BEST MANAGEMENT OF PESTICIDE AND IRRIGATION APPLICATION SYSTEMS: BACKGROUND AND CANDI SOFTWARE

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1. Introduction

In this chapter, we discuss a commonly-used volume balance approach for simulating the movement of water through the root zone. We then show how this approach can be coupled with pesticide leaching prediction. Finally we show how information about irrigation system design can be used with the previous processes. The result is an integrated approach for estimating the environmental consequences of irrigation and pesticide management.

2. Volume Balance

Several methods can be used to simulate water movement in the vadose zone. A common purpose is to estimate how water infiltrates within and beyond the root zone in response to precipitation and/or irrigation. The methods include one-, two-, and three-dimensional unsaturated flow equations and piston flow or volume balance.

The volume balance approach was frequently used for irrigation scheduling (Hansen et al., 1979). However, this useful approach has the advantages of simplicity, minimal data requirements, and relative accuracy. To calculate the daily depth of infiltrated water, the following assumptions are used:

1. Water entering a soil layer redistributes instantaneously to field capacity. This assumption is more accurate for coarse-textured soils than for fine-textured soils.

2. Water is removed by evapotranspiration from each layer in the root zone in proportion to the relative amount of water available in that layer. A uniform root distribution is assumed. This assumption is not strictly valid for many situations. More precise schemes for dealing with evapotranspiration would require more information about the root distribution and the soil hydraulic properties.

3. Upward movement of soil water does not occur anywhere in the soil profile. Water is lost from the root zone by evapotranspiration and is not replenished from below by capillary rise from groundwater. This assumption is not satisfied for shallow groundwater tables. However, for most agricultural systems where a drainage system exists, this assumption will be satisfied.

According to this approach, water is considered available for plants if the water content in any layer of the root zone is above the permanent wilting point, as expressed by the following equation:

$$W_j^a = t_j \ (\theta_j - \theta_j^{pwp}) \quad \ldots\ldots\ldots\ldots \quad (1)$$

where W_j^a is the available water in the layer j (mm), t_j is the thickness of the layer j (mm), θ_j is the current volumetric water content of layer j and θ_j^{pwp} is the volumetric water content at permanent wilting point of layer j. The total available water, W_{tot}^a, in the root zone is the sum of the amounts of water available in each layer. If W_{tot}^a is greater than the evapotranspiration (ET_{crop}) for a day, the water content of each layer in the root zone is depleted in proportion to the amount of water available in that layer as expressed by

$$\theta_j = \theta'_j - (ET_{crop} \ / \ t_j) \ (W_{tot}^a \ / \ W_j^a) \quad \ldots\ldots \quad (2)$$

where θ'_j is the volumetric water content of the layer j prior to adjustment. If the total available water is less than the evapotranspiration demand, all the layers in the root zone are assumed to be at permanent wilting point

$$\theta_j = \theta_j^{pwp} \quad \ldots\ldots\ldots\ldots \quad (3)$$

Equation 3 assumes no effect of soil-water content on ET when the volumetric water content of the soil is approaching wilting point. However, in reality, ET will decrease due to stress long before θ^{pwp} is reached.

When an infiltration event (irrigation and/or rain) occurs, the water content of each layer is adjusted, starting with the layer closest to the surface (j=1). The soil-water deficit for that layer is determined using the equation:

$$swd_j = t_j \ (\theta_j^{fc} - \theta_j) \quad \ldots\ldots\ldots \quad (4)$$

where swd_j is the soil-water deficit of the layer j (mm) and θ_j^{fc} is the volumetric water content of the layer j at field capacity. If the infiltrating amount, I_j, is greater than swd_j, then

$$\theta_j = \theta_j^{fc} \quad \ldots\ldots\ldots\ldots \quad (5)$$

and

$$I_{j+1} = I_j - swd_j \quad \ldots\ldots\ldots\ldots \quad (6)$$

If I_j is less than swd_j, then

$$\theta_j = \theta'_j + I_j / t_j \quad \ldots\ldots\ldots\ldots \quad (7)$$

and

$$I_{j+1} = 0 \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

Notice that the above equations permit the soil properties to change from one layer to another. Also, plant uptake can be distributed according to any ratios among the different soil layers. The root depth can also change with time.

