Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation
(Proceedings of the Vienna Symposium, August 1991) IAHS Publ. no. 203, 1991.

THE LEACHING OF AGROCHEMICALS UNDER DIFFERENT AGRICULTURAL LAND USES AND ITS EFFECT ON WATER QUALITY

S.C. ROSE, G.L. HARRIS, A.C. ARMSTRONG & J.R.WILLIAMS
MAFF Agricultural Development and Advisory Service (ADAS), Field Drainage Experimental Unit, Cambridge CB2 2LF, UK
K.R. HOWSE
AFRC Institute of Arable Crops Research, Rothamsted Experimental Station, Harpenden AL5 2JQ, UK
N. TRANTER
Middlesex Polytechnic, Centre for Urban Pollution Research, Enfield, Middlesex, EN3 4SF, UK

ABSTRACT The effect of different land management practices on soil structure and water movement in clay soils was assessed for various sites. Drainage was important in reducing damage by machinery or by grazing cattle but with compaction, high rates of surface runoff occurred on both arable and grassland sites. Cultivations, soil structure, and hydrologic pathways were important in the leaching process. Greater contact with the soil and mineralization resulting from cultivations increased the amount of $N0_3$-N that was lost by leaching. Losses were lower from non-intensive agricultural systems including some grassland and mature deciduous woodland. Pesticide leaching after rainfall occurred when good soil structure enhanced drainage. The risk of pesticide leaching may be increased by the factors that limit $N0_3$-N leaching.

INTRODUCTION

Over the last 30 years, agriculture on clay soils in the United Kingdom (UK) has intensified, assisted by capital investment in underdrainage and increased use of agrochemicals (Raymond, 1984). However, problems have arisen with leaching of nitrate and pesticides to surface waters. The EC Drinking Water Directive (Anon, 1980), maximum 50 mg l^{-1} nitrate or 11.3 mg l^{-1} nitrate-N (NO_3-N) and 0.1 $\mu g\ l^{-1}$ for any pesticide, has led to the need to identify the source and leaching mechanisms involved. Since the 1970s, ADAS has monitored leaching levels from clay plot lysimeters and small catchments located some distance from drinking water abstraction points. Different cropping and management options were included that were likely to reduce the leaching process. In this paper, the mechanisms of drainage and soil structure on water movement in clayey soils and the resultant leaching of nitrate and pesticides are examined.

EXPERIMENTAL DETAILS

Hydrological monitoring was undertaken on eight clayland sites in England (Fig. 1) by the ADAS Field Drainage Experimental Unit with support from other researchers involved in leaching studies. In these clayey soils (Avery, 1980), underdrainage was supplemented by mole drainage or deep subsoiling. Three of the sites (Table 1) represented replicated long term trials in hydrologically isolated plot lysimeters. A fourth site had larger field plots and the remainder were small catchment studies. On all sites, detailed records of agricultural practices were collected including drainage and, whenever possible, agrochemical usage.

TABLE 1 Site characteristics (PL = Plot Lysimeter; FP = Field Plot; SC = Small Catchment; and Rain = Rainfall, mean for 1941-1970).

Site	Study	Area (ha)	Rain (mm)	Record period	Land use	Soil type
Brimstone Fm	PL	0.2	686	1978-88 1988-90	Arable	Pelo stagnogley
Cockle Park	PL	0.3	724	1979-83 1989-90	Grass Arable	Typical stagnogley
North Wyke	PL	1.0	1058	1979-90	Grass	Pelo stagnogley
Boxworth	FP	1.0 0.6 0.2	559	1989-90	Arable	Calcareous pelosol
Swavesey	SC	500	574	1986-90	Arable Grass Urban	Pelo calcareous alluvial gley Pelo stagnogley
Conington	SC	30 20	574	1989-90	Set-aside	Pelo stagnogley Calcareous pelosol
North Weald	SC	280	650	1988-90	Grass Arable Wood	Pelo argillic stagnogley Pelo stagnogley
Trent	SC	180 210	697	1988-90	Grass Arable Urban	Brown earth Cambic stagnogley

Clay plot lysimeters (Brimstone Farm, Cockle Park, North Wyke)

At the Brimstone Farm site, treatments included both tillage and drainage so that the effect on water movement and $N0_3$-N leaching could be examined (Harris *et al.*, 1988). In 1988 the treatments were modified to investigate how various crop and soil management strategies affect $N0_3$-N and pesticide leaching. The Cockle Park site was established to investigate the effects of drainage and $N0_3$-N leaching in grassland. Installation of drainage was followed by cultivation for a spring cereal, a fallow winter, and subsequent establishment of a grass ley which was grazed (Armstrong, 1984). In 1989, the experimental layout was revised with grassland and arable treatments and the monitoring modified to include both pesticide and $N0_3$-N leaching. The North Wyke site provided opportunities to monitor the hydrological consequences of drainage and $N0_3$-N leaching from grassland of different ages and receiving different fertilizer applications (Armstrong *et al.*, 1990).

