Eutrophication from Agriculture Sources
2000-LS -2 –M2

FINAL REPORT

Nitrate Leaching - Soil Investigation
2000-LS- 2.3.1.2

March 2006

Prepared for the Environmental Protection Agency
by

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ACKNOWLEDGEMENTS

This report has been prepared as part of the Environmental Research Technological Development and Innovation Programme under the Productive Sector Operational Programme 2000-2006. The programme is financed by the Irish Government under the National Development Plan 2000-2006. It is administered on behalf of the Department of the Environment and Local Government by the Environmental Protection Agency which has the statutory function of co-ordinating and promoting environmental research. They also acknowledge the assistance of their colleagues: P. Johnston and P. Bartley (Trinity College Dublin), Mark Healy (National University of Ireland, Galway), O. T. Carton, M. Ryan, D. Noonan and K. McNamara (Teagasc). Laboratory analyses were provided by J. Scott (Teagasc, Johnstown Castle).

The contribution of the Steering Committee for guidance throughout the project and for useful comments is gratefully acknowledged. The Committee included Prof. S. Jarvis, Dr O. Oenema, Dr C. Watson, Dr. D. Daly, Ms M Keegan and Mr P. Duggan.

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Published by the Environmental Protection Agency, Ireland

Printed on Recycled paper

ABSTRACT

Much of the intensive dairy farming in Ireland is located on free-draining unsaturated soils overlying important aquifers. This study was undertaken to measure the concentrations of nitrate-nitrogen (NO_3-N) in soil pore water following land spreading of fertiliser nitrogen (N), dirty water and farm slurry to grassland on a free draining sandy loam overlying a limestone aquifer. Three rates of fertiliser-N, dirty water and farm slurry, corresponding to high, medium and low, were applied. Chemical fertiliser-N, dirty water and farm slurry were applied at the same times as those applied on an adjoining intensively managed dairy farm. Ten experimental field plots, including one control plot, were laid out following a geotechnical survey to establish soil depth and characteristics. There was no evidence of cracks, fissures or macropores below the topsoil (0.3 – 0.4 m thick). The plots were instrumented to 3 m depth with (i) porous ceramic suction samplers to sample the soil pore water at various depths; (ii) tensiometers to measure the pressures of the soil pore water and (iii) neutron probe access tubes to estimate soil water contents at different depths. Pore water samples were taken weekly during the summer and twice weekly during the winter and analysed for NO_3-N; pore water pressures and soil water content were measured at the same time as the soil pore water samples were withdrawn. Over the two year period of measurement, the NO_3-N concentrations in the pore water of the control, the low N fertiliser (174 kg /ha.) and medium N fertiliser (286 kg /ha.) were low, in general. However, there was a tendency for higher NO_3-N concentrations in the pore water of the medium fertiliser treatment in spring following late September and late January - early February N applications. The high N fertiliser (387 kg /hectare) gave rise to high NO_3-N in the soil pore water. The NO_3-N concentrations in the soil pore water generally showed no response to summer and winter applications of low (10 mm) dairy waste water applications. Similarly, medium (25 mm) and high (50 mm) rates of dairy wastewater in summer had little effect on NO_3-N concentrations in the soil pore water. However, applications of medium (25 mm) and high (50 mm) rates in winter increased the NO_3-N concentrations of the soil pore water to high levels. None of the slurry applications of low (15 m^3/ha), medium (30 m^3/ha) and high (45 m^3/ha) had a significant effect on soil pore water NO_3-N concentrations. LEACHN modelling gave fair agreement between measured and modelled NO_3-N concentrations in the soil pore water following low, medium and high dirty water applications. High initial NO_3-N concentrations in the soil pore water at the start of the study at depths greater than 1.5 m declined to low levels over an 18 to 24 month period and are continuing to decline in 9 of the 10 study plots. This indicates that high NO_3-N concentrations in soil decline quickly under Irish recharge conditions. There was very good agreement between the calculated depth of travel of NO_3-N solutions in the soil assuming piston flow (also called plug) and the measured depth of travel. This agreement was obtained at 10 locations for 13 events, confirming the absence of by-pass or macropore flow in the soil at the experimental site.

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CHAPTER ONE

Introduction

1.1 Background

Since the introduction of the Drinking Water Directive (Council Directive 98/83/EC) by the European Community in 1998 (EEC, 1998), there has been a greater emphasis placed on water quality in Ireland. The EPA published a report (McGarrigle *et al*., 2002) that identified the decline of drinking water quality in Ireland in recent years. This decline has occurred as a result of numerous activities but the three main causes identified, by the EPA, are:

1. industrial pollution
2. domestic pollution
3. agricultural pollution

There are three ways in which agricultural pollution can occur:

1. point sources – pollution can occur due to leaking holding tanks, leakage from silage pits, broken irrigators/spreaders and dumping of animal effluents
2. diffuse sources – when fertiliser and animal or farmyard effluents are applied in excess or out of season, the plant uptake isn't sufficient to use all the nutrients available, giving rise to a potential for nutrient transport to receiving waters
3. organic nitrogen (N) in the soil is mineralized and is subsequently leached.

On intensively managed dairy farms, large amounts of nutrients are necessary to maintain a high quality of grass and silage production. Nutrient losses, in particular N loss, are of particular concern in intensive agriculture since the introduction of the European Community's Nitrates Directive in 1991, Council Directive 91/676/EEC, (EEC, 1991). The EU announced that member states are obliged to reduce the nitrate levels in surface and groundwaters resulting from agricultural practices. According to the Directive, each member state is obliged to designate 'nitrate vulnerable zones'. These zones are defined as 'zones where the nitrate (NO_3) concentration in groundwater exceeds 50 mg/l or could exceed 50 mg/l if action is not taken'. Article 3.5 of Directive 91/676/EEC provides an exemption from the obligation to designate nitrate vulnerable zones if the member state applies action programmes (as described in Article 5) throughout the entire territory; such action programmes should set specific limits for the application of livestock manure and shall include monitoring the nitrate content of surface and ground waters at selected points. The Nitrates Directive also states that there should be a balance between the N supply (animal manures and chemical fertilisers) and the N demand of the crop.

In response to the Nitrates Directive, the Irish government launched a Code of Good Agricultural Practice (1996), which outlined procedures to reduce nutrient losses through good agricultural practices (Department of the Environment, Department of Agriculture, Food and Forestry, Ireland, 1996).

Leaching of nitrate-nitrogen (NO_3-N) through soil can result in NO_3-N concentrations in drinking water in excess of the EU maximum admissible concentration (MAC – 11.3 mg/l). Elevated NO_3-N concentrations in receiving waters can also cause algal blooms especially in estuaries where waters rich in mineral and organic nutrients

promote the growth of plant life. The dissolved oxygen content is reduced causing the extinction of some organisms.

1.2 Objectives of the study

The main objective of the study was to monitor the movement of NO_3-N from experimental plots (8 m x 8 m) through a free-draining unsaturated soil with a deep water table following treatment with:

1. three rates of chemical N fertiliser
2. three rates of irrigation with dairy wastewater
3. three rates of slurry application

at various times throughout the year. Low, medium and high rates of nutrient application were applied to separate experimental plots, where, the medium rate of chemical fertiliser N is about 25 % greater than that recommended for grazed swards for a "Whole Farm" stocking rate of 2.4 LU/ha as given in the Department of the Environment and Department of Agriculture, Food and Forestry, Ireland, 1996 Code of Good Agricultural Practice.

The concentrations of NO_3-N in the soil pore water of the dirty water treatments at various depths were modelled using LEACHN and the results from the model were compared to field results.

1.3 Experimental programme

The experimental programme was conducted over a period of 24 months on the Teagasc Moorepark research farm that is located 2 km north of Fermoy, Co. Cork, Ireland. The free draining soil is up to 4 m deep with rock outcrops at a few isolated locations. A 0.4 ha site on the farm, with an estimated soil depth of 3 m, was selected for the experimental programme following a geophysical survey. Ten experimental plots, each 8 m x 8 m, were established on the site and instrumented with ceramic cups, tensiometers and soil water content access tubes. A buffer strip of 3 m separated the plots on all sides.

1.4 Structure of report

Chapter 2 contains a literature review of soils and nitrate leaching. Chapter 3 contains a description of the site, type of instrumentation installed and experiments carried out. Chapter 4 describes laboratory and field testing results for each experimental plot. Chapter 5 describes the LEACHN finite difference model and the results obtained from the model. Chapter 6 contains a discussion of results, conclusions and recommendations for further research.

CHAPTER TWO

Literature Review

2.1 Soil Water

Soil acts as a good reservoir for the storage of pore water. The physical properties (particle size, porosity etc.) of the soil determine how good a soil is for storing pore water. Direct or indirect measurements of soil water content are required in almost every type of soil study. Soil exists in three phases: solid, liquid and gaseous phase (Fig. 2.1).

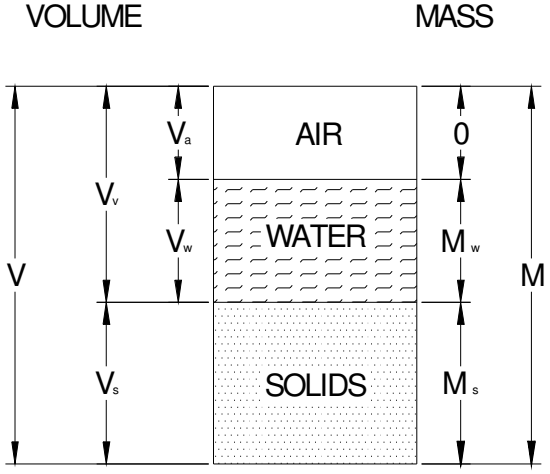

Fig. 2.1 Phase diagram of an unsaturated soil (Craig, 1997)

Soil water content can be defined in terms of mass or in terms of volume. In terms of mass, the gravimetric water content,

$$\omega = \frac{M_w}{M_s} \qquad \textbf{(2.1)}$$

where,
M_w = mass of water
M_s = total mass of oven dry solids.

In terms of volume, the volumetric water content,

$$\theta = \frac{V_w}{V} \qquad \textbf{(2.2)}$$

where
V_w = volume of water
V = total volume of soil.

The void ratio (e) of the soil is the ratio of the volume of voids (V_v) to the volume of solids (V_s):

$$e = \frac{V_v}{V_s} \qquad \textbf{(2.3)}$$

The porosity (η) is the ratio of the volume of voids to the total volume of soil:

$$\eta = \frac{V_v}{V} \qquad \textbf{(2.4)}$$

The degree of saturation S_r is the ratio of the volume of pore water to the total volume of voids:

$$S_r = \frac{V_w}{V_v} \qquad \textbf{(2.5)}$$

A soil is said to be saturated when the degree of saturation is 1 (or 100%).

2.2 Soil water potentials

Total soil water potential is defined as the amount of work per unit quantity of pure water that must be done by external forces to transfer reversibly and isothermally an infinitesimal amount of water from the standard state to the soil at the point under consideration (Hanks and Ashcroft, 1980). Soil water content alone is not sufficient when considering contaminant transport in soil. It is important to know the energy status of the soil, which is expressed through the soil water potential:

$$\psi_T = \psi_g + \psi_m + \psi_o \qquad \textbf{(2.6)}$$

where

ψ_T = hydraulic potential

ψ_g = gravitational potential

ψ_m = matric potential

ψ_o = solute potential

Matric potentials are measured using tensiometers.

2.2.1 Gravitational potential, ψ_g

The gravitational potential is considered as the potential energy stored in a fluid due to its vertical position in reference to an elevation datum (Wilson and Dorrance, 1995). It can also be expressed as:

$$\psi_g = \gamma z \qquad \textbf{(2.7)}$$

where

γ = unit weight of the fluid

z = fluid's elevation in the soil profile

The gravitational potential is independent of soil properties as it depends only on the vertical difference between the point in question and a given reference datum.

2.2.2 Matric potential, ψ_m

Leong *et al*. (2002) defined matric potential (or matric suction) as the equivalent suction derived from the measurement of the partial pressure of the water vapour in equilibrium with the soil water, relative to the partial pressure of the water vapour in equilibrium with a solution identical in composition with the soil water, except that there is no soil matrix present. A fully saturated soil has a matric potential of zero. Matric potentials are measured with tensiometers (Fig. 2.2).

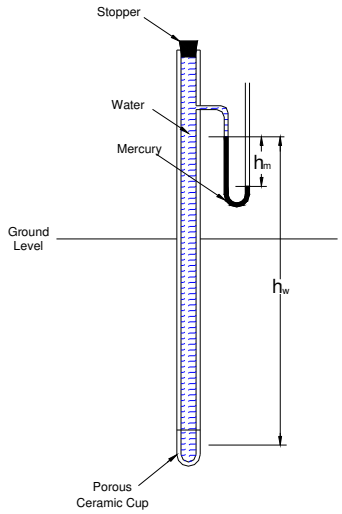

Fig. 2.2 Tensiometer with mercury manometer

The matric suction at the porous ceramic cup is (units of length):

$$h = \left(\frac{\rho_m}{\rho}\right) h_m - h_w \qquad \textbf{(2.8)}$$

and the matric potential (ψ) is expressed as (units of energy per unit volume):

$$\psi = \rho g h_w - \rho_m g h_m \qquad \textbf{(2.9)}$$

where
ρ = density of water
ρ_m = density of mercury
h = suction head at ceramic cup
h_m = height of mercury
h_w = height of water
g = acceleration due to gravity (Marshall *et al*., 1996).

2.2.3 Solute potential, ψ_o

Solute or osmotic potential relates to differences in solute concentration but does not significantly affect the mass flow of water except where large differences in solute concentration in the soil profile exist; this term is ignored in this study.

2.2.4 Pressure potential

Pressure potential is defined as the difference in elevation between the point in question and the water surface in a piezometer connected to that point.

2.3 Transport mechanisms of solutes in porous media

In order to understand the transport of solutes through soil it is necessary to look at the convection-dispersion equation (CDE). In this equation, two movement processes are considered: (i) transport as a result of liquid flow and (ii) spreading as a result of molecular diffusion, mechanical dispersion and hydrodynamic dispersion (Leij and van Genuchten, 1999).

Analytical and numerical techniques have been used to understand the transport of contaminants through soil. Wilson and Gelhar (1981) presented an analytical technique for the analysis of solute redistribution during infiltration in unsaturated soils. Their calculations indicate the effects of convection and dispersion during downward seepage. Their results are applicable to conservative solutes. In an unsaturated soil overlying an aquifer, the seepage is mainly vertical. In this situation, the mean depth of penetration of water in soil can be described by

$$z = qt / \theta_v \qquad \textbf{(2.10)}$$

where z is the mean depth (m) of penetration after t days, q the volumetric flux density, i.e. the mean downward daily flow of porewater or infiltration of rainfall and irrigation water, ($m^3\ m^{-2}d^{-1}$) and θ_v the water-filled pore space ($m^3\ m^{-3}$). The quotient q/θ_v is the mean pore velocity ($m^3\ m^{-2}d^{-1}$).

The flux equation for the transport of solutes in porewater is a combination of convective and dispersive flows:

$$J_s = -\theta_v D(\delta c / \delta x) + qc \qquad \textbf{(2.11)}$$

where J_s is the flux of solute (kg $m^{-2}d^{-1}$), D the dispersion coefficient (m^2d^{-1}) i.e. the sum of molecular diffusion and mechanical dispersion, $\delta c/\delta z$ the concentration gradient (kg m^{-4}) and c the volume mean concentration (kg m^{-3}) (van Genuchten and Wierenga, 1986). Substituting eqn. 2.11 into the equation of continuity (2.12)

$$-\partial J_s / \partial z = \partial / \partial t[\theta_v c + \rho S] \qquad \textbf{(2.12)}$$

where ρ is the dry bulk density of the soil (kg m^{-3}) and S is the adsorbed concentration of solute i.e. the mass of solute per unit mass of oven-dry soil (kg kg^{-1}), yields the transport equation

$$\partial/\partial z[\theta_v D(\partial c/\partial z) - qc] = \partial/\partial t[\theta_v c + \rho S] \qquad \textbf{(2.13)}$$

For a conservative solute, ρS is zero; where the amount of solute adsorbed is linearly related to the concentration of solute in the porewater (linear adsorption), $S = K_d c$, K_d being the volume of porewater per unit mass of soil (m^3kg^{-1}) termed the adsorption or distribution coefficient. In practice, the contribution of dispersive flux is small, often less than 10% (Bolt, 1976), indicating that often the dispersion model with small deviations from plug flow may be used in field situations. If dispersion is neglected, eqn. 2.13 then reduces to

$$-q\partial c/\partial z = \theta_v \partial c/\partial t[1 + \rho K_d/\theta_v] = \theta_v \partial c/\partial t[1 + R] \qquad \textbf{(2.14)}$$

where R (dimensionless) is called the retardation factor. If there are no interactions between the solute and the soil, K_d is zero and R vanishes. Where dispersion is ignored, the concentration profile at the solute front is very steep (van Genuchten and Wierenga, 1986). Small infiltration rates typical of natural rainfall events result in low porewater contents and enhanced retardation of solutes. The results of field experiments by Miller *et al*. (1965) and many other investigations (Charbeneau and

Daniel, 1993) show that long-term displacement of solutes through field soils (solute travel time) may be modelled through the use of average porewater flow rate derived from eqn.2.10, using the mean daily rainfall rate and mean porewater content of the soil. Instead of modelling the transient transport of solutes through a heterogeneous soil in response to individual rainfall and irrigation events, the simplified model can provide appropriate accuracy in many practical applications (Charbeneau and Daniel, 1993).

Following infiltration into soil, the flow of dairy wastewater and solutes is slowly downwards in the dairy wastewater-soil system in a manner analogous to the flow of reactants in a chemical reactor and the theories and laws of chemical reaction engineering can be applied to the process. Dairy wastewater is commonly applied by spray irrigation to soil about twice annually with about 15% of each farm being irrigated each year, although pressure-vacuum tankers are also employed. Irrigation rates commonly vary from 10-25 mm (100-250 m^3/ha) at one irrigation. The irrigator delivers essentially a single pulse. Neglecting plant uptake and microbial synthesis and decay in winter and because of the short residence time in the topsoil, when a pulse of dirty water is irrigated on soil in winter and infiltrates, it moves down slowly through the soil (below the topsoil) driven only by rainfall. Because of the tortuousity of the soil pore system and dispersion and diffusion, there is a range of residence times of individual molecules. This deviation from plug flow gives rise to non-ideal flow. The distribution of residence times for a stream of liquid passing a certain depth plane in a soil can be called the residence time distribution (RTD) or exit age distribution (**E**), Levenspiel (1999). In laboratory experiments a pulse of liquid, often with a tracer, is applied to a column of soil in a closed vessel and the drainage is collected in a fraction collector and analysed for the ion, e.g. NO_3-N, or chemical applied. In the field, porewater or soil samples are taken at discrete depths and times following application of a pulse and likewise analysed. Concentrations plotted against time yield the C_{pulse} curve and when the concentrations are normalised, i.e. divided by the initial concentration per unit time, the **E** curve. Using material balances for the C_{pulse} curve yields

$$A = \int_0^\infty \mathbf{C}dt \cong \sum_i C_i \Delta t_i = \frac{M}{v} \qquad \textbf{(2.15)}$$

$$\bar{t} = \frac{\int_0^\infty \mathbf{tC}dt}{\int_0^\infty \mathbf{C}dt} \cong \frac{\sum_i \mathbf{t_i C_i \Delta t_i}}{\sum_i \mathbf{C_i \Delta t_i}} = \frac{\mathbf{V}}{\mathbf{v}} \qquad \textbf{(2.16)}$$

where A is the area under the C_{pulse} curve, C the concentration (kg or moles m^{-3}), t time (s), $\bar{t}$ the mean of the C_{pulse} curve (s), M mass of chemical (kg or moles), v the velocity (m^3s^{-1}) and V the volume of the soil porewater (m^3), Levenspiel (1999). The **E** curve, derived by dividing the concentrations on the ordinate by Mv^{-1}, has an area $\int_0^\infty E\, dt = 1$.

