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SPRINKLER IRRIGATION-PESTICIDE BEST MANAGEMENT SYSTEMS

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Sprinkler Irrigation-Pesticide Best Management Systems

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Abstract

The relative reduction in potential groundwater contamination due to pesticides at several sites in Utah was determined by comparing alternative irrigation system designs, water management practices, and pesticides.

Alternative sprinkler irrigation distribution coefficients were used to estimate irrigation application depths. The movement of pesticides through soils following sprinkler irrigations was simulated with a one-dimensional model.

Pesticide contamination of groundwater can be reduced by careful selection of pesticides, using properly designed irrigation systems, and improved water management techniques. Procedures for selecting an appropriate sprinkler system design and pesticide are presented.
Keywords. Pesticides, Leaching, Sprinkler irrigation, Irrigation depth, Irrigation system design, Soil, Water management.

Introduction

Pesticides minimize crop losses caused by insects, pathogens, weeds, and other pests, but pesticides also can contaminate groundwater. Potential contamination is of particular concern in areas where groundwater is the main source of water supply for domestic needs.

There are more than 45,000 registered pesticides (USEPA, 1987). Almost 500 million kg of pesticides are used in the U.S. each year (Pimentel and Levitan, 1986). Of these, approximately 60% are herbicides, 24% are insecticides, and 16% are fungicides. About 68% of these are used on agricultural land, where every dollar spent on pesticides returns about four dollars in agricultural production (Pimentel and Levitan, 1986).

Zaki et al. (1982) found aldicarb, a carbamate pesticide, in the groundwater in Suffolk County, New York. Aldicarb levels exceeded the state-recommended safety limits in 13% of 8000 tested wells. According to Sum (1986), the USEPA reported that 17 pesticides were detected in the groundwater of 23 states. Pesticide concentrations ranged from a trace to several hundred parts per million in groundwater. In Oahu, Hawaii, pumping was discontinued at several domestic water wells due to groundwater contamination by pesticides, probably nematicides (Oki and Giambelluca, 1987), used in pineapple production (Lau and Mink, 1987). In the Mahantango Creek watershed, Pennsylvania, atrazine was detected in 14 of 20 wells that were tested (Pionke et al., 1988).

About 50% of the U.S. population obtains drinking water from groundwater (Leonard et al., 1988). This percentage is 63% in Utah (Waddell, 1987). Most rural residents totally rely on groundwater for domestic needs.

Groundwater contamination by pesticides depends on such factors as agricultural practices, soils, plant uptake, geology, hydrology, climate, topography, and pesticide properties.

Objective

This study examined how the use of appropriate management techniques (sprinkler irrigation system design and pesticide selection) affected potential pesticide contamination of groundwater. The main objective of this article is to present an integrated approach for the selection and management of appropriate sprinkler irrigation systems and less mobile pesticides as a best management system (BMS). Use of such a BMS is environmentally safer than less integrated approaches.

Methods

Identification of Study Sites

Sites in the 29 counties of Utah that may be subject to groundwater contamination were identified and ranked (Eisele et al., 1989). First, a rapid screening procedure, DRASTIC (Aller et al., 1985), was used to identify sites with a high risk. Subsequently, a one-dimensional simulation model, CMLS (Nofziger and Hornsby, 1986, 1988), was used to simulate the movement of pesticides in unsaturated soils at locations where the risk of contamination was higher (Eisele et al., 1989). A comparison of DRASTIC and CMLS rankings was performed by Ehteshami et al. (1991).

Six agricultural areas were identified as having relatively high potential for groundwater contamination, based on the findings of Eisele et al. (1989) and Ehteshami et al. (1991). These study sites were located in Cache, Davis, Sevier, Utah, Washington, and Weber counties of Utah.