Field plot study (Boxworth)

The effect of agricultural diversification to lowland farm forestry (deciduous) on $N0_3$-N leaching was examined on three drained plots comprising arable cropping, newly planted and established trees.

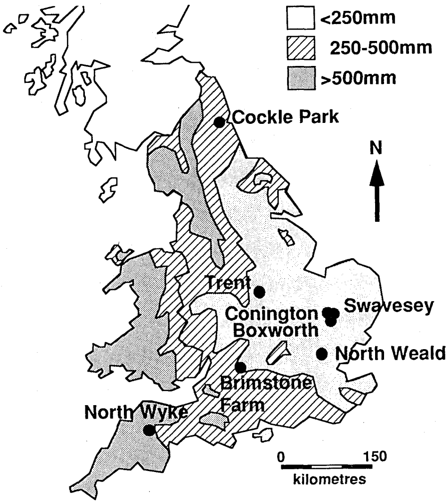

FIG.1 Sites and mean annual excess winter rainfall.

Small catchment studies (Swavesey, Conington, North Weald, Trent)

The $N0_3$-N and pesticide leaching were monitored in all catchments. The Swavesey site had a new lowland pump drainage system and included newly drained arable areas and established mixed agriculture. In addition to diffuse leaching from agricultural land, both runoff and water quality from point sources were measured. At Conington, where intensive cropping preceded conversion to set-aside, monitoring was undertaken in two catchments The North Weald and Trent sites included mixed intensive agricultural land uses with variable underdrainage. The North Weald site also included an area of mature mixed woodland.

Monitoring

On all sites, runoff in response to rainfall was continuously monitored by sharp-crested weirs or flumes designed to BSI 3680 (1981). Drainage treatments were monitored on most sites by automatic water level recorders or dipwells (Armstrong, 1983). However, on the larger catchments, drainage was primarily assessed from crop performance and field observations.

Water samples were collected either manually or by automatic samplers and then frozen or cooled depending on the laboratory analysis. Analysis by flow injection system with photometric detection (Anon, 1986) or ion-specific electrode was undertaken for $N0_3$-N only, as previous studies had shown that this was the principal component of nitrogen loss (Armstrong, 1984). On key sites, soil mineral nitrogen ($N0_3$-N and NH_4-N) was determined to 900mm depth using recognized procedures (Anon, 1986). For pesticides emphasis was placed on the herbicides isoproturon and mecoprop which were used on the UK sites and which are known to leach (FOE, 1988). Analysis for isoproturon was by high pressure liquid chromatography and that for mecoprop by gas chromatography with confirmatory analysis with an alternative chromatographic column of different adsorption characteristics or by reference to mass spectrometry (Anon, 1986).

RESULTS

Hydrology

Although there was considerable variation in total runoff between sites and years, underdrainage increased the depth to the water table by an average 250 mm. Underdrainage reduced the time when the water table was near the soil surface, and hence the likelihood of surface runoff. The plot lysimeters showed that effective underdrainage encouraged rapid water movement through the subsoil to the pipe system. The lag time between peak rainfall and peak drainflow in such situations was of the order of 2 h with surface runoff peaking 30 min earlier. Exceptions were noted in two years at Brimstone Farm and Cockle Park when cultivation pans impeded downward water movement (Armstrong, 1984). The importance of soil structure and macropore flow was demonstrated by the very different hydrologic responses seen at Brimstone Farm, where ploughing transmitted water relatively slowly through the interface between the cultivated layer and subsoil to the pipe drains. In contrast, under direct drilling continuous cracks from the surface to the subsoil were maintained, resulting in rapid transmission of water to depth and a much flashier response (Harris *et al.*, 1988). However, compaction at the surface can occur with direct drilling giving a much flashier surface runoff response even with drainage.

