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Impact of irrigation scheduling practices on pesticide leaching at a regional level☆

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Abstract

Information about how current and proposed management practices impact environmental quality is required to develop best management practices. A modeling approach was used to evaluate the scheduling practices of local farmers and two other irrigation scheduling practices for their potential impact on groundwater pollution in Doña Ana County, New Mexico. Data about farmers' practices came from historical information about the timing and quantity of water delivered to the farms. The irrigation scheduling practices were: tensiometer-based with the tensiometers placed at 50% or 75% of the root-zone depth and irrigations started when tensiometer's readings reached 6 kPa for sandy soils, 23 kPa for sandy loam soils, 44 kPa for loamy soils, and 74 kPa for clay loam soils; and at 50% plant available water depletion (PAWD) level regardless of soil type. The objective was to use irrigation scheduling model (IRRSCHM), a volume balance, mixing-cell, type irrigation scheduling and pesticide transport model, to assess and compare the impact of different irrigation scheduling practices on cyanazine (Bladex) and metolachlor (Dual) concentrations at 180 cm below the soil surface during a 30-year cropping sequence. The region was divided into different soil textural classes to facilitate rapid estimation of soil parameters needed for the model.

Very low Bladex and Dual concentrations were predicted at 180 cm below the soil surface. However, the predicted pesticide concentrations increased as soil sand fractions increased, regardless of the irrigation scheduling practice. The tensiometer based irrigation scheduling resulted in the highest Bladex and Dual concentrations. The lowest concentrations were predicted under the farmer's practices due to deficit irrigation. Dual concentrations at 180 cm depth of the sandy soil

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class were about 20 times less than the 5.25×10^{-1} mg l^{-1} Health Advisory Level under the tensiometer-based irrigation scheduling practices, while, the farmer's practices resulted in Dual concentration about 625 times less than the Health Advisory Level. Similarly, the predicted Bladex concentration in sandy soil class was 3125 times less than the 1.30×10^{-2} mg l^{-1} Bladex Health Advisory Level under the tensiometer-based irrigation scheduling and about 416 000 times less than the Health Advisory Level under farmer's practices. Simulation results suggested that current farmer's practices do not pose a threat to the area's groundwater quality and result in a 15–40% leaching fraction depending on soil type. Tensiometer-based irrigation scheduling was similar to scheduling irrigations at 50% plant available water depletion and resulted in a 35–50% leaching fraction depending on soil type as long as the tensiometer was placed in the proper root zone depth. The model's calculated leaching fractions using farmer's practices were similar to measured leaching fractions in Doña Ana County, giving credibility to the use of simulation models for assessing and comparing the potential impact of different irrigation scheduling practices on environmental quality at a regional level.

Keywords: Simulation; Pesticide leaching; Farming practices

1. Introduction

Nonpoint source pollution from nutrient and pesticide application has the potential to degrade water resources. It is imperative that the impact of farming practices and proposed best management practices (BMPs) on water quality be evaluated so that appropriate BMPs can be developed to minimize pollution. Because direct monitoring or field experiments are expensive and time consuming, models are being used increasingly to evaluate the impact of farming practices on water quality, especially in regional-scale studies. Bleecker et al. (1995) used the model LEACHA (Hutson, 1993) to identify areas potentially susceptible to atrazine leaching in the northeastern region of the United States. Hamlett and Epp (1994) used the model CREAMS to study the potential impact of conservation and nutrient management practices on water quality in Pennsylvania, United States. Although it is convenient both in time and cost to use models for such studies, acquiring the soil parameters required for simulation models can be tedious due to the large number of soil types within regional areas. Consequently, appropriate methods that facilitate rapid parameter estimation must be developed and used.

Groundwater resources in Doña Ana County, New Mexico, United States are potentially vulnerable to pesticide and nutrient pollution, since the water table can rise to about 180 cm below the soil surface. Additionally, crop production is dependent on intensive irrigation, making the area potentially susceptible to leaching. The objectives of this study were to: use the model IRRSCHM (Sitze et al., 1995) to assess the potential impact of irrigation scheduling practices on the leaching of Bladex and Dual and estimate concentrations of these herbicides at the 180 cm depth; identify the irrigation scheduling practices that has the lowest potential impact on groundwater pollution; and propose recommendations to improve irrigation scheduling practices. A methodology for estimating model parameters rapidly in a regional area also is presented.

2. Materials and methods

Doña Ana County, New Mexico, has a semi-arid climate with mean annual precipitation of about 20 cm. Farming activities are restricted to the valley areas, consisting of about 38 800 ha of irrigated land (New Mexico Agricultural Statistics, 1993). The groundwater level in the irrigated fields can rise to about 180 cm below the soil surface. The main field crops grown and the proportion of the total crop acreage are: alfalfa, 0.02; chile, 0.14; corn, 0.07 ; cotton, 0.52; and onions, 0.07 (New Mexico Agricultural Statistics, 1993). The local farmers use cyanazine (Bladex) to control weeds in cotton fields and metolachlor (Dual) on weeds in chile fields. These herbicides are included in the United States Environmental Protection Agency's list of pesticides that require monitoring because they are frequently detected in groundwater.