2.4 Soil water movement

Movement of water through a soil profile is dependent on the size distribution of the pores in a soil. The governing principle behind water movement in soil is Darcy's

law, which states that the flow of fluid through a porous medium is proportional to the gradient in total head acting on that fluid:

$$q = -K(h)\frac{\delta H}{\delta z} \qquad \textbf{(2.17)}$$

where
q = Darcy flux or volume of water flowing through a unit surface area per unit time
K(h) = hydraulic conductivity of the soil, dependent on the matric potential (h) of the soil pore water – at saturation K(h) becomes K_{sat}
H = total hydraulic head
z = distance.

Flow of water in a soil can be described as steady state or transient (non-steady) state flow.

2.4.1 Steady state water flow in soil

Steady state water flow occurs in a soil when there is a constant head gradient. The Guelph Permeameter (Soil Moisture Equipment Corporation, 1991) uses such a principle by creating a constant well head in an augered hole for measuring the field-saturated hydraulic conductivity (K_{fs}) of unsaturated soils. In a paper entitled 'An analysis of the percolation test based on three dimensional saturated-unsaturated flow from a cylindrical test hole', Elrick and Reynolds (1986) calculated K_{fs} from flow rates through a cylindrical hole in soil by the following expression:

$$K_{fs} = \frac{CQ}{\left[2\pi H^2 + \pi a^2 C + 2\pi H_w\right]/\alpha} \qquad \textbf{(2.18)}$$

where
K_{fs} = field-saturated hydraulic conductivity (m/s)
C = dimensionless shape factor
Q = steady intake of water (m^3/s)
H_w = height of water in the well (m)
a = radius of the well (m)
α = ratio of K_{fs}/φ_m where φ_m is the matric flux potential (1/m)

The tension infiltrometer (Reynolds, 1993) is another apparatus for measuring steady state flow in unsaturated soil and is useful for determining hydraulic conductivity values at low tensions.

2.4.2 Transient (non-steady) state water flow in soil

When transient state flow occurs in soil, the volume of water entering a column of soil does not equal the volume leaving it (Hanks and Ashcroft, 1980). This means that changes in storage can be determined from the difference between inflow and outflow. Darcy's equation (Equation 2.17) can be adapted for transient flow conditions by combining it with the continuity equation which is:

$$\frac{\delta\theta}{\delta t} = -\frac{\delta q}{\delta z} \qquad \textbf{(2.19)}$$

where
t = time

Combining equations 2.17 and 2.19 gives the Richards equation:

$$\frac{\delta\theta}{\delta t} = -\frac{\delta}{\delta z}\left\{K(\theta)\frac{\delta H}{\delta z}\right\} \pm U(z,t) \qquad \textbf{(2.20)}$$

where
U = a source or sink term ($m^3/m^3.d$)

This is a non linear equation that can be difficult to solve. Values of hydraulic conductivity change greatly with variation in volumetric water content. Variations in soil density can also affect the hydraulic conductivity. Mulqueen and Rodgers (2001), using a non-steady falling head percolation test, have provided charts to determine K_{fs}.

2.5 Determination of water and solute flux

2.5.1 Water flux

When determining the flux of a solute (e.g. nitrate) that moves through a soil profile it is necessary to calculate the mass of water entering and leaving the profile. When considering a mass balance for water, the following hydrological elements must be considered:

- precipitation and irrigation
- evapotranspiration
- drainage
- change in soil water storage.

A simple equation can then be applied to determine the soil water storage (Wagenet, 1986):

$$P + I = ET + R + \Delta\theta + D \qquad \textbf{(2.21)}$$

where
P = precipitation
I = irrigation
ET = evapotranspiration
R = runoff
$\Delta\theta$ = change in soil water storage
D = drainage.
This equation is then solved for drainage:

$$D = P + I - ET - R - \Delta\theta \qquad \textbf{(2.22)}$$

The terms on the right hand of Equation 2.22can be measured or estimated. In some cases R = 0 where a field is level, and I = 0 when there is no irrigation involved. Precipitation can be measured using a standard rain gauge and evapotranspiration can be estimated using an evaporimeter or by applying the Penman formula.

The soil water storage can be estimated by applying the following expression:

$$\Delta\theta = \int_0^z \theta(t_1)dz - \int_0^z \theta(t_2)dz \qquad \textbf{(2.23)}$$

where
z is the depth of the profile
$\theta(t_1)$ = volumetric water content at time, t_1
$\theta(t_2)$ = volumetric water content at time, t_2
Because of the uniformity of soil water content, equation 2.23 cannot be applied to Irish soils.

2.5.2 Solute Flux

Solute fluxes can be calculated a number of different ways and these are outlined by Wagenet (1986). One method of calculating solute flux is by applying the average concentration method. The water flux from a particular depth is multiplied by the average solute concentration at that depth to give a solute flux:

$$q_s = \frac{(q_w)(c_j + c_{j+1})}{2} \qquad \textbf{(2.24)}$$

where
q_s = solute flux
q_w = water flux
c = solute concentration
The application of this method requires accurate determination of soil water flux.

2.6 Preferential Flow

Preferential flow is the process whereby water and solutes move by preferential pathways through a porous medium (Helling and Gish, 1991). Under saturated conditions localised wetting fronts, e.g. in cracks, may extend considerable depths by passing the matrix pore space. If preferential flow is taking place in a soil, the convection-dispersion equation may not be valid. Hanrahan (1977) observed fissures in Irish clay soil only on rare occasions and considered that fissuring is not widespread in Ireland.
There are three types of preferential flow:

- Macropore flow
- Fingering
- Funnel flow

2.6.1 Macropore Flow

In recent times, much attention has been given to flow of porewater through macropores, such as cracks, worm holes and root channels. This concern centres on their potential to increase infiltration and carry solutes more quickly through soil to groundwaters (Quisenberry and Phillips, 1976). Macropores are commonly found in topsoils of well graded soils and in clay soils under West-European climatic conditions where summer evapo-transpiration greatly exceeds rainfalls. Macropores are rare in Ireland below 0.6 m (Hanrahan, 1977, Daly, 2002) because of a wet climate and low activity clays. In unsaturated soil without macropores and fed by recharge (rainfalls + irrigations), essentially plug flow with dispersion is normally expected. Under these conditions, the mean residence time ($\bar{t}$) to any depth (z) can be calculated by dividing that depth by the mean daily pore velocity ($v_p = q\theta_v^{-1}$)

$$\bar{t} = \frac{z\theta_v}{q} \qquad \textbf{(2.25)}$$

where v_p is the mean pore velocity and q the mean daily recharge (rainfall + irrigation). This can then be compared with the experimental $\bar{t}$ derived from C_{pulse} curves for the various depths; agreement verifies plug flow with dispersion.

2.6.2 Fingering

Fingering occurs in the main as a result of wetting front instability and happens in layered soils (Hill and Parlange, 1972). Fingering in unsaturated soils may cause

solutes to move in columnar structures through the vadose zone at velocities approaching the saturated pore water velocity (Glass *et al*., 1989). Hill and Parlange (1972) describe fingering in layered soils when the upper layer is finer and less permeable than the lower layer. In a laboratory experiment, fine sand (100-50 μm) was placed over coarse sand (1000-500 μm) in a perspex chamber. It was discovered that the width of the fingers was a function of the characteristics of the soil. The wetting front became unstable and fingers formed resulting in higher fluxes of water and solutes. Such geometry was not observed at the experimental site.

2.6.3 Funnel flow

Funnelled flow occurs when sloping layers of soil cause water to move laterally, accumulating at a low region. Where funnelled flow occurs, fingering may also happen in a structured soil. Kung (1990) described funnelled flow using a tracer on a sandy soil in Wisconsin. The dye moved uniformly until it encountered a layer of coarse sand that acted as a capillary barrier. The dye then moved horizontally along the top of the coarse sand and eventually accumulated at a lower region where the dye started to move vertically downwards again. Such geometry was not observed at the experimental site.

2.7 Soil water retention

In an unsaturated soil, water is attracted to soil particles by a capillary force and this force is known as pore water tension or suction. The relationship between the water content, θ, and the suction is a basic property of a soil that is known as the soil water characteristic curve. Typical soil water characteristic curves are shown in Fig. 2.3.

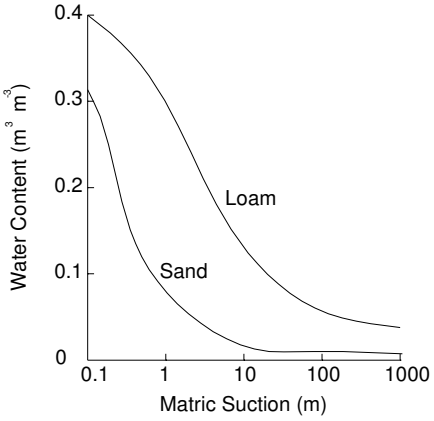

Fig 2.3 Soil water characteristic curves for a sand and a loam soil (Marshall *et al*., 1996)

Sand soils release more water at low suctions than loam soils (Figure 2.3). This is especially important when there is a solute such as nitrate present in the water.

2.7.1 Capillarity

In order to understand water retention in soil, it is necessary to examine the effects of soil capillary tension. Soil capillary tension is caused by adhesion of pore water molecules to soil particle surfaces and the attraction of the soil water molecules to each other (Kramer and Cullen, 1995).

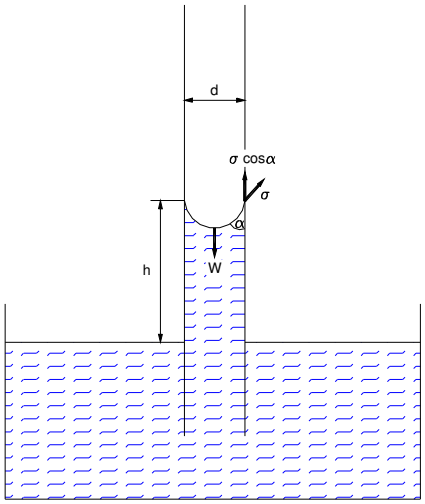

Fig 2.4 Capillary force diagram in a capillary tube

From Fig. 2.4, W is the weight of water acting downwards. The surface tension acting on the internal circumference of the tube is the lifting force. At equilibrium,

$$\text{Weight of water, } W = \text{Lifting force}$$

$$\frac{\pi d^2 h \rho_w g}{4} = \pi\, d\, \sigma \cos\alpha \qquad \textbf{(2.26)}$$

where
d = diameter of the capillary tube (pore size in soil, m)
h = height of water (m)
ρ_w = density of water (kg/m^3)
g = acceleration due to gravity (m/s^2)
σ = surface water tension against air (kN/m)
α = contact angle between the water and the capillary wall.

As $\alpha \rightarrow 0$, cos α becomes unity. $\rho_w g = 9.8$ kN/m^3 and $\sigma = 7.3 \times 10^{-5}$ kN/m

$$h = \frac{4\sigma}{d\rho_w g} \qquad \textbf{(2.27)}$$

solving, $$h = \frac{3 \times 10^{-5}}{d} \text{ m}$$

From the equation 2.27, it can be seen that as the diameter of the pores increases, the capillary rise decreases, i.e. height of capillary rise is inversely proportional to the diameter of the pore. Pore water suctions are high in small soil pores.

2.7.2 Hysteresis

A soil water characteristic curve in the drying mode differs from that in the wetting mode. This effect is known as hysteresis and is illustrated in Fig. 2.5 below.

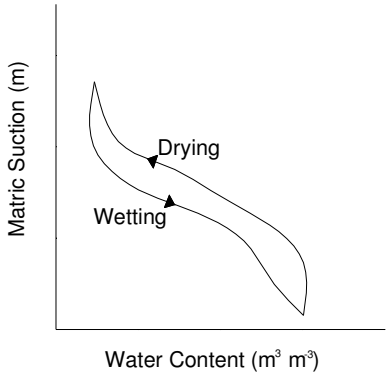

Fig 2.5 Effect of hysteresis on soil water retention curves

2.8 Nitrogen

Nitrogen (N) is a very important element when it comes to food production. Economic optimum plant production requires the application of chemical and organic N fertilisers to supplement the N derived from the mineralisation of organic matter. However, current levels of fertiliser usage are putting a strain on the world's environment and agriculture is a common source of pollution. In order to understand agricultural pollution from nitrogen it is useful to examine the nitrogen cycle (Fig. 2.6).

2.8.1 The Nitrogen Cycle

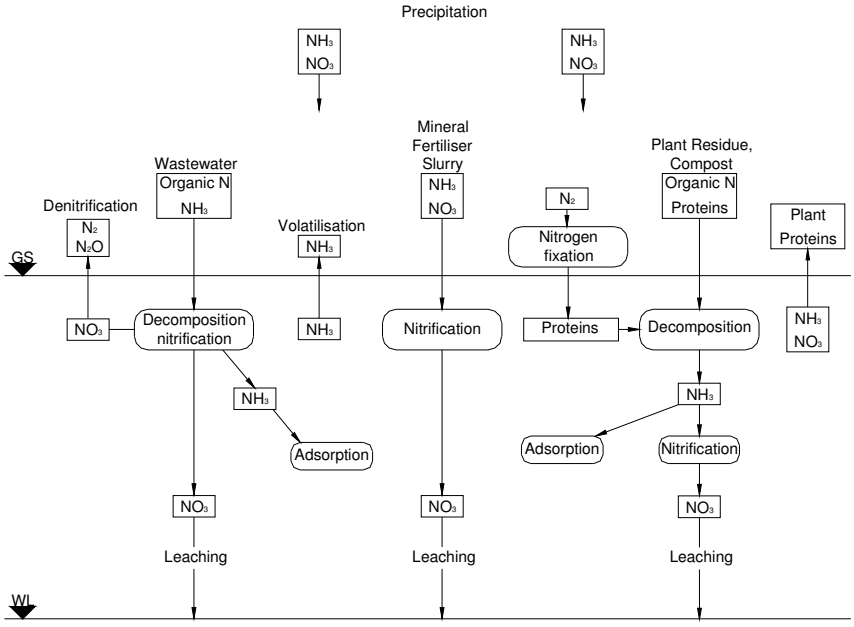

Fig 2.6 Generalised nitrogen cycle (adapted from Metcalf and Eddy, 2003)

Mineralisation and Immobilisation: Mineralisation is the process where organic compounds in soil are broken down to the ammonium ion (NH_4^+) with a release of carbon dioxide (CO_2). Immobilisation is the reverse process of mineralisation.

Denitrification: This can be defined as the microbial reduction of NO_3 to nitric oxide (NO), nitrous oxide (N_2O) and nitrogen gas (N_2).

Volatilisation: Ammonia volatilisation is the process where the ammonium ion (NH_4^+) is broken down into ammonia (NH_3) and the H^+ ion. NH_3 is a gas and is released into the atmosphere.

Nitrification: This is the process where ammonium (NH_4^+) is converted to NO_3-N by aerobic bacteria. *Nitrosomonas* converts ammonium to nitrite and then, *Nitrobacter* converts the nitrite to nitrate. These processes can be described by the following equations (Norton, 2000):

$$NH_3 + O_2 + 2H^+ + 2e^- \xrightarrow{\text{Nitrosomonas}} NH_2OH + H_2O \xrightarrow{\text{Nitrosomonas}} NO_2^- + 5H^+ + 4e^- \quad \textbf{(2.28)}$$

$$NO_2^- + H_2O \xrightarrow{\text{Nitrobacter}} NO_3^- + 2H^+ + 2e^- \quad \textbf{(2.29)}$$

Leaching: Nitrate is a negatively charged ion and is one of the most mobile ions in soil. Unless it is taken up by plants, it can be leached. Nitrate leaching is a major cause of low nitrogen use efficiency and contributes significantly to the loss of nitrogen from agricultural systems.
The principal issues relating to nitrate leaching are:

- Eutrophication of surface waters
- Increased production of nitrous oxide in receiving waters
- Increased nitrate concentration in drinking water

2.9 Nitrate leaching

The two main sources of nitrate for leaching are (Lægreid *et al*., 1999)

- Mineralisation of organic matter
- Applications of N fertiliser that is greater than the plant N uptake rate.

Research into nitrate leaching has been done mainly in the United States and Europe. Nitrogen loss in intensive agriculture is of particular concern and as a result of the European Community's Nitrates Directive in 1991 (Council Directive 91/676/EEC) member states are obliged to reduce the nitrate levels in surface and groundwater resulting from agricultural practice. Groundwater under 22 % of cultivated land in the EU has a nitrate concentration above the EU MAC (McKenna, 1998) so there is a clear need to reduce nitrates in groundwater across Europe.

2.9.1 Health concerns associated with nitrates

The health concerns of nitrate arise from excess concentrations in drinking water. The two conditions that have been associated with the over exposure to nitrate are Infantile Methaemoglobinaemia ('Blue Baby Syndrome') and Gastrointestinal Carcinogenesis. Methaemoglobinaemia occurs when nitrate is reduced to nitrite by bacterial nitrate reductase enzymes. When nitrite oxidises the ferrous ion of the oxyhaemoglobin molecule to ferric iron, the formation of methaemoglobin in blood can arise (Golden and Leifert, 1999). This condition is very rare in Europe. In the last 35 years there have been only 14 reported cases of infantile methaemoglobinaemia in Europe, all associated with domestic shallow wells contaminated with nitrate reducing bacteria (Cottrell, 1987). The link between dietary nitrate intake and gastrointestinal carcinogenesis (stomach cancer) is less clear. Epidemiological studies have failed to substantiate the claim that nitrate is a harmful dietary component, that causes carcinogenesis (McKnight *et al*., 1999).

2.9.2 Eutrophication as a result of excess nitrates

Enrichment with elevated nitrate levels in receiving waters contributes to the development of algal blooms and a consequent decrease in dissolved oxygen in the water. Eutrophication can limit water use and can increase the cost of water treatment. Eutrophication can occur naturally over time as a result of a build up of nutrients but very often the process is accelerated by increased agricultural activity. Phosphorus is most commonly the limiting nutrient in rivers and lakes while nitrogen is the limiting nutrient in seas and oceans (Hornung, 1999). The Organisation for Economic Co-operation and Development (OECD) has set guidelines as to when a lake has become eutrophic and its trophic status and they are presented in Table 2.1.

Table 2.1 OECD boundary values for open trophic classification system [annual (geometric) median values] (OECD, 1982)

Parameter	Oligotrophic	Mesotrophic	Eutrophic
Total P (μg P/l)	<10	10-35	35-100
Total N (μg N/l)	**661**	**753**	**1875**
Chlorophyll a (μg/l)	< 2.5	2.5-8.0	8-25
Chlorophyll a, peak value (μg/l)	<8.0	8-25	25-75
Sechi depth (m) min.	> 3	3-1.5	1.5-0.7

Eutrophication resulting from toxic blue-green algae can be potentially hazardous to humans and the presence of cyanobacteria can be toxic to fish and mammals (Codd, 1995).

2.10 Nitrogen inputs

In order to understand nitrate leaching and what causes it, it is important to examine nitrogen inputs into a soil.

2.10.1 Fertiliser

Chemical fertiliser is necessary to ensure a high quantity and quality of grass production, which will ultimately give a higher yield of milk. There are many types of commercial N fertiliser available, but the two main types are urea (46% N) and calcium ammonium nitrate (CAN, 27% N). Generally, urea is used in the spring and CAN is used later in the growing season. Application rates of fertiliser vary depending on the number of livestock units per unit area of the farm (LU/ha), and can vary from 100 kg N/ha to 390 kg N/ha for 2.1 and 3.0 LU/ha, respectively (Department of the Environment, Department of Agriculture Food and Forestry, 1996).

