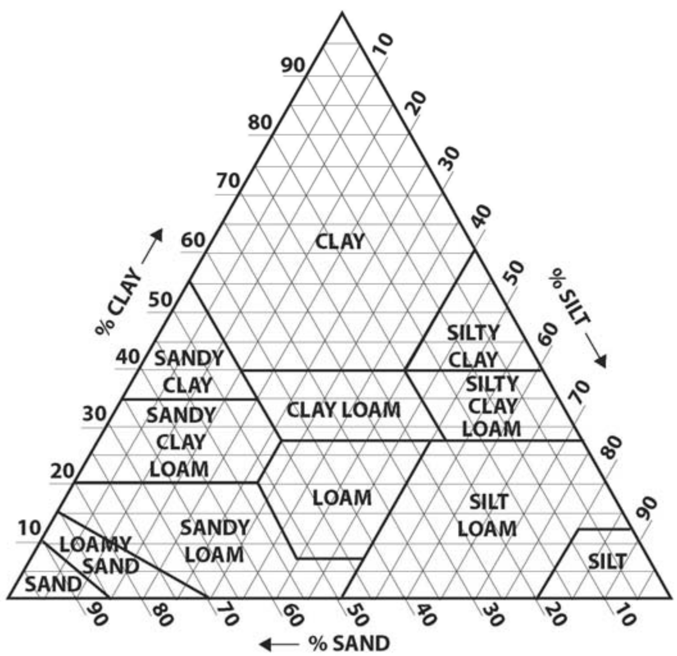


Figure 4.2. Soil texture triangle. Soil textural classification by percent sand, percent clay, and percent silt.

Source: USDA

Table 4.9. Ranges, rating, and weight values for Soil Media.

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
DRASTIC Weight: 2	Pesticide DRASTIC Weight: 5

Source: Aller *et al*. 1987

Topography (T)

In terms of slope and slope variability, topography is a controlling factor for pollutant runoff or infiltration. Inherent to this component is soil development as an input to contaminant attenuation. At 0 to 2 percent slope, the greatest potential exists for pollutant infiltration whereas with an 18+ percent slope little potential exists for infiltration, however, contamination to surface water increases along with a greater probability of erosion (Aller *et al*. 1987).

Calculating percent slope for topography is the same process as that taken for net recharge. A 30m digital elevation model (DEM) of the study area is used and reclassified according to the range criteria in Table 4.10. In this case, ratings corresponding to 18+ percent slope have a value of 1, and for a 0 to 2 percent slope, a value of 10. The product of rating and the Pesticide DRASTIC weight result in an index value for topography (Tr x Tw). Similar to the weighting value for Soil Media, the significance of this hydrogeologic element is also reflected in an elevated weight value of 3 as compared to a weight value of 1 used in non-agricultural environments.

Table 4.10. Range, rating, and weight values for Topography.

Topography (% Slope)	
Range	**Rating**
0 – 2	10
2 – 6	9
6 – 12	5
12 – 18	3
18+	1
DRASTIC Weight: 1	Pesticide DRASTIC Weight: 3

Source: Aller *et al*. 1987

Impact of the Vadose Zone Media (I)

"The vadose zone is defined as that zone above the water table which is unsaturated or discontinuously saturated." Lying between the soil horizon and water table, the type of media in this zone determines attenuation characteristics. "Biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion are all processes which may occur within the vadose zone" (Aller *et al*. 1987). As with Aquifer Media, this element of the DRASTIC model is also constructed from geological data created by the MDNR and GSRAD and published by MSDIS as a GIS vector file. From Table 4.11, the typical ratings and Pesticide DRASTIC weight (4) are used to determine the final index value (Ir x Iw). Of particular note for this element is a rating value of 1 for a confining layer, indicating low vulnerability to agrochemical contamination. Additionally, the weighting value for the pesticide model is less at 4 than for non-agricultural models weighted at a value of 5.

Table 4.11. Range, rating, and weight values for Vadose Zone Media**.**

Vadose Zone Media		
Range	**Rating**	**Typical 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
DRASTIC Weight: 5		Pesticide DRASTIC Weight: 4

Source: Aller *et al*. 1987

Hydraulic Conductivity of the Aquifer (C)

This final component of the DRASTIC model can be described in terms of aquifer material and its ability to transmit water for a given hydraulic gradient. Contamination is controlled by the rate at which groundwater flows. Hydraulic conductivity is a measure by which voids, fracturing, and bedding planes are the controlling elements. With a higher hydraulic conductivity, there exists a greater potential for pollution (Aller *et al*. 1987).

Hydraulic Conductivity is derived from generalized data provided in the DRASTIC model literature for the glaciated and non-glaciated central groundwater region of the United States (Aller *et al.* 1987; Tables 4.12, 4.12.1, and 4.12.2) as well as from USGS Professional Papers 1414-D and 1305 (Imes 1985, Imes and Emmett 1994). As with Aquifer Media and Impact of the Vadose Zone elements, geological data created by the MDNR and GSRAD and published by MSDIS as a GIS vector file are used as the base layer to understand the aquifer material present. Rating values are assigned for six range divisions. A higher rating is indicative of higher hydraulic conductivity. Weighting criteria are reduced from 3 for the regular DRASTIC model to 2 for the Pesticide DRASTIC model. The product of rating and weight is the final index value (Cr x Cw).

Table 4.12. Range, rating, and weight values for Hydraulic Conductivity.

Hydraulic Conductivity (GPD/FT^2)	
Range	**Rating**
1 – 100	1
100 – 300	2
300 – 700	4
700 – 1000	6
1000 – 2000	8
2000+	10
DRASTIC Weight: 3	Pesticide DRASTIC Weight: 2

Source: Aller *et al*. 1987

Table 4.12.1. Glaciated setting (Carroll, Chariton, and northern Saline Counties)

Feature	Range	Rating	Weight
Glacial Till Over Bedded Sedimentary Rocks	100 – 300	2	2
Glacial Till over Sandstone	300 – 700	4	2

Source: Aller *et al*. 1987

Table 4.12.2.Non – Glaciated setting (southern Saline County)

Feature	Range	Rating	Weight
Alternating Sandstone, Limestone and Shale – Thin Soil	1 – 100	1	2
River Alluvium with Overbank Deposits	1000 – 2000	8	2

Source: Aller *et al*. 1987

DESIGN AND BUILD

The creation and manipulation of data elements, as a design and build function, is closely associated with the data collection process. Information collected is either in a raw format that requires extraction or is available in a digital format that can be tailored to the specific requirement of the model parameters. From this point forward, GIS tools are used almost exclusively to integrate model elements for analysis and display.

Database Creation

Creating databases for representation within a GIS is accomplished by compiling data from several dissimilar sources into a common format or by editing GIS point and vector attribute tables to reflect DRASTIC rating and weight assignments. An attribute table is a tabular file that identifies geographic features as rows and attributes of that feature in columns. A well, for example, as a geographic feature, may consist of several columns of attributes (e.g., depth, location, aquifer media) that make up the information for a particular well. In Table 4.13, key attributes for creating the depth to water element of the DRASTIC Model consist of location (i.e., DDLat, DDlog) and the depth of the water in feet below the surface (DTW). In this case, originating database source information has been extracted and included for reference.

Table 4.13. Example of raw data extracted and compiled for creation of data layer within a GIS.

ID	Database	Mapname	County	DDLat	DDLog	DTW
024425	WellLogs	Saline City	Saline	39.13926	-92.9294	20
013641	WellLogs	Sumner	Chariton	39.63705	-93.2026	21
000233	WellLogs	Salisbury	Chariton	39.42394	-92.8077	25
007519	WellLogs	Marshall N	Saline	39.17642	-93.1340	25
009959	WellLogs	Slater	Saline	39.21174	-93.1230	25
004819	WellLogs	Napton	Saline	39.10754	-93.1172	39
012531	WellLogs	Tina	Carroll	39.58729	-93.4760	100
011663	WellLogs	Coloma	Carroll	39.55673	-93.5960	285
023335	WellLogs	Roads	Carroll	39.43485	-93.7003	40
022292	WellLogs	Norborne	Carroll	39.35172	-93.6786	75
390405	USGS	Blackburn	Saline	39.06807	-93.4394	2.3
390406	USGS	Blackburn	Saline	39.01307	-93.4044	2.5
391359	USGS	Malta Bend	Saline	39.19558	-93.3169	5.3
2010778	SPSWELL	Sumner	Chariton	39.65269	-93.2476	0
2010722	SPSWELL	Salisbury	Chariton	39.42620	-92.8718	30
2010578	SPSWELL	Norborne	Carroll	39.30311	-93.6758	0
0084480	CertWell	Saline City	Saline	39.22375	-92.9274	10
0098967	CertWell	Mendon	Chariton	39.53520	-93.2422	10
0004090	CertWell	Bosworth	Carroll	39.46479	-93.3120	10

A second case of database creation is accomplished by editing the attribute tables within existing GIS vector files. Table 4.14 is a common example of geologic features that are assigned DRASTIC Model index values based on attributes. Representative of the Aquifer Media element, alluvium is rated with a value of 8 and a weight of 3 whose product is 24 (Ar x Aw). The subjectivity of this process is in the rating assignment. Using a GIS to calculate and build attribute selections of this type requires minimal manual data entry and manipulation.

Table 4.14. Example ArcGIS attribute table with geologic feature, rating, weight, and DRASTIC element index values highlighted.

Mapcode	System	Series	Gentype	Perm	Rating	Weight	ArxAw
Pm	Pennsylvanian	Desmoinesian	Limestone	Medium	6	3	18
Pp	Pennsylvanian	Missourian	Sandstone	Medium	6	3	18
Qal	Quaternary	Holocene	Alluvium	Medium	8	3	24
Pcc	Pennsylvanian	Desmoinesian	Limestone	Medium	6	3	18
Pm	Pennsylvanian	Desmoinesian	Limestone	Medium	6	3	18
Pm	Pennsylvanian	Desmoinesian	Limestone	Medium	6	3	18
Pkc	Pennsylvanian	Missourian	Limestone	Medium	6	3	18
Pm	Pennsylvanian	Desmoinesian	Limestone	Medium	6	3	18
Pkc	Pennsylvanian	Missourian	Limestone	Medium	6	3	18
Pkc	Pennsylvanian	Missourian	Limestone	Medium	6	3	18
Pkc	Pennsylvanian	Missourian	Limestone	Medium	6	3	18
Mo	Mississippian	Osagean	Limestone	High	6	3	18
Pm	Pennsylvanian	Desmoinesian	Limestone	Medium	6	3	18
Pcc	Pennsylvanian	Desmoinesian	Limestone	Medium	6	3	18
Ppwm	Pennsylvanian	Missourian	Clay	Low	1	3	3
Ppwm	Pennsylvanian	Missourian	Clay	Low	1	3	3
Pkc	Pennsylvanian	Missourian	Limestone	Medium	6	3	18

Manipulate Elements

Spatial reference for all data elements are defined in terms of the North American Datum of 1983 (NAD 1983) and the Universal Transverse Mercator (UTM) system Zone 15 North. Data elements exist in GIS point, vector, and raster formats. Manipulation of individual DRASTIC index elements produces the integrated model that is the focus of this investigation. To create this integrated model, databases undergo various transformations. The tools within the GIS perform the geoprocessing operations required for the production of layers that represent the seven model elements (Table 4.1).

The literature provides examples of summary approaches taken by other investigators. Familiarity with software functionality and individual data files within this study area dictate the strategy for data manipulation. Decisions regarding the approach to operation selection are also dependent upon the element evaluated (e.g., resampling using nearest neighbor for discrete data vs. cubic convolution for continuous data or symbolizing in terms of unique values vs. classified values vs. stretched values). In the case of well locations that exist as GIS point files, the Inverse Distance Weighting (IDW) spatial interpolation technique is used to transform depth to water information into a continuous surface. The water depth range is then classified into seven range categories as defined in Table 4.3, rated appropriately and weighted to arrive at the index value for this model element.

The Spatial Analyst extension within the ArcGIS software package provides many of the operation selections for manipulating the elements within the DRASTIC model. In addition to the IDW functionality, a surface analysis tool is available for calculating the percent slope from a Digital Elevation Model (DEM) of the study area. Net Recharge and Topography elements are evaluated using the parameters in Table 4.6 and Table 4.10 based on this generated data (Net Recharge also incorporates soil permeability and precipitation).

To generate the remaining model elements (Aquifer Media, Impact of the Vadose Zone, Hydraulic Conductivity, and Soil Media), topological integration using various data management, analysis and conversion tools (e.g., union, buffer, clip, dissolve, update) provide the mechanisms for creating the desired data structures. Data manipulation occurs based on the description of the geologic formation or soil textural information acquired. Evaluation of the data layers will result from the value assignments in Tables 4.8, 4.9, 4.11, and 4.12.

Integrate Model

Conversion to a raster format for all vector formatted data is necessary for integration of the model elements within the GIS. By selecting the field that represents the DRASTIC index value (i.e., Sr x Sw) the grid cell values reflect the characteristic at that site (e.g., soil type) based on the evaluation parameters embodied in the rating and weight assignments. The data layers representing each DRASTIC element will be combined based on the Pollution Potential equation using the raster calculator functionality within the ArcGIS Spatial Analyst extension. The resulting raster file will be the layer used to evaluate groundwater vulnerability.

GIS-BASED DSS

Display

The ESRI ArcGIS 9.0 software package provides the means by which each element of the DRASTIC index has been created. Existing as point and vector files, the DRASTIC index feature for each file (e.g., Ar x Aw) is converted into raster format. Individually, each layer developed allows for a display of how a particular DRASTIC element impacts the vulnerability model. Adding each raster layer together using the raster calculator function provides for an integrated

DRASTIC model showing where in the study area the potential exists for groundwater contamination. The DEM of the study area is used as an underlying layer for the integrated map layer to enhance the visual effect of the display and evaluation of the model.

Assess Vulnerability

In conjunction with the display of the integrated raster dataset is the assessment of the vulnerability of groundwater from the application of agrochemicals. Based on the Pollution Potential equation defined above, the integration of the seven data layers results in a range of values based on the grid cell values of each DRASTIC element. Higher values will represent higher groundwater vulnerability relative to lower values. From this quantified data, a classification scheme is implemented based on the statistical grouping of data. In order to maximize the difference between classes, a Natural Breaks method is chosen for identifying areas that fall within a low, medium, or high vulnerability region. Classifying the data based on three categories provides for a useful division of values that demonstrate relative vulnerability without excessive attempts at precision (more classifications) for a region where data accuracy is variable. The pollution potential map that emerges from the assessment methodology provides a mechanism for a comparison analysis of vulnerability potential with land use practices currently in place or under consideration for future implementation.

Comparison Analysis

In addition to investigating where there is potential for contamination of groundwater within the study area, an application of this research is to understand if the DRASTIC model output, in the form of a vulnerability map, correlates with existing measured patterns of contaminant data. The types of data that are used for a comparison analysis include known detections of contaminants, wellhead distribution, and land use and land cover data as made available by the Missouri Department of Natural Resources and Missouri Resource Assessment Partnership. The implications for decision making of a comparison analysis are an enhanced awareness of the relationship between groundwater vulnerability and the anthropogenic impact from agricultural production decisions.

CHAPTER 5

RESULTS

Implementation of the Pesticide DRASTIC model methodology produces seven datasets that can be represented as GIS maps. When combined, according to the pollution potential equation, an integrated map of the study area is produced, which depicts classified ranges of groundwater vulnerability to agricultural chemical applications. Results of the integrated Pesticide DRASTIC model for this investigation are provided as Figure 5.1. The maps show the spatial distribution of the hydrogeologic elements that define groundwater vulnerability.

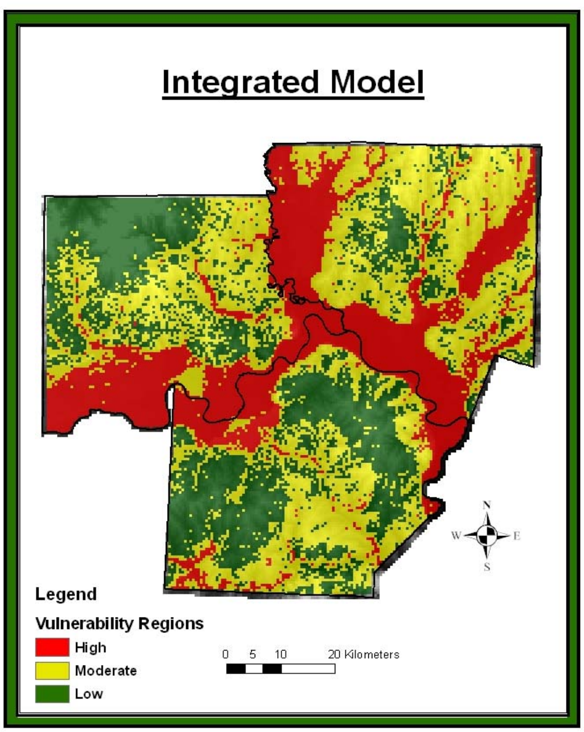
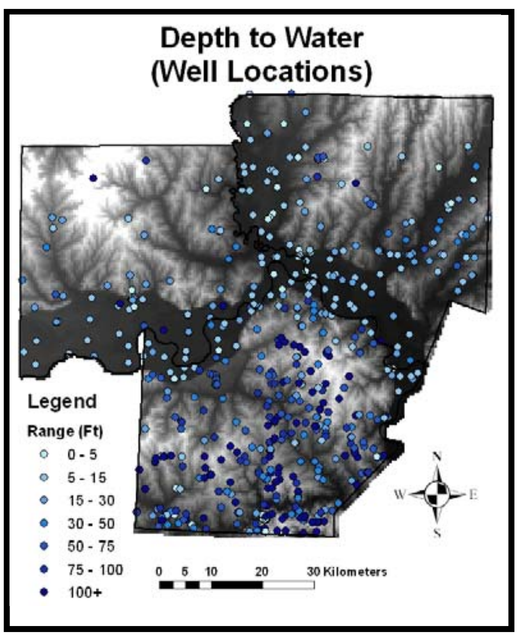


Figure 5.1. Study area integrated model. GIS map of an integrated Pesticide DRASTIC model for groundwater vulnerability in Carroll, Chariton, and Saline Counties, Missouri. Vulnerability regions are depicted as High (Red), Moderate (Yellow), or Low (Green).

