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LAND APPLICATION OF ORGANIC MANURES AND SILAGE EFFLUENT

Research Centre, Athenry, Co. Galway

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SUMMARY

There is increasing interest in the landspreading of slurries, sludges, effluents and fertilisers, resulting from the need to recycle increasing volumes of waste from high production agriculture units, old and new sewage treatment works and industrial facilities. Wastes should be spread only on suitable unsaturated soils at normal loading rates, such as 20 to 40 m^3/ha.yr, to avoid contamination of surface and ground waters.

This experimental study at Teagasc Athenry Centre examined the leaching of NO_3-N derived from cattle and pig slurries and silage effluent - spread on the surface of free-draining unsaturated soils - down to depths of 1.5 m; these gravelly, stony loam soils less than 5.0 m in depth overlie limestone bedrocks with fissures and solution channels which are good sources of water supply (aquifers). The watertable at the study site is about 25 m below ground surface.

Six experimental plots were selected and instrumented after a geophysical survey. Cattle slurry and silage effluent were applied separately to 4 of the plots at normal and heavy rates; pig slurry was applied 150 days later to the cattle slurry plots also at normal and heavy rates. A chloride tracer was sprayed on a grass and fallow plot to simulate the likely movement of a conservative anion through the soil. The grass plot sprayed with the tracer served as control for the slurry and silage effluent plots.

Various field and laboratory methods were used to measure the hydraulic conductivity of the soil down to depths of 1.5 m. Soils moisture contents were measured using a neutron probe, soil suctions by tensiometers and the rainfall was recorded on-site throughout the duration of the study. Suction samplers with ceramic cups - installed at different depths - provided

samples for chemical analyses of $N0_3$-N. Samples of groundwater were taken from a nearby well and analysed for $N0_3$-N and a number of other parameters.

The soil at Site 1, representative of the vast majority of soils on the farm, was studied in detail and was used for the landspreading of the slurry manures, silage effluent and tracer. The soils at two other sites, Site 2 and Site 3, representative of most of the remaining soils were studied in outline. At Site 1 the soils in two test holes to a depth of 3 m were described. As the holes were being deepened, soil density and moisture content were measured by nuclear gauge. A small plot covered by a polythene shed housed a 1.2 metre diameter steel ring which was driven into the soil and flooded. The downward rate of water flow was measured to determine the hydraulic conductivity, which is the rate of flow of water through soil under defined conditions. Soil water can flow through the soil (i) when all its pores are full of water (saturated soil) (ii) when nearly all its pores are filled with water (field saturated) as when a pond of water on the surface of a soil percolates slowly downwards to a deep watertable (iii) when a significant portion of its pores are filled with air and the rate of flow of soil water is controlled by the soil moisture content (unsaturated hydraulic conductivity) as happens when rainfall at a rate less than the field saturated value enters a soil. To determine unsaturated values, soil water pressure (suction) and content were measured. Hydraulic conductivity was also measured in small wells into which water was poured and the rate of fall of its surface was timed as it percolated through. In another infiltration method the rate of water flow into the soil was controlled at various suctions. The hydraulic conductivity was obtained from all the tests by applying the appropriate formulae.

Measurements of soil water pressures and contents were also made in the plots landspread with slurry and silage effluent and on one of the tracer plots. Suction samplers at various depths were used to extract soil water for NO_3-N analysis.

Both cattle and pig slurries were landspread. Two rates of spreading of both slurries were used (i) normal at 30 to 33 m^3/ha, representing a diffuse source of nitrates (ii) excessively heavy at 200 to 250 m^3/ha representing a point source such as a leakage from a farmyard. Cattle slurry was landspread in mid-July and pig slurry in mid-December. The excessively heavy loadings were applied over several days to avoid surface run-off. Samples of the soil pore water were taken as often as possible and analysed for NO_3-N. Silage effluent was landspread at a normal loading of 25 m^3/ ha and an excessively heavy loading of 250 m^3/ha in late June and pore water samples from the plots were analysed for NO_3-N. The tracer used was calcium chloride, sprayed at 86 m^3 /ha on a grassland and a fallow plot; this tracer supplies Cl^- ions which are not adsorbed by soil. Pore water samples were analysed to trace the leaching of Cl^- ions. Pore water samples were taken over most of one year.

A farm well 600 m from the landspreading area was sampled seven times during the period of recharge from the end of September to the end of January; the samples were analysed for parameters listed in the EU Drinking Water Directive (1988).

A mathematical model was used to predict the NO_3-N concentrations with depth in the soil. The model chosen was LEACHN, an acronym for Leaching Estimation And Chemistry Model, developed at Cornell University, USA. Measurements made in the field were used in the model. Outputs of the model include pore water pressures, soil water contents and

NO_3-N concentrations of the soil water with depth.

Soils at Sites 1, 2 and 3 are very stony and gravelly loams. Site 1 soil is very stony and gravelly and about 4 m deep; Site 2 soil is typical of soils in depressions and contains a silt layer, commonly 0.3 to 1 metre thick beginning about 0.5 m below ground surface; Site 3 soil, typical of soils on hillocks, is an extremely stony and gravelly soil and stone content can be 40%. The soils increase in density with depth, until at a depth of 1 metre and greater they are very dense (dry density of 2 t/m^3). The high density and the high stone and gravel content reduce the hydraulic conductivity below 1 metre to very low values.

The mean vertical hydraulic conductivity to a depth of 1.5 m is 11 mm/day, which is slow. Contaminants such as NO_3-N going into solution in the pore water have a long residence time during which they can be decomposed or absorbed. Hydraulic resistance varied from 167 to 300 d in the top 3 m of soil - this is a high value when considered against a value of 1000 d used by groundwater hydrologists for impervious saturated layers. The hydraulic conductivity declines from about 500 mm/day in the surface layers to about 9 mm/day at 1.5 m depth. There was reasonable agreement between the hydraulic conductivity measured by the different methods at each site and between that of the different sites. Because of the difficulty and expense of measuring hydraulic conductivity in stony and gravelly soils, methods for its prediction should be considered.

Cattle and pig slurries spread at normal rates of 30 to 33 m^3/ha did not give rise to leaching of NO_3-N. Cattle and pig slurries spread at excessively heavy rates did give rise to leaching of NO_3-N to a depth of 1.2 m; the winter spreading of pig slurry gave rise to the greatest leaching with NO_3-N levels of 14.6 mg/l at 0.9 m and 17.5 mg/l at 1.2 m depth. Below 1.2 m,

NO_3-N concentrations were little different from those of control at 1.5 m depth. Silage effluent behaved similar to the farm slurries, with no leaching of NO_3-N from the landspreading of 25 m^3/ha effluent and high concentrations of 19 mg/l at 1.2 m depth from excessively heavy loading of 250 m^3/ha of effluent. There was no significant leaching at the 1.5 m depth.

Calcium chloride tracer was leached beyond the 1.5 m depth where a very high concentration of 35 mg/l Cl^- was measured in the fallow plot. In the grassland, the peak concentration at 1.5 m was 15 mg/l Cl^-, due to plant uptake. The leaching of Cl^- especially in the fallow plot indicated that significant leaching could take place in the absence of a growing crop or biological and chemical transformation.

Analyses of groundwater in the well indicate that there is no significant leaching of NO_3-N from the well-fertilised pastures for intensive dairy farming. Likewise, there is no leaching of phosphorus.

The LEACHN model correctly predicted that the levels of NO_3-N in the pore water of the control and the plot landspread with slurries at 30 to 33 m^3/ha would be equal to or less than 6 mg/l. The model also predicted correctly the peak concentrations of NO_3-N in the excessively loaded plot; the model peak was about 30 days ahead of the field peak.

The experimental measurements from the soil and soil water flow, from landspreading farm slurries and silage effluent at normal rates and the well data indicate a low vulnerability for the aquifer. They do not support the high vulnerability rating given in the Dept. of Environment and Local Government, EPA and GSI (1999) publication Groundwater Protection Schemes in relation to landspreading.