Elephant butte irrigation district (EBID) sells and delivers water to farmers for irrigation purposes. Each farmer is allotted about 91 cm of water per growing season, which is delivered in portions to the farmers' fields on request. All fields are dead level irrigated with no runoff. Farm locations and a five-year irrigation scheduling database, which consisted of the time and amount of water applied per irrigation for each crop, were obtained from EBID. The farm locations were used to identify the major soil types under cultivation. Also, the type, time, and amount of pesticide applied and the planting and harvest dates for each crop were obtained from the farmers. The farmers have wells to supplement EBID water, for pecans and onions in the winter months. The groundwater quality is poor, so farmers do not use the groundwater when EBID water is available. Farmers traditionally stress the alfalfa crop for water because of the problem of harvesting the crop at the same time the fields need to be irrigated. Consequently, the alfalfa yields are reduced due to water stress. Yearly evapotranspiration was only 109 cm, based on county yield and the alfalfa water production function (Sammis, 1981). Nonstressed yearly evapotranpsiration is 192 cm. The irrigation scheduling model, when automatically scheduling irrigations based on relative plant available water, assumes that harvest conditions do not prevent irrigation from occurring.

2.1. Description of the model IRRSCHM

IRRSCHM, a modification of IRRSCH (Asare et al., 1992), is a management-oriented model that simulates soil moisture, nitrogen, and pesticide dynamics in soils. The model operates on a daily time step and uses soil hydrologic parameters developed for the general soil classes. The soil moisture dynamics were modeled based on the field-capacity, tipping-bucket approach. The soil profile was divided into discrete layers and water filled each layer to field capacity with the excess water moving into the next soil layer below. Water conservation in a soil layer was expressed by the following equation

$$M_i^{n+1} = M_i^n + I_i^{n+1} - O_i^{n+1} - S_i^{n+1}, \tag{1}$$

where M was the amount of water in a soil layer (m), I the flux of water into a layer (m), O the flux of water out of a layer (m), S the evapotranspiration (m), n time step, and i was the soil layer index. Crop growth processes simulated by IRRSCHM are root growth, leaf area index, and crop coefficients used in estimating actual crop evapotranspiration. Root growth and crop coefficients are influenced by the cumulative heat units expressed in growing degree days (Sammis et al., 1985). S was calculated using the crop coefficients, reference evapotranspiration using Penman's equation and daily climate data, and a soil water stress function (Abdul-Jabbar et al., 1983). A detailed description of IRRSCHM is given by Sitze et al. (1995).

The dynamics of contaminants were modeled based on the mixing-cell concept, in which the content of each discrete soil layer was assumed thoroughly mixed at every time step. The diffusion–dispersion component ($D(\delta^2 C/\delta x^2)$) of the convection–dispersion equation of the solute transport equation was neglected in the mixing-cell formulation but was accounted for by numerical dispersion. D was the diffusion–dispersion coefficient. The flow equation for a conservative contaminant is, therefore,

$$\frac{\delta C}{\delta t} = -u\frac{\delta C}{\delta x}. \tag{2}$$

Eq. (2) was implemented numerically based on the following finite difference approximation (Van Ommen, 1985):

$$C_i^{n+1} = C_i^n + \left(\frac{u\Delta t}{\Delta x}\right)\left(C_{i-1}^n - C_i^n\right), \tag{3}$$

where C was the concentration of the contaminant (kg m^{-3}), u was the pore velocity (m s^{-1}), Δx was the thickness of the soil layer (m), Δt was the time step (s), n was the time index, and i was the layer index. In order for numerical dispersion to equal the diffusion–dispersion component of the convective–dispersion equation, the time step must be a function of D, u, and Δx described by Van Ommen (1985).

The concentration of a herbicide that undergoes first-order degradation and has a linear adsorption was estimated using the equation

$$C_{si}^{n+1} = C_i^{n+1}\left(1 - k_d\left(\frac{M_i}{V_i}\right) - (1 - \exp(m\Delta t))\right), \tag{4}$$

where k_d was the partition/distribution coefficient (m^3 kg^{-1}) and m was the first-order decay rate constant (s^{-1}), C_s was the concentration of the herbicide in soil solution (kg m^{-3}), M was the mass of soil in a layer (kg), V was the volume of soil solution (m^3) in a layer, n was the time index and i was the soil layer index. At each time step in solving Eq. (3), the concentration in the soil solution was corrected for absorption and decay. Consequently, the model kept tract, over time and depth, of the total herbicide in each layer, the amount absorbed by the soil, the amount in the soil water, and the amount degraded.