For each of the selected sites the necessary data were obtained and using CMLS, computer simulations

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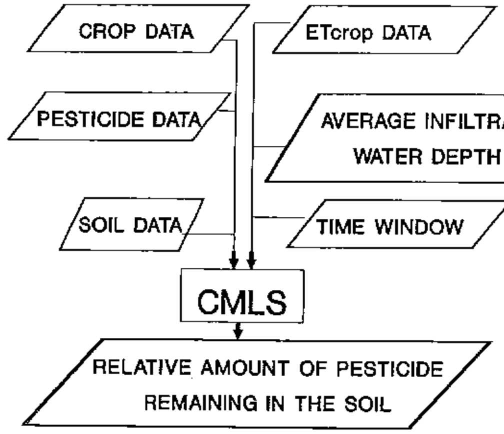

Figure 1–Schematic representation of the procedure to estimate relative amount (RA) of pesticides remaining in the soil.

performed for alternative water management practices, pesticides, and crops. Stepwise representation of the simulation procedure to estimate the potential existence of pesticides in soils is illustrated in figure 1. The amount of infiltration was estimated using a distribution coefficient (Ha) approach (Hart and Reynolds, 1965). Infiltration values were then used in CMLS to predict pesticide movement. The relative potential for groundwater contamination was determined and relative importance of each factor on groundwater contamination was assessed.

Simulation of Pesticide Movement Using CMLS

Based on the study of Eisele et al. (1989), we selected the CMLS as the most appropriate pesticide transport model for this study. The following assumptions (abbreviated by the author) are used in CMLS (Nofziger and Hornsby, 1986, 1988):

- All the soil water residing in pore spaces participate in the transportation process. No preferential flow is assumed.
- Water entering the soil redistributes instantaneously to field capacity.
- Water is removed by evapotranspiration from each layer in the root zone in proportion to the relative amount of water available in that layer.
- Upward movement of soil water does not occur anywhere in the soil profile.
- The adsorption process can be described by a linear, reversible equilibrium model.
- The half-life time for biological degradation of the chemical is constant with time and soil depth.

CMLS simulates (a) the movement of the chemical, and (b) the degradation of the chemical. Chemicals move only with soil-water movement. A soil-moisture volume balance approach is used to calculate water movement. At the beginning of the simulation, each layer in the soil profile is assumed to be at field capacity. Soil moisture is depleted at the rate of daily crop evapotranspiration from the available soil water in each layer of the root zone. Water is available for plants if the water content in any layer of the root zone is in excess of the permanent wilting point. After an irrigation and/or rain occurs, the water content of each layer is adjusted, starting with the upper soil layer.

Due to adsorption processes, chemicals advance far less in depth than water. In CMLS, only the sorption and biodegradation processes of the chemicals are considered and diffusion of chemicals (usually insignificant for organic pesticides) is disregarded. A reversible equilibrium and linear adsorption model simulates the retardation of the chemical movement. The following equations predict chemical movement:

if $W_p > 0$,

$$d^s - d'^s = W_p / \left(RF\, \theta^{fc}\right), \quad (1)$$

if $W_p \le 0$,

$$d^s - d'^s = 0, \quad (2)$$

$$RF = 1 + \left(BD\, K_d / \theta^{fc}\right), \quad (3)$$

$$K_d = K_{oc}\, f_{oc}, \quad (4)$$

where

W_p = amount of water passing the depth d^s (mm or in.),
d^s = solute front depth (mm or in.),
d'^s = solute front depth prior to the adjustment (mm or in.),
RF = retardation factor, θ^{fc} is the soil-water content on a volume basis at field capacity,
BD = soil bulk density (g/cm^3),
Kd = partition coefficient of the chemical in soil (mL/g soil),
K_{oc} = organic carbon partition coefficient (mL/g OC), and
f_{oc} = organic carbon fraction of the soil (OC fraction).

In the soil, chemicals are continuously exposed to degradation processes. Relative amount (RA), the fraction of the applied chemical remaining in a soil profile, is predicted by CMLS:

$$RA = e^{-tr \ln(2) / t_{1/2}}, \quad (5)$$

where

tr = travel time since the chemical was applied (days), and
$t_{1/2}$ = the biological degradation half-life of the chemical (days).

In CMLS, the following parameters are used as input:

- soil properties (bulk density, water content at field capacity, permanent wilting point, and soil organic carbon content);
- chemical properties of the pesticide (partition coefficient and degradation half-life);
- climatic and cultural factors (plant root depth, daily rainfall + irrigation, and daily evapotranspiration amounts).

