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A SPATIALLY VARIED INDEX METHOD TO DEFINE RELATIVE RISKS ASSOCIATED WITH PESTICIDE CONTAMINATION OF GROUNDWATERS

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ABSTRACT

In order to assess groundwater contamination from pesticides, a method was developed and applied to a large section of the state of Oklahoma. The method, which is titled the PESTICIDE RISK INDEX, used the DRASTIC Index along with pertinent data defining Oklahoma's hydrogeological and agricultural conditions to identify areas with the potential for contamination. The probability and extent of leaching for various soil and pesticide combinations found in Oklahoma were defined with a Monte Carlo analysis of 540 years of simulated field conditions using the Pesticide Root Zone Model (PRZM). The risk of human exposure to contaminated sources of drinking water was assessed by consideration of the Environmental Protection Agency's Reference Doses for selected pesticides, and the groundwater usage statistics for Oklahoma. The Index resulted in a series of maps which identified the locations of greatest relative susceptibility.

The Pesticide Risk Index identified three areas of Oklahoma with potential high risk for exposure to pesticide contaminated groundwater. The Monte Carlo analysis indicated that certain site and chemical pairings could result in significant leaching. It was found that soil retardance was the most determinant factor in the leaching of pesticides.

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INTRODUCTION

Pesticide contamination of the groundwater has become an increasing concern as ever more compounds are discovered more frequently and in deeper aquifers. As the apparent threat to the source of drinking water for half of the people in this country increases, regulation of pesticides may become more stringent. Rather than impose outright bans on pesticides which are most often detected in the groundwater, a method for site specific restrictions might eliminate the application of particularly mobile and persistent compounds to agricultural fields overlying highly susceptible aquifers. The method for devising these site specific regulations would have to combine readily available information with a simple and easy-to-apply technique. The method would also be useful for conducting a large-scale assessment concerning the probable locations for pesticide contamination. Including the consideration of toxicity and exposure mechanisms would provide an assessment of risk for human populations who use the groundwater resources.

Several methods for assessing groundwater contamination susceptibility have been applied on a national scale or with limited data sets. Application of these methods to the state or regional scale with further development of the methodology and of more inclusive data, would refine and focus their assessment capabilities. The objectives of this research were to evaluate the efficacy of using the existing assessment methods in the state of Oklahoma, and to adapt them or create new methods, as appropriate.

METHOD DEVELOPMENT

Groundwater and Risk

The contamination of groundwater by pesticides may be attributable to a combination of specific site conditions and certain characteristics of the pesticide. Contributing factors may include the pesticide's solubility, sorptive properties, and soil persistence, and the site specific conditions including soil properties, climatic conditions, crop type, and depth to groundwater [1, 2].

In the assessment of risk, the common convention is that risk is a result of exposure to hazards. Hazards in a groundwater contamination scenario are the combination of the availability and toxicity of contaminants at the ground surface and their transport to the water table.

The risk associated with exposure to pesticide contaminated groundwater was derived in the form of a Pesticide Risk Index, which was composed of three equally weighted indices named Physical Index, Pesticide Transport Hazard Index, and Exposure Index. The relationship of these three indices is graphically presented in Figure 1. The Physical Index partially determined how readily pesticides would leach through the unsaturated zone to the groundwater while the

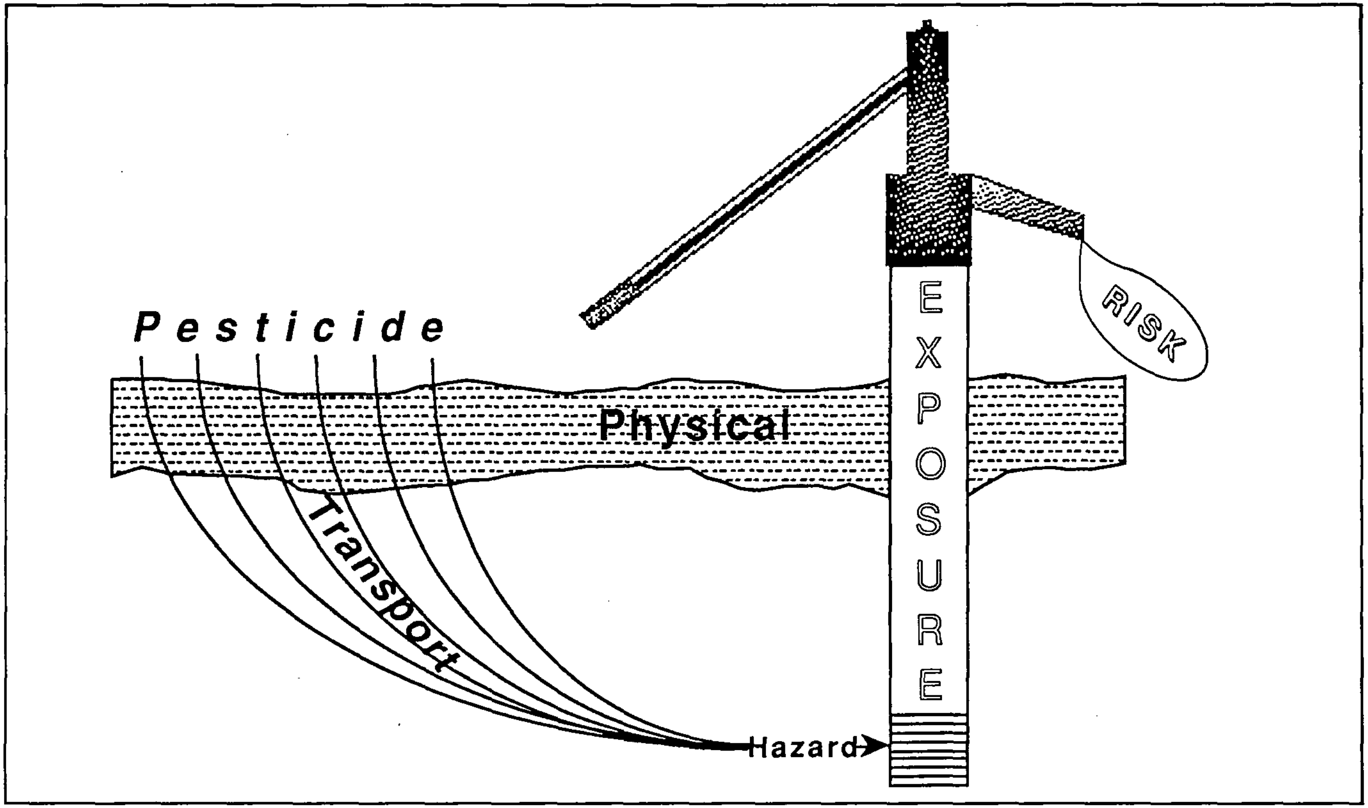


Figure 1. Pesticide risk.

Pesticide Transport Hazard Index measured the actual amount of pesticide leached as a function of pesticide application rates and chemical properties. The potential hazard of the pesticides was also considered by the Pesticide Transport Hazard Index. The degree to which humans are exposed to a pesticide hazard was determined by the Exposure Index. By connecting the potential hazard to the exposure, the assessment of risk was derived. Therefore, a combination of the above three indices yielded the Pesticide Risk Index.