The presented approach has several advantages. It is conceptually simple and easy to implement on a computer. It also requires much less data than solutions based on the unsaturated flow equation (Richards equation). Nevertheless, it gives the amount of infiltrated water in each layer, I_j, on a daily basis.

3. Pesticide Leaching

The pesticide leaching approach discussed here was presented by Rao et al. (1976) and modified by Nofziger and Hornsby (1986). In this approach, the following assumptions are made:

1. The chemical is non-polar.

2. The adsorption process can be described by a linear, reversible equilibrium model. If the sorption coefficient is described by a non-linear isotherm, the partition coefficient decreases with increasing concentration of the chemical. Thus the depth to which the chemical will be leached will depend upon the concentration. This aspect is probably not significant for the concentration range of interest in most agricultural applications. When adsorption equilibrium is not instantaneous, the chemical will be leached to a greater depth than predicted here. Irreversible sorption would result in less leaching.

3. The half-life time for biological degradation of the chemical is constant with time and soil depth. In reality, degradation rate coefficients are dependent upon a variety of environmental factors, primarily temperature and soil-water content. Hence, seasonal changes in rate coefficients can be expected. Also, with decreasing microbial activity at greater soil depths, the degradation rate coefficient may decrease with depth. Sufficient data are not available to formulate mathematical relationships to describe these effects.

According to this approach, chemicals move only in the aqueous phase in response to soil-water movement. Two processes are considered here (a) movement of the chemical through the soil matrix; and (b) degradation of the chemical.

The depth of infiltrated water (I_j) is calculated as explained in the previous section. Pesticides adsorb to soil particles and advance less far than water. A linear and reversible equilibrium adsorption model simulates the retardation of the chemical movement. The following equations are used to predict chemical movement:

$$d^s - d'^s = I_j / (RF \quad \theta^{fc}); \qquad I_j > 0 \quad ... \quad (9)$$

$$d^s - d'^s = 0; \qquad I_j \leq 0 \quad ... \quad (10)$$

where

$$RF = 1 + (BD \quad K_d / \theta^{fc}) \quad .... \quad (11)$$

$$K_d = K_{oc} \quad OC \quad .... \quad (12)$$

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

Chemicals are continuously exposed to degradation processes in soil. The relative amount (RA) of the chemical is defined to be the fraction of the applied chemical remaining in the entire soil profile. RA is calculated from:

$$RA = e^{-tr \ln(2) / t_{1/2}} \quad .... \quad (13)$$

where tr is the travel time since the chemical was applied (days) and $t_{1/2}$ is the biochemical degradation half-life of the chemical (days). ln(x) denotes the natural logarithm of x.

This approach (Nofziger and Hornsby, 1986) has several advantages. It is conceptually simple and easy to implement on a computer. It requires much less data than solutions based on the unsaturated solute transport equation. The approach was also adequately accurate when compared to four other approaches using field data for aldicarb leaching, it proved to be comparable (and sometimes more accurate) than more complex models (see the excellent study by Pennell et al. 1990).

Notice that when the volume balance approach was discussed, we assumed that we know the amount of amount of infiltrated water at the soil surface (I_0). In application, this amount of water can only be known when information about the irrigation system is available. The following two sections show how the amount of infiltrated water is calculated.

4. Irrigation System

The irrigation system is the means by which water is applied to the soil. Irrigation systems that cause less water to leach downward below the root zone are expected to cause less pesticide leaching. Such systems are also considered more efficient in terms of water management. Here, we discuss two of the most popular irrigation systems, furrow and sprinkler irrigation.

4.1. Furrow Irrigation

Estimating the amount of water infiltrating through the soil in a furrow irrigation system involves solution of the Saint-Venant equations, which are written as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + \frac{\partial Z}{\partial \tau} = 0 \quad . \; . \; . \; . \; . \; . \; . \; . \qquad (14)$$

and

$$\frac{1}{Ag}\frac{\partial Q}{\partial t} + \frac{2Q}{A^2 g}\frac{\partial Q}{\partial x} + (1-F^2)\frac{\partial y}{\partial x} - (S_o - S_f) = 0 \quad . \; . \qquad (15)$$

where
- A = cross-sectional area, m^2
- Q = discharge, m^3/sec
- t = elapsed time, sec
- x = distance from the field inlet, sec
- τ = intake opportunity time, sec
- Z = cumulative intake, m^3/m
- g = acceleration of gravity, 9.81 m/sec^2
- y = flow depth, m
- F = the flow Froude number
- S_o = field slope
- S_f = friction slope