The outputs given by CMLS, among others, include, travel time (tr) for chemicals to move to selected depths and RA of pesticides remaining at those times in the soil profile.

The average sprinkler irrigation depth applied over a field was estimated using the distribution coefficient (Ha) approach (Hart and Reynolds, 1965). Their approach recognizes that the average applied water depth on a field is a function of both uniformity coefficient (UC) and the percent of area that is at least adequately irrigated.

They assumed that the distribution of applied water depths in an overlapped sprinkler pattern approximates the normal distribution. Then the average applied depth of water, Vi (mm or in.) can be determined by:

$$Vi = Zreq / Ha, \qquad (6)$$

where

Zreq = required irrigation depth (mm or in.) at a given date, and

Ha= distribution coefficient (a fraction of the mean applied depth).

Hart and Reynolds reported Ha values for a range of UC values (60 to 99.9%) and an assumed range of a fraction of the field area (50 to 100%) that can be adequately irrigated. The UC is given by the following empirical relationship (Christensen, 1942):

$$UC = 100\left(1.0 - \sum|z-m| / \sum z\right), \qquad (7)$$

where

UC = uniformity coefficient (%),

z = individual depth (mm or in.) of catch observations from uniformity test, and

m = mean depth (mm or in.) of observations.

In this study, Ha values reported by Hart and Reynolds (1965) were used to estimate average depth of water applied. We selected table combinations of fraction of area adequately irrigated (50, 60, 70, 80, 90, and 100%) and UC (60, 80, and 96%). The UC values over 96% were omitted because irrigation uniformity higher than this is not economically feasible, as excessively close spacing of sprinklers is required.

For all combinations, the irrigation amount required in the soil profile was assumed 45 mm (1.8 in.) i.e., an irrigation was applied whenever the soil moisture depletion was 45 mm (1.8 in.). The average applied depth of irrigation (Vi) for each combination was computed by dividing Zreq (45 mm or 1.8 in.) by the appropriate Ha. For example, for UC value of 96% and fraction of area adequately irrigated of 100%, the Ha value reported by Hart and Reynolds (1965) was 0.85 (Table 1). Therefore, the average applied depth of irrigation (Vi) for a Zreq of 45 mm (1.8 in.) is 53 mm (2.1 in.) i.e., 45 mm/0.85 = 53 mm (2.1 in.) (Table 1). These applied irrigation depths were used in CMLS to predict the RA of a pesticide for a known site, crop, irrigation system, and schedule.

Out of many analyses performed for each of the six selected areas, only representative results are presented here. These illustrate the two methodologies presented in this article. The first methodology illustrates the selection

TABLE 1. Effect of selected sprinkler design parameters (UC and fraction of area adequately irrigated) on the average applied water depth, average deep percolation, and RA

UC	Fraction of Area Adeq. Irrigated	Distribution Coefficient (Ha)	Required Depth (Zreq)	Applied Water Depth (Vi)	Storage Effic. (Es)	Amount of Water Stored	Average Deep Percolation	RA at 2 m Soil Depth
(%)	(%)	(fraction)	(mm)	(mm)	(fraction)	(mm)	(mm)	(fraction)
1	2	3	4	5	6	7	8	9
Given	Given	Given	Given	(4/3)	(Given)	(5 × 6)	(5 − 7)	Predicted
60	100	–	45	–	–	–	–	–
60	90	0.357	45	126.05	0.333	41.97	84.08	0.75
60	80	0.578	45	77.85	0.521	40.56	37.29	0.60
60	70	0.737	45	61.06	0.641	39.14	21.92	0.55
60	60	0.873	45	51.55	0.730	37.63	13.92	0.49
60	50	1.000	45	45.00	0.799	35.96	9.04	0.43
80	100	0.225	45	200.00	0.225	45.00	155.00	0.82
80	90	0.679	45	66.27	0.667	44.20	22.07	0.55
80	80	0.789	45	57.03	0.761	43.40	13.63	0.49
80	70	0.869	45	51.78	0.821	42.51	9.27	0.43
80	60	0.937	45	48.03	0.865	41.55	6.48	0.43
80	50	1.000	45	45.00	0.900	40.50	4.50	0.43
96	100	0.845	45	53.25	0.845	45.00	8.25	0.43
96	90	0.936	45	48.08	0.933	44.86	3.22	0.39
96	80	0.958	45	46.97	0.952	44.72	2.25	0.39
96	70	0.974	45	46.20	0.964	44.54	1.66	0.39
96	60	0.987	45	45.60	0.973	44.37	1.23	0.39
96	50	1.000	45	45.00	0.980	44.10	0.90	0.39