INTRODUCTION

In recent times there is increasing interest in the hydraulic properties of free-draining unsaturated soils and on the fate of slurries, sludges, effluents and fertilisers applied to these soils. This is especially so where relatively thin soils overlie bedrocks such as limestones with fissures and solution channels (karstic aquifers). Irish soils are commonly gravelly and stony and present special problems in determining their hydraulic properties. In this project, various field and laboratory methods were employed to measure the hydraulic conductivity of unsaturated gravelly and stony soils overlying karstic limestone with a watertable 25 m below ground surface at the Teagasc Centre at Athenry. In parallel with these measurements, cattle and pig slurries and silage effluents were applied at normal and very heavy rates in summer and in winter to a series of experimental plots. A chloride tracer was also used. Rainfall and soil moisture contents and hydraulic potentials of the soil of the various plots were measured. Samples of soil water were collected in suction tubes and analysed for nitrate nitrogen (NO_3-N). In addition, samples of groundwater were taken from a nearby well and analysed for NO_3-N and a number of other parameters. Finally, a finite difference computer model was used to predict contaminant transport to the groundwater.

SOILS AND METHODS

Soils at three locations in the Centre were selected for the study of the soil, soil pore water and hydraulic conductivity: Site 1, typical of the great bulk of the farm, contained soil of a stony loam to silt loam texture; Site 2, located in local depressions, contained a reddish silt layer of variable thickness beginning about 0.5 m below the soil surface and sandwiched between gravelly and stony soils of silt loam texture and at Site 3 the soil was a very stony and gravelly sandy loam on hillocks and higher ground, At Site 1, the experimental site for the agricultural slurry and effluent applications, the soil water and hydraulic conductivity were measured in detail and the soils at all sites were described and characterised. Hydraulic conductivity was measured by both infiltration and well testing methods; infiltration methods used were a tension infiltrometer and the instantaneous profile; the well methods employed were the Guelph permeameter as described by Elrick and Reynolds, (1986; 1992) and a percolation test for stony and gravelly soils (Mulqueen, 1995). Flooding ring infiltrometers were also used to measure infiltration capacity.

Saturated [K_s], field saturated [K_{fs}] and unsaturated [$K(\psi)$] hydraulic conductivity

K_s a measure of the hydraulic conductivity of soil when all the pores are filled with water. K_{fs} is measured under ponded infiltration while a small proportion of the soil pores are still filled with soil air which has not yet dissolved or moved out. $K(\psi)$ is the matric (ψ) potential dependent hydraulic conductivity when the soil is unsaturated. K_s is usually about 2 times K_{fs} (Bouwer,1978). In the tension infiltrometer method used, a circular ceramic disc placed on the soil is supplied with water from a measuring cylinder in which a constant negative pressure is maintained by a bubble tower connected to it. The bubble tower contains three adjustable vertical Mariotte type tubes which control the suction at three selected values (Soil Measurement Systems,1994). The apparatus gives steady-state unconfined infiltration under constant negative pore water pressures (suctions). By carrying out steady-state measurements at two or three suctions and using an exponential relationship between $K(\psi)$ and ψ, a value for K_{fs} [$= K(\psi); \psi= 0$] can be derived. In the instantaneous profile method due to Watson (1966), an area of soil 1.44 m^2 is enclosed by a steel frame and is heavily ponded to wet the soil beyond the maximum depth for which measurements are required (Green, Ahuja and Chong, 1986). K_{fs} is measured using the steady state infiltration. At the moment that all the water has infiltrated and with the soil covered with a plastic sheet to prevent evaporation, vertical drainage downwards takes place. By measuring the volumetric soil moisture content and the hydraulic potentials at successive depths at given time instants, the hydraulic conductivity at different moisture suctions can be derived. Moisture contents are measured by a neutron probe and hydraulic potentials by tensiometers.

In the Guelph permeameter well method, percolation into the soil takes place from an unlined (uncased) hole in unsaturated soil in response to pressure, gravitational and matric forces. Both constant head and falling head tests can now be analysed after Elrick and Reynolds (1986, 1992). Square holes can be approximated by equivalent plan area cylindrical holes with little loss in accuracy; this is useful since uniform cylindrical holes cannot be bored in practice in gravelly and stony soils. K_{fs} values can vary from 10^{-9} m/s for tightly packed clays to 10^{-2} m/s for gravelly coarse sands. In order to minimise the effects of this variation, a ratio is introduced; this is the ratio of $K_{fs}/\phi_m = \forall$, where ϕ_m is called the matric flux potential and $\forall$ is a parameter depending on the soil. The ratio of K_{fs}/ϕ_m varies within an order of 1 or 2 magnitudes (White and Sully, 1987) and a value of $\forall$ is readily derived from two measurements of flow against tension with the tension infiltrometer or the Guelph permeameter well method. Elrick and Reynolds (1986) advise to use the following values for α: 12/m for loams; 4/m for unstructured fine textured soils; 1/m for compacted clay liners and 36/m for coarse sands and highly structured soils. No great error is introduced if in-between soil texture-structural conditions are assigned to the incorrect class, when the great range in values of hydraulic conductivity is considered. Values of hydraulic conductivity could be out by a factor of 2, which is small when the range of values of K_{fs} commonly found even in a small field is considered.

K_{fs} was also estimated from a simplified field percolation test in a square hole developed by Mulqueen (1995). In the original paper, K_{fs} was derived using unit gradient theory, viz. employing the gravitational potential gradient only. In a later development, Mulqueen and Rodgers (1999) have solved for the falling head arrangement using pressure, gravitational and matric potential gradients. For a 150 mm square hole into which 0.5 l of water is poured, the equation is

$$K_{fs} = 12.2/\Delta t \qquad [1]$$

where K_{fs} is in m/d; Δt is the time in minutes for the water to percolate out of the hole. For the SR6 percolation test (NSAI, 1991) using a 0.3 m square hole with the water level falling from 0.3 to 0.2 m above the base of the hole and defining T as the average time required for the water level to fall 25 mm over the 0.3 to 0.2 m range, the relationship between the T value and K_{fs} is K_{fs} (m/d) = 4.3/T (min) and for the BS6297 test (BSI,1983), K_{fs} = 26.4/Vp, where Vp is expressed in s/mm.

Flow of water in stony soils

Stony soils are very common in Ireland and especially in limestone areas with relatively thin soil covers as at Athenry with its very pure limestone (termed Burren limestone). They present special problems in determining their moisture contents and hydraulic conductivities. Earlier workers such as Berger (1976), developed equations for estimating the moisture content of stony soils from the percentages of gravel and stones and the moisture contents of the latter and the soil materials. Recently, the problem with moisture contents in stony soil has been solved by the use of nuclear gauges and probes except for the problem of soil disturbance on the installation of probes.

Peck and Watson (1979) using heat flow analogy, developed an equation for K of stony soils which reduced to

$$K_b = 2K(1 - V_r)/(2+V_r) \qquad [2]$$

where K_b = bulk hydraulic conductivity of the stony soil

K = hydraulic conductivity of the soil alone (<2 mm)

V_r = volume fraction of stones

Equation [2] shows that as the stone content increases from say 10% to 75%, the ratio of K_b/K declines from 0.86 to 0.18, or a 1/5th decline in K. Using laboratory packed layers of stones from a river deposit and a concrete sand (D50 = 0.27 mm) Bouwer and Rice (1984) found better agreement using the formula

$$K_b = K(e_b/e_s) \qquad [3]$$

where e_b and e_s are the void ratios of the bulk stone sand mix and of the sand alone respectively. Equation [3] can be used to determine the $K(\psi)$ vs ψ of the stony soil by suitable translation of the $K(\psi)$ vs ψ curve for the soil alone (without the stones), Bouwer and Rice (1984). These estimates necessitate disturbance of the soil and its reconstitution.