One of the most common solutions to the Saint-Venant equations is the kinematic wave model, which is based on the assumption that the first three terms in Eq. 15 are negligible, thus

$$S_o - S_f = 0 \quad \ldots\ldots\ldots\ldots \quad (16)$$

The kinematic wave model can be applied to furrow and border systems in which: (1) the field has a non-erosive slope greater than about 0.0001; and (2) the water is able to drain freely from the field at its lower end (Walker and Humpherys 1983).

Walker and Humpherys (1983) presented SIRMOD, a comprehensive software for simulating the hydraulics of surface irrigation systems. SIRMOD solves the kinematic wave model and hence estimates the total amount of infiltrated water in a furrow irrigation system when an application depth (Z_{req}) is to be satisfied at the end of the furrow. The two parameters considered for the design of furrow irrigation systems are furrow length and inflow rate. SIRMOD outputs include, among others, soil storage efficiency (E_{ss}) and total infiltrated water depth. Soil storage efficiency is defined as the ratio between the amount of water retained in the root zone to the amount of water that infiltrates the root zone. Thus, the depth of infiltrating water at the soil surface can be calculated from

$$I_0 = Z_{req}/E_{ss} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

where Z_{req} is the required irrigation depth. Figure (1) shows the variation of the infiltrating water depth along a typical furrow.

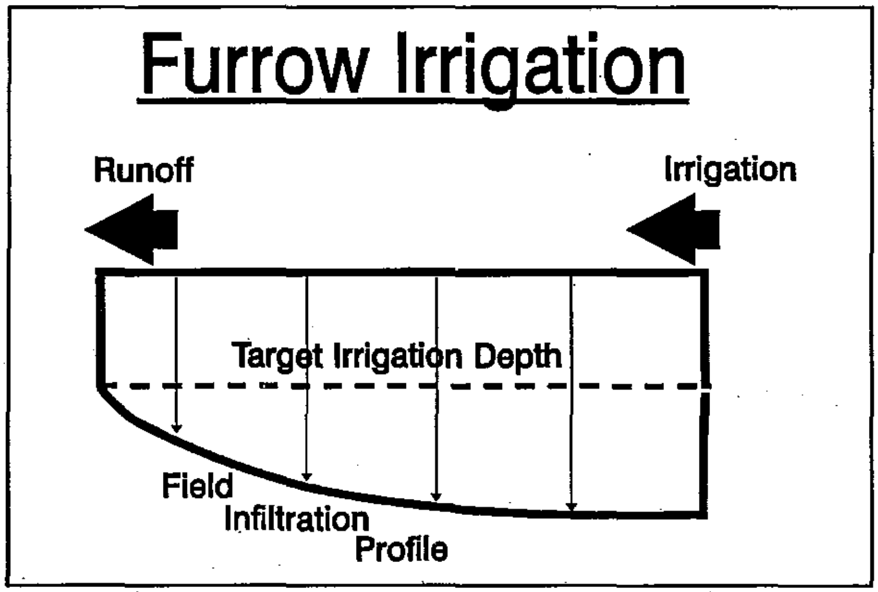

FIGURE 1. Infiltrating Water Depth in Furrow Irrigation

The depth of infiltrated water significantly affects pesticide leaching. In arid regions most infiltration results from supplemental irrigation. However, in humid regions, rainfall might significantly exceed irrigation. In that case, improving irrigation efficiency will not significantly reduce pesticide leaching. There, the better way to reduce pesticide leaching is to select a less mobile or more degradable pesticide (one having lower K_{oc} or shorter $t_{1/2}$). Ranjha et. al. (1992a) showed how SIRMOD and CMLS can be used to provide furrow irrigation/chemical application design charts.

4.2. Sprinkler Irrigation

In this irrigation scheme, the depths of applied water are assumed to be normally distributed over the field area with a mean application of m and a standard deviation of s.

