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IDENTIFICATION OF OPTIMAL LOCATIONS FOR SAMPLING GROUND WATER FOR PESTICIDES IN THE MISSISSIPPI DELTA REGION OF EASTERN ARKANSAS

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ABSTRACT

Concerns about the presence of pesticides in the Mississippi River Valley alluvial aquifer in the Arkansas Delta have generated the need to develop a map of ground water vulnerability for this region comprised of approximately 10 million acres. Based on the availability of digital data and the scale of this study, we used a modified Pesticide DRASTIC model in a GRASS GIS environment to identify areas that were physically more sensitive to pesticide contamination than other areas within the Delta. Spatial distribution of pesticide loading was estimated from pesticide application rates in different crops and crop distribution map interpreted from satellite imagery. Relative ground water vulnerability index was expressed as a product of aquifer sensitivity index and pesticide loading index. The resulting map showing the spatial distribution of relative ground water vulnerability index values was intended for use in selecting optimal locations for sampling ground water for pesticides in the Arkansas Delta and for aid in implementing the Arkansas Agricultural Chemical Ground-Water Management Plan. The most sensitive areas in the Delta are distributed mostly along major streams where a combination of shallow depth to ground water, thin confining unit, permeable soils, and high recharge rate usually prevails. It is also in many of these areas where large acres of crops are grown, and pesticides are used. Consequently, many areas along major streams are also most vulnerable. These vulnerable areas may be targeted by planners and governmental agencies for further detailed evaluation. Uncertainties in the methodology and mapped input data, plus the dynamic nature of model factors, require continued and improved efforts in ground water vulnerability assessment for the Arkansas Delta.

INTRODUCTION

Agriculture in the Mississippi Delta region of eastern Arkansas (the Arkansas Delta) has been quite productive for decades and significantly contributes to the economies of Arkansas, Mississippi and Louisiana. The extensive plantings of agronomic crops in this region have contributed greatly to the US crop production. Currently, Arkansas ranks first in the nation in rice production, fourth in cotton, fifth in grain sorghum, and eighth in soybeans (Arkansas Agricultural Statistics Service, 1995). The topography of Arkansas is such that most of its agronomic cropland is in the Delta region. With high crop productivity in this region, pesticides including insecticides, herbicides, fungicides, and defoliants are used extensively.

The Mississippi River Valley alluvial aquifer underlies nearly all of the Arkansas Delta region, with the exception of Crowleys Ridge (Mahon and Poynter, 1993). The alluvial aquifer lies from near 0 feet to over 140 feet below the land surface (Gonthier and Mahon, 1993). More than 4 billion gallons of water were withdrawn from the alluvial aquifer per day in 1990 for irrigation, aquaculture, industry, and municipal water supplies (Holland, 1993). Water conservation and availability of high quality ground water resource within this region are vital to sustainable and enhanced agriculture, urban development, wetlands, recreation, and the maintenance of high environmental quality. However, the wide use of pesticides in the region, plus the abundance of rainfall (about 50 inches per year), the extensive irrigation (about 3 million acres of cropland are irrigated annually), the spatial complexity of soils and geological strata, and diverse crop management activities, contribute greatly to the potential for pesticide contamination of the ground water. Several pesticides, including metolachlor, bentazon, alachlor, atrazine, acifluofen, fluometuron, and diazinon, have been detected in wells in this region in recent years (Cavalier et al., 1989; Pereira and Rostad, 1990; Nichols et al., 1993; Nichols et al., 1994; Senseman, 1994). There is concern over these findings and a need to assess the vulnerability of ground water to pesticide contamination in this highly productive agricultural region so that optimal management practices and preventive measures can be taken to reduce future risks.

A large number of factors, such as land use/land cover, topography, soils, geological strata, weather, and aquifer media, are involved in the assessment of ground-water vulnerability to pesticide contamination. The interactions among these factors and their spatial and temporal variability in the landscape further complicate the prediction of pesticide fate in subsurface environment. The National Research Council (NRC) report (1993) grouped current methods for assessing ground water vulnerability into three general categories: (1) overlay and index methods, (2) methods employing process-based simulation models, and (3) statistical methods. After reviewing various current approaches to assess ground water vulnerability, the National Research Council (1993) concluded that each method has its own strengths and limitations, and none is best for all situations. Because of limitations in process-based models and because of a lack of monitoring data required for statistical methods, overlay and index methods have been developed based on assumptions that a few major factors largely control ground water vulnerability and that these factors are known and can be weighted to provide a relative evaluation (NRC, 1993).

Although numerous mathematical models have been developed to predict water and chemical movement in soils and geological materials, most process-based simulation models are generally difficult to use owing to inadequate methods of measuring and/or estimating the necessary model input parameters (Rao and Jessup, 1982). This difficulty is more severe when considering a large land area, such as the Arkansas Delta considered in this study. The Arkansas Delta encompasses all or parts of 27 counties and about 10 million acres (Fig. 1). Most numerical modeling techniques developed today for assessing ground water pollution potential rely upon the use of site-specific data for local evaluations, rather than for regional scale assessment (Evans and Myers, 1990). Furthermore, very few existing process-based simulation models have a good interface with a Geographic Information System (GIS) for spatial database management and for generating maps from model output. GIS is a useful tool that can enhance spatial assessment of ground water vulnerability, because spatial data from a variety of sources can be integrated in a GIS, manipulated and transformed to produce new derived maps that are useful for decision-making and for understanding spatial interrelationships.

Among various overlay and index methods, the DRASTIC method developed for USEPA by the American Water Well Association (Aller et al., 1985, 1987) is perhaps the best known. The wide applications of DRASTIC methodology in many areas of the U.S. and in some other counties have received both appreciation and doubt (Texas Water Commission, 1989; Banton and Villeneuve, 1989; Evans and Myers, 1990; Mullen, 1991; Scott and Smith, 1993; Smith et al., 1994; Rosen, 1994). Nevertheless, the DRASTIC method has provided a relative evaluation tool to aid in the identification of areas which are most likely to be susceptible to ground water contamination relative to one another. This method is particularly useful in large area studies (regional or state level) in viewing of data availability and interface with GIS for geographical display of assessment results. Pesticide DRASTIC - a special case of the DRASTIC for evaluating pesticides - has been recommended by the Arkansas Soil and Water Conservation Commission (1991) as the best alternative for use in Arkansas for an immediate and economical initial assessment of an area using readily available mapped data. This recommendation has been accepted by the Arkansas Agricultural Chemical Ground-Water Management Plan (ASPB, 1995). We realize, meanwhile, that the DRASTIC method does not provide absolute answers (and, in fact, it was not designed to do so), and that the method requires further improvements or use with other approaches in order to obtain a more reliable assessment.

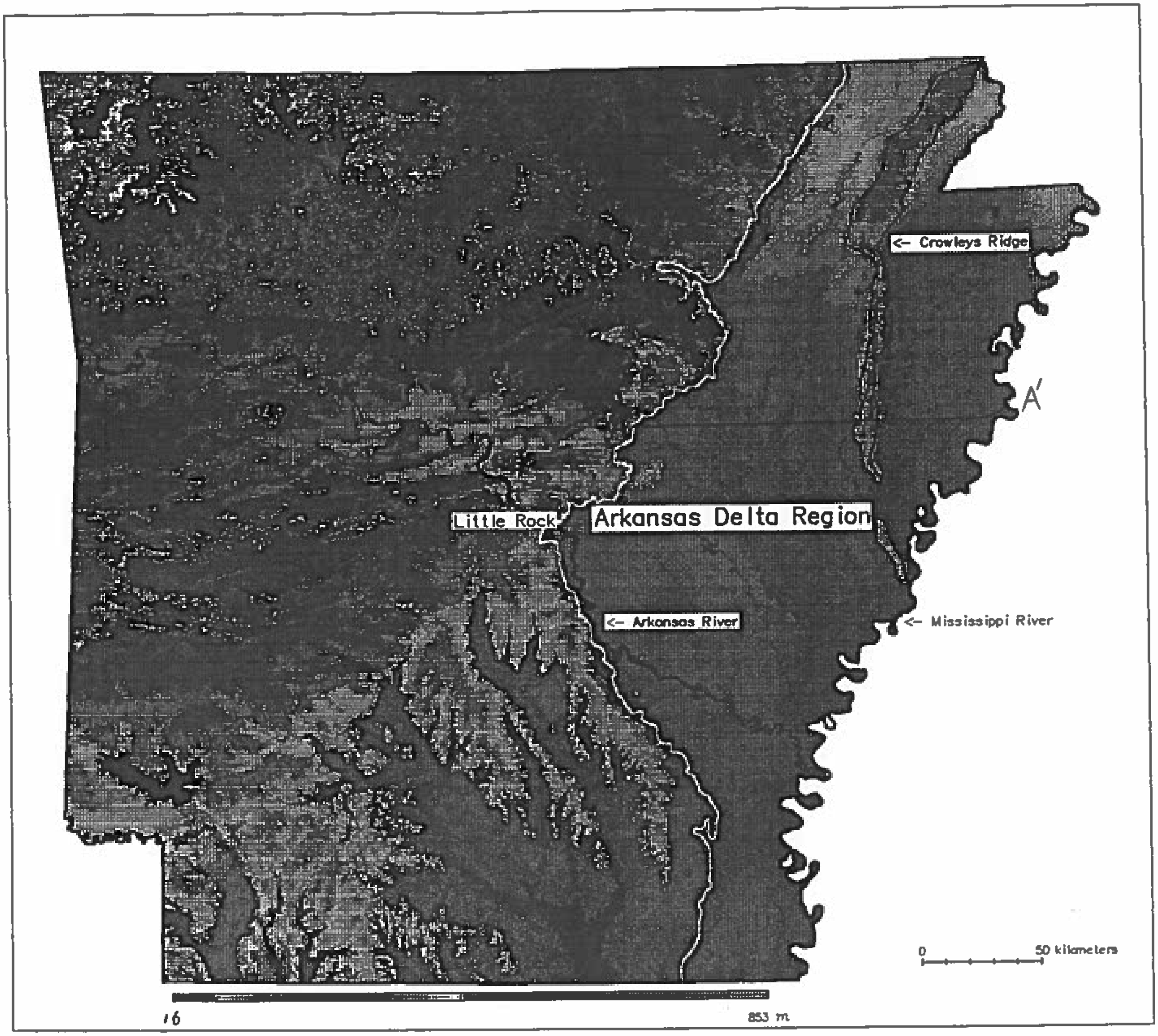

Fig. 1 Elevation map of Arkansas showing the Arkansas Delta region. Hydrogeologic section of the cross A-A' is shown in Fig. 2.

For state and federal regulatory agencies, evaluation of potential ground water contamination begins with considering those areas where pesticides are used and where the ground water is sensitive to contamination. With a large area of crops grown in the Arkansas Delta and only limited financial resources available for chemical analyses by state and federal agencies, the question of where these agencies should begin to sample and monitor the ground water for pesticides is pertinent. The selection of optimal locations for sampling and monitoring ground water is an important aspect of the Arkansas Agricultural Chemical Ground-Water Management Plan (ASPB, 1995).

To assist the implementation of the Arkansas Agricultural Chemical Ground-Water Management Plan, this study was conducted to rank the areas in the Arkansas Delta according to their relative contamination potential in the alluvial aquifer. Based on readily available mapped or digital data, a vulnerability map showing the spatial distribution of relative ground water vulnerability index values was sought using a modified Pesticide DRASTIC model. It is important to keep in mind, however, that because of the scale of this study and the lack of detailed model input parameters, this study did not intend to provide site-specific investigations, but, rather, to provide a general mechanism for comparison of different areas within the Delta with respect to ground water vulnerability to pesticide contamination. These vulnerable areas may be targeted by planners and governmental agencies for further detailed evaluation and the development of sampling strategies in the ground water monitoring program. After identifying vulnerable areas, the next step is to further evaluate the migration potential of specific pesticide under local conditions.

MATERIALS AND METHODS

Study Area

The Mississippi Delta region of eastern Arkansas encompasses all or parts of 27 counties and has 9.78 million acres of land with 68.56% in cropland in 1992. The Mississippi River Valley alluvial aquifer underlies nearly all of the region, with the exception of Crowleys Ridge. The shallow alluvial aquifer lies from near 0 feet below the land surface in some locations to over140 feet in northeastern Greene County. Several relatively large rivers, such as the Mississippi, Arkansas, White, Cache, and St. Francis, flow across the alluvial plain and exchange water with the aquifer. There are also numerous smaller streams and bayous distributed throughout the region. The elevation in the region ranges from near 25 m above the sea level in the south to 219 m in the north. The region is generally flat with 77% of the area having 0% slope and 19% area 1% slope.

The uppermost aquifer system in the Arkansas Delta is part of a much larger sedimentary system known as the Mississippi embayment (Mahon and Poynter, 1993). Deposition of sediment from the Mississippi and Arkansas Rivers during Pleistocene and Holocene time has produced a sequence of sands, silts, and clays that constitute the alluvial aquifers and semiconfining units in the Delta. From a regional perspective, this collection of sediment can be divided into two units (Fig. 2). The lower unit, which contains the alluvial aquifer, is composed of coarse sand and gravel that grades upward to fine sand. The upper unit, consisting of clay, silt, and fine sand, confines the alluvial aquifer and is often referred to as the confining unit or clay cap (Gonthier and Mahon, 1993).

Because of the depositional conditions of the alluvial aquifer and confining unit, the top and bottom of the aquifer are not planar, but are marked by numerous highs and lows (Fig. 2). Deposition of the confining unit onto the coarser alluvial aquifer deposits has reduced the relief of the land surface. Confining unit thickness varies within the study area and ranges from 0 where the unit is absent, to slightly more than 80 feet in the Grand Prairie and to about 140 feet in other locations. Thickness of the confining unit can vary substantially over short distances. The integrity of the confining unit partly governs recharge to the aquifer and is a function of the thickness of the sediments and the interconnection of transmissive sediments within the confining unit. As a result of the variability of confining unit thickness and the interconnection of the transmissive sediments, surficial recharge to the alluvial aquifer varies within the alluvial plain.

