

Assessing Pesticide Contamination to Ground Water: A Rapid Approach

by Majid Ehteshami , Richard C. Peralta , Hubert Eisele , Howard Deer , and Terry Tindall

Assessing Pesticide Contamination to Ground Water: A Rapid Approach

by Majid Ehteshami^a, Richard C. Peralta^b, Hubert Eisele^c, Howard Deer^d, and Terry Tindall^e

Abstract

A methodology has been developed for identifying hazardous pesticides/site combinations threatening ground-water contamination. Screening methodologies are required to determine which locations and pesticides now in use should receive the greatest attention to safeguard the public health. The presented method uses a hazard to ground-water hydrogeological screening model (DRASTIC) and employs a one-dimensional pesticide transport model (CMLS). The method is an efficient and practical technique to identify where particular combinations of pesticides, water management practices, soils, and geology result in the greatest potential hazard to ground-water contamination. Use of the presented approach can reduce sampling needs and expense.

Introduction

Pesticide sales in the U.S. total approximately 1.1 billion pounds annually. The use of pesticides is an integral part of today's agriculture. In many cases, pesticides safeguard crops from severe pest infestation, or increase yield by suppressing competing weed growth. Pesticides often make the difference between profits and losses in farming operations. However, some pesticides can pose a risk to human health and to the environment even in extremely low concentrations. Applied to plant or soil surfaces, or injected into the soil, pesticides may leach to the ground water or may be washed off with surface water. Pesticide-contaminated surface water can reach ground water which, in turn, can reach the surface and contribute to surface-water pollution. Once in the ground water, pesticides can persist for years, rendering the water unsuitable for human and animal consumption. Effectively treating drinking water to reduce pesticide residues to acceptable levels or to restore ground-water quality can be difficult and expensive.

Recent sampling in many states revealed pesticide contamination of ground water. Based on a national survey, Parsons (1988) notes: "The principal criterion for whether or not pesticides had been detected in the ground water in a state appears to be whether or not they have looked. The information on occurrences of pesticides in ground water is burgeoning to the point that it is difficult to assemble an accurate overview of the nature and scope of the national problem."

There are numerous publications concerning pesticide contamination. Rao et al. (1985), Leonard et al. (1988), and Pionke et al. (1988) reported concentration of pesticides in their experimental field and agricultural areas in states from Florida to California. Oki and Giambelluca (1987) reported pesticide contamination and closure of water-supply wells on Oahu Island, Hawaii. Loague et al. (1989) presented a statistical method to assess areas with high potential to ground-water contamination on the same island. They used first-order uncertainty analyses correlating soil and pesticide data. In their study they use a geographic information system (GIS), a relatively expensive approach for determining the sites which have higher leaching potential for pesticides. Rao et al. (1985) presented a method to screen a large number of pesticides to determine their potential to contaminate ground water. In their study they used indices to rank pesticides in terms of their potential to leach past the crop root zone. Jury et al. (1987) used soil and pesticide chemical characteristics to model pesticide contamination. Their model used uniform values of soil-water content and soil bulk density and did not consider the effect of actual rainfall and irrigation water on pesticide movement and ground-water contamination. Carsel et al. (1988) used a pesticide root zone model (PRZM) as a screening procedure for aldicarb contamination in the peanut growing areas in

^aAssistant Engineer, Imperial Irrigation District, Imperial, California 92251.

^bAssociate Professor, Agricultural Engineering Department, Utah State University, Logan, Utah 84322-4105.

^cSenior Engineer, Holinger LTD., Baden, Switzerland CH-5401.

^dExtension Pesticide Coordinator, Utah Agricultural Experiment Station, Utah State University, Logan, Utah 84322-4649.

^eExtension Soil Fertility Specialist, Idaho Agricultural Experiment Station, University of Idaho, Twin Falls, Idaho 83301.

Received June 1990, revised December 1990, accepted January 1991.

Discussion open until May 1, 1992.

North Carolina. Their simulations indicate a significant mass flux to ground water. Banton and Villeneuve (1989) compared the pesticide DRASTIC index and the PRZM leaching quantity model for evaluation of ground-water vulnerability to pesticides contamination. They concluded that chemical characteristics of the potential contaminants, which are not considered in the DRASTIC index, are important. In addition, simulation models appear to be the best tool for evaluating the ground-water vulnerability, because they quantify this pollution potential in terms of physical magnitude, which can be compared with water quality criteria.