Urea

Urea is the most concentrated solid N fertiliser available. The commercial synthesis of urea involves the combination of ammonia and carbon dioxide at high pressure to form ammonium carbamate which is subsequently dehydrated by the application of heat to form urea and water (EFMA, 2000 a):

$$2NH_3 + CO_2 \longleftrightarrow \underset{\text{ammonium carbamate}}{NH_2COONH_4} \longleftrightarrow CO(NH_2)_2 + H_2O \quad \textbf{(2.30)}$$

In the soil, urea is converted from carbamide nitrogen to ammonium ions (NH_4^+) by a series of enzyme reactions. Under normal soil conditions, the ammonium ions are adsorbed by the soil (i.e. become attached to the negatively charged soil particles) and the nitrogen becomes available to the plant, either in its ammonium form or as nitrate following microbial oxidation (EFMA, 2000 b).

Calcium ammonium nitrate (CAN)

The production process of CAN comprises three main unit operations (EFMA, 2000 c):

Neutralisation:- An exothermic reaction where neutralisation of nitric acid with ammonia gas produces ammonium nitrate and steam. The steam is also purified in this process

Evaporation:- Evaporation removes the majority of the water which is present in the ammonium nitrate solution to the desired water content and prepares it for the solidification process. A moisture content of 1% is required for a prilled fertiliser

Solidification:- The ammonium nitrate is formed into droplets which drop down a tower which is air cooled and then solidified.

The chemical formula for ammonium nitrate is NH_4NO_3 and CAN is a mixture containing ammonium nitrate and calcium carbonate ($CaCO_3$). CAN supplies NH_4^+ and NO_3^- directly for plant uptake, whereas urea must be hydrolysed by enzymes produced by bacteria. While urea is the cheapest form of N, it is only used in spring.

2.10.2 Dairy wastewater

Dairy wastewater consists of washings from milking parlours, dairies, run-off from holding yards for cows assembled for milking; it can also include run-off from yards, silos, silage pits and contaminated rainwater. On an intensive dairy farm, large volumes of dairy wastewater are produced. Dairy wastewater is high in biochemical oxygen demand (BOD) and nutrients (N and phosphorus (P)) which are beneficial when spread on land. Healy *et al*. (2004) found that the BOD of dairy wastewater was in the range of 1800 to 6000 mg/l. Most of the inorganic N in dairy wastewater is in the ammonium form (NH_4-N) with low concentrations of NO_3-N. Richards (1999) tested dairy wastewater over a period of 13 months and found seasonal variations; the highest NH_4-N value was 284 mg/l in mid-August while the lowest value was observed in February at a concentration of 1 mg/l. Ryan (1990) reported that the NH_4-N concentrations were 43 and 126 mg/l in winter and summer, respectively. ADAS *et al*. (1994) reported NH_4-N winter concentrations in dairy wastewater of 94 mg/l and summer concentrations of 586 mg/l. Healy *et al*. (2004) found that the average NH_4-N concentration was 84.8 mg/l with the highest value being 265 mg/l. It is a variable effluent.

Volumes of dairy wastewater produced per cow have been estimated by many investigators. Department of the Environment, Department of Agriculture Food and Forestry (1996) in the Code of Good Agricultural Practice have stated that the average volume of dairy wastewater produced per dairy cow is 30 l/cow/day. ADAS (1985) report that the amount of dairy wastewater produced is 35 l/cow/day. In this study, the mean volume of dairy wastewater produced per cow in 2002 was 71.2 l/cow/day, due to the higher usage of cleaning waters under experimental husbandry conditions.

Pumphouse flows and depth of application of dairy wastewater
On different dates in July and August 2002, buckets were placed under an irrigator at Moorepark Research Farm to determine the irrigation hydraulic load. The buckets were numbered and their plan area measured. A stone was placed in the bottom of the bucket to prevent the wind from blowing it over. The buckets were placed under the irrigator and the volume of dairy wastewater was measured and the irrigation hydraulic load was calculated and the instantaneous flow rate was noted. The average depth of application was 6.70 mm with a marked trend for higher applications at the extremities of the irrigator (Fig 2.7)..

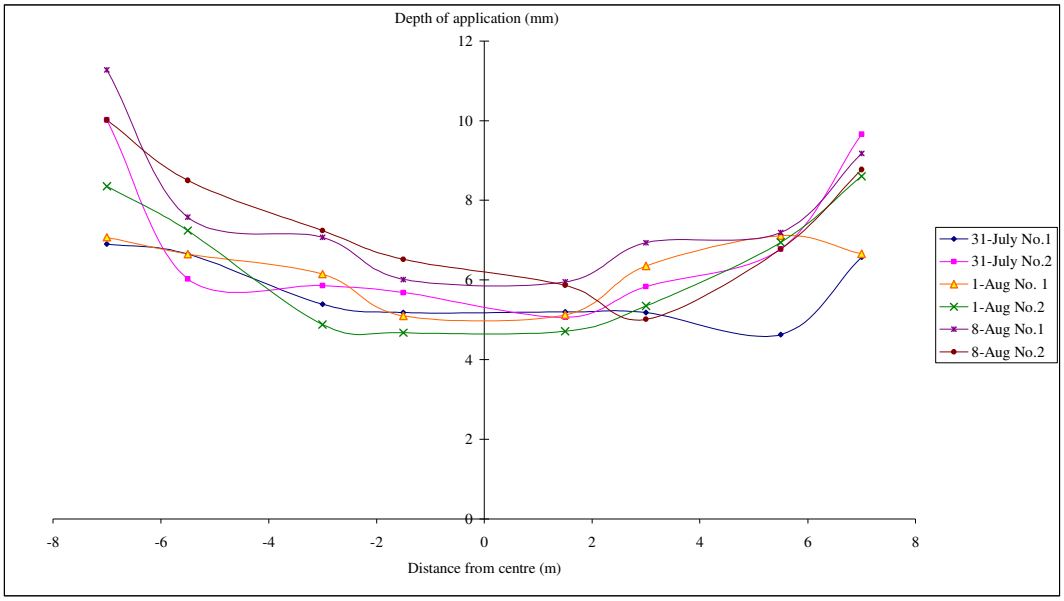

Fig. 2.7 Graph of depth of application from irrigator versus distance from centre of irrigator

2.10.3 Slurry
Slurry is a mixture of urine and faeces collected over the winter period when the cows are housed. Slurry is spread as early as practicable in the growing season. The Department of the Environment, Department of Agriculture Food and Forestry Code of Good Agricultural Practice recommends that half of the slurry produced in the growing season be landspread by July 1st and the remainder spread by 30th September. Landspreading is better in drier conditions when the soil has low pore water content. The Department of the Environment, Department of Agriculture Food and Forestry, Ireland (1996) states that the volume of neat excreta (faeces and urine) is 330 l/week for a 560 kg dairy cow. The nutrient content of cow slurry was analysed by Bouchier (1995) who found that total N was 3820 mg/l, NH_4 -N was 1140 mg/l and NO_3 -N was 82 mg/l.

2.10.4 Dung/urine patches
Dung and urine patches occur where animals excrete while grazing pastures in summer. Approximately, 80% of the N consumed by a cow is returned to the soil in the form of urine and dung (Addiscott *et al.* 1991). These patches contain more N than the grass can utilise and NO_3-N may leach as a result. Cows urinate 2 l at a time over an area of about 0.4 m^2 which can represent an application of between 400 and 1200 kg N/ha. Urine patches can also increase the soil pH which affects the nitrogen processes in the soil (Condon *et al.*, 1998). Dung patches can cause grassland to

accumulate organic matter and large amounts of N can be released through mineralisation.

2.10.5 Atmospheric N deposition

Atmospheric deposition of N can occur due to the presence of N compounds in the atmosphere. The majority of emitted NH_3 and NO_x is deposited with rainfall. Total annual deposition of N from the atmosphere in north-western Europe varies from 10 – 40 kg N/ha (EMEP, 1997). Nitrate can also be formed by passage of lightning discharges through air (N_2 and O_2).

2.10.6 Silage effluent

Run-off of effluent from a badly managed silage pit can result in nitrate leaching. Effluent from a silage pit should be diverted into a wastewater or slurry tank for landspreading. Bouchier (1995) reported that silage effluent contained a total N concentration of 1833 mg/l, a NO_3–N concentration of 37 mg/l and an NH_4-N concentration of 471 mg/l. The BOD value measured was 55,000 mg/l which was higher than that for cow slurry reported in the same experiment.

2.11 Porous ceramic cups

Porous ceramic cups are widely used for sampling soil porewater in unsaturated soils in the field as functions of depth and time (Rhoades and Oster, 1986). Following saturation of the porous ceramic cup, it is inserted to the desired depth according to procedures described by e.g. Rhoades and Oster (1986) and Soil Moisture Equipment Corporation (1997, 1999). It is then placed under vacuum, commonly 50-85 kPa (Rhoades and Oster, 1986), although in soils of high porewater pressures lower suctions of 10 kPa can be used and indeed are desirable to sample drainage of porewaters percolating downwards to the ground watertable, as porewater movement becomes very slow at matric potentials of <-30 kPa. Depending on the soil porewater content, porewater samples can be collected at 1-3 day intervals. Problems identified with the use of porous ceramic cups are variations in concentrations due to: the disruption of drainage patterns caused by sampling (Corwin, 2002); the rate of extraction of the porewater; the rate of porewater movement and; inhomogeneity of porewater concentrations (Rhoades and Oster, 1986). Spatial variability of porewater concentrations at the same depth requires large numbers of samplers (Hansen and Harris, 1975; Cuttle, 1992) to obtain reliable mean concentrations of solute in an area. Large ceramic cups are best (Silkworth and Grigal, 1981). Nevertheless, porous ceramic cup samplers are considered to be the most reliable instrument for sampling soil porewaters (Corwin, 2002). If each of a series of porous ceramic cups at sequential depths in a soil is regarded as a point sampler (Biggar and Nielsen, 1976) and is operated at low suction, such an arrangement can provide a good indication of concentration changes of solutes in soil porewaters in response to inputs at the soil surface as they (the porewaters) drain downwards over time. A concern with the use of porous ceramic cups in structured soils is bypass flow that may not be sampled adequately or at all in soils with fissures, worm-holes and root channels. For such soils, zero-tension samplers have been recommended (Corwin, 2002). Many of the problems reported have been in saturated soils, e.g. Beasley, (1976) and Shaffer *et al*., (1979) and under flooding infiltrometers. Zero-tension samplers primarily sample saturated flows and remain dry in unsaturated soils. Experience with deep test pits all over Ireland by the authors indicates that cracks, fissures and wormholes are very rare below the topsoil (0.2-0.6 m) in Ireland as also stated by Hanrahan (1977) and Daly

(2002). In Ireland, recharge rates are two orders of magnitude less than the saturated hydraulic conductivity of free-draining soils indicating that under ambient rainfall conditions, the infiltration is supply controlled and macropore flow is not significant (Hillel, 1980). Infiltration of a liquid front into an unsaturated fractured soil exhibits three main flow periods (Nitao and Buscheck, 1991): [1] at early times, flow is determined by the fracture inlet and gravity flow in the fracture; [2] at intermediate times, matrix imbibition retards flow in the fracture and; [3] at late times the matrix adjoining the fissure approaches saturation and the flow approaches a limiting velocity if the crack continues to be supplied with water. However, these transient changes are sensitive to fracture properties (Wang and Narasimhan, 1985). Because of supply-controlled infiltration resulting from low rainfall intensity and due to the rarity of macropores below about 0.6 m, bypass flow is unlikely to be significant in Irish soils

2.12 Summary

Chapter 2 provides background theory behind solute and water movement through soil. The nitrogen cycle and nitrogen inputs into soil have also been discussed.

CHAPTER THREE

Soil Measurements and Field Instrumentation

Measurements of soil physical properties are important to understand nitrate movement through soil. Soil types, densities, porosities and hydraulic conductivities give a good indication as to how water will move in a soil profile. However, in a free-draining soil, the actual rate of movement of water through soil downwards is determined by the net recharge rate, that is the mean (rainfall – evapotranspiration) rate when there is no ponding or surface run-off.

3.1 Wet/dry densities

Density measurements were taken using two methods:

- Stainless steel cores
- Nuclear density gauge

3.1.1 Stainless steel cores

Stainless steel cores, of diameter 5 cm, measuring 100 cm^3 in volume were driven into the soil using a hammer and were then dug out using a spade. Excess soil from the top and bottom of the core was trimmed using a spatula and the sample was sealed using plastic lids to contain soil water. The mass of the soil in the core was recorded and the bulk density (ρ_s) was calculated using the following formula:

$$\rho_s = \frac{m_s}{v} \qquad \textbf{(3.1)}$$

where

m_s = mass of soil and water (kg)

v = volume (m^3) of the stainless steel core

The sample was dried at 110 °C for 24 hours and the mass of dry soil was recorded (m_d). The dry bulk density (ρ_d) was calculated using the following formula:

$$\rho_d = \frac{m_d}{v} \qquad \textbf{(3.2)}$$

Stainless steel cores were difficult to use at depth due to the stony and gravelly nature of the deeper layers of soil at Curtin's farm, Moorepark.

3.1.2 Nuclear density gauge

The model 5001P nuclear density gauge (Fig. 3.1) was manufactured by Humboldt Scientific and it was specifically designed to measure the water contents and bulk densities of soils to a depth of 300 mm. The adsorption of gamma rays by the material can be related to its bulk density. The Humboldt gauge has a microprocessor with built in calibrations which give readings in bulk density. An isotope of cæsium (^{137}Cs) with a half life of 30.17 years is used to produce the gamma radiation. The standard calibration procedure is based on a soil having 50% limestone and 50% granite derived particles. The measurement of soil water content is based on the slowing down of fast neutron radiation, which is a function of the hydrogen concentration of materials. Errors may occur due to the presence of elements such as boron. If a material contains hydrogen which is not removed during an oven drying procedure,

errors can also occur. As Irish soils are low in boron and the Moorepark soil has minimal swelling clays, such errors are not significant in this investigation.

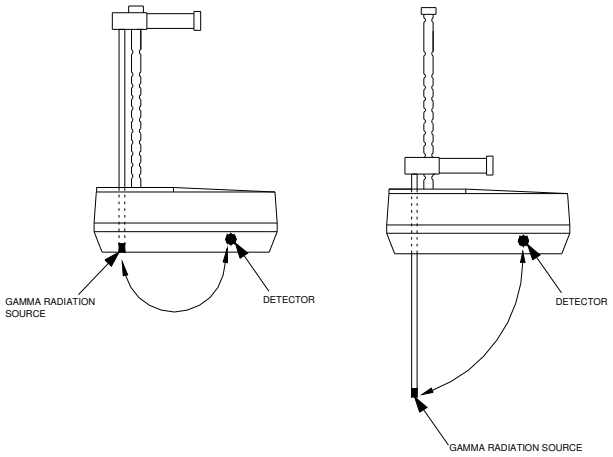

Fig. 3.1 Nuclear density gauge in (a) backscatter mode and (b) direct transmission mode

The nuclear density gauge can be used in backscatter mode or direct transmission mode. Backscatter mode involves placing the radiation source and the detector on the same side of the material as shown in Fig. 3.1 (a). The direct transmission mode (Fig. 3.2 (b)) involves putting the material between the radiation source and the detector giving a more accurate measurement of density (Bouchier, 1995). Water contents (MC) recorded in the soil must be adjusted by a 'k' factor to give a more accurate value (Humboldt Scientific, 1988):

$$k = \frac{\%MC_{oven} - \%MC_{gauge}}{\%MC_{gauge} + 100} \quad \textbf{(3.3)}$$

$$\%MC_{adjusted} = [k \times (\%MC_{gauge}+100)] + \%MC_{gauge} \quad \textbf{(3.4)}$$

3.2 Hydraulic conductivities

Two different methods for measuring hydraulic conductivities were used in the field:

- Percolation test method
- unsteady drainage flux method

3.2.1 The percolation test method

The percolation test method is a simple field method to determine the field-saturated hydraulic conductivity of soil. A 300 mm square hole was excavated to a depth of 400 mm. The sides and bottom of the hole were scratched with a wire brush to remove any compacted soil. At 10.00 am on Day 1, the hole was filled with clear water and the surrounding soil was flooded and the water was allowed to percolate through the soil and the surrounding soil again was field-saturated. This procedure was repeated at 5.00 pm later the same day and the water was allowed percolate overnight. At 10.00 am on Day 2, clear water was poured into the hole again. The water was allowed percolate until the water reached the 0.3 m level. The time in minutes, was recorded for the water level to drop from 0.3 m to 0.2 m while at the same time maintaining the surrounding soil field-saturated by spray irrigation. The hole was refilled to 0.3 m and the time taken for the water to drop to 0.2 m was recorded again with field-saturated

conditions in the surrounding soil. Three tests were completed. The average time taken to drop from 0.3 m to 0.2 m was taken and this value was divided by 4 to give the time (t_m) taken to drop, on average, 25 mm

Mulqueen and Rodgers (2001) modelled this geometry and K_{fs} can be determined from a measured t_m value using their Fig. 3.2.

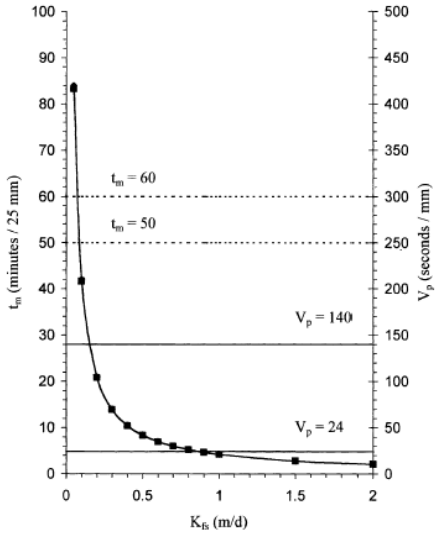

Fig. 3.2 Graph for determining K_{fs} from a calculated t_m value (Mulqueen and Rodgers, 2001).

3.2.2 The unsteady drainage flux method

This method of determining the unsaturated hydraulic conductivity is based on Darcian analysis of transient soil water content and hydraulic head profiles during vertical drainage following heavy irrigation or rainfall. The procedure is suitable for measuring K(h) in free draining soils in the range near saturation to field capacity, the range in which significant unsaturated flow occurs.

The equation for describing one-dimensional, isothermal, nonhysteretic, unsaturated flow of water during drainage is (Green *et al*., 1986):

$$\frac{\delta\theta}{\delta t}(z,t) = \frac{\delta}{\delta z}\left[K(h)\left\{\frac{\delta H}{\delta z}(z,t)\right\}\right] \qquad \textbf{(3.5)}$$

where

$\theta(z,t)$ = transient volumetric water content
$H(z,t)$ = hydraulic head, a function of soil depth and time
$K(h)$ = unsaturated hydraulic conductivity dependent on the pore water pressure head
z = vertical distance
t = time

The initial condition for Equation 3.5 is the soil water profile at the moment infiltration of water at the soil surface ceases. The surface is covered to prevent evaporation so zero flux is the upper boundary condition at z = 0. Equation 3.5 is integrated as follows:

$$\int_0^{z1} \frac{\delta\theta(z,t)}{\delta t} dz = K(h) \frac{\delta H(z,t)}{\delta z} \Big|_{z1} \qquad (3.6)$$

Equation 3.6 is used to determine K(h) at desired depths of z_1 from analyses of θ (water content probe) and H (tensiometer) profiles measured at frequent time intervals.