The uniformity of application of irrigation water is of primary concern in the sprinkler irrigation design procedure. A parameter that is widely used to evaluate sprinkler irrigation efficiency is the coefficient of uniformity defined by Christiansen (Keller, 1990) :

$$UC = 100\ (1.0 - \frac{\Sigma|z-m|}{\Sigma z}) \quad \ldots\ldots \quad (18)$$

where

UC = Christiansen Uniformity coefficient, %

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

m = mean depth of observations, mm (in)

The test data for UC > 70% usually forms a bell-shaped normal distribution and is reasonably symmetrical about the mean (Keller 1990).

Hart and Reynolds (1965) correlated (s/m) with Christiansen's uniformity coefficient (UC) by the following empirical relationship:

$$s/m = (1.0 - UC/100)\ (\pi/2)^{1/2} \quad \ldots\ldots \quad (19)$$

where s in the standard deviation of the infiltrated water depths (square root of variance). Under a normal distribution, for any probability that 90% (for example) of observations will equal or exceed a certain value, K, the following relationship is used to compute K:

$$K = Zs + m \quad \ldots\ldots\ldots\ldots \quad (20)$$

where K is any required value of the water depth and Z is the value of the standard normal variate (mean = 0 and standard deviation = 1) for the remaining 10% area under the standard normal curve. According to Hart and Reynolds (1965),

$$K = m\,Ha \quad \ldots\ldots\ldots\ldots \quad (21)$$

where m is the average or mean applied depth of water and Ha is the fraction of the mean application (m) exceeded over the field area.

The procedure for computing average infiltration depth is as follows. Given the value of UC, the value of (s/m) is first calculated from Eq. 19. Next, a numerical expression is used to calculate the value of the standard normal variate (Z) for a given area under the standard normal distribution curve (Appendix A). Assuming m=1, s is calculated. Hence, K can be calculated from Eq. 20. This value of K is, by definition, the value of the distribution coefficient Ha. Then, the following equation is used to calculate the average infiltrated water depth:

$$I_0 = Z_{req} / Ha \quad \ldots\ldots\ldots\ldots \quad (22)$$

where I_0 is the average infiltrated water depth and Z_{req} is the required application depth. Ranjha et. al. (1992b) showed how sprinkler irrigation system simulation can be linked with pesticide simulation to provide useful design charts.

5. Available Computer Software

In the previous sections, we showed how computational approaches can be combined to predict the movement of pesticides through the root zone. It is clear that several computer simulation modules are needed to accomplish this task. The desire to have these modules linked in an efficient manner motivated the development of a decision support system. The CANDI software (Aly and Peralta 1993) estimates the relative amount of chemical leaching under different irrigation systems. The acronym CANDI stands for Chemicals AND Irrigation management. Figure (2) shows the flow chart for CANDI.

CANDI facilitates estimating how improved water/pesticide management can reduce potential pesticide contamination of groundwater. By comparing the potential contamination results of different water management schemes, best management systems (BMSs) can be selected. When BMSs are implemented, the likelihood of groundwater contamination is reduced.

CANDI contains several simulation modules. The modules are efficiently coded and integrated to achieve rapid processing for all applications (see Aly 1992).

The first module simulates the irrigation system, either furrow or sprinkler. In any irrigation system, reduction in potential pesticide contamination can be achieved by improvement in water application efficiency. Efficiency, in turn, is a function of several factors.

In surface irrigation, efficiency is a function of the furrow length, inflow rate, topography, and soil characteristics. These variables are used as inputs for the surface irrigation simulation module, part of SIRMOD (Walker and Humpherys 1983). It predicts the water storage efficiency for a specified surface irrigation system at the site of interest and for a specific irrigation schedule. The module predicts the total infiltrated depth of water for the prescribed combination of parameters. CANDI provides a database of information needed to apply this simulation approach to Utah conditions.

In sprinkler irrigation, efficiency is a function of the uniformity coefficient, the fraction of area adequately irrigated, and soil characteristics. These variables are required as inputs. The sprinkler irrigation module estimates the soil storage efficiency. The module uses the approach of Hart and Reynolds (1965) to predict the total infiltrated depth of water for the prescribed combination of parameters.

Total infiltrated depth, soil data, crop data, and pesticide data are subsequently used as inputs for a module that emulates the simulation abilities of the widely-used Chemical Movement in Layered Soil, CMLS (Nofziger and Hornsby, 1986). This module calculates the relative amount of pesticide that reaches a prescribed depth after a period of time has elapsed.