HYDROGEOLOGIC ELEMENTS

Depth to Water

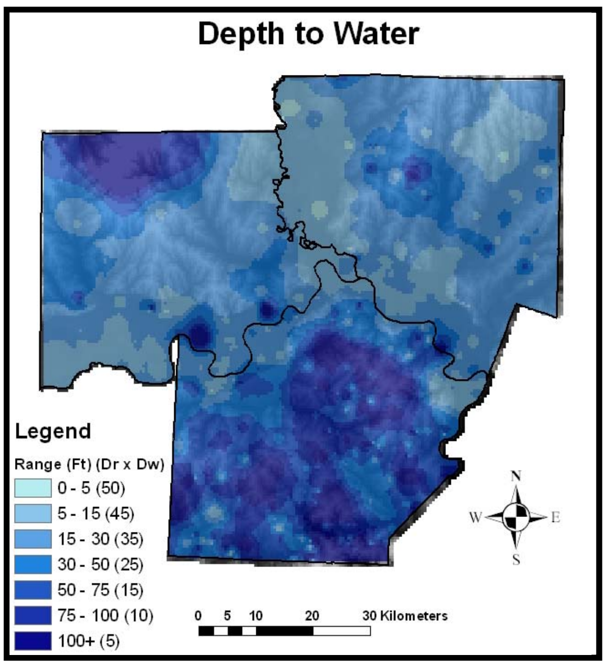
The depth to water element of the DRASTIC model determines the depth of material a contaminant travels enroute to the aquifer. The compilation of depth to water data results in 585 point locations for wells documented by Missouri's Geological Survey and Resource Assessment Division (GSRAD) and the United States Geological Survey (USGS). These data points provide a depth to water range from zero to over 100 feet below the ground surface. Divided into seven categories based on the depth to water element within the DRASTIC model, statistical data shows that the majority of wells are at a depth greater than 15 feet. This accounts for 67 percent of the total wells considered in the analysis. The highest percentage of wells, at 26 percent, falls within the 5 to15 foot range. Wells that are in excess of 100 feet account for 17 percent of all wells (Figure 5.2). These wells are located in stream valley alluvium, glacial drift, and bedded sandstone, limestone, and shale sequences.



Range (Ft)	Percent of Wells
0 - 5	6.84%
5 – 15	25.98%
15 – 30	16.41%
30 – 50	11.28%
50 – 75	10.26%
75 – 100	11.79%
100 +	17.44%

Figure 5.2. Identification of well locations for depth to water analysis. Wells are categorized by depth to water below the ground surface and the percentage of wells that fall within each category. Source data: U S. Geological Survey (USGS), Geological Survey and Resource Assessment Division (GSRAD) Missouri Spatial Data Information Service (MSDIS)

The well location points in Figure 5.2 are converted to a continuous surface by using the Inverse Distance Weighted (IDW) technique for spatial interpolation resulting in the representation of depth to water areas in Figure 5.3.The depth to water index value (Dr x Dw) ranges from a value of 5, representing the deepest and least vulnerable water levels, to 50 where the water table is at or near the surface. Whereas the greatest percentage of wells fall within the 5 to 15 foot range, water that is from 15 to 30 feet below the surface accounts for over 35 percent of the total area and the predominant depth to water index value (35) impacting the DRASTIC model. Overall, 92 percent of the area has water levels less than 100 feet. The deepest water levels, those over 100 feet, make up the remaining 8 percent of the study area. The greatest depth to water values are predominantly found in Saline and northwestern Carroll Counties.



Range (Ft)	Rating	Dr x Dw	% Area
0 – 5	10	50	0.40%
5 – 15	9	45	17.71%
15 – 30	7	35	35.45%
30 – 50	5	25	16.98%
50 – 75	3	15	11.71%
75 – 100	2	10	9.71%
100 +	1	5	8.03%
Weight = 5			

Figure 5.3. Depth to water element of the modified Pesticide DRASTIC Index. Lighter hues represent shallow wells progressing with depth to darker hues. Source: Aller *et al.* 1987

The depth to water element “does not include saturated zones which have insufficient permeability to yield significant enough quantities of water to be considered an aquifer,” according to Aller *et al*. (1987). Imes (1985) asserts in his study of the northern Missouri geohydrology that there is enough water within the alluvial fill and glacial drift for these deposits to be considered a significant aquifer. Accordingly, he states that these are “primary sources of fresh water in northern Missouri”…and “are a source of water for domestic and non-irrigation farm use.”

Net Recharge

Precipitation is the primary source of this region’s groundwater. Net recharge, under the DRASTIC Model is described as the total quantity of water which is applied to the ground surface and infiltrates to reach the aquifer (Aller *et al*. 1987). The amount of precipitation that contributes to the net recharge value for the study area is over 39 inches per year, and by itself would imply a maximum vulnerability rating (normally 10+ inches per year) for this element of the model over the entire study area. Refining this model element by enhancing the data input expands upon precipitation as the single factor for evaluating recharge. Aller *et al*. (1987), in describing the criteria for net recharge, support the inclusion of additional recharge factors when the data are available. As discussed in the methodology, this includes precipitation, percent slope, and soil permeability.

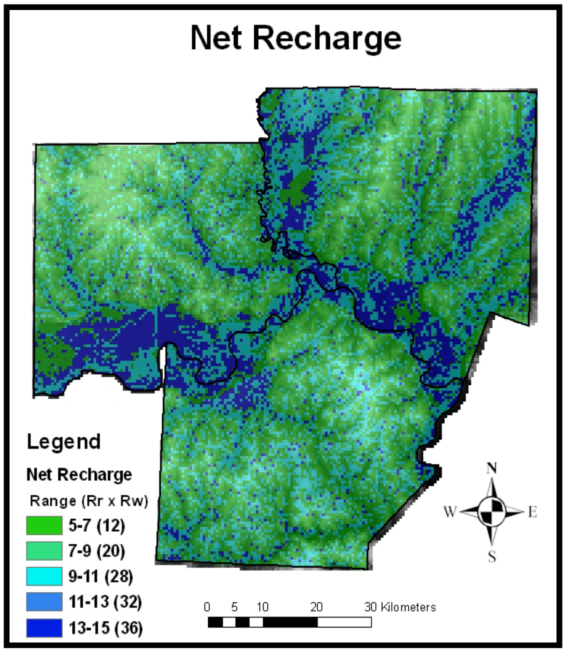
From Miller and Vandike (1997) evapotranspiration accounts for losses estimated at 28 inches per year from the total precipitation for the study area.

Another 8 inches may be lost to runoff, however, dependent on the intensity and spatial distribution of rainfall; a portion of this may contribute to net recharge. Statewide, the average recharge is 4 inches per year and is used in the Net Recharge calculation. Combining precipitation, with percent slope and soil permeability after work by Al-Adamat *et al*. (2003) and Piscopo (2001), rating values are created that are used to calculate the recharge index value (Rr x Rw) and show recharge variation over the study area using the recharge equation:

Recharge = Slope(%) + Precipitation + Soil Permeability

This equation then allows for a minimum and maximum recharge value to be ascertained. An ascending range and rating scale is then devised from which an index value can be assigned.

Figure 5.4 illustrates the recharge values. The areas of vulnerability for this element are identified by the recharge index values (Rr x Rw) 12 through 36, representing the ranges of recharge vulnerability from lowest to highest respectively. The moderate vulnerability index value 20 represents 50 percent of the study area, distributed relatively evenly across all three counties. The higher recharge values are mostly associated with river drainages and alluvial floodplains. Piscopo (2001) notes that: "In general, the greater the recharge, the greater the potential for groundwater pollution." These higher recharge areas combined are 16 percent of the total area.

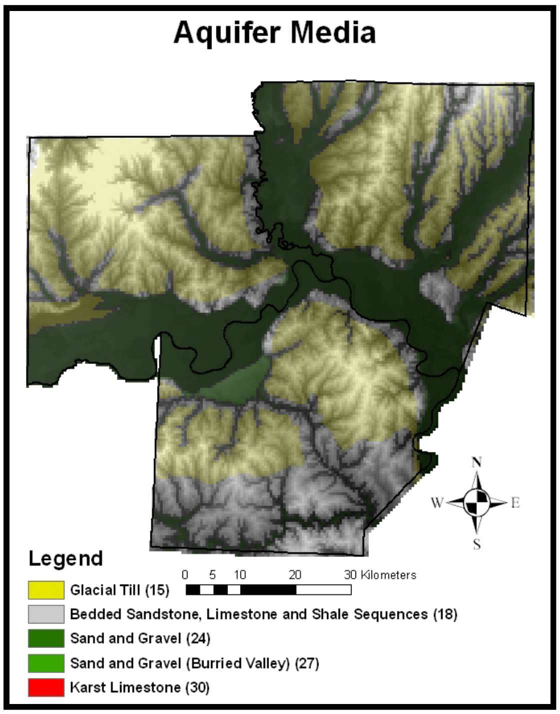


Range	Rating	Rr x Rw	% Area
3 - 5	1	4	0%
5 - 7	3	12	0.68%
7 - 9	5	20	50.22%
9 - 11	7	28	33.23%
11 - 13	8	32	14.44%
13 - 15	9	36	1.43%
15 - 17	10	40	0%
Weight = 4			

Figure 5.4. Net Recharge element of the Pesticide DRASTIC model. As the index value (Rr x Rw) increases, vulnerability increases. Source data: Natural Resources Conservation Service (NRCS), Missouri Climate Center (MCC), Missouri Spatial Data Information Service (MSDIS)

Aquifer Media

The aquifer media affects the flow within the aquifer. This flow path controls the rate of contaminant contact within the aquifer. This element requires a combination of available geological system data, extracted from individual GIS files. Data characterizing glacial drift and alluvium have been integrated with the generalized geology of the area for a composite model element representing the aquifer media for the study area. The media represented is identified as glacial till, bedded sandstone, limestone, and shale sequences, sand and gravel, and karst limestone. The aquifer media index value (Ar x Aw) is moderately low (15) in areas comprised of glacial till and highest value (30) in the areas with karst limestone, however karst formations occur in less than .01 percent of the study area. The highest percent of the study area where the aquifer media is exposed at the surface consists of glacial till at 49 percent, followed by sand and gravel alluvium at 30 percent. Bedded sandstone, limestone, and shale sequences make up the remainder of the area at approximately 20 percent (Figure 5.5). An area characteristic of a “buried valley,” known locally as the Teteseau Flats, is also identified in northwestern Saline County which is rated slightly higher than other sand and gravel alluvium due to the coarser composition of the material grain size (Barnett 1998, Aller *et al*. 1987, and Miller 1968). The Teteseau Flats area is less than one percent of the total study area.

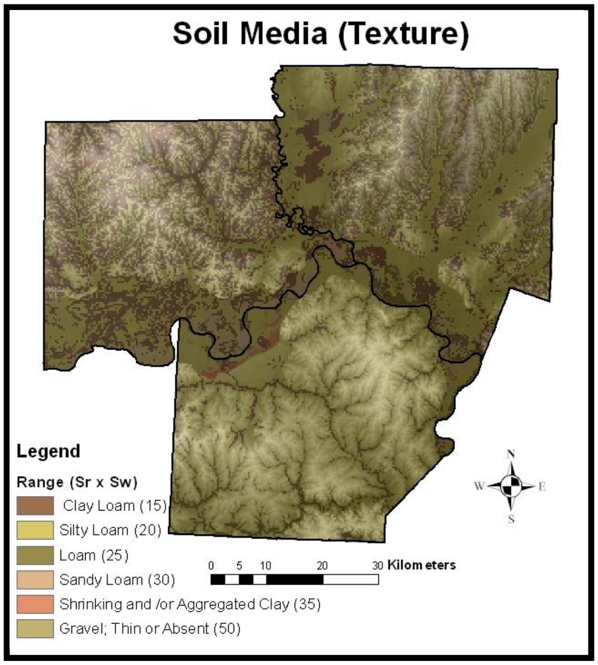


Range	Rating	ArxAw	% Area
Massive Shale	1 – 3	6	0%
Metamorphic / Igneous	2 – 5	9	0%
Weathered Metamorphic / Igneous	3 – 5	12	0%
Glacial Till	4 – 6 (5)	15	49.37%
Bedded Sandstone, Limestone, and Shale Sequences	5 – 9 (6)	18	19.76%
Massive Sandstone	4 – 9	18	0%
Massive Limestone	4 – 9	18	0%
Sand and Gravel	4 – 9 (8)	24	29.88%
Sand and Gravel (Buried Valley)	4 – 9 (9)	27	0.99%
Basalt	2 – 10	27	0%
Karst Limestone	9 – 10 (10)	30	<0.01%
Weight = 3			

Figure 5.5. Aquifer Media element of the Pesticide DRASTIC model. As the index value (Ar x Aw) increases, vulnerability increases. Typical rating assignments have been made according to Aller *et al.* (1987). Glacial till (49%), bedrock sequences (20%), and sand and gravel (31%) predominate within the study area. Source data: Geological Survey and Resource Assessment Division (GSRAD), Missouri Spatial Data Information Service (MSDIS)

Soil Media

Soil media composition directly impacts the amount of groundwater recharge and the ability of contaminants to infiltrate the vadose zone. The USDA texture classifications determine the rating assigned for the soil media element. The decision to choose a particular classification results from an evaluation of the predominance of a textural type based on its depth, and percentage of sand, silt, and clay. Other factors such as permeability and organic matter can also assist in determining how a soil is evaluated and rated for the Pesticide DRASTIC Model (Aller *et al*. 1987).



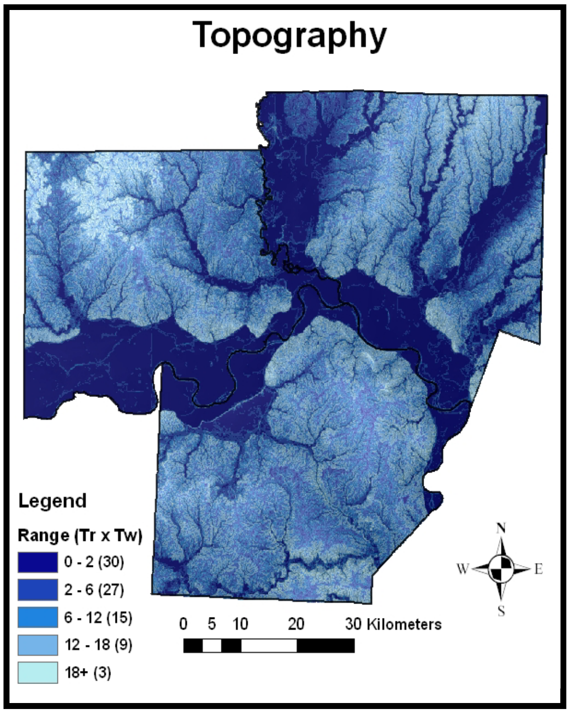
Range	Rating	Sr x Sw	% Area
Thin or Absent	10	50	1.53%
Gravel	10	50	1.53%
Sand	9	45	0%
Peat	8	40	0%
Shrinking and / or Aggregated Clay	7	35	0.35%
Sandy Loam	6	30	1.65%
Loam	5	25	14.04%
Silty Loam	4	20	60.53%
Clay Loam	3	15	21.91%
Muck	2	10	0%
Nonshrinking and Nonaggregated Clay	1	5	0%
Weight = 5			

Figure 5.6 Soil Media element of the Pesticide DRASTIC model. As the index value (Sr x Sw) increases, vulnerability increases. Silty Loam accounts for 60% of the total area, followed by clay loam (22%) and loam (14%).The silty loam soil class is concentrated predominantly in Saline County. Source data: Geological Survey and Resource Assessment Division (GSRAD), Missouri Spatial Data Information Service (MSDIS)

Silty loam soils, rated moderately low (20) in terms of the soil media index value (Sr x Sw), are the predominant textural type comprising 61 percent of the study area. This soil type can be found throughout the study area, but is particularly prevalent south of the Missouri River in Saline County. Clay loam and loam follow at 22 and 14 percent respectively, also with moderate to moderately low index values (15 and 25). These soil types occur most frequently in Carroll and Chariton Counties north of the Missouri River. Shrinking and/or aggregated clay (35) occurring mostly adjacent to Teteseau Flats in northwestern Saline County and areas that are gravel, or where the soil media is either too thin to evaluate or absent (50; e.g., open water), make up the remaining area at approximately 2 percent of the total study area (Figure 5.6).

Topography

Topography is a controlling factor for pollutant runoff or infiltration. At 0 to 2 percent slope, the greatest potential exists for pollutant infiltration. At 18+ percent slope little potential exists for infiltration. Distribution of categories across the study area, while not uniform, is divided nearly equally. With the exception of the 2 to 6 percent slope range, which represents over 15 percent of the study area, the remaining range categories each make up approximately 21 percent of the area, plus or minus less than 1 percent slope. The topography index value (Tr x Tw) in this case is just as prevalent as the value for over 18 percent.