Gravelly and stony soils are of great interest in engineering in relation to construction of compacted earth liners for landfills, lagoons for storage of agricultural slurries and soiled waters and for sludge and tailings ponds and of embankments and foundations. The United Sates Department of Interior

(1974) recommends clayey gravels for embankments, cores for dams and compacted earth linings. Holz and Lowitz (1957) found that compaction of the finer material became difficult as the gravel content of sandy, silty and clayey soils approached one third by weight; above two thirds by weight there were often insufficient fines to fill the voids between the gravel particles. Voids were also more likely at the walls of a permeameter apparatus, inducing leakage and errors in hydraulic conductivity. Shelley and Daniel (1993) concluded that regardless of the gravel content of gravelly soil up to 60%, the moulding moisture content appeared to be the dominant characteristic influencing hydraulic conductivity. Similar results were obtained by Boer (1995), working with a sandy gravel from a pit at Ballypatrick, near Clonmel.

Methods of testing

In this study particle size analyses were carried out using BS1377 (BSI,1990) for particles down to 0.063 mm and for finer particles by a Malvern scanning laser diffraction analyser. Plastic and liquid limits were determined by the procedures of BS1377 (BSI,1990).

Dry bulk density was determined by a Humboldt gamma-neutron probe on soil platforms at various depths in a test hole. Some comparisons were made with the core and clod methods in the top 0.55 m of soil. There was close agreement between results from the nuclear gauge and the core method; the clod method gave differences, though not consistent, likely due to the stoniness and the small size of the clod.

Moisture characteristic curves were obtained on undisturbed samples to 0.45 m depth and on reconstituted samples to 2.0 m depth after the method of Stakman (1974). Results are not shown but are available in Bouchier (1995).

Hydraulic conductivity in the field was determined by the instantaneous profile method of Watson (1966) and the tension infiltrometer method (Ankeny, Kaspar and Horton, 1988). Well methods used were the Guelph permeameter (Elrick and Reynolds, 1986, 1992; Reynolds and Elrick, 1985, 1986; Reynolds, 1993) and a percolation test (Mulqueen, 1995). Infiltration capacity was determined in 1.2 m and 0.45 m diameter single ring flooding infiltrometers.

Installation of tensiometers, neutron probe access tubes and soil moisture samplers

An illustration of the instruments installed is shown in Figure 1. Installation of tensiometers, neutron probe access tubes and soil moisture samplers at depth present special difficulties in stony and gravelly soils. Some disturbance is unavoidable. If a drill is forced into the soil to fail the soil in compression and shear, then an annulus of compacted soil is formed about

Figure 1: A cut-away section illustrating layout of the instruments.

the perimeter of the hole resulting in a modification of the soil. The procedure employed to install the above instruments deeper than 0.75 m for this investigation was to drill 150 mm diameter well boreholes and to air lift the soil out of the bore holes. Unavoidably, some cobble stones fell to the bottom, which could not be lifted. To overcome this problem the hole was drilled deeper than required and a soil slurry made up from soil representing the appropriate depth was poured in until it built up the base of the hole to the required depth. The instruments were later installed and surrounded by a viscous soil slurry which was placed to establish good contact with the surrounding soil. Instruments at depths of 0.75 m or less were installed in boreholes drilled by hand and any annulus was filled with a soil slurry.

RESULTS

Geohydrology and soils

The solid bedrock underlying the soil was Burren limestone, a pale grey bedded fossiliferous limestone. It is a karstified aquifer. Depending on the topography, the watertable may be deep, shallow and even artesian (Carey, 1994). The watertable is about 25 m below ground surface at the sites used for this study. The bedrock is overlain by a generally thin cover of glacial drift, varying from 1.8 to 4.6 m thick (Diamond and Ryan, 1965), derived from the local limestone.

Site 1 was selected after a geophysical survey (using electromagnetic very low frequency resistivity and offset Venner electrical sounding) indicated a soil depth of at least 3 m and two test pits were excavated to this depth by hydraulic digger. It is the most widely occurring soil (Diamond and Ryan, 1965). Site 2 is located on the slope of a depression and contains a silt layer. Site 3 is on the crest of a ridge; the soil is shallow and very stony. An iron pan profile, unusual for a limestone glacial drift, was also discovered on this farm but was not investigated.

Description of soils

The soils are described in the Appendix. Soils at Site 1 were described in detail and soils at Sites 2 and 3 in outline. Site 1 has a stony and gravelly silt loam soil, friable in the upper 0.7 m layer and becoming stiff and very dense with depth. There are also some thin layers and lenses of looser and slightly plastic soil in among the denser layers at depth. Site 2 comprises a silt loam containing a reddish brown silt layer of variable thickness, over 1 m in places, and overlying a gravelly and stony loam similar to that of Site 1. Site 3 has a shallow stony and gravelly sandy loam soil; cobbles and gravel are very frequent.

Soil texture, structure and Atterberg limits

Figure 2 shows typical particle size distributions for the soils at the three sites after particles larger than gravel size (76 mm diameter) were removed. All the soils are very gravelly except for the silt layer at Site 2, which has 60% silt and 3% gravel. The soils are well graded with uniformity values (D_{60}/D_{10}) greater than 5 (Table 1). None of the soils has any clay size fraction, as measured in the laser diffraction analyser. Between 31% and 45% of the gravelly sandy loam at Site 3 is gravel; the cobble content comprises an additional significant percentage of the soil, about 40% in places. The structure is sub-angular blocky, tending towards granular. The structure in the silt is massive with some vertical cracks. Except for the silt layer, the soils are either non-plastic or barely plastic (Table 2).

Table 1: Uniformity coefficients (U) for soil layers at Site 1 and the silt layer at Site 2

	Layer (m)				
	0.25-0.55	0.55-0.78	0.78-1.00	1.00-1.25	0.45-0.55*
D_{60}	0.10	2.0	7.0	0.9	0.045
D_{10}	0.01	0.009	0.012	0.009	0.0075
$U(D_{60}/D_{10})$	10	222	583	108	6

Figure 2: Grading curves for soils at Sites 1, 2 and 3

Table 2: Plasticity[1] values for the subsoils at the three sites

Site	Layer (m)	Soil	PL (%H_20)	LL (%H_20)	PI (%H_20)
1	0.75 to 1.0	Loam	13	21	8
2	0.45 to 0.55	Silt	20	34	14
3	0.4 to 0.5	Sandy loam	np[2]	-	-

[1] PL = plastic limit, LL = liquid limit, PI = plasticity index

[2] np = non plastic

Bulk density , porosity, moisture content and suction

Dry bulk densities at Site 1 are about 1.3 t/m^3 in the topsoil; they increase steadily with depth until they reach about 2.0 to 2.1 t/m^3 at a depths of 1.15 m and greater (Figure 3). The deeper soil layers are very dense. Bulk densities of the soils at Sites 2 and 3 at depths of 0.15, 0.2 and 0.5 m at about 1.3, 1.3 and 1.5 t/m^3, respectively, are similar to those of Site 1. These well graded soils are dense soils. In the trial holes, lenses and discontinuous layers of softer soil were noticeable in places directly above and between the dense soil layers; these softer soils were wet and close to saturation. Porosity varied from 40 to 50% in the surface 0.5 m and then declined with depth to about 20% below 1.75 m (Figure 3).

Figure 3: Dry bulk density and porosity of soil in trial hole at Site 1

Field saturated moisture content (Figure 4) determined during and after ponded infiltration in the instantaneous profile ring almost equalled the porosity in the surface layer and declined rapidly with depth until deeper than 0.75 m the field saturated moisture contents were almost constant at 22% volume. This low value reflects very dense soil, which in this area approached the soil surface closer than in the trial hole, reflecting soil variation. In the surface soil layers, there was a 6 to 12% reduction in volumetric moisture content as the matric potential declined to -2.9 kPa. At depth, greater matric potentials were developed; at -0.6 kPa reductions of 2 to 4% in volumetric moisture were realised. Low dewatering at the surface reflects compaction and at depth a very dense tightly packed soil. Volumetric moisture contents at Sites 2 and 3 varied from 32% at the soil surface down to 17% at a depth of 0.5 m; values at the gravelly site were 1 to 5 % lower than at the site with the silt layer.