Similar results were found on grassland when limitations in drainage resulted from surface compaction by stock causing much flashier runoff (Armstrong, 1984). Under grassland in the absence of compaction at Cockle Park and North Wyke, good subsoil structure caused rapid water movement to the underdrainage system (Armstrong, 1984; Armstrong *et al.*, 1990). The water table under arable land at Swavesey recently converted from permanent grassland was notably lower than in adjacent established arable areas. The general effect of drainage, under any of these clay sites, was to decrease the total runoff rate due to a reduction in the occurrence of surface runoff.

Nitrate leaching

Variations in the rainfall/runoff patterns over the study period and the differences between sites make direct comparison of leaching results difficult. However, trends are apparent demonstrating that several leaching mechanisms were operating.

On the arable site at Brimstone Farm average NO_3-N losses were much less from the surface layer on undrained land (5 kg ha^{-1}) than from the mole drains (34 kg ha^{-1}) (Dowdell *et al.*, 1987). All plots received, on average, 135 kg ha^{-1} N spring fertilizer. The NO_3-N concentrations in drainage water were highest in autumn following a flush of NO_3-N from the soil after heavy rainfall. These decreased steadily over the winter period before a second, usually smaller, peak followed spring fertilizer applications (Fig. 2). The effect of cultivation (direct drilling or ploughing) on leaching (Goss *et al.*, 1988), was that 90% of the winter loss on the drained plots was through the drains for both treatments. The average NO_3-N leached from the drained ploughed plots was 40 kg ha^{-1} compared to 30 kg ha^{-1} on the drained direct-drilled plots.

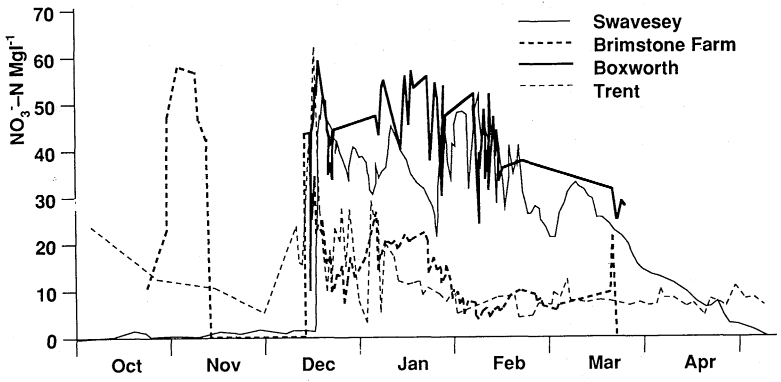

FIG. 2. NO_3-N leaching, winter 1989/90 at Boxworth, Trent, Swavesey and Brimstone Farm.

Results from grassland at North Wyke (Armstrong *et al.*, 1990) also suggest that NO_3-N losses from the surface of undrained plots were only one third of those from drained plots. With large fertilizer applications (400 kg ha^{-1} N), concentrations were greatest (up to 60 mg l^{-1}) in drains under old swards where high organic matter and drainage encouraged better soil physical conditions.

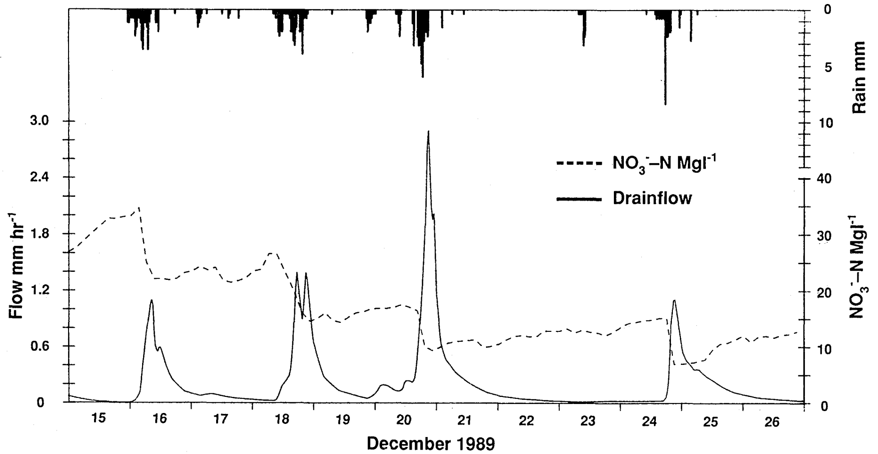

FIG. 3 NO_3-N leaching in a runoff event - Brimstone Farm.