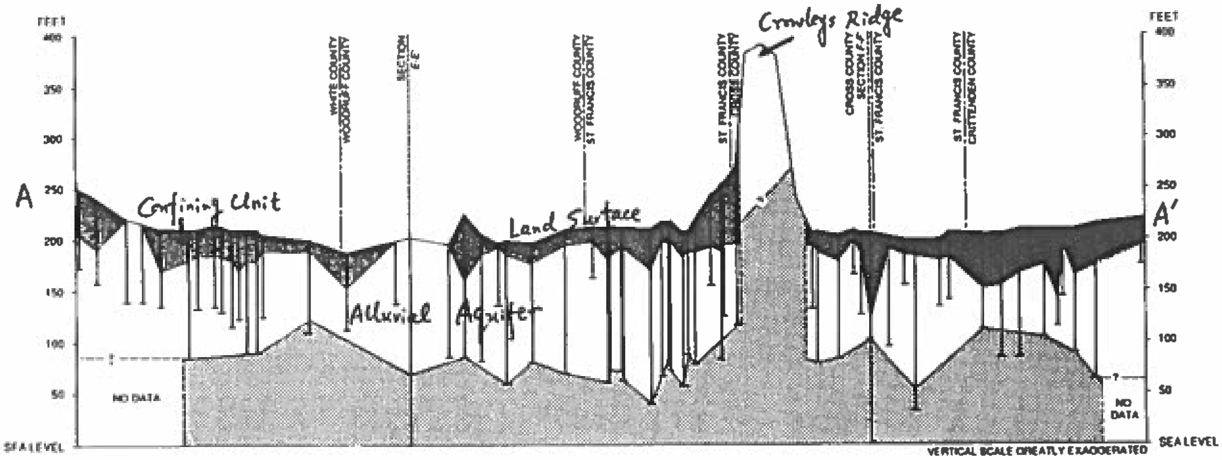

Fig. 2 Thickness of the confining unit with respect to land-surface attitude and thickness of the alluvial aquifer in the hydrogeologic cross section A-A' shown in Fig. 1. Vertical lines with "⊥" bottom are locations of wells used to obtain data (After Gonthier and Mahon, 1993).

Because the alluvial aquifer does not exist beneath Crowleys Ridge, no consideration was given to this area in this study. Crowleys Ridge significantly obstructs the flow of ground water across the ridge, and the flow from the ridge to the aquifer is considered insignificant (Mahon and Ludwig, 1990; Mahon and Poynter, 1993).

Assessment of Ground Water Vulnerability

The assessment of ground water vulnerability in this study consisted of two separate evaluations: 1) aquifer sensitivity assessment, i.e., the physical landscape parameters indicating the ease of pesticide leaching from land surface to the alluvial aquifer, and 2) pesticide loading assessment, i.e., the likelihood of having a certain amount of pesticide applied to a land surface. Those areas with congruent high aquifer sensitivity and high pesticide loading were considered to be most vulnerable to pesticide contamination.

The Geographical Resources Analysis Support System (GRASS), a raster-based GIS, was used as a spatial data manager and analyzer. Primary spatial data layers used in this study and their input scale/resolution are listed in Table 1.

Table 1. Primary spatial data layers used in this study.

Data layer	Source*	Scale/Resolution	Data type
Elevation	USGS	80 m	Raster
Potentiometric	USGS	Base map: 1:500,000 / 20 ft interval	Vector/contours
Recharge rate	USGS	1x1 mile grid	Site/point
Soils	NRCS	1:250,000	Vector/polygon
Thickness of confining unit	USGS	Base map 1:500,000 / 10-20 ft interval	Vector/contours
Land use/land cover	Landsat	30 m	Raster

* USGS - U.S. Geological Survey; NRCS - USDA Natural Resources Conservation Services.

1. Aquifer Sensitivity Assessment

Following the recommendation of the Arkansas Soil and Water Conservation Commission (1991), a modified Pesticide DRASTIC was used in this study to evaluate the relative sensitivity of the alluvial aquifer to pesticide contamination. This recommendation was driven largely by data availability in Arkansas and expert judgment. The sensitivity assessment was not directed toward any particular pesticide or family of pesticides. Further assessment of potential contamination by a specific pesticide can be performed using process-based simulation models after identifying vulnerable areas in the Delta.

The DRASTIC index (DI) was calculated by (Aller et al., 1985, 1987)

$$DI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \qquad [1]$$

where D = depth to ground water, R = (net) recharge, A = aquifer media, S = soil media, T = topography (slope), I = impact of the vadose zone, and C = hydraulic conductivity of the aquifer. These factors have been arranged to form the acronym, DRASTIC. Each factor considered in the DRASTIC model was evaluated with respect to the other model factors and assigned a relative weight (w) ranging from 1 to 5. For agricultural usage of pesticides, the relative weights of the factors are: $D_w = 5$, $R_w = 4$, $A_w = 3$, $S_w = 5$, $T_w = 3$, $I_w = 4$, $C_w = 2$ (Aller et al., 1987). The selection of weights was accomplished by the expert committee using a Delphi (consensus) approach (Aller et al., 1985; Dee et al., 1973). Within each factor, ranges of characteristics were evaluated and assigned a relative rating (r) varying between 1 and 10. This rating system is essentially a classification scheme for each model factor. Similar classification systems have a fairly long tradition in geology and soil surveys.

Modifications were made to the original Pesticide DRASTIC. Thickness of the confining unit overlying the alluvial aquifer, instead of the type of geological material, was used to represent the impact of the vadose zone. Because similar type of sediments overlies the aquifer in the study area. Thickness of the confining unit partly governs the recharge to the aquifer and pesticide adsorption/degradation processes in the vadose zone, and thus, the potential for a pesticide to reach the ground water. The weight of the impact of vadose zone (i.e., I_w in Eq. [1]) was increased from original 4 to 7, because expert judgment of the Arkansas Ground Water Protection and Management Committee considered this factor to be more important than other factors in determining the aquifer sensitivity in the Arkansas Delta. The use of qualitative soil textural class to assign ratings for soil media was replaced by the use of soil fabric permeability estimated from soil texture and structure. More detailed ratings were also used for net recharge rate. The listings of ratings and criteria for the modified factors are shown in Table 2. The ratings and criteria for other Pesticide DRASTIC factors were adopted from Aller et al. (1987).

The aquifer sensitivity index (SI) was expressed by scaling the DI to a range of 0 to 100:

$$SI = (DI / DI_{max}) * 100 \qquad [2]$$

Table 2. List of ranges and ratings for the impact of the vadose zone, soil media and net recharge rate in the modified Pesticide DRASTIC.

Confining unit thickness (feet)		Soil permeability (inch/hour)		Net recharge rate (inch/year)	
Range	Rating	Range	Rating	Range	Rating
0	10	> 20	10	> 20	10
1-5	9	6-20	9	11-20	9
6-10	8	2-6	7	8-10	8
11-20	7	0.6-2	5	5-7	6
21-30	6	0.2-0.6	3	3-4	3
31-40	5	0.06-0.2	2	0-2	1
41-50	4	< 0.06	1		
51-75	3				
76-100	2				
> 100	1				

where DI_{max} is the maximum DRASTIC index (i.e., 290). To facilitate data analysis, the SI was then grouped into ten classes with SI = 90-100 the highest class and SI = 0-9 the lowest class. The implementation of the Pesticide DRASTIC model in the GRASS GIS environment is described in the following.

1) Depth to ground water (D)

Depth to ground water was calculated by subtracting potentiometric surface values from elevation data. Because the ground-water depth fluctuates seasonally and in response to pumping, a source of uncertainty is inherent. We used the most recent available data - the potentiometric surface of Spring 1992 (Westfield and Poynter, 1994). This potentiometric surface was recorded in contour lines at 20-feet interval. To use this data layer for raster map calculation, the contour lines were interpolated into a full surface using a surface modeling function in GRASS, called regularized spline with tension (s.surf.tps, Matasova, 1992). The optimal parameters set in s.surf.tps calculation for this data layer were: tension = 120, smoothing value = 0.01, segmax = 40, and npmin = 150. Because of the noise in measured data and possible limitations in the surface interpolation algorithm, a few areas (mostly along rivers and streams) had potentiometric value exceeding elevation value. In this case, depth to ground water was assumed to be zero. The resulting map of depth to ground water for the Delta region is shown in Fig. 3.

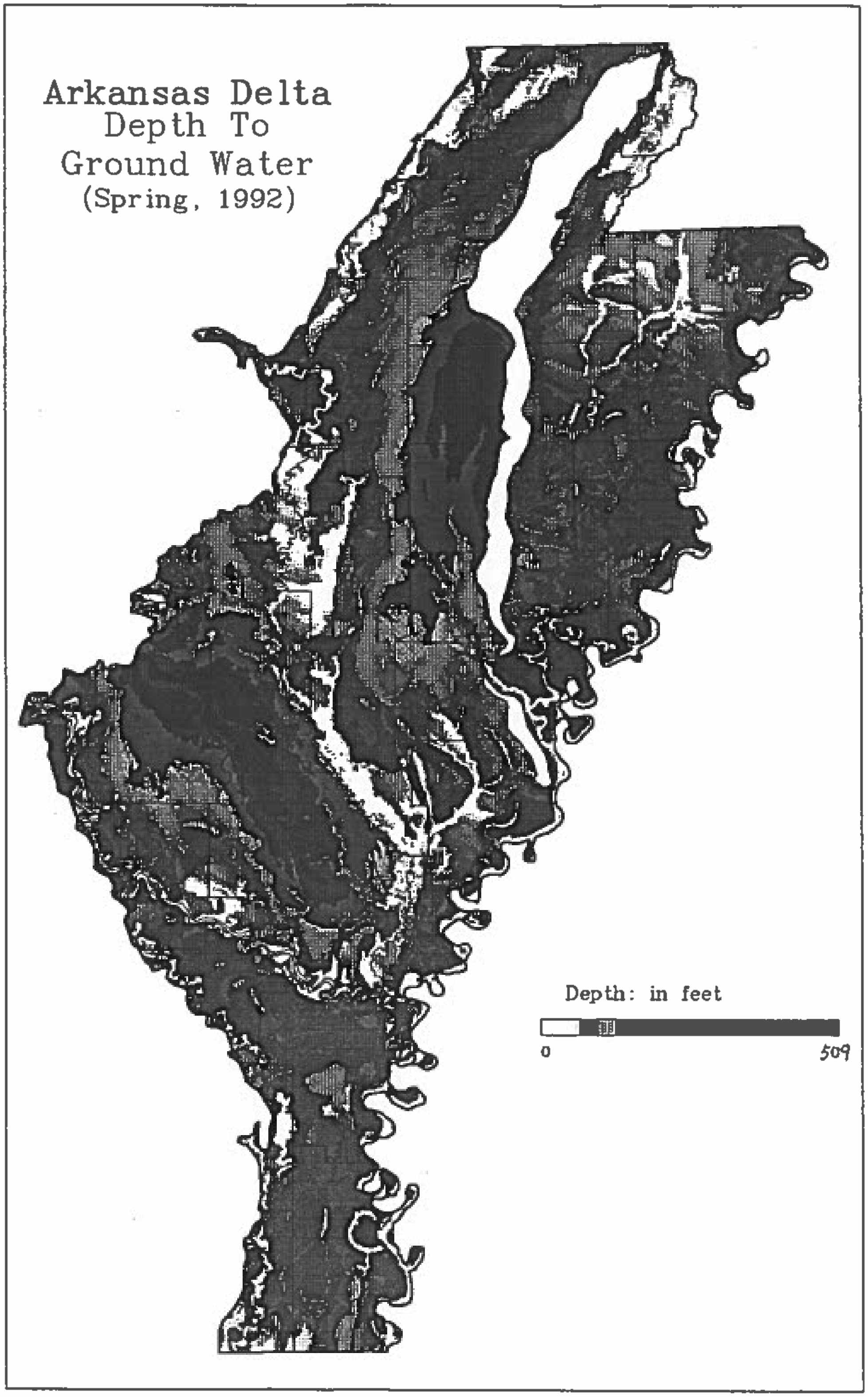

Fig. 3 Spatial distribution of the depth to the alluvial aquifer in the Arkansas Delta.

2) Recharge rate (R)

Net recharge rate was obtained from USGS for the entire Mississippi River Valley alluvial aquifer. Net recharge rate was calculated based on the past behavior (water level change) of the alluvial aquifer using the MODFLOW model at a one-square-mile cell scale (Mahon and Poynter, 1993). The MODFLOW model simulated ground water flow in one layer with recharge entering the aquifer from surface infiltration through the overlying confining unit and from seepage through riverbeds. The one-square-mile grid site file was interpolated into a full surface using the regularized spline with tension approach (s.surf.tps, Fig. 4).

3) Soil media (S)

Because of the unavailability of county-level soil maps (SSURGO) for the study area, the state-level soil map (STATSGO) was used in this study. The general state soil map provides an overview of the distribution and extent of the dominant soils in the region. While such a generalized soil map is useful in general planning and in identifying relatively vulnerable areas in regions such as the Delta, more detailed soil maps, i.e. SSURGO, should be used for refining the assessment once they become available.

