Chapter 7: Conclusions

This chapter summarizes the conclusions of this work, and restates the major results presented in the preceding chapters. The chapter is divided into three sections: a summary of the vulnerability assessment method, a discussion of the results the method's application to nitrate measurements in Texas, and recommendations for the future use of the method and its results.

7.1 Vulnerability Assessment Method Summary

The primary result of this work is the development of a generally applicable method for assessing the vulnerability of groundwater supplies, using a geographic information system and a database of historic water quality measurements. The method is summarized by the six steps listed at the end of Chapter 2. These steps are recapped here in the specific form they were used in this work, followed by comments on their application.

7.1.1 Method Summary

1. *Select a constituent or set of constituents whose presence indicates the degree of vulnerability of a groundwater source.* The selected constituent for this study is nitrate.
2. *Identify a set of distinct mappable regions of the surface or subsurface.* Texas was divided into 7.5' quadrangles for mapping. Five aquifers were selected as an alternative set of mapping units. In the quadrangles , all measurements, regardless of well depth or aquifer association, were

grouped together for analysis. In the aquifers only measurements associated with particular geologic formations were grouped.

3. *Assemble a body of measurements of the constituent identified in step 1 that can be linked with the regions identified in step 2.* Nitrate measurement records were retrieved from the Texas Water Development Board (TWDB) Ground-Water Data System for the years 1962–1993. These measurements can be linked to quadrangles by the location of the wells from which water samples were collected for analysis. They can also be linked to aquifers through the TWDB well description database.

4. *Calculate descriptive statistics for the body of measurements linked with each region.* Exceedence probabilities for four nitrate concentration thresholds (0.1, 1.0, 5.0, and 10.0 mg/l nitrate as nitrogen) were calculated. Two methods were tried for estimation: non-parametric calculation of threshold exceedence probabilities for quadrangles based on the model of water sampling as a Bernoulli process, and fitting of all measurements in a quadrangle to a lognormal probability distribution. A minimum of twelve measurements was required for the exceedence probability estimates to be included in maps.

5. *Map the variation of the descriptive statistics from region to region.* The estimated exceedence probability for each threshold were divided into five ranges (<20%, 20–40%, 40–60%, 60–80%, >80%) and quadrangles with twelve or more measurements were color-coded according to this division.

6. *Relate the variation of the descriptive statistics to the variation of indicator parameters by forming a mathematical expression that mimics the relationship between the descriptive statistics and indicator values mapped over the same set of regions.* Stepwise multiple regression was used to form a linear expression relating quadrangle-averaged estimates of precipitation, soil thickness, soil organic content, and nitrogen fertilizer sales, to the exceedence probability estimates.

7.1.2 Comments

Selection of Constituents. In this work, nitrate was selected as the constituent to act as a surrogate for vulnerability. It was chosen because a large body of nitrate measurements is available in Texas, making statistical descriptions of its occurrence feasible, and because nitrate is commonly associated with agricultural sources, making it a potential surrogate for herbicides and other agricultural chemicals. Nitrate has many sources and is found in groundwater throughout Texas, which makes it suitable as an indicator of groundwater vulnerability, since its occurrence is not limited to regions where human activity generates concentrated sources. The drawbacks of nitrate as an indicator of vulnerability include the fact that it often occurs naturally, making it difficult to attribute high concentrations unambiguously to human influences. A similar study carried out using a constituent or constituents with no natural sources might present a clearer picture of vulnerability to human influences.

Selection of Study Regions. The selection of mappable regions should result in spatially compact regions with uniform properties. Since statistical descriptions of the measurements in the regions lump together all the measurements from the regions, it is important the regions chosen can be adequately described by a few numbers. In effect, mathematical methods used to form the statistical descriptions of the regions assume that the regions are homogeneous, and the regions should be chosen in a way that does not violate that assumption. Neither the 7.5' quadrangles nor the aquifers used as study regions in this work fit these requirements exactly. Some of the quadrangles contain wells (and thus measurements) from several geologic formations, forming a heterogeneous population poorly suited to statistical description. Similarly, the aquifers are not spatially compact, which reduces the homogeneity of the populations of measurements they contain. In spite of these shortcomings, clear trends in vulnerability to nitrate are found between regions mapped in both sets of study regions. The division of the aquifers into quadrangles for the maps presented in Section 6.2 comes close to meeting the requirements of compactness and homogeneity, but at a cost of reducing the number of measurements in each cell.