The relationship between the three indices was not determined in this research. It was assumed that they were independent and of equal importance. Efforts were made to remove duplication of parameters inherent in several of the techniques. However, it must be recognized that these methods are not entirely precise, and that judgment should be used in the interpretation of the results.

Hydrogeological Considerations

The hydrogeological characteristics of an agricultural field play a major role in determining whether a pesticide will contaminate the groundwater. The overall effect of the hydrogeological features were readily assessed with the DRASTIC Agricultural Index [3]. DRASTIC is a relative ranking method, developed for the U.S. Environmental Protection Agency, which is used as a screening tool to evaluate the pollution potential of hydrogeological settings. By using a special set of weights to emphasize certain hydrogeological factors, DRASTIC is applicable to pollution from agricultural pesticides. Previous applications of DRASTIC were less effective due to the inability to evaluate specific land use practices and pesticides [4].

Data for the seven factors were obtained from the *Water Atlas of Oklahoma,* from *Benchmark and Key Soils of Oklahoma* and from United States Geological Survey personnel [5-8]. The major aquifers of the state were the only geologic formations where a hydraulic conductivity was known so all nodes occurring outside of these areas were given the lowest DRASTIC rating for this particular factor since less productive aquifers affect fewer people and a low DRASTIC rank indicates a low pollution hazard potential.

The pollution potential was determined at the nodes of a twenty-mile square grid, and the result was titled the Physical Index. It was assumed that as an initial effort a twenty-mile grid would be adequate for the delineation of trends on a state-wide scale. The grid resulted in a total of 182 nodal points for the state of Oklahoma.

Pesticide Transport

Groundwater Modeling

Numerical models such as the Pesticide Root Zone Model (PRZM) have been used to predict the leaching from agricultural fields and this model was used to predict the mobility of pesticides for this study [9]. PRZM has flexibility in the consideration of surface land use practices and specific pesticide properties, however, it requires the input of data which may not be readily available. Validation of PRZM at depths of less than three meters has been determined from fields in several states [1, 9, 10]. Numerical modeling as the sole technique for the assessment of pesticide contamination from larger areas may not be appropriate. At a state-wide scale it becomes necessary to address the variability in soils, climate, and agricultural practices. Combining a one-dimensional model such as PRZM with stochastic methods may define the inherent variability in large areas without having to resort to massive databases.

The Monte Carlo technique is a stochastic process that repeatedly models variables that are randomly selected from statistically defined distributions thereby addressing parameter uncertainty [11]. Carsel et al. and Lai and Vevers utilized distributions from actual data sets to apply to the Monte Carlo technique [9, 12]. This development allowed the resultant statistical inferences to apply to a specific situation rather than a general set of conditions. Analysis of the many simulations necessary with the Monte Carlo approach yielded probabilistic determinations. This process expanded a site specific model into a general purpose planning or screening tool.

Development of Index

Assessment of pesticide leaching in the state of Oklahoma necessitated the inclusion of three evaluations. First, the variability of pesticide use in the state was determined by prorating the pesticide applications reported by Criswell for the year 1981 on the different cash crops according to the acres of the crop grown in each county [13, 14]. To adequately address pesticide use in Oklahoma, the twenty most frequently applied compounds were considered. Descriptive transport coefficients for nine pesticides were not available so the remaining eleven were utilized and presented in Table 1. This group of eleven pesticides represented 55.4 percent of the total and included the five most heavily applied pesticides. Second, the ability of each pesticide to leach was predicted with the Monte Carlo technique. A previous effort had utilized the Leaching Evaluation of Agricultural Chemicals Handbook (LEACH) to determine the mobility of specific pesticides, however, it was desired to more closely model the specific climatological, soil, and agricultural factors found in Oklahoma [4]. Third, the toxicity of pesticides which were predicted to leach to the groundwater was included in the analysis.

Monte Carlo Method

In this application of the Monte Carlo Method, as many variables as possible were randomized. It was necessary, however, to fix the variables relating to surface management to later define causal effects between agronomic practices and resultant pesticide leaching. By fixing these variables, the Monte Carlo

Table 1. Pesticide Transport Coefficients

Pesticide	Log K_{ow}	K_{oc}	K_s
Parathion	3.81	3,981.07	0.0046
Methyl Parathion	3.32	1,288.25	0.0165
2,4-D	2.81	398.11	0.1036
Trifluralin	4.75	34,673.69	0.0026
Atrazine	2.45	173.78	0.0063
Dicamba	0.48	1.86	0.0151
Diuron	2.81	398.11	0.0064
Propazine	2.94	573.03	0.0056
Disulfoton	3.41	1,603.00	0.1604
Carbofuran	2.44	169.82	0.0040
Malathion	2.89	478.63	0.4152

technique became a cause and effect simulator which was a novel application for the technique.

The parameters which were fixed were crop type and select growing conditions. Wheat, which comprised 62 percent of all crops in the simulated counties was selected for modeling. Another set of parameters were chosen for their ability to define agricultural management practices and were applied to the model over a range of three values which were representative of the actual conditions. The chosen descriptive parameters were pesticide retardance, pesticide decay, and the Soil Conservation Systems Curve Numbers, Table 2. Curve Numbers (CN) were used by PRZM to define the infiltration of rainfall, propagation of runoff, and the driving mechanism of pesticide leaching.

The basis of most Monte Carlo approaches is to apply statistically defined distributions of input parameters and then randomly select values from the distribution for each variable. This random selection of variables is performed for every one of a multitude of simulations. Rather than using predefined statistical distributions, an alternative that was utilized in this study, due to minimal variance in certain parameters, was to let observed data define the distribution. The observed data used to define their own distributions included soil and climatological parameters which were gathered from available sources, randomized and applied to the individual one-year PRZM simulations, however, certain areas in Oklahoma were excluded for the simulation on the basis of availability of data and unusual agricultural practices. The Oklahoma Panhandle and the western edge of the state were eliminated from consideration due to the large amount of irrigation that is applied to crops in that region. The southern edge of Oklahoma is an area of minor agricultural activity and it contained no appropriate climatological

Table 2. Descriptive Parameters

Item	High	Median	Low
Koc	1200	600	2
Ks	0.1	0.05	0.001
CN	88	73	59

reporting stations, so it was also excluded. These areas were later reintroduced into the indices developed. Their inclusion was based on region-wide conditions.

Climatological data from twelve reporting stations scattered throughout the area to be simulated were obtained from the Oklahoma Climatological Survey. Gumbel showed that a twenty-five year data set was sufficient to describe the inherent variability in climatological conditions [15]. Therefore, a twenty-five year period of record between 1954 and 1978 was obtained. The daily data for the twelve stations were averaged to create a single twenty-five year record that was assumed to be representative of the entire area of simulation. Temperature and pan evaporation values should not be appreciably distorted by averaging over a large area, however, rainfall events were noticeably "smoothed" out over a longer time span. Since each year for the period of record was equivalent in significance, they were randomly selected for application to the one-year PRZM simulations.

Soil data from two sources were combined in order to define the soil distribution in Oklahoma in three dimensions [6, 7]. The spatial distribution of the soil was used to define the distribution of the modeling input by measuring the surface are occupied by each soil group. Soil properties were weighted according to their real distribution and then were randomly selected for the PRZM simulations, (Table 3). The randomization procedure for soil and climatological data, along with the creation of the PRZM input files was performed by a custom program written for this effort. Soil types, climatological reporting stations, and the overall simulated region are presented in Figure 2.