Soils in the Delta were mostly developed in deep, clayey or loamy alluvial sediments. Many of them are structured to some extent. Because of the lack of field-measured soil hydraulic properties, estimated soil permeability values from the SOILS5 database (National Soil Survey Center, Lincoln, NE) were used in this study to indicate the potential capacity of a soil to transmit pesticide vertically from land surface down to the bottom of a solum (usually 60 feet deep). Seven permeability classes are used in the SOILS5 database, i.e., very slow (<0.06 in/hr), slow (0.06-0.2), moderately slow (0.2-0.6), moderate (0.6-2), moderately rapid (2-6), rapid (6-20), and very rapid (>20). The existing permeability values, however, were estimated based primarily on soil textural consideration. We thus called them matrix permeability. In reality, soil permeability is influenced not only by texture, but also by soil structure, bulk density, and the size and continuity of large pores. Increasing evidences have shown that field-applied pesticides may reach ground water quicker than would be expected from uniform movement through the soil matrix because of by-pass or preferential flow (Flury, 1996; Beven and Germann, 1982; Bouma, 1991). It has been shown that many fine-textured soils may transmit water through the solumn as quickly as coarse-textured soils as long as they have moderate to strong structure and/or a minimum number of channels (Coen and Wang, 1989). Soil structure often determines the extent of preferential flow in field soils (Quisenberry et al., 1993; Lin and McInnes, 1995). The possible influence of soil structure on the movement of pesticides was taken into account by adjusting matrix permeability (P_m) to fabric permeability (P_f, matrix plus macroscopic features).Considering the nature of this small scale study and the generality of the soil map used, we proposed a preliminary general

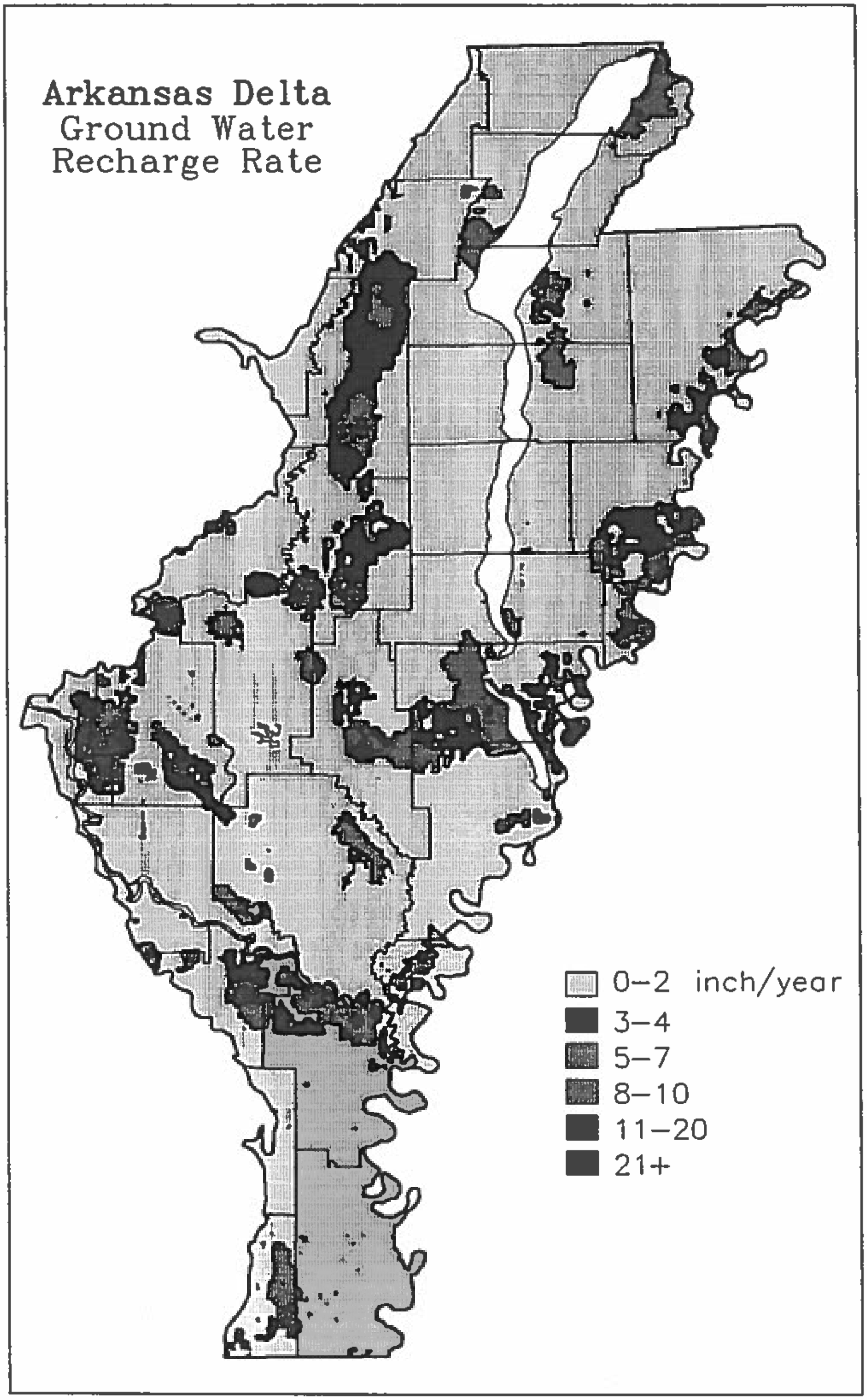

Fig. 4 Spatial distribution of net recharge rate to the alluvial aquifer in the Arkansas Delta.

guideline for adjusting P_m class to P_f class using soil structure information: if a soil horizon was structureless (massive, single grain), platy, or if the structure grade was weak, no adjustment was made; if a soil had moderate grade structure, its P_f was increased to one class higher than its P_m; if a soil layer had strong grade structure, two class higher permeability than its matrix value was assigned to this soil. For example, if a soil had a slow P_m (0.06-0.2 in/hr) because of its fine texture, but strong grade structure developed in this soil, then its estimated P_f was moderate (0.6-2 in/hr). On the other hand, we also considered the change of soil P_m from negative impacts: if a soil layer was compacted (e.g. plowpan), its P_f was adjusted to one class lower than its P_m; if a soil horizon was cemented (e.g. fragipan), its P_f was adjusted to two classes lower than what would be expected if that soil was not cemented.

Soil permeability adjustment was determined for each horizon in a profile. The effective permeability of a soil profile (P_e) was then calculated using horizon-thickness-weighted values (Jury et al., 1991):

$$P_e = \sum_{i=1}^{n} D_i \Big/ \sum_{i=1}^{n} (D_i / P_{fi}) \qquad [3]$$

where D_i is the thickness of horizon i in a soil profile, P_{fi} is the adjusted fabric permeability of horizon i, and n is the total number of soil horizons in the solum. To facilitate the calculation, the average permeability value within each class was used in Eq. [3].

Final soil permeability value for each mapping unit was obtained by aerially averaging P_e of dominant soil series within a mapping unit. The spatial distribution of soil fabric permeability (P_e) used in the Pesticide DRASTIC model in the Delta is shown in Fig. 5. The soil data layer was reclassed into appropriate rates based on permeability classes (Table 2).

4) Topography (T)

The slope of an area determines the extent and the direction of water as infiltration or runoff. The elevation data layer of the Delta was utilized by GRASS to generate a map of percent slope (Fig. 6). The Arkansas Delta is generally flat with over 98% of the area having $\leq 2\%$ slope (excluding Crowleys Ridge). This suggests that the dominant flow of water and pesticide in this region should be vertical.

5) Impact of vadose zone (I)

Thickness of the confining unit overlying the alluvial aquifer, instead of the qualitative description of geological material, was used for this data layer. Thickness of the confining unit

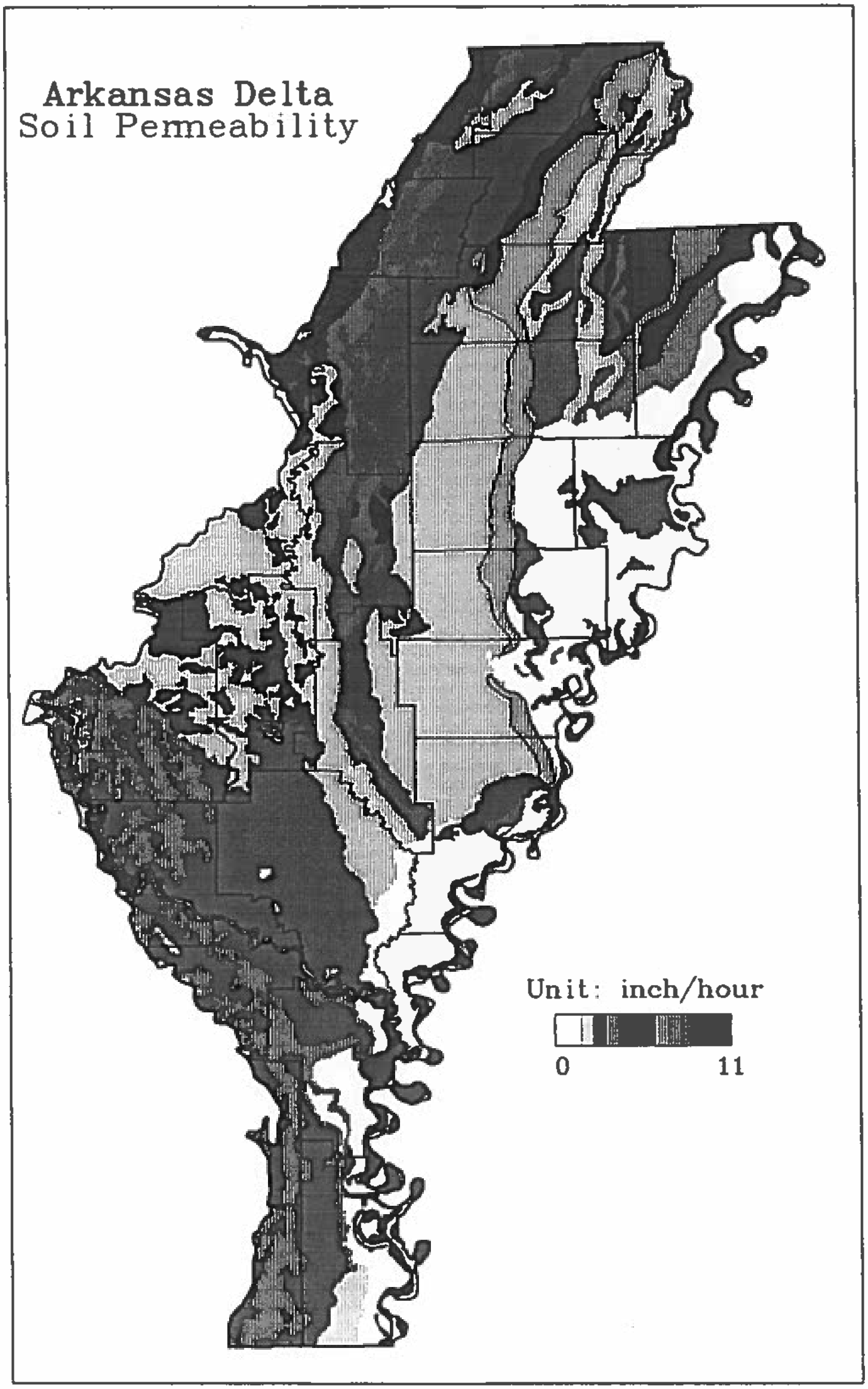

Fig. 5 Spatial distribution of soil fabric permeability in the Arkansas Delta.

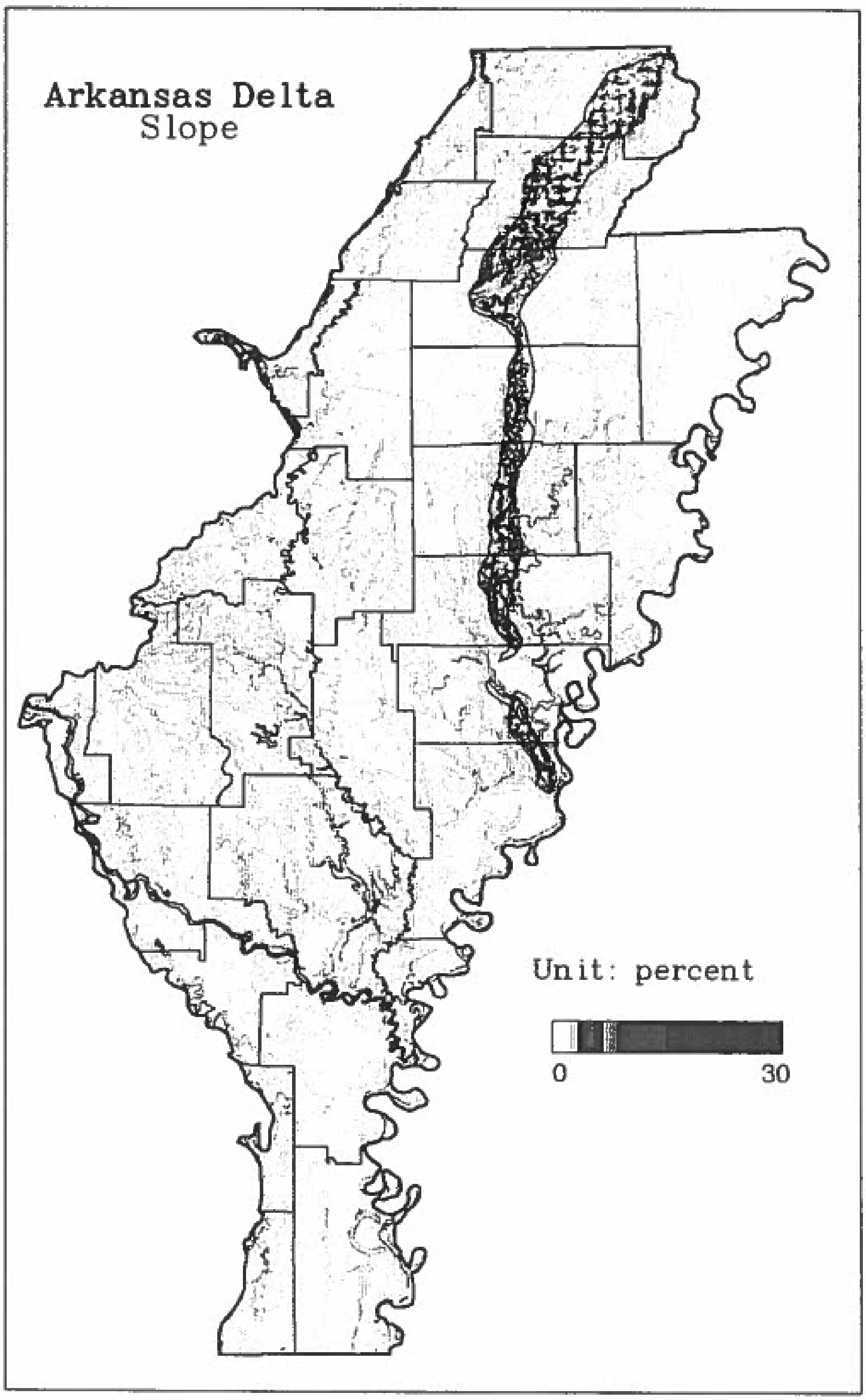

Fig. 6 Spatial distribution of the slope in the Arkansas Delta.

partly governs the recharge to the aquifer and pesticide adsorption/degradation processes in the vadose zone, and thus, the potential for a pesticide to reach the shallow ground water. Spatial interpolation was performed to extend the contour lines of confining unit thickness to a full surface using the regularized spline with tension (s.surf.tps) (Fig. 7).