Figure 4: Volumetric moisture contents of soil at different matric potentials on instantaneous profile test area (Site 1)

Hydraulic potentials were measured at depths of 0.6, 0.9, 1.2 and 1.5 m in two plots where farm slurry was applied at 33 m^3/ha (3 mm) and in two other plots where the application rate was 250 m^3/ha (25 mm). Data from

Figure 5: Hydraulic potentials with depth on a plot landspread with slurry at 33 m^3/ha

one of the 33 m^3/ha plots are shown in Figure 5. At a depth of 1.5 m in this plot, soil moisture suction varied from 0 to 0.15 m (0 to 1.5 kPa) over the growing season. At a depth of 0.6 m, a maximum soil moisture tension of 0.7 m (7 kPa) developed. Matric potentials in the topsoil become very negative in dry summer weather (Hosty and Mulqueen, 1996). When the soil is wetted up (late autumn to spring), rainfall that infiltrates the soil flows slowly down to the deep watertable as soil moisture under unit gradient. In the 2nd plot, landspread at 33 m^3/ha with slurry, soil moisture suctions at the various depths were similar. At depths of 1.5 m and greater, the Athenry soil is close to field saturation (high matric potentials) throughout the year and there is slow downward drainage to the watertable under unit gradient.

Hydraulic conductivity

Figure 6 shows unsaturated hydraulic conductivity values [$K(\psi)$] at various depths at Site 1, determined by the instantaneous profile method. Values shown are for narrow bands of soil moisture tension (matric potential) since values for the same tension were not available at each depth. At tensions of about 3 kPa, K(ψ) values of the surface soil layers decline from 0.01 m/d at 0.15 m depth to 0.001 m/d at 0.6 m depth. At depths below 0.6 m, K(ψ) values at low tensions of 0.39 to 0.66 kPa (high matric potentials) vary about 0.006 m/d. Using a decaying exponential relationship between K(ψ) and ψ, equation [4],

$$K(\psi) = K_{fs}e^{\alpha\psi} \qquad [4]$$

where ∀ *is a decay constant*

Figure 6: Hydraulic conductivity with depth by the instantaneous profile method

K_{fs} is estimated at 0.009 m/d. The rate of infiltration from the steel ring at steady state could not be used to derive values of K_{fs} of soil below the surface layers because of lateral divergence of flow caused by the slowly permeable layers at depth (Evans, Kirkham and Frevert, 1951). At depths of 0.15, 0.25, 0.35 and 0.45 m, K_{fs} values were 0.73, 0.49, 0.39 and 0.34 m/d respectively. K_{fs} values, by the square hole method, were 0.42, 0.19, 0.14, 0.24 and 0.08 m/d at depths of 0.05, 0.25, 0.5, 0.9 and 1.3 m respectively; these values were determined in an area offset from the area of the instantaneous profile method. There was reasonable agreement between the values to a depth of 0.5 m; values for 0.9 and 1.3 m appear high when compared with those from the instantaneous profile method and considering the high dry bulk densities; high values at depth are likely due mainly to lateral flow from the ponded hole. K_s values in the topsoil averaged 1.43 m/d, ranging from 2.07 to 0.82 m/d. These K_s values were 2 to 3 times the K_{fs} values, in agreement with Bouwer (1978).

Figure 7: Influence of matric potential on hydraulic conductivity of the different soil layers by the instantaneous profile method

Figure 7 shows values for $K(\psi)$ calculated using the instantaneous profile method at various depths over a range of tensions. $K(\psi)$ remains constant with increase in depth at decreasing soil moisture tensions. This is a reflection of the tight packing of the soil particles at depth. $K(\psi)$ declines in an exponential manner with increase in soil moisture tension at all depths. K_{fs} of the 0.15, 0.25 and 0.45 m layers is estimated at 0.1, 0.064 and 0.006 m/d respectively and the deeper layers have K_{fs} values of a similar order to that of the 0.45 m layer. The curves at depths of 0.95 and especially 1.25 m resemble that of a sand with steep gradients while the other curves are typical of loams (Marshall, Holmes and Rose, 1996)

Figure 8 shows $K(\psi)$ values of the soil toplayers to a depth of 0.7 m determined by the tension infiltrometer. K_{fs} values, estimated from the decaying exponential relationship of equation [4], were 0.2 to 0.6 m/d in surface 0.3 m. Measurements on platforms at depths of 0.55 and 0.7 gave K_{fs} values of 0.09 to 0.02 m/d respectively. $K(\psi)$ declined exponentially as soil moisture tension increased at all depths as in the instantaneous profile method; values at a tension of 0.1 m water were up to an order of magnitude less than those at field saturation. K_{fs} and $K(\psi)$ values by the tension infiltrometer were in reasonable agreement with those by the instantaneous profile method; K_{fs} values by the square hole method, which employs flooding, were greater than those from above methods at depths of 0.7 m and deeper.

Figure 8: Hydraulic conductivity of soils at Site 1 by the tension infiltrometer method

Figure 9 shows values of $K(\psi)$ against ψ by the tension infiltrometer on Site 2, with the stratified silt layer. K_{fs} values were similar to those at Site 1, at 0.13, 0.14 and 0.35 m/d in the topsoil. The silt layer extended from 0.35 m to 0.6 m; K_{fs} for the silt layer was 0.05 m/d and for the underlying gravelly loam, 0.21 m/d. $K(\psi)$ values at Site 2 were of a similar order to those at

Site 1 and as in Site 1, there was an exponential decline in $K(\psi)$ with y. Infiltration capacities measured in 6 flooding ring infiltrometers using small heads averaged 0.52 m/d, reflecting some structural cracking on the surface. Infiltration capacities were about 2.5 times the mean K_{fs} value. The Guelph permeameter could only be used in the top 0.2 m at Site 2; measured values were in good agreement with those from the tension infiltrometer.

Figure 9: Hydraulic conductivity of soils at Site 2 (silt site) by the tension infiltrometer

Figure 10 shows values of $K(\psi)$ against ψ by the tension infiltrometer on the very gravelly and stony soils (Site 3). K_{fs} values at the soil surface were 0.05 and 0.12 m/d; at a tension of 0.1 m, $K(\psi)$ values were 0.02 and 0.03 m/d. $K(\psi)$ values were of a similar order at all depths and declined exponentially with increase in soil moisture tension. Infiltration capacities measured in 6 flooding ring infiltrometers averaged 2.32 m/d with a range of 1.3 to 3.0 m/d. Infiltration capacities at this site were 20 to 40 times the values measured for K_{fs}, reflecting a combination of some cracking in the topsoil and larger pore sizes between particles of the gravelly and stony sandy loam.

Figure 10: Hydraulic conductivity of soils at Site 3 (gravelly/stony site) by the tension infiltro meter method

Matric flux potentials (ϕ_m)

Values for ϕ_m were derived from tension infiltrometer tests and from three Guelph permeameter tests in Site 2; ϕ_m was derived from the relationship $K_{fs}/\phi_m = \alpha$, (Elrick and Reynolds, 1992). Values for α derived from Sites 2 and 3 were 11/m and 13.5/m respectively , similar to those recommended by Elrick and Reynolds (1992) for most structured soils and medium and fine sands. Mean values of ϕ_m were 0.008 (6 tests) and 0.005 m^2/d (3 tests) by the tension infiltrometer and permeameter methods respectively in the top 0.6 m soil. Mean values were 0.008 m^2/d in the top 0.35 m of soil at Site 3 by the tension infiltrometer method.

