THE MAGNITUDE AND COSTS OF GROUNDWATER CONTAMINATION FROM AGRICULTURAL CHEMICALS: A NATIONAL PERSPECTIVE

by

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ABSTRACT

Evidence is mounting that agricultural pesticide and fertilizer applications are causing groundwater contamination in some parts of the U.S. This paper synthesizes national data to identify regions potentially affected by contamination from these sources, summarizes the types of damages that can result, and assesses the potential costs of avoiding damages.

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THE MAGNITUDE AND COSTS OF GROUNDWATER CONTAMINATION FROM AGRICULTURAL CHEMICALS: A NATIONAL PERSPECTIVE

Over 97 percent of all rural domestic water in the U.S. comes from underground sources, along with 55 percent of livestock water and 40 percent of all irrigation water (Solley, et al.). Heavy reliance on groundwater is not limited to rural America, however: in 1980, groundwater served 40 percent of the population using public water supplies -- nearly 74 million people (Solley, et al.). Moreover, total groundwater withdrawals grew 158 percent from 1950 to 1980, compared to a 107 percent growth of surface withdrawals (Solley, et al.).

Little is known about the extent or magnitude of most groundwater contamination induced by human activities (Cohen, P.). The question, however, is critical. There are documented and suspected risks to human health from exposure to contaminated groundwater (National Research Council, 1977). Because of the slow movement of groundwater in many areas, contamination can persist for years or centuries. Clean-up costs can be prohibitive. Moreover, the interactions between surface waters and ground waters can mean that aquifer contamination may ultimately lead to pollution of the surface environment.

Although groundwater contamination can stem from many sources, evidence suggests that agriculture's relative contribution to groundwater contamination from human activities may be significant. The Office of Technology Assessment (OTA) recently completed a report summarizing groundwater contamination and its impacts. By several criteria developed by OTA, agricultural pesticide and fertilizer applications were listed as significant groundwater contaminants at the national level. This OTA conclusion appears to be further substantiated by reports of contamination incidents from agricultural chemicals around the nation, including Pennsylvania, Florida and Iowa (Pionke and Urban, Hebb and Wheeler, and Hallberg).

The objective of this paper is to assess the magnitude and costs of groundwater contamination caused by the agricultural use of fertilizers and pesticides in the U.S. While other agricultural activities such as livestock operations are potentially significant contributors to groundwater contamination in many localities, crop-oriented chemicals are the primary focus of this report because of broad scale usage across diverse regions of the U.S.

Information on the magnitude of contamination is a prerequisite to an assessment of the risks of incurring damages to health and property. The costs of these damages represent the benefits of groundwater protection. The groundwater protection policies and programs now being implemented by several states, including Arizona and Wisconsin, and discussed by other states and the U.S. Environmental Protection Agency (EPA) require a better understanding of the benefits of groundwater protection. Only when the benefits are well-understood can they be compared to the costs of alternative prevention and control measures for the identification of efficient policy options.

In this report, data from a variety of sources are combined to develop an overview of the regions of the U.S. potentially affected by agricultural chemical contamination of groundwater. A summary of the types of damages incurred from agricultural chemical contamination of groundwater is presented along with an assessment of the costs of avoiding potential damages. Implications for groundwater protection strategies are summarized.

AGRICULTURE AND GROUNDWATER QUALITY

The lack of a consistent and comprehensive data base has made it difficult to establish direct relationships between human activities and contamination episodes. This is particularly true with respect to diffuse, or "non-point" sources, which characterize many agricultural activities. It is clear, however, that several trends over the past forty years have increased the potential for agriculturally caused groundwater contamination.

The use of inorganic nitrogen fertilizers, a major source of nitrate-nitrogen groundwater contamination, increased eleven-fold between 1950 and 1980; a major cause has been heavier fertilizer applications, with the per-acre rate doubling between 1965 and 1984 (USDA, 1972; USDA, 1982; USDA, 1985). Concurrently, the agricultural use of pesticides has risen sharply, nearly tripling since 1964 (EPA, 1982). Most of the increased use has been accounted for by herbicides, which in 1982 constituted 82 percent of all pesticide use on major field and forage crops (USDA, 1983).

Other trends have increased the potential for contamination, at least in some areas. Wastes generated on concentrated animal production and dairy operations have stretched the land's waste assimilative capacity and have caused a potential for nitrate contamination, particularly in areas where commercial fertilizers are also applied. An increase in conservation tillage may imply an increase in both pesticide and fertilizer contamination due to increased water infiltration and less run-off, although the relationships are not well-understood. Expansion of irrigated acreages over the years also may have contributed to groundwater contamination; irrigation leads to the concentration of salts, pesticides and fertilizers in return flow; which may move down with the water as it percolates to the water table.

The potential for groundwater contamination, as well as the magnitude, extent and duration of contamination, depend not only on land uses and agricultural practices, but also on a variety of hydrogeological and other conditions. These include soil characteristics, net aquifer recharge, depth to the water table, and characteristics of the unsaturated zone and the aquifer. The characteristics of a potential pollutant (e.g., water solubility, sorption and persistence) strongly affect its ultimate fate. Again, pesticide usage trends imply an increased potential for contamination because some of the most widely used pesticides are prone to leach.[1/] The method, timing and placement of chemical application, in addition to tillage and irrigation practices, also affect the likelihood of leaching. Of course, accidents, leaks and improper disposal practices can lead to point-source contamination episodes on a localized basis.

Clearly, predicting groundwater contamination requires consideration of diverse factors which interplay in the process. The data presented and described in the following section reflect the

1/ For example, over one-half of all herbicide use on major field and forage crops is accounted for by four chemicals -- alachlor, atrazine, butylate and metolachlor -- all of which have a high potential to leach (USDA, 1983; Cohen, S.Z., 1985).

interaction of agricultural activities with physical vulnerability to the agricultural contaminants of pesticides and nitrates. These are combined to estimate regional groundwater contamination trends.

POTENTIAL PESTICIDE AND NITRATE GROUNDWATER CONTAMINATION IN THE U.S.

In this section, an estimate of the areas of potential groundwater contamination from pesticides and nitrates in the U.S. is developed. Areas of potential contamination are first defined by actual levels of contaminants in groundwater, where data are available. If such data are not available, potential contamination is defined by synthesizing data on physical vulnerability to contamination with chemical usage data. In both cases, the population in areas of potential contamination is assumed to face a greater risk from agricultural chemicals in groundwater than the population in other regions. As the costs associated with these risks largely depend upon the population potentially exposed, the numbers and distributions of people using groundwater in areas of potential contamination are also projected.

The estimate of potentially contaminated areas is based upon a synthesis of several data sources. While each of these sources has limitations, which in aggregate decrease the validity of localized analysis, we believe that they represent the best available data and that, in combination, they accurately depict regional trends.

The remainder of this section is presented as follows. The data, methodology, and the identification of areas of potential contamination are presented, first for pesticides and then for nitrates. These are combined to identify total areas of potential contamination from agricultural chemicals. An analysis of the population affected in areas of potential contamination is discussed. Finally, a summary of the data implications is presented.

Potential Pesticide Contamination

Data Sources and Methodology

Because no national data base on pesticide levels in groundwater exists, a method was developed to obtain a "proxy" for agriculturally caused pesticide contamination, or the potential for such contamination. This method involved the synthesis of two data bases.

The first data source is the DRASTIC index, a system for evaluating the relative vulnerability of areas to groundwater contamination from various sources of pollution (Aller, et al.). The hydrogeologic factors which determine the DRASTIC score, and which are the basis for the acronym "DRASTIC" are: Depth to Water, Recharge (net), Aquifer media, Soil media, Topography (slope), Impact of the vadose zone, and Conductivity (hydraulic) of the aquifer.

For the geographic area under consideration, each DRASTIC factor receives a rating which is in turn multiplied by a weight reflecting the relative importance of the factor with respect to contamination potential. The weighted ratings are totalled to derive the DRASTIC score. A higher score implies a higher degree of vulnerability. Two sets of weights form the basis for two distinct DRASTIC indexes: the DRASTIC index for agricultural pesticides, and the generic DRASTIC index for all other contaminants.[2/]

In 1985, EPA commissioned DRASTIC assessments at the county level for the entire U.S. to aid in the design of a sampling strategy for

2/ The former has higher weights on the "S" and "T" factors and lower weights on the "I" and "C" factors, than the latter.

its planned national survey of pesticides in well water (Alexander, et al.). The county pesticide DRASTIC scores constitute the first data base for this assessment.

The second data base consists of county-level agricultural pesticide usage estimates developed by Resources for the Future (RFF) (Gianessi, et al.). These are based primarily upon U.S. Department of Agriculture (USDA) state, regional and national unpublished survey data (principally the 1982 Crop and Livestock Pesticide Usage Survey), and the State of California's annual report of pesticide use for 1981. (State of California). Application estimates (pounds of active ingredient applied per year) were made for 184 currently used pesticides, representing uses on 76 crops.

