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Use of the LEACHM model and the DRASTIC index to map relative risk of groundwater contamination by pesticide leaching

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Abstract

The risk of groundwater contamination, associated with soil types in the Levels Plain area, South Island, New Zealand, was analysed using the LEACHM model. Sensitivity analysis was carried out on three soil factors and three irrigation treatments for two contrasting soil types. Analyses were run for 2 years with 2 crops (spring-sown wheat and potatoes), and 2 pesticides (MCPA and metalaxyl). The analysis indicated larger effects on pesticide leaching from natural variations in saturated hydraulic conductivity (K_{sat}) and irrigation, and smaller effects from natural variations of soil horizon thickness and organic matter.

A pesticide leaching index was developed for the soils of the Levels Plain based on the simulation of metalaxyl fungicide leaching to the water table in a wet year. The index ratings indicated that water table depth and soil depth are the most critical factors in differentiating the potential for different soils to allow pesticides to leach to groundwater. It also indicated the importance of K_{sat}, and the lesser importance of organic carbon.

The soil units for Levels Plain were also classified for vulnerability to contamination according to the DRASTIC overlay classification system. Close correlation was found between the pesticide leaching index derived from the LEACHM simulation and the rating derived for the DRASTIC index.

The LEACHM simulations had greatly retarded translocation of pesticides through sandy gravel substrates, typical of vadose zones overlying many aquifers from alluvium in New Zealand. We doubt that these results are valid. We therefore recommend that the model should be tested against field data and modified before it is applied to soils with these materials.

Keywords

vulnerability, leaching index, soil, simulation, vadose, contamination, MCPA, metalaxyl

Introduction

Recent investigations have identified pesticides within the groundwater of a number of regions within New Zealand (Smith, 1993a; Hadfield *et al.*, 1996; Close, 1996). Most measurements have shown only trace amounts, well within accepted health limits. However, even though the evidence for high pesticide contamination is relatively rare, there still may be a significant risk to human health. Only a limited number of wells are tested, and the wells are tested infrequently due to the high cost of analysis, so there is a high probability that higher pesticide levels do occur.

The potential for pesticides to leach to groundwater depends upon many factors: climate (rainfall, evapotranspiration, temperature), soil and vadose zone characteristics (texture, thickness, hydraulic conductivity, organic matter content), depth to groundwater, pesticide properties, and farm management practices. Given the diversity of conditions, and the varying times, quantities, and locations of pesticide application, the influx of pesticides to the groundwater will be highly variable.

Local authorities and farming communities, confronted with these uncertainties, face the question of where to best expend their limited budgets, both to investigate current levels of contamination and to encourage or adopt improved land management practices. Computer modelling can assist these decisions by estimating the relative risks of groundwater contamination associated with various sites, management scenarios, and climate conditions within an area. Aquifers can then be monitored within high-risk areas and, should monitoring indicate significant pesticide contamination, aquifer protection strategies may be focussed on those areas where greatest improvement may be gained. The two most common methods of estimating the risk of groundwater contamination are those using overlay/index systems and those using simulation models (Barrett and Williams, 1989).

The DRASTIC Index (Aller *et al.*, 1987) is an example of a simple index method of rating the intrinsic vulnerability of land to groundwater contamination. DRASTIC has been used widely overseas and to a limited extent within New Zealand (Close, 1993; Brown *et al.*, 1994). The index is based on the rating of seven physical factors within each environmental setting. The factors are: depth to the water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity of the aquifer. Each factor is assigned a rating between 1 and 10, based on the setting, and a weighting from 1 to 5 according to the factor's importance, as perceived by the authors of the index. Each factor is then multiplied by its weight, and these values are summed to arrive at a numerical DRASTIC index. The DRASTIC Index has been criticised because of its poor correlation with measured levels of groundwater contamination (Banton and Villeneuve, 1989; Barrett and Williams, 1989; Kalinski *et al.*, 1994).

Part of this problem may lie in the application of a standard set of weights. The weighting of the factors reflects the specific conditions for which they were developed in the USA. These weightings may need to be re-evaluated wherever environmental conditions differ from those for which the model was developed. For example, in many parts of New Zealand aquifers have very high transmissivities and this has a profound influence on the dilution of contaminants within aquifers (M. Close, ESR, *pers. comm.*1998). The aquifer media factor may therefore need to be accorded greater weightings in these areas, than elsewhere. Furthermore, aquifers in the Canterbury Plains (including the aquifer under Levels Plain) may have significant recharge from rivers. Where the extent of this recharge from rivers is known, it needs to be taken into account in the method of rating.

A number of simulation models have been developed to predict pesticide movement and degradation within the soil profile (Cohen *et al.*, 1995).The models have met with mixed success in predicting pesticide movement within soil profiles. Gallant and Moore (1993) state that we should not expect simulation models to accurately predict absolute pesticide values. However, they argue that simulation models are quite effective for vulnerability assessments of the relative risk of pesticide leaching for different environmental settings.