Discussion on soils and unsaturated hydraulic conductivity

The soils at Athenry are well graded very gravelly and stony with the exception of a silt layer in some hollows. The cobble-stone content can be 40%. Apart from the high stone and gravel content, the most significant feature of the main soil is the 50% increase in dry bulk density and the corresponding halving of the porosity with depth. As a result, there are large reductions in K_{fs} with values of about 0.009 m/d below 1 m, although this low value is in part due to the high gravel and stone content. The mean vertical K_{fs} in a horizontally layered soil is the harmonic mean of the values for the different layers, provided the latter are not too thin. Using all the values of K_{fs} available to a depth of 1.25 m, the mean vertical K_{fs} is 0.011 m/d. This same value has been obtained for the K_s of a gravelly silt from near Clonmel (75% gravel, 25% silt) when compacted in a Proctor mould to a dry bulk density of 2.11 t/m^3 at a volumetric moisture content of 16% (7.6% gravimetric) (Boer, 1995). K_{fs} rates are adequate to percolate average rainfall rates of 5 mm/d in winter; for short duration high intensity rainfalls, e.g. 7 mm/hr, there is adequate short-term storage in the soil toplayers, which then release the storage slowly to drainage. In relation to leaching, the hydraulic resistance, Ra, defined in equation [5], is a useful indicator of retention time.

$$R_a = z/K_{fs} \qquad [5]$$

where z is the layer thickness.

R_a of the 0 to 1.5 m layer is estimated at 136 d; of the 1.5 to 3.0 m deep layer at 167 d and of the 0 to 3 m layer at 300 d. In groundwater hydrology, aquitards with R_a values of 1000 d or more are regarded as aquicludes. Since the governing factor in solute transport to the groundwater is the rate of pore water flow, this has relevance to groundwater protection schemes such as those of DOELG, EPA and GSI (1999); such long hydraulic resistance indicates a low risk of aquifer contamination. K_{fs} and $K(\psi)$ values are high in the surface layers as also is infiltration capacity. However, the topsoil is known to be compressible and surface ponding and surface run-off into local depressions can occur in wet summers under frequent treading by animals. This surface compaction can be successfully undone by loosening the soil using tining machines when it is relatively dry and brittle (Mulqueen, 1988).

Direct field methods for measuring K_{fs} and $K(\psi)$ are difficult and laborious to carry out. The tension infiltrometer and square hole methods were found the most suitable for the gravelly and stony soils of Athenry; however, both methods are very time consuming on slowly permeable soils. Some tests, such as the instantaneous profile method, are very expensive and should be followed by a trial hole on the site of the ponding to evaluate the soil properties *in situ*. In view of this, there is need for predictive methods, which can provide reasonable estimates of $K(\psi)$ from more easily measured data such as particle size analysis, bulk density and soil water retention curves. The most promising seems to be the inverse method (Feddes et al.,1993a, b; Kool et al., 1987). In this approach, the direct flow problem can be formulated for any set of initial or boundary conditions and solved analytically or numerically. Simple inputs only are required, e.g. measured soil pore water contents. Another procedure that may be used is the Zero Flux Plane (Hosty and Mulqueen, 1996); in this method it is not necessary to know K_{fs} and $K(\psi)$ to determine a water and solute balance, but the soil moisture and hydraulic potentials and, for solute balance, the pore water concentration must be measured or known.

LANDSPREADING OF A TRACER, FARM SLURRIES AND SILAGE EFFLUENT

Field Instrumentation

Instruments were installed in field plots to monitor water and nutrient (NO_3-N) fluxes through the unsaturated soil. Rainfall at the site was measured by a tilting siphon rain gauge. Hydraulic potentials were measured by multi-point mercury tensiometers and by automatic logging tensiometers which were scanned in sequence by a central manifold of solenoid latching valves. The manifold was connected to a single negative pressure transducer and to a Campbell CR10 WP data logger powered by a 12 volt d.c. heavy duty battery. The data logger was also programmed to open the latching valves in sequence. Two tensiometer stations each operated 11 automatic tensiometers at depths to 1.5 m. To relate the hydraulic potentials to local ground surface, each tensiometer was levelled back to a datum in its respective monitoring station. Soil moisture was measured by an Institute of Hydrology (Wallingford) neutron probe. Aluminium access tubes were installed in drilled holes to depths of 2 or 1 m. Volumetric moisture contents were derived from calibration curves for the probe (Bell, 1976).

Pore water samples were obtained from the soil by ceramic cup suction tubes, 48 mm in diameter and 78 mm long, with a bubbling pressure of 100 kPa. Sample tubes were installed at depths down to 1.5 m, the depth to which ceramic samplers work in practice. Where each tube sampler exited from the soil surface, a bentonite seal was formed. An initial vacuum of 50 kPa, after Everett and McMillion (1985), was applied to each cup by means of a hand vacuum pump and each tube was inspected and checked 1 to 2 times weekly. Samples of pore water were collected by falling head partial vacuum and withdrawn from the cup into a sampling bottle after which the initial partial vacuum of 50 kPa was reset. Suction tube samplers have a sampling radius of the order of 10^{-2} m; initially, large pores near the ceramic cup contribute water under the high suction; later large and small pores contribute and finally large pores at distance (Wilson et al., 1995). Ceramic cups are very efficient in the sampling of NO_3-N, with up to 96% recovery. Since only one cup at each depth was installed, the sampling was of a monitoring nature; for accurate flux estimates, a number of samplers is required at each depth due to the spatial variation of the soil (Wilson et al., 1995).

Instrumentation installed in the separate plots is summarised in Table 3.

Table 3. Instruments installed in treated plots

Plot treatment	Tensiometers	Neutron Probe	Pore water samplers
Slurry (grass) Silage effluent (grass)	Automatic and multi-point at Depths of 0.2 to 2 m	to a depth of 2 m	at depths of 0.2, 0.6, 0.9, 1.2 and 1.5 m
Tracer (fallow)	multi-point at depths of 0.1, 0.2, 0.3, 0.4 and 0.5 m	to a depth of 1 m	at depths of 0.2, 0.6, 0.9, 1.2 and 1.5 m
Tracer (grass)	n.d.[1]	n.d.	At depths of 0.2, 0.6 0.9, 1.2 and 1.5 m

[1] n.d. = not done

Landspreading treatments and methodology

Landspreading of a tracer The tracer used was the Cl^- ion, as a $Ca\ Cl_2$ solution with 1000 mg/l Cl^- (Table 4) sprayed at 86 m^3/ha (8.6 mm). The rate of application was designed to simulate the landspreading of 43 m^3/ha (4.3 mm) of a manure slurry containing 2000 mg/l NO_3-N. The tracer was applied on the 23 April 1994 (day 113) and pore water sampling began 60 days afterwards to trace the Cl^- concentrations at depths beyond the root zone. The tracer was applied to a grassed plot and a fallow plot where the grass was killed off by a herbicide and there was also a control grassed plot. Rainfalls following spraying the tracer were unusually heavy; 28.3 mm to end of April (day 120) followed by 50.6 mm to 12 May (day 132) or almost 79 mm from day 113 to day 132. Thereafter, rainfalls were low to the end of June (day 181).

Table 4. Treatment of experimental plots

Date (1994)	Application	Rate (mm)	Rate (m^3/ha)	Plot
21 to 26 April	$CaCl_2$	8.6	86	Fallow & Grass
23 to 25 June	Silage Effluent	25.0	250	Point Source
25 June	Silage Effluent	2.5[1]	25[1]	Diffuse Source
15 to 18 July	Cattle Slurry	25.0	250	Point Source
16 July	Cattle Slurry	3.3	33	Diffuse Source
13 to 16 December	Pig Slurry	20.0	200	Point source
13 December	Pig Slurry	3.0	30	Diffuse Source

[1] The quantity of silage effluent applied to the diffuse source plot (25 m^3/ha) was diluted 1:1 with water before application.

Landspreading of slurries Both cattle and pig slurries were landspread as from diffuse and point sources (Table 4) on grassland. Point sources were simulated by very heavy rates, viz; 25 and 20 mm respectively (250 and 200 m^3/ha respectively, Table 4), which completely covered the soil surface; to avoid overland flow the slurries were applied over several days. Slurries were applied by hand from buckets by subdividing each plot into a grid to insure uniformity. Slurries were sourced at the Athenry College farm. Plots were instrumented as described in Table 3. Analyses of the slurries used are shown in Table 5. The cattle and pig slurries were applied sequentially to the same plots about 150 days apart, and the results are presented in sequence on each graph.

