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Potential Risk of Groundwater Contamination with Herbicides in the Wet Zone of Sri Lanka

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ABSTRACT. The use of herbicides in the production of agricultural commodities is widespread in Sri Lanka. Assessing the fate of herbicides applied to soil environment is necessary to minimize the adverse offsite effects. Therefore, this study was conducted to predict the groundwater contamination by herbicides in the wet zone soils of Sri Lanka for three commonly used herbicides, namely glyphosate (N-[phosphonomethyl] glycine), 2,4-D (2-5 dichloro phenoxy acetic acid) and diuron (3-[3,4- dichlorophenyl] -1, 1- dimethyl urea) using LEACHM (Leaching Estimation and Chemistry Model). Physical and chemical properties of 20 soil series and weather data of the wet zone along with chemical properties of pesticides were used as model input parameters. The fate of herbicides as predicted by the LEACHM model varied widely among herbicides, as well as among different soil series. Leaching losses were negligible with diuron and glyphosate in all soil series. A potential risk of groundwater contamination was indicated with 2,4-D, but only in certain soil series, which are more prone to leaching of herbicides. Predicted leaching losses were more than 10% of the added 2,4-D in Katunayake, Agalawatte, Boralu, and Minuwangoda soil series. A high risk of groundwater contamination with 2,4-D was indicated in Katunayake series, mainly due to its high sand content and very low clay and organic matter contents.

INTRODUCTION

Herbicides are extensively used in Sri Lanka for weed control in cultivation of many crops. There is a growing concern about the fate of these herbicides that are continuously introduced into the soil system over a long period of time. Even at very low concentrations, there are evidences of trace amounts of herbicides being present on non-agricultural lands, in the atmosphere and in water far from the sites of their application (Comfort *et al.*, 1992; Cogger *et al.*, 1998a,b; Mersie *et al.*, 1999).

Downward movement of herbicides in soils leading to contamination of groundwater has received considerable attention during the past few decades. There is sufficient evidence to show that herbicides added to soil contaminate groundwater (Comfort *et al.*, 1992; Veeh *et al.*, 1994; Elliott *et al.*, 1998; Cogger *et al.*, 1998a,b; Mersie *et al.*, 1999). In Sri Lanka, very few studies have been conducted to assess the risk of groundwater contamination with pesticides. Kuruppuarachchi (1995) has reported possible groundwater contamination with carbofuran in sandy regosols from Kalpitiya.

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Sri Lanka is divided into three zones based on the intensity and distribution of rainfall, and the wet zone receives more than 2500 mm rainfall per annum. Soils of the wet zone of Sri Lanka have been formed under a wide range of terrain, parent material, vegetation, climate and hydrological conditions. The climatic conditions, under which the wet zone soils have been formed, provide a range of leaching environments (Kumaragamage *et al.*, 1999). Therefore it is important to assess the behaviour of herbicides in different soil series in this zone to minimise the adverse effects.

Herbicide leaching could be assessed by field experiments. Field experiments however, are expensive, and due to the large number of herbicides that are being used at present, it is quite impractical to test each herbicide under different soil and environmental conditions. Computer models are widely used to understand the fate of and behaviour of herbicides in soils. Simulation models can be used as an inexpensive, time saving, and environmentally safe technique to evaluate the fate of herbicides in soils. Such models have been successfully used in many countries to predict groundwater contamination.

LEACHM (Leaching Estimation and Chemistry Model) developed by Wagenet and Hutson (1987) is a widely used computer simulation model for such studies (Comfort *et al.*, 1992; Veeh *et al.*, 1994; Walker *et al.*, 1996; Dust *et al.*, 2000). Such a model can be used to predict the fate of different herbicides applied to soil under Sri Lankan conditions.

In that context this study was conducted to assess the potential of ground water contamination by commonly used herbicides in the wet zone soils of Sri Lanka. Three herbicides namely, glyphosate (N-[phosphonomethyl]glycine), 2,4-D (2-5 dichlorophenoxy acetic acid) and diuron (3-[3,4-dichlorophenyl]-1,1- dimethyl urea) were used as reference herbicides in this study.