To determine K(h) using the unsteady drainage flux method, a 1.2 m diameter steel ring was driven into the ground in a plot 3 m x 3 m in plan. A multi-point tensiometer was installed to a depth of 0.5 m and tensiometers were installed to a depth of 2.0 m. An aluminium neutron probe access tube was also installed for water content determination. A 1.5 m x 1.5 m (plan) steel hut was constructed and placed over the ring to prevent any infiltration of rainfall or evapotranspiration. A section of the experimental setup is shown in Fig. 3.3.

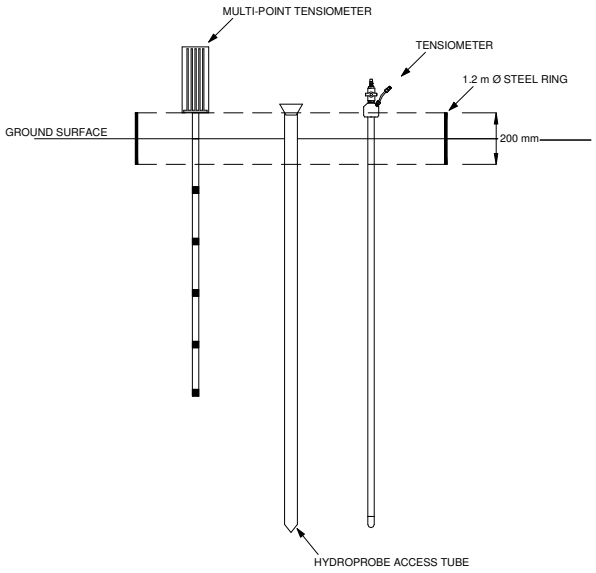

Fig. 3.3 Layout of instrumentation for unsteady drainage flux method

Once the instrumentation was set up, the procedure was as follows:

1. the inside of the steel ring was filled and the 3 m x 3 m plot was flooded and the rate of infiltration was measured
2. the soil water content and tensiometer readings were recorded
3. the water supply was disconnected and the time when the ponded water disappeared was recorded. The time at which this occurred was taken as t = 0
4. the water content and tensiometer readings were taken frequently for three weeks
5. equation 3.6 was used to determine unsaturated hydraulic conductivity

3.3 Soil water characteristic curves

The soil water characteristic (SWC) curve (also referred to as the soil pF curve) is an important soil function that describes the relationship between soil water content and suction under equilibrium de-sorption conditions. This relationship is used for many soil-water related investigations such as water conservation, irrigation scheduling, soil water storage and movement, and solute migration. It is also used to estimate soil

parameters such as unsaturated hydraulic conductivity, chemical diffusivity, water storage, thermal conductivity and shear strength. It is affected by soil structure, texture, pore size geometry and pore size distribution. Several relationships in the literature relate the SWC curve and unsaturated soil properties. For example, the hydraulic conductivity function for an unsaturated soil can be estimated by using its saturated hydraulic conductivity and the SWC curve (Marshall, 1958; Mualem, 1986). Similarly, because the SWC curve defines the degree of saturation corresponding to a particular suction, it can be used to estimate the particle size and pore size distribution of the soil (Fredlund and Rahardjo, 1993).

Since the SWC curve is used as the basis to predict other unsaturated parameters, it is important to have an accurate characterisation of this function for a particular soil. Laboratory measurements were carried out to establish a relationship between soil water content and soil water suction. Soil cores were collected at 0.05, 0.15, 0.25, 0.50, 0.75, 1.0, and 1.5 m depths in test pits. Undisturbed samples were taken by pushing 100 cm^3 stainless steel cylinders into the soil. The cylinders were dug out and the excess soil was trimmed. The intact cores were saturated and subsequently drained on tension tables using a hanging water column up to 10 kPa suction and a vacuum pump arrangement up to 80 kPa. The equilibrium water contents were determined by weighing the soil filled cylinders at each corresponding suction, when they had achieved constant weight. The dry bulk density was obtained by dividing the oven-dry weight of the soil cores for the respective depths at the end of the tests by 100 cm^3 and converting to kg/m^3. The porosity (η) was estimated (i.e. $\eta = 1 - \frac{\rho_d}{2650}$) by assuming the particle density of soil to be 2650 kg/m^3 and ρ_d the dry bulk density of the soil at its corresponding depth. A diagram of the apparatus used to determine the soil water characteristic curves is shown in Fig 3.4.

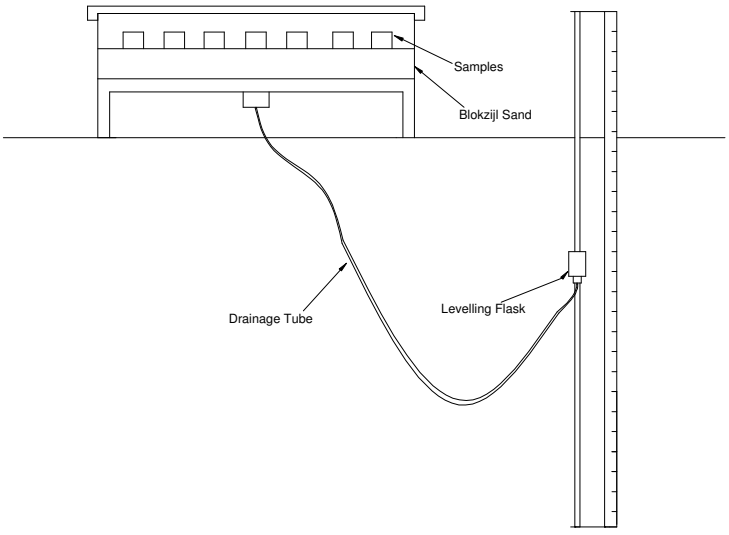

Fig. 3.4 Layout of pF curve apparatus

3.4 Field instrumentation

In order to understand the movement of nutrients in the field experiment, the site was well instrumented. Hydraulic gradients and the zero-flux plane in the experiment were determined using tensiometers. The zero flux plane is the plane in the soil profile

where soil pore water is neither moving up nor down. Soil water moves upwards as a result of evapotranspiration and moves down to drainage. Tensiometer data also give an indication as to when leaching is likely to begin. The NO_3-N solute concentrations in the soil were determined using porous ceramic suction cups to depths of 1.5 m and pressure vacuum ceramic cups below 1.5 m. They were installed at various depths down to 3 m and samples were taken once weekly in summer and twice weekly in winter.

A 0.4 ha site was chosen in Curtin's Farm, Teagasc, Moorepark, Fermoy, Co. Cork. The farm has soil that is typical of a nitrate sensitive zone. Ten plots, measuring 8 m x 8 m each (Fig. 3.5), were marked out and instrumented with ceramic suction cups, tensiometers and neutron probe access tubes as illustrated in Fig. 3.6. The plots were separated by a 3-m wide buffer strip.

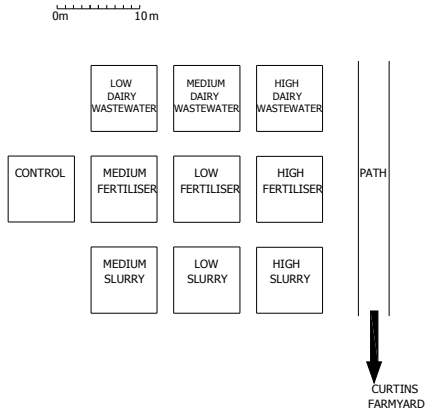

Fig. 3.5 Layout of plots in 0.4 ha site

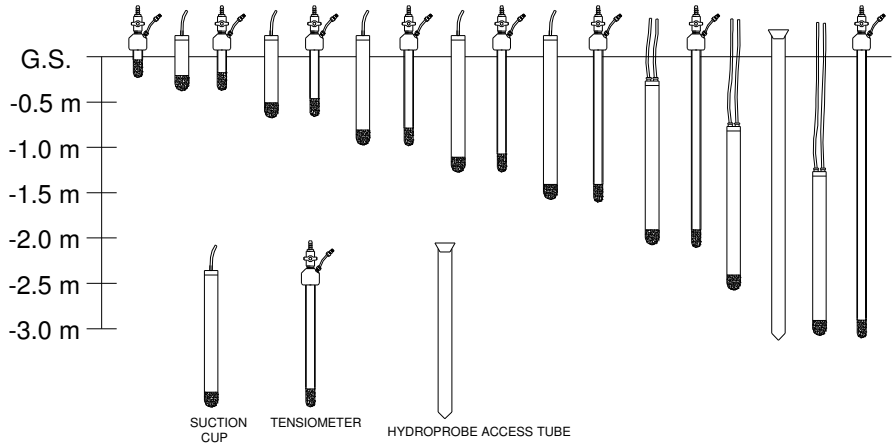

Fig. 3.6 Typical plot profile

Nine of the plots were treated at low, medium and high rates as follows: three plots with chemical nitrogen fertiliser, three plots were treated with dairy wastewater and three plots received slurry applications. Fertiliser was applied at rates of 174, 286 and 387 kg N/ha (Table 4.6). Dairy wastewater was applied twice annually at rates of 10 mm, 25 mm and 50 mm per application. Slurry was applied once per year at 15 m^3/ha,

30 m^3/ha and 45 m^3/ha. A control plot was set up and this received no N applications. A typical plot profile with instrumentation is illustrated in Fig. 3.6.

3.4.1 Tensiometers

Hydraulic potentials were measured using tensiometers. There were two types of tensiometers used in this study: standard ceramic cup tensiometers and a multipoint mercury-water manometer tensiometer.

Tensiometers

The tensiometers used in this study were modified from tensiometers manufactured by Soil Instruments (UK). They consisted of:

1. porous ceramic cup
2. high density plastic tube
3. nylon tubing
4. airtight cap with valve.

The tensiometers were adapted by attaching a hypodermic syringe reservoir onto the nylon tubing and by sealing the reservoir with a septum stopper.

Before installation, the ceramic cup was saturated. This was done by inserting the ceramic cup into a tank of de-aired water for 24 hours. A small vacuum was applied to the tensiometer to break the surface tension between the water and the ceramic. Each tensiometer was tested to a pressure of 100 kPa to check for leakage. The valve on the tensiometer was opened and water was poured through the syringe reservoir. When water flowed out the top of the tensiometers – above the valve – without any air bubbles, the valve was closed and a septum stopper was placed in the syringe reservoir to seal the tensiometer, leaving an air volume below the septum stopper. A tensimeter (Soil Measurement Systems, Arizona, USA) with a hypodermic needle connected to a pressure transducer, was used to take the gauge pressure readings of the tensiometer. The actual water tension in the soil around the porous ceramic cup is the number on the readout (in millibars/cm) of the tensimeter minus the length (cm) of the water column in the tensiometer (vertical distance between the water level in the tensiometer and the centre of the porous ceramic cup) (Fig 3.7).

Example

Depth of tensiometer = h_t = 30 cm
Height of water meniscus above G.S. = h_w = 15 cm
Height of water meniscus above ceramic cup = h = $h_w + h_t$ = 45 cm
Reading on tensimeter = h_a = -60 cm
Pore water pressure head at ceramic cup = h = $h_a + h_w + h_t$
h = -60 + 45 = -15 cm
Hydraulic head, H = -45 cm with datum at ground surface.

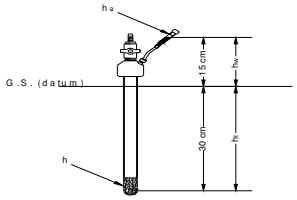

Fig. 3.7 Example showing calculation of hydraulic potentials.

3.4.2 Neutron Probe

The neutron probe is a non-destructive and time efficient method of measuring soil water contents in the soil. The Model 503 DR Hydroprobe Neutron Depth Moisture Gauge is manufactured by Campbell Pacific Nuclear International Inc. (CPN) and uses 50 mCi Americium-241-beryllium mixture as a source of fast neutrons.

Theory of operation

The hydrogen atom has the same mass as the high energy neutrons. Most hydrogen atoms present in the soil are present in the form of soil water. When the fast neutrons collide elastically with the hydrogen atoms, the fast neutrons become slow neutrons. The slow neutrons rebound back towards the probe and are absorbed by helium-3 gas in the probe. A higher energy state results and emitted photons can be detected as electrical pulses with an electronic counting device. The number obtained from the counting device is the count ratio (the ratio of slow neutron counts at a point in the soil to a standard count measured with the probe in its shield) and this is used to calculate the water content of the soil (Fig 3.8).

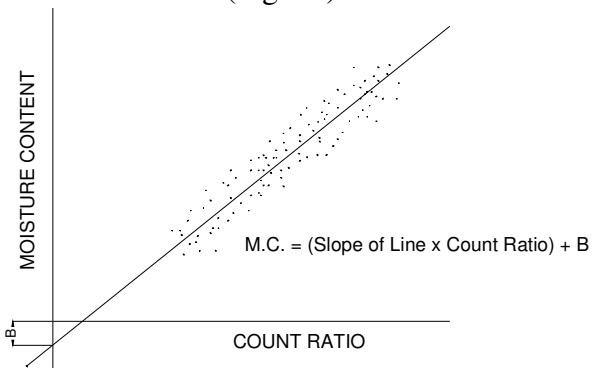

Fig 3.8 Calibration curve for neutron probe

Operating procedure

A 50 mm diameter aluminium tube was installed in three plots on the experimental test site, and each aluminium tube was sealed with a rubber bung. Aluminium tubes are used because they are virtually transparent to neutrons (Yuen *et al*., 1997). The probe was lowered in the aluminium tube to 0.3 m and a 64-second count was taken. The same procedure was repeated for depths of 0.6, 1.0, 1.5, 2.0 and 3.0 m.

Limitations

- error can occur due to random counting error – variation in neutron emission from the source.
- weekly measurements from the neutron probe only provide information at the time the measurement is taken.
- the effects of soil density on neutron probe calibration have been investigated by several researchers (e.g. Holmes, 1966; Greacan and Schrale, 1976). A change in density could affect the neutron count. An increase in the soil density will mean an increase in soil bound hydrogen which can cause differences in values between locations. This effect is not likely to be significant at Curtin's Farm
- hydrogen atoms present in soil organic material will be detected; this is also likely not to be significant at the depths the measurements were taken.

3.4.3 Ceramic suction cups

The soil pore water samplers used in this study were manufactured by The Soil Moisture Equipment Corporation, USA. Two types of ceramic sampler were used: standard ceramic cup samplers and pressure-vacuum ceramic cup samplers.

3.4.3.1 Standard ceramic cup sampler

These samplers consisted of a 48 mm diameter ceramic cup (air entry value = 200 kPa) attached to a 48 mm diameter plastic tube which varied in length depending on depth of sampling. The tubes were sealed at the top - just above ground surface - by means of a rubber bung with a neoprene rubber tube which was used to place the sampler under vacuum. The sampler (Fig. 3.9 a) was sealed using a ring clamp that was placed over the neoprene tube (Fig. 3.9 b). Standard ceramic cup samplers can be used at any depth to 1.5 m.

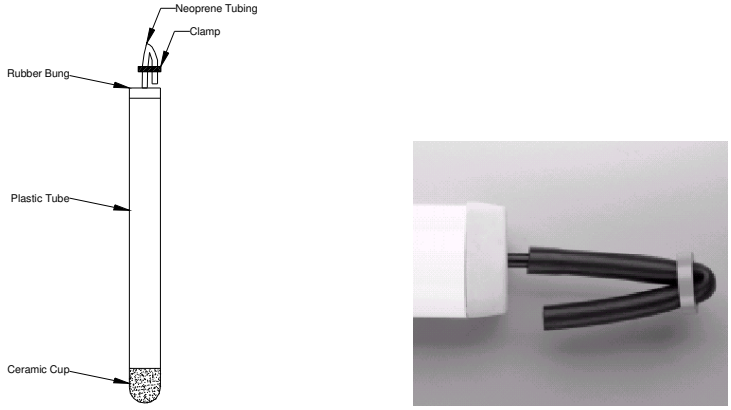

Fig 3.9 Standard ceramic sampler 1900 series (a) general layout of sampler and (b) top of sampler showing neoprene tubing and clamping ring (Soil Moisture Equipment Corporation, 1999)

3.4.3.2 Pressure-vacuum ceramic cup sampler

Because standard ceramic cup samplers do not work at a depth greater than 1.5 m, it was necessary to use pressure-vacuum ceramic samplers for deeper depths. Pressure-vacuum ceramic samplers can be used to sample soil pore water at any depth to 15 m (Soil Moisture Equipment Corporation, 1997). These samplers also consist of a 48 mm diameter ceramic cup (200 kPa air entry value) attached to a 48 mm diameter plastic tube which is 76 cm in length. There are two connections on the top of the sampler (Fig. 3.10). The white tube connector indicates the "Pressure/Vacuum" side and is used exclusively for pressurizing and evacuating the sampler. The green tube connector is used to recover the collected sample. Each pressure-vacuum ceramic sampler was pressure tested before installation to check for leakage/loose connections and to ensure that the ceramic cup was saturated. The sampler was placed under a positive pressure of 100 kPa and submerged in water. The presence of any air bubbles meant that there was a leak, and the sampler would not hold a vacuum.

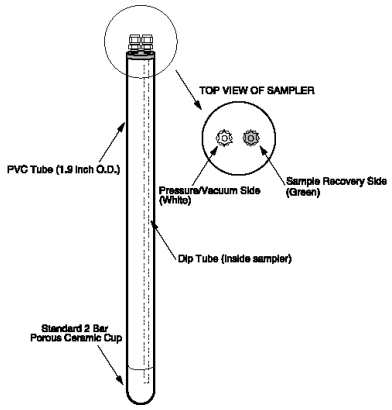

Fig 3.10 Layout of pressure-vacuum sampler (1920 series) showing pressure-vacuum connection and sample recovery connection (Soil Moisture Equipment Corporation, 1997)

3.4.4 Installation of equipment

Installation of equipment in the site took place in May, 2001. Because the soil in Moorepark is stony below a depth of 0.6 m, a mechanical augering device was used to core holes for the samplers. The mechanical auger used was manufactured by Giddings Soil Exploration Inc. and the holes were cored using a 60 mm Archimedes' screw powered by a 7.45 kW (10 hp) engine. The soil removed was sieved through a 3.35 mm sieve and a soil slurry suspension was made. The slurry suspension was poured into the hole to establish good hydraulic contact between the ceramic of the sampler/tensiometer and the soil. A bentonite seal was created on the top to prevent preferential flow down the sides of the sampler/tensiometer (ASTM, 2000).

3.5 Summary

Chapter 3 outlines the field and laboratory techniques used in the experiment. Field instrumentation was installed to determine the soil pore water content, pore water pressures and pore water NO_3-N concentrations. The equipment included:

1. tensiometers to determine the forces driving the nutrients into groundwater.
2. aluminium access tubes for a neutron probe to determine the water content in the soil.
3. ceramic suction cups to determine NO_3-N concentrations in the soil pore water.

The equipment and theory of operation has been discussed. The advantages and disadvantages of the equipment were presented. The installation of the equipment is detailed.

CHAPTER FOUR

Site Characterisation, Laboratory and Field Results of Leaching Tests

Various soil properties were determined in the laboratory and on site in order to assess the vulnerability of the soil to leaching. Different nutrient applications (fertiliser, dairy wastewater and slurry) were applied to the plots and pore water was sampled and analysed for NO_3-N. The following data were measured:

- wet densities, dry densities and porosities
- particle size analyses and plasticity values
- saturated and unsaturated hydraulic conductivities
- soil water retention curves
- soil water contents
- hydraulic potentials
- volumes of pore water samples
- nitrate-nitrogen concentrations in pore water samples

The physical properties of the soil are important for soil classification and to assist in clarifying the range of applicability of the experimental results. The type of soil also gives a good indication as to the likelihood of leaching occurring. The chemical properties of the soil give an indication as to how much organic matter is present in the soil which is important when considering the chemical processes that occur in soil such as nitrification and denitrification. The soil water retention curves indicate the water content in the soil at different suctions. Hydraulic potentials are used to determine the driving forces of water through the soil. Soil water contents are used to derive water fluxes.