Table 5. Analysis of cattle slurry, pig slurry and silage effluent used in the experiments

Parameter	Cattle slurry	Pig slurry	Silage effluent
Dry Matter (g/kg)	85	65	60
Nitrogen (mg/l)	3,820	3,700	1,833
Phosphorus (mg/l)	743	1,700	592
Potassium (mg/l)	4,461	1,650	5,907
Magnesium (mg/l)	410	850	277
Sodium (mg/l)	743	300	426
Calcium (mg/l)	1871	2,800	1,277
Nitrate-Nitrogen (mg/l)	82	37	37
Ammonium-Nitrogen (mg/l)	1,140	1,887	471
BOD[1] (mg/l)	17,500	15,200	55,000
COD[2] (mg/l)	62,500	55,000	75,000
PH	-	-	4.6

[1] Biological oxygen demand

[2] Chemical oxygen demand

RESULTS

Tracer

Figure 11 shows that Cl- concentrations in the control plot varied from 5 to 12 mg/l in the month of June (days 152 to 181). On 1 July (day 182) they were about 5 mg/l at all depths and they fell to values of 1 to 5 mg/l until mid-November (day 319). From mid-November to end of January (day 396) the concentrations of Cl^- at 0.9, 1.2 and 1.5 m depths rose to 5 to 10 mg/l while the 0.6 m depth layer remained at 1 to 2 mg/l (Figure 11).

The concentrations of Cl^- in the pore water from early June to late January (day 152 to 390) in the treated plots are also shown in Figure 11. It is clear that Cl^- was leached in both the grassed and fallow plots. However, the Cl^- concentrations in general and the peak in particular were much lower in the grassed plots; the fallow peak Cl^- levels were 1.65, 2.4, 1.0 and 2.3 times those of the grassed plot at the respective depths of 0.6, 0.9, 1.2 and 1.5 m. This is due at least in part to absorption of Cl^- by grass roots. The leaching of Cl^- in the fallow plot, with a peak value of 34 mg/l at 1.5 m depth, indicates that the NO_3-N ion, which is also an anion, could be leached in the absence of a growing crop or biological transformation. There was a significant attenuation in Cl^- concentration with depth due to dispersion and dilution. In general, the amplitude of the variation also declined with depth. Taking a background value of 7.5 mg/l for Cl^- in January, the amplitude was 4.7, 3.5, 4 and 2 times this value at the respective depths of 0.6, 0.9, 1.2 and 1.5 m in the grassed plot and similarly 7.1, 8.2, 4 and 4.5 in the fallow plot. The rate of leaching depends on the balance between rainfall and evapotranspiration. After a dry September, there was heavy rainfall (30.5 and 46.3 mm) in the first 2 weeks of October (days 274 to 288), with minimal evapotranspiration and this led to a rapid decline in Cl^- concentration in the 0.6 and 0.9 m planes. Likewise, after heavy rainfall in

Figure 11: Cl$^-$ concentrations in pore water in control, grassland and fallow plots over time after Cl- was applied on day 113.

August (day 213 to 243), the peaks in concentration moved downwards especially in the fallow plot with its zero transpiration water loss. The Cl^- curves were multi-peaked with peaks following heavy rainfalls moving downwards. The curves in Figure 11 can be used to give an indication of pore and Darcy velocities. From the time of application, 23 April to 10 September, (time to peak at 1.5 m in the grassed plot) the mean pore velocity was 0.011 m/d over the 140 d; using a mean volumetric moisture content of 0.315, the Darcy velocity was 3.5 mm/d slow. Over this period the matric suction varied from 0.6 to 0.2 m, 0.35 to 0.07 m, 0.25 to 0 m and 0.07 to 0 m water at the respective depths of 0.6, 0.9, 1.2 and 1.5 m. In the fallow plot in September a peak appeared to move from 0.9 m to 1.2 m in 9 days after an exceptionally wet August. This gives a theoretical travel time of an average molecule of water of 0.033 m/d. As there was a unit hydraulic gradient and the volumetric moisture content was 0.25, the Darcy hydraulic conductivity was 8 mm/d; this is close to the value measured in the instantaneous profile test (Figures 6 and 7). In the treated plots no suction samples were obtained below 0.6 m until 54 days after the commencement of sampling or 114 days after application; the two samples obtained at 0.6 m in both the grassed and fallow plots during this period were small and the concentrations may have been influenced by this. The trends of the Cl^- concentrations indicate that very considerable hold-back of leaching takes place in periods of dry weather and that grassland reduces peak concentrations by about half. The time to first arrival and the time to peak concentration of a contaminant, reflecting the maximum and average pore water velocities, are slowed down in dry weather, enhancing the opportunity for root absorption and biological reductions of the NO_3-N ion.

Slurries and silage effluent

Figure 12 presents NO_3-N concentrations with depth in control. NO_3-N concentrations, at 3 mg/l or less, were minimal at the 0.6 and 0.9 m (not shown) planes in the soil. In early August (days 70 to 77) levels rose with

Figure 12: NO_3-N concentrations in pore water with depth in control over time (1 June = day 1).

depth to 5 and 9 mg/l NO_3-N at the 1.2 and 1.5 m planes but fell off rapidly in September, again to minimal values.

Figure 13 shows volumetric moisture contents (θ_v) with time on the diffuse and point slurry spread plots with time. In the diffuse plot, there is a decline in θ_v from about 37% to 30 % with depth from 0.6 m to 0.9 m. θ_v at 1.5 m is 0.04 to 0.06 of total volume higher than θ_v at 1.2 m. This can be explained by the occurrence of very compact and associated looser layers and lenses in the profile, i.e. at 1.5 m a looser layer underlies a very compact layer at 1.2 m deep about the aluminium casing of the probe in this plot. This can be expected from the variation found at depth in the test holes (Tables A1 and A2 in Appendix). On the point spread plot, θ_v values at 0.6 and 0.9 m were almost identical; this indicates that θ_v at 0.9 m is high and greater than in the diffuse spread plot Decline in θ_v in the 1.2 to 1.5 m slab of the point spread plot follows the general trend of decline of porosity with depth. Variations in response to weather conditions were about 6% at 0.6 m, 4% at 0.9 m, 2.5% at 1.2 m and 2.6% at 1.5 m. Soil moisture tensions (not shown) varied from a peak of 7 kPa in early September to a

Figure 13: Volumetric moisture content in point spread and diffuse spread plots over time (1 June = day 1).

low of 0.2 kPa in December at 0.6 m; from 3.5 to 0.7 kPa at 0.9 m; from 3.0 to 0 kPa at 1.2 m and from 1.5 to 0 kPa at 1.5 m.

Figure 14 shows NO_3-N for the diffuse spread slurry plot (33 m^3/ha cattle slurry on day 46 (16 July) and 30 m^3/ha pig slurry on day 196 (13 December 94) and for point spread slurry plot, viz. 250 m^3/ha cattle and 200 m^3/ha pig slurry landspread at the same time as the diffuse slurry. In both

Figure 14: NO_3-N concentrations in pore water with depth in point spread and diffuse spread over time (1 June = day 1)

diffuse and point source loaded plots there are peaks in the NO_3-N concentration of the pore water following on spreading. The peak curves are tall and slender, similar to those for a non-reactive ion (Davis et al., 1985). Outside these peaks the pore water NO_3-N concentrations in the diffuse spread plot are little different from those of the control. Highest pore water NO_3-N concentrations were found at 0.9 m in summer and at 0.6 m in winter. At 1.5 m depth (not shown), the NO_3-N concentrations had attenuated and resulting concentration curves were not peaky, representing average flow conditions with rainfall events damped out. The peak of 6 mg/l of NO_3-N in the pore water on day 253 followed a very wet week. There was no significant leaching from either application in the diffuse spread plot.

On the point spread slurry plot, NO_3-N concentrations in the pore water were significantly increased. Cattle slurry landspread at excessive rates (which could also happen with uneven spreading) raised the pore water NO_3-N to a peak of 16.8, 17.9, 6.8 at the 0.6, 0.9 and 1.2 m planes respectively. Pig slurry applied at very high rates in mid December resulted in a still larger elevation of NO_3-N levels in the pore water; 36 mg/l at 0.6 m, 14.6 mg/l at 0.9 m and 17.5 mg/l at 1.2 m. Where only 1.2 m or less of soil exists, there would be a risk of contamination of the groundwater with NO_3-N from excessive winter applications of farm slurries or from overflows onto fields from farmyards even in soils with dense subsoils since in winter recharge is high (high rainfalls and negligible evapotranspiration). Concentrations of NO_3-N attenuated below 1.2 m and were little different from those of the control at 1.5 m depth (not shown).