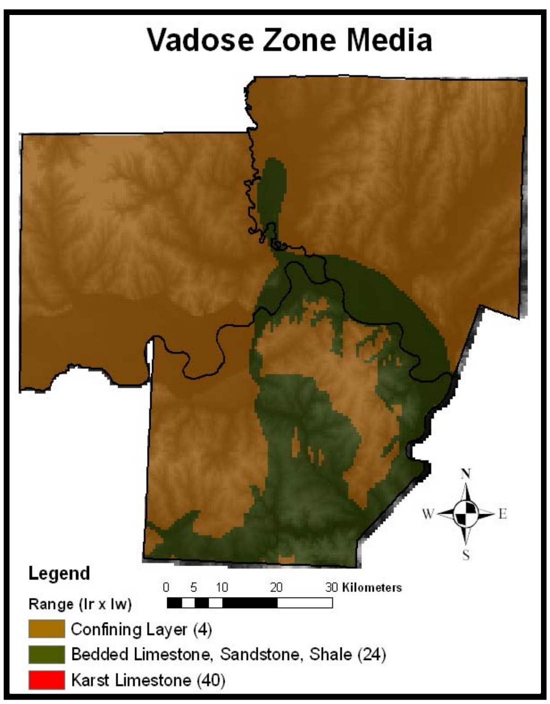
Range(% Slope)	Rating	Tr x Tw	% Area
0 – 2	10	30	21.94%
2 – 6	9	27	15.45%
6 – 12	5	15	20.26%
12 – 18	3	9	20.71%
18+	1	3	21.65%
Weight = 3			

Figure 5.7. Topography element of the Pesticide DRASTIC model. As the index value (Tr x Tw) increases, vulnerability increases. Source data: Geological Survey and Resource Assessment Division (GSRAD), Missouri Spatial Data Information Service (MSDIS)

The difference is in where a particular range category occurs. For the 0 to 2 percent slope range, the occurrences are concentrated within the major floodplain areas. At the other extreme, the over 18 percent slope category is most frequently observed adjacent to hydrologically connected drainage patterns. The three categories that comprise the 2 through 18 percent slope range are distributed throughout the remaining 56 percent of the study area (Figure 5.7).

Impact of the Vadose Zone Media

Lying between the soil horizon and water table, the type of media in this zone determines attenuation characteristics. The aquifer systems within the region are highly complex. The impact to bedrock aquifers and the potential for the transmission of groundwater between surficial and bedrock aquifers is accounted for in this element layer. A combination of available GIS and report data serve to define the Vadose Zone media for the study area (Figure 5.8). The Vadose Zone media is evaluated with 78 percent of the study area being controlled by a confining layer, which underlies alluvial and glacial till deposits. Where the confining Pennsylvanian layer, predominantly limestone and sandstone, is not represented (predominantly in Saline County), Mississippian age formations of limestone and shale (also partially overlain with alluvium and glacial till deposits) compose the remainder of the bedrock formation, accounting for 22 percent of the study area. Both the Pennsylvanian and Mississippian layers underlay the Missouri stream-valley aquifer. Minor occurrence of karst formations make up an insignificant portion of the remaining area (<0.01%). The confining layer (rating =1) is a low vulnerability index value (Ir x Iw) present in most of the study area. The remaining Mississippian aged formations are bedded limestone, sandstone, and shale and are moderately rated (6).

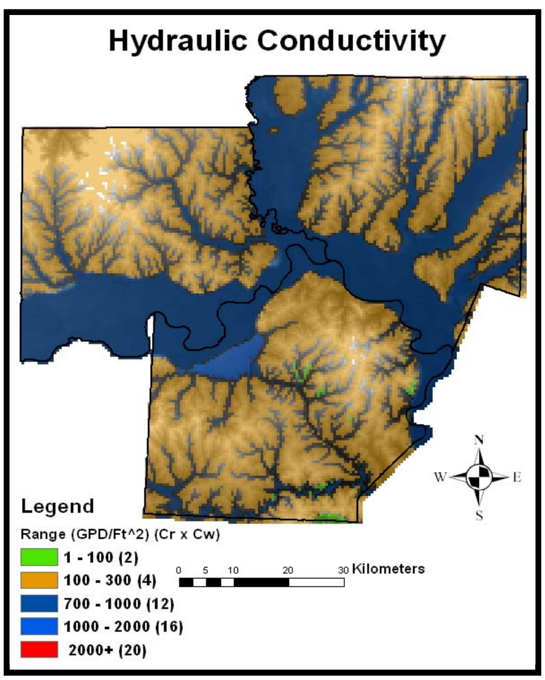


Range	Rating	Ir x Iw	% Area
Confining Layer	1(1)	4	77.68%
Silt/Clay	2-6	12	0%
Shale	2-5	12	0%
Limestone	2-7	24	0%
Sandstone	4-8	24	0%
Bedded Limestone, Sandstone, Shale	4-8 (6)	24	22.32%
Sand &Gravel with significant Silt &Clay	4-8	24	0%
Metamorphic/ Igneous	2-8	16	0%
Sand and Gravel	6-9	28	0%
Basalt	2-10	36	0%
Karst Limestone	8-10 (10)	40	<0.01%
Weight = 4			

Figure 5.8. Impact of the Vadose Zone Media. Data constructed from text and digital data. Source: Geological Survey and Resource Assessment Division GSRAD, Miller and Appel 1997

Hydraulic Conductivity of the Aquifer

The Hydraulic Conductivity is described in terms of aquifer material and its ability to transmit water for a given hydraulic gradient. The map for this final model element is a compilation of surface and bedrock geological features evaluated on a regional scale. Analysis of data from Imes (1985), Aller *et al*. (1987), and Imes and Emmett (1994) result in five categories of hydraulic conductivity index values (Cr x Cw) for all aquifers. A range of 100 to 300 gallons per day per foot squared (GPD/ft^2) is the most prevalent value covering 64 percent of the study area. This is followed by 35 percent of the area ranging from a relatively high 700 to 1000 GPD/ft^2 concentrated along the Missouri River floodplain and adjoining stream drainages. The remaining categories make up less than two percent of the area shown in Figure 5.9. Under the Pesticide DRASTIC model, high hydraulic conductivity is associated with high pollution potential (Aller *et al*. 1987).

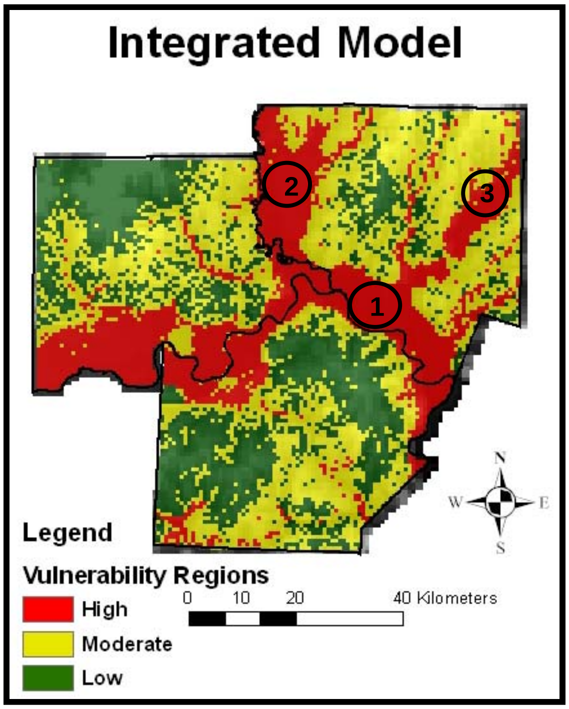


Range	Rating	Cr x Cw	% Area
1-100	1	2	0.89%
100-300	2	4	63.42%
300-700	4	8	0%
700-1000	6	12	34.69%
1000-2000	8	16	0.99%
2000+	10	20	<0.01%
Weight = 2			

Figure 5.9. Hydraulic Conductivity of the Aquifer element of the Pesticide DRASTIC model. As the index value (Cr x Cw) increases, vulnerability increases. Source: Imes 1985, Aller *et al*. 1987, and Imes and Emmett 1994

MODEL INTEGRATION

Combining the hydrogeological setting elements results in a range of numerical values termed the DRASTIC Index. Derived by combining the seven DRASTIC element index values, a range of values are developed that have been classified to represent groundwater vulnerability. These numbers are relative and have no intrinsic meaning other than in comparison with other like DRASTIC indices. Using the Pesticide DRASTIC index, a composite layer representing the study area has been created combining the grid files described in Figures 5.3 through 5.9. As the methodology indicates, statistical data grouping has been implemented in order to differentiate three categorical index ranges (High, Moderate, Low). Index values for this integrated model range from 58 to 221 and the distribution of the data in this model indicates that over 32 percent of the study area has high vulnerability (values 140 – 221). Moderately vulnerable areas (values 104 – 140) comprise nearly 39 percent of the area, and the least vulnerable areas (values 58 – 104) make up the remaining 29 percent of the total area. From Figure 5.10, the areas with the highest vulnerability can be visually evaluated to be concentrated within the Missouri River floodplain corridor (1) and adjoining Grand (2) and Chariton River (3) drainages. Moderate and low vulnerability areas can also be determined from this map. Given these results, the model that has emerged can be used as a tool for making decisions on where agricultural chemical applications pose the greatest potential for contaminating groundwater resources.



Index Range	Rating	% Area
140 – 221	High	32.14%
104 – 140	Moderate	38.89%
58 – 104	Low	28.98%

Figure 5.10. Integrated Pesticide DRASTIC model. Index values are a result of the pollution potential equation which adds each individual layer values to arrive at a composite score. Vulnerability regions are classified and depicted as High (Red), Moderate (Yellow), or Low (Green) vulnerability. The areas of highest vulnerability are the Missouri River floodplain corridor (1) and adjoining Grand (2) and Chariton River (3) drainages. Source data: Figures 5.3 through 5.9

The most critical hydrogeologic elements that contribute to groundwater vulnerability in this study are a combination of shallow depth to water, high net recharge, and topography with low percent slope. Using the same approach as with the integrated model on classifying the study area into high, moderate, or low vulnerability areas, each individual element in Figure 5.11 has been similarly classified to show how each element impacts the total combined model results. Depth to water values evaluated as moderate to high vulnerability make up 71 percent of this individual element. Additionally, moderate to high vulnerable areas make up 98 of the net recharge index and 78 percent for the topography element. Analysis of aquifer and soil media, the vadose zone, and hydraulic conductivity also show areas of elevated vulnerability over the three county area and combined with depth to water, net recharge, and topography produce an integrated model with 71 percent of the total area as either high or moderately vulnerable to contamination from agrochemicals.

PESTICIDE DRASTIC MODEL ELEMENTS

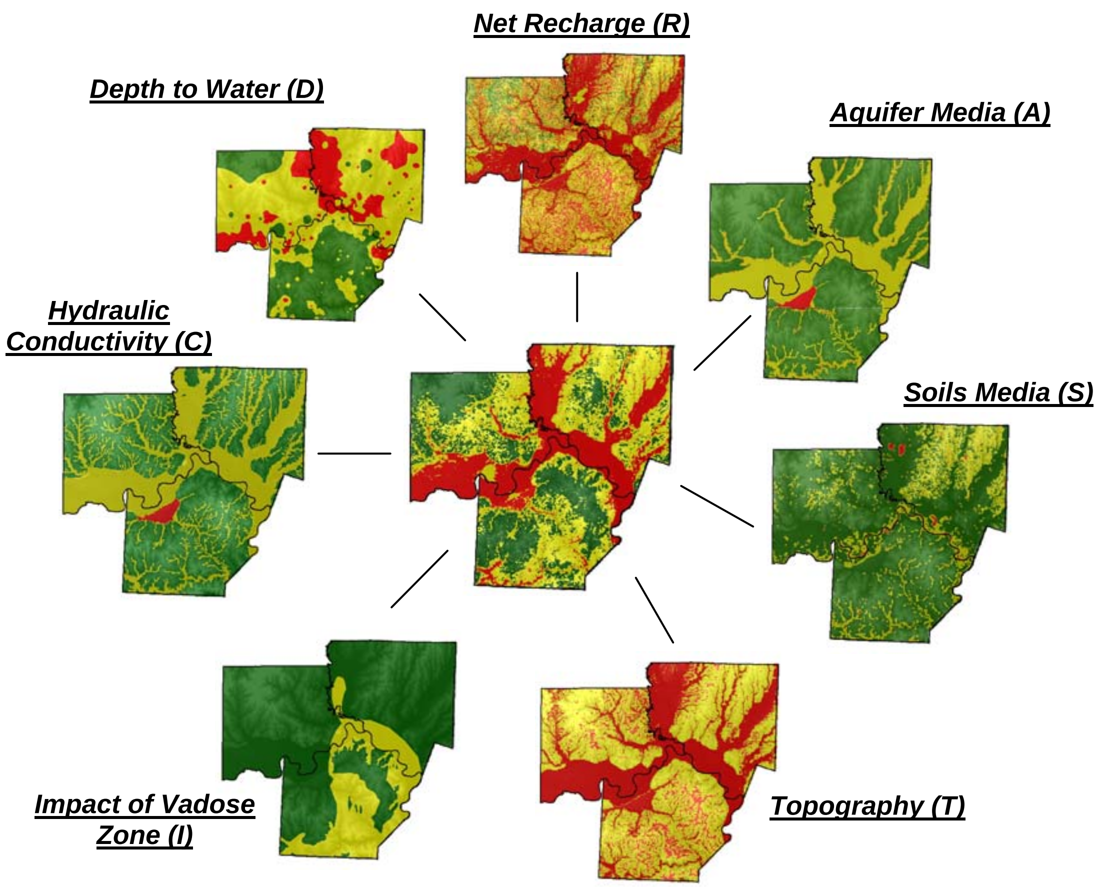
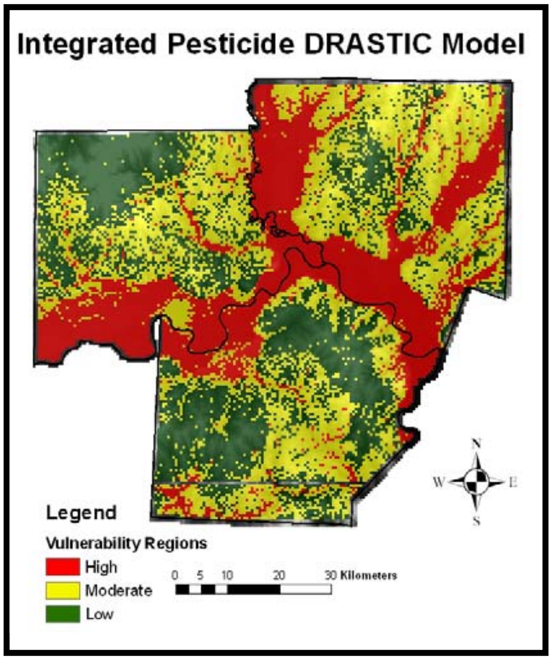


Figure 5.11. Seven elements are combined to form an integrated Pesticide DRASTIC model. Individually, each is classified into Low (Green), Moderate (Yellow), or High (Red) vulnerability areas to show the relationship between contributing elements.

MANAGEMENT IMPLICATIONS

Comparison of the Pesticide DRASTIC Model results with published land use and land cover data, contaminant detections, and wellhead locations creates an opportunity for landowners, agricultural producers, and natural resource and conservation agencies to make informed decisions as to the assessment of best management practices for maintaining the integrity of the natural ecosystem. A comparison analysis using a groundwater vulnerability map provides for a regional scale evaluation for supporting established environmental stewardship programs or for implementing adaptive management (Lee 1999) solutions.

In Figure 5.12, the resulting vulnerability map produced in this investigation of Carroll, Chariton, and Saline Counties, Missouri is used as a tool for comparing areas of groundwater vulnerability with a recent land use / land cover classification map. Visual interpretation of the areas evaluated as highly or moderately vulnerable to agrochemical contamination are clearly the same areas that are in agricultural production. This visual interpretation is supported by data which confirm that 78 percent of the study area is used as cultivated and/or non-cultivated cropland. Additionally, in 2002, USDA Census of Agriculture estimates indicate that for this area, 540,281 acres were treated with pesticides and 559,582 acres were treated with fertilizers (USDA 2005a, AgEBB 2005, MASS 2005). These values are of significance for the land manager when compared with the 71 percent of the total area calculated as either highly or moderately vulnerable to groundwater contamination from the application of chemicals used in agricultural production.



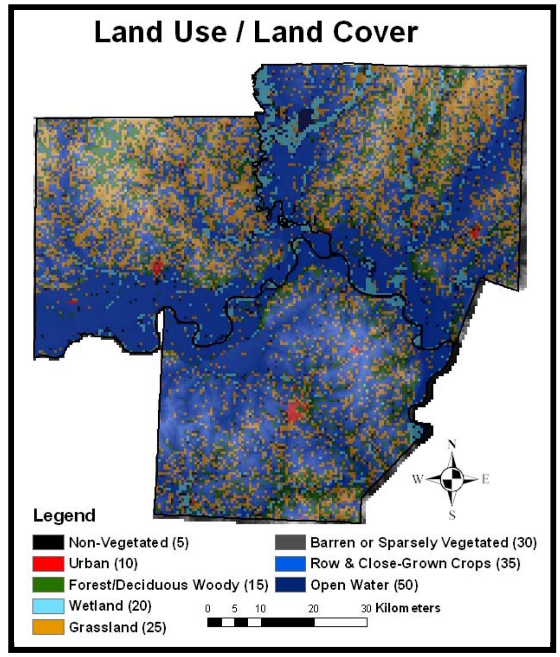


Figure 5.12. A comparison analysis of vulnerability regions with land use/land cover reveals that areas of greatest vulnerability are also areas of intensified agricultural production. Approximately 78 percent of the study area is in cultivated and/or non-cultivated cropland and 71 percent of the total area has either high or moderate vulnerability to contamination from agrochemicals. Data sources: Missouri Resource Assessment Partnership (MORAP), Missouri Spatial Data Information Service (MSDIS), AgEBB 2005, MASS 2006

A spatial analysis of potential groundwater vulnerability areas with documented wellhead, water distribution systems, and contaminant detections is another application of the groundwater vulnerability map. Figure 5.13 compares the integrated model results with drinking water wells and public water system treatment plants whose primary source is supplied from groundwater. The townships whose primary source of drinking water is groundwater are Bosworth, Carrollton, and Norborne in Carroll County, Keytesville, Brunswick, Salisbury, and Sumner in Chariton County, and Marshall and Slater in Saline County with a combined population of 23, 685 people. All other communities either purchase groundwater from these primary sources or purchase groundwater from outside of the study area. Only four communities acquire their drinking water from surface water sources.