2.2. Description of farmers' practices and proposed irrigation scheduling practices

The farmers use level furrow or basin irrigation systems in Doña Ana County, New Mexico. All applied irrigation water infiltrates with zero runoff. Timing of irrigation is based on the farmers' experience. Review of historical irrigation scheduling data for farmers showed that EBID does not always deliver water on time to farmers when requested. Because of delays in water delivery, crops undergo water stress conditions for a few days before water is applied. The amount of water applied in the model on the farmers' fields was obtained from EBID. The model used an average irrigation depth of water applied by the farmers for each crop when modeling other irrigation scheduling methods. In addition to farmers' irrigation practices, the following irrigation scheduling practices were evaluated using the IRRSCH model: tensiometer-based irrigation scheduling with a fixed tensiometer porous cup position at 30 cm soil depth and a tensiometer porous cup position moving with the dynamic root zone and placed at 0.5 and 0.75 of the root zone depth; and irrigation scheduling at 50% plant available water depletion (PAWD) level. The tensiometer-based irrigation scheduling used local natural resource and conservation service (NRCS) recommendations of: 6 kPa for sandy soils, 23 kPa for sandy loam soils, 44 kPa for loamy soils, and 74 kPa for clay loam soils. The local NRCS office also recommends that the tensiometer be placed in the middle of the root zone. Harrison and Tyson (1993) recommend that the tensiometer be placed between 0.25 and 0.5 of the root zone depth. They recommend that the irrigation be started when the tensiometer reaches between 20 and 60 kPa. Goodwin (1995) recommends placing tensiometers at half of the root zone and irrigating when the tensiometer reaches 30–40 kPa for sand and 50 kPa for loams and clay soils. The estimated relative plant available water (RPAW) levels at the proposed tensiometer levels were 0.51 for sandy soils, 0.65 for sandy loam soils, 0.77 for loamy soils, and 0.86 for clay loam soils. For clay soils, an 80 kPa tensiometer reading was proposed. However, this tensiometer level resulted in a high RPAW level at irrigation. Consequently, 210 kPa was used instead to obtain a 0.81 RPAW level. Plant available water (PAV) needed to calculate RPAW was calculated using

$$\mathrm{PAV} = \mathrm{FC} - \mathrm{PWP}, \tag{5}$$

where FC was the soil moisture content at field capacity ($\mathrm{m}^3\ \mathrm{m}^{-3}$), and PWP the moisture content at permanent wilting point ($\mathrm{m}^3\ \mathrm{m}^{-3}$).

The relative plant available water (RPAV) was estimated using the equation

$$\mathrm{RPAW} = \frac{\mathrm{MC} - \mathrm{PWP}}{\mathrm{PAV}}, \tag{6}$$

where MC was the soil moisture content ($\mathrm{m}^3\ \mathrm{m}^{-3}$) at the recommended tensiometer reading.

The relative plant available water ranged from 0 (when MC = PWP) to 1 (when MC = FC). Fifty-percent plant available water depletion (PAWD) was equivalent to an RPAW value of 0.5. Thus, the estimated RPAW level was equivalent to 49% PAWD for sandy soils, 35% PAWD for sandy loams, 23% PAWD for loamy soils, 14% PAWD for loams, and 19% PAWD for clayey soils. This shows that, generally, crops grown under tensiometer-scheduled irrigation were irrigated frequently. The RPAW levels were estimated using the Campbell soil moisture release curve model (Campbell, 1974) with the mean field capacity (FC) and permanent wilting point (PWP) values for each soil class taken from data published by Israelsen and Hansen (1962). The model assumes that field capacity is reached within 24 h and that water lost to deep drainage when the soil drains from saturation to field capacity is not taken up by the crop. This assumption could overestimate deep drainage, if drainage does not occur in 24 h, which may be the case for clay and clay loam soils. Irrigation water applied after daily evapotranspiration is subtracted from the profile.

2.3. Setting up the model IRRSCHM

IRRSCHM was modified for this study to handle multiple-year simulations. The modification allowed for continuous assessment of a 30-year cropping sequence on pesticide leaching. Planting and harvest dates, FC, PWP, and organic matter and Bladex and Dual half-life distributions in the soil profile are required for the model. The organic matter and herbicide half-life distributions in the soil profile were estimated using soil texture data for each soil series described in the Doña Ana County Area New Mexico soil survey report (Bulloch and Neher, 1980). The surface soil organic matter data (38 soil samples), obtained from the Southern Forest Nursery Soil Testing Program report (South and Davey, 1983) and from several fields in Las Cruces, New Mexico, were correlated with soil sand fraction. The resultant regression equation ($r^2 = 0.895$) was

$$\mathrm{OM} = -0.007S + 1.581, \tag{7}$$

where OM is the percent organic matter content in the soil layer's top 30 cm , and S is the soil's sand fraction. The sand fraction data ranged from 30% to 90%, and organic matter content ranged from 0.2% to 2.5%. Eq. (7) appears to represent irrigated conditions in Doña Ana County, based on several samples collected in the valley. However, the organic matter content also depends on farming practices and crop rotation, and this data was not available to include in the regression model.