Anomalous results were obtained from Cockle Park in winter 1979/80 under fallow following a spring barley crop (fertilized at 146 kg ha^{-1} N). Peak concentrations and total leaching losses of NO_3-N on drained land (16 mg l^{-1} & 11.5 kg ha^{-1}) were similar to those on undrained land (18 mg l^{-1} & 10.5 kg ha^{-1}). Peak flows from the undrained plots also were lower than from the drained plots reflecting improved subsoil water movement following subsoiling undertaken to remove a cultivation pan. The following year, under grassland (receiving 75 kg ha^{-1} N), $N0_3$-N concentrations and total losses were low (less than 1 mg l^{-1} and 1 kg ha^{-1}) from all plots.

Data from the mixed agricultural catchments at Trent and North Weald showed various rates of $N0_3$-N leaching dependent on land use. In the winter 1989/90 at North Weald, water draining from the mature woodland had the lowest $N0_3$-N concentrations (typically 5 mg l^{-1}). Similar results for the same year were obtained from established woodland at Boxworth (1-7 mg l^{-1}) and under set-aside at Conington (up to 8 mg l^{-1}). Generally $N0_3$-N leaching concentrations from the agricultural land at North Weald typically were 10-20 mg l^{-1}, much lower than those for more intensive arable areas such as Boxworth (50-60 mg l^{-1}) or Trent (20-40 mg l^{-1}). However, the same general pattern of leaching was observed with highest concentrations in the autumn following the first heavy rainfall (Fig. 2). The leaching pattern following rainfall, seen at Brimstone Farm (Fig. 3), also was reflected at the catchment sites. In each event, a small rise in $N0_3$-N concentration was seen at the onset of runoff which was followed by dilution in response to higher flows.

At Swavesey, the importance of mineralization of soil organic matter following drainage and conversion from grassland to arable cropping was demonstrated by the concentrations of $N0_3$-N in the drainage water. $N0_3$-N leaching from the whole catchment generally was similar to the other sites with a winter peak of 55 mg l^{-1} in 1989/90 (Fig. 2), but in newly converted arable areas concentrations in excess of 150 mg l^{-1} were found. These areas also had enhanced soil mineral nitrogen in the profile of 150-900 kg ha^{-1}, compared to the more typical 100-150 kg ha^{-1} seen on other established arable sites. By comparison, after 18 months of set-aside, low $N0_3$-N leaching with only 25-35 kg ha^{-1} soil mineral nitrogen was observed.

Pesticide Leaching

Detailed hydrological monitoring at Brimstone Farm provided the basis for assessing the effect of rapid water movement through cracking clay soils on the leaching of autumn applied herbicides. Prior to the application of isoproturon and mecoprop in autumn 1989, both rainfall and runoff were limited and concentrations were below the detection limit (typically 0.1 μg l^{-1} for isoproturon and 0.2 μg l^{-1} for mecoprop). Heavy rainfall after autumn application resulted in rapid water movement through open soil cracks causing the pesticide to be leached. Although the sample bulking procedure prevented correlation of the peak concentration with the timing of the hydrograph, a peak of 35 μg l^{-1} for isoproturon was recorded in the subsurface drains which decreased to 1-5 μg l^{-1} later in the winter period.

In a mid-winter runoff event at Brimstone Farm, the isoproturon peak in spot samples occurred soon after peak drainflow. Total isoproturon loss was only 1% of that applied. Mecoprop leaching was below the detection limit in both the autumn and winter.

Spot samples were collected at other sites in 1989/90 in both runoff events and baseflows. At Swavesey, the highest concentrations were found in response to summer thunderstorms, when the runoff was influenced by paved areas. The highest isoproturon concentration was 240 μg l^{-1} which correlated with an accidental spillage understood to have occurred during farmyard mixing. In the winter period when agricultural drainage dominated runoff, isoproturon concentrations in drainage water were less than 1 μg l^{-1}. Several other commonly applied pesticides also were found in the small catchments. The most frequently detected were atrazine, simazine, and dimethoate with peak concentrations in the range 1-8 $\mu g\ l^{-1}$, observed usually in the early winter period. However, in the first 18 months of set-aside, leaching of residual pesticides was only detected regularly for isoproturon, with concentrations of 0.1-0.6 $\mu g\ l^{-1}$.

DISCUSSION AND CONCLUSIONS

Concern over water quality in the UK has been reinforced by the need to meet EC Drinking Water Directives. Much of the problem in UK surface water systems is considered to be due to leaching following increased agrochemical usage. However, it is likely that the mechanisms necessary to reduce leaching of one agrochemical may result in other water quality problems. For example, Magette & Shimohammadi (1989) suggested that improved drainage might control soil erosion and reduce phosphate leaching but that the resultant increased flow through the subsoil may worsen the $N0_3$-N problem.