In Utah, ground water is a valuable and necessary resource. About 63 percent of Utah's population depends on ground water for drinking supplies (Waddell, 1987). In rural areas, ground water is often the only source of drinking water. However, in some of these same areas, ground water is close to the surface and, therefore, easily subject to contamination by agricultural chemicals. There are up to 50,000 wells statewide supplying water for various purposes. The Utah Department of Health, for the purpose of developing a statewide ground-water management strategy, has called for the identification of potential and existing ground-water quality problems (Barnes and Croft, 1986). Of initial importance is assessing the potential magnitude of the problem. Sampling all existing wells is too expensive and impractical as a means of assessing existing problems. Therefore, an educated selection of representative sampling sites is desired.

The objective of this paper is to demonstrate an efficient method to determine the areas where particular combinations of pesticides, water management practices, soils, and geology result in the greatest potential hazard to ground-water contamination. The procedure uses questionnaires, hydrogeological screening, and a one-dimensional chemical transport simulation model. Use of the presented approach can result in more effective sampling programs and expenditures than would be possible using hydrogeological screening alone.

Procedure

The following procedure was adopted to assess the potential hazard that pesticides might pose to ground-water quality: 1. collection of data on pesticide applications including areas of pesticide use, crops treated with pesticides, types of pesticides used, and pesticide application practices; 2. application of a "hazard to ground water" hydrogeological screening model; 3. employment of a one-dimensional pesticide transport model and application of the model to sites identified by the hydrogeological screening model; 4. regional comparison of simulated vertical pesticide movement and its relation to health advisories; and 5. identification of areas where pesticides might threaten acceptability of ground-water quality.

Operational Considerations

Utah has approximately 13,600 farms (DelRoy, 1988). Because surveying even a small number of these farms was determined unrealistic, county agents of Utah State University's Cooperative Extension Service were enlisted as survey

respondents. The county agents were chosen based on familiarity with farming operations throughout the state. The agents were asked to respond for the areas within the county which they were working. The data collected from the survey include: 1. crop rotation for a particular farm; 2. crop name, planting date, date of emergence, date of maturity, date of harvest; 3. pesticide name, formulation, application date, application rate; 4. irrigation method, rate, frequency, duration, starting date in season; and 5. soil type. Survey respondents were also requested to provide information on crop rotations and were asked to sketch crop rotation patterns on 1:100,000 scale USGS (United States Geological Survey) topographic maps.

Because rigorous evaluation of contamination potential for all agricultural fields was not practical, the use of a rapid assessment or screening procedure was essential. The purpose of the screening method was to identify potentially safe site/chemical combinations that could be excluded from further investigation, and/or to target potentially hazardous site/chemical combinations on which intensive attention could be focused.

DRASTIC (Aller et al., 1985) was used as a hydrogeological screening tool. DRASTIC, "A Standardized System for Evaluating Ground-Water Pollution Potential Using Hydrogeologic Settings," was developed by the National Water Well Association for the Environmental Protection Agency. DRASTIC serves as a screening tool for the systematic evaluation of the relative vulnerability of areas to ground-water contamination and serves to help direct available resources, waste disposal, and other land-use activities to appropriate areas.

In this method, quantitative ranking factors are weighted and summed, yielding a total score, called the DRASTIC index. The higher the index, the greater the ground-water pollution potential; however, the index is a relative value that is used only for comparative assessments. DRASTIC has advantages such as: 1. ease and rapidity of use while including factors important to pesticide movement "depth to ground water" and "net recharge"; 2. appropriateness for use in a large area; and 3. ease with which results are conducive to representation on large scale mapping.

Agricultural DRASTIC Index Calculation for Cropped Areas in Utah

The agricultural DRASTIC index is the weighted sum of seven factors that might affect pesticide movement. The index is expressed as:

$$\text{Index value} = D_R \cdot D_W + R_R \cdot R_W + A_R \cdot A_W + S_R \cdot S_W + T_R \cdot T_W + I_R \cdot I_W + C_R \cdot C_W \quad (1)$$

where the subscript R stands for rating, the subscript W stands for weight, and D = depth to ground water; R = net recharge; A = aquifer media; S = soil media; T = topography (slope); I = impact of vadose zone; and C = hydraulic conductivity.

The weights indicate the relative importance of each factor with respect to the other factors. Each DRASTIC factor has been assigned a relative weight ranging from 1 to

5. The most significant factors have the weight of 5; the least significant, a weight of 1. These weights are constants and may not be changed. Also, for each DRASTIC factor, the designated rating varies from 1 to 10. The highest pollution potential of a factor is expressed by the rating 10; the lowest by the rating 1; for example, a depth to the ground water of 0 to 5 feet would yield the rating 10 whereas a depth to the ground water of more than 100 feet would be linked to a rating of 1.