To ensure uniform coverage of all geographic areas and crops, RFF derived application estimates via extrapolations from one region or state to another where data gaps existed. The basis for the extrapolations was harvested cropland acreage, by crop, as reported in the 1982 Census of Agriculture. In a similar manner, the county-level estimates were derived from the state and regional totals.

Our analysis was limited to 38 of the pesticides in the RFF file; these include currently used chemicals placed by EPA in high priority categories for the national well water survey due primarily to their leaching potential and known occurrences in groundwater (Table 1). These 38 pesticides represent 60 percent of all uses accounted for in the RFF file, or roughly 660 million pounds per year. Over two-thirds of the high priority pesticides are herbicides, and they account for over 80 percent of all usage.

We translated the total county-level usage estimates into average per-acre applications, using acres of cropland from the Agricultural

Table 1. Pesticides Included in the Analysis of Potential Groundwater Contamination

Pesticide	Use[1]	Estimated usage[2]	#States found in groundwater[3]	Primary rationale
ACIFLUORFEN	H	1,398,639	0	Leacher
ALACHLOR	H	85,014,905	4	Leacher
ALDICARB	I,N	2,271,322	15	Mobile; marginal persistence
AMETRYN	H	96,225	0	Leacher
ATRAZINE	H	77,316,058	5	Leacher
BENTAZON	H	8,409,963	0	Leacher; toxicological concern
BROMACIL	H	1,233,705	1	Leacher
BUTYLATE	H	55,094,855	0	Mobile; toxicological concern
CARBOFURAN	I,N	7,694,590	3	Leacher
CHLORAMBEN	H	6,069,198	0	Leacher
CHLORDANE	I	11,066	0	Persistent; possible direct contamination via termiticide use
CYANAZINE	H	21,625,698	2	Leacher
CYCLOATE	H	52,374	0	Mobile; toxicological concern
DALAPON	H	261,418	0	Leacher
DACTHAL/DCPA	H	195,668	1	Leacher
DICAMBA	H	4,157,594	0	Leacher
2,4-D	H	37,216,637	0	Marginal leacher; heavy use
DINOSEB	H	8,834,549	1	Leacher
DIPHENAMID	H	698,379	0	Marginal leacher; toxicological data gaps
DISULFOTON	I,A	2,104,944	0	Leacher
DIURON	H	1,860,925	0	Leacher
FENAMIPHOS	I	347,693	0	Moderate leacher; toxicological concern
FLUOMETURON	H	2,943,237	0	Leacher
HEXAZINONE	H	11,384	0	Leacher
MALEIC HYDRAZIDE	H	286,783	0	Leacher; toxicological data gaps
MCPA	H	9,860,784	?	Marginal leacher; possible occurrence in groundwater
METHOMYL	I	425,314	0	Leacher
METOLACHLOR	H	37,939,980	2	Leacher
METRIBUZIN	H	10,603,307	1	Leacher
OXAMYL	I,N	50,943	2	Leacher
PICLORAM	H	549,469	0	Leacher
PRONAMIDE	H	82,657	0	Leacher
PROPAZINE	H	1,286,559	0	Leacher
PROPHAM	H	444,773	0	Leacher
SIMAZINE	H	3,974,598	3	Leacher
2,4,5-T	H	203,877	0	Marginal leacher
2,4,5-TP	H	6,943	0	Marginal leacher
TERBACIL	H	832,995	0	Leacher

1/ A = Acaricide; H = Herbicide; I = Insecticide; N = Nematicide

2/ Pounds of active ingredient per year used for agricultural purposes only, from the RFF data file.

3/ Source: Cohen, et al., 1986.

Census. These ranged from 0 to 3.4 pounds/acre, with an average of 1.0, and we apportioned them into high, medium, and low categories. Similarly, the DRASTIC scores, which had a maximum of 245 and averaged 133, were apportioned into three categories based upon the variable's distribution. Utilizing the hypothesis that hydrogeologic and pesticide usage factors provide more information on the potential for contamination than do either of the indices alone, we then calculated three combinations of the high and medium categories for the two variables.

Results

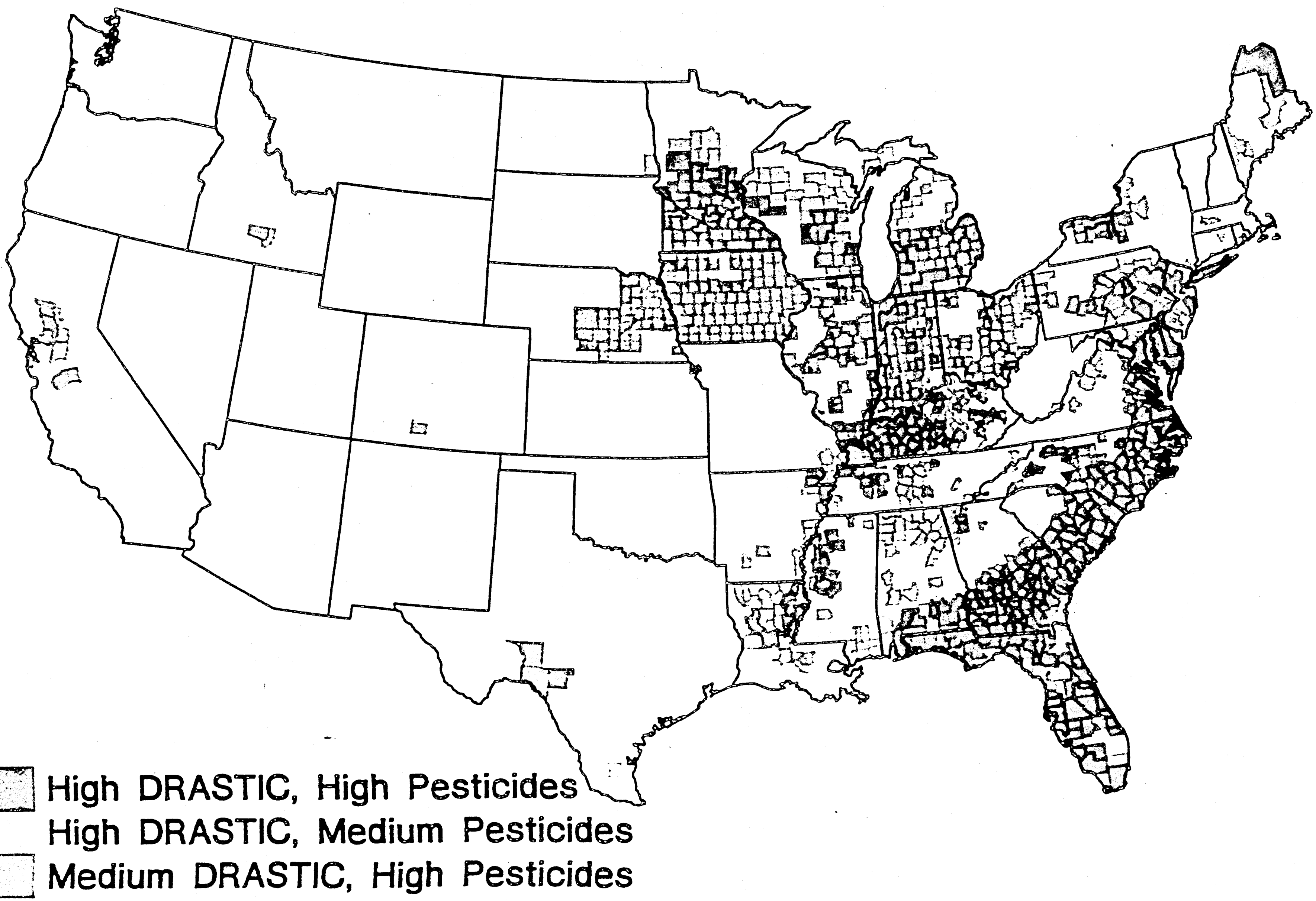
Figure 1 depicts those areas falling into the categories described above. Areas in red are those counties with both high pesticide use and high DRASTIC, and include 360 counties. Green represents areas with high use and medium DRASTIC, while yellow indicates high DRASTIC and medium usage categories. Together, green and yellow areas account for 766 counties. A total of 1,126 counties are represented on Figure 1, or roughly one-third of the counties in the continental U.S.

In general, the Southern Coastal Plain (including Florida), the Central Atlantic region, the Mississippi Delta, the Northern Corn Belt, Western Kentucky and the Central Valleys of California are the major regions with potential pesticide contamination problems. Other smaller areas in the Northeast, Texas and Idaho also have potential contamination problems.