In most years, $N0_3$-N concentrations from the UK sites were only consistently below EC limits where diversification, such as set-aside or lowland farm forestry, was practiced. Even on land that was uncropped and unfertilized for 50 years, 23 kg ha^{-1} $N0_3$-N could be leached annually (Russell & Richards, 1920). $N0_3$-N concentrations over the drainage period in all studies were typically 30-50 mg l^{-1}, with highest concentrations following an autumn flush. Webb & Walling (1985) also reported similar annual leaching patterns with lag time between peak runoff and peak $N0_3$-N leaching dependent on the season. However, land management effects, such as cultivations or surface compaction, markedly affected the route by which excess water was removed. For example, at Brimstone Farm the highest $N0_3$-N concentrations and losses under cultivations were observed with drainage. When compaction at the soil surface occurred, for example with reduced tillage, surface runoff was greatly increased so $N0_3$-N losses were low. Goss *et al.* (1988) also showed that in the absence of cultivation the development of continuous cracks aided rapid water movement to depth, limited contact time with the soil, to cause a 25% reduction in $N0_3$-N leaching. Schwab *et al.* (1985) reported a similar result for a no-tillage crop.

Under grassland, highest $N0_3$-N leaching losses occurred on drained land as a result of greater nitrogen availability and water movement through the soil profile (Armstrong, *et al.*, 1990). Where water movement into the profile was restricted by stock induced surface compaction, this leaching loss was reduced. Cultivations on undrained grassland enhanced water movement into the soil and, hence, increased leaching losses. High $N0_3$-N concentrations were found in drainage water on the arable sites where the mineralization of organic matter followed cultivations. In newly drained grassland converted to arable cropping at Swavesey, the combination of lower water tables introduced by underdrainage and the breakdown of organic matter, gave $N0_3$-N leaching concentrations in excess of 150 mg l^{-1}.

Pesticide concentrations above the EC Drinking Water limit were found in 1989/90 at these sites, all some distance from drinking water abstraction points. Highest concentrations were found in the autumn, after rainfall, following pesticide applications. Diffuse agricultural leaching of isoproturon in the catchments gave concentrations up to 2 $\mu g\ l^{-1}$ but at the plot scale, on the cracking clay soil at Brimstone Farm, concentrations in the first autumn flush event exceeded 30 $\mu g\ l^{-1}$. Other high pesticide concentrations were found from point source contamination, for example following runoff from paved areas. Once pesticides were no longer applied, as in the set-aside example, concentrations in leaching water quickly declined towards the EC Drinking Water limit. Monke *et al.* (1989) studied movement of pesticides in U.S. soils and found total losses of spring applied pesticides were less than 1% of the applied dose, with no detectable losses in the following autumn. This was supported by results from Brimstone Farm for autumn applied isoproturon. However, in set-aside residual isoproturon was detected in runoff more than 18 months after the last application. The fate of pesticides was also investigated by Hall *et al.* (1989) on different U.S. soils and tillage treatments. They concluded that for the herbicides examined, mobility or leaching characteristics were not exclusively related to solubility, and that no-tillage treatments, where macropores were well developed, caused the most pesticide to leach. In contrast, with tillage there were greater opportunities for adsorption of applied pesticides. This suggests that the factors noted in the UK studies for reducing $N0_3$-N leaching, namely decreasing both mineralization and contact of percolating water with the soil, may exacerbate pesticide leaching. The opportunities offered by cracking clay soils such as seen at Brimstone Farm in transmitting water rapidly through the soil profile may also encourage pesticide leaching because they decrease opportunities for adsorption of pesticide on soil clay and organic matter. Comparative data were not available for the other UK sites. However, the highest diffuse leaching was observed in the autumn when summer formed cracks had not fully closed.The principal conclusions from these UK. studies were:

(a) Underdrainage lowered the water table and increased subsurface flow, but surface compaction by stock or the use of direct drilling increased surface runoff. Improved subsoil structure, including crack development was very important to water movement through soils.
(b) Surface flow removed little $N0_3$-N under all land uses. Cultivations resulted in mineralization of organic matter and increased $N0_3$-N leaching. Minimum cultivations resulted in improved soil structure which reduced $N0_3$-N leaching.
(c) Highest $N0_3$-N leaching occurred in the autumn period following the first heavy rainfall with smaller flushes in spring following fertilizer applications.
(d) The mechanisms that could be used to reduce $N0_3$-N leaching, in particular by reducing cultivations, may increase the leaching problem for some pesticides from clay soils.