Weight and rating definition and selection are described in detail by Aller et al. (1985). Two different DRASTIC indices are described, a general index and an agricultural index. The two indices differ in the weight selection. Results using the general index should not be compared with results using the agricultural index. This study uses the agricultural index.

Data used to compute DRASTIC indices were computed from published sources and supplemented by field information. Sources of the information include technical bulletins and basic data reports of the U.S. Geological Survey and field information obtained via questionnaire. Some reports provide "depth to ground water" mapping, whereas others list data on selected wells (including depth to water surface). The net recharge rates depend on precipitation and irrigation. In most of Utah's agricultural areas, precipitation contributes up to 2 inches to net recharge. However, due to irrigation, total annual net recharge can exceed 10 inches (a value that yields the maximum DRASTIC rating). For estimation of aquifer and vadose zone media and aquifer hydraulic conductivities, technical bulletins and basic data reports revealed important information. Soil media and soil topography data were obtained from soil surveys provided by Soil Conservation Service (SCS).

An example of how DRASTIC was applied to Utah County is presented. Based on the county agent survey, cropped areas are mapped as shown in Figure 1. Figure 2 shows the geographical representation of DRASTIC index calculations for cropping areas in this county. Generally, evaluation areas were located on a uniform grid pattern.

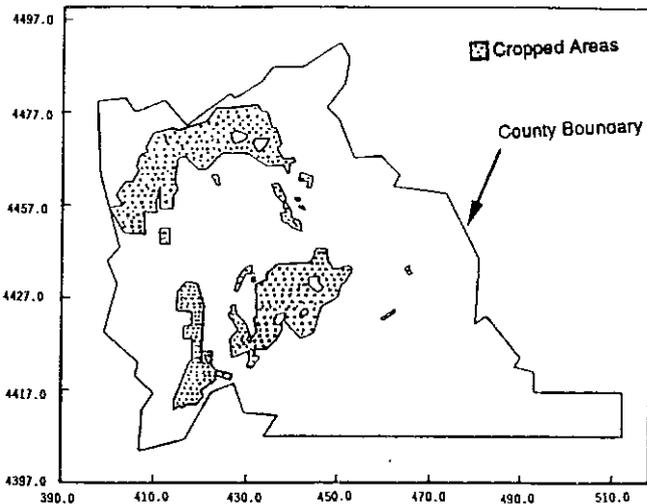


Fig. 1. Cropping areas in Utah County.

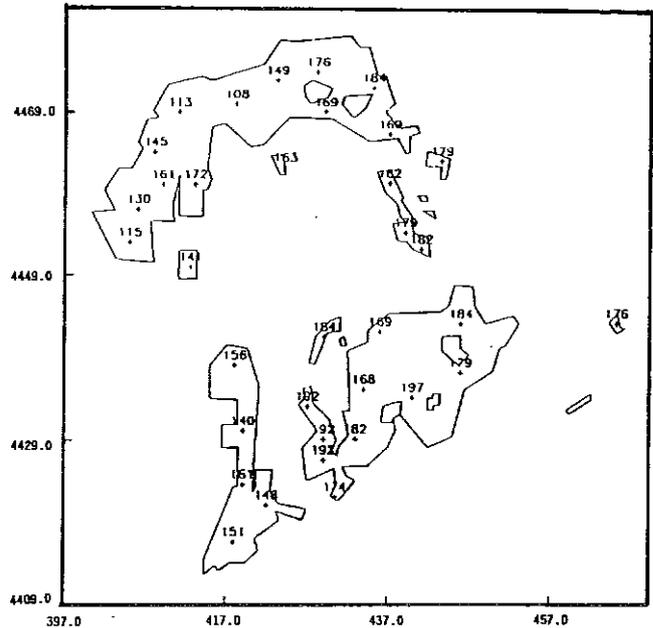


Fig. 2. Agricultural DRASTIC index for Utah County.

Additional areas were evaluated when a higher vulnerability to ground-water contamination is indicated. Areas of higher vulnerability included sites with a shallow depth to ground water, a highly permeable soil, or a very slight ground slope. The low DRASTIC values in the northwestern part of Utah County's cropped area in Figure 2 is a result of low net recharge (unirrigated agriculture) and deep ground water.

The results of the statewide screening for potential hazard to ground water were represented and mapped by Eisele et al. (1989). Table 1 presents the lowest, highest, and average agricultural DRASTIC values computed for each county. These values alone are not adequate for county comparison. Averaging over too many points might disguise some problem areas (if very low or very high values are included in the average). In addition, averaging over too few points might not provide an indication of the spatial extent of the problem. DRASTIC represents a weighted average of how a location is vulnerable to ground-water contamination compared to other locations. Having one high DRASTIC index does not necessarily mean that a county is the worst in ground-water contamination. Also, it is not useful to use total averages as a ranking scheme, since a 5 point average in Daggett County would be compared to a 72 point average in Box Elder County.