The randomizing program also performed the task of selecting a pesticide retardance coefficient. PRZM required the input of K_d, the distribution coefficient, however, this is a soil dependent parameter. It was desired to separate site and pesticide characteristics since the Physical Index had been previously used to determine the effect of the soils on pesticide leaching.

The organic carbon distribution coefficient (K_{oc}) describes the retardance of a compound in relation to the amount of organic carbon present in the soil. The relationship between K_d and K_{ocv} is defined as

$$K_d = (K_{oc}) \cdot OC) \tag{1}$$

where OC is the percentage of organic carbon.

Table 3. Properties of Selected Soils

Soil Name	Area (%)	Field Capacity	Wilting Point	Bulk Density	Organic Carbon %
Bethany	13	0.32	0.14	1.14	0.98
Clarksville	6	0.30	0.12	1.37	0.51
Dennis	1	0.36	0.17	1.13	1.50
Dougherty	2	0.12	0.04	1.45	0.38
Eufaula	1	0.20	0.11	1.47	0.72
Hartsell	11	0.25	0.12	1.35	0.85
Parsons	18	0.31	0.13	1.26	0.95
Pondcreek	4	0.37	0.18	1.17	1.21
Quinlan	5	0.15	0.07	1.49	0.55
Renfrow	11	0.37	0.19	1.15	1.54
St. Paul	1	0.29	0.14	1.26	0.85
Stephenville	11	0.12	0.05	1.48	0.46
Summit	7	0.48	0.26	1.09	2.98
Tivoli	5	0.09	0.04	1.51	0.22
Yahola	4	0.18	0.08	1.41	0.53

Note: All data, except for areas, are weighted average for 0 to 12 inches. Field capacity is water retained at –0.33 Bar Tension (cm^3/cm^3). Wilting point is water retained at –15.0 Bar Tension (cm^3/cm^3). Bulk density in units of g/cm^3.
Source: [6, 7]

The octanol/water distribution coefficient (K_{ow}) which measures a pesticide's absorptive behavior between octanol and water to predict the adsorption to soil, was available for most pesticides. K_{ow} was related to K_{oc} by an equation from the PRZM User's Manual:

$$\text{Log}\,(K_{oc}) = [\text{Log}(K_{ow})] - 0.21 \tag{2}$$

Therefore, K_{ow} which was a soil independent parameter, was combined with the percent of soil organic carbon in the soil group randomly selected for the simulation, to determine a value for K_d. Pesticide retardance was calculated for the upper soil horizon which was selected to be equivalent to the 12-inch deep root zone for wheat. Pesticide persistence was defined by the decay coefficient (K_s) which was also available from the PRZM User's Manual.

The nine Curve Number, K_{oc} and K_s values from Table 2 formed twenty-seven possible combinations of pesticide and site specific parameters. The range of these combinations was inclusive of all probable conditions to be found in the study areas. In an earlier study, Carsel et al. determined that 500 years of simulation would achieve a steady-state outcome, therefore, for the initial effort, it was

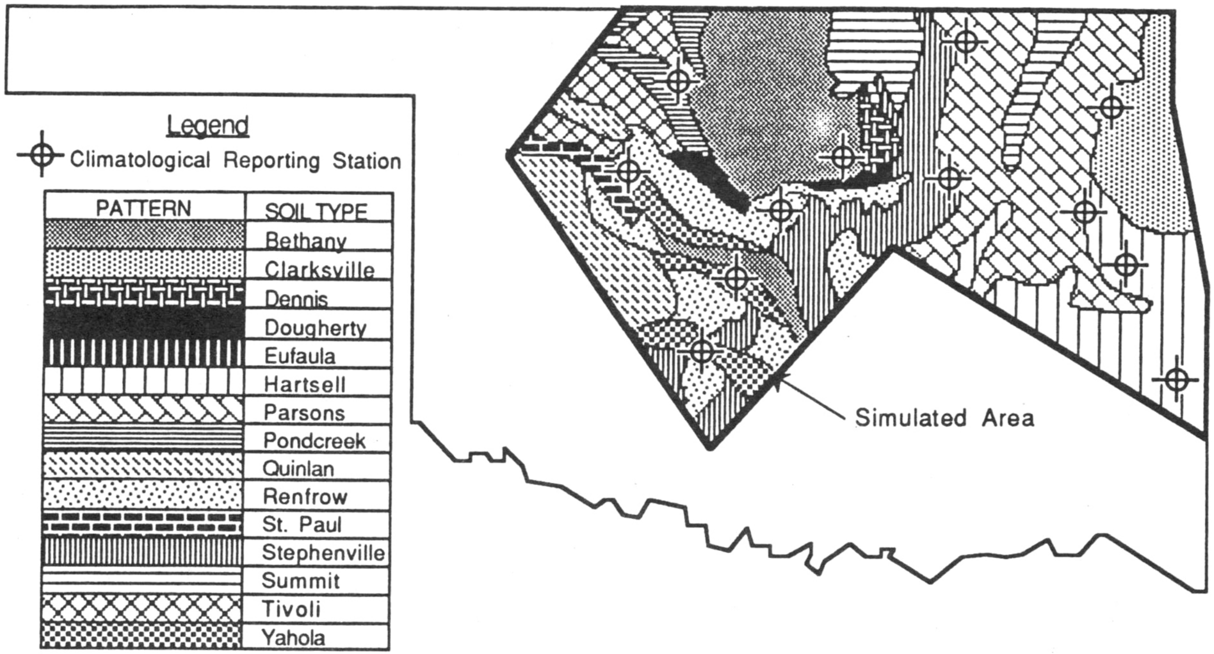


Figure 2. Simulated parameters.

decided to model twenty years for each combination of fixed parameters resulting in 540 computer simulations [9].

The percentage of the applied pesticide that was predicted to leach past the root zone at an average Curve Number of 73 for all appropriate simulations was evaluated with probability analysis. The value associated with a 50 percent probability was used to determine a specific pesticide's propensity for leaching. It was assumed, for this preliminary effort, that the amount of a specific pesticide which leached past the root zone was representative of its relative potential for groundwater contamination. The pesticides which resulted in significant leaching are presented in Table 4.

Pesticide Toxicity

The toxicity of contaminants is an important consideration in the assessment of risk. Olivieri, Eisenberg, and Cooper applied toxicity values to a relative ranking method for priority ranking of hazardous waste sites [16]. The most comprehensive measure of chronic toxicity currently available is the Environmental Protection Agency's Reference Doses (RFD) which were obtained for significant pesticides.

Factoring the Reference Doses into the index required that they be transformed to a distribution compatible with the previously described input data. This was necessary because multiplication of the index by the widely varying Reference Dose values would have overemphasized some of the data. It was desired to manipulate the distribution of the Pesticide Transport Hazard Index to one similar to that obtained by the DRASTIC Index in order to minimize subsequent interpolation or weighting. Several transform functions were investigated and the one deemed most appropriate was used to convert the Reference Doses to a Transformed Reference Dose (TRfD) by

$$\mathrm{TRfD} = (\mathrm{Rfd})^{0.5} \tag{3}$$

Table 4. Pesticide Toxicity and Leaching

Pesticide	Reference Dose (mg/Kg/day)	Transformed Reference Dose	Percent Leached
Dicamba	0.00013	87.70	20
Carbofuran	0.005	14.14	15
Diuron	0.002	22.36	2
Propazine	0.005	14.14	1
Atrazine	0.00035	53.45	10
2,4-D	0.01	10.00	0.002

The Reference Dose for each pesticide that was predicted to leach, along with the Transformed Reference Dose values are also presented in Table 4.