MATERIALS AND METHODS

Computer simulation was carried out using the LEACHM version 3.0 (Hutson and Wagenet, 1992). LEACHM model was selected based on many reports indicating its better performance compared to other pesticide leaching models for simulating pesticide concentrations in soil and ground water (Borah and Kaila, 1999; Gottesburen *et al.*, 2000). This model uses finite difference form of the one-dimensional Richards equation for predicting the water fluxes and the convection - dispersion equation to estimate chemical fluxes and distribution in the profile.

Input parameters

Soil properties

Out of the 28 soil series identified and characterised in the wet zone (Mapa *et al.*, 1999), only 20 soil series were investigated in this study. Poorly drained soils and soils with severe physical limitations were not considered. Soil texture, bulk density, organic matter content, moisture retention, saturated hydraulic conductivity are required as soil parameters for the model. The properties of soil series of the wet zone of Sri

Lanka were obtained from the database of the Soil Science Society of Sri Lanka (Senarath *et al.*, 1998). Where certain soil properties were not given in the database, appropriate values were assumed based on literature.

The Campbell's water retention and conductivity function parameters (Campbell, 1974) as required by LEACHM model were estimated using the equations proposed by Ghosh (1980). The dispersivity coefficient, according to the LEACHM manual (Hutson and Wagenet, 1992) was calculated as 0.16 multiplied by segment thickness (mm).

Herbicide properties

Chemical properties of the selected herbicides were taken from literature (Hornsby *et al.*, 1996). Degradation rate constants were calculated using the half-life of herbicides assuming that degradation is a first order reaction. Vapour density values were calculated from vapour pressure using the universal gas law equation. Application rates of glyphosate, 2,4-D and diuron were 4.0, 1.0, and 2.0 l ha^{-1} respectively at respective concentrations of 360, 550 and 480 g l^{-1}. Only one application of each herbicide was considered for the entire growth period of 17 weeks. All cultivation practices were simulated.

Climatic and crop factors

First four-month climatic data for 1999, including mean weekly temperatures, rainfall and pan evaporation rates were taken from five different meteorological stations located at different elevations in the wet zone of Sri Lanka (WL1, WL3, WL4, WM2 and WU3), and used as input parameters for the appropriate soil series. A three-month tomato variety was used as the reference crop. Crop cover was assumed as 0.8. Irrigation practices were included assuming a daily irrigation requirement of 7 mm for the crop.

Simulation using LEACHM

In LEACHM the entire profile is divided into number of segments of equal thickness. In this study LEACHM was run with 20 equal soil segments with input soil parameters varying depending on the horizon. The thickness of segments varied according to the soil series.

The model output included breakthrough curves at the bottom of the soil profile along with the amount of herbicide remaining in the profile and amounts lost due to various mechanisms at the end of the study period, which was 17 weeks. The breakthrough curves and the predicted fate of herbicides were compared for each herbicide under different soil series.

RESULTS AND DISCUSSION

Variations in soils, climate and herbicide properties

The wet zone soils of Sri Lanka showed a high variation in soil texture from sandy to clay. Higher sand percentages were observed in Ratupasa and Katunayake series. Lowest sand percentage was observed in Pugoda series. Organic matter content also showed a wide variation with Horton series, exhibiting the highest value of nearly 10% and Ratupasa series exhibiting the lowest value with less than 0.6 %. Soils showed different levels of compaction as indicated by their bulk density values (Table. 1 and 2).

In the wet zone of Sri Lanka, variable weather conditions were observed during the simulation period. The highest rainfall was observed in the low country wet zone (WL1) and the lowest in the up country wet zone (Table 3). Highest temperature recorded was in the low country wet zone (WL1) while the lowest was in the up country wet zone (Table 2). Highest evaporation rate was observed in the low country wet zone (WL3) and the lowest evaporation rate was observed in the up country wet zone of Sri Lanka (Table 3).