Organic matter content by soil depth data for 93 soil series (Gile and Grossman, 1979) was normalized by dividing the soil layer organic matter content by the maximum organic matter content for the soil series. The normalized soil organic matter content data for all the soil series were pooled together and regressed against the corresponding soil depth. The resulting regression model ($r^2 = 0.67$) was

$$\mathrm{OMR} = -0.1733\ln(x) + 1.0904, \tag{8}$$

where OMR was the relative organic matter content, and x was soil depth in cm. Eqs. (7) and (8) were used to estimate organic matter content distribution in the soil profile for each soil class in the valley.

We assumed that pesticide degradation was mediated mainly by microbial activity, organic matter was the main energy source for the microbes, and pesticide half-life was inversely related to soil organic matter content. Consequently, the pesticide degradation rate was assumed to decrease with decreasing soil organic matter content. It was further assumed that the degradation rate of pesticides was similar. These assumptions were used to estimate Bladex and Dual half-life distributions in the soil profile. A power function was fitted to the soil organic matter content and aldicarb (Bowman, 1988; Pennell et al., 1990) and atrazine half-life data (Bacci et al., 1989; Ghadiri et al., 1984; Hiltbold and Buchanan, 1977; Walker, 1978). A corresponding pesticide half-life value, which was assumed to be the maximum value, was estimated at 0.03% soil organic content. The estimated maximum half-life value was 205 days for aldicarb and 122 days for atrazine. The half-life values were normalized by dividing each half-life value by the maximum half-life. Also, the organic matter content associated with each pesticide half-life value was normalized with the mean value of Alfisols, Aridisols, and Mollisols organic matter contents. Organic matter content data for Alfisols, Aridisols, and Mollisols were used, because most of the soils in the pesticide studies fall in these three soil orders. The mean organic matter content value used was 2.7% based on soil organic matter data for the three soil orders published by Brady (1990). The normalized half-life (HLN) data were regressed against the corresponding normalized organic matter content (OMN). The resulting regression equation ($r^2 = 0.725$) was

$$\mathrm{HLN} = -0.634\ln(\mathrm{OMN}) + 0.76316. \tag{9}$$

Half-life values for Bladex and Dual were estimated by multiplying Eq. (9) with the base half-life value. The base half-life value used for Bladex was 14 days and 90 days for Dual (Wauchope et al., 1992). The partition/distribution coefficient value used in the model was based on organic matter content in the soil and was 0.19 $\mathrm{m}^3\,\mathrm{kg}^{-1}$ for Bladex and 0.20 $\mathrm{m}^3\,\mathrm{kg}^{-1}$ for Dual (Wauchope et al., 1992).

Cropping sequence for a 30-year simulation was generated by randomly selecting one crop each year. The chance of occurrence was determined by the percentage of the crop under cultivation in the area. Alfalfa, when selected, was modeled by setting a January planting date for three consecutive years. The first year represented a new crop and the second and third years a mature alfalfa crop. The planting dates for the annuals were: chile, 15 March; corn, 27 April; cotton, 15 April; and onions, 31 January. The harvest dates were expressed by cumulative growing degree days (CGDD) from planting to harvest based on daily climate data. The cumulative growing degree days were computed as (Sammis et al., 1985)

$$\mathrm{CGDD} = \sum_{i}^{n}\left(\frac{T_{\max} + T_{\min}}{2} - T_{\mathrm{base}}\right), \tag{10}$$

where $T_{\max}$ was maximum daily temperature (°C), $T_{\min}$ was minimum daily temperature (°C), T_{base} was the threshold temperature (°C) below which crop growth ceases, i was the planting date and n was the harvest date. Growing degree day was not accumulated on the days for which the estimated growing degree day was negative or zero. When $T_{\max}$ exceeded the maximum cutoff temperature, the temperature was set to the maximum cutoff temperature. The same procedure applied when $T_{\min}$ was less then the minimum cutoff temperature. The maximum cutoff, minimum cutoff, and base temperatures used in estimating CGDD for the crops are shown in Table 1. The estimated CGDD from planting to harvest was 550 for alfalfa (at cutting); 3205 for chile; 1379 for corn; 2015 for cotton; and 1775 for onions. The maximum rooting depth was set at 60 cm for onions and 120 cm for alfalfa, chile, corn, and cotton.