For our study, we chose the LEACHM simulation model (Leaching Estimation And CHemistry Model) (Wagenet and Hutson, 1987) because it uses important soil parameters as input factors, enabling it to be used to investigate the relative influence of various physical, chemical, and biological processes on the fate of pesticides within the unsaturated zone (Mutch *et al.*, 1993). Also LEACHM has a generally favourable record of prediction in comparison with other models (Pennell *et al.*, 1990) and has been tested under New Zealand conditions (Close *et al.*, 1998; Close *et al.*,1999).

The objectives of this study were (i) to use LEACHM to test the sensitivity of soil parameters and irrigation rate for pesticide leaching, (ii) to develop a pesticide leaching index based on LEACHM simulation results for soils within the Levels Plain, and (iii) to compare this index with the DRASTIC index.

Materials and method

Study area

Levels Plain, a 9250-ha triangular segment of the Canterbury Plains, located between the Opihi River, the downlands, Pleasant Point and the Pacific Ocean, was chosen as a site to apply the pesticide leaching index (Fig. 1). This area was chosen for our study because: (a) it has a range of soil types representative of most of the soils on the Canterbury Plains, (b) it includes a wide range of land uses including extensive areas of dryland, and irrigation farming (both spray and border-dyke irrigation), and (c) it has a shallow, vulnerable aquifer and records of a number of wells containing pesticide residues (Smith, 1993b).

Levels Plain is composed of three geomorphic surfaces, with soils with a wide range of depth, drainage, and permeability characteristics (Table 1). Silt loam is the predominant texture in the upper 0.5 m of the soil profiles, except for Waterton soils, that are predominantly clay loam, and Waimakariri soils that are predominantly sandy loam. All the soils are underlain by sandy gravels with high permeability. The greatest depth to groundwater is about 5 m in the central plain area. Depth decreases to less than 0.5 m near the coast and to about 1.5 m near the Opihi River.

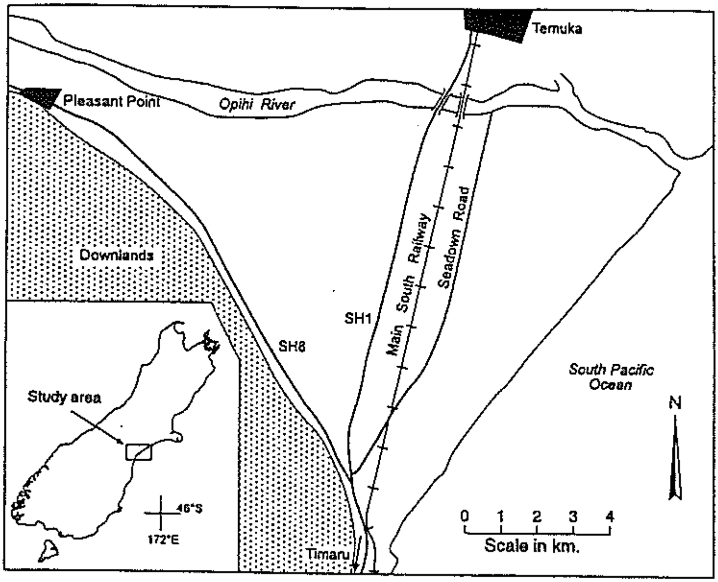

FIGURE 1 – Location of study site – the area between Opihi River, the downlands, Pleasant Point and the Pacific Ocean.

TABLE 1 – Key characteristics of main soil types within Levels Plain.

Soil symbol	Soil series	Depth to sandy gravels (m)	Drainage	Permeability of slowest horizon	Depth to groundwater (m)	Effective[1] depth to groundwater (m)
			Soils on young terrace			
Wa1[2]	Waimakariri	0.5-0.9	well	moderate	0.9	0.75
Wa2	Waimakariri	0.3-0.5	well	rapid	0.9	0.5
			Soils on intermediate terrace			
Te0	Templeton	0.9-2	well	slow	2.4	1.98
Te1	Templeton	0.5-0.9	well	mod. slow	2.4	1.25
Ey2	Eyre	0.3-0.6	well	mod. rapid	2.4	0.98
Wk0	Wakanui	0.9-3	imperfect	v. slow	1.8	1.80
Mt0	Motukarara	0.9-1.5	poor	slow	0.3	0.33
			Soils on old terrace			
Ph1	Pahau	0.5-0.9	imperfect	v. slow	2.4	1.27
Lm2	Lismore	0.3-0.6	well	moderate	4.0	1.46
Lm3	Lismore	0.3-0.4	well	mod. rapid	4.0	1.33
Wt1	Waterton	0.5-0.9	poor	v. slow	0.9	0.85
Wt2	Waterton	0.3-0.6	poor	v. slow	0.9	0.60

[1] Effective depth is the total depth minus the depth occupied by stones

[2] 0 = deep, 1 = moderately deep, 2 = shallow, 3= stony

Input data

Soil and groundwater

Table 2 shows an example of the soil data assembled for all soil units within Levels Plain. Soil types and thickness of strata were determined from soil survey investigations in Levels Plain in 1996/1997. Soil physical data were derived from soils sampled for soil hydrological and organic matter analysis during 1996-1998. Soils were sampled within the Canterbury Plains, and included 3 profiles from each of the Pahau, Wakanui, Templeton and Waterton soil series in the Levels Plain area. Average groundwater depth was estimated for each map unit from data supplied by the Canterbury Regional Council.