By policy directive, contaminant data are compiled by the Missouri Department of Natural Resources (MDNR) inventory, assessment, and ongoing chemical detection programs which document 86 water well locations and nine primary groundwater treatment plants within the study area. Detections for this dataset reveal a chemical presence in 52 percent (45) of the water wells and 100 percent of the water treatment plants. Synthetic Organic Compounds (SOCs) are prevalent in private water supplies whereas only 13 detections of either Volatile Organic Compounds (VOCs) or nitrates are documented for public water wells. All of the water treatment plants have documented nitrate detections. These statistical data in the context of groundwater vulnerability show that of water wells that have a chemical presence, 51 percent fall within the high vulnerability category, 31 percent within the moderate vulnerability category, and 18 percent within a low vulnerability category. For all well locations regardless of chemical detections, 63 percent fall within the high vulnerability category, 27 percent fall within the moderate category, and only 10 percent fall within the low vulnerability category (Figure 5.13).

Susceptibility to contamination has also been documented by the MDNR and Center for Agricultural, Resource and Environmental Systems (CARES). This concept suggests that if a contaminant has been detected within a well, the system should be considered susceptible to future contamination and actions should be taken to reduce susceptibility. Susceptibility determinations also suggest that drinking water systems are vulnerable if producing aquifers are less than 100 feet below the surface. Of the public wells investigated, 68 percent have a total depth less than 100 feet. In all cases where data are available, the wells that are less than 100 feet are producing from aquifer material made up of glacial deposits or alluvium. Of the wells that are producing from aquifers deeper than 100 feet, only 23 percent are producing from geologic formations other than glacial deposits or alluvium.

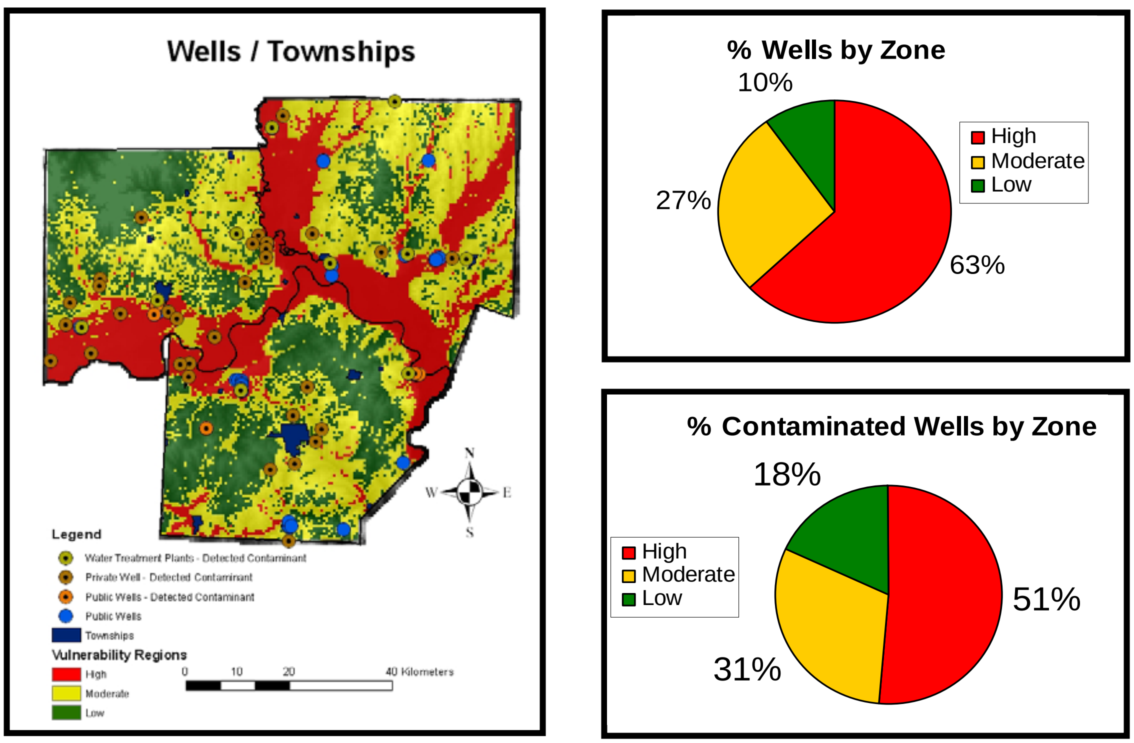


Figure 5.13. Water well, water treatment plant and township locations relative to vulnerability regions. Statistical data shows 90% of all drinking water sources fall within high or moderately vulnerable areas and 82% of wells that have contaminant detections fall within high or moderately vulnerable areas. Source: Missouri Department of Natural Resources (MDNR), Missouri Spatial Data Information Service **(**MSDIS)

These results demonstrate the application of coupling the Pesticide DRASTIC model with a GIS to create a groundwater vulnerability map. This analysis establishes a mechanism to assess vulnerability, and suggests implications regarding the impacts of current agricultural production practices in Carroll, Chariton, and Saline Counties, Missouri.

CHAPTER 6

DISCUSSION

Within the last half century, the contamination of groundwater resources from agrochemical applications has gained significant attention. Yet annually, tons of pesticides and nitrates continue to be applied to cropland. This investigation of groundwater vulnerability presents an analysis of three mid-Missouri counties that represent an agricultural production region that is physiographically and hydrogeologically complex. For nearly 200 years, the economic base of Carroll, Chariton, and Saline Counties, Missouri has been agriculture. Fertile soils and sufficient precipitation continue to support agrarian communities in this region, however, the desire to maximize yields by applying herbicides, insecticides, and fertilizers puts the ecosystem and local populations at risk for contamination as these chemicals infiltrate into the underlying groundwater system.

The National Research Council (1993) has addressed the complexities of evaluating the groundwater ecosystem and notes that: “Groundwater vulnerability assessment is a dynamic and iterative process that requires the cooperative efforts of regulatory policy makers, natural resource managers, and technical experts.” Aller *et al.* (1987) also inform researchers that assessing groundwater vulnerability to contamination requires a subjective evaluation of interacting hydrogeologic elements. Assessment modeling is an important tool and leverages the subjective interaction between hydrogeologic elements. The

DRASTIC model is a demonstration of assessment modeling using an index-based approach to groundwater vulnerability analysis.

THE HYDROGEOLOGIC-ANTHROPOGENIC SYSTEM

Interaction of Hydrogeologic Elements

The interaction of the DRASTIC elements is dependent on the hydrogeologic setting and “nature of the material present” (Aller *et al.* 1987). How a contaminant acts as it moves through a material enroute to groundwater resources is dependent on the characteristics of that material it comes into contact with. Layer thicknesses and structure (i.e., fracturing of bedding planes) are examples of characteristics that may vary and can potentially determine the absorption of a pesticide or rapid movement of a nitrate through the vadose zone. A loosely compacted vadose zone would be less likely to slow the movement of a chemical as it travels to a shallow depth to water. Similarly, the textural make-up of the soil horizon has the capacity to impact the hydraulic conductivity and attenuation based on grain size or degree of cementation between particles. Net recharge as well, as a function of precipitation, topography, and soil media interact and can determine the transport and dilution mechanisms of a contaminant. Therefore, in any given area, the characteristics of the hydrogeologic elements determine the potential for groundwater vulnerability.

In the case of this investigation, a complex aquifer sequence exists throughout the study area with both confined and unconfined aquifers present. A confining unit of Pennsylvanian aged formations is present in 78 percent of the study area, which in effect helps to protect the deeper bedrock aquifers from contaminant infiltration. Unconfined surficial aquifers overlie this confining unit and are the most vulnerable to non-point source contamination resulting from agricultural chemical applications. These surficial aquifers that consist of glacial and alluvial material, supply groundwater for domestic and commercial uses for the majority of residents within the study area and are the primary focus of planning and management implications of this study. Therefore, the system of hydrogeologic elements in this study is evaluated in terms of the unconfined aquifers rather than the deeper and highly mineralized bedrock aquifers. These unconfined surficial deposits determine the criteria for depth to water, aquifer media, and hydraulic conductivity rating values, evaluating these elements in terms of the glacial till, bedded lithologies, or sand and gravel deposits as distinguished from confined bedrock characteristics at greater depth. The appropriate adaptation to this, as similarly implemented in a previous Saline County study (Barnett 1998), is the vadose zone media element of the Pesticide DRASTIC model. Evaluating this element in terms of the confining unit rather than the glacial and alluvial overburden creates an analysis that highlights the interconnectivity between aquifers and the potential for contaminant infiltration by recharge from hydraulically connected lithologies where the confining unit is less prevalent. This variability creates a desired effect within the model that provides for relative differences in model grid values, within a GIS, that might otherwise be masked by rating the unconfined aquifer material according to a narrow range across the entire study area (Figures 5.8 and 5.11 demonstrate the separation of rating values). Conceptually, if the vadose zone were to be rated in terms of the glacial, alluvial, and bedded sequences, the values would lie between 4 and 9 (typical ratings would be 6 – 8; see Figure 5.8). This would result in raising all of the integrated model GIS grid values similarly and negating any significant impact of the vadose zone media in determining groundwater vulnerability regions based on this element. Alternatively, rating the vadose zone in terms of the existence of a confining unit (rating = 1) and bedded limestone, sandstone, and shale (rating = 6), yields a separation of values that highlights the relative differences in the media present. This provides for a greater vulnerability potential in the bedrock aquifers that are in contact with surficial aquifers as compared to bedrock aquifers totally confined, and is a superior approach for the representation of data in the study area. The NRC (1993) points out that uncertainty and subtle differences of obscure data are considered realities that require an in depth familiarity with the data for effective interpretation. The consideration of the interaction between hydrogeologic elements is summed up well by Aller *et al*. (1987): "Their selection [hydrogeologic elements] is based not on available data quantitatively developed and rigorously applied, but on a subjective understanding of "real world" conditions at a given area."

Augmentation and enhancements to the basic DRASTIC model have been incorporated by various investigators that address specific aspects or perceived deficiencies in vulnerability assessment (Merchant 1994). This has been demonstrated by Fritch *et al.* (2000) with a refinement of unconfined and confined aquifer parameters unique to the Central Texas hydrogeologic environment. Adjustments in other regions have been implemented by Secunda (1998) and Al-Adamat *et al.* (2003) with the development of an additional element (Lr x Lw) to characterize land use, and extending the DRASTIC Index (DI) in the modified form of: MDI = DI + Lr x Lw. Piscopo (2001) and Al-Adamat *et al*. (2003) also enhanced the net recharge element with the addition of soil permeability and slope. Al-Adamat *et al*. (2003) eliminates hydraulic conductivity entirely for lack of data. These measures demonstrate the subjectivity and flexibility of the DRASTIC model under varying hydrogeological circumstances and the potential for leveraging the strengths of a GIS to manipulate and display modeling alternatives.

Vulnerability and Groundwater Resources

Loague and Corwin (1998) state that: "One of the greatest challenges today is to quantitatively assess the vulnerability of precious groundwater at regional scales, as they are affected by the long term applications of agrochemicals that cover thousands of hectares." This statement is appropriate for the study area. Spatially distributed processes (e.g., degradation, attenuation) in an open system are influenced by the physical conditions of the media that precipitation comes into contact with as it travels from the surface to its subsurface destination. Potentials, rather than absolutes, are the essential characteristic of such a process. This is the case in the DRASTIC model where it is necessary to interpret the DRASTIC index relative to the hydrogeologic setting that controls groundwater movement and vulnerability. The intent of vulnerability maps produced by applying the DRASTIC model is to present a planning and management decision support tool. Subsequent model validation and site-specific applications should be verified in the field using the vulnerability map as a guideline. A high vulnerability rating does not necessarily mean that pesticides will be present in groundwater nor does a low vulnerability rating mean that pesticides will not be present. It is a “tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer” (NRC 1993). It is an assessment of processes that are taking place below the earth’s surface.

The vulnerability map produced in this study is classified into three categories (high, moderate, low) based on the evaluation of the hydrogeologic setting (Figure 5.1). A comparison of the DRASTIC vulnerability assessment with the groundwater contamination potential described by Miller and Vandike (1997) for the Northwestern and West-Central Groundwater Provinces, and Missouri River Alluvium Subprovince reveals similar results. High vulnerability exists in alluvial aquifers and low to moderate vulnerability exists for glacial drift aquifers. Low vulnerability is characteristic of deeper bedrock aquifers. Contaminant detections have been documented in all areas, however, surficial aquifers that exhibit shallow depth to water, high net recharge, and mildly sloping topography show a greater tendency toward a moderate or high vulnerability classification. High vulnerability in this study is found along the Missouri River floodplain corridor and adjoining Grand and Chariton River drainages as a result of these hydrogeological factors that dominate other model components. These areas are also impacted by the characteristics of hydraulic conductivity and the aquifer media present. Loam soils also contribute to moderate vulnerability in Chariton County and unconfined bedding of sedimentary rocks contribute to moderate vulnerability in Saline County. Lower vulnerability in the study area is attributed to a lower hydraulic conductivity rating outside of river or stream drainage areas, a deeper water table in northwestern Carroll County and much of Saline County, silty and clay loam soils predominantly in Carroll and Saline Counties, and the protective confining Pennsylvanian aged rocks for deeper formations in all areas.

Immediate beneficiaries of this data are landowners, agricultural producers, and natural resource and conservation agencies tasked with managing land and water resources. Decisions as to an appropriate mitigation strategy for protecting vulnerable areas can be developed when model indices show a particular area to fall within a region of potential contamination. A comparison analysis of land use / land cover with vulnerability mapping is an applied decision-making scenario and provides an opportunity to consider the groundwater implications of current agricultural production. Specifically, areas in Carroll, Chariton, and Saline Counties that are highly and moderately vulnerable to contamination from agricultural chemicals fall within the same areas that are subjected to intense agricultural production. Likewise, high and moderately vulnerable areas also contain a majority of water producing wells. Strategies to properly place and construct wells, and create protective buffer zones can help to mitigate the potential for contamination to infiltrate the water supply. The presence of a contaminant (i.e., pesticides and nitrates) along with a hydrogeologic profile that is conducive to susceptibility can increase the probability that a well becomes contaminated. Detections of pesticides and nitrates in wells documented by the MDNR are speculative as to whether the source is point or non-point contamination (the MDNR specifically issues a disclaimer of no warranty regarding the accuracy of collected data). For the purposes of this investigation, the reference to vulnerability is from non-point source contamination from agrochemicals. Results for well sites within the study area that have available chemical detection data, show that a majority are statistically susceptible to contamination, or have had a chemical detection documented. Additionally, a majority of all wells fall within highly vulnerable areas, and a majority of residents draw groundwater from these wells for potable water supplies.

Legislation and the Land

Federal, state, and local protections and incentives have been implemented via legislation and programs for the nation's groundwater resources (Appendix A). Major strategies in Missouri are described in published resources such as the State Water Plan, Non-point Source Management Plan, and Source Water Assessment Plan and there is considerable effort to address the issue of groundwater vulnerability at the state and local level through technical assistance and funding opportunities. It is an important finding of fact however, that control of non-point agricultural chemical contamination sources is a voluntary rather than regulated endeavor and solutions to resolve hazardous conditions fall to a discussion of best management practices. Therefore early detection, monitoring, and education are of paramount importance if impacted decision making managers are to make a difference in preservation and conservation efforts of groundwater resources.

Decision Support

Application of a GIS for data creation, manipulation, display, and analysis facilitates an effective and efficient decision support process. The coupling of the DRASTIC model with a GIS moves the decision support mechanism from a cumbersome, manually produced map overlay procedure that is limited in distribution by its physical character to a digitally available vulnerability mapping system that is accessible simultaneously to individuals or a team of researchers. Data may be stored and accessed by a single desktop computer or distributed widely across a network of computers. Collaborative solutions are enhanced by leveraging the full capabilities of technology, staff, and funding resources. Consensus building and stakeholder relationships are improved by refined techniques and the seamless integration of spatially distributed data that clearly display the multiple attributes of analytical models. In an excerpt from Johnston (1997) on the rationality of land use decisions, he describes several assumptions relevant to decision-making behavior of which the following is most pertinent:

> "Choices are made on the basis of knowledge. Only very rarely can decision-makers bring together all of the information relevant to their task, however, and they are frequently unable to assimilate and use all that is available."

With a GIS-based decision support process, there is an increased probability that better choices can be made with greater frequency, based on the superior assimilation capability of accumulated knowledge. From a systems analysis perspective, creating a decision support mechanism via spatial modeling of groundwater vulnerability contributes to the understanding of the relationship between hydrogeologic-anthropogenic system elements and the integrated environment in which they operate.

CHAPTER 7

CONCLUSIONS

The goals of this study have been to (1) provide a spatial analysis of the elements and conditions under which the groundwater of a three county region in central Missouri may become contaminated, and (2) to develop a model and decision support process for identifying particular portions of the study area that are vulnerable to agricultural chemical applications. To meet these goals a map has been created using the DRASTIC model and a GIS to represent groundwater vulnerability in Carroll, Chariton, and Saline Counties. Areas that have been classified as highly vulnerable represent over 32 percent of the study area. Moderately vulnerable areas comprise nearly 39 percent of the area, and the least vulnerable areas make up the remaining 29 percent of the total area.