For a 30-year simulation under the farmers' management practices, irrigation scheduling dates and application depth data were randomly selected from the 5-year irrigation scheduling database obtained from EBID, along with the corresponding climatic data. Irrigation depths of 14.5 cm for alfalfa, 10.4 cm for chile, 13.3 cm for corn, 12.9 cm for cotton, and 8.2 cm for onions were used for irrigations scheduled with tensiometers and the 50% PAWD level. The date of irrigation was determined when the

Table 1
Maximum cutoff, minimum cutoff and base temperatures used in estimating cumulative growing degree days

Crops	Temperature (°C)		
	Maximum	Minimum	Base
Alfalfa	Undefined	Undefined	5
Chile	30	5	5
Corn	30	10	10
Cotton	30	12	12
Onions	25	7	7

tensiometer or PAWD level reached the irrigation criteria. These irrigation application amounts represented the average values used by the farmers.

2.4. Simulation runs

Simulation runs were made for all the soil series for all the management practices. The soil classes were clay with 2 soil series, clay loam with 10 soil series, sandy clay loam with 2 soil series, loam with 9 soil series, sandy loam with 22 soil series, loamy sand with 15 soil series, and sand with 1 soil series. No simulation runs were made for the soils of the sandy clay loam and loamy sand classes for tensiometer-based irrigation scheduling because there were no tensiometer recommendations from NRCS for triggering irrigation. The mean seasonal irrigation, leaching fraction, and relative evapotranspiration values for each soil class were calculated for the 30-year simulation period. Also, the maximum pesticide concentrations at the 180 cm soil depth that occurred during the 30-year period were recorded for the soil series and averaged over each soil class. The mean Bladex and Dual concentrations for each soil class were expressed in relation to their respective Health Advisory Levels. The Health Advisory Levels were 5.25×10^{-1} mg l^{-1} for Bladex and 1.30×10^{-2} mg l^{-1} for Dual (Hall and Rumack, 1977).

3. Results

3.1. Seasonal irrigation, leaching fraction, and relative evapotranspiration

The mean annual irrigation requirements were highest for the tensiometer-based irrigation scheduling and lowest for the farmers' management practices. The 50% PAWD level fell between the two extremes (Fig. 1). The fix tensiometer-based irrigation scheduling resulted in large amounts of excess water applied compared to the tensiometer with the porous cup position moving with the dynamic root zone and placed at 0.5 and 0.75 of the root zone depth. A tensiometer with one fixed depth of 30 cm should not be used to schedule irrigation for either shallow or deep rooted crops Tensiometer-based irrigation scheduling with the tensiometer placed at the middle of the root zone resulted in water applications that are similar to scheduling water at the 50% depletion level for sand and sandy loam soils. In clay and clay loam soils, it is necessary to place the

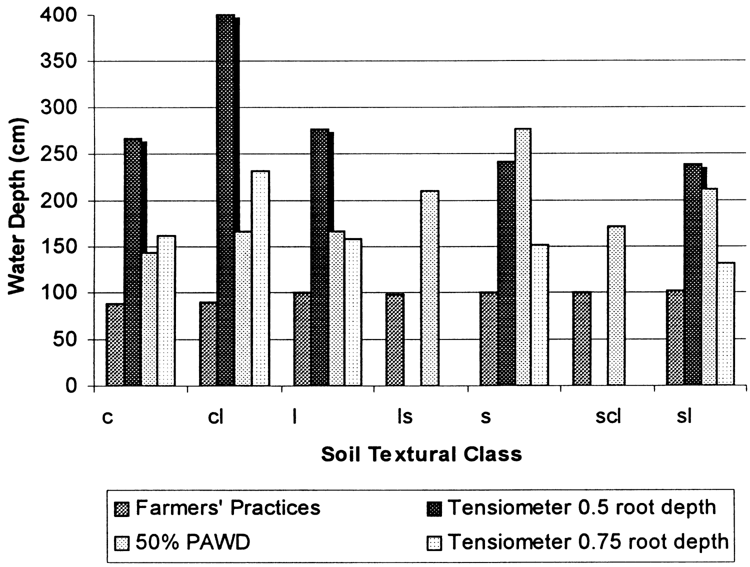

Fig. 1. Mean seasonal irrigation levels resulting from different management practices grouped by soil textural classes: c — clay, cl — clay loam, scl — sandy clay loam, l — loam, sl — sandy loam, ls — loamy sand, and s — sand.

tensiometer at a depth equal to 0.75% of the root zone in order to schedule irrigations using the tensiometer and not over water. The amount of water applied by the farmers was the same regardless of soil type and was 97 cm. The farmers are only allocated 91 cm of water from the irrigation district. Water applications above 91 cm have to be bought when surplus water is available or the water has to come from wells. Consequently, farmers under irrigated compared to the evapotranspiration requirements of the crop, resulting in lower yields and less evapotranspiration of the crop compared to nonmoisture stress conditions. The number of irrigations was least for the farmers' practices (7) and was similar (9–24) for irrigation scheduled at 50% plant available water and tensiometer scheduled irrigation (Table 2).