The regions depicted in Figure 1 as having potential groundwater contamination from pesticides correspond with production of pesticide-intensive crops. Corn and soybean patterns, in particular, are reflected in the figure. Tobacco, cotton, rice and peanut production

Figure 1

Potential Groundwater Contamination from Pesticide Usage



in the Southeast also show high pesticide usage. In Florida, California, and portions of the Northeast and Lake States, fruit and vegetable production is represented by high usage.

Although the data in Figure 1 are not based on actual levels of contaminants in groundwater, Figure 1 does correspond with verified incidents of groundwater contamination from normal agricultural pesticide usage as shown, by state, in Figure 2 (Cohen, et al.). The map reflects occurrences of 17 pesticides in groundwater in 23 states, and shows a large number of occurrences along the Eastern Seaboard, Midwest, and some agricultural areas of the West. Since the data do not represent a random sample, and since sampling patterns vary dramatically from state to state, they might be considered the lower bound on actual incidents.

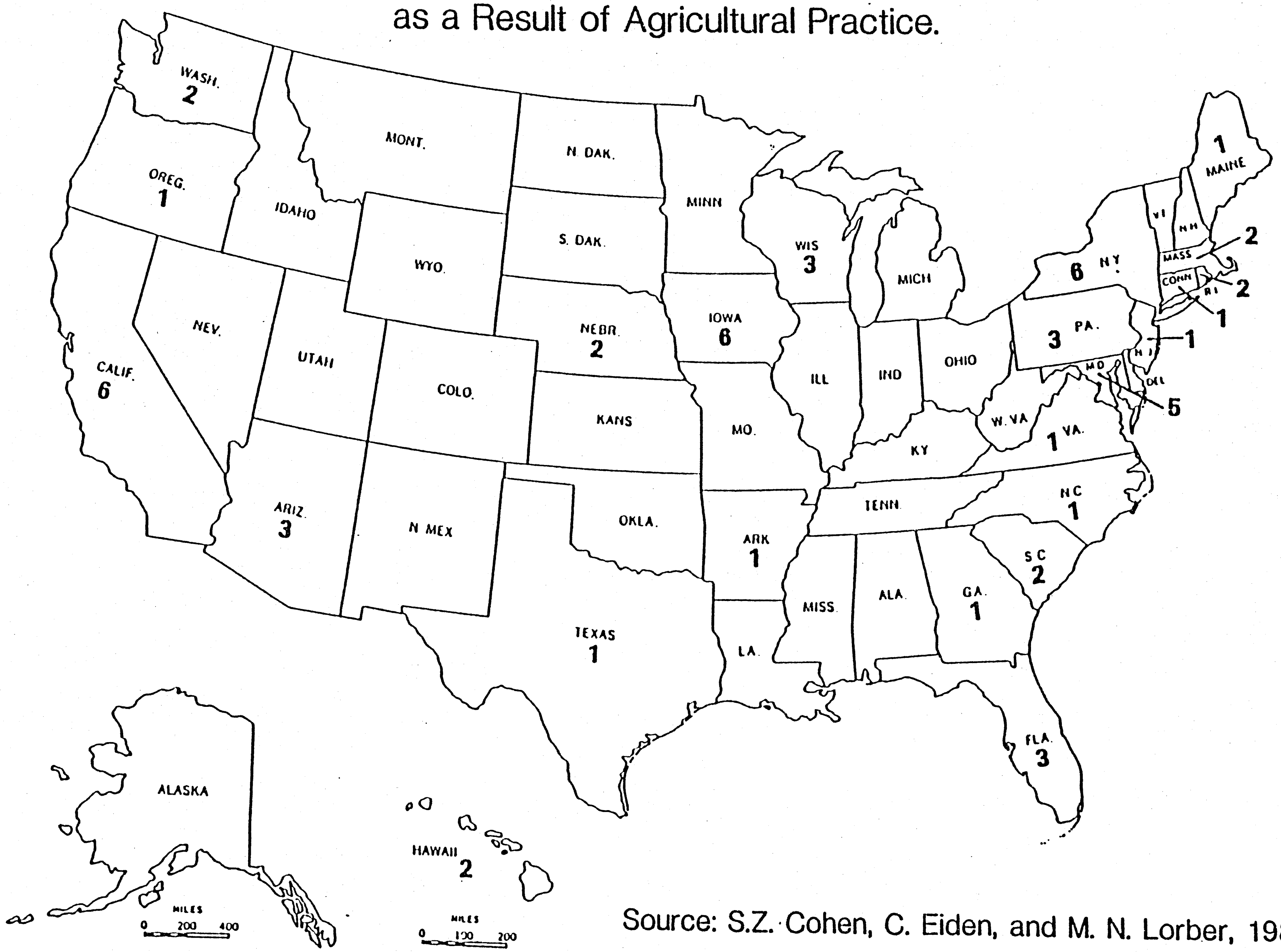
Data Limitations

County-wide averaging of DRASTIC data allows localized, highly vulnerable areas to be overshadowed by larger, less vulnerable areas. Likewise, county-level aggregations of pesticide usage allow applications on high-intensity crops to be diluted where less pesticide-intensive crops also grow in the same county. Conversely, moderate to high pesticide applications may put the entire county "on the map" even if the high-application area is a very small percentage of the total county land area. These points are raised in order to illustrate why the maps should not be used to single out individual counties; rather, they should be viewed with regional trends in mind.

In addition to limitations stemming from county-level aggregation, other characteristics of these data bases should be borne in mind. First, there may be some measurement errors and

Figure 2

Numbers of Pesticides Found in Ground Water as a Result of Agricultural Practice.



Source: S.Z. Cohen, C. Eiden, and M. N. Lorber, 1986.

inconsistencies in the DRASTIC data base. One limitation is that DRASTIC scores for some irrigated areas may be underestimated. However, the DRASTIC distribution does correspond reasonably well with known hydrogeologic conditions (Alexander, et al.).

Second, some distortions in regional crop pesticide usage estimates may have been introduced by the extrapolation process. In particular, application of California pesticide use coefficients for vegetables to all other states growing those crops may be the most significant source of bias.[3/] However, we consider the alternative of implicitly assuming no applications in areas lacking better data to be a less attractive option. Additionally, the application of state or regional coefficients to all counties within the area, where county-level data do not exist, hides cross-county variations.

Potential Nitrate Contamination

Data Sources and Methodology

Estimating areas of potential contamination from agricultural fertilizer usage involved the synthesis of three data bases. The primary source was the National Water-Data Storage and Retrieval System (WATSTORE) of the U.S. Geological Survey (USGS), which contains nitrate levels in samples collected over the past 25 years from 87,000 wells throughout the U.S. These were supplemented by USGS with data

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3/ An alternative pesticide usage data base is available, based on survey information from Doane Marketing Research, Inc. While the problem of cross-regional extrapolation is avoided with this data base, a number of crops are not represented. Since some of these crops (e.g., vegetables) are often grown in areas vulnerable to contamination and typically receive significant pesticide applications, we chose to utilize the RFF data base.

on 36,000 wells from the Texas Natural Resources Information System of the Texas Department of Water Resources. Because regional gaps exist in the USGS file, we developed a proxy for contamination from DRASTIC and fertilizer usage data.

Starting with the USGS data, multiple criteria, based on metropolitan status and percent of county in cropland, were constructed in order to exclude areas with a high potential for nitrate contamination from non-agricultural sources, such as septic tanks. Application of these criteria excluded 753 counties, or about one-fourth of the counties in the data base. From the remainder, counties with fewer than five wells sampled (661 counties) were omitted from the analysis on the basis of insufficient information. After these exclusions, 1,663 counties remained in the data base for analysis with respect to levels of nitrates in groundwater.

Following Madison and Brunett, well data were analyzed according to the following categories:

0-3 mg/L -	Assumed to represent natural background levels, with minimal human influence
3.1-10 mg/L -	May indicate elevated concentrations resulting from human activities
More than 10 mg/L -	Exceeds maximum concentration in National Interim Primary Drinking-Water Regulations.

Because of the large number of counties with insufficient data, a contamination proxy was developed to supplement the USGS data. Similar to the pesticide pollution potential analysis described earlier, the generic DRASTIC index county ratings were combined with estimates of nitrogen fertilizer applications to project areas of potential nitrate contamination.

State-level averages of the percentage of acres fertilized with commercial nitrogen, as well as application rates, are available by crop, from unpublished data provided by the USDA Economic Research Service for corn, cotton, wheat, soybeans and sorghum. We combined these data to form measures of intensity of application per acre by crop, and projected the state figures to the county level based upon harvested acres.

The county-level estimates of pounds applied per acre were summed across crops, and totals were distributed equally into high, medium, and low categories. Counties at the higher end of the scale tend to be those growing corn, cotton and corn/soybeans. Soybeans represent generally the lowest levels, while wheat falls into the moderate range. Application rates and percent of acres treated vary widely, however, across states for the same crop.