Note: Source for data in columns 1, 2, 3, and 6: Hart and Reynolds (1965).
To convert mm to in. or m to ft, use the following conversions: mm / 25.4 = in.; m × 3.3 = ft.

of a sprinkler irrigation system design for a range of pesticide RA values for a given site, crop, and irrigation schedule. The second methodology illustrates the selection of a pesticide for a given irrigation system, schedule, site, crop, and desired RA. These methodologies are being used to develop decision-support computer models for devising integrated best management practices (BMPs) for various soils, crops, pesticides, irrigation systems, and schedules.

Results and Discussion

Sprinkler Irrigation Uniformity and Pesticide Leaching

Ideally, sprinklers would apply a uniform depth of water to all areas in a field. This would make it possible to meet crop and leaching requirements without excessive deep percolation. Unfortunately, sprinkler systems do not apply water uniformly. Different areas in the field receive varying irrigation depths.

Irrigation system design greatly affects pesticide leaching in irrigated areas. Pesticide leaching can be significantly reduced by efficient sprinkler irrigation design. Figure 2 illustrates how irrigation distribution coefficient (Ha) and the RA of pesticide remaining in the soil are affected by design parameters. Considered parameters are the fraction of area adequately irrigated (%) and uniformity coefficient (%).

In the following example, we have compared field average deep percolation values and their respective predicted pesticide leaching. Deep percolation is the difference between the amount of water infiltrated into the soil and the amount of water stored in the root zone of a crop after each irrigation. Thus, average deep percolation refers to the spatial average amount of infiltrating water that percolates below the root zone.

Soil nonhomogeneities and deviation from average deep percolation values may cause pesticides to leach more than predicted. Thus, presented results represent relative comparisons rather than exact predictions.

Example

Consider a crop of alfalfa on Kidman (sandy loam) soil that is irrigated each time it requires (Zreq) 45 mm (1.8 in.) of the available soil water in its root zone. For illustration

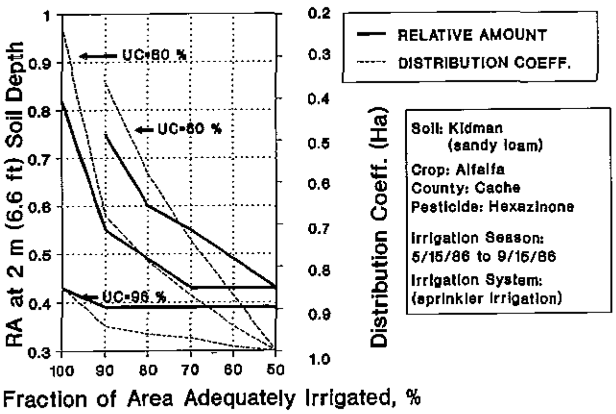

Figure 2–Effects of uniformity coefficient (UC) and percent of area adequately irrigated on distribution coefficient (Ha) and on the relative amount (RA) of hexazinone remaining at 2 m (6.6 ft) soil depth under alfalfa irrigation season.

purposes, we assume three different sprinkler systems which will supply the same amount of irrigation water. In other words, each of them uses the same irrigation schedule and has the same average irrigation depth to be applied at each irrigation. Each system has very similar distribution coefficients.