Similarly, leaching fraction values were highest under tensiometer-based irrigation scheduling, while the farmers' management practices resulted in the lowest leaching fraction (Fig. 2). The mean seasonal leaching fractions for all the soil classes, averaged over 30 years, were: 0.58 under the tensiometer-based irrigation scheduling with the tensiometers placed at 50% of the root zone and 0.41 for the tensiometers placed at 75% of the root zone, 0.42 under irrigation scheduling at 50% PAWD level, and 0.27 under the farmers' management practices. Thus, a large proportion of the seasonal irrigation water moved below the crop root zone. Only 43–59% of water applied was used by crops under tensiometer-based irrigation scheduling, 58% for 50% PAWD, and 73% for farmers' practices. Generally, leaching fractions increased with increasing sand content under the farmers' practices (Fig. 2). The mean leaching fraction of 0.27, resulting from the farmers' practices, suggests poor irrigation timing by the farmers when considering that the mean seasonal irrigation water was only 97 cm.

Table 2
Number of irrigations per season for the different irrigation scheduling practices grouped by soil textural classes

Soil textural class	Irrigation scheduling practices		
	Farmers' practices	Irrigation at 50% PAWD	Scheduled by tensiometer[a]
Clay	7	9	10 (0.75)
Clay loam	7	12	16 (0.75)
Sandy clay loam	8	12	
Loam	8	17	16 (0.75)
Sandy loam	8	18	16 (0.50)
Loamy sand	8	16	
Sand	8	21	24 (0.50)

[a] Depth percent of root zone is given in parentheses.

The relative evapotranspiration (R-ET) or relative crop yield values were at least 0.93 for crops grown on all the soil classes, except sand and sandy loam, which ranged from 0.7 to 0.8 under the tensiometer-based irrigation scheduling with the tensiometer located at 0.75 of the root depth (Fig. 3). The R-ET of 0.93 is about 10 cm less than the mean of 118 cm for nonstressed, seasonal evapotranspiration. Thus, the frequent irrigation levels used under tensiometer-based irrigation and 50% PAWD maintained adequate soil moisture level within the crop root zone throughout the growing period. Additionally, both irrigation scheduling practices ensured timely water application that consequently minimized water stress effects on crop growth and water use. The relative evapotranspiration under farmers' practices was 0.58 for sandy soils, 0.68 for sandy loams, 0.72 for loamy soils, 0.66 for loamy sand soils, 0.70 for clay loams, 0.73 for sandy clays, and 0.73 for clayey soils. Thus, R-ET under farmers' practices decreased with increasing soil sand content (Fig. 3). Crops grown on coarse-textured soils experienced water stress from poor irrigation timing and leaching losses. Consequently, irrigation

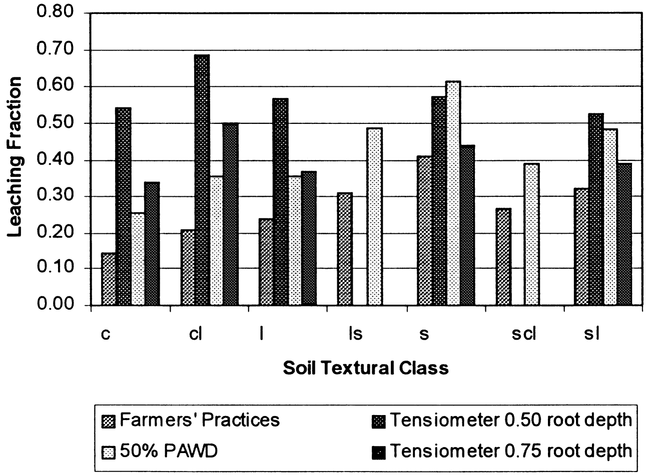

Fig. 2. Mean leaching fraction values resulting from different management practices grouped by soil textural classes defined as in Fig. 1.