4.1 Bed-rock geology of the Fermoy region

The geology of the East Cork region is shown in Fig. 4.1.

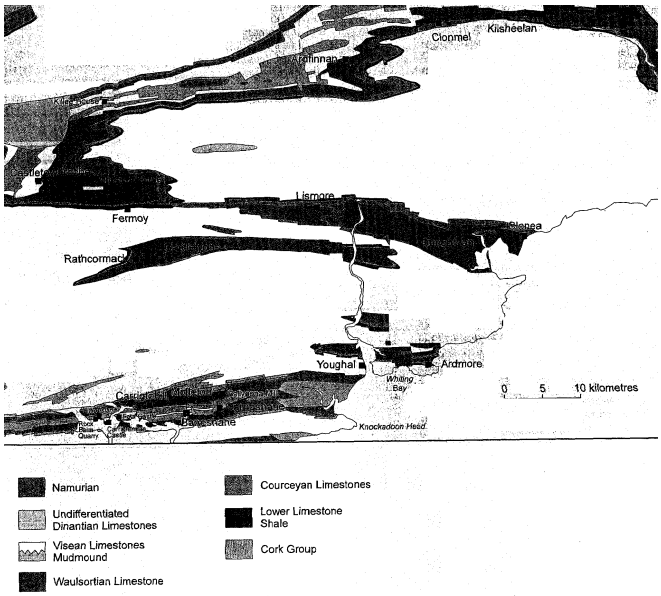

Fig. 4.1 Outcrop of carboniferous rocks in the East Cork region (Sleeman and McConnell, 1996).

The experimental site is located on Waulsortian Limestone, a karstic limestone which is vulnerable to nitrate pollution. Limestone areas are vulnerable to pollution where they have a thin overburden. Soils overlying limestone rock generally have good drainage characteristics and the rock is unable to appreciably attenuate nutrient concentrations in recharges (Bouchier, 1995). The aquifer is classed as a Regionally Important Aquifer.

4.2 Location and description of site

The site chosen was a 0.4 ha area on Curtin's Farm (Fig. 4.2) in the townland of Ballyvoskillakeen which has a geo-reference of N52º09 W8°16 and an altitude of 65 m above sea level. It is gently undulating lowland with a glacial drift that is derived mainly from Old Red Sandstone and Carboniferous Limestone (glacial) deposits. The slope of the site is 2° north.

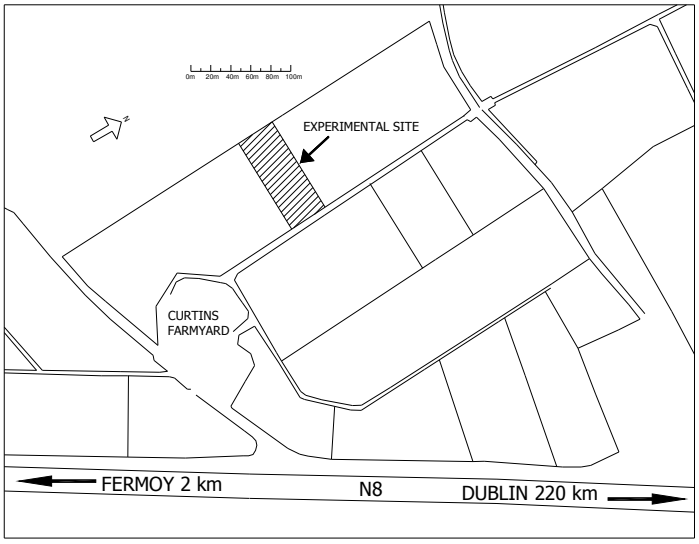

Fig. 4.2 Location of the experimental site on Curtin's Farm.

A geophysical survey was carried out as part of the study to estimate the depth of soil to bedrock on the farm. It varies down to 4 m with rock outcrops present in a few places. When test pits were excavated, the depth to bedrock on the experimental site varied from 2.3 m to 3.0 m (Fig. 4.3). In the test pits, no water table was encountered which indicated that the soil was unsaturated. A description of the soil of one of the test pits is presented in Table 4.1, with other test pits being similar. The soil texture was described using the British Soil Science Classification Pyramid.

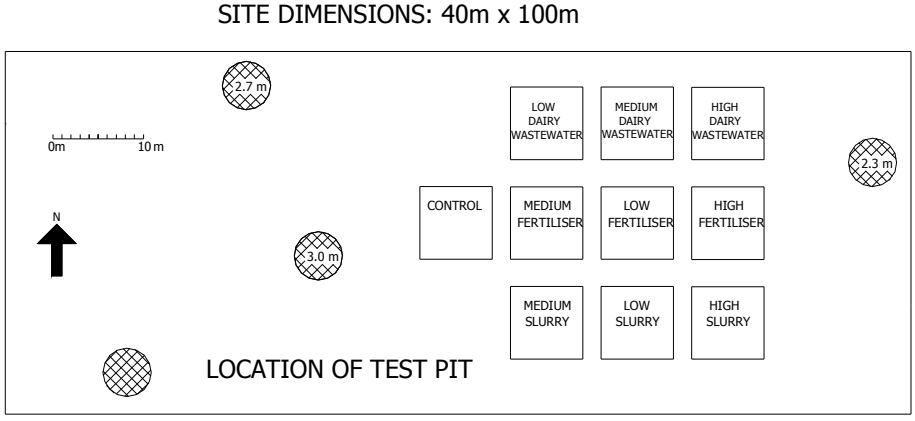

Fig. 4.3. Location and depth of some test pits and of experimental plots.

4.2.1 Soil properties

In all, ten test pits were examined in connection with the project. Seven of the pits were located at the experimental site, one adjoined Curtin's farmyard and two pits adjoined the meteorological station at Moorepark. Two of the test pits were described in detail, one by Michael Walsh, a soil surveyor from Teagasc, Athenry and his description is shown in Table 4.1. In addition, a typical profile of the soil is described in Gardiner and Radford (1980). The test pits and the Gardiner and Radford description show a soil with 0.3 – 0.4 m topsoil resting on a reddish brown sandy loam (gravelly sandy SILT) subsoil to 1.0 – 1.5 m and underlain by a clay loam (gravelly clayey sandy SILT) to bedrock. The bedrock is jointed and weathered karstic limestone, with the joints infilled with a plastic clay loam. The bedrock commonly occurs at 2 – 3 m below ground surface. A fine sand layer was found in one of the Moorepark pits between 1.5 and 2.3 m depth.

There was no evidence of cracks, fissures, roots or earthworm channels or macropores below about 0.6 m in any of the test pits examined.

Table 4.1. Soil characterisation on Curtin's Farm - Test Pit 1

Depth (cm)	Description
0-13	Dark brown loam; moderate fine granular and fine sub-angular blocky; friable; abundant very fine roots; clear smooth boundary to:
14-35	Brown to dark brown loam; moderate fine granular and fine sub-angular blocky; friable; plentiful very fine roots; clear wavy boundary to:
36-80	Brown to dark brown fine gravelly loam with common small sandstone and chert fragments; weak medium to coarse sub-angular blocky; firm; rare very fine roots to 60 cm; diffuse boundary to:
81-150	Reddish brown loam with clay loam inclusions and common 8-10 cm diameter mainly sandstone and smaller chert fragments; weak coarse prismatic to massive; firm to brittle; few micro and very fine pores (< 0.5 mm); no roots, diffuse boundary to:
151-230	Reddish brown clay loam and common 8-10 cm diameter mainly sandstone and smaller chert fragments; weak coarse prismatic to massive; non-sticky plastic; clay skins in voids; few very fine pores (< 0.5 mm); few blackish pockets - limestone fragment 'ghosts'; no roots; irregular sharp boundary to:
231+	Limestone (cavernous) bedrock

Particle size analyses and plasticity indices

Soil samples were taken from various depths in a test pit on the experimental site and were analysed by wet sieving for particle sizes from 75 mm to 0.063 mm (BS 1377: Part 2: 1990). Particles less than 0.063 mm were analysed using a laser diffraction analyser. Particle size for the 10% by weight (D_{10}) value and the coefficient of uniformity (C_u) derived from grading curves are shown in Table 4.2, which indicate a well graded soil with a C_u in excess of 50 for the five layers examined. This soil tends to pack tightly to give a high bulk density. The top 1.5 m of soil is a gravelly sandy SILT (sandy loam) with a clay content of 8 – 17%. Below 1.5 m the soil is slightly

plastic, gravely, clayey, sandy SILT (clay loam). Figs. 4.4 and 4.5 show particles size analyses for Curtin's soil.

Table 4.2. D_{10} and Cu values for different soil layers

	Soil depth (m)				
	0 – 0.13	0.14 - 0.35	0.36 - 0.80	0.81 - 1.50	1.51 - 2.30
D_{10}	0.0033	0.0017	0.0015	0.0017	0.0009
C_U (D_{60}/D_{10})	52.52	75.83	251.32	114.69	139.91

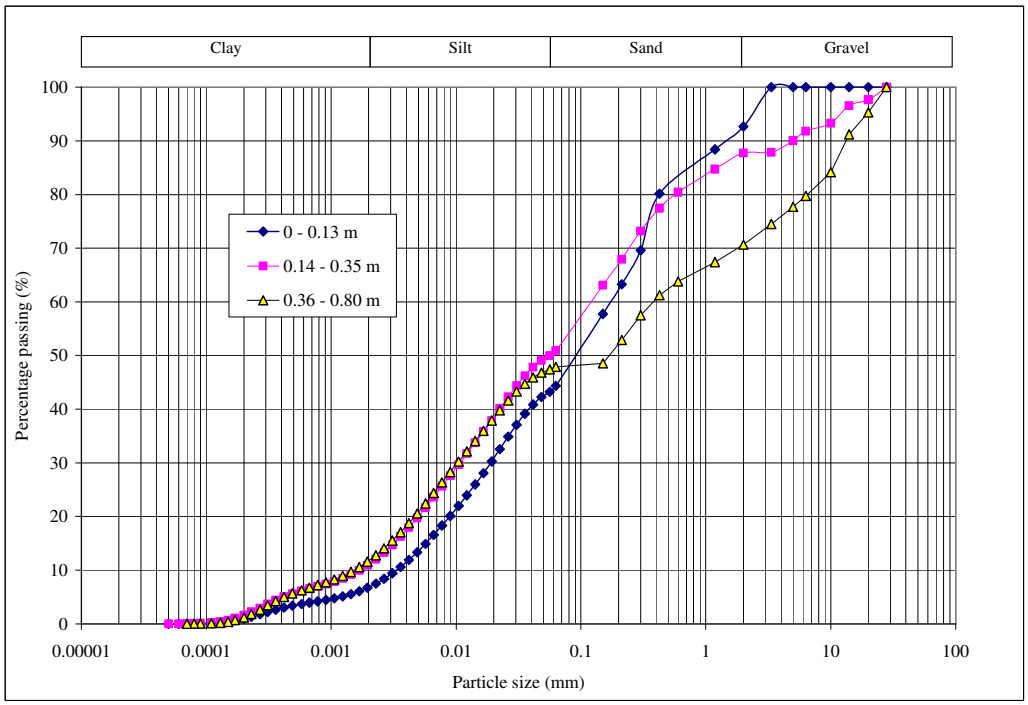

Fig. 4.4 Particle Size Analysis of Soil - Depth 0.0 m to 0.80 m

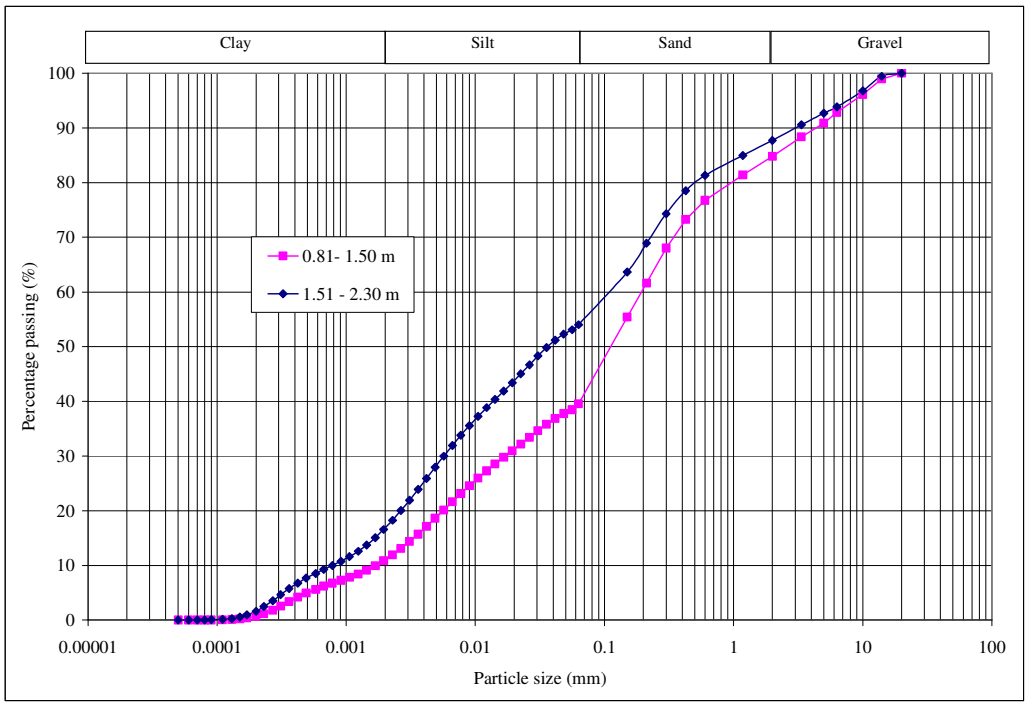

Fig. 4.5 Particle Size Analysis of Soil - Depth 0.81 m to 2.3 m

Plasticity measurements were also carried out on subsoil samples from the test pit. These are used along with particle size analyses to classify the soil and to estimate its workability and strength characteristics. The plastic limit (when the soil changes from solid to plastic) at 16 – 19% water and the liquid limit (when the soil changes from plastic to liquid) at 23 – 25% water at various depths, are both low indicating a soil low in clay with little swell-shrink minerals. The plasticity indices, the difference between the plastic and the liquid limits, at 4.6 – 7.1% are low, and the soil layer with an index of 4.6 is considered non-plastic. The indices indicate a non-shrinking soil of good workability and high strength.

Dry bulk density and porosity

As the test pits were excavated, dry bulk density and pore water contents of the various layers were estimated using a nuclear density gauge. Porosity values were calculated from the bulk density data. Dry bulk density in the topsoil is 1200 kg/m^3, an indication of the high organic matter and root content. From about 0.5 metres depth, the soil bulk density increases to 1850 kg/m^3 at 1-1.6 m depth; below this level, the dry bulk density declined to about 1700 kg/m^3. The corresponding porosities are 55% in the topsoil, 30% at 1.0-1.6 m depth and 35% at 2.0–2.8 m depth. Bulk densities and porosities indicate a strong soil below the topsoil (Fig. 4.6).

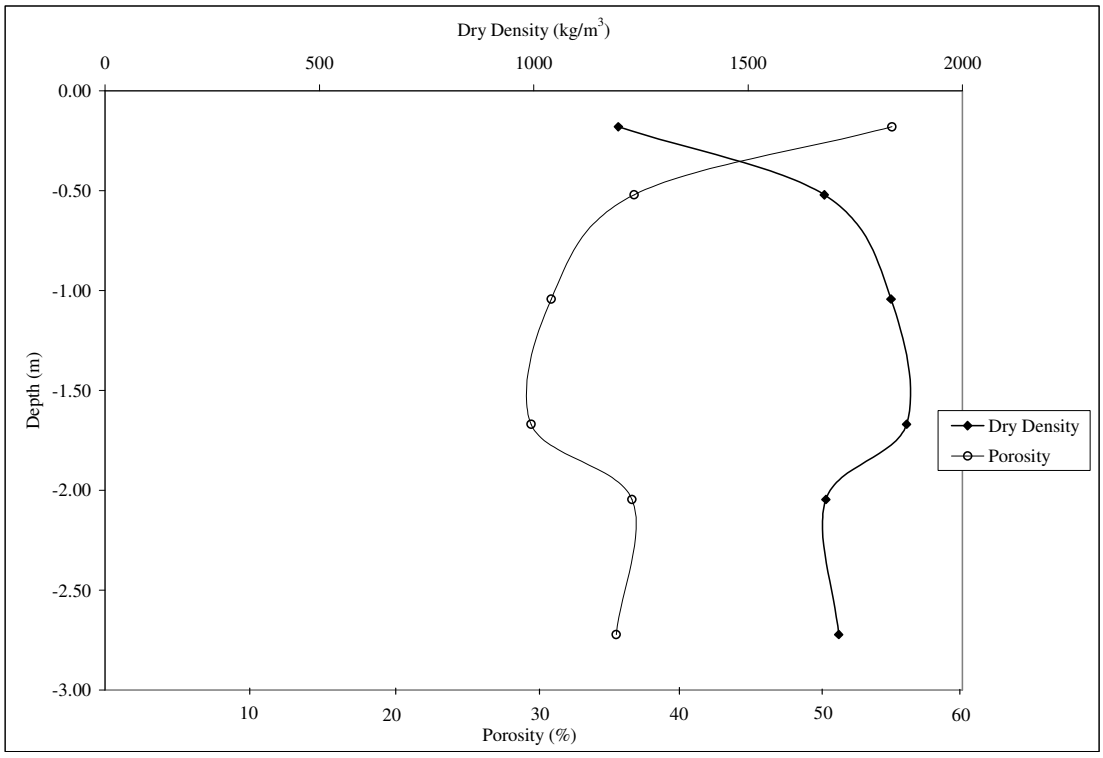

Fig. 4.6. Graph of dry bulk density and porosity versus depth from nuclear density gauge measurements.

4.2.2 Soil water characteristic curves

Table 4.3 shows dry bulk densities measured on core samples in the laboratory. The dry bulk densities ranged between 1149 and 1341 kg/m^3 in the top 0.05 to 0.25 m depth. The density values in the upper layers are low as compared to deeper ones. Lower bulk density values in these layers reflect organic matter content of soil and shallow rooting of grasses. Below 0.25 m, there was a linear increase with depth to a

maximum value of 1897 kg/m^3 at 1.5 m. The high dry density values indicate a compact soil down to 1.5 m.

The porosities for different soil layers were calculated using measured dry bulk density on core samples and values are shown in Table 4.3. In general, porosity decreased with depth and ranged from 0.57 to 0.49 in the top 0.25 m depth to 0.49 to 0.28 down to 1.5 m depth.

Table 4.3. Soil physical properties for different layers determined on core samples.

Depth (m)	Dry density (kg/m^3)	Porosity	θv at 0.25 kPa	θv at 80 kPa	($\theta v_{0.25}$ - θv_{80})
0.05	1149	0.57	0.55	0.32	0.23 (41.8%)
0.15	1304	0.51	0.50	0.28	0.22 (43.6%)
0.25	1341	0.49	0.49	0.28	0.21 (43.2%)
0.50	1603	0.40	0.39	0.26	0.13 (34.4%)
0.75	1688	0.36	0.36	0.25	0.11 (31.9%)
1.00	1746	0.34	0.33	0.22	0.11 (33.4%)
1.50	1897	0.28	0.26	0.18	0.08 (30.8%)

Percentages in parentheses reflect the reduction in volumetric water content (θv) between 0.25 and 80 kPa suction.

The soil water characteristic (SWC) curves derived from measurements on soil cores in the laboratory are shown in Fig. 4.7. The shape of these curves is similar for all depths. However, they show higher water content at the top layers as compared to deeper depths. The low θ_v curve is indicative of the compact nature of the soil at 1.5 m.