6) Aquifer media (A) and aquifer hydraulic conductivity (C)

Because the same alluvial aquifer was considered throughout the study area, aquifer media factor was set to a constant in this study. A rate of 8 was assigned to the aquifer media, which consists primarily of sand and gravel (Aller et al., 1987).

The hydraulic conductivity of the aquifer is included in the DRASTIC model because it determines to some extent the rate at which ground water travels laterally through aquifer media. Since the alluvial aquifer considered in this study is consistently sand and gravel throughout, its hydraulic conductivity was estimated to be nearly a constant (2000+ gpd/ft^2, Mahon and Poynter, 1993), resulting in a constant factor in the model. A rate of 10 was used for the alluvial aquifer according to Aller et al. (1987).

2. Pesticide Loading Assessment

This assessment dealt with spatial identification of pesticide application rates in different land use/land cover areas. Satellite imagery of 1992 Landsat 5 thematic mapper (TM) was employed to identify land use and crop distribution for the Arkansas Delta. Six TM scenes (numbered 23/35, 23/36, 23/37, 24/25, 24/36, and 24/37) were mosaiced together to cover the entire region. The scenes, obtained for June and October of 1992, were corrected for atmospheric conditions among scenes and geo-referenced using USGS DLG roads. The location and aerial extent of soybean, rice, cotton, wheat, grain sorghum, corn, wooded areas, grass, and others were determined by closely examining the TM scenes. The majority of the images (~ 85% of the region) were interpreted for different crop fields and other land covers through a supervised classification process using ground truth data. Ground truth data were selected based upon field size, type of crop and location within a 7.5-minute USGS quadrangle. A representative sample from each part of the quadrangle was outlined and labeled according to crop. The field was then transferred to the computer and outlined on the black and white image map for use as ground truth data. The remainder of the region (~ 15%) was classified through an unsupervised isodata clustering routine (ISODATA in PCI Imageworks), and calibrated with the results from supervised classification in overlapped areas.

Average application rates of commonly-used pesticides for major crops grown in the Arkansas Delta were obtained from the Arkansas Cooperative Extension Service according to their pesticide use surveys in the region (Table 3). These pesticides have been classified in Arkansas as

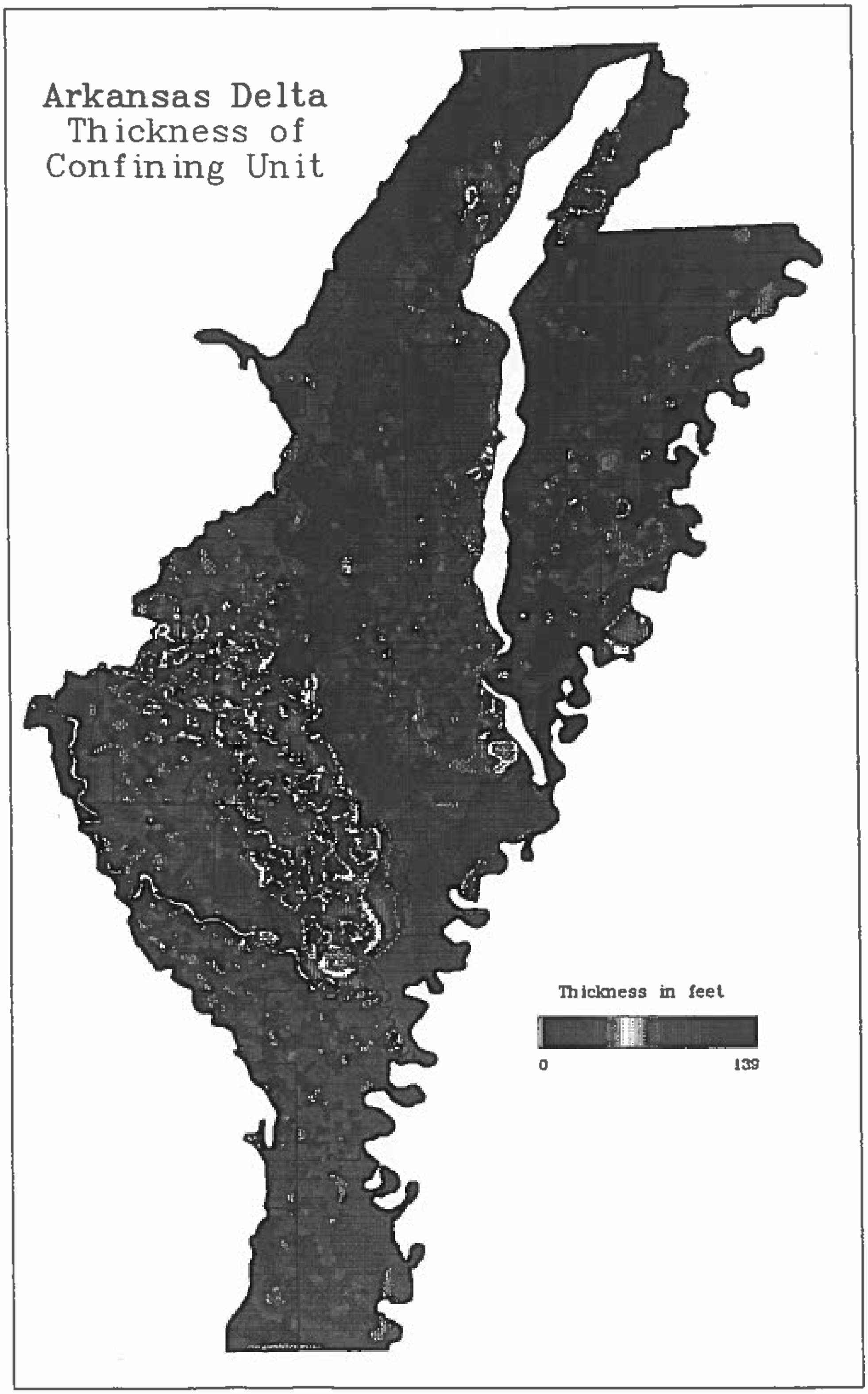

Fig. 7 Spatial distribution of the thickness of the confining unit in the Arkansas Delta.

Table 3. Average pesticide application rates for major crops grown in the Arkansas Delta in 1992. These rates were based on surveys from growers in the region conducted by the Arkansas Cooperative Extension Service.

Pesticide		Major crop					
		Soybean	Rice	Cotton	Wheat	Grain Sorghum	Corn
		------------------------- lbs ai/acre -------------------------					
Pesticides analyzed in ground water sample	2, 4-D	0.2	1.25		0.75	0.5	0.5
	Acifluorfen	0.44	0.188				
	Alachlor	3.0				2.0	2.0
	Atrazine					2.25	2.25
	Bentazon	0.75	0.75			0.75	0.75
	Cyanazine			0.8			1.6
	Diuron			1.1			
	Fluometuron			1.4			
	Linuron	0.375		0.75		0.75	
	Metolachlor	2.13		1.6		2.0	2.0
	Metribuzin	0.44			0.375		
	Molinate		4.0				
	Norflurazon			1.5			
	Subtotal	**7.335**	**6.188**	**7.15**	**1.125**	**8.25**	**9.1**
Pesticides not analyzed but applied	Aldicarb	1.0		0.3		1.0	
	Carbofuran			1.0	0.25	1.0	1.0
	Chlorimuron	0.008					
	Fomesafen	0.375					
	Imazaquin	0.11					
	Oxamyl			0.25			
	Propiconazole		0.125		0.25		
	Subtotal	**1.493**	**0.125**	**1.55**	**0.5**	**2.0**	**1.0**
Total		**8.828**	**6.313**	**8.7**	**1.625**	**10.25**	**10.1**

having either high or moderate mobility in soil. Among those pesticides, 13 pesticides are now being analyzed regularly in ground water samples in the Arkansas Agricultural Chemical Ground-Water Management Plan. Summation of application rates of pesticides applied in a given crop was used as pesticide loading index (PI) for that crop field. In a double-cropped field, the PI value was the sum of total pesticide application rates applied to both crops. For this study, no pesticides were considered to be applied on grass, forest, surface water bodies, urban areas, and layout lands in the region. Therefore, the PI for these land use/land cover categories was set to zero.

3. Relative Ground Water Vulnerability Index

Relative ground water vulnerability index (VI) was expressed as a product of the aquifer sensitivity index (SI) and the pesticide loading index (PI):

$$VI = \frac{SI * PI}{VI_{max}} * 100 \qquad [3]$$

where VI is scaled to a range of 0 to 100 by being divided by its maximum value, VI_{max} (910 in this study). To facilitate data analysis, the VI was grouped into ten classes with VI = 90-100 the highest class and VI = 0-9 the lowest class.

RESULTS AND DISCUSSION

Sensitive and Vulnerable Areas in the Region

Values of the alluvial aquifer relative sensitivity index (SI) in the Arkansas Delta ranged from 31 to 87 with a majority of the region falling in moderate classes, i.e. SI = 50-59 and SI = 60-69 (Fig. 8). The range of the relative ground water vulnerability index (VI) was from 0 where no pesticide was applied to 100 where pesticides were used most intensively in soybean-wheat double-cropped fields in the most sensitive areas (Fig. 9). The near-normal frequency distribution of both SI and VI in the region (Fig. 10) suggests that random sampling of wells would not be an efficient approach for monitoring pesticide contamination. There was 0.31% area of the Delta region having a SI ≥ 80 and 11.95% area having a SI ranging from 70 to 79. Areas with highest VI class (90-100) occupied only 0.12% of the region, and areas with relative high VI (≥ 70) were 12.56% of the region. Therefore, when resources and funds are limited, prior attention to those most sensitive or vulnerable areas for sampling and monitoring ground water will probably be a more effective approach. Obviously, caution should be taken when applying pesticides in these sensitive areas, i.e. where SI ≥ 70.

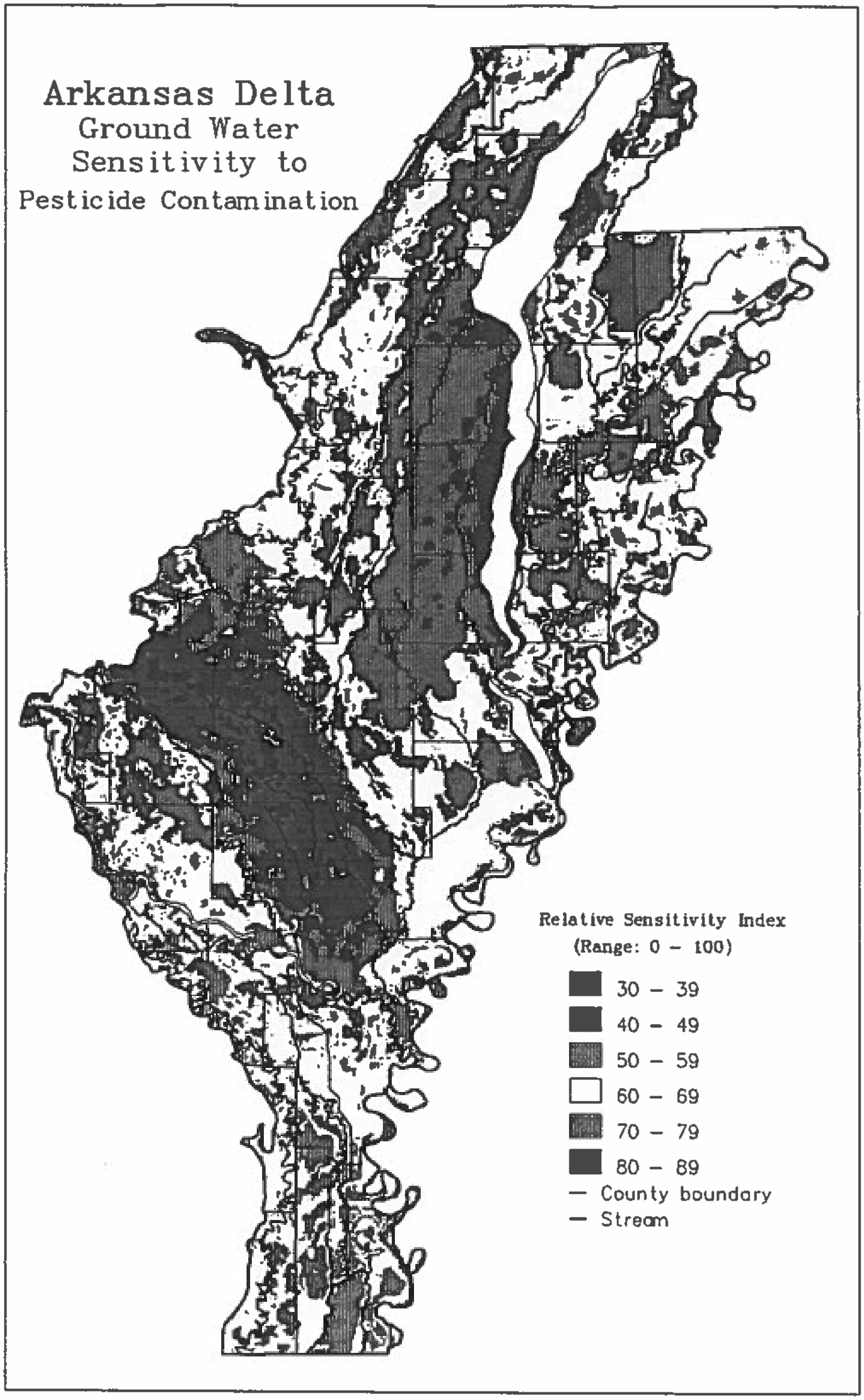

Fig. 8 Spatial distribution of the relative aquifer sensitivity index in the Arkansas Delta. The higher the index, the more sensitive the area.