Table 1 also shows more useful partial averages derived using the 5, 10, 15, or 20 points with the highest DRASTIC indices in each county. Recognizing the disparity in sample numbers between the counties, it was recommended that the 5 point average be used as an indicator of high risk for a given county. The ranking scheme was found to be adequate to represent for classifying counties vulnerability to ground-water contamination. Using these, one can rank and identify the counties with highest vulnerability to ground-water contamination. For example, those counties with a 5 point average value higher than 190 are Wayne, Weber, Duchesne, Cache, Davis, Summit, Utah, and Uintah.

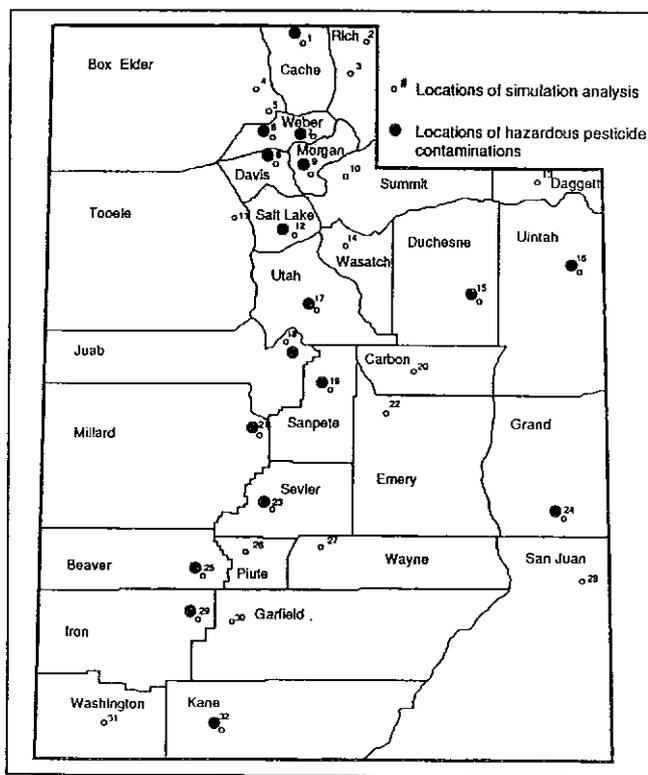


Fig. 3. Site number/county simulated identification and locations of potentially hazardous pesticide site contaminations.

Table 1. Range and Average Agricultural DRASTIC Values for Each County

County	Min.	Max.	5 pt.	10 pt.	15 pt.	20 pt.	Tot. ave.	W
Beaver	147	178	176.4	173.2	164.5	168.3	165.4	21
Box Elder	87	189	184.4	178.5	173.7	169.6	136.8	72
Cache	102	202	198.8	191.9	187.3	182.6	164.3	32
Carbon	162	174	175.0	—	—	—	171.0	8
Daggett	165	207	185.6	—	—	—	185.6	5
Davis	170	196	195.0	189.4	—	—	184.5	12
Duchesne	155	203	199.4	187.9	180.7	175.2	173.4	22
Emery	143	183	177.0	168.0	162.0	—	160.8	16
Garfield	134	187	178.2	164.2	—	—	158.0	13
Grand	163	188	178.8	176.2	—	—	173.2	14
Iron	138	183	199.0	174.0	170.6	165.6	163.2	22
Juab	129	196	186.8	182.2	179.4	172.6	158.8	33
Kane	145	202	187.6	177.6	—	—	169.6	14
Millard	107	175	169.2	165.2	162.7	158.5	146.5	31
Morgan	125	197	182.2	196.0	—	—	165.0	13
Piute	152	188	184.8	180.0	—	—	175.3	14
Rich	142	194	184.9	181.1	176.3	—	172.3	17
Salt Lake	143	188	182.6	178.6	173.9	—	169.5	19
San Juan	130	181	169.0	161.0	158.0	—	150.8	20
Sanpete	137	194	188.6	196.1	182.5	178.8	173.8	25
Sevier	153	199	189.4	183.1	—	—	177.0	14
Summit	148	201	192.2	185.8	178.5	173.6	169.1	28
Toole	155	194	186.4	181.6	—	—	174.4	15
Uintah	123	200	190.0	183.9	179.6	173.6	162.0	32
Utah	108	197	191.4	189.1	184.0	180.5	164.6	35
Wasatch	158	188	188.0	188.0	186.7	185.2	174.2	44
Washington	161	194	188.8	181.8	—	—	177.7	13
Wayne	146	209	202.4	195.8	—	187.3	183.7	17
Weber	180	203	201.6	198.0	195.1	192.7	192.1	21