The three herbicides studied, namely, glyphosate, diuron and 2,4-D showed a wide variation in their chemical properties. Glyphosate was more soluble and more volatile than 2,4-D and diuron. Diuron exhibited the lowest solubility and was less volatile with the lowest vapour pressure value. Glyphosate, when applied to soil gets strongly bonded to soil particles, and as such it had a high sorption coefficient normalised to organic carbon (Koc value). In contrast, 2,4-D, which is anionic in nature showed the lowest Koc value. The most persistent of the pesticides was diuron with the longest half-life, while 2,4-D quickly degraded and exhibited the shortest half-life (Table 4).

Fate of herbicides in the wet zone soils of Sri Lanka

The fate of herbicides as predicted by the LEACHM model varied widely among pesticides, as well as among different soil series under different agro-climatic zones. Leaching losses were negligible with diuron and glyphosate. Potential risk of groundwater contamination was indicated with 2,4-D, but only in certain soil series, which are more prone to leaching of pesticides.

Glyphosate

Fate of applied glyphosate to soil was similar in all soil series as predicted by LEACHM. Degradation was the main mechanism of glyphosate removal from soil. In all soil series about 82% of the applied glyphosate was degraded. A high proportion of glyphosate (17% of the amount added) remained in the soil 17 weeks after application, but leaching losses were negligible. This is probably due to the higher Koc value of glyphosate, which strongly binds the chemical to soil particles. According to the model prediction, groundwater contamination with glyphosate is not a problem in any of the soil series. It has been previously reported that glyphosate is tenaciously bound to soil particles without any tendency of leaching (Cheah *et al.*, 1997).

Table 1. Properties of the soil series of the low country wet zone used as input parameters in modelling.