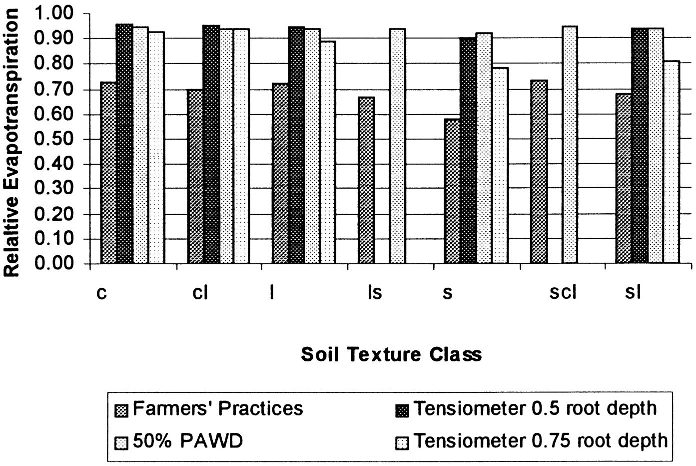

Fig. 3. Mean seasonal relative evapotranspiration resulting from different management practices grouped by soil textural classes defined as in Fig. 1.

scheduling under the farmers' practices requires improvement in order to minimize leaching and maximize crop yield.

3.2. *Pesticide leaching resulting from farmers' management practices*

The relative Bladex concentrations at the 180 cm soil depth varied among soil classes, reflecting differences in soil hydraulic properties and organic matter content distributions in the soil profiles. The relative Bladex concentrations ranged from 2.4×10^{-6} in the sandy soil class to 1.2×10^{-18} in the clayey soil class, showing that Bladex concentrations increased with increasing soil sand fraction (Table 3). However, these concentrations were insignificant compared to the 1.30×10^{-2} mg l^{-1} Bladex Health Advisory Level. For example, the mean relative Bladex concentration at 180 cm depth of the sandy soil class was about 0.4 million times less than the 1.30×10^{-2} mg l^{-1} Bladex Health Advisory Level.

The trend in the relative Dual concentrations for the different soil classes (Table 4) was similar to that observed for Bladex (Table 3), except that Dual concentrations were higher. The mean relative Dual concentration for the sandy soil class was 1.6×10^{-3}, which is about 630 times less than the 5.25×10^{-1} mg l^{-1} Dual Health Advisory Level. The area's groundwater is potentially more susceptible to Dual pollution than to Bladex, because Dual can persist longer in the soil profile due to its 90 day base half-life. Consequently, some of the Dual present in the soil profile can leach with subsequent irrigations.

3.3. *Pesticide leaching resulting from tensiometer-based irrigation scheduling*

Bladex and Dual concentrations predicted under tensiometer-based irrigation scheduling were higher than those predicted under farmers' management practices

Table 3
Relative maximum Bladex concentrations[a] resulting from the different irrigation scheduling practices grouped by soil textural classes

Soil textural class	Irrigation scheduling practices			
	Farmers' practices	Irrigation at 50% PAWD	Scheduled by tensiometer	
			0.5 depth	0.75 depth
Clay	1.2E-18	3.2E-12	1.5E-06	4.5E-09
Clay loam	8.4E-14	2.3E-07	2.2E-04	6.7E-06
Sandy clay loam	1.0E-11	2.0E-06	N/A[b]	N/A[b]
Loam	6.8E-10	8.9E-07	4.7E-05	5.5E-07
Sandy loam	1.6E-07	9.5E-06	3.0E-05	9.2E-07
Loamy sand	6.4E-07	4.2E-05	N/A[b]	N/A[b]
Sand	2.4E-06	4.3E-04	3.2E-04	1.2E-05

[a] Predicted Bladex concentrations were divided by 1.30×10^{-2} mg l^{-1}, Bladex Health Advisory Level.

[b] No simulation runs were made for the soil class.

(Tables 3 and 4). For example, Dual concentrations at the 180 cm soil depth of the sandy soil class was about 20 times less (tensiometer at 0.5% of root depth) than the 5.25×10^{-1} mg l^{-1} Dual Health Advisory Level compared to about 630 times less under the farmers' management practices.

3.4. Pesticide leaching from irrigation scheduling at 50% plant available water depletion level

The predicted Bladex and Dual concentrations at the 180 cm soil depth when irrigation was scheduled at 50% PAWD generally followed the trend observed under the farmers' management practices. However, Bladex and Dual concentrations were higher than those

Table 4
Relative maximum Dual concentrations[a] resulting from the different irrigation scheduling practices grouped by soil textural classes

Soil textural class	Irrigation scheduling practices			
	Farmers' practices	Irrigation at 50% PAWD	Scheduled by tensiometer	
			0.5 depth	0.75 depth
Clay	4.8E-09	1.7E-04	1.4E-02	1.1E-03
Clay loam	1.3E-06	1.2E-03	3.4E-02	1.3E-02
Sandy clay loam	7.5E-05	4.1E-03	N/A[b]	N/A[b]
Loam	2.5E-05	3.0E-03	2.3E-02	2.4E-03
Sandy loam	5.1E-04	1.3E-02	1.9E-02	3.7E-03
Loamy sand	6.9E-04	2.4E-02	N/A[b]	N/A[b]
Sand	1.6E-03	5.4E-02	5.1E-02	1.0E-02

[a] Predicted Dual concentrations were divided by 5.25×10^{-1} mg l^{-1}, Dual Health Advisory Level.