Computer Simulation of Pesticide Movement

Of 642 sites evaluated using the DRASTIC procedure, those 32 sites with the highest potential for ground-water contamination are shown in Figure 3. Because DRASTIC does not consider the mobility of utilized pesticides, a second layer of screening was needed to identify the chemical/site combinations posing the greatest threat to ground-water contamination. CMLS (Nofziger and Hornsby, 1986) was used as the second step screening model. This model was judged most appropriate for comparing the relative potential hazards at various sites throughout Utah. CMLS, "Chemical Movement in Layered Soil," is a management model that can be used to make decisions regarding the behavior of agrichemicals in soils. The model estimates the location of the peak concentration of organic chemicals as the chemicals move through a soil in response to downward movement of water. The model also estimates the relative amount of each chemical still remaining in the soil at any time. The advantages of using CMLS include: 1. accuracy in the prediction of pesticide movement; 2. small simulation time requirement; 3. minimum input value requirement; and 4. easy accessibility of model output.

The CMLS model integrates two basic concepts: (a) the movement of the chemical; and (b) the degradation of the chemical (Nofziger and Hornsby, 1988). In this model, chemicals move only in the liquid phase in response to soil-water movement. Water movement is calculated using a volume balance approach. Chemicals are exposed to adsorption and degradation processes. The concentration of chemicals decrease as a function of travel distance and travel time due to the adsorption and degradation processes. A linear and reversible equilibrium adsorption model simulates the retardation of the chemical movement. CMLS uses the following equations to predict chemical movement:

$$dd_s = \frac{q}{R \cdot T_{FC}} \quad (2)$$

$$R = 1 + \frac{BD \cdot K_D}{T_{FC}} \quad (3)$$

$$K_D = K_{OC} \cdot OC \quad (4)$$

where: dd_s = change in depth of the solute; q = amount of water passing the depth d_s ; d_s = depth of the solute front in a uniform soil; R = retardation factor; T_{FC} = soil-water content on a volume basis at field capacity; BD = soil bulk density; K_D = partition coefficient of the chemical in soil; K_{OC} = organic carbon partition coefficient; and OC = organic carbon content of the soil.

In CMLS model chemicals are exposed to degradation processes. The model predicts the fraction F of the applied chemical remaining in the entire soil profile as:

$$F = \exp\left(-t \cdot \frac{\ln(2)}{t_{1/2}}\right) \quad (5)$$

where: t = elapsed time since the chemical was applied; and $t_{1/2}$ = biological degradation half-life of the chemical.

Input data necessary to run the CMLS model includes daily precipitation, daily evapotranspiration, crop rooting

depth, pesticide, soil, and pesticide application method. For evaluation, Utah was divided into seven uniform climatic zones. Weather data for each zone was obtained from the state weather office. Pesticide movement is directly related to precipitation; however, precipitation varies considerably with time. In order to compare results throughout the state, pesticide movement was analyzed at all locations for the same time period. A six-year simulation period was selected for analyzing downward pesticide movement through the vadose zone. This study analyzed pesticide movement using climatic data from 1980 through 1985.

In the simulation, daily evapotranspiration was approximated using the Hargreaves and Samani (1985) method which requires only minimum and maximum temperature and latitude. Daily water balance simulation was used to schedule irrigation. The irrigation scheduling followed a customary practice and provided crop-water needs for the cropping period. The relevant soil data were gathered from Wilson et al. (1975) and modern soil surveys and soils data from unpublished SCS surveys.

Pesticide movement and degradation in soil are related to two pesticide-dependent values; the organic carbon partition coefficient (K_{oc}), and the half-life time ($t_{1/2}$). Utilized data for chemical partition coefficient and the half-life time were based on materials from the water quality workshop presented in Fort Worth, Texas (SCS and the Extension Service, 1988).

Results

The site-specific movement of pesticides identified in the survey was calculated using the CMLS model. Figure 4 illustrates model results for a May application of the insecticide diazinon to corn planted in Vineyard sandy loam soil. The lower graph shows the downward insecticide movement in the soil in response to irrigation and precipitation events.