ACKNOWLEDGEMENTS We thank the many field and analytical laboratory staff who have made this review possible together with additional UK collaborators at the Faculty of Agriculture — University of Newcastle Upon Tyne, the Natural Environment Research Council — Institute of Terrestrial Ecology and the Agricultural and Food Research Council — Institute of Grassland and Environmental Research. We also thank the landowners and farmers for their cooperation and assistance throughout these field studies. The work was funded by the Ministry of Agriculture, Fisheries and Food, with support from the Natural Environment Research Council and the University Grant support system.

REFERENCES

Anon (1980) EC Council Directive Relating to the Quality of Water intended for human consumption (80/778/EEC). *Off. J. Eur. Commun* **L229**:11-29.

Anon (1986) The Analysis of Agricultural Materials. Ministry of Agriculture, Fisheries and Food, Agricultural Development and Advisory Service, Reference Book 427, H.M.S.O., London.

Armstrong, A.C. (1983) The measurement of water table levels in structured clay soils by means of open auger holes. *Earth Surf. Proc.* **8**:183-187.

Armstrong, A.C. (1984) The hydrology and water quality of a drained clay catchment, Cockle Park, Northumberland. In: Catchment Experiments in Fluvial Geomorphology, T.P. Burt & D.E. Walling (eds.), Geobooks, Norwich, 153-168.

Armstrong, A.C., Hallard, M. & Scholefield, D. (1990) Soil water drainage and the production of grassland. *Proceedings of the Second Research Conference*, British Grassland Society, Hurley, UK. September 1990.

Avery, B.W. (1980) *Soil classification for England and Wales*. Harpenden, UK.

BSI (1981) British Standards Institution, Methods of measurement of liquid flow in open channels, BS 3680 Part 4: Weirs and flumes. BSI, London.

Dowdell, R.J., Colbourn, P. & Cannell, R.Q. (1987) A study of mole drainage with simplified cultivation for autumn-sown crops on a clay soil. 5. Losses of nitrate-N in surface runoff and drain water. *Soil Till. Res.* **9**:317-331.

FOE (1988) *An Investigation of Pesticide Pollution in Drinking Water in England and Wales*. Friends of the Earth, London.

Goss, M.J., Howse, K.R., Colbourn, P. & Harris, G.L. (1988) Cultivation systems and the leaching of nitrates. *Proceedings of the 11th International Conference, ISTRO* **2**:679-684, Edinburgh.

Hall, J.K., Murray, M.R. & Hartwig, N.L. (1989) Herbicide leaching and distribution in tilled and untilled soil. *J. Environ. Qual.***18**:439-445.

Harris, G.L., Pepper, T.J. & Goss, M.J. (1988) The effect of different tillage systems on soil water movement in an artificially drained clay soil. *Proceedings of the 11th International Conference, ISTRO* **2**:685-690, Edinburgh.

Magette, W.L. & Shirmohammadi, A. (1989) Nitrate in shallow unconfined ground water beneath agricultural fields. In: *Land and Water Use*. Dodd & Grace (eds.), Balkema, Rotterdam, 297-304.

Monke, E.J., Kladivko, E.J., Van Scoyoc, G.E., Martinez, M.A. & Huffman, R.L. (1989) Movement of pesticides and nutrients in drainage water. In: *Land and Water Use*. Dodd & Grace (eds.), Balkema, Rotterdam 305-310.

Raymond, W.F. (1984) Trends in agricultural land use: the lowlands. In Agriculture and the Environment. *Proceedings of ITE Symposium, Monks Wood Experimental Station*,U.K., Feb 1984, 7-12.

Russell, E.J. & Richards, E.H. (1920) The washing out of nitrates by drainage water from uncropped and unmanured land. *J Agric. Sci.***10**:22-43.

Schwab, G.O., Fausey, N.R., Desmond, E.D. & Holman, J.R. (1985) Tile and surface drainage of clay soils. Ohio Agricultural Research and Development Center Research Bulletin **1166**.

Webb, B.W. & Walling, D.E. (1985) Nitrate behaviour in streamflow from a grassland catchment in Devon, UK. *Wat Resour Res.* **19**(8):1005-1016.