Selection of the Database. The primary requirements for the database used to form statistical descriptions of the regions are that the data it contains should be of reliable and uniform quality and that the measurements be sufficiently plentiful to support statistical analysis. The TWDB database is certainly plentiful, although there are reasons—described in Section 3.1—to suspect some unevenness in the quality of the data it contains. The data in the Water Utilities Division data set have been subject to more rigorous and uniform quality control imposed by the provisions of the Safe Drinking Water Act, but are not yet plentiful enough to support a study of this type, except as a test of predictions made from a larger data set.

Statistical Description of Regions. The exceedence probabilities calculated in this work are an attempt to describe the probability that threshold values of nitrate concentrations will be exceeded in the study regions. This approach to statistical description was chosen over the more common measures of central tendency and spread (like mean or median and standard deviation or inter-quartile range) because it more directly addresses the nature of regulations based on threshold concentrations such as detection limits and maximum contaminant levels (MCLs). A region is more clearly at risk if its MCL exceedence probability is high than if its average concentration is high.

Two statistical approaches to calculating exceedence probabilities were considered. One approach estimated probabilities of exceeding threshold concentrations by counting the number of exceedences in the database records associated with the regions and treating this as the result of a Bernoulli process, the other approach fits the data from 7.5' quadrangles to a lognormal distribution function. The results of the study indicate that there are few advantages to the lognormal-fit method. As graphical comparison of the two estimation methods (Figure 6.10) shows, forcing data to fit a particular distributional form incorrectly evaluates the exceedence probabilities in regions where that distribution does not fit well. A single distributional form simply lacks the flexibility to capture the range of variation in exceedence probability over a large and heterogeneous area like Texas. The computations required to fit the lognormal model are more complex than those for the Bernoulli-process method, and the reduction of the distribution to two parameters offers little advantage. The number of measurements and exceedences of any threshold concentration in a region can be found easily through the use of a database management system and the estimation of the exceedence probability from those numbers is a simple process of division. Also, meaningful confidence intervals can be estimated for the Bernoulli-process method, and not for the lognormal-fit method.

Mapping Results. Mapping of the results of the statistical analysis makes spatial patterns in detection of nitrate very evident. This adds considerably to the value of the database for understanding variations in water quality through the State. Maps and statistics form a complementary description of the database. Summary statistics of exceedence patterns reduce a large quantity of data to a smaller, more easily interpretable set of numbers. As with the maps, the ease of interpretation comes at the expense of a loss of detail. The parallel between the maps and statistics can be extended further by analogy: Summary statistics reduce large amounts of data to a few meaningful numbers, and maps reduce large amounts of data to a few meaningful images. Proper interpretation of either maps or statistics requires an understanding of both the physical processes under study, and the mathematical or cartographic processes that produce the summary numbers and images.

Just as it is important to understand the limitations of statistical summary, which tends to obscure heterogeneity in the data, it is likewise important to understand the limitations of the images presented in the maps. Because a set of discrete colors was used for identifying the quadrangles' exceedence probabilities, some differences are exaggerated and others minimized. Cells with 39% and 41% exceedence probabilities have different colors, while cells with 41% and 59% exceedence probabilities have the same color. The maps best serve to identify regions where consistently low or high probabilities are found, aiding in, but not replacing the interpretation of statistical analyses.

Statistical methods can be used to confirm and quantify relationships suggested by visual examination of maps. Some degree of correlation between precipitation and increased incidence of high nitrate concentrations is apparent when maps of the two are compared. The regression analysis presented in Chapter 6 confirms this relationship, and allows it to be compared to other potential indicators of nitrate contamination.

Forming a Mathematical Model. Stepwise multiple linear regression was used to form an estimate of exceedence probabilities for the 7.5' quadrangles based on values of average annual precipitation, soil thickness, soil organic content, and nitrogen fertilizer sales. The regressions showed little dependency on any of these parameters except average annual precipitation. Although this was, in some respects, the least successful aspect of this study, the lack of correlation to nitrogen fertilizer sales and soil properties is an interesting result in itself. The regression results are discussed further in Section 7.2.

Given the lack of significant correlation to the selected indicators, it is difficult to determine from the results of this work whether the method of multiple linear regression is suitable for forming a model of groundwater vulnerability.