Climate

Daily rainfall, evaporation and temperature data to represent a 'wet year' were selected from a 20-year record of climatic data representative of the lower Canterbury Plains. We selected a wet year because we recognise that pesticide leaching to groundwater is an unusual event requiring periods of

TABLE 2 - Example of soil data used as input for the simulation analysis.

Horizon property	Horizon A	AB	B(g)1	B(g)2	Bg	Cg	C
Depth to base (m)	0.22	0.28	0.45	0.70	1.00	1.80	2.40
Stone content (% v/v)	0	0	0	0	50	70	70
Effective depth (m)	0.22	0.28	0.45	0.70	0.83	1.09	1.27
Root content (%)	55	10	20	15	0	0	0
Bulk density (t m^{-3})	1.3	1.5	1.6	1.8	1.7	1.7	1.7
Carbon (%)	3.0	1.4	0.4	0.3	0.3	0.2	0.2
Carbon (arable) (%)	1.7	0.6	0.4	0.3	0.3	0.2	0.2
Field capacity (% v/v)	39	38	36	34	30	15	12
Wilting point (% v/v)	20	20	25	25	22	4	4
Silt (%)	68	68	68	72	70	17	5
Clay (%)	24	24	24	20	20	3	4
K_{sat} (mm hr^{-1})	200	10	0.5	0.01	1	500	1000

substantial recharge. A two-year period was simulated to cover the full period of pesticide leaching. Total rainfall for the 12 months from July 1967 to June 1968 amounted to 1010 mm and the following 12 months totalled 534 mm. Monthly rainfall data used for the simulation period are shown in Figure 2.

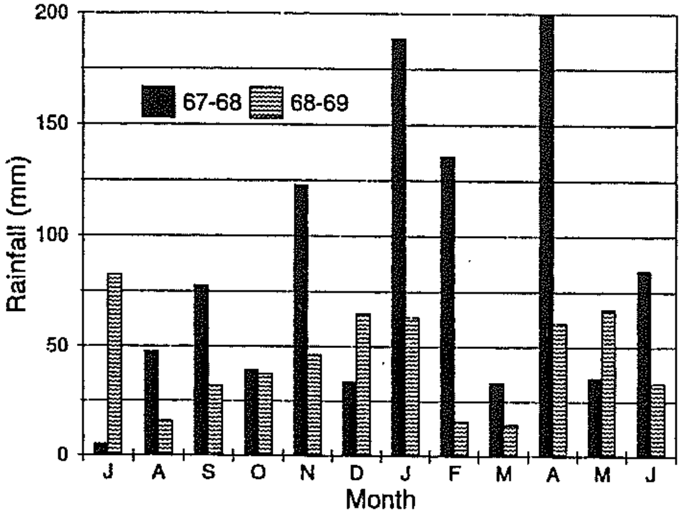

FIGURE 2 – Monthly rainfall record for period of simulation.

Farm management

Farm management data were derived from interviews with selected farmers from the Levels Plain. From these interviews, we determined the crops grown, pesticide use, and management practices such as irrigation and cultivation methods. The pesticides selected for this study were those considered to have a potential to persist in the soil (long half-life) and to be available for transport in the soil water (low soil sorption - K_{oc}) (Table 3). Two crop-pesticide combinations were selected for the sensitivity analysis: wheat using one application (0.94 kg active ingredient ha^{-1}) of MCPA post-emergence herbicide, and potatoes, using two applications (0.25 kg active ingredient ha^{-1}) of metalaxyl fungicide. Both pesticides showed very similar patterns of leaching within the sensitivity analysis, so metalaxyl, which has greater persistence, was selected for the development of the pesticide leaching index.

TABLE 3 - Pesticide transport and degradation characteristics of Metalaxyl and MCPA (From Wauchope *et al.*, 1992)

Chemical attribute	**Pesticide** **Metalaxyl**	**MCPA**
Soil sorption (K_{oc})	50	1000
Dispersivity (mm)	100	100
Half life (days)	70	30
Solubility (mg l^{-1})	7.14E +03	8.3E +02
Vapour density (mg l^{-1})	3.32E -05	1.65E -05

LEACHM model and model-derived analysis

Simulation

We used EXPRES (Mutch *et al.*, 1993) to run the simulations. EXPRES is a user-friendly expert system that incorporates LEACHM within a framework that facilitates input of data and examination of outputs. It contains a number of default settings to supply missing data, and a database providing chemical parameters for 175 pesticides. The LEACHM model subdivides the soil profile into 30 to 50 layers of equal thickness. The model uses the process-based Richard's equation to determine diffusive flow of water, and a combined aqueous and gas phase, advection-dispersion equation for chemical movement of water in the profile for both aqueous and gas phases.

Pesticide properties were taken from the EXPRES database and were the values suggested by Wauchope *et al.* (1992). We decided to use a constant degradation value for all horizons because (a) little information is available on the factors that change the degradation rate within different horizons, (b) we were interested in relative, and not absolute pesticide concentrations, and (c) the use of variable half-lives could introduce greater uncertainties into the analysis,.