Series with Agro-Ecological region	Horizon with depth (cm)	Silt %	Clay %	Bulk density ($Mg\ m^{-3}$)	Moisture Retention % at 0.33 bar	Sat. hydraulic conductivity (cm/h)	Organic carbon (%)
Ratupasa (WL4)	Ap1 (0-10)	0.9	5.3	1.5	Nd	54.1	0.51
	Ap2 (10-30)	2.2	6.3	1.5	Nd	49.6	0.35
	AB (30-50)	1.1	10	1.4	Nd	61.6	0.27
	B1 (50-100)	4.4	11	1.5	Nd	66.5	0.2
	B2 (100-150)	0.4	13.8	1.5	Nd	Nd	0.12
	B3 (150-200)	2	14	1.5	Nd	Nd	0.09
Minuwangoda (WL3)	Apc (0-19)	7	27.9	1.38	16.9	200.7	1.37
	Batc (19-34)	7.9	44.6	1.64	21.9	169.9	1.06
	Btc (34-65/120)	5.8	51	1.72	27.6	127.4	0.62
Galigamuwa (WL1)	Ap (0-12/15)	6.2	29	1.2	18.9	35.8	2.26
	Batc (12/15 - 20/33)	3.7	21.9	1.6	15.6	26.2	1.18
	Bt1 (20/33-85)	11.6	28.1	1.7	17.8	20.1	0.28
	Bt2 (85 - 120/145)	9.5	25.9	1.8	19	3.5	0.2
Pallegoda (WL1)	Ap1 (0-14)	6.9	24.6	1.4	32	32	1.9
	BA (14-46)	7.8	33	1.5	30	19.6	1.1
	Bt1 (46 – 85)	8.9	39.9	1.3	34	51.6	0.7
	Bt2 (85 –180)	16.6	40.3	1.2	37	1.7	0.4
Pugoda (WL1)	Ap ()-20)	34	40.5	1.1	35.3	Nd	1.3
	B1 (20 – 40)	28.9	44.3	1.1	33.4	Nd	0.9
	B2 (40 – 80)	26.4	44.5	1.3	29.4	Nd	0.6
	B3 (80 –1 35)	31.4	46.7	1.3	31.5	Nd	0.4
	B4 (135 – 180+)	27.2	47.1	1.3	32.5	Nd)	0.3
Katunayake (WL3)	Ap1 (0-5)	2.5	4.6	Nd	Nd	Nd	0.58
	Ap2 (5 - 20)	3.3	5.9	1.5	Nd	Nd	0.33
	AC (20 - 50)	4.2	6.7	1.3	Nd	Nd	0.3
	C1 (50 - 100)	4.4	8.1	1.5	Nd	Nd	0.25
	C2 (100 – 160)	1.9	10.8	1.3	Nd	Nd	0.16
Malaboda (WL1)	Ap (0-23)	16.6	9.9	1.34	19	Nd	2.86
	A/B (23 – 43)	7.7	24.5	1.37	16.5	Nd	0.72
	Bt1 (43 – 65/80)	13.1	27.1	1.33	22.5	Nd	0.17
	Bt2 (65/80– 90/120)	Nd	Nd	1.31	20.5	Nd	0.31
Dodangoda (WL1)	Ap (0 –15)	3.4	15.8	1.3	Nd	Nd	1.16
	AB (15 – 55)	5.6	31.4	1.5	Nd	Nd	0.32
	Bt1 (55 – 90)	7.8	40.6	1.5	Nd	Nd	0.36
	Bt2 (90 – 210)	11.8	39.4	1.4	Nd	Nd	0.06
Agalawatte (WL1)	Ap (0 –20)	2.4	16.5	1.3	Nd	Nd	1.35
	AB (20 – 40/43)	0.9	22.7	1.4	Nd	Nd	1.05
	B1 (40/43 - 90/110)	0.3	34	1.5	Nd	Nd	0.63
	B2 (90/110 - 145)	0.1	33.7	1.6	Nd	Nd	0.17
	B3 (145 - 195+)	3.5	33.9	1.6	Nd	Nd	0.12
Boralu (WL4)	Ap (0-5)	4.7	29	Nd	17.5	Nd	1.57
	Abc (5-50)	2.4	40	Nd	18.3	Nd	1.2
	Btc1 (50 – 93/125)	5.3	50	Nd	26.5	Nd	0.54
	Btc2 (93/125 –163)	9	56	Nd	25.8	Nd	0.45
	Bv (163 -188)	11.6	43.5	Nd	21.9	Nd	0.41
Homagama (WL1)	Ap1 (0-35)	4.7	12.3	1.3	10.9	Nd	1.82
	BA (35 –50/65)	8.6	18	1.4	10.7	Nd	0.87
	BC (50/65–80/150)	5.8	9.4	Nd	6.8	Nd	0.35

Nd – Not determined; Estimated values were used for the model
Source: Senarath *et al.*, 1998.

Table 2. Properties of the soil series of the mid and up country wet zone used as input parameters in modelling.