Pesticide movement predictions are also expressed in relative amounts of pesticide remaining in the soil profile. The relative amounts can be converted to concentrations by assuming a mixing depth in the saturated zone of the aquifer. The resulting concentrations can then be compared to health standards by calculating a ratio as follows:

$$\text{Ratio}_{\text{depth}} = \frac{\text{Concentration of pesticide}}{\text{Health standard}} \quad (6)$$

Table 2 illustrates predicted downward movement of the insecticide diazinon for a site in Utah County. This Table shows travel times (in days after application) to depths of 1.0 m, 1.5 m, 2.0 m, 3.0 m, and the relative amount of pesticide remaining in the soil profile at that time. Notice that the

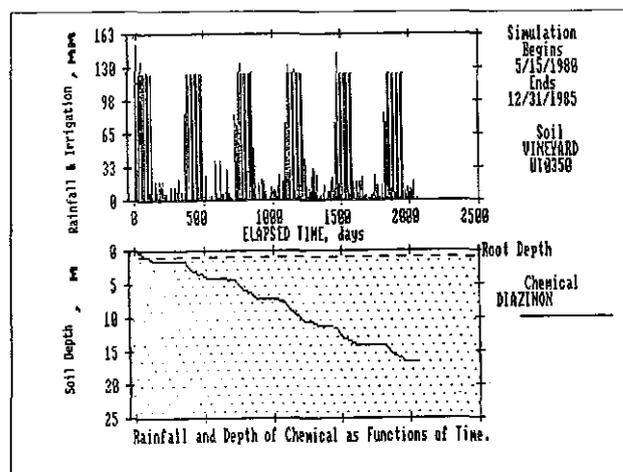


Fig. 4. Water application and pesticide movement.

pesticide reaches the depth of one meter after 92 days. At this time and depth, the concentration of the pesticide in the soil water is 134 ppb. This amount is 212 times higher than the health advisory (0.63 ppb). Notice also that the pesticide reaches a depth of three meters after 426 days, but by that time the assumed concentration is 0.1 ppb which is far below the limit set by the health advisory.

Table 3 ranks potentially hazardous pesticides for combinations of pesticide/site, resulting from the CMLS simulations. The results in Table 3 are a relative comparison only and show which pesticide is more hazardous to ground-water contamination and where it could be found. Soil is a highly variable medium, depth to ground water varies in time and space, irrigation efficiencies depend on farmers, and the chemical-physical properties of many pesticides are not very clearly known. Furthermore, macropores, which are not specifically considered in this study, may lead to unexpectedly rapid and deep movement of pesticides. Therefore, pesticides not included in Table 3 might pose problems at sites other than those listed.

Figure 3 shows the location of the potentially most hazardous site/counties. The information given to this figure and in Table 3 can be used to guide sampling. Based on the health advisory ratios one would sample for aldicarb contamination in Davis and Iron Counties and for atrazine contamination in Cache, Sevier, Sanpete, and Uintah Counties.

Funds available for sampling are generally limited. Agencies wish to know which sites are the most important to sample. In retrospect, it is interesting to compare the locations an agency would sample based on DRASTIC indices

Table 2. Health Standard Ratio

Crop	Pesticide (common/trade)	Quantity (kg/ha)	Depth (m)	Time (days)	Rel. amount	Quantity (ppb)	Health advise (ppb)	Ratio
Corn	Diazinon/ Dianon	1.12	1.0	92	.1194	134	0.63	212
			1.5	316	.0007	0.8		1.2
			2.0	371	.0002	0.2		0.4
			3.0	426	5.3E-5	0.1		0.1

Table 3. Ranking of Pesticide-Site Combinations Posing a Threat to Ground-Water Quality

Rank	Pesticide	Site/County	Rank	Pesticide	Site/County
1	Metolachlor	6/Weber	18	Carbofuran	18/Juab
2	Aldicarb	8/Davis	19	Hexazinone	16/Uintah
3	Carbofuran	23/Sevier	20	Carbofuran	1/Cache
4	Dicamba	23/Sevier	21	Hexazinone	6/Weber
5	Atrazine	1/Cache	22	2,4-D Acid	6/Weber
6	Atrazine	23/Sevier	23	Dicamba	19/Sanpete
7	Carbofuran	28/Sanpete	24	2,4-D Ester	19/Sanpete
8	Carbofuran	6/Weber	25	Dicamba	15/Duchesne
9	Carbofuran	25/Beaver	26	Hexazinone	23/Sevier
10	Dicamba	1/Cache	27	2,4-D Acid	1/Cache
11	Atrazine	28/Sanpete	28	Hexazinone	21/Millard
12	Barban	23/Sevier	29	Hexazinone	25/Beaver
13	Bentazone	8/Davis	30	Chlorsulfuron	1/Cache
14	Atrazine	16/Uintah	31	Aldicarb	29/Iron
15	Hexazinone	9/Morgan	32	2,4-D Amine	21/Millard
16	Hexazinone	24/Grand	33	Oxydemeton-Methyl	21/Millard
17	Dicamba	9/Morgan			

alone, with those based on sequential DRASTIC and CMLS screening. The most simple approach is simply to perform DRASTIC analysis for a number of sites and to assign a sampling priority based on the DRASTIC indices. For example, the horizontal axis of Figure 5 ranks, on the basis of their DRASTIC indices, the 16 counties having the highest indices. Note that when doing this, one assumes conservative contaminants. Since pesticides are nonconservative, they will not move as far as conservative contaminants. As a result, sampling might reveal no pesticides even if the site is favorable for ground-water contamination based on DRASTIC.