Sensitivity analysis

Sensitivity analysis was undertaken on two strongly contrasting soil series: (i) Lismore shallow, well-drained soils, with moderate permeability and a deep water table and (ii) Waterton moderately deep to deep clay loam, with low permeability, and a shallow water table. Analyses were run for a simulation period of 2 years with 2 crops (spring-sown wheat and potatoes), and 2 pesticides (MCPA and metalaxyl). Variables tested in the sensitivity analysis are recorded in Table 4. Datasets for the two soils were factored into LEACHM, and each series of simulations were performed after a single input factor was varied. The effect of the change in the input factor was assessed from the change in estimated maximum concentration of pesticide at soil depths of 0.4, 0.8, and 1.2 m soil depths.

TABLE 4 - Input factors used in the sensitivity analysis.
(C = Control value)

Factor	Level of factor used in simulation					
Carbon		0.5 x C	C	2 x C		
K_{sat}	0.1 x C	0.2 x C	C	5 x C	10 x C	
Soil thickness	0.5 x C	0.75 x C	C			
Irrigation		0.5 x C	C	2 x C	3 x C	4 x C

Pesticide leaching index

The assessment of our pesticide leaching index was based on the use of LEACHM to simulate the leaching of metalaxyl fungicide used for potatoes. Datasets for all the soil units in Levels Plain were factored into LEACHM and the maximum concentrations of pesticide at 0.9 m depth (the base of the root zone) and at the top of the water table were determined. The concentrations were grouped into classes for representation of the pesticide leaching index. Simulations were run for all soil units and for three irrigation treatments. The irrigation treatments consisted of conservative spray irrigation (four applications of 30 mm), a high-application spray irrigation (four applications of 60 mm) and a border-dyke system (four applications of 120 mm). Separate simulations were also run for soils with low topsoil organic carbon, which is common in soils under long-term mixed cropping. Carbon levels measured in soils under arable farming had topsoil organic carbon levels about half that of soils under pastoral use. After generating the pesticide values reaching the water table, the leaching index was constructed by subdividing the values into six nominal classes. Results are reported for eleven of the most representative soil types.

DRASTIC Index

The DRASTIC index was determined for each of the soil units. Three of the seven factors were considered to be uniform over the entire area (topography, aquifer media, and aquifer hydraulic conductivity) and were not used in the index calculation. The Index values were subdivided into six nominal classes, and the classes were compared with those for the pesticide leaching index.

Results and discussion

Sensitivity analysis

Leaching of pesticides increased with decreasing carbon content. Changes were relatively small, except within the upper layer of the Waterton soil (Fig. 3). Halving and doubling carbon in a soil profile encompasses the variation expected to occur naturally within a soil series. This result indicates that the pesticide leaching index shows little sensitivity to natural levels of soil organic matter.

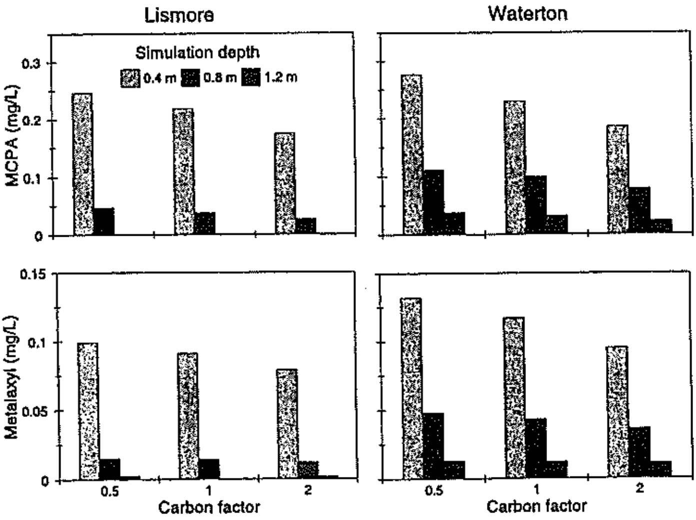

FIGURE 3 – Effect of carbon on pesticide leaching shown by the simulated concentration of pesticide in soil water at three depths.

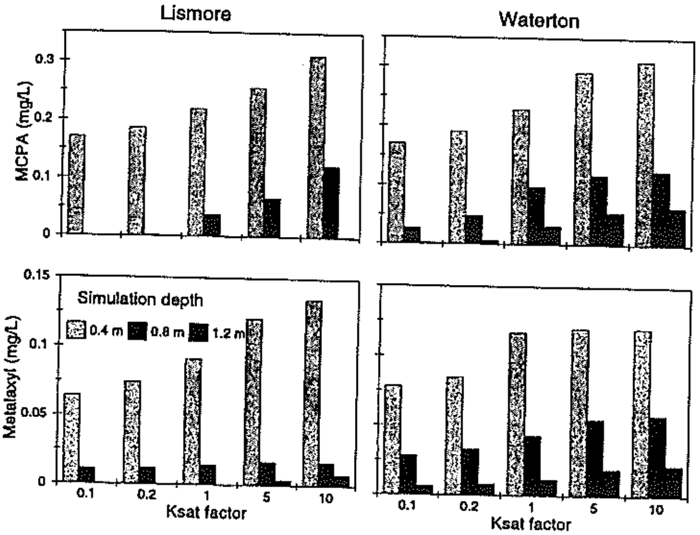

FIGURE 4 – Effect of K_{sat} on pesticide leaching, shown by the simulated concentration of pesticide in soil water of three depths.