Calculation of Index

The Pesticide Transport Hazard Index was designed to give a relative indication as to the risk involved in possible exposure to toxic pesticides in the groundwater. Since pesticide usage was not calculated at each node on the state grid, but by counties, the Pesticide Transport Hazard Index was also determined on a county basis. In order to assign the index value for a county to each node occurring in the county, the land area was factored into the equation. This provided equal importance to the differently sized counties. The Pesticide Transport Hazard Index (PTHI) for each county was calculated by

$$PTHI = \frac{\Sigma(\text{Pest Tran TRfD})}{A}(1189.0707) \tag{4}$$

where

Pest is the annual amount of a particular pesticide used in a county in pounds of active ingredient.

Tran is the fraction of that pesticide that is transported below the root zone as defined by the Monte Carlo Method.

TRfD is the hazard of the pesticide as defined by the Transformed Reference Dose toxicity from Equation 3.

1189.0707 is a scalar.

All pesticides that were identified by the Monte Carlo method to be transported past the root zone were used in Equation (4). It was predetermined that the Pesticide Transport Hazard Index had an importance equal to that of the Physical Index in the total assessment of risk, so a scalar was determined which made the maximum county vale of PTHI equal to the maximum nodal value for the Physical Index. The PTHI for each county was assigned to all nodes that were inside county lines. Nodes within five miles of county lines were given an average for the adjoining counties.

Human Exposure to Hazards

The third part of the Pesticide Risk Index is the Exposure Index which is a relative measure of the potential for human exposure to pesticide contaminated groundwater. Information that was to be considered by this index included groundwater consumption rates and population totals. The formula used to estimate the Exposure Index was

$$EI = [(\text{Pop } 10^{-6}) + 1] \cdot GW \cdot 116.6422 \tag{5}$$

where

EI is the unitless Exposure Index.

Pop is the county's population.

GW is the fraction of municipal water that originates from groundwater sources.

116.6422 is a scalar.

The scalar again serves the function of equalizing the Exposure Index's maximum value to that of the Physical Index and Pesticide Transport Hazard Index, allowing equal weight to all three indices.

County populations were transformed to a number which would give extra weight (50% of the total) to counties containing 500,000 or more people. Less populous counties were weighted accordingly in this equation. Population statistics and water consumption information were obtained from Bureau of Census estimates and the Water Atlas of Oklahoma, respectively [5]. Due to the nature of the relevant data, the Exposure Index, like the Pesticide Transport Hazard Index, was also calculated on a county basis and assigned to the appropriate nodes.

Summation of Contributing Indices

The Pesticide Risk Index which is a relative measure of the risk from human exposure to pesticide contaminated groundwater was calculated by the equation

$$PRI = PI + PTHI + EI \qquad (6)$$

where

PRI is the Pesticide Risk Index

PI is the Physical Index

Other terms are as previously defined

RESULTS AND DISCUSSION

Monte Carlo Simulation

A sensitivity analysis of the results for all 540 PRZM simulations indicated that pesticide leaching was most sensitive to the organic carbon distribution coefficient, K_{oc}. The decay coefficient, K_s, and Curve Numbers were also determinate factors but not to the same extent as K_{oc}. Figure 3, which presents the results for simulations having an average Curve Number of 73, was used to determine leaching potentials for the specific pesticides. Extreme leaching was only reported in Figure 3 at K_{oc} of two, however, intermediate values of K_{oc}, which were interpreted on a log scale, also resulted in significant leaching.

Common pesticide selections which may present hazards, based on this Monte Carlo Analysis, include dicamba, carbofuran, and atrazine. Dicamba was used primarily on wheat in the central and western parts of the state. This could present

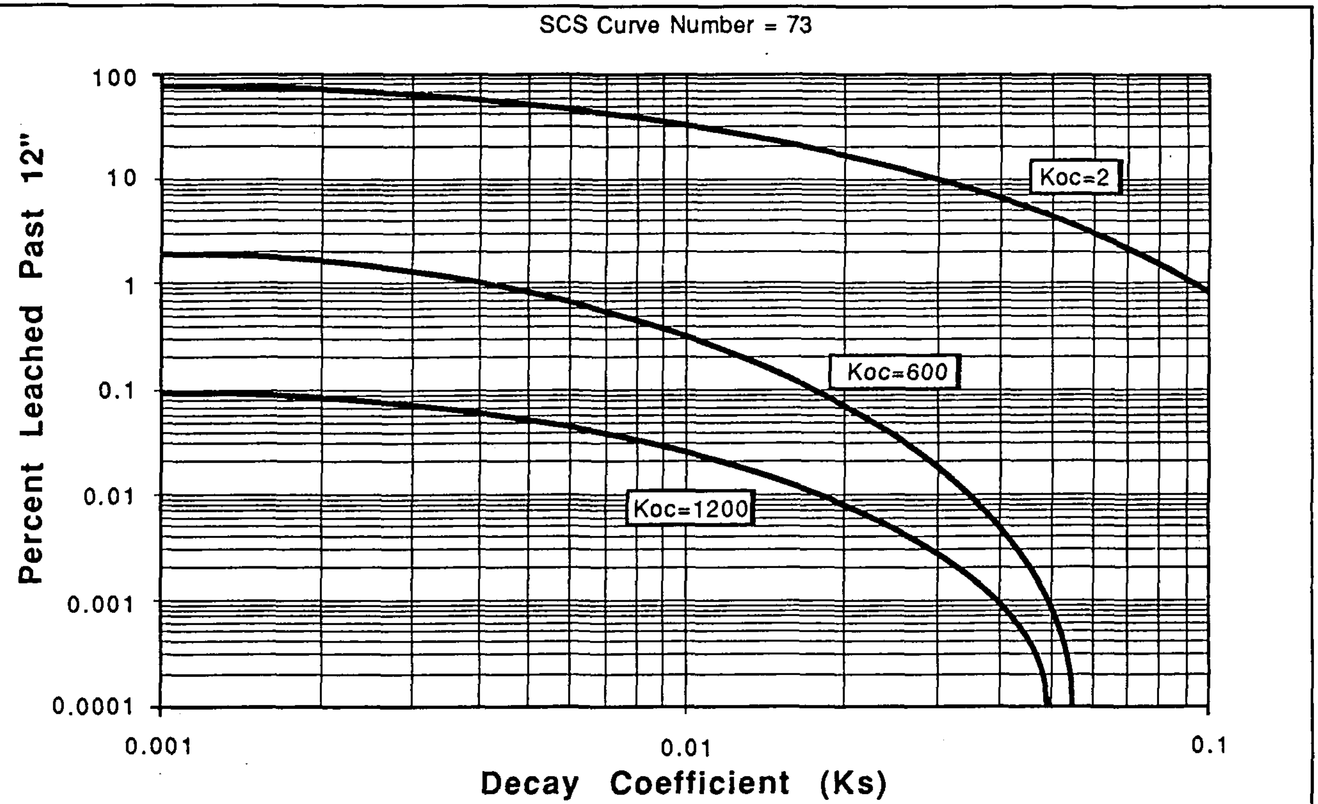


Figure 3. Monte Carlo Results for Oklahoma.

a contamination potential for soils exhibiting high infiltration and low run-off characteristics. In particular, wheat fields in the north-central areas of Oklahoma, located on alluvial or terrace deposits that are sources of drinking water, may present a high risk potential.