As an applied problem, this work answers the original research questions in the affirmative: (1) There are portions of the study area that are vulnerable to groundwater contamination as identified by the application of the DRASTIC model, and, (2) the DRASTIC model output is correlated with measured patterns of contaminant data. Statistical data show 82% of wells that have documented contaminant detections fall within high or moderately vulnerable areas and that 90% of all drinking water sources fall within high or moderately vulnerable areas.

The National Research Council (1993) emphasizes that: “All groundwater is vulnerable.” Strategies for managing groundwater resources are thus best conceived in terms of prevention but are realistically often reactionary. Many groundwater environments are considered susceptible to contamination due to the hydrogeologic profile of an environmental setting or from chemicals already detected as a result of monitoring programs. Comprehensive protection strategies such as those outlined by the USEPA (USEPA 2006c) consider a combination of regulatory policy, technology, monitoring, research, and education approaches at the federal and state level. Prevention is preferred in lieu of the cost and difficulty of cleanup although remediation is often required.

In this study, raw spatial data have been analyzed and transformed into a decision support system that can be applied as a screening tool for ecosystem planning and management. When compared to land use data, the seven hydrogeologic model elements that are integrated to create a vulnerability map depict that the current agricultural practices are subjecting the region to a potential for contamination from non-point source agrochemical applications.

Groundwater vulnerability assessment models are not a sole source methodology for ecosystem management decisions, but are more appropriately used in the context of relative vulnerability leading to site specific evaluations. On a regional basis, areas evaluated as high, moderate, or low groundwater vulnerability are of sufficient detail for comparison with agroproduction land use practices and water supply systems to understand how a resident population may be broadly impacted. It is in this context that the GIS-based application in this research is successful as a predictor of relative groundwater vulnerability.

Within a decision support structure, vulnerability mapping can be used to prioritize chemical monitoring sites or establish specific protection areas (e.g., pesticide restricted areas or study area zoning), determine the location for well site surveys, allocate resources for restoration efforts, recommend best management practices for spatially distributed agroproduction, or encourage the development of chemical management plans and protection strategies for groundwater resources (Aller *et al*. 1987, NRC 1993). Looking beyond these potential uses, innovative new work in groundwater vulnerability studies have resulted in sophisticated GIS-based DSS modeling techniques that seek to leverage developing decision making concepts that include analytical hierarchy and fuzzy logic processes (Dixon *et al.* 2002, Thirumalaivasan *et al*. 2003). Commercial ventures have also found a niche market for groundwater flow and contaminant transport simulation models and are available from a variety of vendors.

Expanding the availability of resulting vulnerability maps produced by the application of the DRASTIC model within a GIS is a logical next step. The distribution of interactive maps and GIS data via the World Wide Web is currently being implemented using Internet Map Server (IMS) functionality. The advantage of this tool is that it provides a method for the public to view, query and analyze groundwater vulnerability mapping data about a particular area of interest without requiring specialized GIS skills (ESRI 2006). By making this type of digital information available, landowners, agricultural producers, and state and local agencies will be empowered to collaborate widely and make informed decisions regarding land management practices. It is envisioned that the availability of this kind of data would encourage agroproducers and landowners to take the initiative in finding solutions to groundwater contamination problems. This could take the form of conducting chemical tests on privately owned wells, moving from chemically intensive row crops in high vulnerability areas to low impact agricultural production, or participation in other land uses, such as enrolling cropland in the Conservation Reserve Program (CRP).

Coordination of groundwater management strategies at the local level requires a synthesis of technology, data, and a comprehensive integration of resources to be effective. Significant effort has been expended in counteracting the effects of groundwater contamination by creating wellhead protection programs, water quality standards through regulatory action, and conducting an inventory of known pollution contributors to sensitive ecosystems. Where data have been published, positive trends have resulted as demonstrated by the public wells in this study that show less prevalence of chemical detections than private wells. Work remains, however, in mitigating the causes of groundwater contamination. The USEPA (1999) in a congressional groundwater report noted three primary barriers to a more comprehensive approach to groundwater management. These consist of (1) groundwater programs that are fragmented between agencies with conflicting goals and priorities, (2) limited understanding of the impact of the hydrogeology on groundwater and contaminant behavior at the local and regional level, and (3) a lack of targeted funding for groundwater protection strategies. A groundwater vulnerability map, created in a distributed GIS environment, has the potential for resolving these barriers. A digital representation of vulnerability conditions can establish a point of reference from which comprehensive and preventative strategies can be created, an enhanced awareness of groundwater vulnerability communicated, and specific areas identified for targeted funding. The results of this study have provided this type of comprehensive approach by modeling the regional hydrogeologic profile and producing a geospatial structure from which areas that are sensitive to groundwater contamination from agrochemical applications can be analyzed and evaluated. Communicating these results to decision making managers is suggested via academic departments, research organizations, geospatial extension programs, and state and local agencies.

This research, founded on the implementation of the DRASTIC model via a GIS, has created a digital representation of a groundwater vulnerability map for Carroll, Chariton, and Saline Counties, Missouri. The immediate results warrant a cautionary approach to agrochemical applications in the areas depicted as highly and moderately vulnerable. This position is advocated in view of data that show a significant portion of acreage within the study area is being treated annually with pesticides and nitrates in the course of traditional agricultural production. Continued and expanded monitoring of non-point source contamination by targeted field surveys based on the vulnerability map presented in this study is strongly recommended with special consideration given to monitoring private, as well as public water wells. It is appropriate to consider groundwater vulnerability and the mobility of agrochemicals through the hydrogeologic profile in the context of decades. It is equally appropriate to act now to protect regional groundwater resources for future generations.

APPENDIX A
FEDERAL AND STATE LEGISLATION

FEDERAL LEGISLATION, PROGRAMS, AND PLANS

1) National Environmental Policy Act (NEPA) of 1969

Signed into law on January 1, 1970, the National Environmental Policy Act (NEPA) of 1969 (42 U.S.C. § 4321-4347) provides for an integrated environmental policy across federal agencies. Specifically, the Congressional Declaration of Purpose states:

> "The purposes of this chapter are: To declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man; to enrich the understanding of the ecological systems and natural resources important to the Nation; and to establish a Council on Environmental Quality."

The Council on Environmental Quality (CEQ) serves to liaison between federal agencies and the White House on environmental issues and policies. Established within the Executive Office of the President by Congress, the CEQ chair is the principal advisor to the President on environmental policy. Furthermore, the CEQ reports annually to the President on the state of the environment and oversees federal agencies that are required to assess, via environmental impact statements (EISs), federal actions that significantly affect the environment and alternatives to those actions. Federal agencies are required to assist in the implementation of preventive programs and initiatives relative to the decline in quality of environmental systems (CEQ 2005, USEPA 2005a).

2) Federal Water Pollution Control Act Amendments of 1972

Concern over the discharge of pollutants into the nation's water resources led to the enactment of the Federal Water Pollution Control Act Amendments of 1972. Commonly known as the Clean Water Act (CWA) as amended in 1977 (33 U.S.C. § 1251 et seq.), the basic infrastructure for regulatory action was established, giving the USEPA authority to implement pollution control measures for the discharge of contaminants in surface waters (USEPA 2006a).

Although the Act was implemented primarily as a provision to control point source pollution, there is recognition of the need to address the contamination potential from non-point sources of pollution as well recognizing that surface water is significant in replenishing groundwater. Section 106 and 319 of the Clean Water Act provides a mechanism for State, Territories, and Indian Tribes to receive federal assistance funding and support activities relative to non-point source management programs. The USEPA specifically cites fertilizers, herbicides, and insecticides from agricultural lands as non-point pollution sources that are, in addition to lakes, rivers, wetlands, and coastal waters, finally deposited in our underground sources of drinking water.

Section 106(e) of the CWA requires that all states, tribes, territories, and jurisdictions monitor, compile, and analyze data on the quality of their water and report their findings every two years to the USEPA. Assessment criteria of water quality conditions are described in section 305(b) of the CWA and is summarized by the USEPA and presented as the National Water Quality Inventory. A Ground

Water Quality assessment is included as part of the 305(b) report (USEPA 2003, USEPA 2005b, USEPA 2005c).

3) Safe Drinking Water Act (SDWA) of 1974

Passed by Congress in 1974, the intent of the SDWA (42 U.S.C. § 300f et seq.) has been to ensure the safety of the public health and the nation's drinking water supply through regulatory action. The USEPA is authorized by the SDWA to set health-based standards and protect against contaminants found in drinking water. The types of threats identified are both naturally occurring and man-made contaminants, including chemicals applied in agricultural production (USEPA 2005d).

Enhancing the law in the 1996 amendment, the concept of "source to tap" protection expanded the focus of the SDWA beyond treatment of distribution systems by the recognition that public awareness, funding for system improvements, trained operators, and source water protection were required in order to manage the quality of drinking water. As overseer of the nation's drinking water supply and state drinking water programs, the USEPA sets standards and testing requirements, provides guidance and assistance, conducts inspections, and implements corrective action when necessary in order to ensure water systems are in compliance with the established law. The national drinking water standards are three-fold:

1) Based on peer-reviewed science, identify contaminants that may occur in drinking water and affect public health.

2) Determine a Maximum Contaminant Level Goal (MCLG) for contaminants. This is the level below which there are no known or expected health risks.

and

3) Specify a Maximum Contaminant Level (MCL) which is delivered to any user of a public water system (USEPA 2005d, USEPA 2005j)

There are two categories of drinking water standards that have been established by the USEPA. 1) The National Primary Drinking Water Regulations are legally enforceable standards that limit levels of contaminants that can be found in public water systems. Primary standards protect public health. 2) The National Secondary Drinking Water Regulation is a non-enforceable guideline. Under this secondary standard, cosmetic and aesthetic effects are considered (e.g., tooth discoloration or taste). Each state may choose to adopt a secondary standard as an enforceable standard.

A third category of contaminants are unregulated. This category is known or anticipated to occur in the public water supply but does not currently meet the criteria for being regulated. Unregulated contaminants are prioritized for research and data collection (USEPA 2002).

Assessments must be conducted in order to identify potential vulnerability of water systems to contamination. Standards that are not being met are legally enforceable. Water suppliers are required to provide annual consumer confidence reports on the source and quality of their tap water that are compiled and summarized by the states and USEPA. These reports are made available to the public (USEPA 2005d).

Source water is defined by the USEPA as “untreated water from streams, rivers, lakes, or underground aquifers which is used to supply private wells and public drinking water.” Threats to source water include microbial, inorganic, pesticides and herbicides, organic chemical, and radioactive contaminants (USEPA 2005e). Source water protection is addressed in the 1996 amendment of the SDWA. Specific sections that address assessment and funding mechanisms for the protection of source water are set forth as follows (USEPA 1996):

- **Section 1414**: Consumer Confidence Reports
- **Section 1428**: Wellhead Protection Program
- **Section 1429**: State Ground Water Protection Programs
- **Section 1453**: Source Water Assessment Programs

Source water assessment and pollution prevention are of particular importance relative to the issue of groundwater vulnerability. Sections 1453 and 1428 of the SDWA 1996 amendment provide guidance for the development and linkage of state Source Water Assessment and Wellhead programs. The assessment, as intended by Congress, is to provide three fundamental steps as part of a full prevention program: “delineating the source water protection area, inventorying the significant potential sources of contamination, and understanding the susceptibility of the source waters of the Public Water Systems to contamination.” The results of these steps are to be made available to the public

(USEPA 2005e, USEPA 2005f, USEPA 2005g). Action to protect source water resources have been taken at the federal, state, and local levels. The collective efforts of this action may be found across a network of organizations and legislative programs. Within these programs, authorities, financial support, and technical assistance are made available to protect sources of drinking water, especially groundwater (USEPA 2005e, USEPA 2005f).

Reporting requirements under the SDWA are found under section 1428 and 1429. The Wellhead Protection Program Biennial Report (section 1428) has covered periods from 1991 to 1999. Subsequent reporting is in the context of annual source water protection measures rather than a stand-alone report. The Ground Water Report to Congress (section 1429) is required every three years. The intent of section 1429 is to report to Congress on the quality of groundwater and to evaluate the effectiveness of funded State programs (USEPA 1997a, USEPA 1999).

4) Farm Security and Rural Investment Act of 2002 (2002 Farm Bill)

The U.S. Department of Agriculture administers, through the Natural Resources Conservation Service, the 2002 Farm Bill (P.L. 171-170) providing farming and ranching enterprises with incentives for managing environmental challenges through conservation funding programs. Many of the Farm Bill programs have the capacity to directly impact the decision management options available to private landowners by providing financial and technical assistance for maintaining healthy and productive natural resources. The conservation provisions relevant to the study area that are directly impacting to the management of groundwater resources are embodied in the following programs:

- **Environmental Quality Incentives Program (EQUIP)**

  The goal of the Environmental Quality Incentives Program (EQUIP) is to promote both agricultural production and environmental quality. Its provisions provide for financial and technical assistance to farmers and ranchers for mitigating threats to soil, water, air, and related natural resources. EQUIP seeks to optimize environmental benefits that have been prioritized nationally. In addition to priorities to improve air quality standards, reduce soil erosion and sedimentation, and promote the conservation of habitat for at-risk species, the reduction of non-point sources of pollution qualify for assistance. This includes nutrients, sediment, pesticides, and excess salinity in impaired watersheds. Groundwater contamination and the conservation of ground and surface water resources fall within this category as a special initiative through EQUIP (NRCS 2004a).

- **Conservation Security Program (CSP)**

  Farmers and ranchers who are managing private agricultural lands and are engaged in conservation and environmental practices are eligible for financial and technical support for the maintenance of conservation stewardship and the implementation of additional conservation enhancement measures. This is a program that rewards those who have a history of meeting high standards for conservation and environmental management and provides incentives for continued improvements (NRCS 2005).

- **Grassroots Source Water Protection**

  The Grassroots Source Water Protection program authorizes an annual appropriation for state rural water associations to utilize technical capabilities for the operation of a well-head or groundwater protection program (NRCS 2002a).

Programs that have the potential for indirectly influencing the quality of groundwater by contributing to the conservation of related natural resource elements include the:

- **Resource Conservation and Development Program (RC&D)**

  The objective of the Resource Conservation and Development Program (RC&D) is to provide “quality of life” improvement opportunities through resource conservation and community development. This program provides assistance to local elected and civic leaders in initiating and implementing projects that lead to a sustainable community, prudent land use, and the effective management of natural resources. The eligibility criteria specifies “land conservation, water management, community development and land management elements” as falling within program parameters (NRCS 2004b).

Other programs which do not mention water as an element of the legislation but nevertheless may indirectly benefit groundwater quality are the Grassland Reserve Program and Wildlife Habitat Incentives Program. These programs provide for land use and land cover alternative that may otherwise be converted to cropland. Finally, partnerships and cooperation are encouraged through the National Natural Resources Conservation Foundation (NNRCF). A nonprofit organization established by Congress, the Foundation is authorized to accept tax deductible funding from the private sector for the promotion of innovations that conserve natural resources on private land (NRCS 2002b, NRCS 2004c, NRCS 2004d).

5) Conservation Reserve Program (CRP)

Administered by the Commodity Credit Corporation through the Farm Service Agency, this program is supported by the NRCS, Cooperative State Research and Education Extension Service, state forestry agencies, and local Soil and Water Conservation Districts (USDA 2005b). The Conservation Reserve Program (CRP) provides technical and financial assistance to promote soil and water conservation by converting highly erodable cropland, or other acreage that may be sensitive to environmental impairment, to vegetative cover. This may be achieved by establishing tame or native grasses, wildlife plantings, trees, filter strips, or riparian buffers. Among the benefits are reduced soil erosion, reduced stream and lake sedimentation, and the establishment of wildlife habitat. The potential for the improvement in water quality is included as a beneficial part of this program (USDA 2005c).

6) National Water Quality Assessment (NAWQA) Program

The U.S. Geological Survey (USGS) through the National Water-Quality Assessment (NAWQA) Program monitors, assesses, and reports on the quality of the nation's surface and groundwater resources. The chemical and biological information collected and analyzed, on more than 50 major river basins and aquifers, is the primary source of data used for long-term decision support functions. The major river basins and aquifer systems which make up study units, frequently cross state boundaries and typically are comprised of an area in excess of 10,000 kilometers squared (approximately 3,900 miles squared). Assessments conducted under the NAWQA program provide a scientific baseline on the occurrence of contaminants relative to hydrogeologic conditions and human activities on a nationwide scale (USGS 2005).

7) Comprehensive State Ground Water Protection Program

The intent of the Comprehensive State Ground Water Protection Program, to form a partnership between states and the USEPA, originates from the identification of over 30 categories of potential sources of groundwater contamination, considered threatening to drinking water and other beneficial uses. In overview of the program, the USEPA asserts that:

> "The specific goals are to prevent contamination and to consider use, value, and vulnerability in setting priorities for both prevention and remediation."

Flexibility, efficiency, and effectiveness in executing state programs and the clear delineation of relationships with federal agencies are further opportunities for success incorporated within this program. The preferred strategy under this program is prevention as a mitigation technique as opposed to expensive and time consuming remediation efforts. The process recommended is fully compatible with an approach using the DRASTIC model as a decision support mechanism as evident from the following statement (USEPA 1997b, USEPA 2005i):

> "Always use resource-oriented decision making based on vulnerability, uses, and the benefits to be expected from the decision in coordination with other programs."