Generally, consistent and large increases in estimated pesticide leaching resulted from large increases in K_{sat} values (Fig. 4). In the Waterton soil, at 0.4 m depth, increases in K_{sat} had little effect at high values of K_{sat}. This indicates that high K_{sat} allows pesticides to pass beyond the 0.4 m depth. Values of K_{sat} for different soils and different horizons commonly vary by an order of magnitude, so these differences are indicative of the sensitivity that may be expected between soils with large differences in K_{sat}.

Decreasing the thickness of all soil horizons within a soil profile is expected to have a large effect on leaching potential. The 0.5 x thickness for Waterton soils (Fig. 5) showed an increase in pesticide concentration at 0.8 m and 1.2 m for MCPA and Metalaxyl and at 0.8 m for MCPA. Otherwise the model predicted surprisingly little change in estimated pesticide concentrations with decreasing horizon thickness (Fig. 5).

The lack of any evident major effect of soil horizon thickness on pesticide leaching is considered to be partly related to a problem in simulating stony-sandy horizons within the LEACHM model. This effect is evident in a number of other results. For example, much lower levels of pesticide were estimated in the two lower soil depths (where sandy gravels occur) within the Lismore profile when compared to the Waterton profile (Figs. 3–6). The Lismore soil has lower water-holding capacity and much greater K_{sat} and is expected to have greater leaching potential. We discovered that, in simulations with the LEACHM model, pesticides did not move far through the sandy gravel substrate underlying the Lismore soils (and underlying all Waterton soils at greater depth). In the sensitivity analysis, we attempted to represent the sandy gravels by decreasing the values for field capacity and wilting point (10 and 3% respectively by volume), but this was only partially successful. We therefore lack confidence in the results for depths below 0.5 m in the sensitivity data for Lismore soils. In the subsequent risk assessment, the stone content was accounted for by reducing the thickness of horizons containing stones by the volumetric proportion of stones, and leaving the sandy matrix as the medium for transport. The resultant depth to the base of any horizon (Table 2) or to the groundwater (Table 1) is referred to as the 'effective depth' (Table 5). We believe that this method is a fair representation of the soil materials that are active in transport and attenuation of the pesticides. By this method we were able to simulate pesticide leaching to a depth of 4 m or more within the Lismore soils. However, as discussed below, we still question whether the model accurately represents this highly permeable and low water-holding-capacity medium.

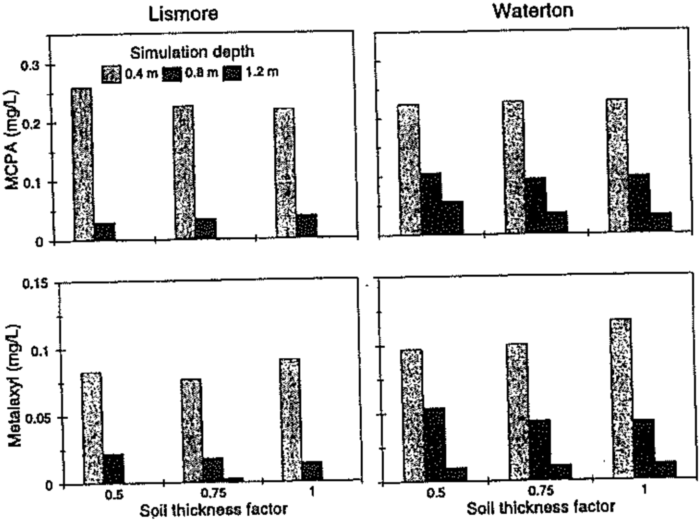

FIGURE 5 – Effect of soil thickness on pesticide leaching, shown by the simulated concentration of pesticide water at three depths.

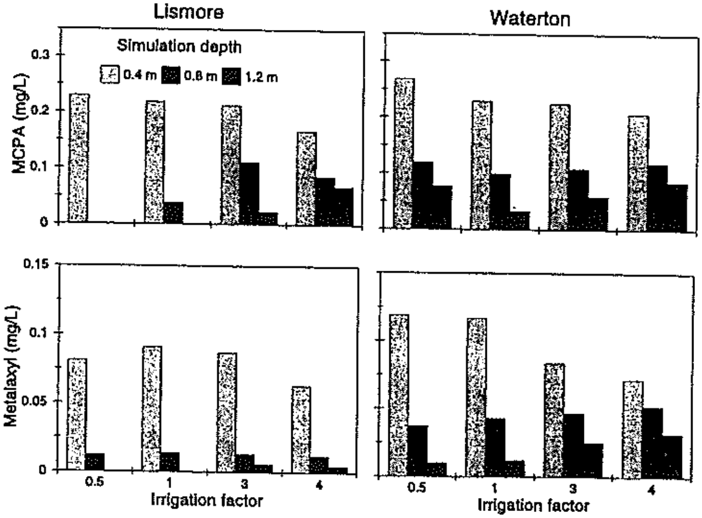

FIGURE 6 – Effect of irrigation on pesticide leaching, shown by the simulated concentration of pesticide in soil water at three depths.