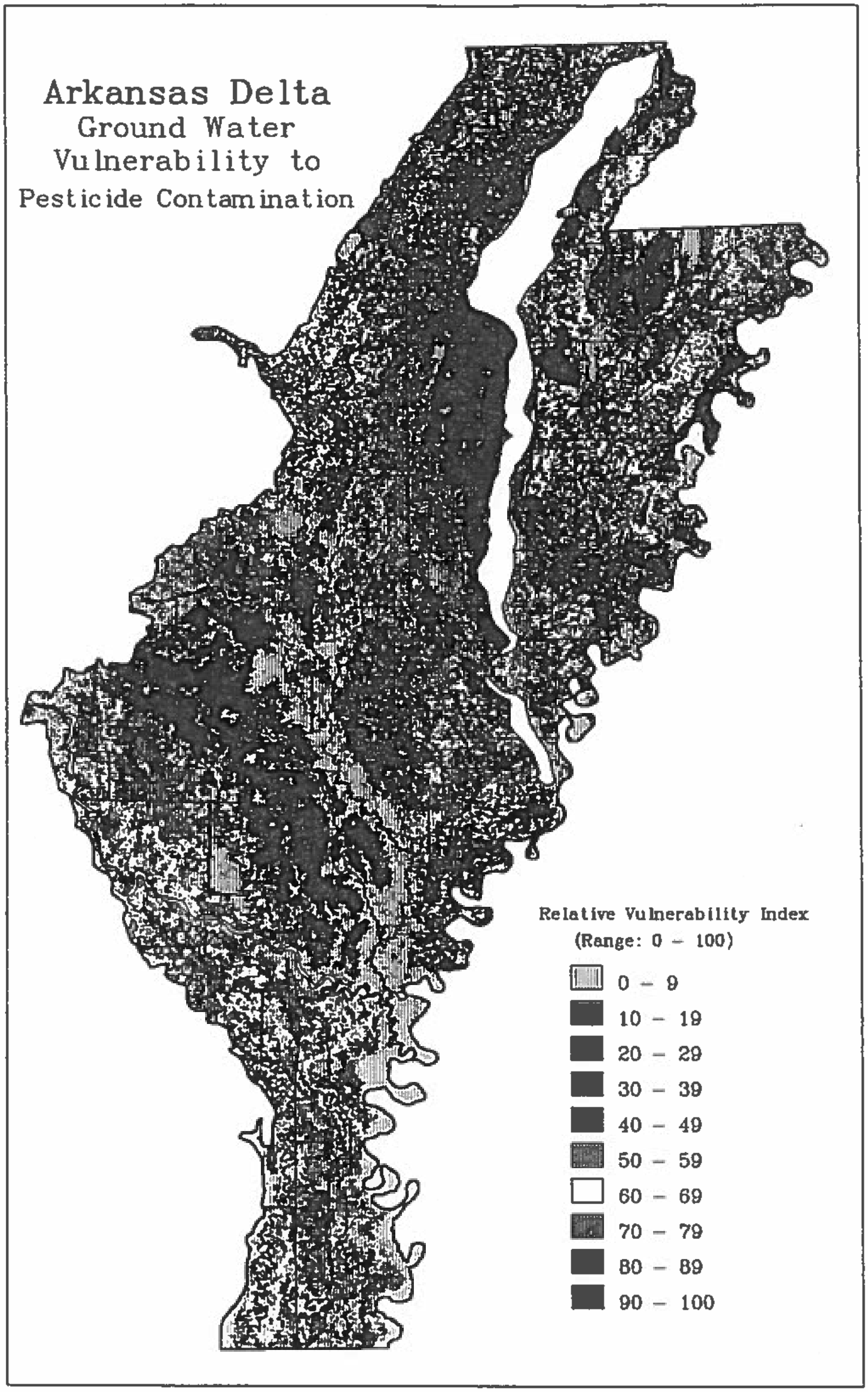

Fig. 9 Spatial distribution of the relative aquifer vulnerability index in the Arkansas Delta. The higher the index, the more vulnerable the area.

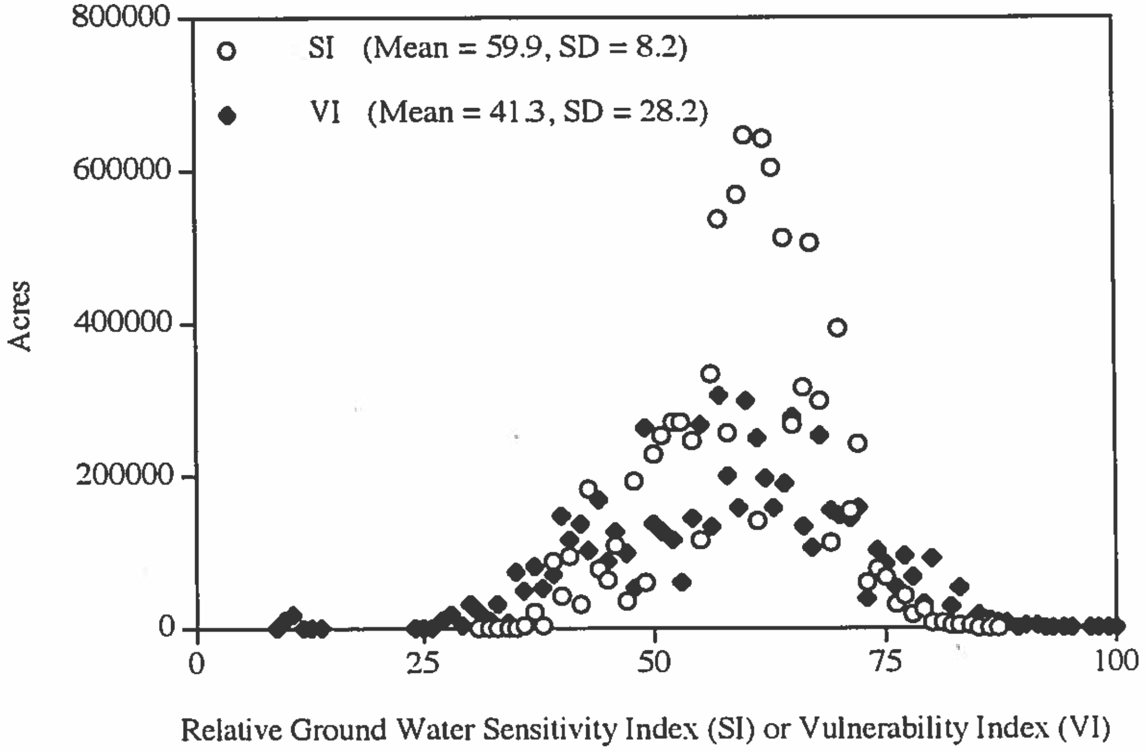

Fig. 10 Areal distribution of the relative sensitivity index (SI) and vulnerability index (VI) for the alluvial aquifer in the Arkansas Delta. (Note: 2.6 million acres of 0 value of VI not shown.)

Notably, the most sensitive areas in the Delta are distributed mostly along major streams, such as the Arkansas, White, Cache, Mississippi, St. Francis, and Bayou Bartholomew rivers, except in the Grand Prairie areas and the west side of Crowleys Ridge (Fig. 8). In these river basins, a combination of shallow depth to ground water, thin confining unit, permeable soils, and high recharge rate usually prevails, leading to high sensitivity for the alluvial aquifer to be potentially contaminated by pesticides. Furthermore, It was also in many of these areas where large acres of crops are grown, and pesticides are used (Fig. 11). Consequently, many areas along major streams were most vulnerable in the region (Fig. 9). Meeks and Dean (1990) also reported, in their study of DBCP (a soil fumigant) occurrence in ground water in Stockton East Water District in California, that the areas adjacent to rivers and sloughs generally had the highest leaching potential.

Among the seven factors considered in the Pesticide DRASTIC, the depth to ground water and the impact of the vadose zone appeared to be the dominant factors that controlled the aquifer sensitivity in the Delta. For example, the transection data of the SI and model factors (Fig. 12) along a cross section similar to A-A' shown in Fig. 1 indicated that the aquifer sensitivity index had better relationship with the depth to ground water ($R^2 = 0.550$) and the confining unit thickness ($R^2 = 0.365$) than with net recharge rate ($R^2 = 0.178$), soil permeability ($R^2 = 0.227$), and slope ($R^2 = 0.000$).

Comparison of areal extent of sensitive areas ($SI \geq 70$) and vulnerable areas ($VI \geq 70$) in each county that lies within the Delta indicated that the top three counties in terms of the total acres of vulnerable areas are Mississippi, Crittenden and Clay (Table 4). The areal extent of the crops grown in the vulnerable areas ($VI \geq 70$) in the Delta showed that wheat-soybean double-cropped fields have the highest potential to be vulnerable (Table 5).

The Grand Prairie is the largest local region in the Delta where the SI is relatively low. Historically, extensive rice production began in the Grand Prairie because of two hydrological reasons: 1) the alluvial aquifer provided an abundant source of water for irrigation, and 2) the thick confining unit overlying the alluvial aquifer inhibited the downward movement of water when rice fields were flooded. Nowadays, the severely declined water table in this area due to pumping for irrigation gives even less potential for pesticides to migrate to the ground water because of increased travel distance.

Although areas with low SI generally have less chance of being polluted by pesticides, caution should still be taken in managing pesticides. Misuse of pesticides, particularly at mixer/loader sites, may also lead to point-source contamination. For example, 2-year monitoring study by Senseman (1994) reported that eight pesticides were detected in 1% of ground water samples at 16 mixer/loader sites, including those in the Grand Prairie (Lonoke, Prairie, and Arkansas Counties).

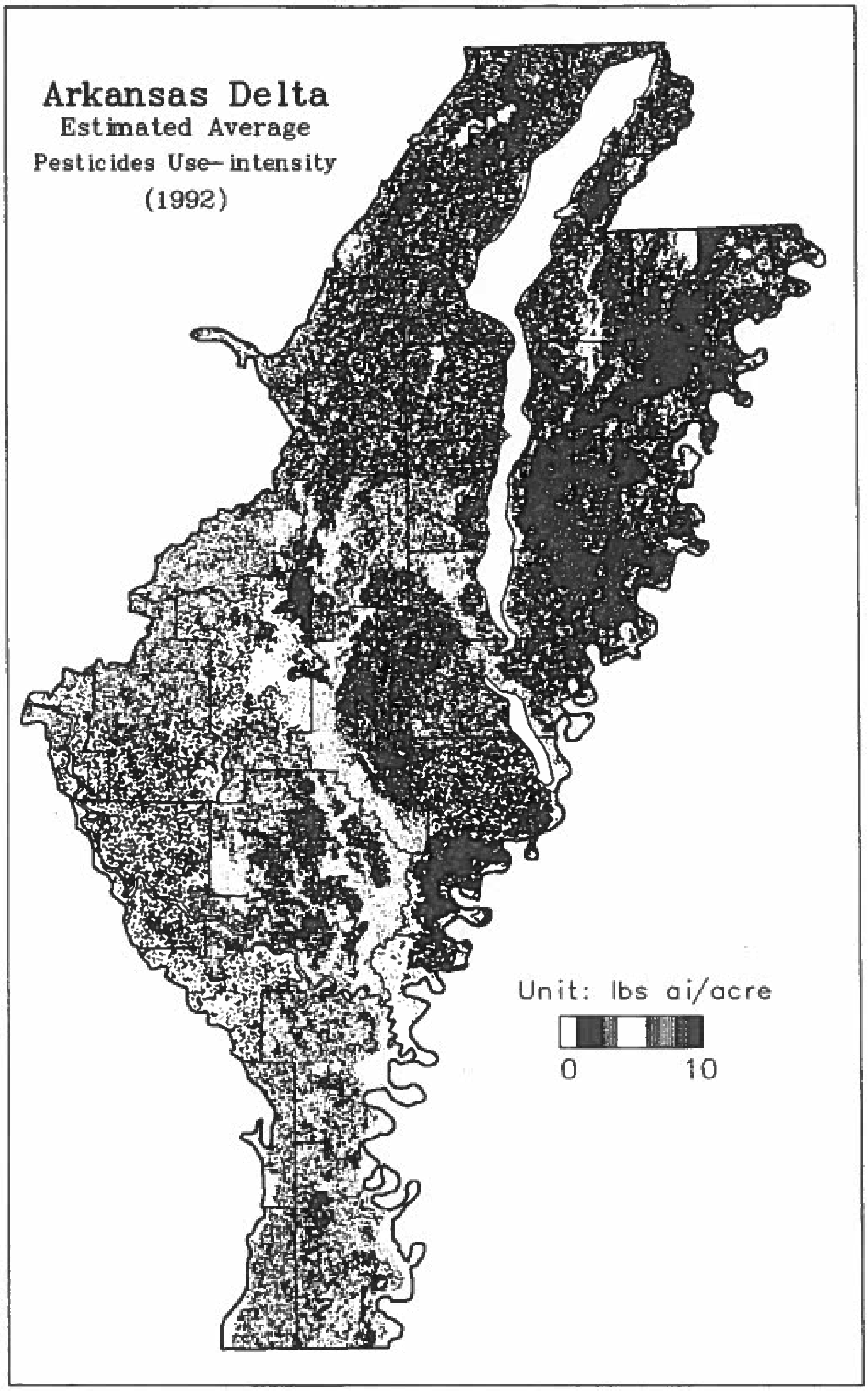

Fig. 11 Spatial distribution of pesticide use-intensity in the Arkansas Delta.