Changes in volumetric water content between 0.25 and 80 kPa suctions (Table 4.3) reveal that water steadily drains from soil cores; however, in the top 0.25 m depth this rate is higher compared with deeper depths. Volumetric water content decreased from 0.55 to 0.28 showing an overall 43% reduction in the top 0.25 m. However, volumetric soil water content decreased from 0.39 to 0.26 (34.4%), 0.36 to 0.25 (31.9%), 0.33 to 0.22 (33.4%) and 0.26 to 0.18 (30.8%) at 0.5, 0.75, 1.0, and 1.5 m depths, respectively. These volumetric changes against applied suction show that the topsoil-having high porosity and low bulk density-tends to drain quicker than the subsoil. They also show that the amount of water stored and readily available is large in the topsoil.

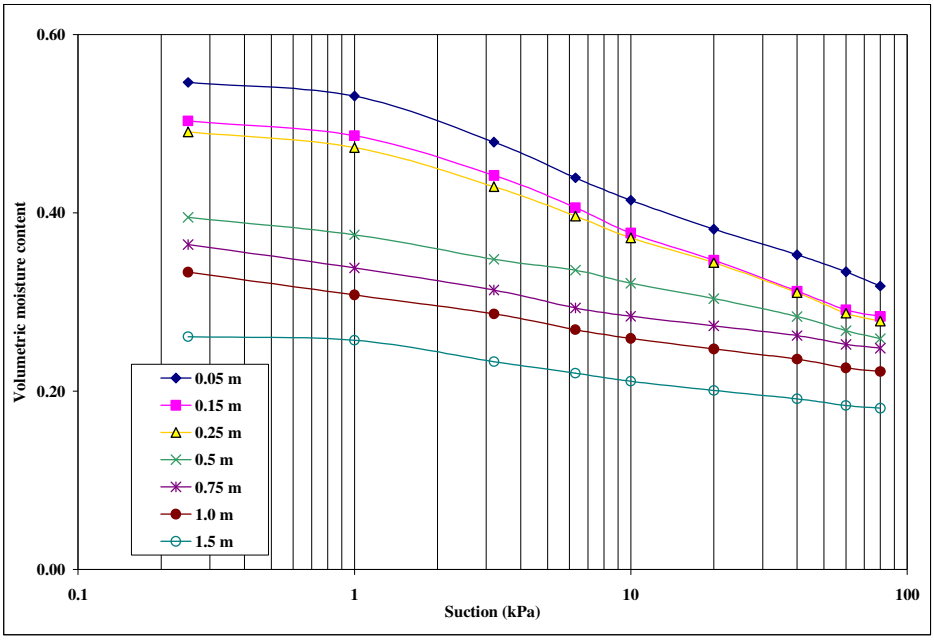

Fig. 4.7. Soil water characteristic curves from laboratory measured data at various depths.

4.3 Hydraulic conductivities

4.3.1 Percolation test method

Table 4.4 shows the results from the percolation test method using a square hole. These results are used with the graph shown in Fig. 3.2 to determine the field-saturated hydraulic conductivity of the soil. The values in Table 4.4 are normal for free draining soils; values at depths of 1.4 and 1.5 m reflect the compact nature of the soil at those depths.

Table 4.4. Field-saturated hydraulic conductivity results by the percolation test method for Curtins's and Moorepark soils.

Curtin's Soil			Moorepark Soil		
Depth (m)	**T value** (mins)	**K_{fs}** (m/day)	**Depth** (m)	**T value** (mins)	**K_{fs}** (m/day)
Topsoil	11.88	0.40	0.5 m	38.50	0.12
1.4 m	26.88	0.16	1.4 m	13.43	0.32
1.5 m	22.94	0.19	2.4 m	1.48	1.75
2.2 m	4.75	1.13			

4.3.2 Unsteady drainage flux method

Fig. 4.8 shows the unsaturated hydraulic conductivity at various depths determined by the unsteady drainage flux method. Values in the 0.2 m depth vary from 0.002 to 0.0004 m/day with suctions of 2.14 and 5.45 kPa, respectively. Hydraulic conductivities were also calculated at saturation and the results are in good agreement with those derived from the percolation tests for depths of up to 2.0 m (Table 4.5). There are no comparisons for depths in excess of 2.0 m.

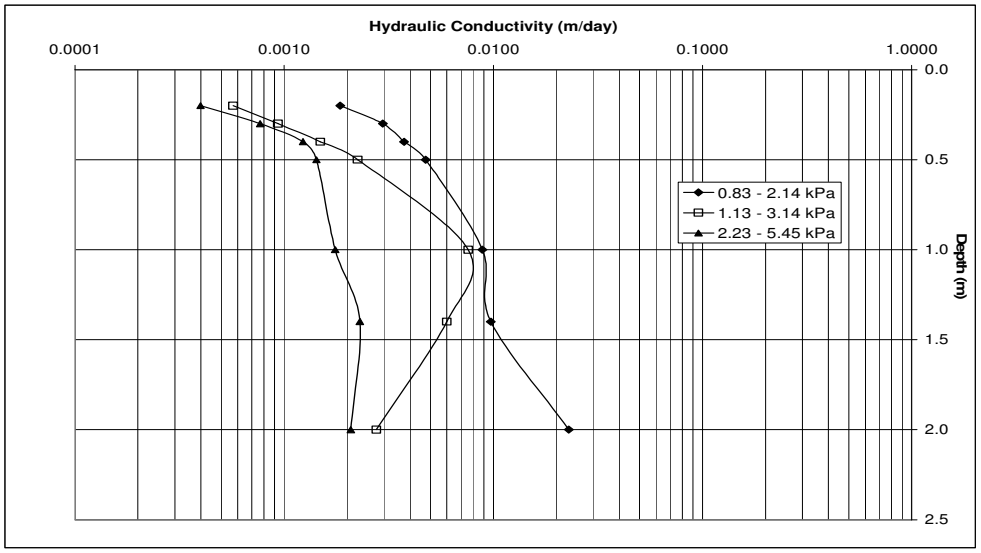

Fig. 4.8 Hydraulic conductivities at different suctions for the unsteady drainage flux method.

4.4 Rainfall data

Daily rainfall figures have been collected at Moorepark (1 km from the experimental site) since 1970 and these data were analysed. The total rainfall for the site each year since 1970 is presented in Fig. 4.9. The average annual rainfall for the 1970 – 2001 period was 1000.8 mm. Rainfall in 2001 was the third lowest since 1970 with 1971 and 1973 the only years drier than 2001. Annual rainfall in 2002 was the second highest since 1970 with an annual rainfall of 1200 mm.

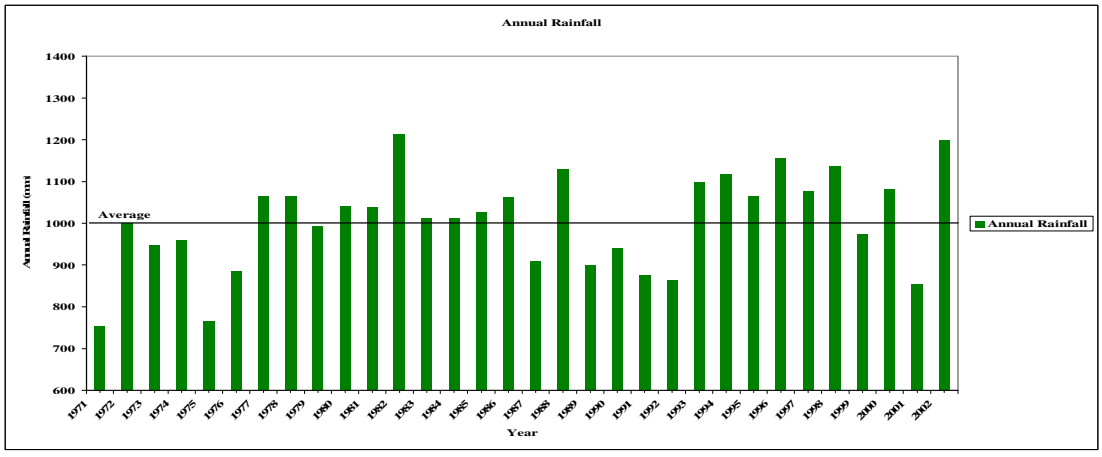

Fig. 4.9. Annual rainfall amounts for Moorepark weather station, also showing the average annual rainfall.

Table 4.5 Hydraulic conductivity data from unsteady drainage flux method.

Depth	Suction	Volumetric Moisture Content	Hydraulic Conductivity
m	**kPa**	**$m^3 m^{-3}$**	**m/day**
0.2	0	0.395	0.551
	0.24	0.369	0.0149
	0.94	0.368	0.0084
	3.54	0.350	0.0024
	8.45	0.308	0.0009
0.3	0	0.369	0.785
	0.26	0.364	0.0171
	0.76	0.364	0.0120
	3.56	0.350	0.0034
	7.56	0.303	0.0015
0.4	0	0.393	0.887
	0.20	0.385	0.0389
	0.58	0.378	0.0289
	3.08	0.364	0.0135
0.5	0	0.397	0.315
	0.20	0.384	0.0287
	0.60	0.377	0.0196
	3.40	0.361	0.0035
	6.81	0.312	0.0015
1	0	0.386	0.414
	0.21	0.378	0.1123
	0.64	0.378	0.0374
	0.84	0.361	0.0170
	2.72	0.319	0.0078
1.4	0	0.384	0.204
	0.10	0.370	0.0777
	0.20	0.370	0.0186
	0.70	0.360	0.0172
	1.8	0.321	0.0060
2	0	0.429	0.212
	0.23	0.425	0.1254
	0.33	0.426	0.0109
	1.43	0.416	0.0120

Fig. 4.10 shows the rainfall for the duration of the experiment. High rainfalls between January and March 2002 and between November and December 2002 could lead to leaching of nutrients as they result in significant recharges.

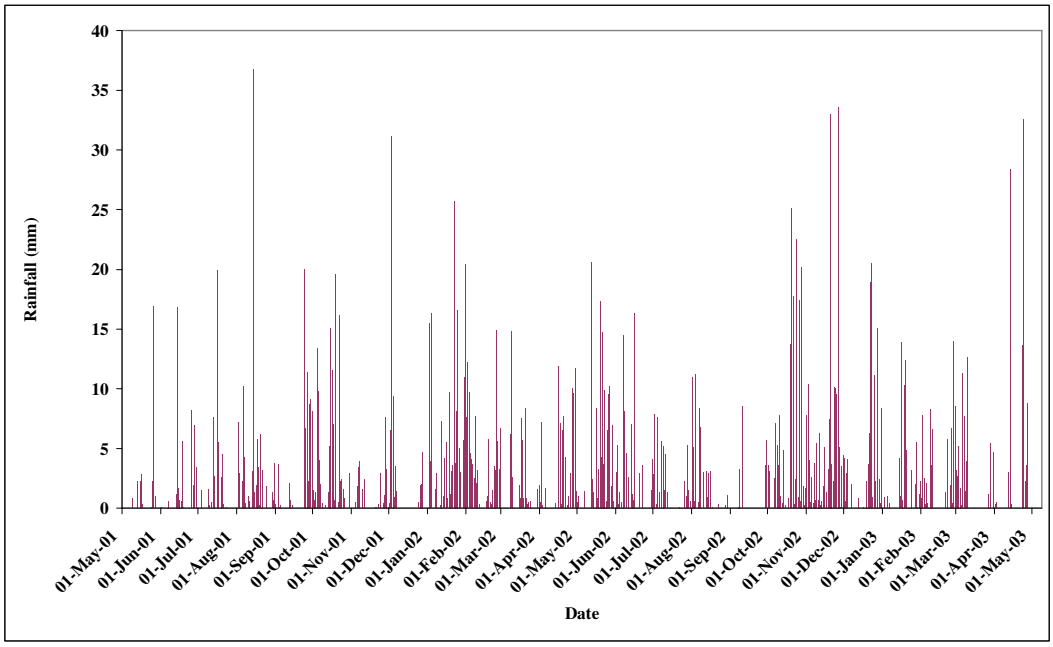

Fig. 4.10. Rainfall amounts for Moorepark weather station from May 1st, 2001 until May 1st, 2003

4.5 Treatment of plots

A total of 10 grass plots, (each measuring 8 m x 8 m) received N applications from different sources – N fertiliser, cow slurry and dairy wastewater. The fertiliser N application dates and rates are shown in Table 4.6. Fertiliser N was spread evenly over the plots by hand. The application rates and dates of dairy wastewater and slurry are shown in Table 4.7. The dairy wastewater was applied to the plot using a 10 l bucket while the slurry was spread using a 10 l watering can t. Table 4.8 shows the N values for dairy wastewater applied on the four different dates. The slurry, applied on 28th March, 2002, had a total N concentration of 3548 mg/l. The herbage that accumulated on the plots was harvested and removed on a regular basis.

Table 4.6. Dates and rates of chemical fertiliser application

Day number*	Date	Fertiliser type	High	Medium	Low
			kg N/ha	kg N/ha	kg N/ha
38	08-Jun-01	CAN**	45.7	33.8	20.6
59	29-Jun-01	CAN	45.7	33.8	20.6
80	20-Jul-01	CAN	45.7	33.8	20.6
101	10-Aug-01	CAN	45.7	33.8	20.6
122	31-Aug-01	CAN	45.7	33.8	20.6
143	21-Sep-01	CAN	45.7	33.8	20.6
2001	**TOTAL*** **		**274.2**	**202.8**	**123.6**
265	21-Jan-02	Urea	67.2	49.7	30.2
351	17-Apr-02	CAN	45.7	33.8	20.6
372	08-May-02	CAN	45.7	33.8	20.6
396	01-Jun-02	CAN	45.7	33.8	20.6
424	29-Jun-02	CAN	45.7	33.8	20.6
455	30-Jul-02	CAN	45.7	33.8	20.6
477	21-Aug-02	CAN	45.7	33.8	20.6
503	16-Sep-02	CAN	45.7	33.8	20.6
2002	**TOTAL**		**387.1**	**286.3**	**174.4**
647	07-Feb-03	Urea	67.2	49.7	30.2
695	27-Mar-03	CAN	45.7	33.8	20.6
753	24-May-03	CAN	45.7	33.8	20.6
774	14-Jun-03	CAN	45.7	33.8	20.6
802	12-Jul-03	CAN	45.7	33.8	20.6

* Day number 1 = May 1st 2001; **CAN = Calcium ammonium nitrate (27% N);
*** Lower total fertiliser applied because experiment started on May 25th 2001.

Table 4.7. Dates and rates of application of dairy wastewater and slurry

Day No.	Date	Dairy wastewater (DW) /Slurry	High DW/ Slurry rate	Medium DW/ Slurry rate	Low DW / Slurry rate
189	06-Nov-01	Dairy wastewater	50 mm	25 mm	10 mm
331	27-Mar-02	Slurry	45 m^3/ha (4.5 mm)	30 m^3/ha (3.0 mm)	15 m^3/ha (1.5 mm)
370	05-May-02	Dairy wastewater	50 mm	25 mm	10 mm
572	24-Nov-02	Dairy wastewater	50 mm	25 mm	10 mm
695	27-Mar-03	Slurry	45 m^3/ha (4.5 mm)	30 m^3/ha (3.0 mm)	15 m^3/ha (1.5 mm)
738	09-May-03	Dairy wastewater	50 mm	25 mm	10 mm

Table 4.8 Nutrient concentrations of dirty water

Date	NO_3-N mg/l	NH_4-N mg/l	NO_2-N mg/l	TN mg/l	PO_4-P* mg/l
06-Nov-01	<0.1	346	< 0.1	430	36.5
05-May-02	0.8	63.8	< 0.1	309	22.4
24-Nov-02	0.1	217	< 0.1		36.2
09-May-03	0.1	169	<0.1	257	43.3

*PO_4-P – orthophosphate phosphorus

4.6 Results from field experiments

Moisture contents and tensiometer readings were taken from the field on the same day the pore water sampling was carried out. Selected tensiometer data are presented in Figs. 4.11 to 4.14 and selected pore water content values in Fig. 4.15. Nitrate-nitrogen concentrations from all plots at selected depths are presented in Figs. 4.16 to 4.30.

4.6.1 Tensiometer data from the control, medium fertiliser and high dairy wastewater plots

The tensiometer data for selected dates are presented in Figs. 4.11 to 4.14. Fig. 4.11 shows the hydraulic potentials for the control plot at different dates over a period of a year. The hydraulic potential line shifts towards the gravitational potential line from September onwards and reached near saturation in the month of November 2001 (not shown). A similar pattern is shown in the hydraulic potentials in the medium and high fertiliser plots (Figs. 4.12 and 4.13) with high suctions in September and low suctions in the winter e.g. February and following the wet month of May 2002.