If an agency uses only CMLS, without preliminary DRASTIC screening, it might expend much effort unnecessarily and not identify those locations most conducive to ground-water contamination. Using CMLS for a site requires several times as much effort as employing DRASTIC. In addition, although CMLS computes the rates of chemical reaching specific depth, this might have little to do with ground-water contamination unless other information is considered. Data on the proximity of the water table, and the effect of land slope on runoff and percolation are needed. These data are already part of the DRASTIC procedure. Thus, it is more systematic to precede use of CMLS with use of DRASTIC.

The vertical axis of Figure 5 contains the 16 counties rated as having the most severe potential for hazardous ground-water contamination based on CMLS. Recall that this ranking was developed using CMLS for those 32 sites having the highest DRASTIC index. Symbols in Figure 5 allow comparison of county rating developed using DRASTIC alone (a hydrogeologic/site evaluation) versus using DRASTIC followed by CMLS (a chemical/site evaluation). The two ranking procedures give different results. Of the 16 counties that appear in the DRASTIC ranking order, 11 appear in the CMLS ranking also. However, the order of ranking from DRASTIC is dissimilar to that from CMLS. Thus, both screening methodologies are needed.

They augment each other. One screens for hazardous hydrogeological sites. The other screens for hazardous pesticide/site combinations by simulating the rate of leaching of a particular pesticide in a specific physical/chemical environment. By using both screening methodologies, the probability of locating hazardous pesticides is increased and an agency better knows "where to look and what to look for."

Conclusions

In Utah, contamination of shallow ground water by pesticides can be expected. Based on a two-stage screening procedure, the sites which have the highest threat to ground-water contamination were identified. In the first stage, DRASTIC was used to identify sites in 29 counties which

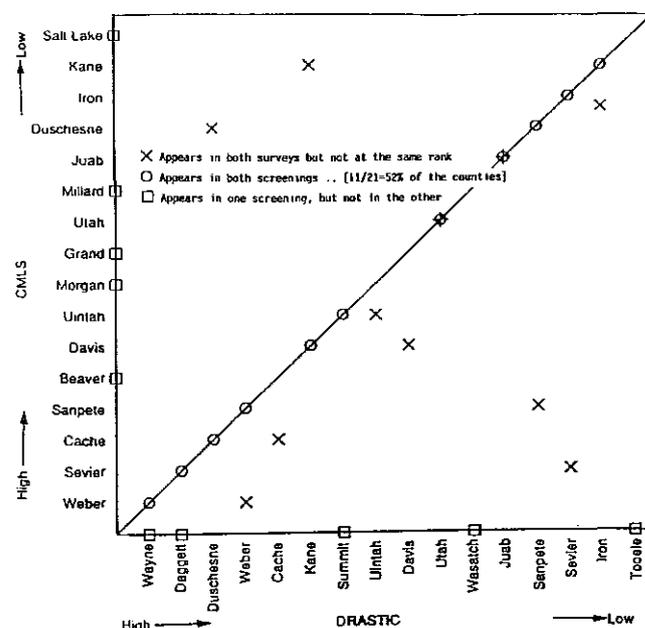


Fig. 5. Comparison of two screening techniques for counties with high potential for pesticide contaminations.

could be considered as most vulnerable to ground-water contamination. In the second stage, extensive computer simulation of potential pesticide movement was conducted utilizing CMLS for locations identified by the DRASTIC procedure. The second screening permitted more accurate determination and comparison of those particular pesticides and sites which have high potential risk of ground-water contamination. Sixteen sites and pesticides were identified and ranked as most promising for sampling. The presented results are being used by regulatory agencies to make the best use of funds available for sampling.