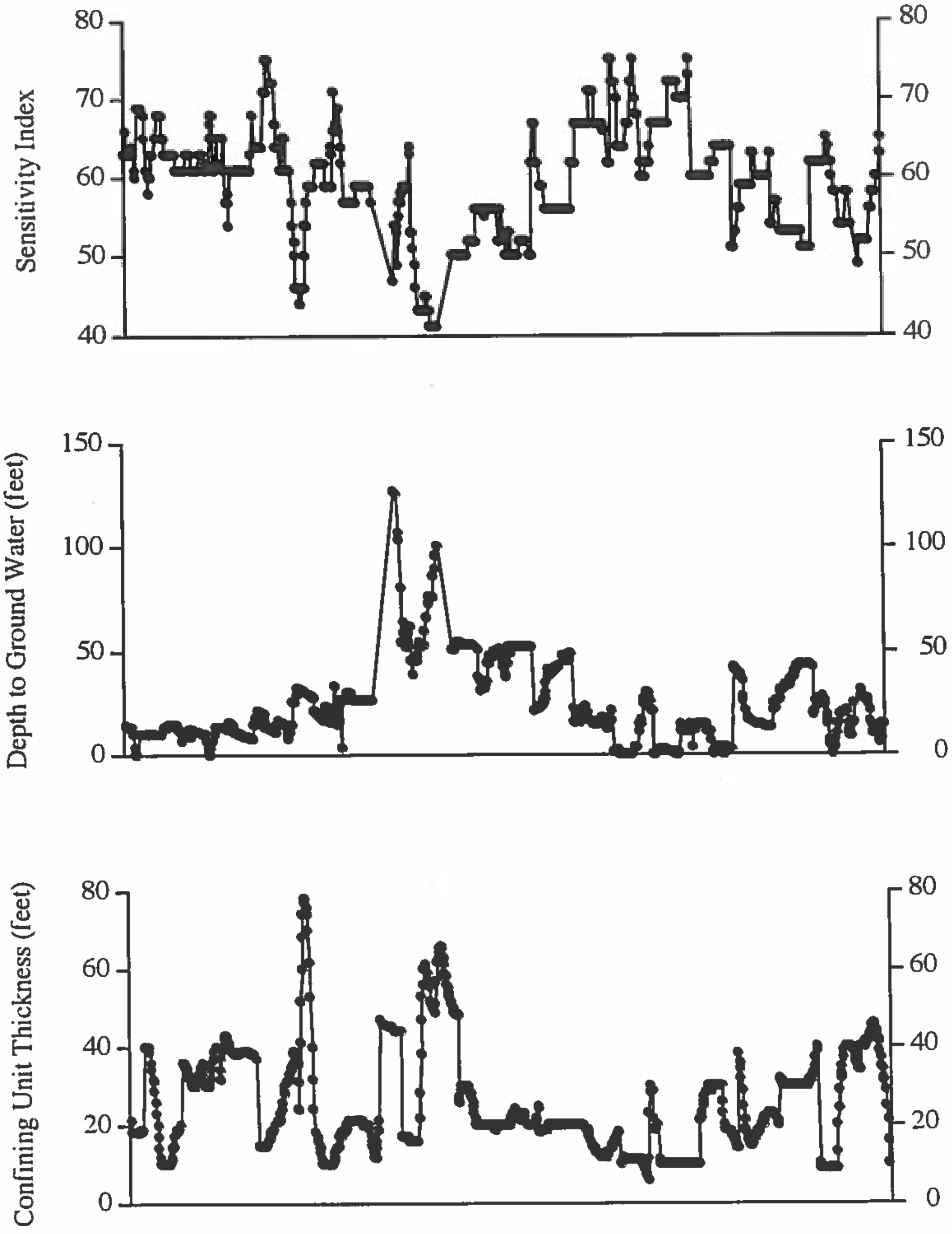

Fig. 12 (a) The transection of the sensitivity index and the Pesticide DRASTIC model factors along a cross section similar to A-A' shown in Fig. 1.

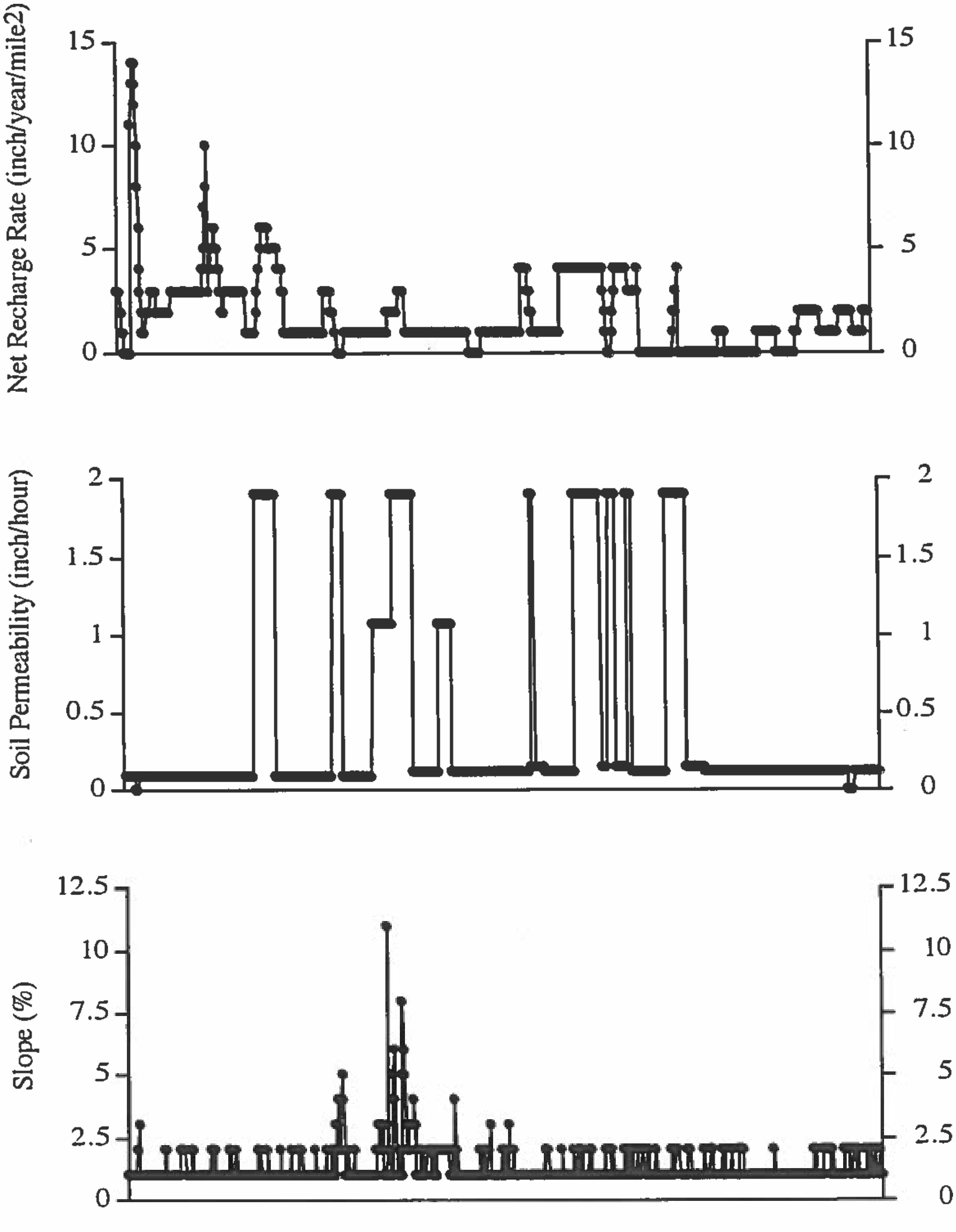

Fig. 12 (b) The transection of the sensitivity index and the Pesticide DRASTIC model factors along a cross section similar to A-A' shown in Fig. 1.

Table 4. Relative sensitivity index (SI) and vulnerability index (VI) distribution in each county of the Arkansas Delta region.

	SI			SI ≥ 70		VI			VI ≥ 70		
County	Mean	SD	Range	Acres	% *	Mean	SD	Range	Acres	% *	Rank §
Arkansas	50.1	7.4	36-77	7264	1.11	20.8	22.8	0-82	1245	0.19	25
Ashley	65.9	5.5	49-81	44433	26.67	35.2	30.7	0-88	11375	6.83	19
Chicot	60.4	4.5	50-77	18629	4.21	27.0	26.9	0-76	820	0.19	26
Clay	66.1	4.9	42-83	89360	27.66	56.8	21.3	0-95	90250	27.94	3
Craighead	61.8	8.4	41-77	105904	29.78	55.5	21.1	0-88	75158	21.14	5
Crittenden	62.2	5.3	46-79	42466	10.4	50.6	26.8	0-91	101299	24.82	2
Cross	53.1	5.7	37-72	99	0.03	42.3	22.3	0-83	10219	2.95	21
Desha	63.2	5.0	48-82	60009	11.61	29.2	29.3	0-88	13540	2.62	18
Drew	62.6	4.4	46-72	6483	6.15	31.0	29.3	0-72	277	0.26	27
Greene	56.8	6.4	32-72	3014	1.23	51.2	18.3	0-83	19331	7.89	16
Independence	60.6	8.9	31-72	13233	11.51	45.9	25.8	0-81	6720	5.85	23
Jackson	63.0	5.4	33-83	45560	12.13	56.1	19.0	0-93	72835	19.38	7
Jefferson	62.1	5.3	42-82	38177	10.16	42.9	27.7	0-92	25240	6.72	15
Lawrence	63.3	6.6	40-83	56282	23.92	53.7	21.5	0-95	48476	20.6	10
Lee	61.7	6.6	41-87	49858	13.35	39.4	30.2	0-100	53960	14.45	9
Lincoln	62.0	5.5	40-83	20101	9.45	40.4	27.8	0-84	9260	4.35	22
Lonoke	53.0	9.5	34-81	24065	5.59	38.5	23.7	0-93	17364	4.03	17
Mississippi	64.7	5.4	44-86	134031	22.73	60.4	22.8	0-99	223430	37.9	1
Monroe	61.8	7.6	40-81	69605	17.49	32.4	30.0	0-93	41073	10.33	11
Phillips	62.2	5.6	43-86	41913	9.3	44.6	28.2	0-91	85703	19.03	4
Poinsett	58.2	8.1	37-79	34254	7.76	51.0	21.5	0-91	75129	17.02	6
Prairie	49.7	9.2	33-82	16277	3.79	26.5	24.6	0-90	11059	2.57	20
Pulaski	66.0	7.9	38-84	44463	33	38.0	33.2	0-95	26693	19.81	14
Randolph	66.3	5.5	40-72	49750	40.59	52.8	27.1	0-83	39324	32.08	12
Saint Francis	56.6	5.6	38-75	4408	1.19	37.4	27.3	0-83	33414	9.04	13
White	58.4	4.2	43-73	128	0.05	34.7	27.6	0-79	4843	2.04	24
Woodruff	64.9	6.8	46-84	113020	29.73	38.2	31.2	0-93	63200	16.63	8

* Percentage of total county area considered in this study - being either whole or parts of a county that lies within the Arkansas Delta region (excluding Crowleys Ridge, Arkansas River and Peckerwood Lake).

§ Rank in terms of total acres of the area with VI ≥ 70 in each county.

Table 5. Areal extent of crops grown in the vulnerable areas with the VI ≥ 70.

Crop	VI = 90-100		VI = 80-89		VI = 70-79	
	acres	%	acres	%	acres	%
Soybean	0	0	2,145	0.023	186,587	2.02
Rice	0	0	0	0	0	0
Cotton	0	0	198	0.0022	30,913	0.33
Wheat	0	0	0	0	0	0
Grain sorghum	998	0.011	22,721	0.25	132,716	1.44
Corn	247	0.0026	6,167	0.067	30,943	0.33
Wheat-Soybean	9,883	0.10	193,644	2.09	524,273	5.67
Corn or Sorghum	237	0.0025	4,546	0.049	14,597	0.16
Total	11,365	0.12	229,419	2.48	920,455	9.96

To examine the impact of the scale of input soil map on ground water vulnerability assessment results using the Pesticide DRASTIC method, comparison was made in Lonoke and Prairie counties using SSURGO (1:24,000) and STATSGO (1:250,000) as input soil maps (while keeping other model factors the same). No significant difference was found in the overall frequency distribution of the SI and VI (Fig. 13 and 14), despite the fact that a few more sensitive and vulnerable areas were depicted using SSURGO soil maps (Fig. 15 and 16). This may be due to the fact that the depth to ground water and the confining unit thickness were the dominant factors controlling the aquifer sensitivity in the Arkansas Delta, as revealed in Fig. 12. The reason why more sensitive and vulnerable areas were indicated using SSURGO than using STATSGO can be explained through Fig. 17. Soil permeability was clustered largely in slow permeability class in STATSGO, whereas SSURGO indicated that there were more permeable soils in the area.