Series with Agro-Ecological region	Horizon with depth (cm)	Silt %	Clay %	Bulk density (Mg m^{-3})	Moisture Retention % at 0.33 bar	Sat. hydraulic conductivity (cm/h)	Organic carbon (%)
Kandy (WM2)	Ap (0-5)	11.1	27.4	Nd	Nd	Nd	Nd
	B1 (5 – 40)	8	41.2	1.4	29	0.81	Nd
	B2 (40 – 85)	8.6	34.4	1.7	19	0.46	Nd
	B3/C (85 – 185+)	8.1	34.4	1.3	25	0.33	Nd
Ukuwela (WM3)	Apc (0-20/25)	15.3	47.1	Nd	30	1	Nd
	Btc1(20/25–85/100)	7.2	73.6	Nd	34	0.9	Nd
	Btc2(85/110–190+)	16.2	38.7	Nd	27	0.4	Nd
Gampola (WM2)	Ap1 (0-18)	27.6	35.5	1.3	36.9	Nd	1.78
	Ap2 (18 21)	Nd	Nd	Nd	Nd	Nd	0.98
	Ap3 (21- 37)	21	34.2	1.6	30.1	Nd	0.85
	B1 (37-50)	19.6	32	1.6	28.9	Nd	0.59
	B2 (50-64)	25	31.7	1.5	29	Nd	0.48
	B3 (64 – 112)	23.8	30.7	1.6	29	Nd	0.32
	B4 (112 – 145)	38.3	17.8	1.5	33	Nd	0.32
	B5 (145 – 180+)	2.4	29	1.4	22	Nd	0.17
Weddagala (WM1)	Ac (0-11/18)	10.8	16.6	Nd	21.3	5.1	Nd
	BA (11/18 – 25/35)	5	18.2	Nd	11.8	1.6	Nd
	Bt1 (25/35-55)	7.2	18.7	Nd	12.9	1	Nd
	Bt2 (55 - 95)	13.2	19.2	Nd	17.4	0.6	Nd
	B3 (95 140/150)	11.3	38.5	Nd	24.8	0.5	Nd
	B4(140/150– 180+)	13.1	40.4	Nd	29.8	0.5	Nd
Matale (WM3)	Ap (0-25)	11.1	42.4	1	34	1.6	Nd
	AB (25-42)	9.4	48.7	1	31	1	Nd
	Bt1 (42 – 125)	8.3	66.4	1	36	0.6	Nd
	Bt2 (125 200+)	7.7	63.1	1.2	39	0.4	Nd
Mawanella (WM1)	Ap (0-14/15)	10	17.6	1.23	40	1.76	1.15
	AB (14/15 – 30/36)	14.1	20.8	1.38	26	1.75	0.54
	Bw (30/36-44/72)	18.3	13.6	1.26	32	1.75	0.17
	C (44/72 180+)	16.7	9.1	1.34	31	1.75	0.11
Akurana (WM3)	Ap (0-30)	29.9	18	1.28	Nd	Nd	1.4
	AB (30 50)	26.3	25.1	1.4	Nd	Nd	0.9
	B2 (50- 75)	28.4	38.9	1.25	Nd	Nd	0.8
	B/C (75-110/120)	28.1	28.4	1.18	Nd	Nd	0.5
	C (110/120 – 150+)	18.2	6.8	Nd	Nd	Nd	0.5
Mattakelle (WU2)	Ap (0-23)	25.5	38.2	0.85	27.9	Nd	3.52
	B1 (23 – 53)	49.5	5.2	0.95	25.8	Nd	1.96
	Bt2 (53 – 84)	45.4	11.5	1.11	24.5	Nd	1.5
	Bt3 (84 –112)	44.8	8.6	1.48	25.3	Nd	1
	B4 (112 132)	42.3	13.3	1.31	26.9	Nd	0.53
	BC (132 160+)	32.5	27.4	Nd	29.8	Nd	0.45
Horton (WU3)	Ah (0-20/30)	27.6	28.1	0.69	48.6	Nd	9.9
	Abch (20/30–45/55)	Nd	Nd	0.76	Nd	Nd	6.9
	B/C (45/55 – 180+)	23.6	14.2	Nd	19.1	Nd	0.8

Nd – Not determined. Estimated values were used for the model
Source: Senarath *et al.*, 1998.

Table 3. **Mean weekly rainfall (mm), evaporation rate and maximum and minimum temperatures (°C) of five meteorological stations located at different elevations in the wet zone of Sri Lanka.**