DRASTIC scores, which averaged 109 nationally and ranged from 48 to 214, were similarly distributed into high, medium, and low categories. Combinations of high and medium categories were identified and mapped.

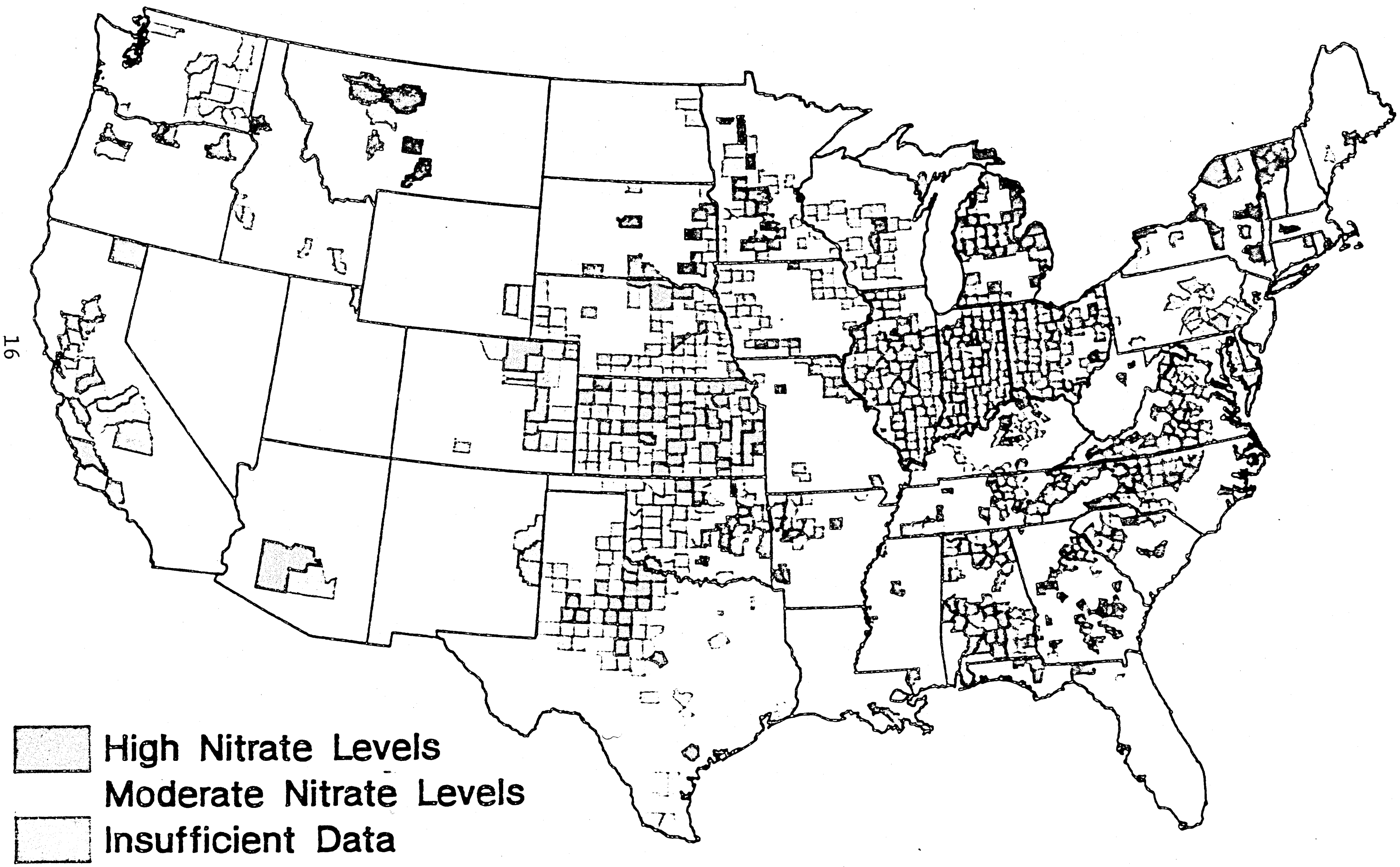
Results

The USGS data indicate that of the 1,663 counties analyzed, 474 have 25 percent or more of sampled wells exceeding 3 mg/L of nitrate-nitrogen. These are shown in red and yellow in Figure 3. The counties in red are a subset of these, including those in which 25 percent or more of wells exceed 10 mg/L; these total 87. In Figure 3, green represents those 661 counties with insufficient data.

According to these data, nitrate-nitrogen contamination of groundwater appears to be concentrated in several regions of the

Figure 3

Nitrate-Nitrogen Distribution in Groundwater in Agricultural Areas



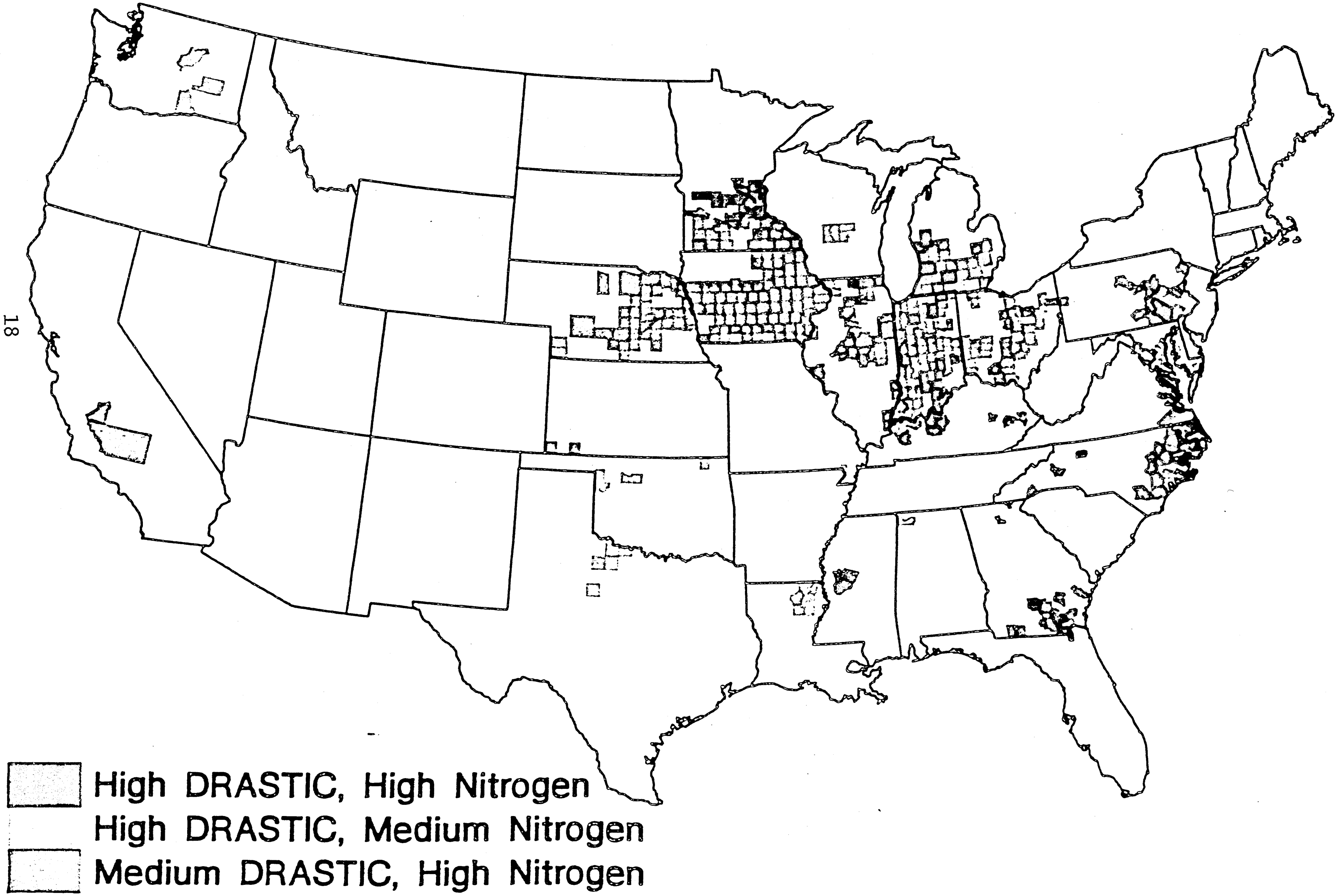
country. The Central Great Plains, the Palouse and Western Washington State, portions of Montana, Southwest Arizona, the irrigated fruit and vegetable areas of California, portions of the upper Corn Belt, and Southeast Pennsylvania, Maryland and Delaware have the highest reported concentrations of nitrate-nitrogen in groundwater. Within these regions, Kansas, West Texas and Southern Arizona have the highest recorded concentrations, with 25 percent or more of sampled wells exceeding 10 mg/L of nitrate-nitrogen. In many cases, the areas highlighted in Figure 3 represent a combination of fertilizer applications and irrigation, particularly in California, the Palouse, Northern Texas and portions of Kansas and Oklahoma. However, not all areas with this combination appear as problem areas in Figure 3; Florida is an important example.