CANDI also delineates the capture zones for all wells within a study area. CANDI incorporates the Multiple Well Capture Zone module (MWCAP) for this purpose (USEPA, 1990). MWCAP provides efficient delineation of steady-state, time-related, and hybrid capture zones for wells in homogeneous aquifers. Knowing the capture zone of his well, the user might select different water/pesticide management schemes for inside the capture zone than for outside it.

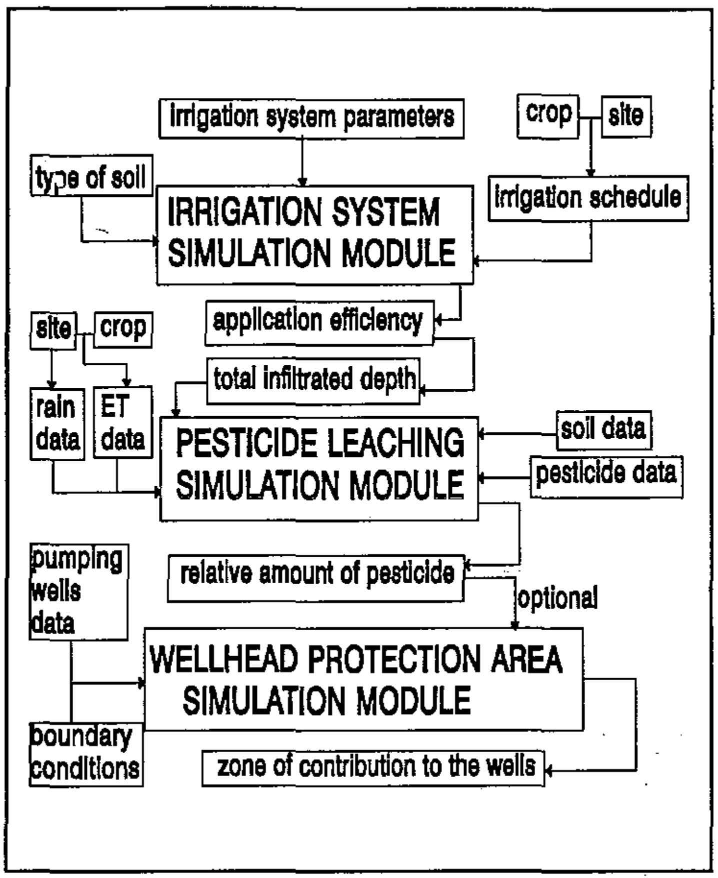

FIGURE 2. Flow chart of CANDI

CANDI can do the following:

1. For a particular irrigation system design, CANDI can predict which pesticide will yield the most acceptable relative amount of pesticide at a specific depth. In this case, the user must provide CANDI with the irrigation system efficiency, soil and crop data, weather information, pesticide application dates, and depth for evaluation (possibly the depth to water table or capillary fringe). Figure (3) shows typical output from CANDI for this scenario.

2. For a selected range of possible irrigation system designs, CANDI can show which irrigation system design will result in the least relative amount of pesticide reaching a specific depth. For this option, the user provides CANDI with the pesticide's physical and chemical properties, application dates, cultivated crop data, soil data, and weather information. For the surface irrigation system, CANDI produces curves showing relative amount as a function of

furrow inflow rate for a range of furrow lengths. Figure (4) shows typical output from CANDI for the furrow irrigation comparison option. For sprinkler irrigation systems, relative amount is shown as a function of a range of two design parameters, uniformity coefficient and fraction of area adequately irrigated. Figure (5) shows typical output from CANDI for the sprinkler irrigation comparison option.

3. CANDI can delineate the zones of contributing groundwater to specified wells during prescribed travel times. This permits the user to know where using pesticides is especially hazardous to groundwater consumers. For this optional output, the user must provide CANDI with pumping wells data and aquifer parameters (storativity and transmissivity or hydraulic conductivity). Figure (6) shows typical output from CANDI for the wellhead protection area option.

CANDI is a microcomputer-based software (it runs on an IBM PC or compatible). CANDI has a sophisticated user interface that is designed to be used by people having minimum experience on a PC. CANDI presents its output in the form of full-screen enhanced graphics. Figures (3) through (6) show some output from CANDI (see Aly and Peralta, 1993).