Uncertainty Analysis

Few published ground water vulnerability assessments account for uncertainties from either model or data errors. More is usually implied about the apparent certainty in vulnerability assessments than is stated about the underlying uncertainties. In fact, uncertainty is pervasive in both spatial databases and computational schemes; as a result, all vulnerability assessments are inherently uncertain (NRC, 1993). Therefore, information obtained from various ground water vulnerability assessments, including the one presented in this report, should be used with caution. To provide a reasonable use of information discussed in this report, sources of uncertainty and/or possible error involved in the methodology and data used in this study are discussed below.

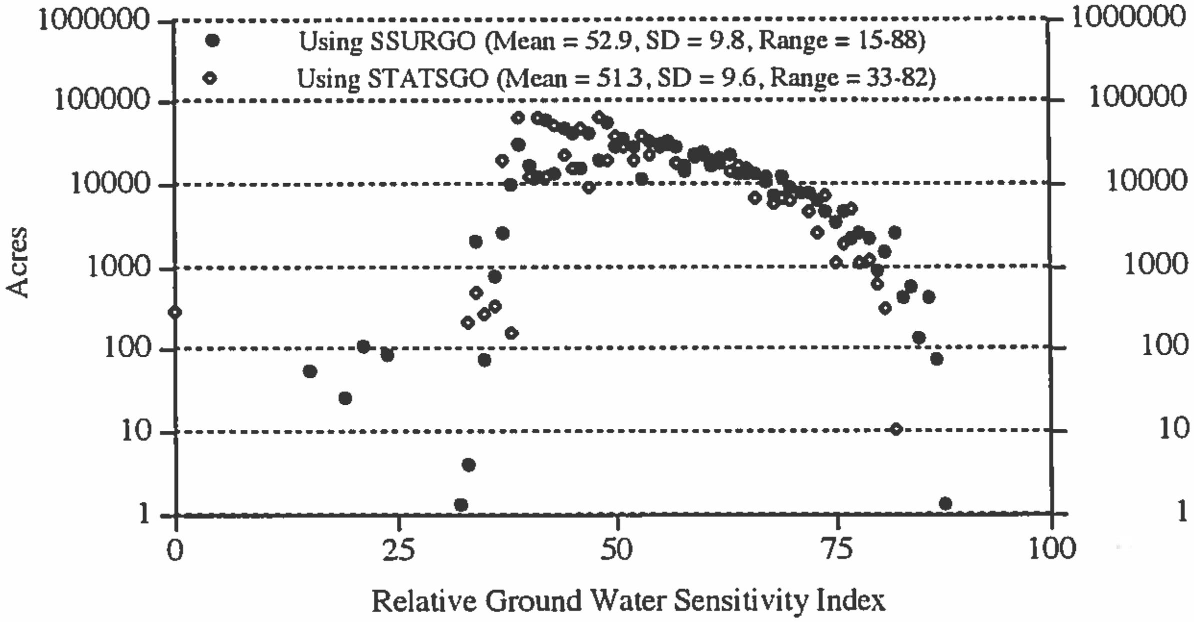

Fig. 13 Comparison of ground water sensitivity index in Lonoke & Prairie counties using SSURGO vs. STATSGO input soil maps

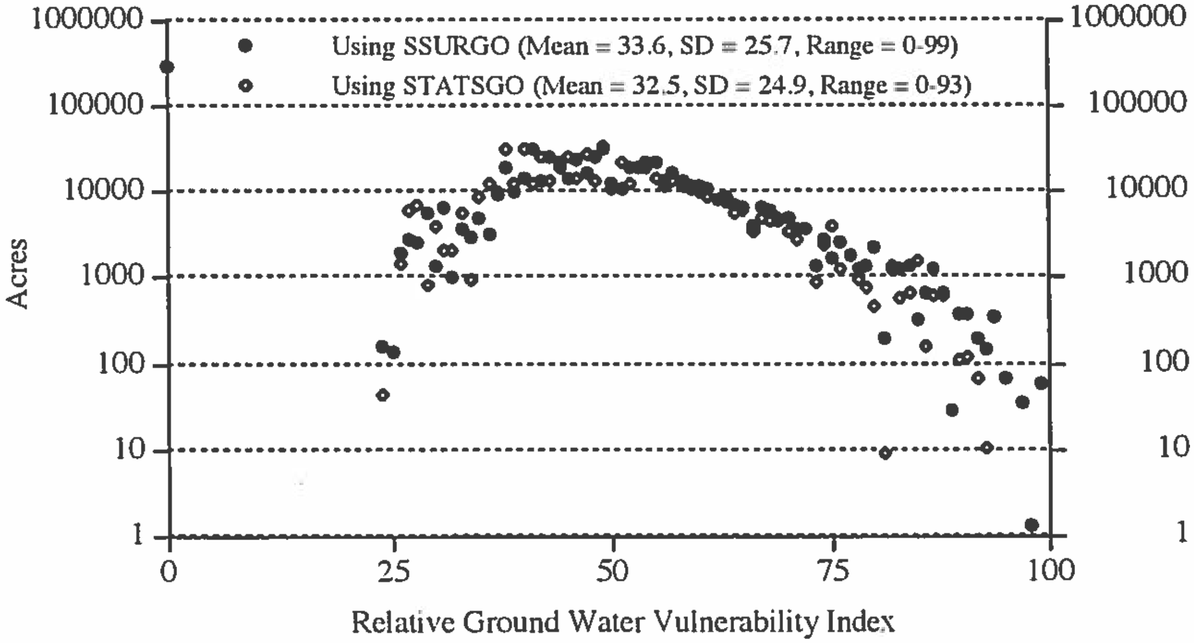

Fig. 14 Comparison of ground water vulnerability index in Lonoke & Prairie counties using SSURGO vs. STATSGO input soil maps

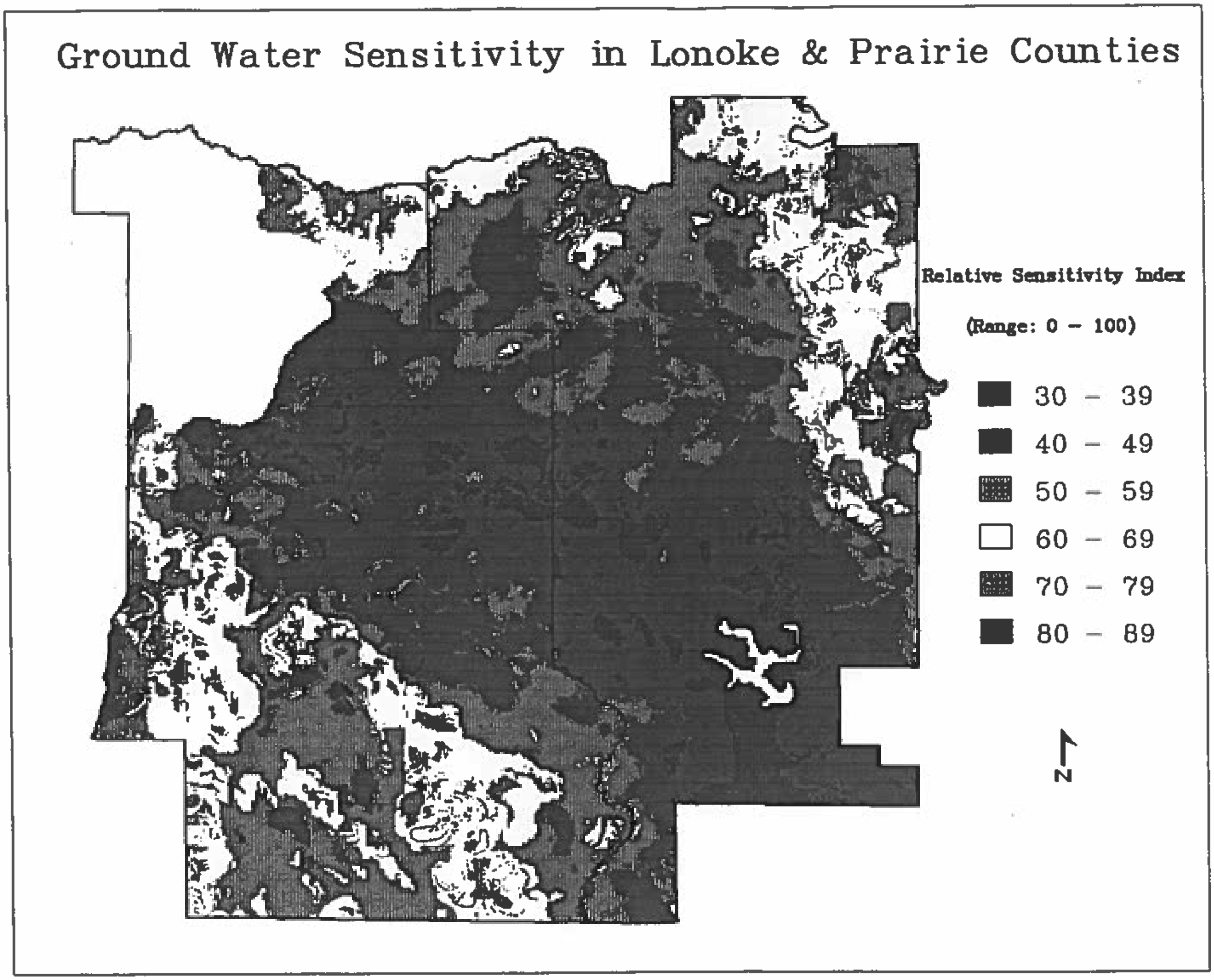

Fig. 15 Spatial distribution of relative ground water sensitivity index in Lonoke & Prairie counties using SSURGO as input soil maps

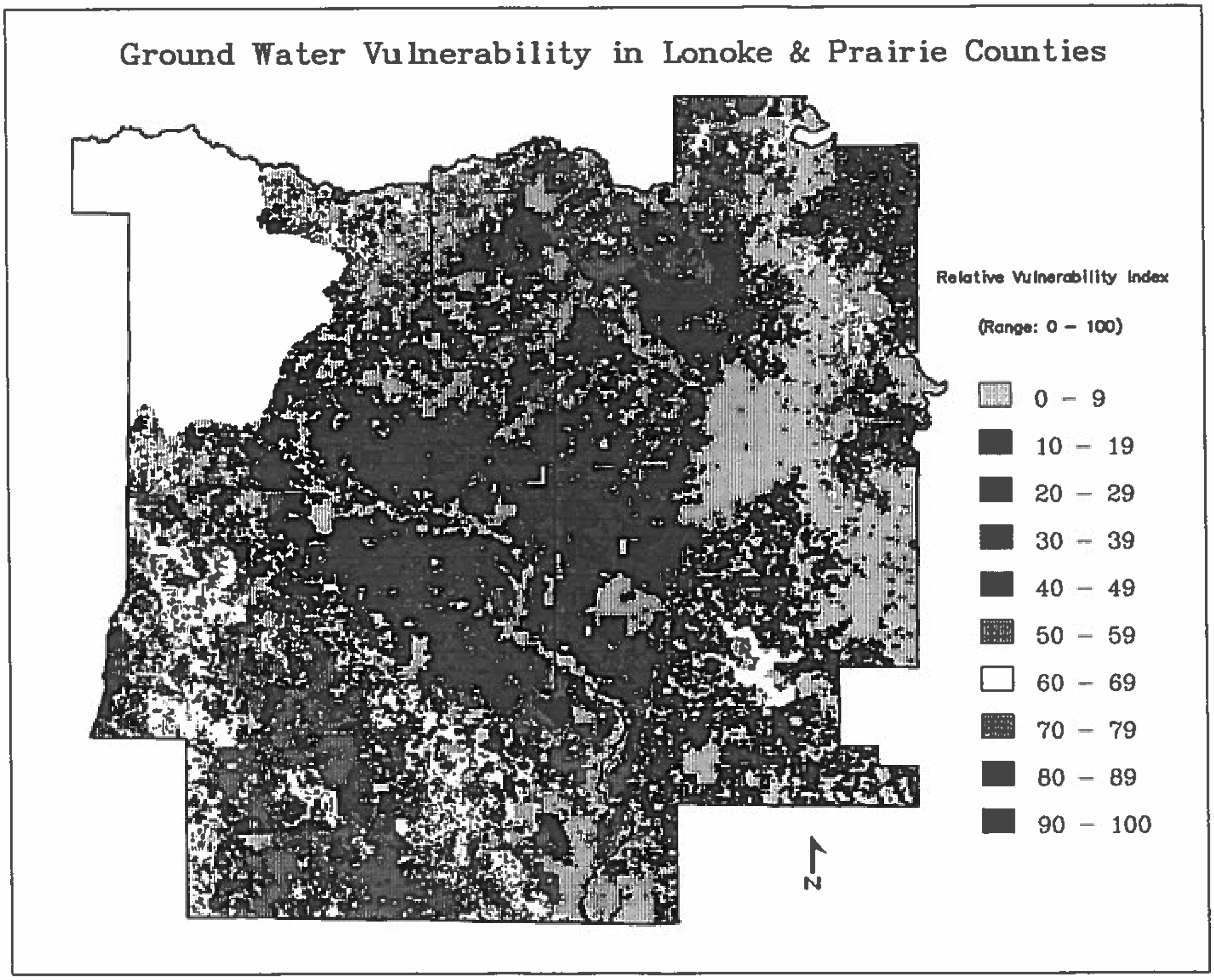

Fig. 16 Spatial distribution of relative ground water vulnerability index in Lonoke & Prairie counties using SSURGO as input soil maps