Convenience of Databases and GIS. Because a printed document like this one is a static object, the advantages of easily accessible on-line data are not well represented here. An example illustrates some of these advantages. In Section6.2.4, a single quadrangle in the Ogallala Aquifer with an unusually high 5 mg/l exceedence probability was described. The wells in the quad were found to be mostly shallow domestic supply wells, and the quad was found to be near the town of Big Spring amid a number of small oil fields. A regulator considering vulnerability waivers for herbicide monitoring might undertake a similar examination of the region surrounding a water supply well or well field. Once the quadrangle was identified by number (after some programming effort has been invested, this can be accomplished with a mouse point-and-click operation) all the descriptive data about wells and measurements in the quadrangle were accessible in seconds. In contrast, the information about nearby towns and oil fields required examination of paper maps and consumed about twenty minutes time.

Now that the programs used in this study have been written and tested, they can be applied with little modification to any set of water quality measurements. Modifying the programs to estimate exceedence probabilities from the Water Utilities Division data set required only a few minutes work. The process of acquiring that data set, mapping it into the existing quadrangles, and counting measurements and exceedences was the work of less than one day.

Similarly, additional indicators can easily be incorporated into the analysis, if they are available in the form of GIS coverages.

7.2 RESULTS IN TEXAS

The preceding section presented general conclusions about the methods developed for this study and their usefulness in describing the vulnerability of groundwater to contamination by nitrates, or by other constituents. This section is concerned with the results of the application of those methods to nitrate in Texas groundwater.

Interpreting Nitrate Results. Two assumptions are fundamental interpreting nitrate exceedence probabilities as an indication of groundwater vulnerability. The first of these is that the frequency of detection of elevated nitrate levels in regions as reported in a database of historic measurements collected from a variety of wells is a useful indicator of the likelihood of detecting nitrate in public water supplies in the same regions at the present and in the future. The second is that vulnerability to nitrate contamination is related to vulnerability to other contaminants.

The first assumption is confirmed by the nitrate measurements in the Water Utilities Division database. A comparison of the exceedence probabilities estimated from the TWDB data set of 46,507 records with the measurements listed in the WUD data set of 11,698 records shows that nitrate measurements taken over a short, recent period (February 1993 to October 1994) from public water supply wells conform to exceedence probabilities estimated from measurements collected over a much longer period (January 1962 to October

1993) from a more diverse set of wells. The correspondence between the two data sets is far from exact, but the recent measurements from public supply wells in the WUD database are much more likely to yield elevated nitrate levels if the wells are located in quadrangles with high exceedence probabilities, as estimated from the TWDB data set.

The second assumption, that nitrate exceedence probabilities are indicative of an intrinsic vulnerability is confirmed by two observations. The first is that the occurrence of elevated nitrate levels appears to be nearly independent of the sources of nitrate examined in this study. Nitrate in groundwater is uncorrelated with nitrogen fertilizer sales, indicating that its presence at elevated levels is due to other factors, such as the ease with which contaminants can enter the groundwater. The fact that the incidence of groundwater nitrate contamination is low in parts of east Texas where nitrogen fertilizer sales exceed four tons per square mile strongly suggests that the groundwater in that region is isolated from human influence to a much greater degree than in the Texas Panhandle, where fertilizer sales are lower and nitrate detections are more frequent.

The second confirmation comes from data collected in a reconnaissance of the Midwestern U.S. for nitrate and herbicides. A comparison of nitrate and herbicide data shows that when water quality measurements are grouped by hydrogeologic factors and these groups of measurements are ranked by the rates of detection of nitrate and herbicides, the rankings are virtually identical. Although neither of these observations forms conclusive evidence that nitrate levels are indicators of general vulnerability, they are both consistent with that assumption.

Best Indicator. Of the four threshold concentrations, the 1 mg/l exceedence probabilities appear to be the best indicator of groundwater vulnerability. This is the level most likely to show increases over time, a more suggestive indicator than high concentrations alone. Maps of this exceedence probability also show more variability than the others, and geologic associations appear most strongly in the map of this threshold. Finally, nitrate detections at 1 mg/l correlate well to herbicide detections in the data from the Midwest reconnaissance study.

Statewide Patterns. The maps presented in Chapter 6 clearly reveal large-scale patterns in the occurrence of nitrate in Texas groundwater. Large, cohesive regions within the State can be seen to have high exceedence probabilities for nitrate at the 0.1, 1.0, 5.0, and 10.0 mg/l concentration thresholds. This strongly suggests that such regions can be identified and classified by groundwater vulnerability for regulatory purposes.