TABLE 5 - Comparison of LEACHM and DRASTIC risk ratings for pesticide contamination at the water table. (V = very, X = extremely, L = low, M = moderate, H = high)

Soil	Effective depth	Risk ratings	
		LEACHM	DRASTIC
Wa2	0.50	H	H
Wt2	0.40	M	M
Wa1	0.75	M	M
Lm3	1.33	L	L
Wt1	0.85	L	VL
Ey2	0.98	VL	M
Ph1	1.27	VL	VL
Wk0	1.80	VL	XL
Te1	1.25	XL	L
Te0	1.98	XL	XL
Lm2	1.46	XL	L

There are some inconsistencies in the results for irrigation treatments (Fig. 6), but two trends are evident. At first, increasing the water application increased the leaching of pesticides, but at the highest rates of application there was a dilution of pesticide concentration in the upper soil horizons. Increasing the rate of irrigation markedly increased pesticide concentrations at 1.2-m depth. This is an expected result - evidently the larger quantity of water was sufficient to leach pesticide through to greater depth, before it attenuated within the soil profile. The environmental effect of irrigation rate should be based on values for the lowest horizon simulated, and at this depth concentration increased with increased irrigation rate.

An additional feature of the results in Figures 3–6 is the large difference in maximum pesticide concentration at different depths, within all treatments. These differences can be taken as surrogates for the effect of water table depth (shallow depth being equivalent to a high water table) and indicate the high sensitivity of depth to water table.

Simulation of soil types from Levels Plain

Figure 7 records the estimated pesticide concentrations at the water table. All simulations indicated pesticides at the water table, but some values are too small to be seen at the scale of the figure. The soils are plotted along the x-axis in order of increasing effective depth to the water table (Table 1). The four soils with the greatest concentrations of pesticide (soils on the right side of Fig. 7) are shallow to moderately deep soils with shallow groundwater. The two soils with the lowest concentrations (Te0, Wk0) are deep soils with moderately deep groundwater. Waimakariri shallow soil (Wa2) has much greater pesticide concentrations than its moderately deep counterpart (Wa1). This is due to the greater stoniness and higher hydraulic conductivity of Wa2 in the subsoil horizons. The same is true to a lesser extent for Lm3 (stony soils) compared with Lm2 (shallow soils).

Irrigation treatments had little effect on pesticide leaching except that, at high irrigation rates, some soils (notably Te1, Te0, and Wk0) had large increases in leaching (Fig. 7). The dilution effect of high-volume irrigation applications is evident in the results for a number of soils.

Figure 8 shows the estimated pesticide concentrations at the base of the root zone (0.9 m depth). Concentrations are much higher than those estimated for the water table, and differences between soils are smaller than those estimated for the water table. The soils are plotted on the x-axis according to increasing concentration of pesticide under the low irrigation treatment. As expected, four shallow and stony soils (Lm2, Wt2, Lm3, Wa2) have greatest pesticides concentrations. The interrelationship between the remaining soils is difficult to explain. For example we anticipated that the deepest soils (Wk0 and Te) would have lowest leaching potential but the

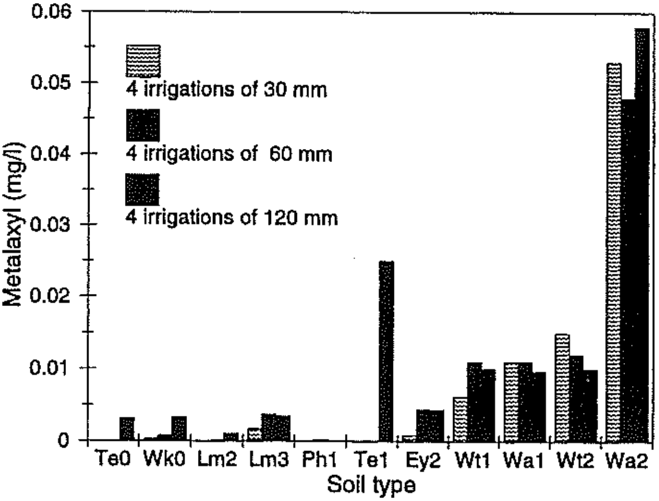

FIGURE 7 – Effect of soil type and irrigation rate, shown by simulated concentration of metalaxyl at the water table.