<u>STATE LEGISLATION, PROGRAMS, AND PLANS</u>

1) Missouri Clean Water Law

The provisions of the Missouri Clean Water Law (RSMo 644.006-644-141) create, under the authority of statute 644.021, a Clean Water Commission (10 CSR 20-1.010 - 20-14.030). The responsibility of this commission is to:

> "Develop Missouri's Water Quality Standards, 10 CSR 20-7.031; Develop Missouri's list of impaired waters, 303(d) List; issue permits limiting the discharge of pollutants into the state's waters; take enforcement action against those who violate the Missouri Clean Water Law and implementing regulations; certification of operators of municipal wastewater facilities and the largest Concentrated Animal Feeding Operation waste management systems; oversee financial assistance to protect and preserve water quality; develop the Non-point Source Management Plan outlining Missouri's approach to addressing non-point problems; maintain a 303(e)Continuing Planning Process that brings together and coordinates all aspects of water pollution control in an effort to assure the state maintains progress toward protecting and preserving water quality."

Within these responsibilities, the mandate to address non-point sources of pollution and the overall preservation of water quality are the most significant relative to the potential for groundwater contamination to occur from the application of agricultural chemicals.

2) Non-point Source Management Plan

In response to the Section 319 requirement of the Clean Water Act, the Missouri Clean Water Law, and the USEPA, a Non-point Source Management Plan (NSMP) has been developed by the Missouri Department of Natural Resources (MDNR) with the goal of protecting and restoring impacted waters from non-point sources of pollution. Non-point source (NPS) pollution, as characterized by the MDNR and USEPA:

> "…results when water runs over land or through the ground, picks up natural and human-made pollutants, and deposits them into rivers, lakes, and coastal waters or groundwater."

and

> "Non-point source pollutants are substances of widespread origin that run off, wash off, or seep through the ground, eventually entering surface waters or groundwater. Non-point source pollution results from diffuse sources rather than from discharge at a specific location (such as the outfall pipe from a sewage treatment plant), and the greatest loads of NPS pollution often are associated with a few heavy storm events spread out unpredictably over the year."

The enactment of Section 319 has made available to the states a significant funding mechanism through grants to establish, implement, and support a program for maintaining a standard for water quality and the expectation that there will not be a degradation of that quality. The stated mission of the program is to "preserve and protect the quality of the water resources of the state from NPS impairments." In order to accomplish this, three goals have been set::

A) "Continue and enhance statewide quality assessment Processes to evaluate water quality and prioritize watersheds affected by NPS pollution."

B) "Improve water quality by implementing NPS-related project and other activities."

C) "Maintain a viable, relevant, and effective Non-point Source Management program with the flexibility necessary to meet changing environmental conditions and regulations."

Non-point sources of pollution are prioritized by the state. Agricultural, as one of the state's largest industries with 65 percent of total land area in farms, receives the top priority followed by urban and mining concerns. Primary agricultural pollutants are sediment, fertilizer, pesticides, and animal waste. The NPS program emphasizes a broad-based approach to watershed management and pollution prevention integrating multiple programs, including groundwater and pesticide management, to protect and restore water quality. While much of the emphasis is technical, effective distribution of regional information and efforts to educate stakeholders on NPS pollution are recognized as necessary components of NPS projects.

The assessment and monitoring of water quality is the cornerstone of a functioning NPS program. Data from a fixed chemical monitoring network and interagency data sharing are key components for understanding the effects of NPS pollutants originating from cropland and mixed cropland and pasture areas (MDNR 2004a, MDNR 2005c, MDNR 2005d).

3) Water Quality Report (305(b))

In keeping with the assessment criteria of section 305(b) of the federal Clean Water Act and Missouri Clean Water Law, Missouri's Water Quality Report is published every two years summarizing water quality issues and the degree of progress in water quality management efforts. It is stated within the 2004 report that:

> "Authority for enforcement of the Missouri Clean Water Law and for state regulations concerning water pollution resides with the Department of Natural Resources, Water Protection and Soil Conservation Division. Authority for the regulation of pesticides rests with the Missouri Department of Agriculture."

however,

> "Control of non-point water pollution sources such as runoff from farms, cities, mining areas and construction sites is still essentially a voluntary program…Control of many non-point sources, such as agricultural erosion from cropland and pasture, runoff of fertilizer, pesticides and animal waste, are addressed by Missouri's voluntary non-point source management program. This program works with federal, state and local governments, universities, private groups, and individual landowners to implement watershed projects that employ non-point source control practices and often monitor water quality results…Programs with dedicated funding sources have worked best."

Heavily relied upon as a source of drinking water, groundwater protection measures, monitoring, and educational programs are emphasized within this report. A descriptive background of groundwater resources, well construction, potable aquifers, and major contamination sources (listing pesticides and nitrates as within the 10 highest priorities) provide a high level view of assessment results. (MDNR 2004b, MDNR 2005e).

4) Missouri Water Resources Law

The legislative mandates for the management of water resource for the State of Missouri are found within the Missouri Water Resource Law statute (RSMo 640.400 to 640.435). It is under the "Citation of Law" (RSMo 640.400.2) that the Department of Natural Resources is charged with the following directive:

> **"**The department shall ensure that the quality and quantity of the water resources of the state are maintained at the highest level practicable to support present and future beneficial uses. The department shall inventory, monitor and protect the available water resources in order to maintain water quality, protect the public health, safety and general and economic welfare."

To support this directive, the establishment of an Inter-Agency Task Force (IATF), to collaborate on matters related to surface and groundwater (RSMo 640.430), and an annual report (RSMo 640.426), describing departmental progress and the accomplishment of its objectives, are required.

The specific sections that address the establishment of state programs and plans applicable to the analysis of groundwater are described in several sections:

- **Section 640.409**: Surface and groundwater monitoring program, duties of department, purpose.
- **Section 640.409.3**: Identification of areas highly vulnerable to contamination.
- **Section 640.412**: Inventory to be maintained on ground and surface water uses, quantity and users.

- **Section 640.415**: State water resource plan to be established for use of surface and groundwater--annual report, contents--powers of department.

The mechanisms for achieving the objectives of the water resource law as it relates to groundwater are found in a collection of ongoing studies and programs that include water inventory and use, groundwater monitoring, water well construction and consumer confidence reporting (MDNR 2003a, MDNR 2005f, MDNR 2005g). Additionally, the State Water Plan and Source Water Assessment and Protection programs satisfy departmental accountability to the law as well as providing analytical detail that is directly relevant to the study of groundwater vulnerability to agricultural chemical applications (MDNR 2000, MDNR 2004c, MDNR 2005g).

5) *State Water Plan*

Directed by the Missouri Water Resources Law (RSMo 640.415), the Department of Natural Resources is charged with the development of a state water plan to, among other interest areas, provide for the long-range use of groundwater resources in terms of drinking water, agriculture, and environmental protection. A phased approach has been executed to comply with this directive. Phase I consists of a series of technical assessments to serve as a baseline source of information on Missouri's water resources. A specific report by Miller and Vandike (1997) provides an assessment of seven groundwater provinces in terms of quantity and quality. Phase II is focused on water usage and the problems that confront issues with drinking water quality, agriculture, industry, recreation, and the protection of the environment (MDNR 1998). Phase III is the project plan which incorporates background information, stakeholder participation, and an approach for successful implementation of defined objectives (MDNR 2005h, MDNR 2005i).

6) ***Source Water Assessment Program (SWAP)***

As required under the Safe Drinking Water Act, sections 1453 and 1428(b), the Missouri Department of Natural Resources has developed a plan for source water assessment. The assessment is based on the evaluation of over 3800 active or proposed public wells in conjunction with another 600 inactive public wells. The methodology for the assessment of groundwater as source water is provided for under the Missouri Wellhead Protection Program to include the hydrogeologic information collected for each well (MDNR 2005g). The source water assessment is based on a 10-year time-of-travel area for groundwater movement. With public water supply wells as the mechanism for source water evaluation, it is noted that “the risk of contamination varies greatly, depending on well construction, well location, aquifer type and depth, and many other factors.” It is also affirmed that:

> “The wellhead areas delineated under this project will be crude estimates of the actual well recharge areas. Missing data for certain wells and unseen geologic factors prevent exact delineation of each recharge area without exhaustive data collection and costly study of each well or group of wells. The source water areas delineated under this project will be used for the purpose of completing source water assessments and as guides for communities interested in source water protection. The Department makes no claim that these are the actual recharge areas, and may amend any source water area as new data or delineation methods become available.”

The Missouri Department of Natural Resources Source Water Assessment Program identifies eight groundwater provinces throughout the state and ranks each in terms of susceptibility based on its hydrogeologic characteristics. Aquifers that are not isolated from the effects of surface activities are considered more susceptible to contamination as are the wells that are producing from them. Using this approach, water quality analyses are prioritized. The ranking of the groundwater provinces as taken from the SWAP documentation are as follows:

1) Unconsolidated shallow alluvial and glacial drift aquifers (Mississippi and Missouri River alluvium, Bootheel alluvium, glacial drift excluding drift-filled preglacial valleys)
2) Springfield Plateau (Springfield Plateau aquifer)
3) Salem Plateau (Ozark aquifer)
4) St. Francois Mountains (St. Francois aquifer where unconfined, igneous rock aquifers)
5) Springfield Plateau (Ozark aquifer, St. Francois aquifer)
6) Drift-filled preglacial valleys in northern Missouri
7) Osage Plains (Springfield Plateau aquifer, Ozark aquifer)
8) Southeast Lowlands (Wilcox and McNairy aquifers)"

Of these eight provinces, numbers 1, 2, 5, and 6, exist within the study area. These groundwater provinces correspond to the description of regional aquifer characteristics found in Chapter II of this thesis (MDNR 2000a).

7) Source Water Inventory Project (SWIP) and Vulnerability Assessment (VA) Project

Following the guidelines presented within the state Source Water Assessment Program, the Missouri Department of Natural Resources initiated and implemented a Source Water Inventory Project (SWIP) to identify potential sources of contamination to public drinking water. The Center for Agricultural, Resource and Environmental Systems (CARES) at the University of Missouri – Columbia has performed this function. On-site data collection and contaminant database development have been the focus of the project for both surface and groundwater systems. The threats considered were microbial, inorganic, pesticide and herbicide, organic chemical (including synthetic and volatile organic chemicals) and radioactive contaminants. A final report was issued in January of 2004, however, databases continue to be updated. Contained within this project is information carried over from the Vulnerability Assessment project, originally initiated in response to the SDWA requirement for routine monitoring of chemical contaminants that impact the public water supply. The VA project concluded in June of 2003 (MDNR 2000b, MDNR 2003b, MDNR 2005j).

8) Agricultural Non-point Source (AgNPS) Special Area Land Treatment (SALT) Program

Administered through the Missouri Department of Natural Resource's Soil and Water Conservation Program, the Agricultural Non-point Source (AgNPS) Special Area Land Treatment (SALT) Program seeks to mitigate water quality problems from agricultural non-point source pollution. This can be accomplished at the county level through technical and financial services available to landowners from the soil and water conservation districts (SWCD). The AgNPS SALT program addresses nutrient loading and excessive pesticide application concerns from a watershed-based approach. Eligible practices and incentives for excessive nutrient loading and pesticide applications are provide on a 75% cost-share basis (MDNR 2005k).

APPENDIX B
AGROCHEMICAL CONTAMINANT LIST

Chemical Common Name	Category	Trade Name or Synonyms	County	MCL or (mg/L)[2]	Potential health affects from exposure above the MCL	Common sources of contaminant in drinking water
2,4-D	Regulated SOCs	2,4-Dichlorophenoxyacetic acid, Hedonal, Landmaster, Trinoxol, Weedmaster	Carroll	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops
Alachlor	Regulated SOCs	Alanex, Bullet, Freedom, Lariat,Lasso, Metachlor	Carroll	0.002	Eye, liver, kidney or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops
Atrazine	Regulated SOCs	AAtrex, Bicep, Bullet, Lariat, Marksman, Primatol A	Carroll, Saline	0.003	Cardiovascular system or reproductive problems	Runoff from herbicide used on row crops
Carbaryl	Unregulated SOCs	Sevin, NAC, Denepan, Dicarbam	Carroll, Chariton, Saline	1.0(Advisory)	Observed to cause cholinesterase inhibition, and reduced levels of this enzyme in the blood cause neurological effects.	Insecticide
Carborfuran	Regulated SOCs	Bay 70143, Crisfuran, Furacarb	Carroll	0.04	Problems with blood, nervous system, or reproductive system	Leaching of soil fumigant used on rice and alfalfa
Metribuzen	Listed Pesticides, Listed SOCs	Canopy, Lexone, Preview, Sencor	Carroll, Chariton	NA	There is little information on the adverse health effects of metribuzin exposure to humans.	Runoff from herbicide

Source: USEPA (http://www.epa.gov/safewater/hfacts.html); CARES (Source Water Assessment Plan)

APPENDIX B (Continued)
AGROCHEMICAL CONTAMINANT LIST

Nitrate	IOC	NA	Carroll, Chariton, Saline	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome	Runoff from fertilizer use; leaching from septic tanks; sewage; erosion of natural deposits
Simazine	Regulated SOCs	Amazine, Aquazine, Pathclear, Primatol S, Princep, Simanex	Carroll	0.004	Problems with blood	Herbicide runoff
2,4,5-TP Silvex	Regulated SOCs	2,4,5-Trichlorophenoxyacetic acid, propanoic acid	Carroll, Chariton	0.05	Liver problems	Residue of banned herbicides
Heptachlor	Regulated SOCs	Drinox H-34, Heptamul, Heptox, Velsicol-104	Carroll	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide
Heptachlor epoxide (HCE)	Regulated SOCs	Drinox H-34, Heptamul, Heptox, Velsicol-104	Carroll	0.0002	Liver damage; increased risk of cancer	Breakdown of heptachlor
3-Hydrocarbofuran	Unregulated SOCs	hydrolyzed carbofuran	Carroll	NA	Degrade form of Carbuforan	Degrade form of Carbuforan
Cyanazine	Listed Pesticides	Bladex, Extrazine, Cynex	Carroll, Chariton, Saline	NA	May pose a risk of inducing cancer in humans from dietary, occupational, and residential exposure.	Herbicide runoff. USEPA accepted cancellation of technical and end use pesticide products containing cyanazine pursuant to agreements by the registrants.

Source: USEPA (http://www.epa.gov/safewater/hfacts.html); CARES (Source Water Assessment Plan)

APPENDIX B (Continued)
AGROCHEMICAL CONTAMINANT DEFINITIONS

2,4-D	2,4-D is a colorless, odorless powder used as a herbicide for the control of broad-leaf weeds in agriculture, and for control of woody plants along roadsides, railways, and utilities rights of way. It has been most widely used on such crops as wheat and corn, and on pasture and rangelands.
2,4,5-TP Silvex	2,4,5-TP is a white organic powder with little odor. Its use has been banned since 1985. The greatest use of 2,4,5-TP was as a postemergence herbicide for control of woody plants, and broadleaf herbaceous weeds in rice and bluegrass turf, in sugarcane, in rangeland improvement programs, on lawns. Aquatic uses included control of weeds in ditches and riverbanks, on floodways, along canals, reservoirs, streams, and along southern waterways.
3-Hydrocarbofuran	Hydrolized Carbofuran.
Alachor	Alachlor is an odorless, white solid. The greatest use of alachlor is as a herbicide for control of annual grasses and broadleaf weeds in crops, primarily on corn, sorghum and soybeans. Alachlor is the second most widely used herbicide in the United States, with particularly heavy use on corn and soybeans in Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, and Wisconsin.
Atrazine	Atrazine is a white, crystalline solid organic compound. It is a widely used herbicide for control of broadleaf and grassy weeds. Atrazine was estimated to be the most heavily used herbicide in the United States in 1987/89, with its most extensive use for corn and soybeans in Illinois, Indiana, Iowa, Kansas, Missouri, Nebraska, Ohio, Texas, and Wisconsin. Effective in 1993, its uses were greatly restricted.
Carbaryl	Carbaryl is a wide-spectrum carbamate insecticide which controls over 100 species of insects on citrus, fruit, cotton, forests, lawns, nuts, ornamentals, shade trees, and other crops, as well as on poultry, livestock and pets. It is also used as a molluscicide and an acaricide. Carbaryl works whether it is ingested into the stomach of the pest or absorbed through direct contact. The chemical name for carbaryl is 1- naphthol N-methylcarbamate.
Carborfuran	Carbofuran is a broad spectrum carbamate pesticide that kills insects, mites and nematodes on contact or after ingestion. It is used against soil and foliar pests of field, fruit, vegetable and forest crops. Carbofuran is available in liquid and granular formulations (5, 25, 27, 28).

Source: USEPA (http://www.epa.gov/safewater/hfacts.html); CARES (Source Water Assessment Plan)

APPENDIX B (Continued)
AGROCHEMICAL CONTAMINANT DEFINITIONS

Cyanazine	Cyanazine is a triazine herbicide used as a pre and postemergent to control annual grasses and broadleaf weeds. By 1985 ninety-six percent of cyanazine was used on corn, three percent on cotton, and less than one percent on grain sorghum and wheat fallow (7).
Heptachlor and Heptachlor epoxide (HCE)	Heptachlor is a white to tan waxy organic solid with a camphor-like odor. The epoxide is formed from heptachlor in the environment. It was once used as a non-agricultural insecticide. Most uses of the product were canceled in 1978. The only permitted commercial use of heptachlor products is for fire ant control in buried, pad-mounted electric power transformers, and in underground cable television and telephone cable boxes.
Metribuzen	Metribuzin is a selective triazinone herbicide which inhibits photosynthesis. It is used for control of annual grasses and numerous broadleaf weeds in field and vegetable crops, in turfgrass, and on fallow lands. Metribuzin is available as liquid suspension, water dispersible granular, and dry flowable formulations (2, 17).
Nitrate	Nitrates and nitrites are nitrogen-oxygen chemical units which combines with various organic and inorganic compounds. Once taken into the body, nitrates are converted into nitrites. The greatest use of nitrates is as a fertilizer.
Simazine	Simazine is an organic white solid, used as a pre-emergence herbicide used for control of broad-leaved and grassy weeds on a variety of deep-rooted crops such as artichokes, asparagus, berry crops, broad beans, citrus, etc., and on non-crop areas such as farm ponds and fish hatcheries. Its major use is on corn where it is often combined with AAtrex. Other herbicides with which simazine is combined include: paraquat, on apples, peaches; Roundup or Oust for noncrop use; Surflan on Christmas trees; Dual on corn and ornamentals.