Carbofuran is applied to alfalfa and peanut crops in Oklahoma. Many peanut fields are located on alluvial sandy deposits in the western-central part of the state and these may be potential sites for contamination.

Atrazine, which is more commonly used on sorghum and corn fields, is more often applied to finer grained soils which would result in a lowered potential for leaching. However, incidents of groundwater contamination from atrazine might occur in highly susceptible areas.

Pesticide Risk Index

Spatial Comparisons

The nodal points were assigned their respective values for the three contributing indices and the resulting distributions were contoured and shaded as shown in Figure 4. Similar areal distributions were exhibited in the Pesticide Transport Hazard Index and the Exposure Index. This indicated that regions with a reliance on groundwater often had the highest adverse potential for toxic, leaching pesticides. Specific regions which demonstrated this correlation included the panhandle, the northeastern corner, a large area in the northern-central part of the state, and to a lesser extent, the southwestern corner. One region which did not exhibit his correlation was the southern-central part of the state where groundwater was heavily consumed but relatively few pesticides were applied.

The areal distribution of the Physical Index in Figure 4 was quite different from the other two indices. The Physical Index heavily emphasized the southeastern part of the state due to the high recharge and permeable soils. The range of values for the Physical Index, 83 to 183, was relatively narrow compared to those from the Pesticide Transport Hazard Index, 3 to 183, and the Exposure Index, 0 to 183. Due to the similarities of the latter two indices and their wider ranges of values, it was predicted that their distributions would dominate the overall Pesticide Risk Index.

The Pesticide Risk Index, which is a summation of the previous three indices, is presented in Figure 5. As previously predicted the areas of major emphasis are the panhandle, the northeastern and the southwestern corners, and the northern-central parts of the state. For all 182 nodal points in Oklahoma, the maximum value was 436, the minimum was 126, the mean was 223, and the median was 237, the standard deviation was 77, and the coefficient of variation was 33. Figure 6 presents a frequency histogram of the Pesticide Risk Index along with those for the three contributing indices. The Pesticide Risk Index presented a bi-nodal distribution which resulted from the summation of the distributions of the contributing indices which were either highly skewed or bi-modal.

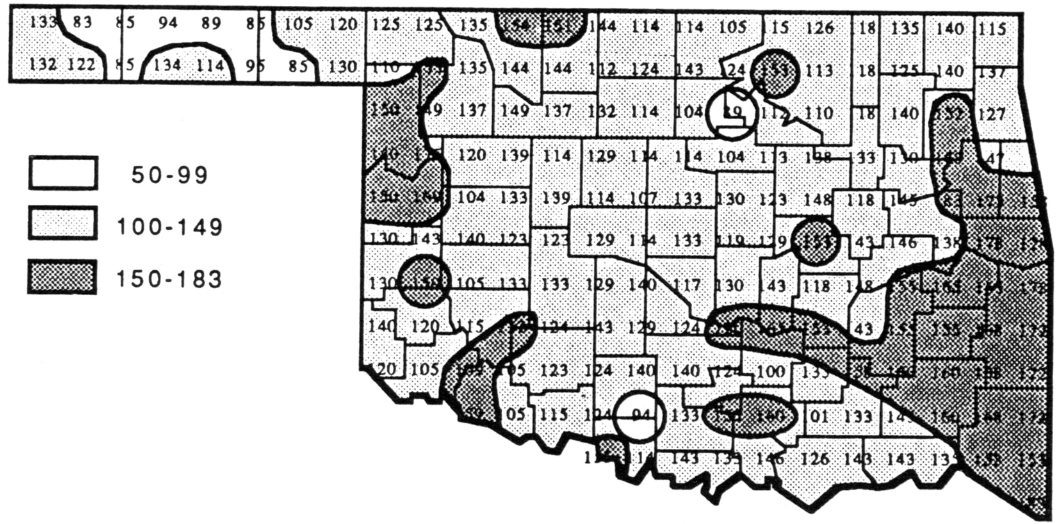


Figure 4. (a) Physical Index.

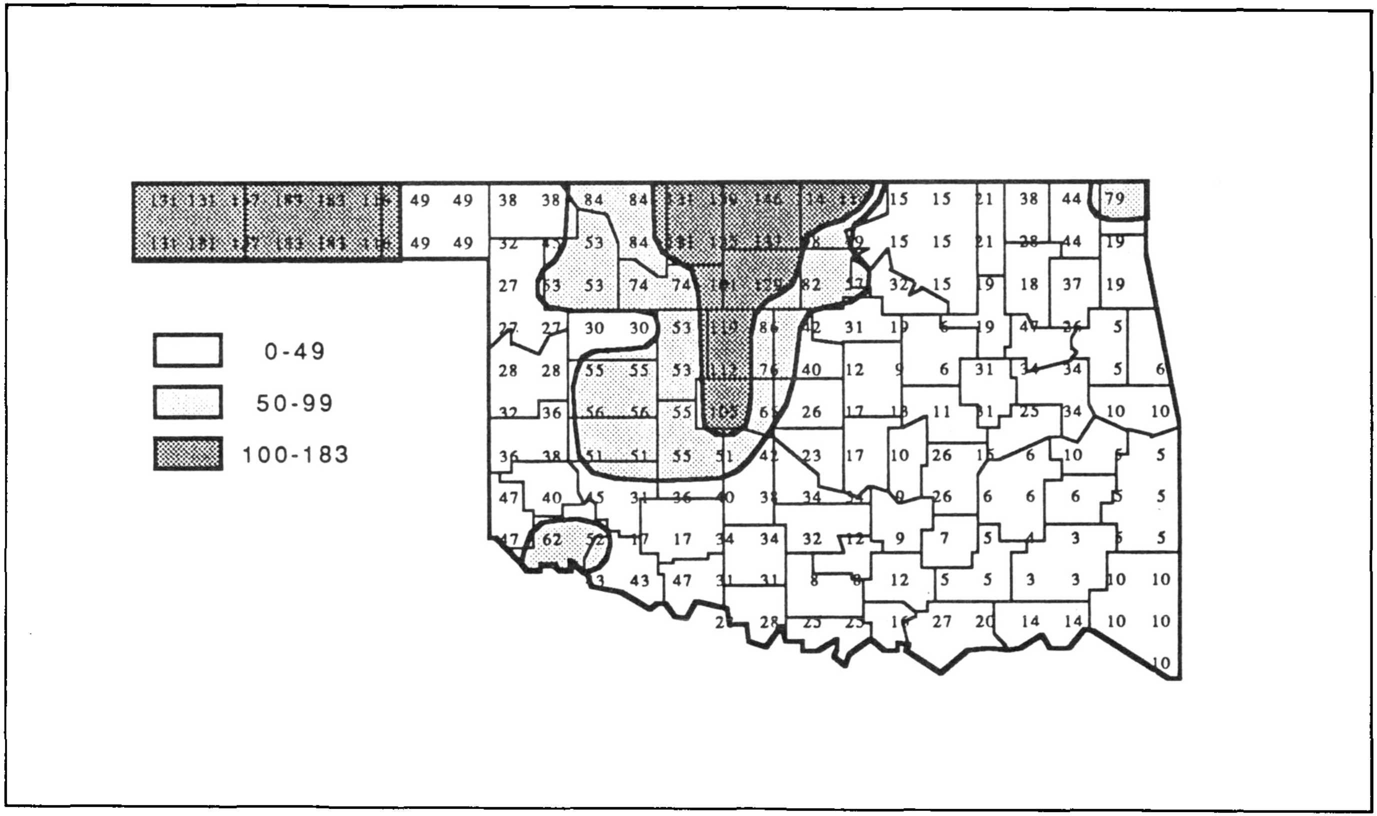


Figure 4. (b) Pesticide Transport Hazard Index.