In all of the maps, the influence of geology on water quality can be plainly seen. The adjacent regions of the Balcones Fault Zone of the Edwards Aquifer and the Carrizo-Wilcox Aquifer contrast sharply at the detection level and the 1 mg/l concentration threshold. At the 5 and 10 mg/l concentration thresholds, the Seymour Aquifer is visible among the few regions where detection rates are high.

Indicators. Of the parameters examined for use as indicators of groundwater vulnerability, only average annual precipitation was tied to substantial variations in exceedence probabilities, and this relationship was found to be opposite to expectation. Of the soil parameters, organic matter content of the soil was correlated to exceedence probabilities, but accounted for only a small part of the observed variation in those probabilities. Soil thickness and nitrogen fertilizer sales were found to have little value as indicators.

The weak link between soil parameters and exceedence probabilities may be due in part to the poor spatial resolution of the STATSGO data. The STATSGO map units are large and heterogeneous regions, with no subdivisions to indicate deviations from average soil parameter values. A map unit with an average soil thickness of fifteen inches, for example, may contain large areas with virtually no soil at all. If a quadrangle falls in such an area, the map unit average soil thickness may be a poor reflection of the actual conditions in that quad.

A similar argument can be made for the lack of correlation between nitrogen fertilizer sales and groundwater nitrate. Fertilizer sales are aggregated by county, and application of those fertilizers may be very uneven within those counties.

Average annual precipitation is subject to less local variation, exhibiting more gradual trends over the State. The size of the units used to map precipitation is more appropriate to the scale of its variation, which may account in part for its relatively high correlation to exceedence probabilities in the quadrangles.

Although there is a relationship between precipitation and nitrate exceedence probability, it is beyond the capability of statistical studies like this one to determine whether that relationship is causal. It is somewhat surprising to see that nitrate concentrations are higher where there is less rain. High recharge rates, which are driven by precipitation, are associated with increased vulnerability in DRASTIC, for example.

There is a pronounced trend in precipitation in Texas: southeast is wet; west is dry. Because of this trend, which also corresponds to important variations in geology, precipitation may be acting as a surrogate for location and aquifer structure. This explanation is supported by the lack of correlation between precipitation and exceedence probabilities *within* aquifers.

Aquifers as Indicators. Within the limited set of parameters tested in the study, geology—as represented by association of wells with the five example aquifers—appears to dominate over surface parameters such as soil properties, precipitation and fertilizer sales as an indicator of groundwater quality. A model of nitrate exceedence probability as good as any produced by the regressions in this work could be constructed by calculating average exceedence probabilities for each geologic formation and ignoring all other factors. Table 7.1 summarizes the exceedence probability estimate for the five aquifers and the State. The aquifers are listed in increasing order of 1 mg/l exceedence probability.

Table 7.1 Exceedence Probability Summary

Aquifer	Threshold Exceedence Probability 0.1 mg/l	1 mg/l	5 mg/l	10 mg/l
Carrizo-Wilcox	24%	7%	2%	1%
Hueco-Mesilla Bolson	79%	46%	3%	0.9%
Ogallala	94%	73%	12%	5%
Edwards (BFZ)	94%	74%	0.8%	0.2%
Seymour	96%	94%	82%	57%
Statewide	64%	44%	16%	9%

The Carrizo-Wilcox aquifer is the least likely of the five study aquifers to produce water with elevated nitrate levels, and the Seymour Aquifer is the most likely. Low exceedence probabilities were found at all thresholds in the Carrizo-Wilcox, and high exceedence probabilities were found at all thresholds in the Seymour.

More complex behaviors were seen in the Hueco-Mesilla Bolson, the Ogallala, and the Balcones Fault Zone of the Edwards. In these three aquifers, the exceedence probabilities were high at the detection level and the 1 mg/l threshold and low at the 5 and 10 mg/l threshold. A plausible explanation of this behavior can be found in the permeable structures of these aquifers (the Ogallala and Hueco-Mesilla Bolson are largely fluviatile, and the Edwards is karst). The aquifers may be vertically penetrable, increasing the vulnerability to nitrate (and other contaminants), and accounting for the high exceedence probabilities at low concentrations. At the same time, rapid horizontal motion of water through the aquifers could disperse the contaminants, preventing concentrations from reaching the higher thresholds. These aquifers also show little variation in concentration with depth, again suggesting that constituents are well mixed and dispersed.