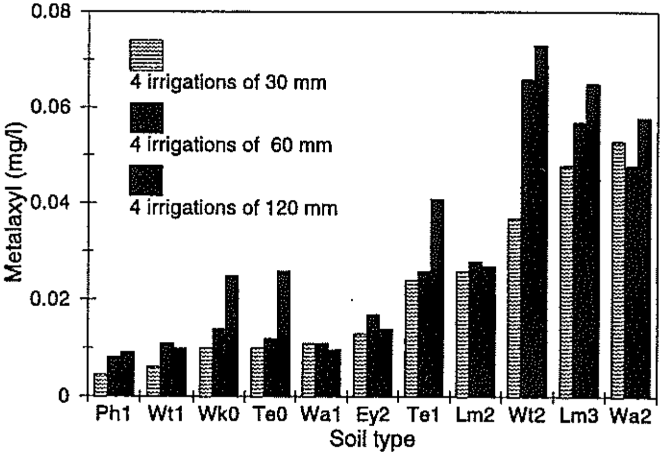

FIGURE 8 – Effect of soil type and irrigation rate, shown by simulated concentration of metalaxyl at the base of the root zone.

simulation indicated relatively high pesticide values particularly under high irrigation rates. Increasing the irrigation rate had variable effects.

The effect of the decrease in organic carbon under long-term arable cropping on pesticide concentration below the root zone is depicted in Figure 9. All, except for the three soils with the lowest pesticide concentrations, have slightly higher pesticide concentrations under arable farming, where carbon content is lower in topsoil horizons.

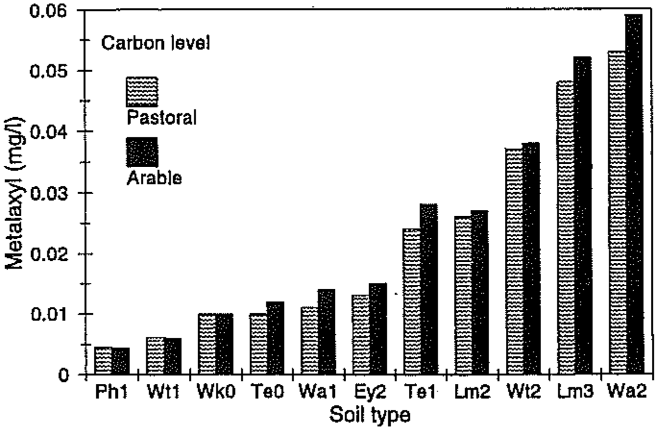

FIGURE 9 – Effect of decreased carbon under arable use compared to pastrol use, shown by simulated concentration of metalaxyl at the base of the root zone.

Pesticide leaching index

The pesticide concentrations were converted to six classes, ranging from extremely low (XL) to very high (VH), and then applied to the map units on Levels Plain (Fig. 10). The map shows the intrinsic risk of groundwater contamination for different areas on Levels Plain. High-risk areas occur beside the coast and the Opihi River, and are associated with high groundwater levels. Large areas with extremely low risk are related either to deep groundwater levels or to deep soils with moderately deep groundwater levels. Please note that the map does not depict actual risk of groundwater contamination. Actual risk would require additional information, such as actual pesticide use, farm management, recent climatic history, and a number of aquifer characteristics.

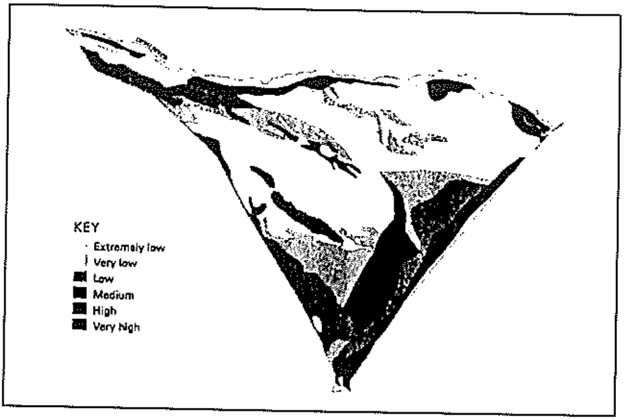

FIGURE 10 – Map of classes of pesticide leaching risk for Levels Plain.

Comparison of ratings from LEACHM and DRASTIC

Rating classes assigned to LEACHM were compared to those for DRASTIC for each of the soil types (Table 5). DRASTIC provided the same ratings as did LEACHM for the four soils with highest ratings and for one soil with low ratings. DRASTIC assigned higher risk ratings to three soil types (Ey2, Lm2 and Te1), and these were considered to be more appropriately ranked by DRASTIC. Two soils types (Wt1 and Wk0) with moderately high water tables were assigned lower risk ratings by DRASTIC, and these were considered to be more poorly ranked by DRASTIC. Within the constraints of the method used, we consider the two systems provided very similar rankings.

Conclusions

Sensitivity analysis using LEACHM indicated potentially large effects on pesticide leaching from variations in K_{sat} and irrigation, and smaller effects from variations of soil thickness and organic matter. The application of the LEACHM model to a range of soils, typical of those in the Canterbury Plains, has indicated that water table depth and soil depth are the most critical factors in differentiating the potential for different soils to allow pesticides to leach to groundwater. It has also indicated the importance of K_{sat} and the lesser importance of organic carbon. These findings need to be tested in controlled field and laboratory studies.