References

- Aller, L., T. Bennett, J. H. Lehr, and R. J. Petty. 1985. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeological Settings. U.S. Environmental Protection Agency.
- Banton, O. and J. Villeneuve. 1989. Evaluation of groundwater vulnerability to pesticides: A comparison between the pesticide DRASTIC index and the PRZM leaching quantities. *Journal of Contaminant Hydrology*. v. 4, pp. 285-296.
- Barnes, R. P. and M. G. Croft. 1986. Ground Water Quality Protection Strategy for the State of Utah. Utah Dept. of Health.
- Carsel, R., R. L. Jones, J. L. Hansen, R. L. Lamb, and M. P. Anderson. 1988. A simulation procedure for groundwater quality assessments of pesticide. *Journal of Contaminant Hydrology*. v. 2, pp. 125-138.
- DelRoy, A. 1988. Water Quality Technical Workshop. Ogden, Utah. U.S. Dept. of Agriculture and Soil Conservation Service.
- Eisele, H., M. Ehteshami, R. C. Peralta, H. M. Deer, and T. Tindall. 1989. Agricultural Pesticide Hazard to Ground Water in Utah. v. I & II, Ag. & Irrigation Engineering Dept. and University Extension Services, Utah State Univ., Logan.
- Hargreaves, G. H. and Z. A. Samani. 1985. Reference crop evapotranspiration from ambient air temperature. Presented at Winter Meeting American Society of Agricultural Engineering, Hyatt Regency, Chicago, IL.
- Jury, W. A., D. D. Focht, and W. J. Farmer. 1987. Evaluation of pesticide pollution potential from standard indices of soil-chemical adsorption and biodegradation. *Journal of Environmental Quality*. v. 16, no. 4, pp. 422-428.
- Leonard, R. A., A. Shirmohammadi, A. W. Johnson, and L. R. Marti. 1988. Pesticide transport in shallow groundwater. *Transactions of the ASAE*. v. 31, no. 3, pp. 776-788.
- Loague, K. M., R. S. Yost, R. E. Green, and T. C. Liang. 1989. Uncertainty in a pesticide leaching assessment for Hawaii. *Journal of Contaminant Hydrology*. v. 4, pp. 139-161.
- Nofziger, D. L. and A. G. Hornsby. 1988. Chemical Movement in Layered Soils: User's Manual. Agricultural Experiment Station, Division of Agriculture, Oklahoma State Univ.
- Nofziger, D. L. and A. G. Hornsby. 1986. A microcomputer-based management tool for chemical movement in soil. *Applied Agricultural Research*. v. 1, pp. 50-56.
- Oki, D. S. and T. W. Giambelluca. 1987. DBCP, EDB, and TCP contamination of ground water in Hawaii. *Ground Water*. v. 25, no. 6, Nov.-Dec.
- Parsons, D. W. 1988. Extension Bulletin. Oregon State Univ. Extension Services.
- Pionke, H. B., D. E. Glotfelty, A. D. Lucas, and J. B. Urban. 1988. Pesticide contamination of groundwater in the Mahantango Creek Watershed. *Journal of Environmental Quality*. v. 17, pp. 76-84.
- Rao, P.S.C., A. G. Hornsby, and R. E. Jessup. 1985. Indices for ranking the potential for pesticide contamination of groundwater. Soil and Crop Science Society of Florida, Symposium, Proceeding. v. 44, pp. 1-8.
- SCS and ES. 1988. Water quality technical workshop. Fort Worth, TX, Oct. 3-7. U.S. Dept. of Agriculture, Soil Conservation Service, and Extension Service.
- Waddell, K. M. 1987. Utah ground water quality. U.S. Geological Survey, Open-File Report 87-0757.
- Wilson, L., M. E. Olsen, T. B. Hutchings, A. R. Southard, and A. J. Erickson. 1975. Soils of Utah. Agricultural Experiment Station, Utah State Univ., Logan, Utah. Bulletin 492.

* * * * *

Majid Ehteshami has a B.S. in Agricultural Engineering from the University of Mazanderan, M.S. in Soil and Irrigation from California State University, Chico, and Ph.D. in Agricultural Engineering from Utah State University. For six years he has been conducting water management study for irrigated agriculture.

Richard C. Peralta has a B.S. in Chemistry from the University of South Carolina, M.S. in Agricultural and Irrigation Engineering from Utah State University, and Ph.D. in Agricultural Engineering from Oklahoma State University. For nine years he has been conducting ground-water management study and developing models for irrigated areas.

Hubert Eisele has a B.S. in Agricultural Engineering from the University of Switzerland, and M.S. and Ph.D. in Agricultural Engineering from Utah State University. For eight years he has been conducting water management study for irrigated agriculture.

Howard Deer has a B.S. in Zoology from the University of Wisconsin, MPH and Ph.D. in Environmental Health, Industrial Hygiene from the University of Minnesota. For 10 years he has been conducting extension duties concerning pest control and pesticide education programs.

Terry Tindall has M.S. and Ph.D. in Soil, Water, and Plant Biology from Oklahoma State University. For eight years he has been conducting extension research work on environmental relationships of nutrient management on irrigated cropland.