Three selected combinations of UC and fraction of area adequately irrigated (96%, 100%; 80%, 70%; and 60%, 60%), respectively, represent the upper, middle, and lower range design parameter values for the three considered sprinkler systems (Table 1). The purpose of selecting these three combinations is to show that with almost the same average depth of water 52 or 53 mm (2.1 in.) applied at each irrigation, which combination is environmentally and economically better and more practical.

As shown in Table 1, with an ideal UC of 96% and almost 100% of the field area adequately irrigated, the average deep percolation is 8.3 mm (0.3 in.) per irrigation. With a more realistic UC of 80% and 70% of the field adequately irrigated, the average deep percolation is 9.3 mm (0.4 in.) per irrigation. With a poor UC of 60% and 60% of the field area adequately irrigated, the average deep percolation is 13.9 mm (0.6 in.) per irrigation. With the lower uniformities less water is available for crop use, crop yield is less (larger area under-irrigated), and more water percolates below the root zone. Therefore, poor sprinkler irrigation uniformities are environmentally and economically undesirable.

The average RA of pesticide reaching the 2 m (6.6 ft) soil depth (fig. 1) is 0.43, 0.43, and 0.49 for the respective combinations of UC and percent area adequately irrigated (96%, 100%; 80%, 70%; and 60%, 60%). The RA for the first two combinations (96%, 100% and 80%, 70%) is the same because the time required for the pesticide to move 2 m (6.6 ft) deep into the soil profile is the same.

Environmentally, either of these two combinations of UC and percent area adequately irrigated (96%, 100% or 80%, 70%) have the same impacts. However, economically and practically, the second combination of UC and percent area adequately irrigated (80% and 70%) is more feasible (less sprinkler hardware is required). The ideal combination of UC (96%) and percent area adequately irrigated (100%) generally achieves the lowest RA of hexazinone (environmentally relatively inoffensive), although it might be expensive and requires much sprinkler hardware. Nevertheless, this sprinkler irrigation system design was used for all subsequently discussed CMLS simulations.

Pesticide Alternatives

A second situation exists when the irrigation system and schedule are in place and farmers must select an appropriate pesticide. Farmers usually have several pesticide selection options. Each chemical has different values of K_{OC} and $t_{1/2}$. To develop decision-support nomograms, many simulations were performed in which K_{OC} varied from 1 to 100 mL/g OC and $t_{1/2}$ ranged from 10 to 100,000 days. We assumed alfalfa was irrigated using a 1986 irrigation schedule in Cache County, Utah. The RA that remained when the pesticide reached soil depths of 0.5 m (1.7 ft) and 2.0 m (6.6 ft) was predicted (figs. 3 and 4, respectively).

Figure 3 illustrates that for low K_{oc} values (< 75 mL/g OC), as the $t_{1/2}$ decreases, the RA remaining at 0.5 m (1.7 ft) soil depth also decreases. For a given $t_{1/2}$, as the K_{oc} increases, the RA remaining at 0.5 m (1.7 ft) soil depth decreases. For higher K_{oc} values (< 75 mL/g OC), the predicted RA is 0.00 regardless of $t_{1/2}$. This shows that all alfalfa pesticides having K_{oc} > 75 mL/g OC are safe to use, regardless of half-life.

Figure 4 shows similar results for RA values for pesticides reaching a 2 m (6.6 ft) soil depth (below the alfalfa root zone). No pesticide with $t_{1/2}$ of 10 days or less percolates to 2 m (6.6 ft). Short half life pesticides biodegrade long before they can percolate deeply at that site. The 2 m (6.6 ft) soil depth adsorbs more pesticides than the 0.5 m (1.7 ft) depth. In summary, only pesticides with K_{oc} values lower than 15 mL/g OC and half-lives ($t_{1/2}$) longer than 10 days will leach below the alfalfa root zone and be likely to cause groundwater contamination.