Variations with Depth and Time. The Texas Water Development Board's descriptions include the depth of all wells, but screened interval depths are available for only a small number of wells, and were not used in this study. A shallow well can draw water only from near the surface, but a deep well may collect groundwater along its whole depth, so well depth is a flawed indicator of water quality variations in the vertical dimension. It is true, however, that for the State as a whole, shallower wells are more likely to exhibit high nitrate concentrations (see Figure 6.12). As stated above, however, this trend is subject to variation within individual aquifers.

Similarly, while there has been an increase in the likelihood of finding nitrate in excess of 1 mg/l over time across the state, this trend can be found in only the Ogallala among the five aquifers studied here. An increase in the presence of any chemical over time is a strong indicator of vulnerability to contamination.

7.3 RECOMMENDATIONS

Recommendations resulting from this study fall into three broad categories: recommendations for use of the method, recommendations for further study, and recommendations for the use of vulnerability assessments in the regulation of groundwater.

Using the Vulnerability Assessment Method. The six steps in the method are repeated one last time, with recommendations for their application.

1. *Select a constituent or set of constituents whose presence indicates the degree of vulnerability of a groundwater source.* If the goal of the assessment is to predict the presence of a particular constituent, measurements of the constituent itself should be used, if possible. If such measurements are unavailable, another closely correlated constituent should be selected.

   If the goal is to assess a more general vulnerability to contamination by human activities, the ideal constituent would be one which has been widely measured and has no natural sources. Nitrate, because of its many sources, is not an ideal constituent for study, although it has been very widely measured. The author was unable to find a strictly anthropogenic constituent with a sufficient record of measurements. One possible way around this problem would be to combine measurements of a group of anthropogenic constituents, as was done in this report in the examination of the midwest data.

2. *Identify a set of distinct mappable regions of the surface or subsurface.* Ideally, the regions should be both homogeneous and highly populated. Because the effects of diminishing population size on confidence in estimated exceedence probabilities can be described mathematically, and the effects of heterogeneity cannot, it is better to sacrifice numbers for consistency.

If the data are sufficiently dense, measurements should be grouped into geologically homogeneous regions first, then stratified by depth or mapped by location in two dimensions.

3. *Assemble a body of measurements of the constituent identified in step 1 that can be linked with the regions identified in step 2.* The availability of data will dictate most of the study design. Although this is the third step in the method, knowledge of the available data is essential before the design of the study (steps 1 and 2) can be carried out.

4. *Calculate descriptive statistics for the body of measurements linked with each region.* Exceedence probabilities for threshold concentrations are, in the author's view, the best available quantitative measure of goundwater vulnerability. Exceedence probability estimates and confidence intervals can be calculated easily from databases, and can be compared through standard statistical methods to indicator parameters.

   As Figures 6.33 and 6.34 indicate, it is unlikely that a single probability distribution form can be used to describe the population of constituent concentrations in a body of groundwater. For this reason, estimates of exceedence probabilities should be calculated for discrete concentration thresholds using the binomial (Bernoulli process) method.

5. *Map the variation of the descriptive statistics from region to region.* Maps are an important and powerful method for communicating information about quantities that vary spatially. The maps produced in this study have provoked much more discussion and thought than tables

of results ever would have. Although it would be possible to carry out the other five steps in this method without creating maps, this step should not be omitted.

Some improvements could be made in the maps presented here, however. The division of exceedence probabilities into ranges of 0–20%, 20–40%, etc. is essentially arbitrary. It is probably of little concern to a regulator to distinguish between a 70% and a 90% probability of exceeding a maximum contaminant level. A scale that provides more resolution where exceedence probabilities are low and less resolution where they are high would be a better aid to regulatory decision-making.

6. *Relate the variation of the descriptive statistics to the variation of indicator parameters by forming a mathematical expression that mimics the relationship between the descriptive statistics and indicator values mapped over the same set of regions.* The use of multiple regression to evaluate the correlation of indicators to exceedence probabilities was inadequately tested in this study because of the lack of correlation between the chosen indicators and the presence of nitrate in groundwater. Some recommendations about potential indicators are in order to provide better tests of the linear regression method, and produce more meaningful predictions of groundwater quality.

   More emphasis should be placed on *sources* of the constituent. Only nitrate fertilizer use was considered in this study, and with poor spatial resolution. Future studies of nitrate should consider sources from sewage, from livestock production, and from natural sources—animal, vegetable, and mineral. The spatial resolution of the data and the directness with which it reflects the amount of nitrate actually available as a contamination source should be improved. The county-averaged nitrogen fertilizer sales used in this study are both spatially unfocused and causally indirect.