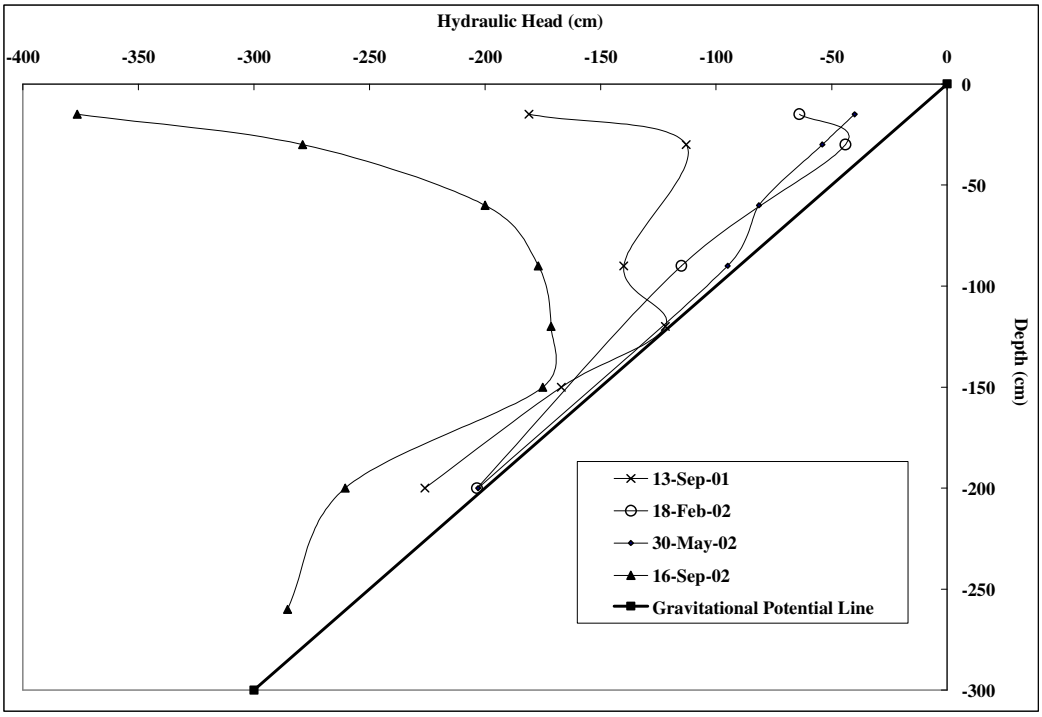

Fig. 4.11 Hydraulic potential curves for the control plot on selected dates**.**

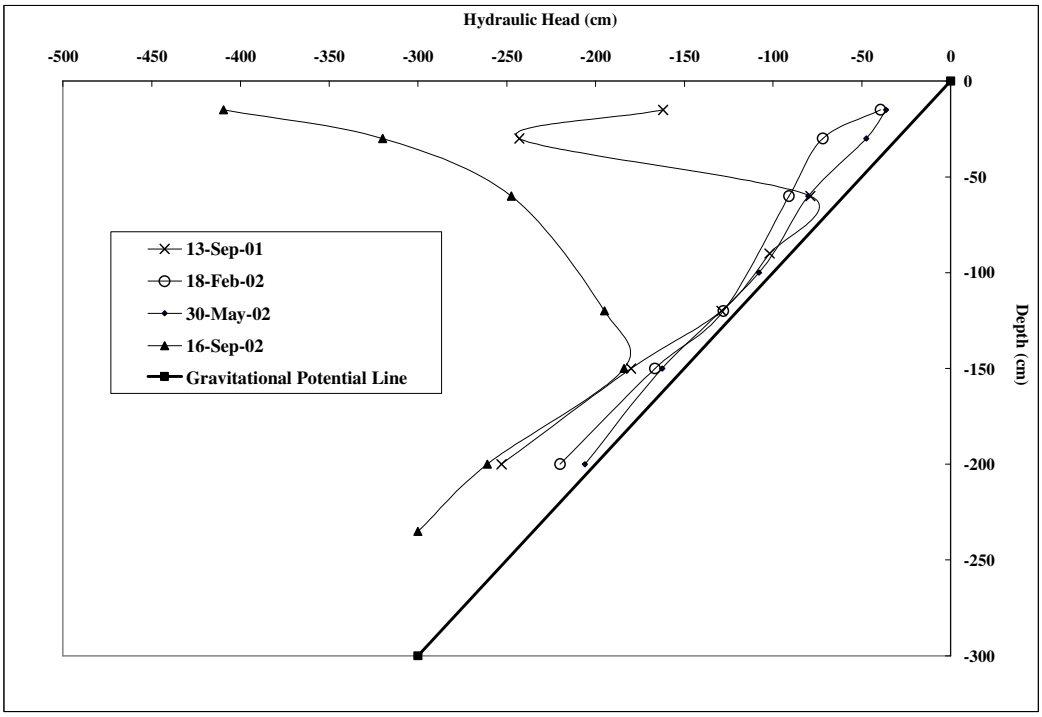

Fig. 4.12 Hydraulic potential curves for the medium fertiliser plot on selected dates**.**

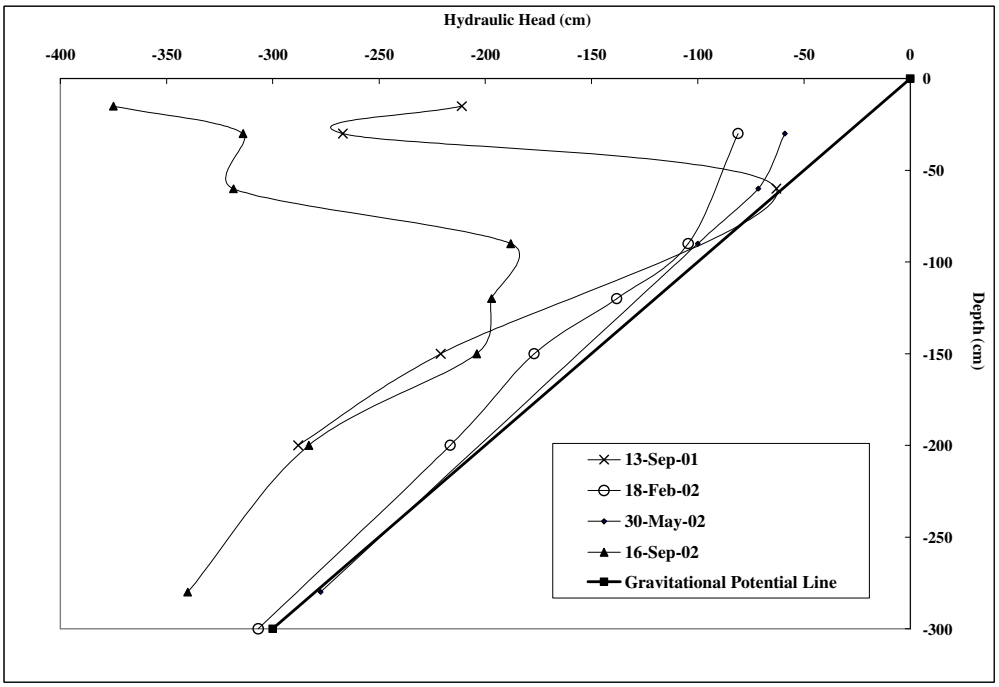

Fig. 4.13 Hydraulic potential curves for the high dairy wastewater plot on selected dates.

Measurements of porewater pressures before, during and after the application of 50 mm of dairy wastewater were taken to determine the response time of the soil porewater to a high hydraulic load. These porewater pressures (Fig. 4.14) show that the soil became field-saturated to 0.9 m during and following hydraulic loads of 25 and 50 mm. However, by the next day, negative pore water pressures were restored as

drainage and water redistribution took place. Hydraulic potentials deeper than 0.9 m were unaffected.

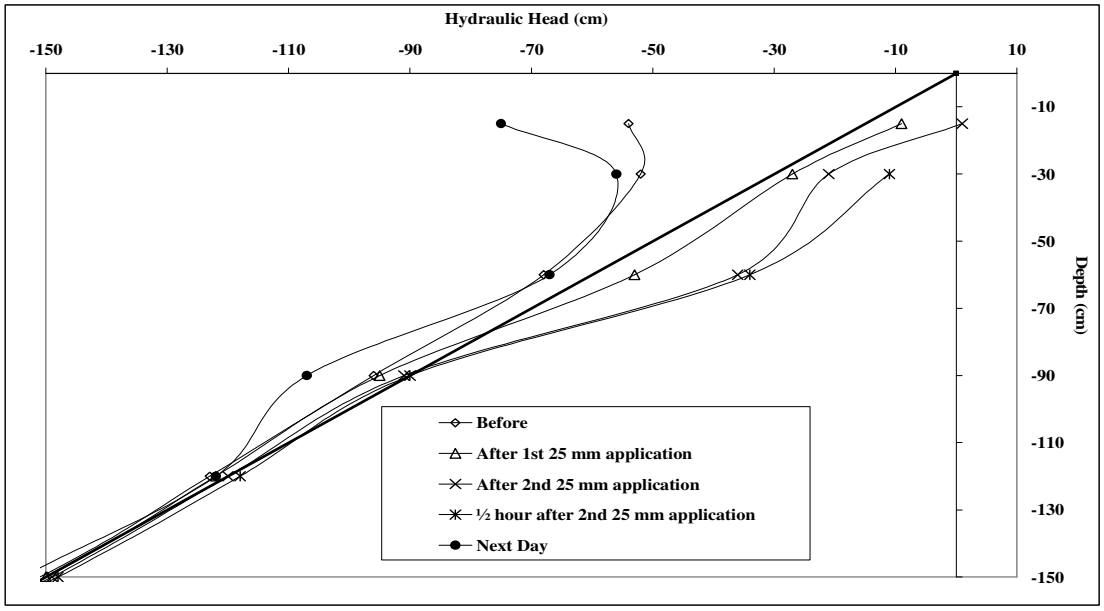

Fig. 4.14 Hydraulic potentials showing the response to dairy wastewater applications in November 2002.

4.6.2 Water content data

Water content readings were taken on each day pore water sampling was carried out. Fig. 4.15 shows a graph of water content against time, with the rainfall amounts on the secondary axis.

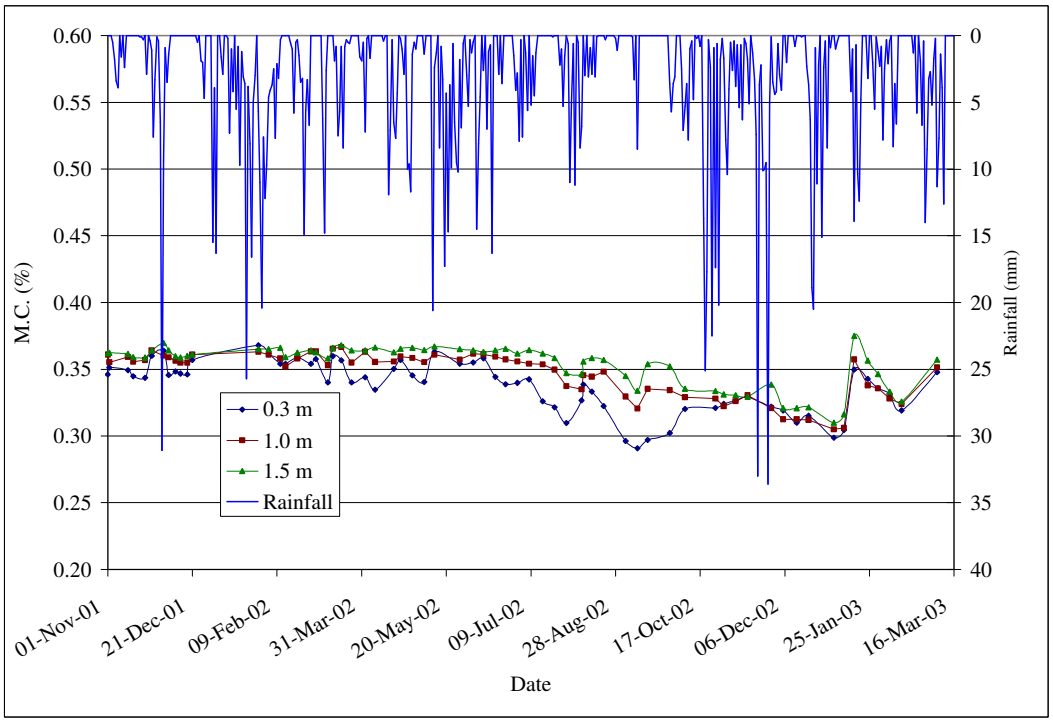

Fig. 4.15 Volumetric water content data at 0.3, 1.0 and 1.5 m with daily rainfall on the secondary axis.

4.6.3 Nitrate-nitrogen concentrations in soil pore water

In this experiment, the NO_3-N concentrations were measured under cutting conditions, i.e. grass was cut to 70 mm height and removed off-site.

In general, the NO_3-N concentrations at depths greater than 1.5 m declined over the 24 month study period. The cause of the initial high NO_3-N concentrations is not known but they are not due to treatments imposed in this investigation since high concentrations (up to 21.4 mg/l) were also measured in the control plot at depths greater than 1.5 m. The declines suggest that due to the high recharge in Irish conditions, high levels of pore water NO_3-N concentrations in soils can reduce to low levels over relatively short periods of time - of the order of 12 to 24 months - following reductions in N inputs.

4.6.3.1 Nitrate concentrations in control and fertiliser plots

In the control treatment (Fig. 4.16), NO_3-N concentrations were low in general after the beginning of December 2001 (Appendix A, p. 85) except at depths of 0.9, 2.0 and 3.0 m, where they were initially above 10 mg/l, but then declined over the duration of the study.

In the low fertiliser treatment (Fig. 4.17), 174 kg chemical N/ha per year was applied in 8 doses. In general, nitrate-nitrogen concentrations were low and did not exceed 10 mg NO_3-N/l except at 2.5 and 3.0 metres depth where the concentrations were initially high at about 40 mg NO_3-N/l but declined exponentially over the 18 month period from the start of the experiment.

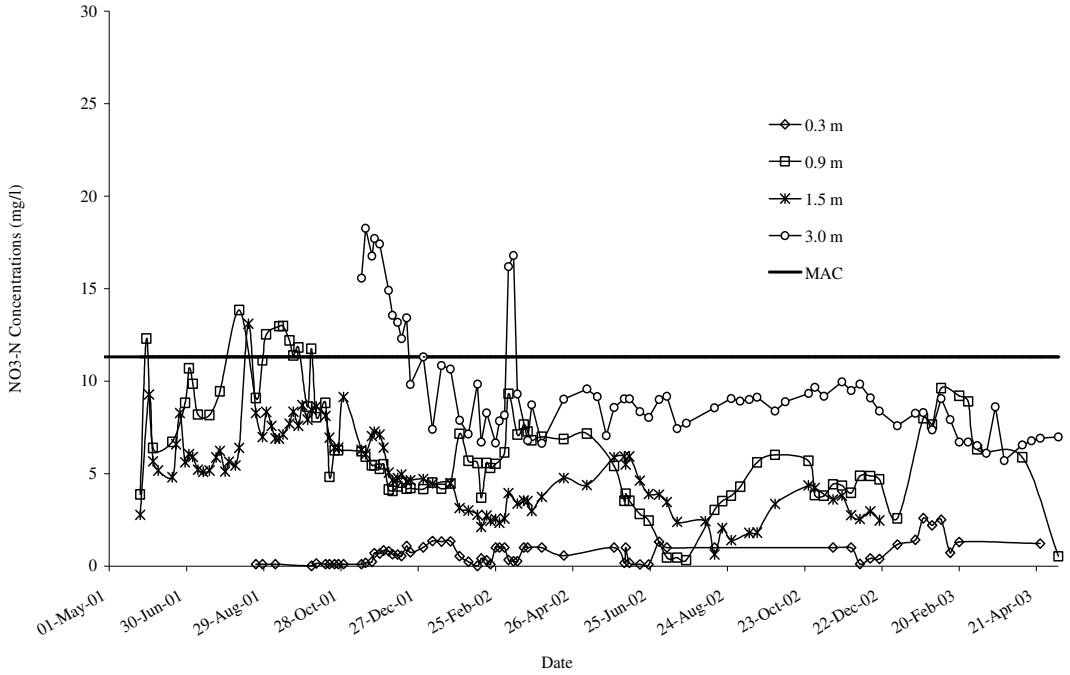

Fig. 4.16 Temporal trends in NO_3-N concentrations for control plot at selected depths.

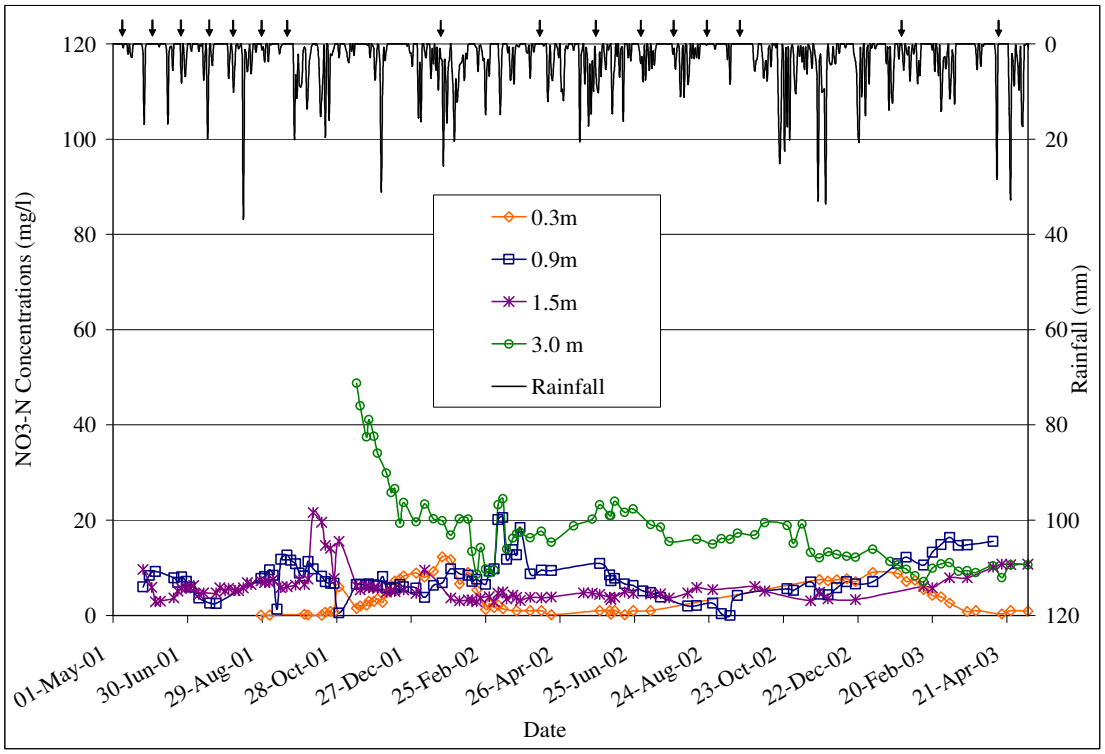

Fig. 4.17 Trends in NO_3-N concentrations for the low N fertiliser (174 kg/ha) treatment at selected depths and daily rainfall amounts. The arrows denote fertiliser application days.

The medium N fertiliser treatment (Fig. 4.18) of 286 kg /ha gave rise to pore water NO_3-N concentrations at 0.9 m depth in the range of 2 – 33 mg/l with high values appearing to be associated with the late season (mid-late September) and early season (mid January–1st week February) applications. It appears that the mid-late September application of N chemical fertilisers should be reviewed, and the early season application should also be reviewed and deferred to bring it more into line with the timing of significant grass growth. It is also significant that the 286 kg/ha N rate used is 61 kg/ha (27%) in excess of that recommended by Teagasc for a rotational grazing system stocked similarly to Curtin's farm. This indicates that further research may be necessary to modify the timing and rate of chemical N applications to minimise high pore water concentrations of NO_3-N. Unlike the nine other plots, NO_3-N concentrations at 3 m depth were not initially very high in this plot but were more or less constant with a median value of 9.0 mg /l. The median NO_3-N concentrations at 1.5 m depth were 8.1 and 25.8 mg/l in 2001-2002 and 2002-2003, respectively. The reason for this anomaly is not obvious, but it may have associations with the very wet year and/or a subsoil layer of low hydraulic conductivity.

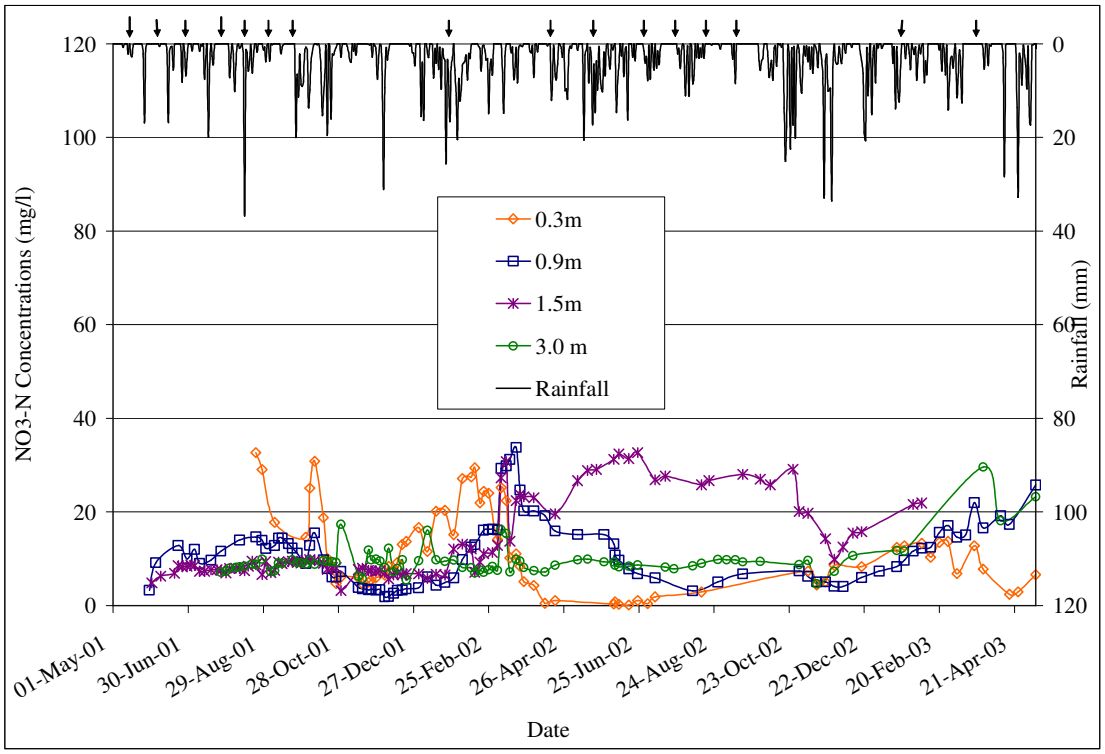

Fig. 4.18 Trends in NO_3-N concentrations for the medium N fertiliser (286 kg /ha) plot at selected depths also showing daily rainfall amounts (arrows denote fertiliser application days).