Figure 4 illustrates the outcome of the nitrogen application-DRASTIC analysis. Counties identified as high DRASTIC and high nitrogen application are in red, high DRASTIC and medium nitrogen application counties are in yellow, and green depicts medium DRASTIC and high application counties. The latter category constitutes the majority of the 441 counties identified on the map, which are situated primarily across the Corn Belt, Eastern Pennsylvania and California. Other areas identified as having potential contamination by these criteria are in Western Washington, Texas, Oklahoma, Georgia, North Carolina and the Chesapeake Bay area.

Although there are many similarities, Figures 3 and 4 do not completely correspond. In particular, elevated concentrations of nitrate-nitrogen in groundwater indicated by Figure 3 in the Great Plains states are not predicted by Figure 4. Figure 4 reflects low nitrogen applications on wheat relative to other crops. On the other

Figure 4

Potential Groundwater Contamination from Nitrogen Fertilizers



hand, Figure 3 may, in part, reflect other influences such as naturally occurring nitrate concentrations. These and other explanations specific to the data sources will be explored in further research.

The synthesis of the two data analyses described in this section involved utilizing information from the nitrogen applications/DRASTIC analysis to supplement the USGS data base. The 447 counties in which 25 percent or more of sampled wells exceed 3 mg/L (red and yellow in Figure 3) were identified as having potential groundwater problems from nitrogen fertilizer use. Those 661 counties with insufficient data (green in Figure 3) were supplemented with information from the 441 counties identified via the nitrogen application/DRASTIC analysis from Figure 4. (Any colored county in Figure 4 corresponding to a green county in Figure 3 became an additional county identified to have potential nitrate problems). This matching process resulted in identification of 149 counties principally in the Midwest, which when combined with the 447 counties in the USGS data base, produced a total of 623 counties with potential problems from nitrogen fertilizer applications.

Data Limitations

The data represented by Figure 3 do not represent a random sample of all wells or aquifers in the U.S.; rather, the types of wells sampled, the numbers of wells, the time period covered, and the areal coverage of sampling networks differ from state to state and within states (Madison and Brunett). Thus, for example, the data from one county in a high category may represent only observations from shallow wells in areas of suspected contamination while another county's data may represent a more diverse sample of wells across the area.

Non-agricultural influences cannot be completely eliminated, nor can those of natural background levels of nitrate-nitrogen, as both are unquantified and vary widely from one location to another. Additionally, other agricultural influences might be reflected in the data, particularly intensive livestock operations such as dairy farming (e.g., in portions of Pennsylvania, New York and Wisconsin) and feedlot operations (e.g., in Texas and other areas of the Southeast). These influences are expected to be primarily of a localized nature, however.

Because the nitrogen fertilizer application data are limited to five crops, and to major producing areas of those crops, the data underestimate commercial nitrogen fertilizer usage nationally. However, because the nitrogen fertilizer data are used to supplement USGS information, the impact of this shortcoming is minimal. The major areas with missing USGS data (the Corn Belt and the Southeast) grow primarily crops for which nitrogen fertilizer data are available. Like the pesticide application data, aggregated figures have been extrapolated to the county level based upon crop acreages. Specific counties may in actuality receive applications significantly different from statewide averages.

Areas with Potential Contamination from Pesticides and Fertilizers

Together, areas of potential contamination from pesticide and fertilizer use account for 1,435 counties, or about 45 percent of the counties in the continental U.S. Strong regional trends are obvious from the data. Counties with only pesticide problems total 812, and are located largely along the Eastern Seaboard and the Gulf Coast. Counties with only potential nitrate problems total 309, and occur principally in the Great Plains and portions of the Northwest and Southwest. It is perhaps surprising that only 314 counties, less than one-fourth of the counties in the sample, have simultaneous pesticide and nitrate problems predicted. These are located chiefly in the Midwestern Corn Belt, the Lake States, and portions of the Northeast.

As one might suspect, these 1,435 counties are cropped intensively, with 33 percent of all land area in cropland as opposed to 16 percent for the country as a whole. Over 70 percent of the crop acreage in the sample is devoted to corn, wheat and soybeans. Though strongly agricultural, while these counties account for only 27 percent of the U.S. land area, they contain 47 percent of the population.

Population Potentially Affected by Agricultural Groundwater Contamination

Those who live in the areas of potential contamination and who obtain their drinking water from the ground have the greatest potential for incurring damages associated with agricultural groundwater contamination. In order to estimate the potentially affected population, we utilized data from the 1980 Census of Population and Housing on drinking water sources, by county, for the 1,435 counties in the sample. The Census gives data on populations using water from private wells and from public supplies. For the public supplies, statewide averages of the percentages of all public water supplies which use groundwater were used to estimate the population in each county using public groundwater supplies.

Figure 5 depicts the distribution of the population relying on groundwater from both individual wells and public sources in the areas of potential contamination from nitrates and pesticides. The denser areas (red) are scattered throughout the South, Northeast, Midwest and portions of the West. The areas of least density (green) lie in the Great Plains and portions of the South and Western Kentucky.

In aggregate, 53.3 million people, an estimated 52 percent of the population in the areas of potential contamination, obtain their water from underground sources. This reflects a disproportionate reliance on wells: while the sample includes 47 percent of the U.S. population, it contains 57 percent of all persons who drink water from private wells. This may imply an additional risk factor faced by these people relative to the rest of the population because individual wells are more vulnerable to contamination than deeper, regulated public wells.

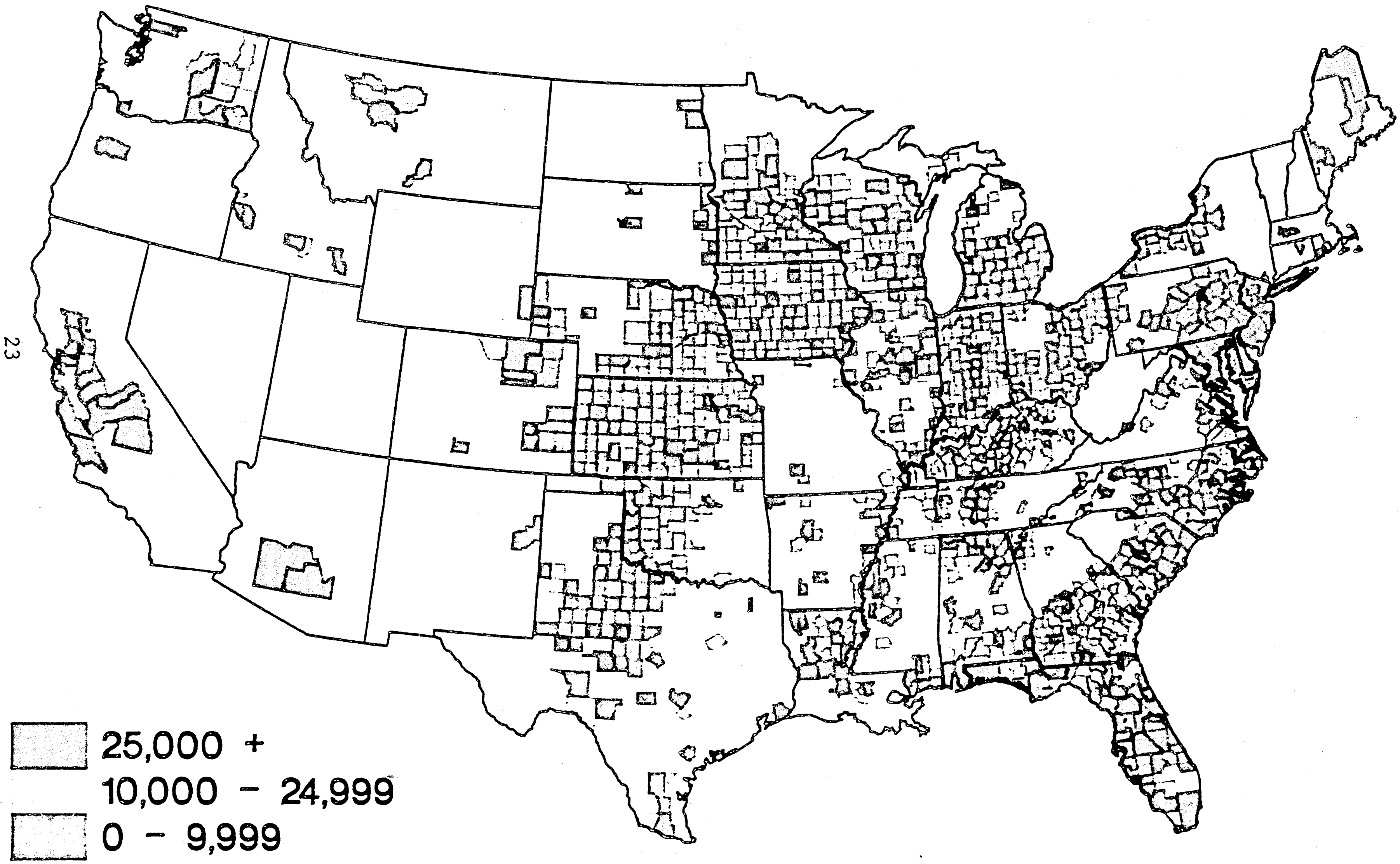
Summary

The data presented in Figures 1-5 have several implications for defining the magnitude of groundwater contamination from agricultural chemicals. First, the data indicate that the problem of groundwater contamination from agricultural chemicals is not a national problem. It does appear to be a regional problem, extending beyond local or state jurisdictions.