Station		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Mean weekly rainfall (mm)															
Ratnapura (WL1)		32.6	81.2	93.8	0.0	96.8	142	70.9	79.3	98.1	118.0	3.0	10.5	61.9	149.0	36.0	37.2
Peradeniya (WM2)		14.3	50.0	2.5	2.8	45.0	36.2	10.8	92.9	6.9	22.5	0.0	4.9	60.9	125.0	7.7	105.7
Sitaeliya (WU3)		41.3	72.4	35.4	26.1	156.0	53.1	12.4	126.0	27.5	45.8	0.8	3.8	1.5	42.5	0.0	31.4
Bombuwala (WL4)		47.1	222.1	14.5	0	98.5	41.3	17.4	18.7	56.5	113	34.9	66.4	22.8	17.8	21.0	103.8
Lunuwila (WL3)		9.2	183.5	18.7	9.2	72.6	1.6	0.0	49.1	3.9	24.4	0.0	111	49.6	44.3	48.0	0.6
		Mean weekly evaporation rate (cm)															
Ratnapura (WL1)		2.1	3.5	3.4	3.5	2.1	4.7	3.8	3.5	2.3	2.2	3.1	2.6	4.0	4.4	3.9	5.9
Peradeniya (WM2)		2.5	2.8	3.3	3.6	2.4	2.9	3.2	2.4	3.2	2.0	3.7	4.3	3.1	2.7	3.7	3.3
Sitaeliya (WU3)		1.2	1.5	2.4	2.5	1.1	1.9	2.4	2.2	2.1	2.0	4.4	3.5	3.7	2.1	3.2	3.2
Bombuwala (WL4)		3.0	2.6	2.8	3.3	2.7	3.4	2.9	3.0	2.8	2.8	4.8	4.3	3.4	3.9	3.9	3.3
Lunuwila (WL3)		3.6	4.0	3.8	5.1	3.8	3.4	4.3	4.0	4.4	3.8	4.2	4.9	3.9	4.0	3.8	4.4
		Maximum and minimum temperatures (°C)															
Ratnapura (WL1)	Min		23.1	22.7	21.5	21.2	22.2	23	22.3	21.7	23.2	23	22.5	22.4	22.8	23	24.2
	Max		31.2	32.8	33.1	34.2	32.8	34.3	33.6	33.8	33.5	33.9	35.2	34.5	34.2	34.2	33.3
Peradeniya (WM2	Min		20.5	21.2	17	16.2	19.2	20.3	18.8	19.4	20	20.6	19.5	17.9	20.2	20.4	20.7
	Max		28.3	29.4	29.2	29.7	28.3	31.4	30.3	30.4	30.6	30.5	31.6	30.9	30.5	31.6	31.3
Sitaeliya (WU3)	Min		13.1	12.9	10	12.7	11.3	11	11.9	12.6	12.4	11.5	11.4	12.8	12.5	11.1	12.3
	Max		17.3	18.6	18.8	19.5	16.9	19.9	19.5	20.4	19.6	19.9	21.5	20.9	20.8	21.2	22.7
Bombuwala (WL4)	Min		22.3	22.3	20.1	20.7	22	22.2	22.4	22	22.3	23.1	22.6	21.8	22.2	22.9	25.1
	Max		30.4	29.4	30.5	30.6	30.4	30.7	30.6	30.4	30.5	30.8	31.2	31.3	31.4	30.9	31.5
Lunuwila (WL3)	Min		23	22.9	21.2	21.2	22.5	22.8	22.2	22.7	22.9	22.9	23.2	21.2	22.5	22.2	21.2
	Max		30.7	30.1	30.9	30.6	31	31.4	30.4	30.7	31.5	31.2	31.7	31.7	31.8	31.5	31.7

Source: Natural Resource Centre, Department of Agriculture, Peradeniya.

Table 4. Chemical properties of herbicides.

Herbicide	Solubility (mg/dm3)	Vapour pressure (mmHg)	Koc (ml/g)	Half Life (days)
Glyphosate	900,000	Negligible	240,000 E	47
2-4D	890	8×10^{-6}	20	10
Diuron	42	6.9×10^{-8}	480	90

Source: Hornsby *et al.*, 1996.

Diuron

According to the model predictions, fate of diuron applied to soil showed substantial variations depending on the soil series (Table 5). Removal of soil-applied diuron occurred mainly through volatilisation and degradation. High atmospheric temperature in the tropical region favours the volatilisation process. Magnitude of diuron losses due to volatilisation was similar in all soil series. Removal of diuron due to plant uptake was substantial in few soil series such as Katunayake, Minuwangoda, Boralu, Agalawatte, Matale, Akurana, Ukuwela, Mattakele and Horton series.

Table 5. Fate of diuron at 119 days after application predicted by the model.