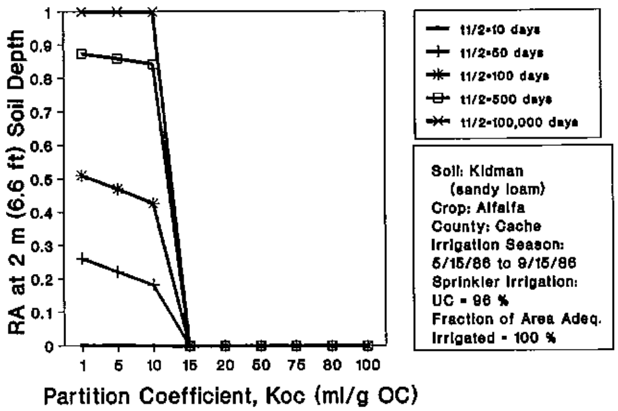

Figure 4–Effects of pesticide parameters on the relative amount (RA) remaining when a pesticide reaches 2 m (6.6 ft) soil depth for known site, system, and irrigation schedule.

Sensitivity Analyses

Values for selected soil physical properties such as organic carbon content (%), bulk density (g/cm³), volumetric water content (%) at field capacity, and at wilting point for different soil textures were used in a sensitivity analysis presented below. Also evaluated is the effect of assuming an average deep percolation value despite the fact that even the best sprinkler system applies significantly different amounts of water to different parts of a field.

Soil

The greater the clay and organic carbon content, the greater a soil's tendency to retain pesticides and the smaller the risk of groundwater contamination. Pesticides require more travel time when moving through heavy soils (e.g., clay soils), than through lighter soils (e.g., sand). The travel time, in turn, determines the time available for pesticide degradation via chemical and biological processes. Figure 5 illustrates how soil texture affects aldicarb RA values. Much more aldicarb reaches 2 m (6.6 ft) depth in sand than in the heavier soils.

Sprinkler Irrigation

Previously in our analysis, we used the (Zreq/Ha) approach to determine a field average applied depth of water. Here we compare that analysis with a more detailed approach. We compare this field average applied depth with the average of 10 normally distributed applied water depths. To do this, the field is divided into 10 incremental subareas of equal size. Using a normal distribution approach for the entire field, the appropriate applied depth was determined for each subarea under a normal curve. Then these 10 applied depths were averaged. Assumed was a uniformity coefficient (UC) of 60%, and 80% of the field area adequately irrigated. A poor uniformity coefficient of 60% was selected because it demonstrated the greatest variations among applied water depths. This combination of UC and fraction of area adequately irrigated gives a distribution coefficient (Ha) of 0.578 (Table 1). The average applied depth (Vi) for the entire field is computed by dividing Zreq (45 mm or 1.8 in.) by Ha (0.578). Thus, Vi is estimated as 78 mm (3.1 in.). This average applied water depth is used to develop a normal curve and then to compute each individual applied water depth cumulatively for each of the 10 subareas of the field.

These 10 applied water depths were then input into 10 different CMLS simulations. Aldicarb, one of the most

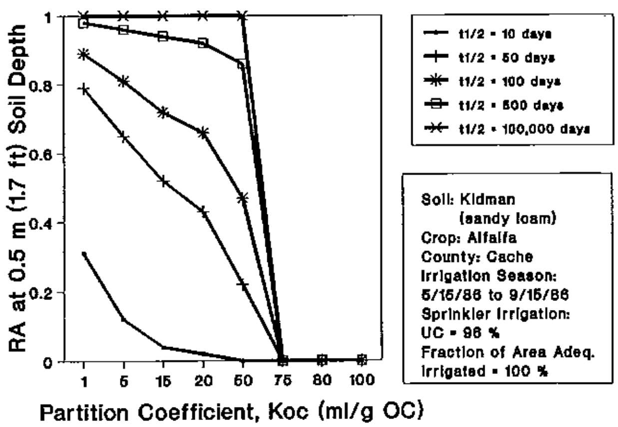

Figure 3–Effects of pesticide parameters on the relative amount (RA) remaining when a pesticide reaches 0.5 m (1.7 ft) soil depth for known site, system, and irrigation schedule.