[b] No simulation runs were made for the soil class.

under the farmers' practices, and lower than those under the tensiometer-based irrigation scheduling (Tables 3 and 4).

4. Discussion

The model indicates that for soils that are clay, clay loam, and sand loam, the leaching fraction is 23% for all crops. Al-Jamal et al. (1997) measured a leaching fraction of 0.24 for chile and onions grown on the same soil types in the valley. Consequently, the model and measure leaching fractions agree, indicating that the water balance portion of the model is functioning correctly. Also, Al-Jamal et al. (1997) reported yields for those same fields that represent 0.77 of maximum yield for onions and 0.87 of maximum yield for chile. This yield data also indicates that the farmers are stressing their crops for water.

The model shows that all irrigation amounts applied by the farmers at the time of irrigation exceed the water-holding capacity of the soil even when fields are irrigated under deficit soil moisture conditions. Excess water depth is applied because of the small turnouts used by farmers. They were designed for graded fields that have been converted to dead level fields. Larger turnouts would increase the advance rate and decrease the total depth of water application because the farmers irrigate until the water reaches either 3/4 or the end of the field.

Tensiometer-based irrigation scheduling resulted in the highest Bladex and Dual concentrations at the 180 cm soil depth due to higher seasonal irrigation levels, frequent irrigations, and high leaching fractions. Irrigation scheduling in the clay soil (based on the evaluated tensiometer levels) resulted in frequent irrigation, creating high soil moisture conditions that enhanced pesticide leaching. When the tensiometer was placed deeper (0.75% of the root zone) the tensiometer-scheduled irrigation results were similar to the 50% depletion irrigation scheduling results. For sandy soils, the tensiometer should be placed at the 50% root zone depth. If the tensiometers are placed at the 75% root zone depth, moisture stress occurs and yields are decreased. Bladex and Dual concentrations were lowest under the farmers' management practices because of the lowest seasonal irrigation and leaching fraction levels. Also, general delays in delivering water to the farmers' fields allowed some of the pesticide to degrade, thereby reducing the pesticide amount available to leach under favorable soil moisture conditions.

Results showed that all the management practices require improvement to maintain high R-ET values (high crop yields), low leaching fractions, and, consequently, very low pesticide concentrations at the 180 cm soil depth. The farmers' practices resulted in the lowest R-ET and Bladex and Dual concentrations due to relatively low levels of applied water. However, the resulting leaching fractions (Fig. 2) and low R-ET tend to suggest poor irrigation timing by the farmers, especially for crops grown on coarse textured soils. On the average, 97 cm applied seasonal irrigation water resulted in about 27 cm of water moving past the root zone. Thus, timely and frequent application of small amounts could reduce the leaching fractions, increase R-ET, and, consequently, further decrease in Bladex and Dual concentrations at the 180 cm soil depth under the farmers' practices. In contrast, R-ET was at least 95% under the tensiometer-based irrigation scheduling and irrigation scheduling at 50% PAWD levels, but more of the irrigation water was lost through leaching (Fig. 2) because the depth of application was to large. Improvements in the two irrigation scheduling practices have to be geared toward minimizing leaching fraction by using high flow turnouts on level fields to reduce the irrigation application . For tensiometer-based irrigation scheduling, putting the tensiometer at the correct depth is necessary and depends on the soil type and the crop's rooting depth.

5. Conclusions

The model IRRSCHM was used to assess local farmers' management practices and three irrigation scheduling practices for their potential impact on Bladex and Dual leaching into the water table at 180 cm below the soil surface during a 30–year cropping sequence. The soils in the study area were grouped into textural classes, so that study results could be categorized by soil class under each management practice. Study results showed that Bladex and Dual leaching were directly related to the soil sand fraction levels, regardless of management practice. The predicted Bladex and Dual concentrations were low and insignificant compared to the corresponding Health Advisory Levels. However, Bladex and Dual concentrations at the water table (180 cm soil depth) were highest under the tensiometer-based irrigation scheduling and lowest under farmers' practices. Consequently, farmers' practices have the lowest potential to adversely impact groundwater resources. Tensiometer-based scheduled irrigation practices (based on the tensiometer threshold levels evaluated and farmers' irrigation water application depths) are the least appropriate for controlling pesticide leaching. However, the pesticide levels were still low compared to the Health Advisory Level, and relative Et and yield were higher than under the farmers' practices.

The study demonstrates the use of simulation models for assessing and comparing the impact of alternate management practices on environmental quality. The method used to estimate soil parameters required to drive IRRSCHM is time efficient and may prove useful for acquiring soil parameters in large areas with numerous soil series.

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