Soil series	Leaching	Volatilisation	Degradation	Plant uptake	Currently in profile
	(% of the amount added)				
Ratupasa	0	17.00	50.67	0	35.2
Minuwangoda	< 0.05	16.67	50.00	2.8	33.2
Galigamuwa	0	16.67	50.78	0	35.2
Pallegoda	0	16.67	50.78	0	35.2
Pugoda	0	16.78	50.78	0	35.1
Katunayake	< 0.05	16.67	50.00	2.8	33.2
Malaboda	0	16.67	50.89	0	35.2
Dodangoda	0	16.78	50.78	0.1	35.2
Agalawatte	< 0.05	16.67	50.11	2.3	33.6
Boralu	< 0.05	16.67	50.00	2.8	33.2
Homagama	0	16.78	50.78	0	35.2
Kandy	0	16.89	50.67	0.1	35
Ukuwela	0	16.89	49.22	5.3	31.2
Gampola	0	16.67	50.78	0.1	35.2
Weddagala	0	16.56	50.89	0	35.3
Matale	0	16.78	50.11	2.7	33.1
Mawanella	0	16.78	50.78	0.1	35.1
Akurana	0	16.78	49.22	5.6	31
Mattakelle	0	16.67	50.22	1.8	33.9
Horton	0	16.56	50.56	1	34.6

Total sometimes exceed 100 because of simulation.

Leaching losses of diuron was observed in Minuwangoda, Katunayaka, Boralu and Agalawatte series. However, predicted concentrations of diuron reaching the groundwater were extremely low and the peak concentration of the breakthrough curves were in the range of 1.55×10^{-13} - 3.0×10^{-4} μg/l.

In all soil series, removal of soil-applied 2,4-D was predicted to be mainly through microbial degradation. Predicted degradation losses of 2,4-D were similar in all the soil series, indicating that soil properties and climatic factors had little effect on degradation losses under the existing conditions. Removal of 2,4-D also occurred through volatilisation and absorption by plants (Table 6). Losses of 2,4-D through drainage were observed in all the soil series studied. This can be mainly attributed to the lower adsorption of 2,4-D to soil particles as it exists as an anion in the soil Leaching losses of 2,4-D had been previously reported in sandy loam soils (Cheah *et al.*, 1997). The losses through drainage varied among soil series, depending on the soil characteristics and the prevailing environmental conditions. Considerable losses through drainage were observed in Katunayake, Agalawatte, Boralu and Minuwangoda series.

Table 6. Fate of 2,4-D at 119 days after application predicted by the model.

Soil series	Drainage	Volatilisation	Degradation	Plant uptake	Currently in profile
	(% of amount added)				
Ratupasa	< 0.05	3.45	91.09	2.73	0.00
Minuwangoda	21.09	2.73	75.64	0.55	0.00
Galigamuwa	< 0.05	2.91	93.45	0.55	0.00
Pallegoda	< 0.05	2.91	93.45	0.36	3.09
Pugoda	< 0.05	3.09	93.27	0.73	3.09
Katunayake	29.63	2.73	65.82	1.82	0.00
Malaboda	< 0.05	2.91	93.09	0.91	3.09
Dodangoda	< 0.05	3.09	91.82	2.36	2.91
Agalawatte	10.90	2.73	85.64	0.18	0.00
Boralu	10.36	2.73	86.18	0.18	0.55
Homagama	< 0.05	3.09	93.45	0.55	3.09
Kandy	< 0.05	3.27	92.73	1.09	2.91
Ukuwela	< 0.05	3.09	85.64	10.55	0.73
Gampola	< 0.05	3.09	93.27	1.09	2.91
Weddagala	< 0.05	2.91	93.82	0.18	3.09
Matale	< 0.05	2.91	88.55	7.27	1.27
Mawanelle	< 0.05	3.09	92.73	1.09	2.91
Akurana	< 0.05	3.09	84.00	12.55	0.55
Mattakelle	0.72	2.73	93.45	0.36	2.91
Horton	< 0.05	2.73	93.27	1.09	2.91