The time of first arrival can be derived from the very heavy loaded pig slurry plot and from this the maximum pore water velocity under prevailing hydraulic loading (rainfall). This is considered valid in view of the very high content of soluble nitrogen compounds (>1900 mg N/*l*) in the pig slurry. The maximum pore water velocities were similar for all depths with a range of 27 mm/d to 33 mm/d. Similarly, the average pore water velocity was estimated from the time to peak in the range 6 to 11 mm/d. The ratio of the estimated maximum to average pore water velocities was in the range 3 to 5. Data for NO_3-N at 1.5 m depth were not used, as they were similar to those for the control. There was an anomaly in that the time to peak was similar for the 0.6 m and 1.2 m depths, reflecting soil heterogeneity.

Silage effluent was landspread at 25 m^3/ha (diffuse source spread) and 250 m^3/ha (point source spread) as outlined in Table 4. There was no significant effect from spreading at 25 m^3/ha on the NO_3-N concentration (Bouchier, 1995). However, the heavy loading did result in transient concentrations of 18.5 and 19.0 mg/l NO_3-N at the 1.2 m plane, lasting 11 to 17 days. There was no significant leaching effect at the 1.5 m plane.

Analysis of groundwater

Groundwater was sampled from a well 600 m west of the study site. This well is overlain with 1.5 m of soil and is a good well with a specific capacity of 40 m^3/d.m when pumped at discharges of 250 to 1000 m^3/d (Daly, 1985). The zone of contribution to this well comprises the intensively farmed grassland, chiefly under dairy farming, of Athenry Agricultural College and an undetermined amount of surrounding farmland, farmyards and rural housing. At each sampling, the well bore was completely pumped out and a sample was taken from the rising main in a sterile bottle and forwarded to an analytical laboratory. Table 6 shows typical analyses indicating that under the intensive farming of the college farm there is little or no contamination of the underlying groundwater with leached NO_3-N and P. Under intensive farming, the underlying karstic aquifer is well protected from NO_3-N and P leaching by the prevailing high bulk density overburden soils. However, very low-level contamination (up to 110 MPN/100 ml) with faecal coliforms with associated high NH4-N levels can take place in this aquifer occasionally from unknown sources as shown for 24 October and 7 November.

Table 6. Analysis of groundwater quality in well

Date	Constituent						Faecal coliforms
	P	NO_3-N	NH_4-N	Na	K	$CaCo_3$	
28 Sep	<0.005	2.5	<0.1	9.5	4.8	469	2
24 Oct	0.07	<0.1	4.0	13.8	11.1	381	96
07 Nov	<0.005	1.9	<0.1	8.9	2.8	356	110
16 Nov	<0.005	1.6	<0.1	10.8	3.3	358	32
01 Dec	0.01	2.5	<0.1	9.9	3.1	345	2
22 Jan	<0.005	1.8	<0.1	12.3	2.8	318	2

[1] Number per 100 ml

MODELLING

The model chosen was LEACHM, a general acronym for Leaching Estimation And Chemistry Model developed by Wagenet and Hutson (1992). It comprises among other versions LEACHW which describes moisture movements in unsaturated soil and LEACHN which describes nitrogen transformations and transport. The moisture version uses the Richard's equation to describe moisture flow; this equation is solved by finite difference techniques. Solute movement is simulated by differentiating the solute flux with depth and adding a source or subtracting a sink of the solute. A finite difference technique is also used to solve the latter differential equation. Nitrogen is subject to many transformations and root absorption. Details of how these are handled in the model can be found in Wagenet and Hutson (1992). Output of the model is:

(i) hydraulic conductivities and volumetric moisture contents for each layer at matric potentials of 0, -3, -10, -30, -100 and -1500 kPa

(ii) cumulative totals and mass balances of water and those solutes considered in the model; including amounts initially and currently in the profile, simulated changes, additions, losses and mass error

(iii) a summary of root density, water and solute uptake by depth

(iv) a summary file containing water contents, fluxes and solute concentrations

(v) a breakthrough curve listing cumulative time, pore volumes and leachate concentrations at selected drainage increments.

The model version LEACHN was used to model NO_3-N concentrations at the depths 0.6, 0.9. 1.2 and 1.5 m for each experimental treatment. Output dates corresponding to sampling dates in the field were specified. Leaching of Cl- tracer was also modelled. Measurements made in the field and used in the model were: rainfalls, hydraulic conductivities, initial qv and hydraulic potentials (yh) and initial N and carbon in the profile.

Hydraulic conductivity

There was good agreement between K_{fs} values computed by the model and those estimated from field measurements. At a matric potential of -3 kPa,

Figure 15: A comparison of soil moisture tensions predicted by the LEACHM model with those measured in the field at depths of 1.2 m and 1.5 m.

agreement between $K(^{(\quad \psi)}$ values was less good; simulated values at about 5.10 to 4 m/d were only 25 to 50% those estimated from measurement. Since the magnitude of these values is so small, such differences have little impact on the overall flux, which is dominated by flows at and near field saturation.

Soil moisture tension

There was reasonable agreement between soil moisture tensions as predicted by the model and field measurements at depths of 0.6, 0.9 and 1.2 m (Figure 15). The model overpredicted the soil moisture tensions at the 1.5 m depth throughout the study period but especially in the wet August of 1994 (day no. 62 to 93, Figure 15).

Tracer simulation

The model predicted Cl^- concentrations much lower than the measured values for the treated grassland plot. Peak values were 16, 6, 12 and 1.5 mg/l lower at the respective depths of 0.6, 0.9, 1.2 and 1.5 m (Bouchier, 1995). Moreover, the model peak values were out of phase with the measured peaks, peaking later by 40 to 70 days. The model redictions for the fallow treatments were also too low and out of phase with the measured values. The model correctly predicted the low Cl- concentrations measured over winter and early spring period in the control but not the rise in values measured at 0.9 m and deeper from 1 April to mid June. Overall, there was poor agreement between the model predictions for the tracer and the measured field values.

Simulation of leaching of NO_3-N

The model correctly predicted that the NO_3-N levels in pore water in the diffuse spread plot would be equal to or less than 6 mg/l (Figure 16).

The model did not show any peak of $N0_3$-N from the point spread application of cattle slurries, although measured peaks at 0.6 and 0.9 m deep were 17 and 18 mg $N0_3$-N/*l*, respectively. At deeper depths, the model and field data were all close to zero. The model peaks of $N0_3$-N from the point source pig slurry application were of the right order; the peaks (field,

Figure 16: A comparison of NO3-N concentrations in pore water predicted by the LEACHN model with those measured in the field at 1.2 m depth

model) were 36, 26 mg/l at 0.6 m; 15, 21 mg/l at 0.9; 17, 18 mg/l at 1.2 m and while the model predicted a peak of 17.5 mg/l $N0_3$-N at 1.5 m no such peak was measured in the field. The model peaks occurred 60, 60 and 30 d ahead of the field peaks; accordingly the average pore velocity would be overestimated by the model. Mean pore water velocities in the model varied from 1.3 to 2.5 times those measured in the field.

DISCUSSION OF RESULTS AND MODELLING

There was no significant leaching of $N0_3$-N from cattle and pig slurries landspread at normal rates of 30 to 33 m^3/ha in one application. True, there were transient peak values of 6 mg/l $N0_3$-N at 0.9 m (cattle slurry landspread mid-July) and at 0.6 m (pig slurry landspread mid-December). These levels attenuated with depth and were minimal at 1.5 m. The values on the diffuse landspread plots were not greatly different from those of the unfertilised control which recorded highs of 5 and 9 mg/l $N0_3$-N at depths of 1.2 and 1.5 m respectively in August.