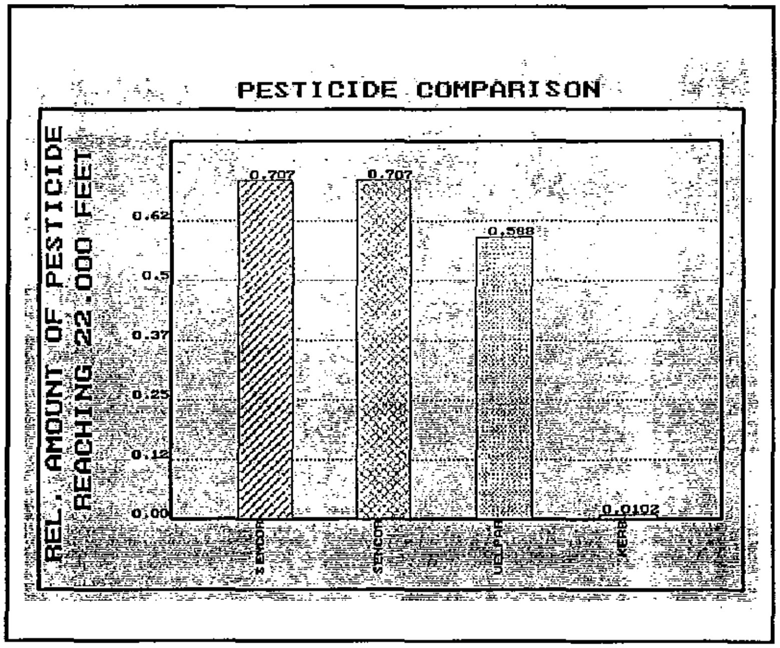

FIGURE 3. **Sample Output from CANDI: Pesticides Comparison Option**

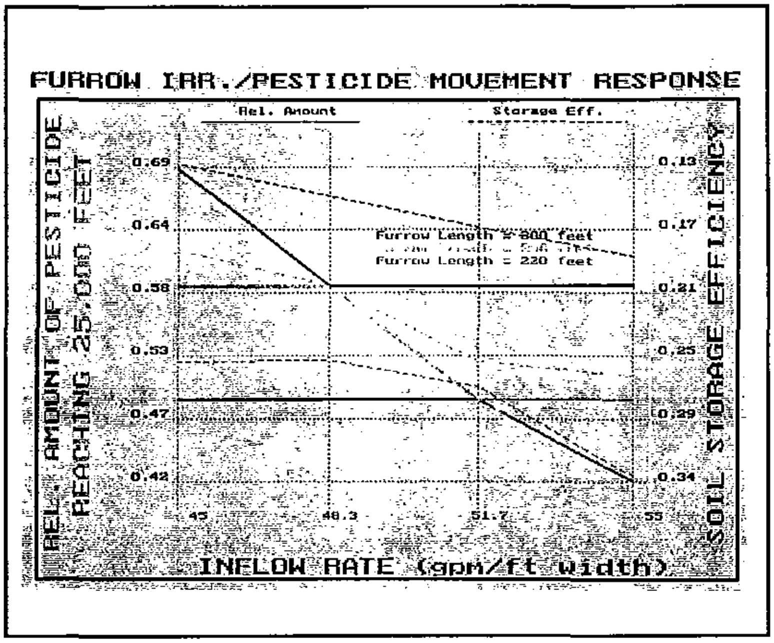

FIGURE 4. Sample Output from CANDI: Furrow Irrigation Comparison Option

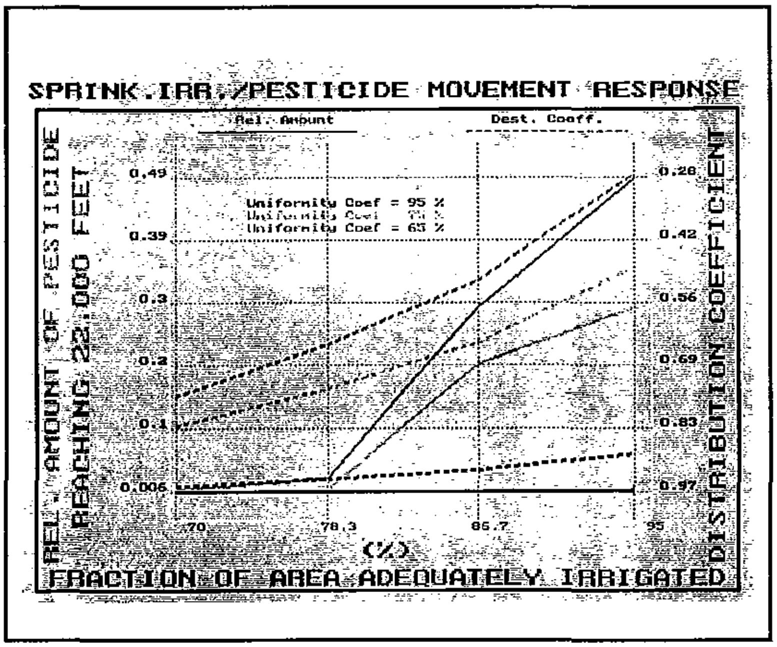

FIGURE 5. Sample Output from CANDI: Sprinkler Irrigation Comparison Option

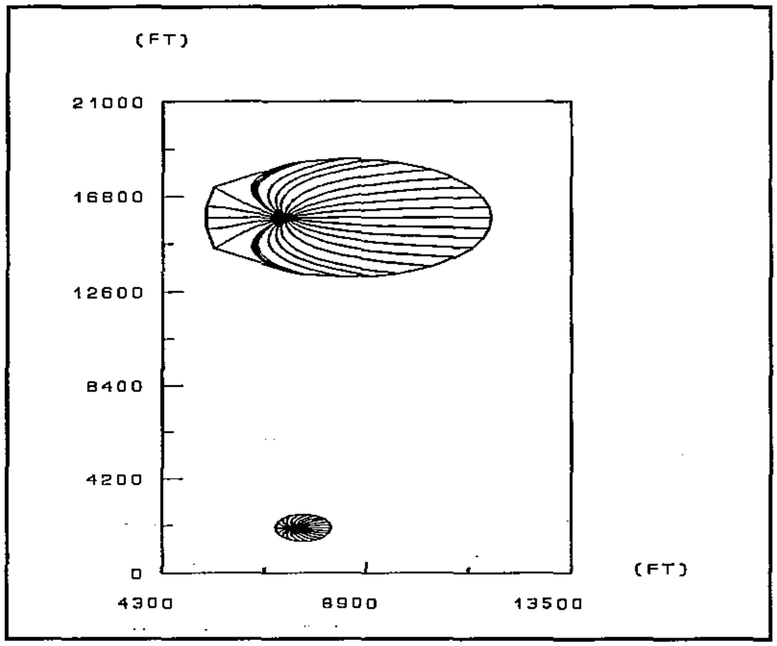

FIGURE 6. **Sample Output from CANDI: Wellhead Protection Area Delineation Option**

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March 15, 1996

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Dear Richard,

Please accept my humble apology for delaying so long in moving forward the publication of the book, "Pesticide Management for Protection of Water Resources." I appreciate that you have spent a lot of time to prepare a manuscript. Although two years have passed in my effort to get the book together, I still observe that the theme of the book is more relevant than ever, and no other book has focused exclusively on this theme. I am anxious to push forward with this endeavor. Somewhat of a shakeup had occurred at Lewis Publishers, and we now have a new publisher, Ann Arbor Press, that is very interested in the book.

It is only fair that I ask whether you would still like to be included. As I review all the manuscripts in relationship to the journal literature over the last two years, I noted that the information is still very contemporary and does not seem dated. However, I want to give you the opportunity to update your manuscript if you would like.

Please let me know via voice, fax, or email whether or not you want your manuscript to still be included. If you do, please decide whether you want to update the manuscript or not. Whatever your decision about revision, send me a diskette of the manuscript. I can handle a Word or WordPerfect file, MAC or PC. Also, send copies of the figures, or alternatively paste these into a Word or WordPerfect file. I will edit the manuscripts into a uniform style for Ann Arbor Press. You will have another opportunity to review the edited form for accuracy.

With some hard work, I hope to push the book through to the publisher by the end of June. I will do a better job of keeping you informed of the status of the publication . Once again, please accept my long overdue apologies. I hope to hear from you soon.

Sincerely,

Allan Felsot
Associate Professor
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enclosure

Pesticide Management for Protection of Water Quality (tentative)

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