The STATSGO database contains values for many more soil parameters than were tested in this study. These should be investigated further. Soil permeability, for example, might be a more valuable indicator than soil thickness or organic content, which were examined here.

Because the results of this study indicate a strong dependence on geology, more detailed data on such parameters as aquifer conductivity, porosity, and depth should be used. Because such quantities vary in three dimensions, some effort will be required either to express these in the two-dimensional domain of geographic information systems, or to expand GIS to deal with three-dimensional data.

Finally, the inverse relationship between high nitrate exceedence probabilities and rainfall is very intriguing. It is possible, for example, that in east Texas, where rainfall rates are higher than in the west, more nitrate is carried away in surface runoff and removed from the groundwater system. It may be that rainfall or recharge rates are less valuable indicators of groundwater quality than the relative weights of runoff and recharge. Some effort should be directed toward developing an index that properly expresses this relationship. The ratio of recharge to runoff might be a good place to start.

Future Work. The original goal of this study was to formulate a method for identifying groundwater sources sufficiently protected from contamination that they could be granted waivers from monitoring for man-made agricultural chemicals. This goal has not been fully met, but progress has been made toward it. In further pursuit of that goal, several steps should be taken.

The method developed in this study should be applied to measurements of herbicides and other man-made contaminants. Because nitrate is the product of both natural and anthropogenic processes, the detection of elevated nitrate levels is somewhat ambiguous as an indicator of vulnerability to human activities. If a groundwater supply shows detectable levels of atrazine, for example, there can be little question that it is vulnerable to human activities.

The 7.5' quadrangles used in this study were in part an artifact of the Texas Water Development Board's well-numbering system. Although they produce a convenient grid for exploring Texas ground water, alternative study regions should be examined. Divisions of groundwater following more physically-based boundaries, like the five aquifers studied here should be considered. Since the ultimate goal of studies like this one is to identify regions of high and low vulnerability, it is appropriate to form study regions on the basis of divisions in factors that influence vulnerability.

If studies of this type are to produce viable methods for vulnerability assessment, the most urgent need is for more complete indicator data sets. At present, data tends to be either detailed, or widespread, but not both. The Soil Conservation Service is producing a set of soil data more detailed than STATSGO, but its coverage is still only a fraction of the country. As this data becomes available, it is possible that closer correspondence between soil parameters and water quality could be found.

Because geology appears to be the dominant influence on water quality, GIS coverages of geological parameters should be developed as part of any serious effort at GIS-based vulnerability assessment. The problems of representing the three-dimensional variations of the earth's structure in the two-dimensional domain of GIS are substantial. One possible approach would be to mimic the STATSGO data structure, identifying horizontal regions of uniform geological properties in a polygon coverage, and representing their vertical variations in tables linked to the coverage. In any case, geological databases are a necessity if GIS is to play a significant role in groundwater vulnerability assessment.

Regulatory Suggestions. The vulnerability assessments for granting waivers for monitoring of agricultural chemicals in public groundwater supplies require evaluation of individual wells. Although this study has focused on regional variations in nitrate concentrations, some recommendations are still appropriate. If a well is to be classified as protected from contamination, it is necessary to show that the well has adequate protection from backwash down the well bore. Aurelius (1989) identified well construction and pesticide mix-and-load operations close to wellheads as important contributors to contamination where pesticides were found in Texas wells.

After well construction, the most important element in assessing the vulnerability of a well to contamination is identification of the aquifers or formations from which it draws water. The EPA's Groundwater Task-Force makes the same recommendation (USEPA, 1991), listing identification of aquifers supplying wells as a high priority for state agencies dealing with groundwater quality. If a well is poorly constructed or draws from an aquifer that has a high incidence of contamination, then other environmental factors such as soil parameters will have very little influence on the well's vulnerability.

The results of this work may have more direct bearing on programs like the EPA's Differential Protection Program, which would restrict the use of certain agricultural chemicals in sensitive areas, rather than banning their use everywhere. The maps in Chapter 6 clearly show that vulnerability to contamination by nitrate varies from region to region. If similar results can be shown for man-made contaminants such as herbicides, then there is a difference in the risks associated with using such chemicals in different regions, and a basis for regionally differing restrictions. Spatial and statistical analysis of existing groundwater contamination can help identify vulnerable regions for such regulatory purposes.