Source: USEPA (http://www.epa.gov/safewater/hfacts.html); CARES (Source Water Assessment Plan)

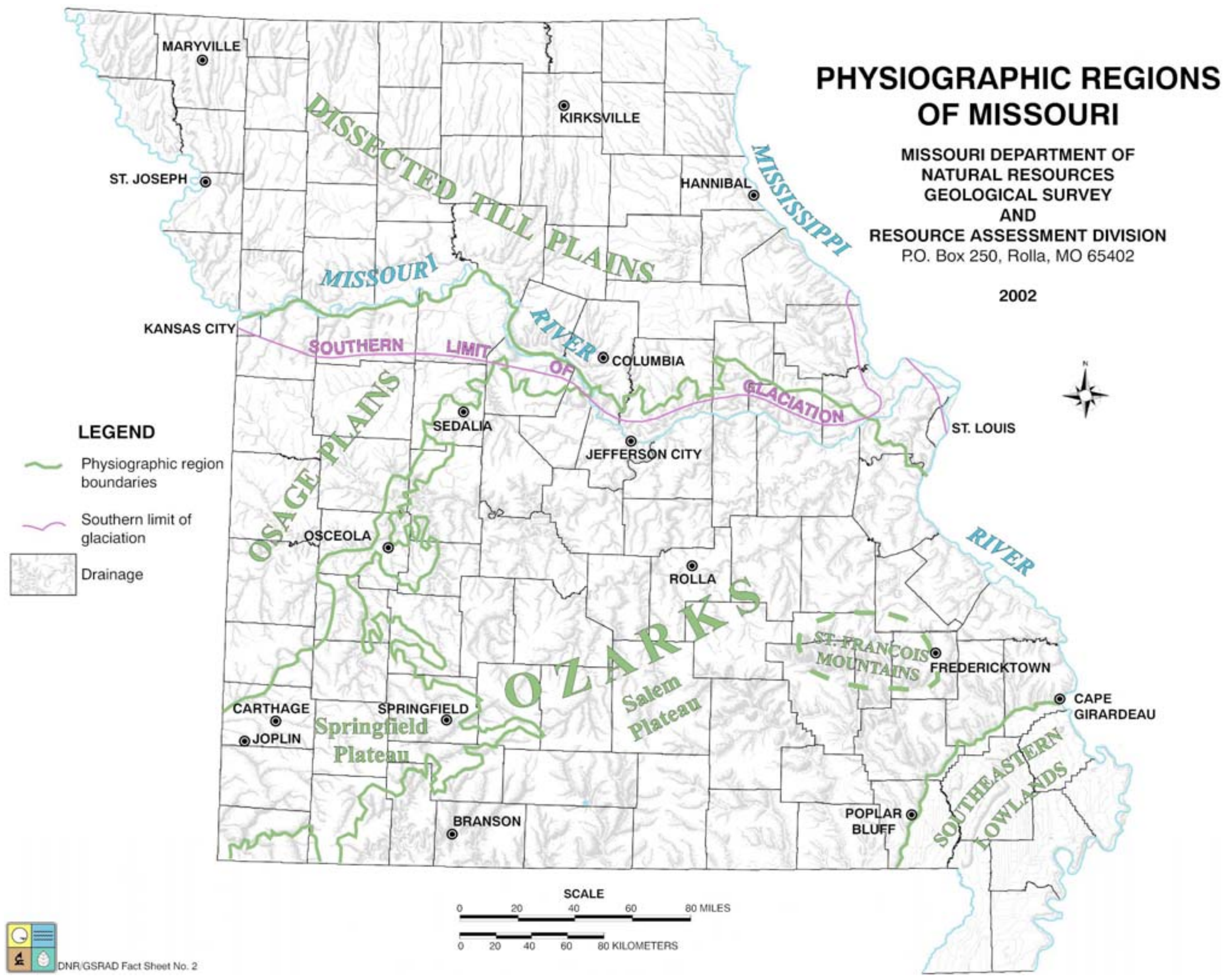
SOC: Synthetic Organic Compound: (http://www.epa.gov/safewater/hfacts.html#Synthetic)
VOC: Volatile Organic Compound (http://www.epa.gov/safewater/hfacts.html#Volatile)
IOC: Inorganic Contaminants (http://www.epa.gov/safewater/hfacts.html#Inorganic)
MCL: Maximum Contaminant Level (http://www.epa.gov/safewater/mcl.html)

APPENDIX C
FARM NUMBERS, ACREAGE AND VALUE

	CARROLL				CHARITON				SALINE			
Year	Number of Farms	Land in Farms	Avg. Size of Farms	Value of Land & Bldgs per Acre	Number of Farms	Land in Farms	Avg. Size of Farms	Value of Land & Bldgs per Acre	Number of Farms	Land in Farms	Avg. Size of Farms	Value of Land & Bldgs per Acre
		-acres-		-dollars-		-acres-		-dollars-		-acres-		-dollars-
1850	NA	90,736	NA	$4.74	NA	128,705	NA	$5.46	NA	186,949	NA	$6.30
1880	3,156	358,615	114	$17.03	3,012	372,227	124	$13.59	3,027	433,087	143	$20.60
1900	3,692	419,245	114	$34.07	3,805	450,367	118	$29.46	3,638	438,976	121	$41.57
1910	3,253	416,514	128	$59.97	3,481	442,719	127	$52.48	3,091	427,016	138	$76.57
1920	3,077	413,347	134	$138.69	3,426	445,102	130	$114.08	3,024	424,702	140	$166.49
1930	2,768	404,514	146	$78.33	2,927	419,900	144	$59.93	2,764	429,795	156	$92.31
1935	2,996	416,910	139	$41.88	3,201	433,129	135	$43.85	2,971	433,555	146	$52.72
1940	2,674	407,748	153	$44.79	2,774	420,471	152	$35.05	2,637	437,199	166	$51.02
1945	2,333	405,763	174	$56.41	2,452	427,251	174	$48.43	2,444	446,712	183	$71.45
1950	2,195	410,306	187	$82.56	2,454	426,219	174	$69.27	2,402	443,121	185	$104.56
1954	1,959	414,588	212	$102.29	2,211	426,807	193	$95.25	2,115	440,323	208	$128.25
1959	1,665	411,900	247	$142.09	1,875	418,576	223	$132.56	1,903	442,953	233	$189.78
1964	1,459	418,945	287	$182.79	1,687	422,765	251	$166.21	1,636	445,655	272	$233.92
1969	1,509	439,527	291	$261.81	1,707	454,710	266	$257.31	1,657	467,452	282	$294.39
1974	1,202	408,235	340	$437.00	1,410	406,880	289	$397.00	1,364	419,424	307	$509.00
1978	1,159	419,389	362	$795.00	1,328	415,196	313	$786.00	1,300	429,610	330	$918.00
1982	1,099	414,189	377	$911.00	1,271	420,754	331	$938.00	1,168	398,118	341	$1,094.00
1987	1,013	404,480	399	$648.00	1,145	402,265	351	$585.00	1,083	435,725	402	$815.00
1992	919	377,000	410	$792.00	1,075	403,597	375	$721.00	939	414,394	441	$861.00
1997	952	395,657	416	$967.00	1,071	414,379	387	$996.00	936	429,631	459	$1,214.00
2002	1,081	417,080	386	$1,295.00	1,095	378,637	346	$1,333.00	945	413,166	437	$1,368.00

Source: U.S. Census of Agriculture; Missouri Agricultural Statistics Service; http://agebb.missouri.edu/mass/agrifact/index.htm

APPENDIX D

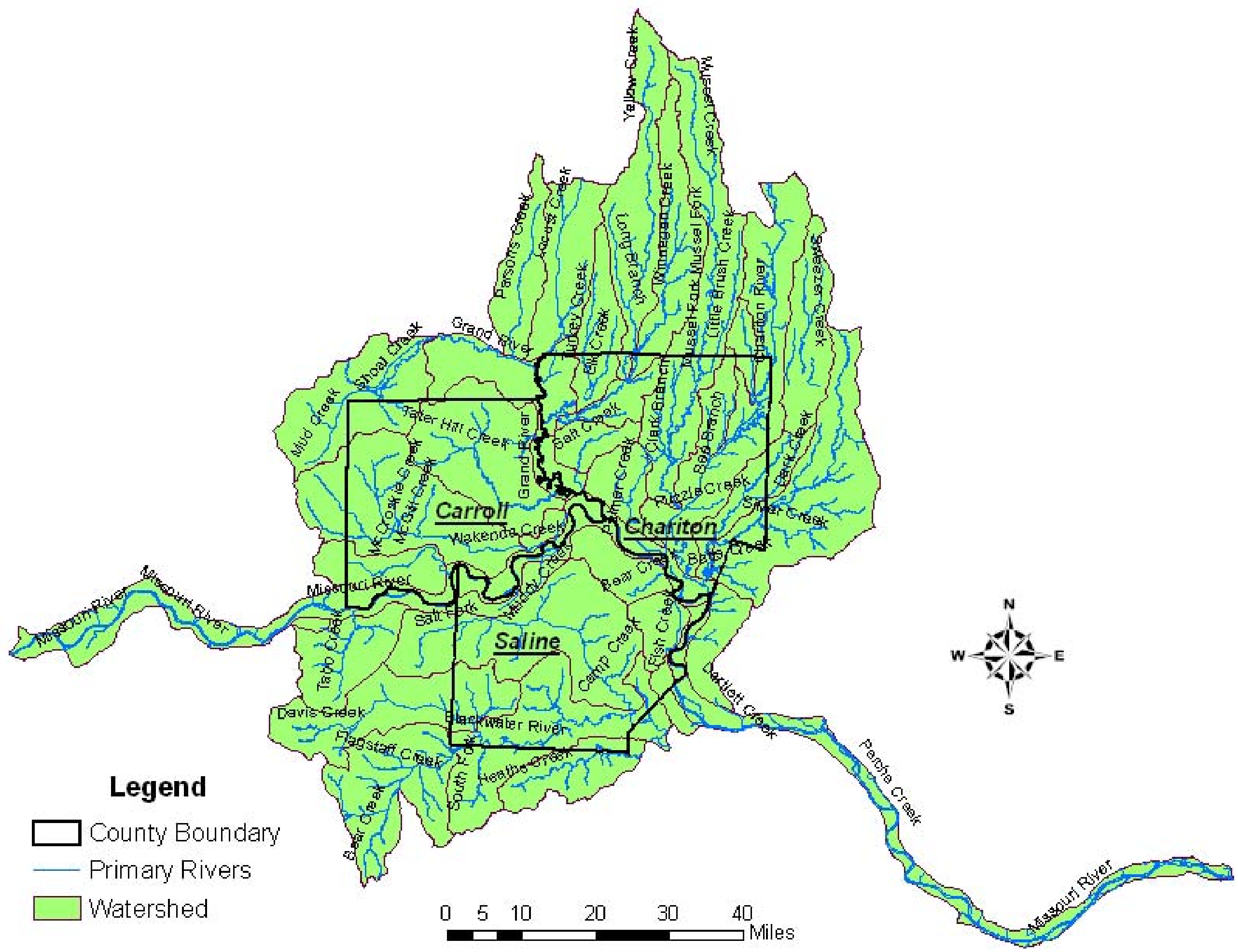

PHYSIOGRAPHIC REGIONS OF MISSOURI
MISSOURI DEPARTMENT OF NATURAL RESOURCES GEOLOGICAL SURVEY AND RESOURCE ASSESSMENT DIVISION
P.O. Box 250, Rolla, MO 65402
2002
LEGEND
Physiographic region boundaries
Southern limit of glaciation
Drainage
MARYVILLE
ST. JOSEPH
KIRKSVILLE
HANNIBAL
KANSAS CITY
COLUMBIA
SEDALIA
JEFFERSON CITY
ST. LOUIS
OSCEOLA
ROLLA
FREDERICKTOWN
CAPE GIRARDEAU
CARTHAGE
JOPLIN
SPRINGFIELD
BRANSON
POPLAR BLUFF
DISSECTED TILL PLAINS
OSAGE PLAINS
OZARKS
Salem Plateau
Springfield Plateau
ST. FRANCOIS MOUNTAINS
SOUTHEASTERN LOWLANDS
MISSOURI RIVER
MISSISSIPPI RIVER
SOUTHERN LIMIT OF GLACIATION
SCALE
0 20 40 60 80 MILES
0 20 40 60 80 KILOMETERS
DNR/GSRAD Fact Sheet No. 2

APPENDIX E
1971- 2000 PRECIPITATION NORMALS
(in inches)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
COLOMA, MO	1.21	1.3	2.64	3.62	4.84	4.19	4.17	3.59	4.23	3.4	2.97	1.93	38.09
CARROLLTON, MO	1.52	1.67	2.88	3.9	4.94	4.55	4.31	3.98	4.42	3.52	3.02	2.18	40.89
SALISBURY, MO	1.56	1.83	2.88	3.71	5.16	4.58	4.06	3.96	4.49	3.25	3.15	2.29	40.92
BRUNSWICK, MO	1.59	1.47	2.69	3.52	5.03	4.5	3.95	3.74	3.82	3.29	3.2	2.03	38.83
SUMNER 3 WSW, MO	1.26	1.43	2.56	3.44	4.67	3.88	4.05	3.24	4.06	3.3	2.69	1.88	36.46
MARSHALL, MO	1.33	1.56	2.84	3.76	4.85	4.13	3.62	3.1	4.01	3.19	3.14	1.8	37.33
SWEET SPRINGS, MO	1.5	1.85	3.13	4.11	4.95	4.08	3.94	3.9	4.45	3.43	3.21	2.25	40.80
												MEAN	**39.05**

Source: High Plains Regional Climatic Center (HPRCC)

APPENDIX F
STUDY AREA WATERSHEDS



APPENDIX G
GEOLOGY

MAJOR DIVISIONS OF GEOLOGIC TIME		TYPES AND DISTRIBUTION	ECONOMIC USES
ERAS	PERIODS		
CENOZOIC	QUATERNARY 0-1 million years ago	Glacial deposits; loess; silt, sand and gravel in modern streams and rivers.	Parent material of much of the state's soil; important sources of water; chief source of sand and gravel.
	TERTIARY 1-64 million years ago	Sand, gravel, clay and shale; largely restricted to Southeastern Lowlands.	Water; ceramic clay; bleaching clay.
MESOZOIC	CRETACEOUS 64-136 million years ago	Clay and sand; restricted to Southeastern Lowlands.	Water; ceramic clay; sand.
	JURASSIC 136-180 million years ago	No rocks in Missouri of Jurassic age.	
	TRIASSIC 180-230 million years ago	No rocks in Missouri of Triassic age.	
PALEOZOIC	PERMIAN 230-280 million years ago	Sandstone; known from single locality in Atchison County.	No economic use.
	PENNSYLVANIAN 280-310 million years ago	Shale, limestone, sandstone, clay and coal; present in more than two-thirds of the state's counties; extensive in western and northern Missouri.	Coal; ceramic materials (including fireclay); limestone and shale for cement manufacture; oil, gas, and water; important source of limestone in many western and northern counties; asphaltic sandstone and iron.
	MISSISSIPPIAN 310-345 million years ago	Predominantly limestone, some shales; principal areas of outcrop are southwestern, central, east-central, and northeastern parts of the state.	Lime, limestone, marble (Carthage), raw material for cement, water, tripoli, lead, zinc and iron.
	DEVONIAN 345-400 million years ago	Predominantly limestone; exposed in central, eastern and southeastern Missouri.	Limestone, marble (Ste. Genevieve County)
	SILURIAN 400-425 million years ago	Predominantly limestone; exposed in northeastern and southeastern Missouri.	Limestone and dolomite
	ORDOVICIAN 425-500 million years ago	Dolomite (magnesian limestone), limestone, sandstone, and shale; extensively exposed in Ozark area as far north as Montgomery County and west to McDonald and St. Clair counties; also exposed in parts of Ralls, Pike, and Lincoln counties.	Sand for glass and ground silica, limestone, dolomite, water, oil (St. Louis County), building stone, raw material for cement, iron and terrazzo chips.
	CAMBRIAN 500-600 million years ago	Dolomite, sandstone and shale; major outcrops restricted to St. Francois Mountians area.	Lead, zinc, silver, cobalt, nickel, copper, barite, iron, water, dolomite, terrazzo chips and building stone.
PRECAMBRIAN 600 million - 4 billion years ago		Igneous and metamorphic rocks; igneous exposed in St. Francois Mountains area.	Iron; granite (for building and monumental stone, roofing granules; roadstone).