Landspreading of farm slurries at excessive rates of 200 to 250 m^3/ha, apart from potentially inducing surface run-off of soiled water if followed soon afterwards by heavy rainfall, can give rise to leaching of $N0_3$-N especially in winter when grass growth is slow and rainfalls are heavy. In shallow soils such leaching from heavy slurry loading could give rise to contamination of groundwater. Landspreading at excessive rates and other events giving rise to similar effects such as run-off from farmyards and strip-wise heavy loading deriving from uneven landspreading should be avoided.

Overall, there appears to be a low risk of groundwater contamination by $N0_3$-N from landspreading farm slurries at normal rates on the soils at Athenry. This is borne out by the low $N0_3$-N levels in the groundwater beneath the soils of Athenry. In rating the vulnerability of the aquifer under the DOELG, EPA, GSI (1999) Groundwater Protection Schemes, the hydraulic conductivity of the overlying subsoil and its thickness are used; according to this scheme the vulnerability of the aquifer at Athenry is “high” as subsoils are less than 10 m (moderate hydraulic conductivity) or equal to or less than 5 m (low hydraulic conductivity). The leaching results and the long residence times of soil solutions in the main Athenry soil do not support this “high” rating in relation to landspreading.

Average pore water velocity in the Cl- treated grassland from April to September was 11 mm/d; similar average pore water velocities (6 to 11 mm/d) were estimated in the heavily slurried grassland. The ratio of the maximum pore water velocity (derived from time of first arrival) to the average was 3 to 5, compared with 2 derived from breakthrough curves synthesised from model studies which included longitudinal dispersion (Charbeneau and Daniel, 1993). The results of many field experiments show that long term leaching of solutes through many field soils can be modelled with average water flow rates and average pore water contents (Charbeneau and Daniel, 1993). Using only simple advection theory, i.e. neglecting dispersion, the net recharge (rainfall - potential evapotranspiration, E_{pot}) and average pore water content ($\theta_{v,av}$), then the pore velocity (v) can be computed from

$$v = q/\theta_{v,av} \qquad [6]$$

where q = *net recharge (mm/d).*

Rainfall from 23 April to 10 September (140 d) was 350 mm and E_{pot} was 333 mm giving a net recharge of 17 mm. Mean daily recharge was 0.12 mm/d and mean pore water content was 31.2%; using these, the average pore water velocity was 0.4 mm/d. This is well below the measured values, indicating that this procedure is not successful in estimating the average rate of advance of a contaminant front after landspreading. Using Darcy’s law, the recharge may be written as

$$q = K(\psi)\,(\delta\psi/\delta z + 1) \qquad [7]$$

where $\delta\psi/\delta z$ = *hydraulic gradient (z measured positive downwards).*

In winter and below about 1 m at all times, gradients in matric potential are small and equation [7] may be replaced by

$$q = K(\theta) \qquad [8]$$

where $K(\theta)$ = *the moisture dependent hydraulic conductivity.*

Equation [8] states that the pore water content adjusts itself such that $K(\theta)$ is sufficient to pass the recharge or volumetric flux downwards toward the watertable. This is what happened in heavy rainfalls during the conduct of the landspread measurements.

The LEACHM model successfully predicted the hydraulic properties [$K(\psi)$ and ψ] of the soil. LEACHN correctly predicted the NO_3-N values in the pore water of the grassland plots landspread at normal rates. At excessive rates of 200 to 250 m^3/ha the model also gave good agreement although there were phase differences of 1 to 2 months. Overall, the model performed reasonably well in predicting NO_3-N concentrations in the pore water.

CONCLUSIONS

- The soils of Teagasc Athenry Centre are very stony and gravelly loams, less than 5 m thick and are very dense (2 t/m^3 dry density) below 1 m depth

- The high density and stoniness result in slow hydraulic conductivities of about 10 mm/d and a long residence time of pore water, minimising leaching

- There was no leaching of NO_3-N from cattle and pig slurry and silage effluent spread at normal rates of 25 - 33 m^3/ha.yr; the pig slurry was spread in winter

- Cattle and pig slurry and silage effluent spread at very heavy rates gave rise to leaching of NO_3-N to a depth of 1.2 m

- Analyses of groundwater show no significant leaching of NO_3-N and P from intensively managed grassland

- The LEACHN model correctly predicted the concentrations of NO_3-N in soil pore water

- Experimental results and groundwater data indicate a low vulnerability of the aquifer to NO_3-N contamination from landspreading and intensive farming

- Results and data do not support the high vulnerability rating of the DOELG, EPA, GSI (1999) publication Groundwater Protection Schemes in relation to landspreading of farm slurries and silage effluent.

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APPENDIX : DESCRIPTION OF SOILS

Table A1. Description of soil in test pit 1, Site 1

Depth (m)	**Description**
0.0-0.23	Stony loam topsoil; dark greyish brown (10YR3/2); moderately firm coarse crumb with some medium and fine crumb; moist; friable; abundant fine roots (topsoil).
0.23-0.37	Loam; brown (7.5YR4/4); moderate, coarse and medium subangular blocky; moist friable; many fine roots to 0.37 m and 0.75 m in tongues.
0.37-0.7	Stony gravelly loam with some small limestone boulders; brownish grey (10YR6/1); firm coarse subangular blocky; moist; moderately friable; very few fine roots.
0.7-1.7	Gravelly silt loam with some small limestone boulders; dark greyish yellow (2.5Y5/2); weak coarse subangular blocky; very dense with moist slightly sticky and slightly plastic thin looser layers and lenses ; no roots.
1.7-2.9	Gravelly silt loam with some small limestone boulders: dark greyish yellow (2.5Y5/2); very weak, coarse subangular blocky tending to massive (granular); dense and hard but moist to wet in thin discontinuous layers and lenses which are slightly sticky and slightly plastic; also discontinuous layers of very tightly packed, dry, stony, greyish yellow (2.5Y6/2) silt loam mostly between 1.7 and 1.9 m with some tongues to the base of the pit, average thickness 0.3 m.

Table A2. Description of soil in test pit 2, Site 1

Depth (m)	**Description**
0.0-0.23	Stony loam topsoil; dark greyish brown (10YR3/2); moderately firm coarse crumb with some moderate medium and fine crumb; moist; friable; abundant fine roots.
0.23-0.75	Loam; brown (7.5YR4/4); moderate coarse and medium subangular blocky; moist; friable; many fine roots to 0.4 m with some to 0.7 m in Tongues.
0.75-1.7	Gravelly silt loam with some small limestone boulders; dark greyish yellow (2.5Y5/2); weak coarse subangular blocky tending to massive (granular); dense; moist in lenses which are damp, slightly sticky and slightly plastic.
1.7-3.0	Gravelly silt loam with more frequent limestone cobbles; dark greyish yellow (2.5Y5/2); very weak (granular) structure; dense with damp slightly sticky and slightly plastic lenses; similar areas of dry, very tightly packed dense stony, greyish yellow silt loam (2.5Y6/2) as in Test pit 1.

Table A3. Description of soil at Site 2 (with silt layer)

Depth (m)	Horizon	Description
0-0.07	A1	Silt loam topsoil; dark greyish-brown iron mottled (gleyed); medium crumb structure; many roots; some worm holes; smooth boundary.
0.07-0.45	A2	Silt loam; greyish-brown iron mottled; cobbles; roots and worm holes; medium and fine granular structure.
0.45-0.55	B	Silt; yellowish red; few worm holes and roots; a few decaying limestones; massive structure.
0.55+	C	Calcareous gravelly and stony silt loam; many cobbles and boulders; decaying limestones; granular structure.

Table A4. Description of soil at Site 3 (very gravelly and stony soil)

Depth (m)	Horizon	Description
0-0.08	A	Sandy loam topsoil; dark brown; many roots; some wormholes; smooth boundary.
0.08-0.35	B	Gravelly and stony sandy loam; dark brown; medium gravelly granular structure.
0.35+	C	Gravelly sandy loam; coarse; many cobbles and boulders; some decaying limestones.