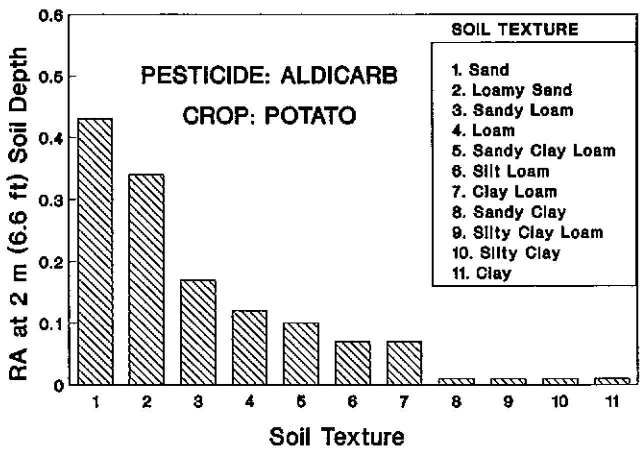

Figure 5–Effects of various soil textures on relative amount (RA) of aldicarb remaining in the soil at a depth of 2 m (6.6 ft).

TABLE 2. Pesticide movement comparison under sprinkler irrigation

Row No.	Pesticide Name	Area (%)	d (mm)	Relative Amount Remaining At 1.0m	1.5m	2.0m	3.0m
1	Aldicarb	10	16	0.0000	0.0000	0.0000	0.0000
2	Aldicarb	10	37	0.0000	0.0000	0.0000	0.0000
3	Aldicarb	10	51	0.0001	0.0000	0.0000	0.0000
4	Aldicarb	10	63	0.0905	0.0001	0.0000	0.0000
5	Aldicarb	10	73	0.1649	0.0001	0.0001	0.0000
6	Aldicarb	10	83	0.1984	0.0905	0.0001	0.0000
7	Aldicarb	10	93	0.1984	0.1371	0.0686	0.0001
8	Aldicarb	10	104	0.2679	0.1649	0.1114	0.0001
9	Aldicarb	10	118	0.2679	0.1984	0.1371	0.0686
10	Aldicarb	10	140	0.3455	0.1984	0.1649	0.1114
11	Subareas Average		78	0.1534	0.0790	0.0482	0.0180
12	Aldicarb	100	78	0.1649	0.0686	0.0001	0.0000

Note: d = depth of water applied in mm or in.
To convert mm to in. or m to ft, use the following conversions:
mm / 25.4 = in.
m × 3.3 = ft

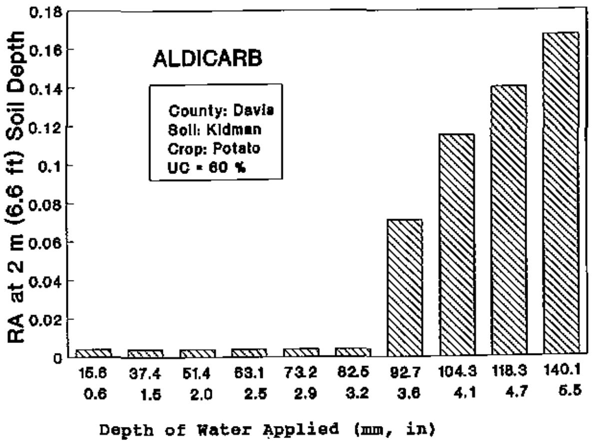

Figure 6–Effect of various applied water depths on relative amount (RA) of aldicarb remaining in the soil when it reaches to a depth of 2 m (6.6 ft).

mobile and commonly found pesticides in groundwater was used. The results of these simulations are shown in Table 2. Also shown is the average of the 10 detailed simulations as well as the values computed by a single simulation using a 78 mm (3.1 in.) average applied water depth (the same approach as used in methodology). By comparing the last two rows in Table 2, we are comparing the average of 10 detailed simulations with the value computed by a single simulation.

The results are very similar down to a depth of 1.5 m (5.0 ft) but are obviously different below that depth. This occurs because applied depth of water in each subarea is not uniform [16 to 140 mm (0.6 to 5.5 in.)]. This nonuniformity produces some subareas with practically no deep percolation and pesticide movement and others with deep percolation and pesticide movement. Clearly, using the single average approach can give misleading results with increasing depth, if the uniformity coefficient is low. Underestimation can also become more important if preferential flow, which is not included in the model, is present causing a portion of the soil matrix to be bypassed during flow. The single depth approach is more accurate with higher irrigation uniformity (higher uniformity coefficients).