Source: Missouri Department of Natural Resources

APPENDIX G (Continued)
GEOLOGY
Northwestern Missouri

System	Series	Group or Formation	Lithology	Hydrology
Quaternary	Recent	Alluvium	Sand and gravel, with interbedded silt and clay deposited by stream action.	Yields 30-500 gpm where sufficient thickness of saturated permeable sand and gravel is present.
	Pleistocene	Glacial Till or Drift	Heterogeneous mixture of clay, silt, sand, gravel, and boulder-size material.	3-50 gpm available to well where clean, permeable sand and gravel are present.
		Preglacial valley fill	Sand and gravel, silt and clay intermixed. Streamed deposited material.	Preglacial alluvium may yield as much as 500 gpm where saturated thickness and permeabilities allow.
Pennsylvanian	Virgilian	Wabaunsee Group	Shale, siltstone & sandstone.	Not considered to be water bearing. Very small quantities of water (1/2-1 gpm) may be obtained locally from the limestone sequences.
		Shawnee Group	Thick limestone formations with intervening shale beds.	
		Douglas Group	Dominantly clastic formations. Shale, sandstone & thin limestone.	
	Missourian	Pedee Group	A thick sequence of shale with limestone at the top.	Small amounts of water (1-3 gpm) locally from thicker limestone formations.
		Lansing Group	Two thick limestone separated by shale & sandstone.	
		Kansas City Group	Thick limestone formations with intervening shale, some sandstone beds, black, fissile shale in lower part.	Not generally water bearing
		Pleasanton Group	Thick shale sequence with sandstone in lower part. Few thin limestone beds and siltstones. Scattered coal beds.	
	Desmoinesian	Marmaton Group	Shale, limestone, clay and coal beds.	
		Cherokee Group	Sandstone, siltstone and shale	Small yields (1-3 gpm) of potable water at depths less than 100 feet in outcrop area.

Source: Missouri Department of Natural Resources

APPENDIX G (Continued)
GEOLOGY
West-Central Missouri

System	Series	Group or Formation	Lithology	Hydrology
Quaternary	Pleistocene and Recent	Un-differentiated glacial drift and alluvium	Clay, silt, sand and gravel, in northern part of province, just south of the Missouri River is glacially derived. Some loess near the river valley.	Missouri River alluvium yields >1,000 gpm. Drift and alluvium-filled preglacial channels may yield 50 to more than 500 gpm. Elsewhere, drift may yield 0-5 gpm.
Pennsylvanian	Missourian	Kansas City Group	Massive limestone formation with intervening shale formations. Some of the shale intervals have included sandstone beds. In the lower part of the group these are thin black, fissile shale members.	Small amounts of water (1-3 gpm) available from limestones and black shales near the outcrop line. Where more deeply buried, water is highly mineralized.
		Pleasanton Group	Thick clastic shale with a basal siltstone or very fine-grained sandstone. Locally, there are two other thick channel sandstones in the upper half of the group.	Not considered to be water bearing. Locally, may yield very small amounts of water from sandstone beds. Water may be poor in quality.
	Desmoinesian	Marmaton Group	Fewer sandstone bodies than preceding group, with more thin limestone and thick shale sequences.	
		Cherokee Group and Krebs Subgroup	Thin sandstones and siltstones with intervening shales. The shales locally have coal seams. Thin limestone beds occur at widely scattered intervals.	May yield small amounts of water from sandstones, (3-20 gpm). Water may be poor in quality.
Mississippian	Osagean	Burlington Limestone	Medium to coarse crystalline, medium to thick bedded limestone	Yields very small amounts of water to wells locally. May contain highly-mineralized water.

Source: Missouri Department of Natural Resources

APPENDIX G (Continued)
GEOLOGY

MAP CODE	ERA	SYSTEM	SERIES	UNIT	GENERAL TYPE	PERMEABILITY	County
Qal	Cenozoic	Quaternary	Holocene	-	Alluvium	Medium	All
Pcc	Paleozoic	Pennsylvanian	Desmoinesian	-	Limestone	Medium	All
Pck	Paleozoic	Pennsylvanian	Atokan/Desmoinesian	-	Limestone	Medium	Saline
Pkc	Paleozoic	Pennsylvanian	Missourian	Kansas City Group	Limestone	Medium	Carroll
Pm	Paleozoic	Pennsylvanian	Desmoinesian	Marmaton Group	Limestone	Medium	All
Pp	Paleozoic	Pennsylvanian	Missourian	Pleasanton Group	Sandstone	Medium	Carroll
Ppwm	Paleozoic	Pennsylvanian	Missourian	Pleasanton / Warrensburg	Clay	Low	Carroll / Chariton
Mo	Paleozoic	Mississippian	Osagean	Keokuk-Burlington	Limestone	High	All
Mk	Paleozoic	Mississippian	Kinderhookian	-	Limestone/Shale	Medium	Saline
D	Paleozoic	Devonian	Lower/Middle/Upper	-	Limestone/Sandstone/Shale	Medium	Saline
Ou	Paleozoic	Ordovician	Cincinnatian/Champ	-	Dolomite/Limestone	Medium	Saline

Source: Missouri Spatial Data Information Service

APPENDIX G (Continued)
GEOLOGY

SYSTEM	DESCRIPTION
Quaternary	The Quaternary and Tertiary deposits mapped along the major stream courses consist primarily of unconsolidated sand and gravel. Tertiary beds consist of unconsolidated to semiconsolidated clay and sand overlain by unconsolidated Quaternary sand and gravel. Glacial drift, till, and loess overly bedrock.
Pennsylvanian	Pennsylvanian strata crop out in large areas of eastern Kansas and western Missouri. These rocks are covered with glacial drift to the west and north of the Missouri River where they are mapped as the shallowest bedrock. Pennsylvanian rocks consist of shale, sandstone, limestone, and some coal beds and were deposited in a series of sedimentary cycles, each of which represents a transgression and regression of the Pennsylvanian sea. Each cycle, known as a cyclo-them begins and ends with nonmarine shale deposits; intervening marine limestone and shale were deposited in shallow to deep water. The thick Pennsylvanian section has been divided into a large number of geologic formations, recognized in exposed Pennsylvanian strata; several additional formations are delineated in the subsurface. Outliers of Pennsylvanian rocks in east-central Missouri show that before they were partly eroded, these strata covered a much greater area than at present.
Mississippian	Mississippian rocks crop out in a wide to narrow band that extends from southwestern Missouri to just north of the Missouri River in central Missouri and as a second, less extensive band in northeastern Missouri parallel to the Mississippi River. Mississippian strata are mostly limestone (commonly cherty) but include some beds of sandstone and shale. Outliers of Mississippian rocks in southern Missouri show that these beds extended over a much larger area before most were removed by erosion.
Devonian	Devonian rocks are exposed in scattered areas of southern, southeastern, and northern Missouri. The lower and middle parts of the Devonian sequence are mostly limestone interbedded with minor sandstone and chert, whereas the upper part is mostly widespread shale.
Ordovician	Ordovician rocks are exposed in a large area in southern Missouri and in smaller areas in northeastern and southeastern Missouri. The thick sequence of Ordovician strata mostly consists of dolomite and limestone interbedded with minor sandstone and shale and has been divided into a large number of geologic formations.
Cambrian	Cambrian rocks are exposed in southeastern Missouri in an area that encircles the Precambrian core of the St. Francois Mountains. These Cambrian rocks are sandstones and dolomite sequences.

Source: Modified from Ground Water Atlas of the United States: Kansas, Nebraska and Missouri (Miller and Appel 1997)

APPENDIX H
SOILS
Carroll County, Missouri

Map Symbol	Soil Name
01B	Lagonda silt loam, 2 to 5 percent slopes
02C2	Lagonda silty clay loam, 5 to 9 percent slopes, eroded
03B	Armster loam, 2 to 5 percent slopes
03C	Armster loam, 5 to 9 percent slopes
04C2	Armster clay loam, 5 to 9 percent slopes, eroded
04D3	Armster clay loam, 9 to 14 percent slopes, severely eroded
05B	Grundy silt loam, 2 to 5 percent slopes
07C2	Knox silt loam, 5 to 9 percent slopes, eroded
07E2	Knox silt loam, 14 to 20 percent slopes, eroded
07F	Knox silt loam, 20 to 30 percent slopes
08D3	Knox silty clay loam, 9 to 14 percent slopes, severely eroded
09B	Sharpsburg silt loam, 2 to 5 percent slopes
09C2	Sharpsburg silt loam, 5 to 9 percent slopes, eroded
11B	Ladoga silt loam, 2 to 5 percent slopes
11C2	Ladoga silt loam, 5 to 9 percent slopes, eroded
14C2	Greenton silty clay loam, 5 to 9 percent slopes, eroded
14D2	Greenton silty clay loam, 9 to 14 percent slopes, eroded
16B	Sampsel silty clay loam, 2 to 5 percent slopes
21B	Wakenda silt loam, 2 to 5 percent slopes
21C2	Wakenda silt loam, 5 to 9 percent slopes, eroded
23C2	Higginsville silt loam, 5 to 9 percent slopes, eroded
25C	Gosport silty clay loam, 5 to 9 percent slopes
25D	Gosport silty clay loam, 9 to 14 percent slopes
25F	Gosport silty clay loam, 14 to 30 percent slopes
30	Nodaway silt loam, frequently flooded
32	Colo silty clay loam, occasionally flooded
34	Zook silty clay loam, occasionally flooded
36	Wabash silty clay, occasionally flooded
42	Bremer silt loam, occasionally flooded
60	Aholt silty clay, occasionally flooded
62	Booker silty clay, occasionally flooded
64	Cotter silt loam, rarely flooded
66	Gilliam silt loam, occasionally flooded
68	Haynie very fine sandy loam, occasionally flooded
70	Hodge loamy fine sand, occasionally flooded
72	Kenmoor loamy fine sand, occasionally flooded
74	Landes fine sandy loam, occasionally flooded
76	Leta silty clay, occasionally flooded
84	Norborne loam, rarely flooded
86	Parkville silty clay loam, occasionally flooded
88	Bremer silty clay loam, rarely flooded
90	Waldron silty clay loam, occasionally flooded
92	Waubonsie fine sandy loam, loamy substratum, occasionally flooded
100	Udorthents, nearly level to strongly sloping
W	Water

Source: Soil Data Mart; http://soildatamart.nrcs.usda.gov/

APPENDIX H (Continued)
SOILS
Chariton County, Missouri

Map Symbol	Soil Name
10B2	Lagonda Silt Loam, 2 To 5 Percent Slopes, Eroded
11C2	Lagonda Silty Clay Loam, 5 To 9 Percent Slopes, Eroded
12B2	Bevier Silty Clay Loam, 2 To 5 Percent Slopes, Eroded
15B	Grundy Silt Loam, 2 To 5 Percent Slopes
16	Crestmeade Silt Loam
19C2	Menfro Silt Loam, 3 To 9 Percent Slopes, Eroded
19F	Menfro Silt Loam, 9 To 30 Percent Slopes
20A	Shannondale Silt Loam, 0 To 2 Percent Slopes
20C2	Shannondale Silt Loam, 2 To 7 Percent Slopes, Eroded, Rarely Flooded
21C2	Knox Silty Clay Loam, 5 To 9 Percent Slopes, Eroded
22F3	Knox Silty Clay Loam, 9 To 30 Percent Slopes, Severely Eroded
23B2	Higginsville Silt Loam, 2 To 5 Percent Slopes, Eroded
23C2	Higginsville Silt Loam, 5 To 9 Percent Slopes, Eroded
25B	Wakenda Silt Loam, 2 To 5 Percent Slopes
25C2	Wakenda Silt Loam, 5 To 9 Percent Slopes, Eroded
26B	Armstrong Loam, 2 To 5 Percent Slopes
26C2	Armstrong Loam, 5 To 9 Percent Slopes, Eroded
26D2	Armstrong Loam, 9 To 14 Percent Slopes, Eroded
27D3	Armstrong Clay Loam, 9 To 14 Percent Slopes, Severely Eroded
28C	Keswick Loam, 5 To 9 Percent Slopes
31F	Winnegan Loam, 9 To 30 Percent Slopes
36D2	Gosport Silty Clay Loam, 9 To 14 Percent Slopes, Eroded
36F	Gosport Silty Clay Loam, 14 To 30 Percent Slopes
37D2	Newcomer Loam, 9 To 14 Percent Slopes, Eroded
37F	Newcomer Loam, 14 To 30 Percent Slopes
40F	Putco Clay Loam, 9 To 50 Percent Slopes
42F	Schuline-Pits Complex, 5 To 30 Percent Slopes
47	Dockery Silt Loam, Frequently Flooded
50	Blackoar Silt Loam, Occasionally Flooded
53	Colo Silt Loam, Occasionally Flooded
54	Zook Silty Clay Loam, Occasionally Flooded
56	Triplett Silt Loam, Rarely Flooded
60	Portage Silty Clay, Occasionally Flooded
61	Carlow Silty Clay, Occasionally Flooded
62	Carlow Silty Clay, Rarely Flooded
64	Tina Silt Loam, Rarely Flooded
66C2	Gifford Silty Clay Loam, 2 To 9 Percent Slopes, Eroded, Rarely Flooded
68	Tuskeego Silty Clay Loam, Occasionally Flooded
70	Speed Silt Loam, Occasionally Flooded
72	Tice Silt Loam, Frequently Flooded
73	Tice Silty Clay Loam, Rarely Flooded
78	Levasy Silty Clay, Rarely Flooded
81	Haynie Very Fine Sandy Loam, Rarely Flooded
82	Sarpy Loamy Fine Sand, Rarely Flooded

APPENDIX H (Continued)
SOILS
Chariton County, Missouri

83	Landes Fine Sandy Loam, Rarely Flooded
84	Haynie-Waldron Complex, Rarely Flooded
85	Waldron Silty Clay, Loamy Substratum, Rarely Flooded
86	Parkville Silty Clay Loam, Rarely Flooded
87	Modale Silt Loam, Rarely Flooded
88	Cotter Silt Loam, Rarely Flooded
89	Norborne Loam, Rarely Flooded
93	Booker Silty Clay, Rarely Flooded
94	Grable Silt Loam, Rarely Flooded
99	Haynie-Waldron Complex, Frequently Flooded
M-W	Miscellaneous Water
W	Water

Source: Soil Data Mart; http://soildatamart.nrcs.usda.gov/

Saline County, Missouri

Map Symbol	Soil Name
03	Aholt clay, occasionally flooded
04	Booker clay, occasionally flooded
05D2	Bluelick silt loam, 9 to 14 percent slopes, eroded
05E	Bluelick silt loam, 14 to 20 percent slopes
07D2	Newcomer silt loam, 9 to 14 percent slopes, eroded
07F	Newcomer silt loam, 14 to 35 percent slopes
09	Bremer silt loam, occasionally flooded
10A	Dameron silt loam, 0 to 3 percent slopes, occasionally flooded
11	Vesser silt loam, occasionally flooded
12	Colo silty clay loam, occasionally flooded
13	Grable very fine sandy loam, loamy substratum, rarely flooded
14	Darwin silty clay, rarely flooded
15	Dockery silt loam, frequently flooded
18F	Moko-rock outcrop complex, 9 to 45 percent slopes
21F	Goss cherty silt loam, 14 to 45 percent slopes
22C2	Greenton silt loam, 5 to 9 percent slopes, eroded
24	Haynie silt loam, rarely flooded
26	Haynie-waldron complex, occasionally flooded
30B	Higginsville silt loam, 2 to 5 percent slopes
30C2	Higginsville silt loam, 5 to 9 percent slopes, eroded
33C	Knox silt loam, 3 to 9 percent slopes
33C2	Knox silt loam, 3 to 9 percent slopes, eroded
33D2	Knox silt loam, 9 to 14 percent slopes, eroded
33F	Knox silt loam, 14 to 35 percent slopes
33F2	Knox silt loam, 14 to 35 percent slopes, eroded
36C2	Ladoga silt loam, 3 to 9 percent slopes, eroded
37A	Leslie silt loam, 0 to 2 percent slopes
37B	Leslie silt loam, 2 to 5 percent slopes

APPENDIX H (Continued)
SOILS

40	Leta silty clay, occasionally flooded
41	Levasy silty clay, occasionally flooded
42F	Plainfield loamy sand, 14 to 35 percent slopes
43B	Macksburg silt loam, 1 to 4 percent slopes
44C2	Arispe silt loam, 4 to 9 percent slopes, eroded
44D2	Arispe silt loam, 9 to 14 percent slopes, eroded
45C2	Mandeville silt loam, 5 to 9 percent slopes, eroded
45D2	Mandeville silt loam, 9 to 14 percent slopes, eroded
45F	Mandeville silt loam, 14 to 30 percent slopes
47B	Monona silt loam, 2 to 5 percent slopes
47C2	Monona silt loam, 5 to 9 percent slopes, eroded
50B	Mcgirk silt loam, 2 to 5 percent slopes
53C	Menfro silt loam, 3 to 9 percent slopes
53C2	Menfro silt loam, 3 to 9 percent slopes, eroded
53D2	Menfro silt loam, 9 to 14 percent slopes, eroded
53F	Menfro silt loam, 14 to 35 percent slopes
57	Joy silt loam
60	Moniteau silt loam, occasionally flooded
63	Nodaway silt loam, occasionally flooded
65	Ackmore silt loam, occasionally flooded
67C2	Sampsel silty clay loam, 5 to 9 percent slopes, eroded
68	Winterset silt loam
70A	Sarpy loamy fine sand, 0 to 4 percent slopes, rarely flooded
73B	Sibley silt loam, 2 to 5 percent slopes
73C2	Sibley silt loam, 5 to 9 percent slopes, eroded
73D2	Sibley silt loam, 9 to 14 percent slopes, eroded
76D2	Snead silty clay loam, 9 to 14 percent slopes, eroded
83	Moville silt loam, occasionally flooded
86	Waldron silty clay, occasionally flooded
90B	Weller silt loam, 2 to 5 percent slopes
90C2	Weller silt loam, 5 to 9 percent slopes, eroded
90D2	Weller silt loam, 9 to 14 percent slopes, eroded
93C2	Winfield silt loam, 3 to 9 percent slopes, eroded
95	Wiota silt loam, rarely flooded
96	Zook silty clay, frequently flooded
99F	Lindley silt loam, 14 to 35 percent slopes
100	Pits, quarries
M-W	Miscellaneous water
W	Water, more than 40 acres

Source: Soil Data Mart; http://soildatamart.nrcs.usda.gov/

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