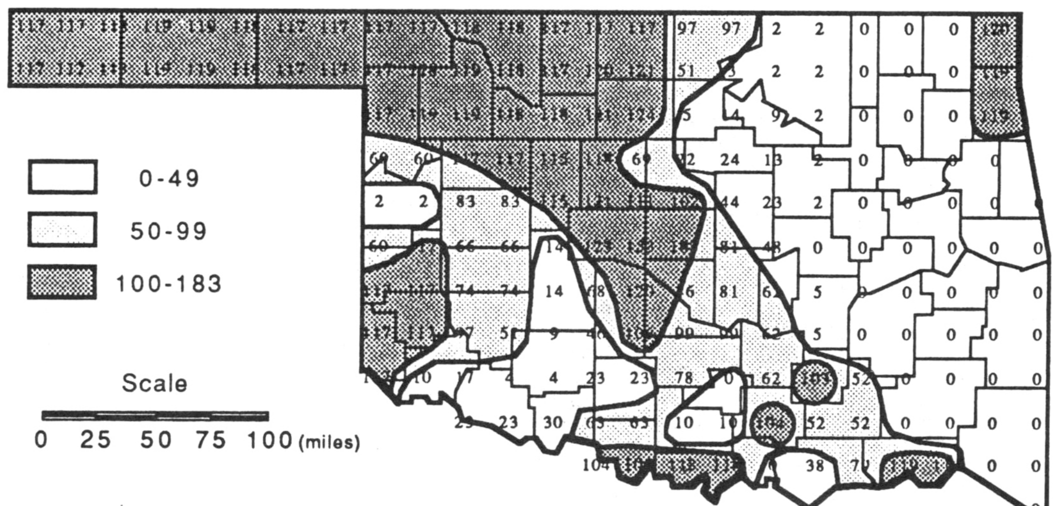


Figure 4. (c) Exposure Index.

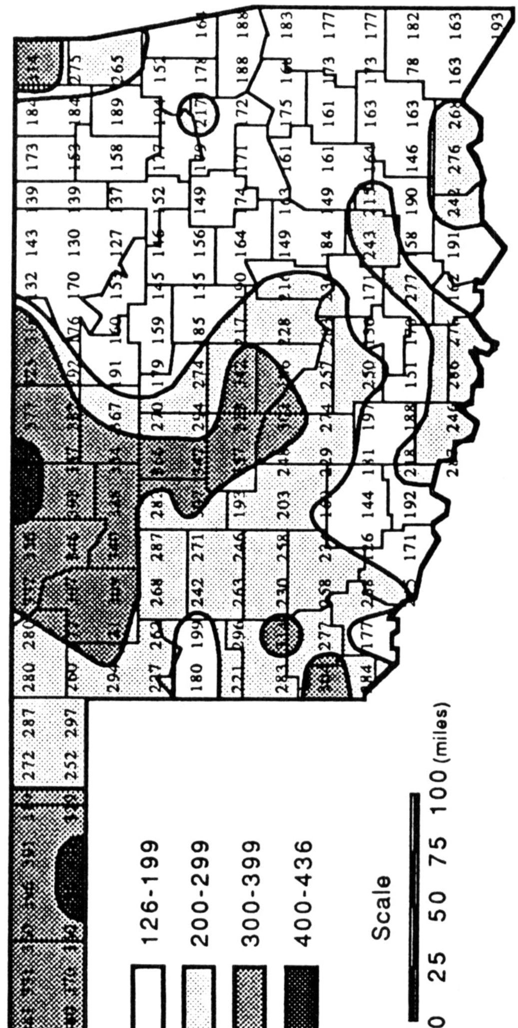


Figure 5.

Sensitivity Analysis

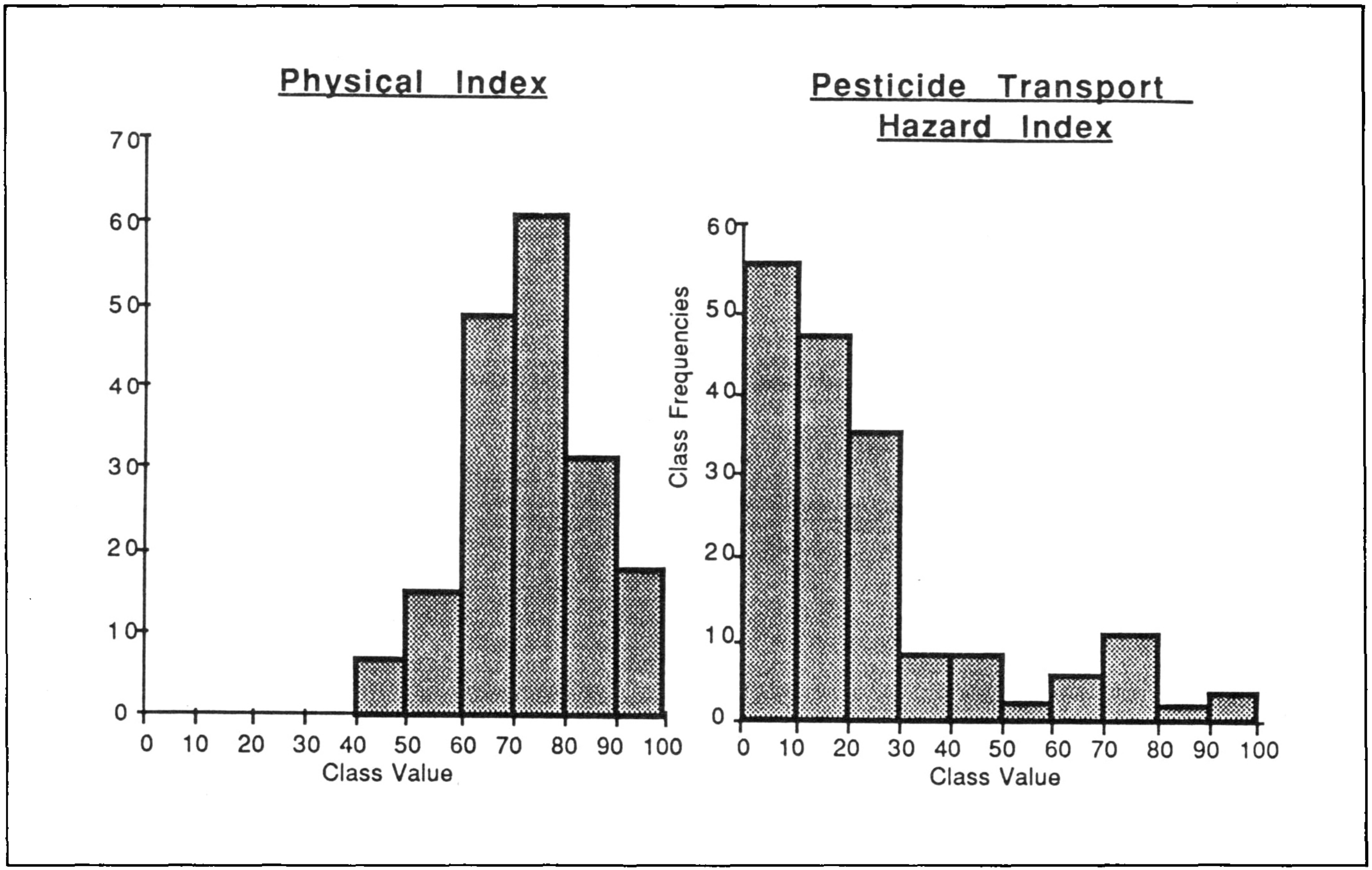
The Pesticide Risk Index was analyzed for sensitivity in three different groups. The nodes having the ten highest values for the Index had relatively equally balanced compositions of the three indices, representing an average of 30, 32, and 38 percent of the total indices. The lowest valued ten nodes were predominantly composed of the Physical Index, that is 84 percent of their total index represents contamination susceptibility, whereas the Exposure Index in the low nodes was very small. This was to be expected since utilization of groundwater in a particular area is normally either considerable or practically nonexistent. Agricultural activity also tends to have a distribution similar to groundwater usage. Therefore, by generalizing that western Oklahoma has high groundwater consumption and agricultural activity, whereas eastern Oklahoma has little of either, the occurrence of high and low index values in the western and eastern portions of the state respectively can be explained. The Pesticide Risk Index resulted in the most nodes having high or low values, and only a few nodes with medium range values due to the above described distributions of agricultural activity and groundwater usage. This resulted in the bi-modal distribution of the output for the index. The sensitivity analysis for ten nodes picked at random showed most sensitivity to the Physical Index, on the order of 66 percent of the total, however, the Physical Index was not the controlling factor due to its dominance by the other two indices.