The DRASTIC index provided very similar ratings to the leaching index developed with the LEACHM model. This result provides some confidence to the application of the DRASTIC system to similar landscapes. However, this study has not taken any account of aquifer features and there are doubts about the application of DRASTIC ratings to New Zealand aquifers.

The LEACHM model is easy to use, particularly within the EXPRES framework, and with the gathering of improved soil physical and hydrological data, there is growing opportunity to apply it more widely.

However, our study has found that in LEACHM simulations had greatly retarded translocation of pesticides through sandy gravel substrates, typical of vadose zones overlying many aquifers from alluvium in New Zealand. We doubt that these results are valid. We therefore recommend that the model should be tested against field data and modified before it is applied to soils with these materials.

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References

Aller, L.; Bennett, T.; Lehr, J. H.; Petty, R. J.; Hackett, G. 1987: *DRASTIC: a standardised system for evaluating ground water pollution potential using hydrogeologic settings.* EPA No 600/2-87/035, United States Environmental Protection Agency: Ada, Okalahoma.

Banton, O.; Villeneuve, J. P. 1989: Evaluation of groundwater vulnerability to pesticides: a comparison between the pesticide DRASTIC index and the PRAM leaching quantities. *Journal of Contaminant Hydrology 4:* 285–296.

Barrett, M. R.; Williams, W. M. 1989: The occurrence of obtrusion in ground water as a result of agricultural use. *Proceedings,* 12th Asian-Pacific Weed Science Society Conference No. 1: 219–234.

Brown, L. J.; Kroopnick, P. M.; Lillico, S. B.; Wood, P. R. 1994: *Compilation of a groundwater conductivity vulnerability map of the Wellington Region.* Institute of Geological and Nuclear Sciences science report 94/43, Wellington, New Zealand.

Close, M. 1993: Assessment of pesticide contamination of groundwater in New Zealand 1. Ranking of regions for potential contamination. *New Zealand Journal of Marine and Freshwater Research 27:* 257–266.

Close, M. E. 1996: Survey of pesticides in New Zealand groundwaters, 1994. *New Zealand Journal of Marine and Freshwater Research 30:* 455–461.

Close, M. E.; Pang, L.; Watt, J. P. C.; Vincent, K. W. 1998: Leaching of picloram, atrazine, and simazine through two New Zealand soils. *Geoderma 84*: 45-63.

Close, M. E.; Watt, J. P. C.; Vincent, K. W.1999: Simulation of picloram, atrazine, and simazine transport through two New Zealand soils using LEACHM. *Australian Journal of Soil Research 37:* 53-74.

Cohen, S. Z.; Wauchope, R. D.; Klein, A. W.; Eadsford, C. V.; Graney, R. 1995: *Off-site transport of pesticides in water: Mathematical models of pesticides leaching and runoff.* Technical Report, International Union of Pure and Applied Environmental Chemistry. IUPAC Reports on Pesticides.

Gallant, J. C.; Moore, I. D. 1993: Modelling the fate of agricultural pesticides in Australia. *Agricultural Systems 43:* 185–197.

Hadfield, J. D.; Jenkinson, D.; Smith, D. 1996: *Pesticides contamination of groundwater in the Waikato Region: Programme Report — year one (1995/1996).* Environment Waikato Internal Series Report 1996/21, Hamilton, New Zealand. 24 p.

Kalinski, R. J.; Kelly, W .E.; Bogardi, I.; Ehrman, R. L.; Yamamoto, P. D. 1994: Correlation between DRASTIC vulnerabilities and incidents of VOC contamination of municipal wells in Nebraska. *Ground Water 32:* 31–34.

Mutch, J. P.; Crowe, A. S.; Resler, O. 1993: *EXPRES: An Expert System for assessing the fate of pesticides in the subsurface. User's Manual.* National Water Research Institute, Canada. Centre for Inland Waters, Ontario, Scientific Series 201. 138 p.

Pennell, K. D.; Hornsby, A. G.; Jessup, R. E.; Rao, P. S. C. 1990: Evaluation of five simulation models for predicting aldicarb and bromide behaviour under field conditions. *Water Resources Research 26:* 2679–2693.

Smith, V. R. 1993a: *Groundwater quality in Canterbury. Results of the Summer 1992/1993 Survey.* Report 93(32), Canterbury Regional Council, Christchurch, New Zealand, 15 p.

Smith, V. R. 1993b: *Groundwater contamination by triazine pesticides, Levels Plain, South Canterbury.* Report 93(36), Canterbury Regional Council, Christchurch, New Zealand, 36 p.

Wagenet, R. J.; Hutson, J. L. 1987: *LEACHM: Leaching Estimation and Chemistry Model, vol. 2.* Water Resources Institute Continuum, Centre for Environmental Research, Cornell University, Ithaca, N. Y. 80 p.

Wauchope, R. D.; Buttler, T. M.; Hornsby; A. G.; Augustijn-Beckers, P. W. M.; Burt, J. P. 1992: *The SCS/ARS/CES Pesticide Database for environmental decision making. Reviews of Environmental Contamination and Toxicology 123.* Springer-Verlag. 164 p.