Secondly, the data indicate that pesticides and nitrates in groundwater do not necessarily occur together. In fact, in three-fourths of the 1,435 potentially contaminated counties, pesticides and nitrate problems are predicted to occur independently. The presence of nitrates may be an indicator of pesticide problems and vice versa,

Figure 5

Population Relying on Groundwater in Potentially Contaminated Areas



but other factors may intervene to prevent the presence of both in groundwater. This suggests that different strategies may be appropriate for pesticides than for nitrates in groundwater.

Finally, the data indicate that agricultural chemical contamination of groundwater, while affecting agricultural and rural areas, has an impact on a significant component of the U.S. population, 53.3 million people. This occurs because of the density of population of areas affected, and the heavy reliance on groundwater and private wells in those areas.

POTENTIAL DAMAGES FROM AGRICULTURALLY CONTAMINATED GROUNDWATER

The economic significance of Figures 1-5 is reflected in the damages or costs that society and individuals incur from agriculturally contaminated groundwater. A summary of potential damages along with documented incidents and available cost data is developed in Table 2. As can be seen from the table, the externalities generated by agricultural chemicals in groundwater can be potentially very significant. Unfortunately, the available data on occurrences and costs are very limited at the national or regional level. In this section, human health risks from contaminated groundwater are reviewed and an assessment of the potential costs of avoiding damages is presented.

Human Health Risks

The primary source of potential damages stems from human health risks. However, evidence on human health risks associated with nitrates and pesticides in groundwater is spotty and often

Table 2. Potential Damages from Groundwater Contaminated by Agricultural Chemicals

Damage Category	Documented Incidents	Costs Incurred
Agricultural Impacts		
Livestock poisoning and health problems	Nitrate/nitrite poisoning of livestock	Unknown
Crop quality or quantity decreases	Salts leached from fertilizers can be concentrated through irrigation. Total contribution to salinity thought minor.	Unknown
Household Impacts		
Health risks		
a) methemoglobinemia from nitrites	Infant deaths and illness	Unknown
b) miscellaneous health problems from pesticides and nitrites	No conclusive documentation	Unknown
c) cancer risk	No conclusive documentation	Unknown
Environmental Impacts		
Damages to vegetation, waterfowl, and aquatic life in recharge areas and in surface water contaminated by groundwater agricultural chemicals	No conclusive documentation	Unknown

contradictory. The known or suspected health impacts are reviewed below.

There are very few documented human health impacts from direct exposures to nitrates. More health problems have been traced to nitrites. Once nitrates enter the body, some proportion is converted to nitrites. Bacteria in the mouth and to a lesser extent other parts of the digestive system convert nitrate to nitrite. The percentage of nitrate converted to nitrite in the body apparently varies among individuals and no human conversion factor is presently known. However, bacterial reduction of nitrate in saliva is probably the major form of nitrite formation (National Research Council, 1978).

The best documented human health risk from nitrites is infant methemoglobinemia. In infants, nitrate is reduced to nitrite in the digestive tract, apparently because of a lack of acidity in the stomach and upper part of the newborn intestinal tract. Nitrite in infants is absorbed into the bloodstream where it interacts with hemoglobin to produce methemoglobin, which does not carry oxygen to body cells. Excess nitrates in drinking water can be fatal to infants, particularly within the first three months of life. Deaths from infant methemoglobinemia in the U.S. are now rare, however, the true incidence is unknown as cases are not required to be reported. In addition to infants, several other categories of individuals have susceptibility to methemoglobinemia, including pregnant women. Bottled water is now recommended in the U.S. where nitrate in the water exceeds the public health standard of 10 mg/L.

The carcinogenic effects of nitrites have been investigated, but a more direct linkage to cancer has been found with nitrosamines than with nitrites. Nitrosamines can be formed when nitrite combines with other substances such as amines. Most researchers are in agreement that it is beyond question that nitrosamines are potent carcinogens for a wide range of target organs in many animal species (National Research Council, 1981).

However, because the human studies are limited, and in some cases produce contradictory results, it is difficult to prove conclusively that nitrites or nitrosamines are true risk factors in the development of forms of human cancer. The weight of animal evidence and the limited human studies that have been conducted suggest that an association between nitrate consumption and its reduced forms of nitrite and nitrosamines and human cancer is plausible. Until further studies are conducted, no definitive conclusions can be reached.

The degree of risk associated with the use and ingestion of water containing pesticide residues is also a much-studied but by no means well-answered question. Since all pesticides are designed to be toxic to certain forms of life, and because few or none are completely selective in their actions, most have the potential to adversely affect human health. The uncertainties regarding risk exist for a number of reasons.

While acute toxicities can be evaluated from laboratory research and accident case studies, no methodology exists to develop meaningful risk estimates for low-dose exposures, such as the exposures normally associated with drinking contaminated groundwater. Some of the effects take years or decades to develop, so that causes are difficult to identify. Also, the effects of interactions within the body of pesticides with each other and with chemicals such as nitrates are even more difficult to analyze than are the effects of single chemicals.

Data are not entirely lacking, however. EPA cancelled the uses of two nematicides, EDB and DBCP, due to evidence that they cause genetic mutations, reproductive disorders and cancer (EPA, 1985). Both of these chemicals have been found in groundwater. Alachlor, an acetanilide herbicide widely used on corn and soybeans, and found in groundwater in four states, has also shown strong evidence of carcinogenicity (EPA, 1985).

Triazine herbicides (e.g., atrazine, cyanazine and simazine) are groundwater contaminants and, though not known to be carcinogens, are suspected of causing long-term effects including central nervous system (CNS) disorders (Environ Corporation). Similarly, widely used phenoxy acid herbicides which are potential leachers, such as 2,4-D, 2,4,5-T and 2,4,,5-TP, are also suspected of causing CNS disorders and a variety of other chronic effects (Environ Corporation, Life Systems Inc.).

In summary, though data are imperfect and often inconclusive, the available evidence suggests that the presence of either pesticides or nitrates in drinking water may pose health risks. The presence of both pesticides and nitrates together in drinking water poses additional unknown risks. Finally, some individuals with the greatest potential for ingestion of groundwater contaminated by agricultural chemicals may also be exposed during chemical application, which necessarily increases the risk of long-term effects.

Avoidance Costs

Because it is difficult to directly address the costs of damages imposed on society by agricultural chemical contamination of groundwater, this analysis will focus on costs of avoiding groundwater contamination. Avoidance costs are one way to estimate what society must pay to minimize an unspecified contamination risk. Avoidance costs for both households using private wells and community systems are analyzed. The household sector is studied because private wells are a significant water source in potentially contaminated areas and the health risks faced by households are the most widely cited impact of groundwater contamination.