The Meaning of the Index

The largest of the four high-risk areas indicated in Figure 5 occurred in the northern-central part of the state and was the result of high levels of toxic pesticides that exhibited high probabilities for leaching and the heavy reliance on groundwater in this area. The Physical Index contains only moderate values in the majority of this region so susceptibility to contamination should not be a widespread concern there. There were, however, two counties in this area, Woods and Alfalfa, that presented a moderately high Physical Index due to the presence of several alluvial aquifers. Therefore, the possibility exists for human exposure to pesticide contaminated groundwater in this region. A specific instance of drinking water extraction from a shallow alluvial aquifer which is near agricultural production in Alfalfa County is cautioned against due to the high risk.

Another area of Oklahoma having a high Pesticide Risk Index was the panhandle. Like the previously described area, this was due to the heavy pesticide and groundwater usage. The panhandle, however, had the lowest Physical Index in Oklahoma as a result of the depth to the aquifer and the relatively impermeable aquifer and soil media. Therefore, the potential for contamination was not indicated by the index.

The next area of concern was the northeastern corner of the state. Ottawa county had the highest Pesticide Transport Index rating in Oklahoma along with a very high Exposure Index. However, as suggested by the Physical Index, this region


Physical Index
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90 100
Class Value
Pesticide Transport
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Class Value

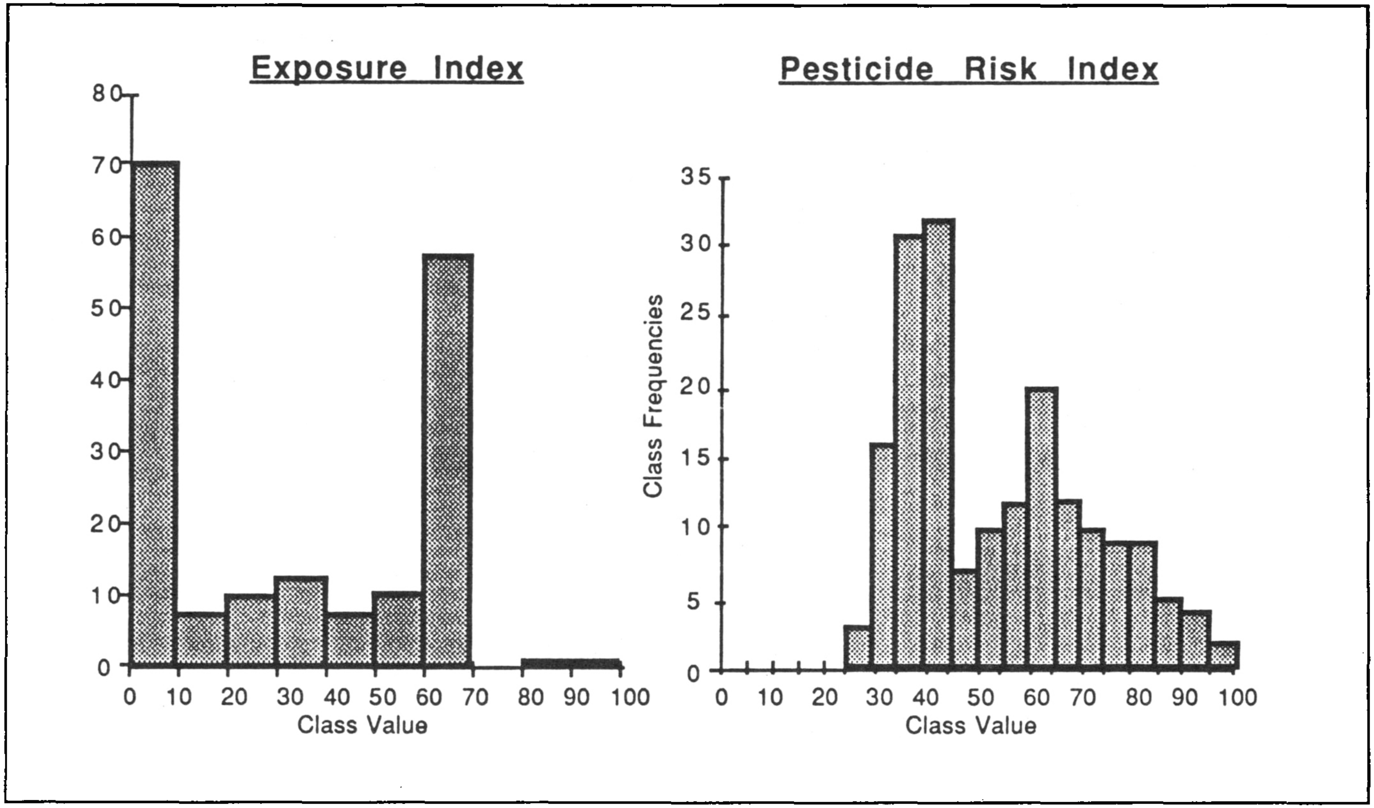

Figure 6. Index histograms.

was not highly susceptible to pesticide contamination since the majority of the water supply originates in deep and confined aquifers. On the other hand, shallow wells in rural areas of Ottawa County may pose a health hazard. Analysis for pesticide compounds in the private wells of this county as well as in the vadose zone, should clarify the hazards.