Figure 6 shows the influence of the different subarea percolation depths (from Table 2) upon aldicarb movement. Clearly, the pesticide will be much more prone to reach a water table at 2 m (6.6 ft) depth in some parts of a homogeneous field than in others.

Summary

Procedures were developed for aiding environmentally safe pesticide/irrigation management. These required simulation of effects of sprinkler irrigation design, pesticide characteristics (partition coefficient and half-life), and soil type on pesticide leaching. First is design of a sprinkler irrigation system for a particular site and pesticide. This enables selection of the uniformity coefficient-percent area adequately watered combinations that avoid excessive pesticide movement. Second is selection of appropriate pesticides for a particular site, crop, and sprinkler design. This permits determining the threshold partition coefficients or half-lives for environmental safety at a particular site.

Analysis also revealed that using field average infiltration predicts inaccurate pesticide RA values at deeper soil depths. However, for shallow soil depths or irrigation system of good uniformity, the field average approach is acceptable.

A combination of BMPs (best management practices) such as efficient sprinkler system design, management, and selection of less mobile pesticides, will minimize the potential for groundwater contamination and associated environmental hazards.

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References

Aller, L., B. Truman, J. H. Lehr and R. J. Petty. 1985. DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. USEPA/600/2-85/018, U.S. Environmental Protection Agency, Washington, DC.

Christensen, J. E. 1942. Irrigation by sprinkler. California Agricultural Experiment Station, Bulletin 670.

Ehteshami, M., R. C. Peralta, H. Eisele, H. M. Deer and T. Tindall. 1991. Assessing pesticide contamination to groundwater: A rapid approach. *Journal of Groundwater* (November-December).

Eisele, H., M. Ehteshami, R. C. Peralta, H. M. Deer and T. Tindall. 1989. Agricultural pesticide hazard to groundwater in Utah, IIC-89/1A, Vols. I-II. Agricultural and Irrigation Engineering Department, Utah State University, Logan.

Hart, W. E. and W. N. Reynolds. 1965. Analytical design of sprinkler systems. *Transactions of the ASAE* 8(2):83-89.

Lau, L. S. and J. F. Mink. 1987. Organic contamination of groundwater: A learning experience. *Journal of American Water Works Association* 79(8):37-42.

Leonard, R. A., A. Shirmohammadi, A. W. Johnson and L. R. Marti. 1988. Pesticides transport in shallow groundwater. *Transactions of the ASAE* 31(3):776-788.

Nofziger, D. L. and A. G. Hornsby. 1986. A microcomputer-based management tool for chemical movement in soil. *Applied Agricultural Research* 1(1):50-56.

———. 1988. Chemical movement in layered soils: User's Manual, Agricultural Experiment Station, Division of Agriculture, Oklahoma State University, Stillwater.

Oki, D. S. and T. W. Giambelluca. 1987. DBCP, EDB, and TCP contamination of groundwater in Hawaii. *Groundwater* 25(6): 693-702.

Pimentel, D. and L. Levitan. 1986. Pesticides: Amounts applied and amounts reaching pest. *BioScience* 36:86-91.

Pionke, H. B., D. E. Glotfelty, A. D. Lucas and J. B. Urban. 1988. Pesticide contamination of ground water in the Mahantango Creek Watershed. *Journal of Environmental Quality* 17:76-84.

Sum, M. 1986. Groundwater: Many diagnoses, few remedies. *Science* 232:1490-1493.

USEPA. 1987. Agricultural chemicals in groundwater: Proposed strategy. U.S. Environmental Protection Agency, Office of Pesticide and Toxic Substances, Washington, DC.

Waddell, K. M. 1987. Utah groundwater quality. U.S. Geological Survey, Open-File 87-0757.

Zaki, M. H., D. Morgan and D. Harris. 1982. Pesticides in groundwater: The aldicarb story in Suffolk County, NY. *American Public Health* 72:1391-1395.