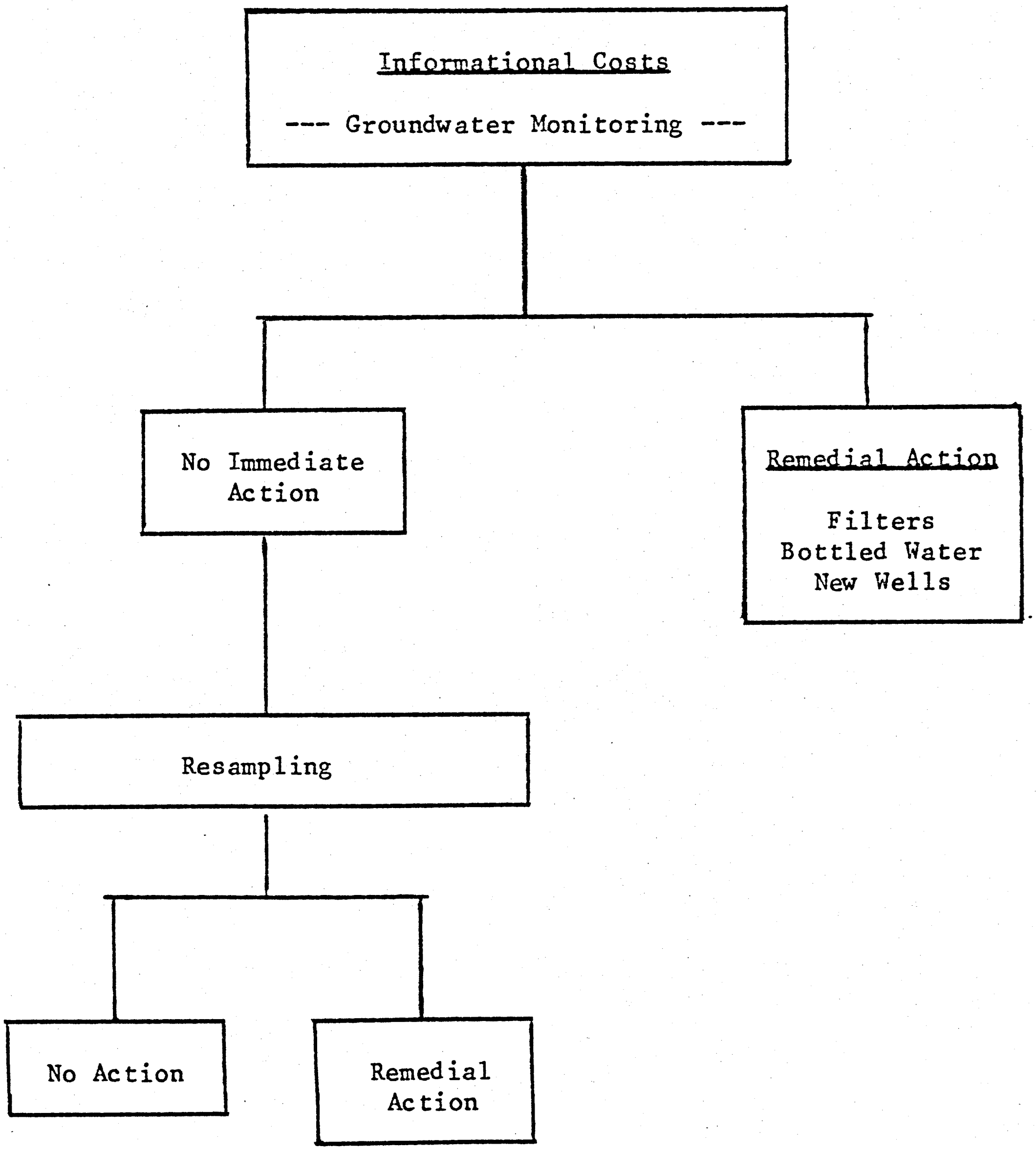
Household Monitoring Costs

Figure 6 presents a framework for household decisionmaking in groundwater contamination areas. The first step in any decisionmaking process is to obtain information about potential risks. In the case of groundwater, this is normally done through well sampling and laboratory tests. Once test results are obtained and verified, if positive, households can then assess the information based on their own risk preferences.

If the monitoring information indicates that groundwater contamination is a problem, or if a household's assessment is that the risks faced by contamination are significant, remedial action can then be taken. Bottled water, filters, or new wells are the most likely alternatives for households in rural areas. Hook-up to deeper, community system wells may be an another alternative for some households.

Even if no immediate remedial action is required or desired at current levels of contamination, if a household is in a potentially contaminated area, resampling at periodic intervals for contaminants is necessary. Remedial action may be necessary at a later time.

Figure 6. Household Decisionmaking in Areas of Potential Groundwater Contamination



The first step in estimating the household avoidance costs of groundwater contamination is a determination of monitoring costs. Not every household in a potentially contaminated area would choose to undergo monitoring. Some would assess any potential risk as enough to warrant remedial action. Others may decide that no matter what the monitoring results indicate, no action is necessary. Our current data base does not allow a determination of individual risk preferences for groundwater contamination. Consequently, the household monitoring cost estimates discussed in this section are a hypothetical upper limit on initial monitoring costs by private households in areas of potential groundwater contamination. These estimates can be used, however, to make comparisons between pesticide and nitrate costs as well as between private well and municipal monitoring costs. These comparisons can provide useful implications for public policies.

Data in Table 3 reflect a range of initial monitoring costs for private wells in areas of potential groundwater contamination. These

Table 3. Range of Initial Monitoring Costs for Private Wells in Areas of Potential Groundwater Contamination

Monitoring Cost Assumptions	Dollars
High	$2.20 Billion
Average	$1.35 Billion
Low	$0.88 Billion

monitoring cost data were obtained through discussions with private laboratories in potentially contaminated areas. The assumptions used to develop these estimates are as follows:

1. Two chemical tests for pesticides are conducted.
2. A 33 percent resampling rate for nitrates and pesticides is included to allow for checking of positive results and additional remonitoring.
3. Pesticide lab costs, including bottles, were estimated to range from $50 to $200 per test, averaging $84.
4. Nitrate lab costs, including bottles, range from $10 to $25, averaging $16.
5. Shipping and labor costs are estimated to be $3.00 per well for nitrates and $5.18 per well for pesticides, with and without additional tests for nitrates.

The estimates range from a high of $2.2 billion to $.9 billion, depending on the laboratory cost estimate used. The average or "best" estimate is $1.35 billion.

Table 4 presents the monitoring data by pesticide and nitrate categories. Only $14 million of the $1.35 billion in monitoring costs are attributable to nitrates alone. Pesticides alone or in combination with nitrates, represent the majority of monitoring costs due to the larger geographical area affected and the higher lab costs involved.

Figure 7 indicates the distribution of monitoring costs by regions. Approximately 74 percent of total monitoring costs are contained in high cost counties which have $1 million or more in monitoring costs. High monitoring cost counties are depicted in red and are concentrated in Wisconsin, Michigan, Ohio, Pennsylvania, New York, Maine, parts of the Southeast Coastal Plain, Florida, and

Figure 7

Groundwater Monitoring Costs in Potentially Contaminated Areas

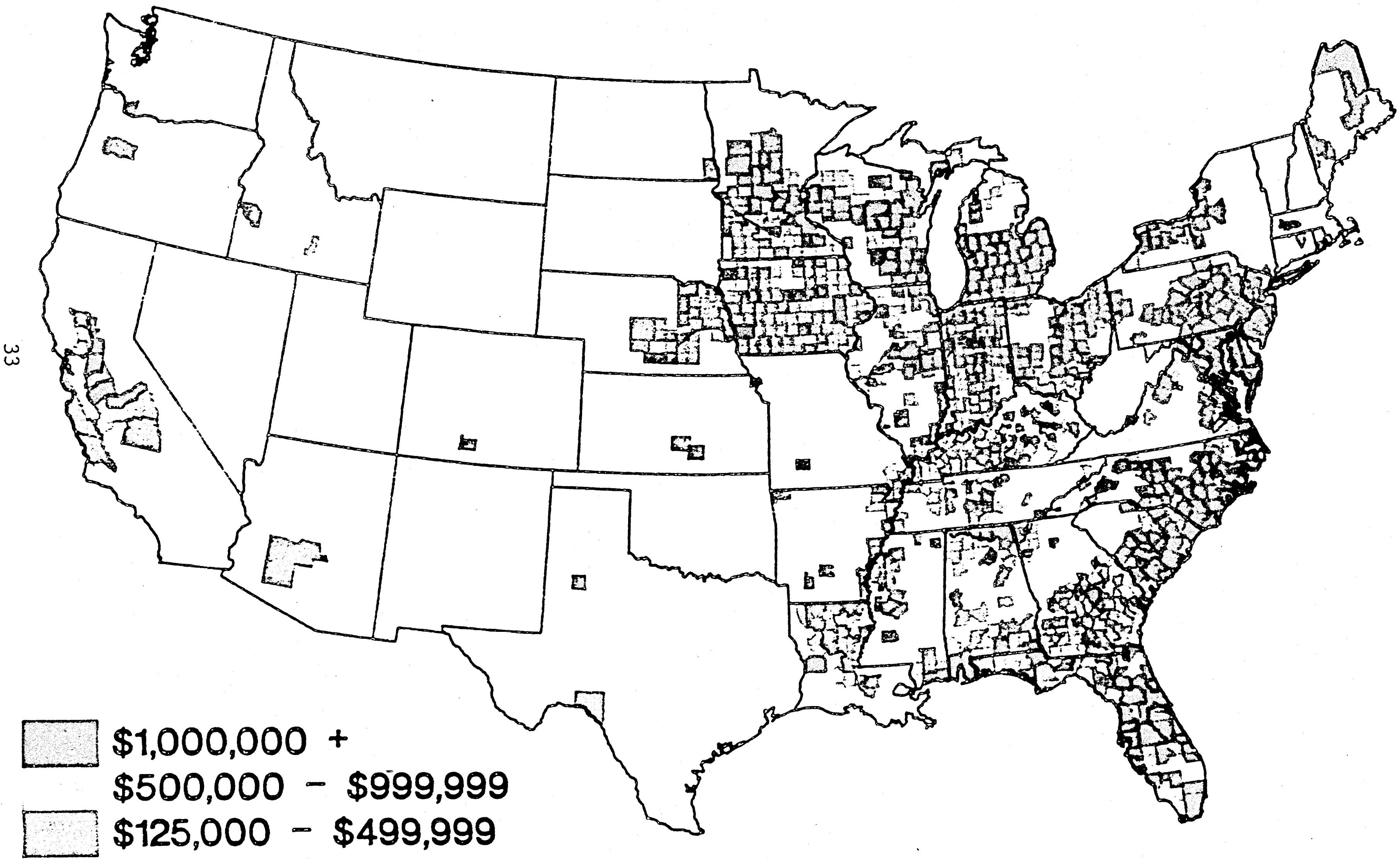


Table 4. Initial Monitoring Costs, by Contaminant, for Private Wells in Areas of Potential Groundwater Contamination