The final area designated by the Pesticide Risk Index was the southwestern corner of Oklahoma where alluvial aquifers again increase the contamination susceptibility. Pesticide applications in this area were only moderate, however, as before, separate factors might combine to create isolated bands of high risk along the alluvial aquifers of this region.

Correlations

The output of the Pesticide Risk Index should reflect the risk of human exposure to pesticides in groundwater. A higher risk would be expected in areas of major aquifers, agricultural activity, or high groundwater consumption. Correlation of risk to major aquifers can be evaluated by comparing Figure 5 with Figure 7, the latter presenting the major aquifers of Oklahoma. Areas of high risk appear to correlate closely to major aquifers except for the Vamoosa formation which extends from Osage County to Seminole County in the eastern-central area of the state. This lack of indicated risk is the result of the small percentage of drinking water drawn from this large aquifer.

Agricultural activity and heavy groundwater consumption also appear to correlate to high risk fairly consistently. Conversely, areas of dense populations do not necessarily correlate to the index. Tulsa County, which is the most densely populated county in the state, has a very low Pesticide Risk Index due in part to the lack of significant agriculture and the total reliance on surface water for municipal water supplies. However, the second most densely populated county, Oklahoma County, does have a high Pesticide Risk Index which may be attributable to the large amount of groundwater consumed.

Sources of Error

Sources of error for the Pesticide Risk Index can be grouped into three categories. Arbitrary layout of nodes and the determination of hydrogeological factors at nodal points may lead to significant distortion of results. This could be rectified by finer discreetization of the grid. Another category for sources of error includes the data. Uncertainty is associated with pesticide use, water consumption, hydraulic conductivity, vadose zone media, depth to water, and other physical factors. Also, the pesticide's descriptive constants, K_d, K_s, and the RfD are more potential sources of error. The final category of error is the Pesticide Risk Index itself. Neither DRASTIC nor PRZM are without uncertainty, and the transform functions and weights developed in this research may cause significant error. Calibration of the index through further applications would result in better assessment capabilities.

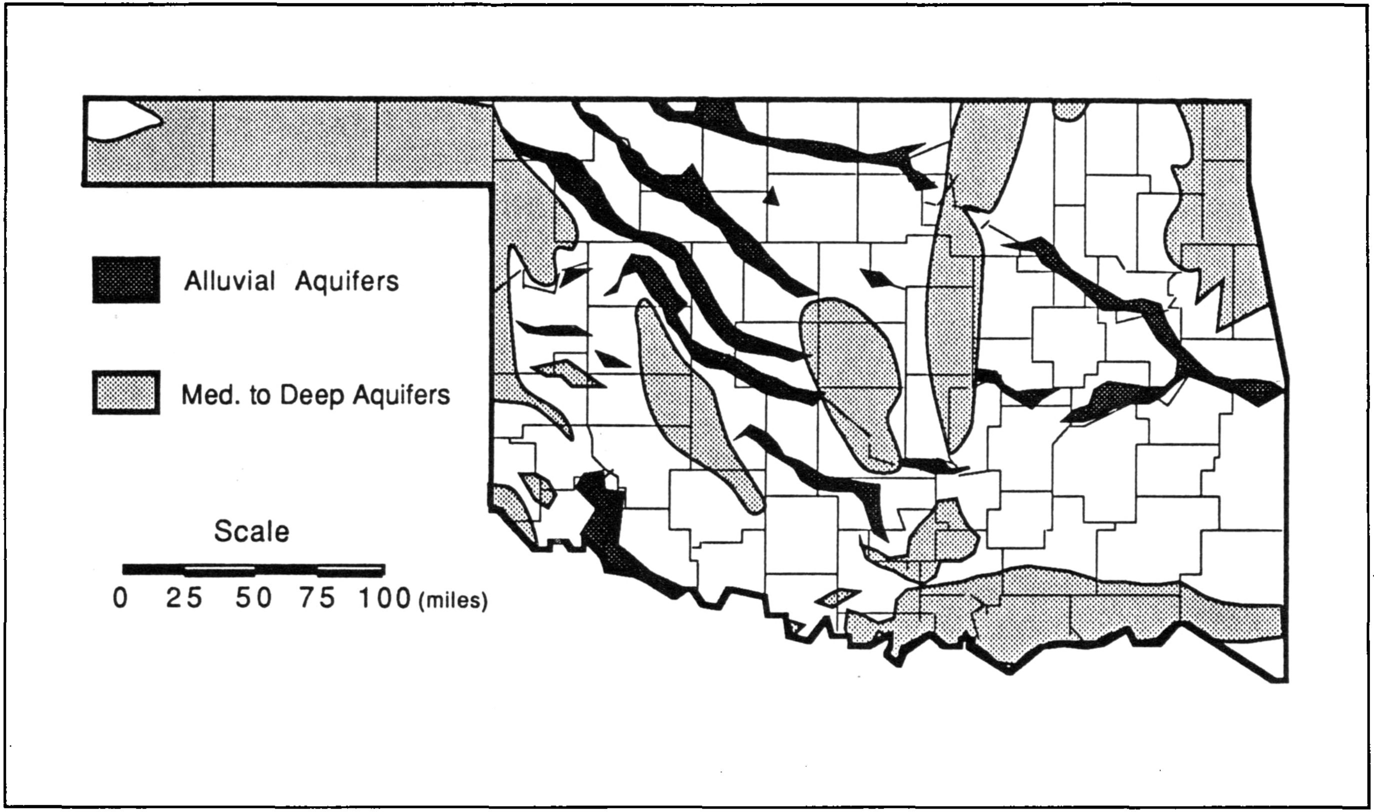

Figure 7. Major aquifers of Oklahoma.

CONCLUSIONS

The Pesticide Risk Index for the state of Oklahoma indicated that certain portions of the state had a much higher potential risk than others. Generally, western Oklahoma was high risk and eastern was low. The three indices which comprise the Pesticide Risk Index also displayed this east/west distribution except for the Physical Index which was more evenly distributed. Therefore, it can be concluded that the physical factors affecting the potential for leaching of pesticides were moderately uniform across the state, whereas pesticide use and groundwater consumption were decidedly spatially distributed. This spatial distribution was transferred to the Pesticide Risk Index which became dominated by it. The Pesticide Risk Index utilized actual data that are recognized as affecting the potential for pollution and should, therefore, afford some insight into contamination susceptibility.

After performing the prerequisite computer simulations for assessing the potential for leaching through the Monte Carlo Method, the Pesticide Risk Index becomes an easily applied method that provides useful results. Due to the constraint that cleanup of pesticide contaminated groundwater is unfeasible, prevention is the best remedy. Perhaps the greatest impediment to the solution of pesticide contamination of groundwater is the lack of knowledge about where contamination exists and what particular pesticide compounds are involved. In the recent past, the only sure way to obtain this information was to conduct broad-scale sampling programs with analysis for all possible pesticides. Due to the great expense involved in a monumental undertaking of this nature, they were seldom performed. The use of an assessment technique, like the Pesticide Risk Index, to identify areas that have the most potential for harm would provide a narrower focus for efforts to control pesticide contamination of groundwater.

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