According to the breakthrough curves the leaching pattern among the 20 soils showed considerable differences (Fig. 1). The highest peak value of 120 μg/l was observed in Katunayake series, which was a sandy soil with a high hydraulic observed in Katunayake series, which was a sandy soil with a high hydraulic conductivity. More than 10% of the amount of 2,4-D added was leached in Katunayake, Agalawatte, Boralu, and Minuwangoda soil series (Table 6). In Katunayake soil series, peak concentrations were above 70 µg/l, which is the maximum permitted level for drinking water according to USEPA (USEPA, 1990). This is probably due to the sandy nature of the Katunayake series. The high mobility of 2,4-D in sandy soils has been previously reported (Cheah *et al.*, 1997). Detection of 2,4-D in groundwater (Waite *et al.*, 1992) provides further evidence of its high potential to leaching. In Katunayake soil series, application of 2,4-D could pose a serious threat of groundwater pollution. The dilution within the aquifer however, would further reduce the concentrations, while degradation would also play a major role in decreasing the concentration with time.

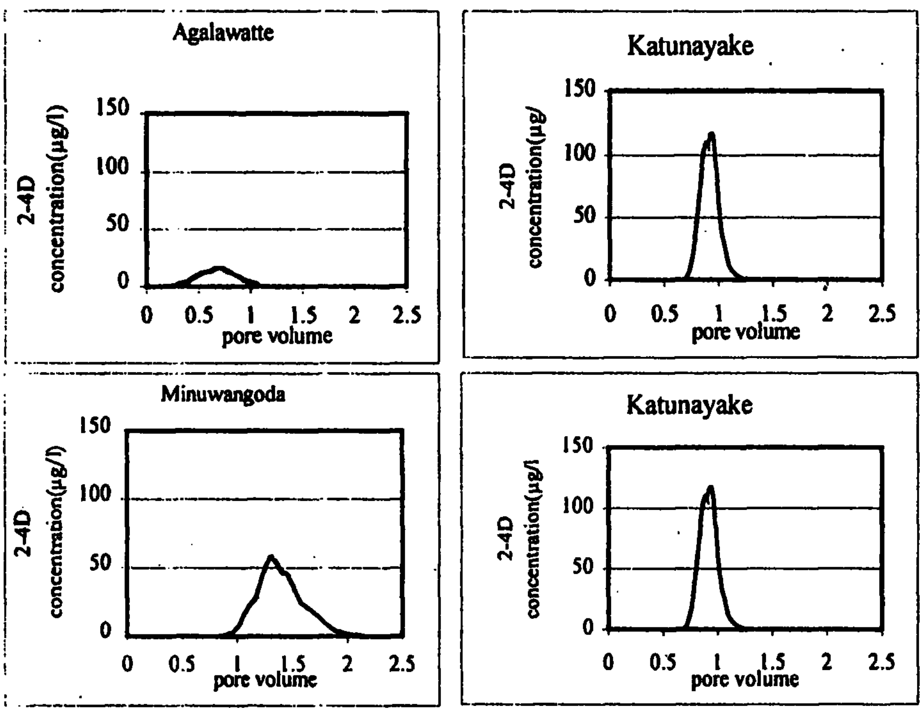

Fig. 1. Breakthrough curves for 2,4-D in Agalawatta, Boralu, Minuwangoda, and Katunayake series.

CONCLUSIONS

The fate of herbicides as predicted by the LEACHM model varied widely among herbicides, as well as among different soil series under different agro-climatic zones. Predicted leaching losses were negligible with diuron and glyphosate. Potential risk of groundwater contamination was indicated with 2,4-D, but only in certain soil series, which are more prone to leaching of pesticides. Leaching of 2,4-D was observed in Katunayake, Agalawatte, Boralu and Minuwangoda soil series. A potential high risk of groundwater contamination was predicted in Katunayake series, which had a high regulation of pesticide use, model predictions should be confirmed by field studies at least in few selected sites.

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