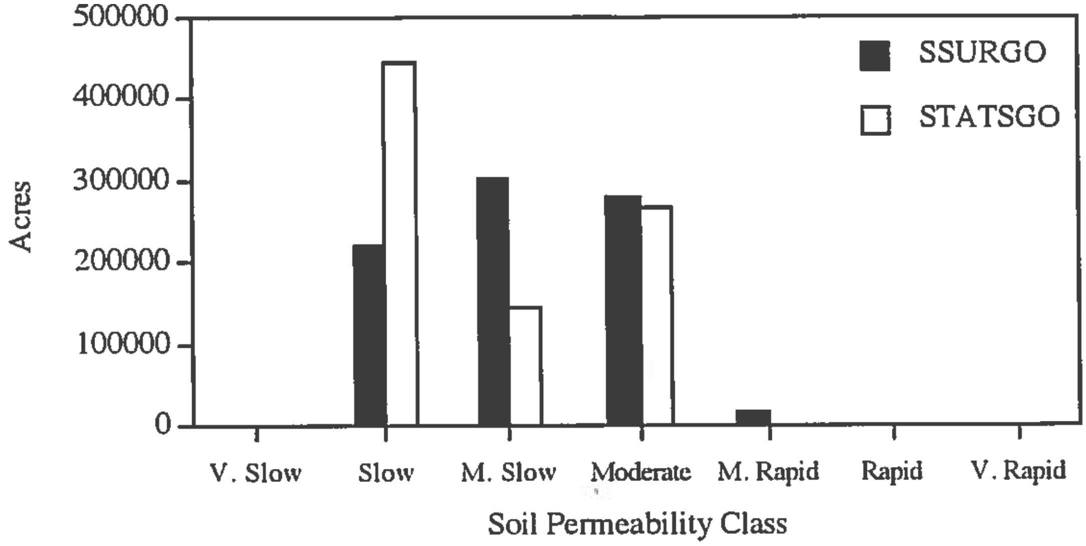

Fig. 17 Distribution of soil permeability class in SSURGO and STATSGO soil maps of Lonoke and Prairie counties.

1. Temporal dynamics of the parameters:

Ground-water depth fluctuates seasonally and in response to pumping. For instance, from Spring 1987 to Spring 1992 as much as >10 feet decline or rise occurred in the potentiometric surface in some areas of the alluvial aquifer (Westerfield and Poynter, 1994; Westerfield, 1990). As a result of this depth change, the distribution of the SI for the Delta has temporal changes as well (Fig. 18).

Temporal variability of soil hydraulic properties has long been recognized. The rate of infiltration and the permeability of soils, for example, may fluctuate significantly from time to time because of changes in soil moisture, cropping practices, and biological activities in soils.

Land use and pesticide application are also highly dynamic depending heavily on human activities. The percentage of cropland in the Delta has decreased from 77.56% in 1972 to 68.56% in 1992 with many significant changes in cropping practices (Fig. 19). This overall loss of cropland and changes in cropping pattern imply that the amount and type of pesticides used have been affected. In general, the development of a better understanding of crop-pest interactions will lead to the trend of fewer pesticides applied more timely and at lower rates.

2. Spatial variability of soil and hydrogeological properties:

Spatial variability is a norm in field conditions. The accuracy of any vulnerability assessment apparently depends on the scale of input maps of soil, potentiometric surface, confining unit thickness, and others. These input maps determine the extent to which the spatial

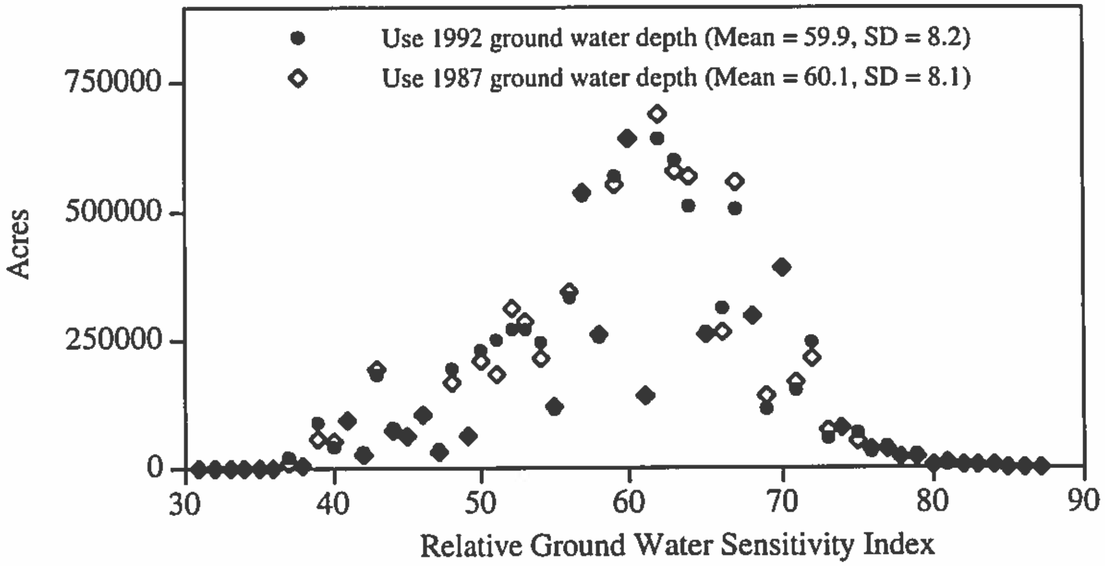

Fig. 18 Temporal change in the distribution of the relative sensitivity index from 1987 to 1992 as a result of the change in ground water depth in the Arkansas Delta.

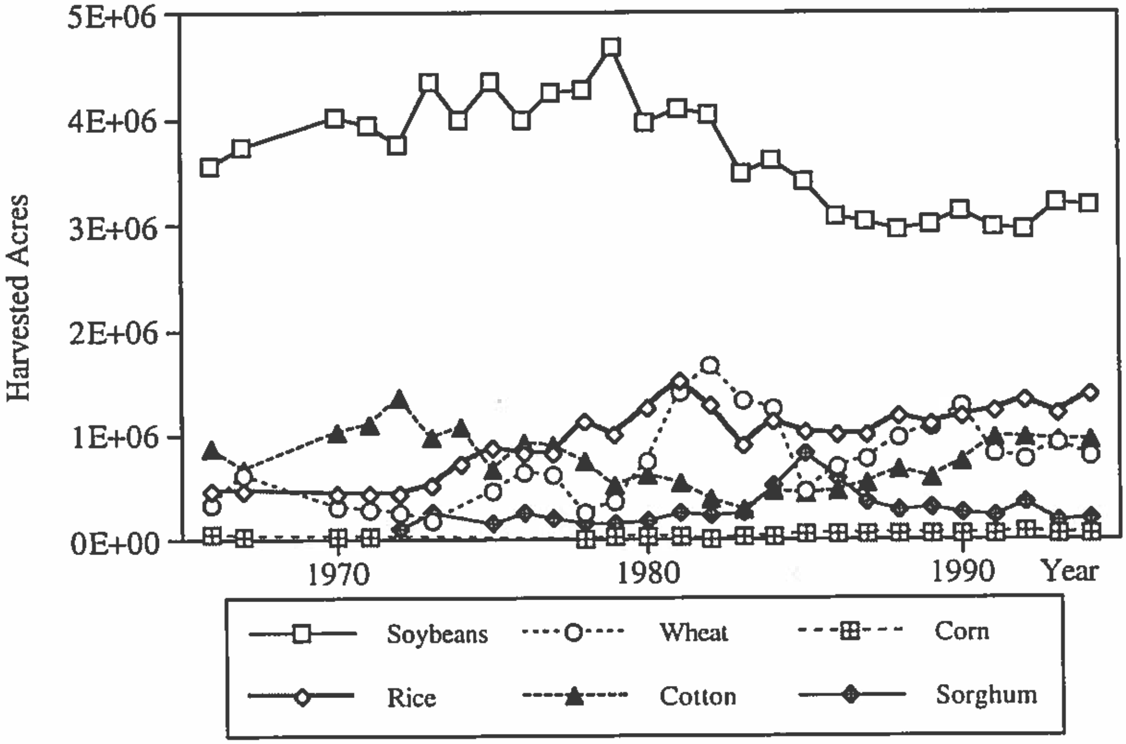

Fig. 19 Change of harvested acres of major crops grown in the Arkansas Delta from 1966 to 1994 based on annual summaries of Arkansas Agricultural Statistics. The reported region included the entire county for each of the 27 counties in the Delta.

variability is captured at the very beginning and to which the spatial variability can be reflected in the end product. Since the available input data used in this study were limited to small scale (large area), the output maps therefore would be best used for general planning. Spatial variability obviously gives arise to the possible variations within each sensitivity or vulnerability class indicated in Figs. 8 and 9.

Spatial variability of soil properties (including permeability) within a mapping unit is common (Mausbach and Wilding, 1991; Wilding and Dress, 1983). A soil association in a generalized soil map (e.g. STATSGO) may consist of up to 3 or 4 dominant soil series and other minor series which could have very different properties that are important to pesticide transport. Even within a county-level soil map (e.g. SSURGO), spatial variability of important soil hydraulic properties also exist (Nordt et al., 1991).

Spatial interpolation of potentiometric surface and confining unit thickness developed at small scale may not meet the needs for local scale studies. For example, thickness of the confining unit can vary substantially over short distances. Locally, the confining unit may be thin or absent within an area where the unit generally is thick or, conversely, the confining unit may be relatively thick at a site within an area where the unit generally is thin or absent (Gonthier and Mahon, 1993).

3. Uncertainty in model concept:

The Pesticide DRASTIC model is basically a relative evaluation of pesticide leaching potential. Although studies have indicated that infiltration of precipitation and irrigation probably accounts for the largest amount of recharge (65-68%) to the alluvial aquifer in the Arkansas Delta (Mahon and Poynter, 1993), other possible sources of contamination from runoff, river leakage, and point-sources are not considered in the DRASTIC assessment. The DRASTIC model also has been criticized for its subjective scoring and the lack of consideration of the interactions between the chemical of concern and the physical environment when scoring vulnerability (Meeks and Dean, 1990; Rosen, 1994). Of course, uncertainty is not only associated with the DRASTIC model. Even with process-based simulation models, inaccurate representation of real-world processes or simplified assumptions built in the models also lead to possible errors. In fact, no model currently available provides a completely accurate simulation of the flow of water and the transport of pesticides processes at field scale, let alone at regional scale (NRC, 1993).

4. Limitations in data calculations:

To use some data layers for raster map calculation within a GIS, contour lines (potentiometic surface and confining unit thickness) and site data (recharge rate) were interpolated into full surfaces using a regularized spline with tension technique. Although this surface modeling algorithm appears to give a better result than many other surfacing methods, the selection of tension and smoothing parameters is still an empirical process (Matasova, 1992).

The calculation of net recharge rate using the MODFLOW model was done based on the assumption of uniform steady water flow in both unsaturated and saturated zones (Gonthier and Mahon, 1993). The input values for the confining unit conductivity lacked solid field-measured data. Final recharge rates obtained from the model calculation were largely calibrated according to past behavior of the aquifer without sufficient consideration of lateral flow within the aquifer. All of these limitations were propagated into the final maps developed.

5. Possible errors/fuzziness in pesticide use information:

Information about pesticide use-intensity were largely based on the surveys from growers. Potential shortcomings always exist in almost every type of survey in terms of representation and accuracy. In addition, the percentage of a given crop treated with a certain pesticide may range from < 1% to over 90% (ACES, 1992), leaving a large amount of uncertainty in probability assessment. It was not known for certain which fields of a given crop were treated with a given pesticide. Such information was difficult to obtain and highly dynamic. Therefore, more emphasis should be given to the sensitivity index in ground water vulnerability assessments.

6. Uncertainty in identifying crop distribution from satellite imagery:

Variables involved in interpreting the TM for crop identification, such as the season of the scenes, irrigation, fertilization, surface soil moisture, possible pest damage to certain crop fields when the scenes were taken, plus limited ground truth data, led to uncertainty in the land use/land cover map developed from satellite imagery. Such uncertainty was carried over to the estimation of pesticide use probability index.

CONCLUSIONS

The most sensitive and vulnerable ground water in the Mississippi River Valley alluvial aquifer in the Arkansas Delta are distributed mostly along major streams in the region. Because of the small scale of this study and the lack of detailed model input parameters, this study provided only a general mechanism for comparison of different areas within the Arkansas Delta with respect to ground water vulnerability to pesticide contamination. The results obtained are relative, not absolute. The ground water vulnerability map developed through this study is intended for use in selecting optimal locations for sampling ground water for pesticides and for a guide in implementing the Arkansas Agricultural Chemical Ground-water Management Plan. More detailed information should be obtained and/or site investigations be made on the most vulnerable areas before specific type of further action can be taken.

It should be noted that because of the dynamic nature of the factors involved in assessing ground water vulnerability, it is important to keep in mind that such assessment is not a one-time task, but, rather, should be performed periodically. The uncertainties inherent in assessment methodology and the limitation of available database further require continued and improved efforts in ground water vulnerability assessment for the Arkansas Delta.

Because each currently available method for assessing ground water vulnerability has its own strengths and limitations, different approaches should be pursued in assessing ground water vulnerability for the Arkansas Delta in order to reduce the uncertainties and to produce a more justifiable and reasonable assessment.

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