Contaminant Category	Total cost (millions)	No. of counties
Pesticides and Nitrates	$414	314
Pesticides	922	812
Nitrates	14	309
Total	$1,350	1,435

California. These areas tend to be more densely populated than other potentially contaminated areas. They average 3.6 persons per square mile compared to .2 persons per square mile in all areas subject to groundwater contamination. These high cost areas also have a higher percentage of population on private wells. About 21 percent of the population in high cost areas is on private wells compared to 19 percent in vulnerable areas in total. Finally, the high cost monitoring areas are those with predominate pesticide problems, or where pesticides and nitrates are found together.

Community System Monitoring Costs

Approximately 34 million people in the areas of potential contamination obtain their water from community groundwater systems. These community wells are also subject to groundwater contamination from agricultural chemicals, although they are likely to be deeper than a typical private well. Community systems are much more regulated than private wells, which are subject to no regulatory standards. Currently, however, community systems are required to monitor for relatively few agricultural chemicals. Nitrates are the only agricultural chemical community groundwater systems periodically investigate on a nationwide basis.

To compare contamination avoidance costs between the private and public sectors, monitoring cost data are developed for community systems in potentially contaminated areas. Only pesticide monitoring costs are analyzed, as nitrates are monitored under an ongoing program.

Because data on community groundwater systems by county were not available for this analysis, the state ratio of the public groundwater population to total population using public supplies was applied to the potentially contaminated counties in a state. An assumption was made that the average community system in the study counties serves 3,300-10,000 people. Then, EPA assumptions about a community system of this size were applied. For an analysis of the costs associated with the implementation of standards for volatile organic chemicals (VOCs), EPA assumed that a system of this size would be served by 8 wells with 4 entry points. Samples are taken at each entry point, giving an average of 4 samples per year for each chemical.

We added to the EPA assumptions one made in the private well analysis, namely, that two chemical tests would be performed. A 5 percent quantity discount on lab costs is presumed available to a system of this size. Monitoring costs then become the product of:

$157, the cost of two chemical tests with a 5 percent discount,

4, the number of entry points, and

4, the number of samples per year,

or $2,512.

Dividing $2,512 by the midpoint of the population served by this typical system, 6,650, yields a monitoring cost estimate of $.38 per person. There are approximately 28.6 million people served by community groundwater systems in counties potentially contaminated with pesticides. This would total approximately $10.9 million in initial monitoring costs for a one year period. When compared to the more than $1 billion estimate developed for private wells in these same counties, the public sector costs are relatively minor. The principal reason for the major differences between private and public sector monitoring costs is the economies of size afforded by a community groundwater system.

The data and assumptions used to develop the community system estimate are not directly tied to the county-level data base used for the majority of this analysis. We anticipate improving and refining this estimate by working with an EPA data base on public water systems, the Federal Reporting Data System, (FRDS), which is now available.

Summary

The monitoring cost approach does not directly address the costs of damages incurred by society as a result of groundwater contamination from agricultural chemicals. The current lack of documentation about those damages, health risks in particular, makes an aggregate damage assessment difficult.

The monitoring cost data are presented to partially illustrate the costs of a damage avoidance strategy by households and communities.

The monitoring costs are the first, informational step in an avoidance strategy. While this approach represents a hypothetical, upper bound on monitoring costs, it does allow useful comparisons among groundwater users in affected areas.

The data suggest that the externalities imposed by agricultural chemical contamination of groundwater are potentially significant. The initial monitoring costs for a household avoidance strategy would range between $.9 and $2.2 billion, with $1.35 billion an average estimate. Household monitoring costs for pesticides are so prohibitive, that is unlikely that such an approach is feasible. Adding any necessary remedial actions to the analysis, lends further support to this conclusion.

The data also clearly indicate that, within the potentially contaminated areas, the externalities created by agricultural chemicals in groundwater will be borne by the rural sector. Monitoring costs do not differ by size of well. Communities with more and larger volume wells can spread any monitoring costs over a network of users. In addition, quantity discounts are likely available. Private well owners must directly bear all costs, monitoring or remedial. Thus, rural residents on private wells, of which farmers are a portion, will be the group most directly impacted by avoidance costs incurred because of agricultural contaminants in groundwater.

IMPLICATIONS FOR GROUNDWATER PROTECTION STRATEGIES

Despite the limitations of the current data, the statistics presented do serve as indicators of broad regional and national trends. These data have implications for groundwater contamination protection strategies.

First, the data suggest a strong role for farmer education programs to prevent or minimize groundwater contamination. If incentives for voluntary action by farmers are ever going to be effective, it is likely to be in the groundwater contamination area. Unlike surface water pollution, farmers are immediately affected by agricultural pollution of groundwater as their wells are closest to the sources of contamination. Unfortunately, there is currently little advice to give to farmers about the impact of agricultural practices, such as conservation tillage, on groundwater contamination. The success of farmer educational programs depends, in part, on well documented research programs, many of which are just being initiated.

The data also suggest that different strategies may be appropriate for nitrates and pesticides. In areas of nitrate contamination, strategies such as input taxes on fertilizers may be sufficient in vulnerable areas to offset well monitoring costs or to provide alternative water sources for those affected. This is because there are about 556,000 private wells in areas potentially affected by nitrate contamination alone compared to 5.6 million private wells in areas with potential pesticide problems, sometimes in combination with nitrates. Monitoring costs for nitrates are relatively inexpensive, and the relatively small number of private wells potentially affected may make a remedial program feasible.

In contrast, pesticide monitoring costs, whether alone, or in combination with nitrates, are so prohibitive that an individual household monitoring program for 5.6 million wells is not feasible, nor is any government monitoring program likely to be fully funded. Prevention, not detection and remedial action, is a more likely strategy, particularly where pesticide contamination is to be avoided. Effective and economical onfarm prevention measures need to be developed.

The data clearly indicate that targeting is needed for any protection strategy. Not all regions are vulnerable. Of those regions with chemical usage, not all are equally dependent on groundwater or are densely populated. The monitoring cost approach combines physical vulnerability characteristics, chemical usage data, number of wells, and population data. Depending on program goals, the monitoring cost data in Figure 7 suggest priority regions for targeting groundwater protection strategies.

CONCLUSIONS

The objective of this paper was to define the physical and economic dimensions of agricultural groundwater contamination in the U.S. Major uncertainties remain concerning the damages and costs associated with contamination, especially those related to human health risks. Despite the limitations of the data and analysis presented, we feel that this paper sets the stage for further, more detailed analyses of the economic issues associated with agriculture and groundwater contamination. The development of economic analysis depends, of course, on the simultaneous development of improved data on the physical processes of groundwater contamination.

A major research issue that will have to be addressed is the relationship between the social benefits and social costs of groundwater protection programs and policies. In the absence of any broad based research results, public decisionmakers are beginning to propose and enact legislation designed to protect groundwater from agricultural chemicals and other contaminants. States such as Arizona and Wisconsin have already enacted groundwater protection programs, and the EPA is currently formulating a protection strategy for agricultural chemicals. Other legislative and regulatory measures are sure to be forthcoming, some of which may impose restrictions on the agricultural sector.

The costs of these regulatory measures on the agricultural sector are not yet understood. The relationships among agricultural practices, farm income, and changes in groundwater contaminant levels need to be defined. In addition, the economic damages from human health and property impacts need to be directly addressed. With these data, the benefits of controlling societal damages from agricultural groundwater contamination can be compared to the social costs of groundwater protection programs and policies. This analysis should lead to the development of more efficient and effective strategies to control agricultural groundwater pollution.

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