The high N fertiliser treatment (387 kg/ha) gave rise to high concentrations of NO_3-N at all depths in the soil e.g. at 0.3, 0.9 and 1.5 metres, maximum NO_3-N concentrations were 137, 70 and 30 mg/l, respectively (Fig 4.19). These concentrations remained high for relatively long periods. Median NO_3-N concentrations at 0.9 and 1.5 m were much higher in 2002 (a wet year) than in 2001 (a dry year), indicating the role of recharge rate. Excessive applications of N fertiliser of this magnitude can give rise to high concentrations of NO_3-N in the soil pore water for long periods, leading to leaching.

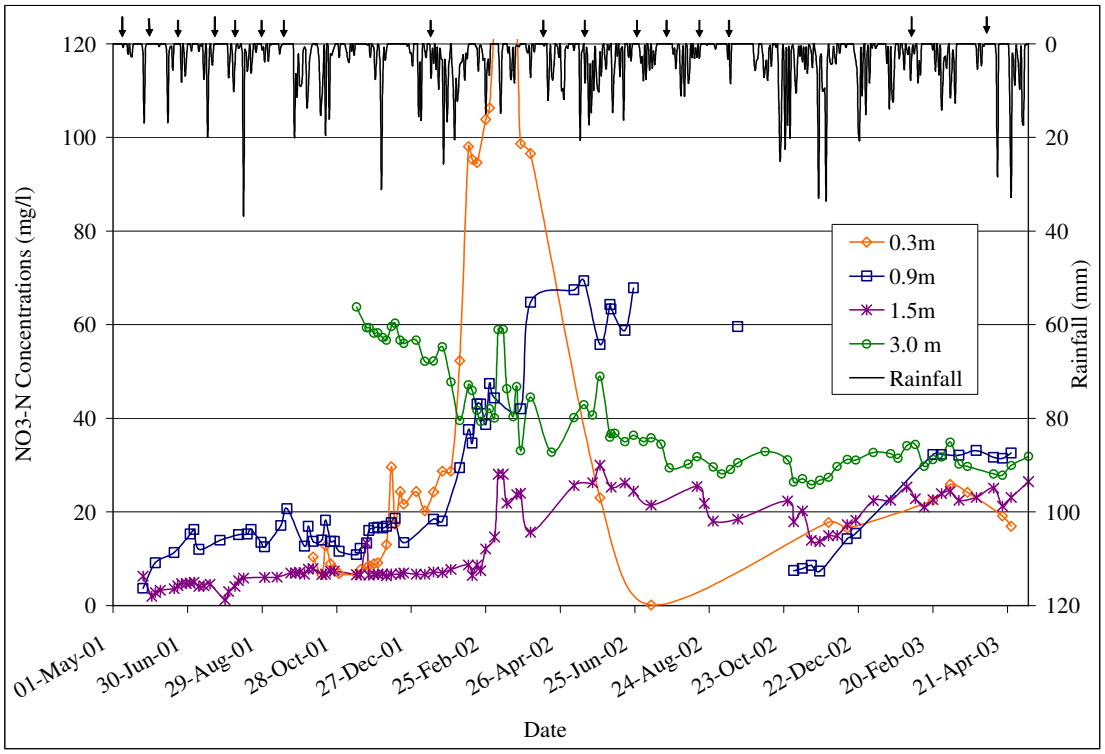

Fig. 4.19 Trends in NO_3-N concentrations for the high N fertiliser plot (387 kg/ha) at selected depths also showing daily rainfall amounts (arrows denote fertiliser application days).

4.6.3.2 Nitrate concentrations in dairy wastewater treatments

In the low (100 t/ha) dairy wastewater applications on November 6th, 2001, May 5th and November 18th, 2002 appeared to have had little effect on the NO_3-N concentrations in the soil pore water at any depth (Fig 4.20). However, NO_3-N concentrations at depths greater than 1.5 m were in general above 12 mg /l initially (12 – 40 mg/l) and declined over the period of the study. The cause of the high initial values is not apparent.

There was an increase in NO_3-N concentrations up to 85, 18, and 33 mg/l in the pore water at 0.3, 0.9 and 1.5 m depth, respectively, following the dairy wastewater application at 250 t/ha (medium) in November 2001 and 2002 (Fig 4.21). There was no effect on NO_3-N concentrations at any of these depths from the medium application rate in May 2002. The NO_3-N at 3 m depth declined from 65 mg/l in spring 2002 to about 10 mg /l in early May 2003.

The November 2001 application of high (500 t/ha) dairy wastewater resulted in an increase in NO_3-N concentrations in the pore water at 0.3, 0.9 and 1.5 m up to 143, 48, and 32 mg NO_3-N /l, respectively (Figure 4.22). The November 2002 application showed a smaller increase in NO_3-N concentrations in the pore water at 0.3, 0.9 and 1.5 m to 75, 38, and 12 mg/l, respectively. There was little or no response at these depths to the May 2002 application. The NO_3-N concentrations in the pore water at the 3.0 m declined from 33 mg/l in November 2001 to just below 11 mg/l at the end of April, 2003. It appears from these data, that winter applications of dairy wastewater should not exceed 100 t/ha. The summer applications should not exceed 250 t/ha irrigation.

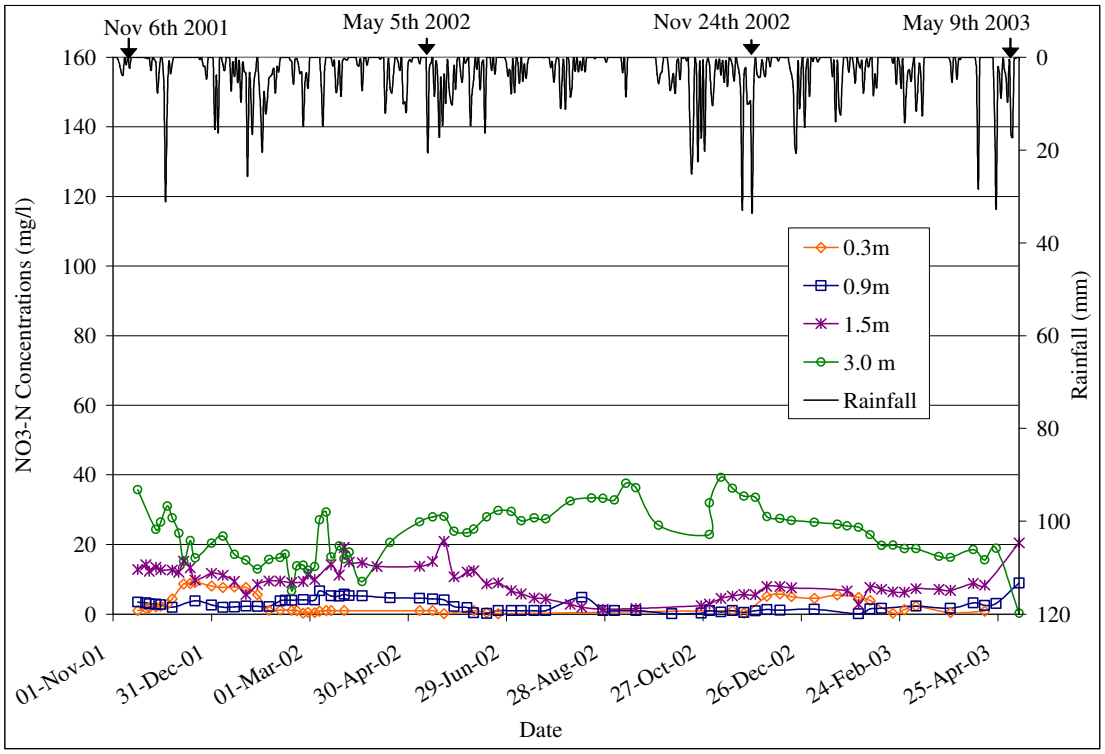

Fig. 4.20 Trends in NO_3-N concentrations for the low dairy wastewater (10 mm) plot at selected depths also showing daily rainfall amounts (arrows denote dairy wastewater application days).

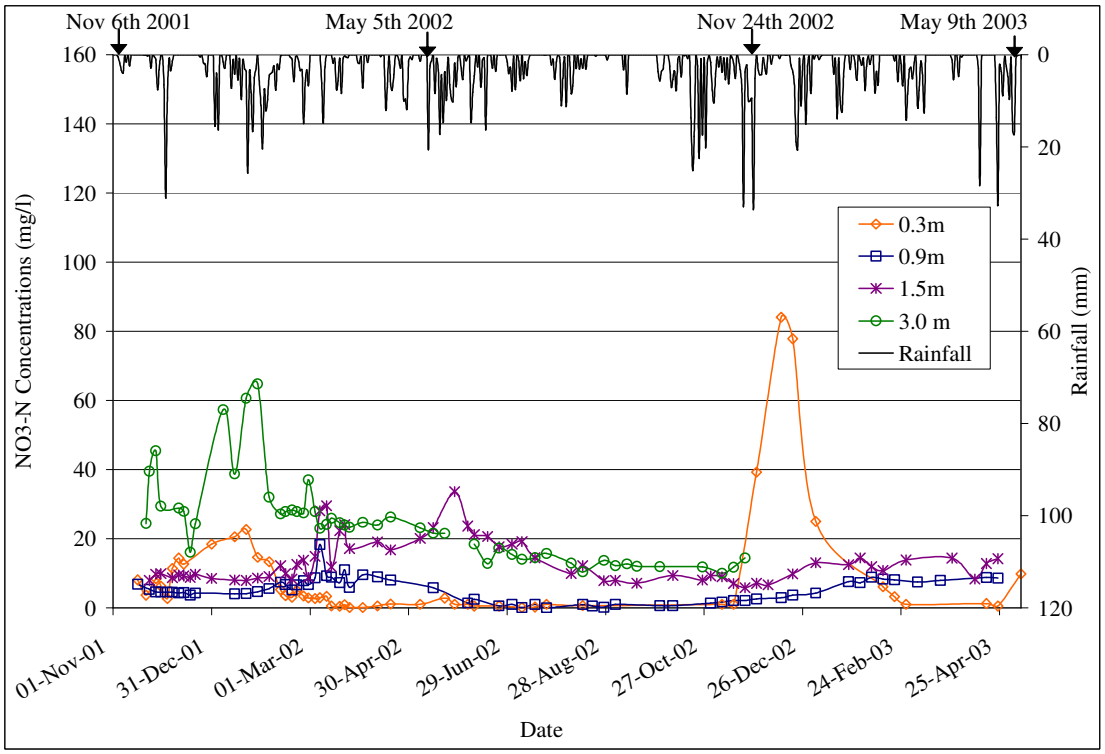

Fig. 4.21 Trends in NO_3-N concentrations for the medium dairy wastewater (25 mm) plot at selected depths also showing daily rainfall amounts (arrows denote dairy wastewater application days)

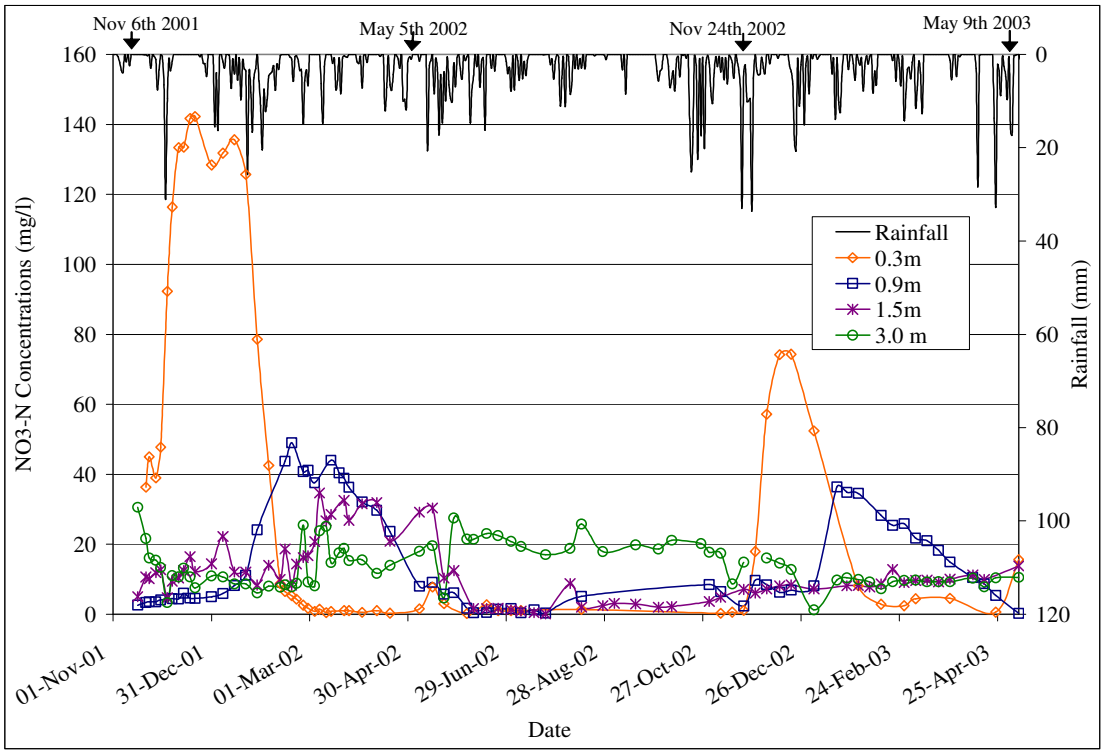

Fig. 4.22 Trends in NO_3-N concentrations for the high dairy wastewater (50 mm) plot at selected depths also showing daily rainfall amounts (arrows denote dairy wastewater application days).

4.6.3.3 Nitrate concentrations in slurry plots

The results from the Spring 2002 slurry applications (15, 30 and 45 t/ha) indicate little or no effect on NO_3-N concentrations at any of the depths. In all treatments, at each depth, NO_3-N concentrations declined to 10 mg/l or less by the end of the study period. (Figs 4.23 – 4.25)

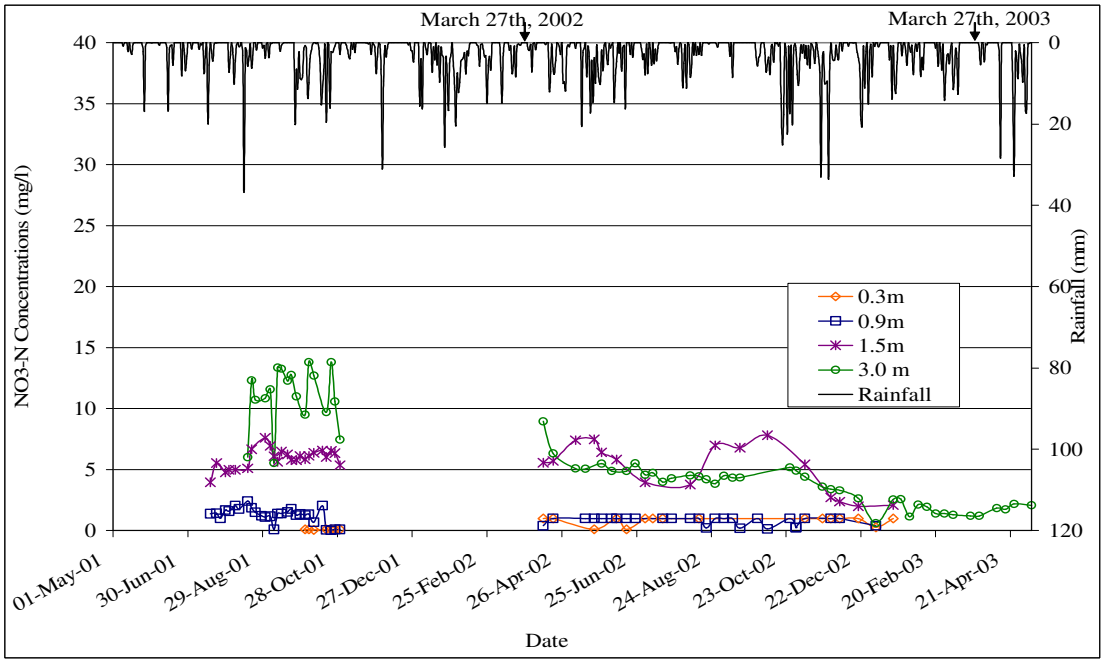

Fig. 4.23. Trends in NO_3-N concentrations for the low slurry (15 t/ha) treatment also showing daily rainfall amounts (arrows denote slurry application days).

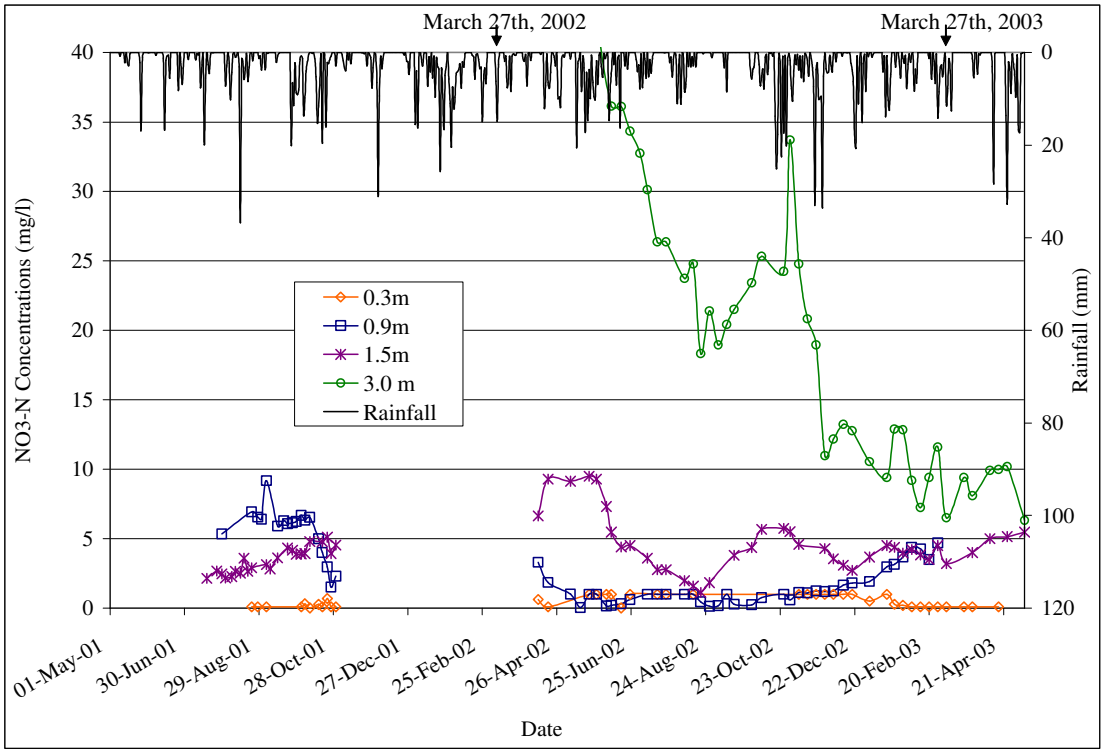

Fig. 4.24. Trends in NO_3-N concentrations for the medium slurry (30 t/ha) plot also showing daily rainfall amounts (arrows denote slurry application days).

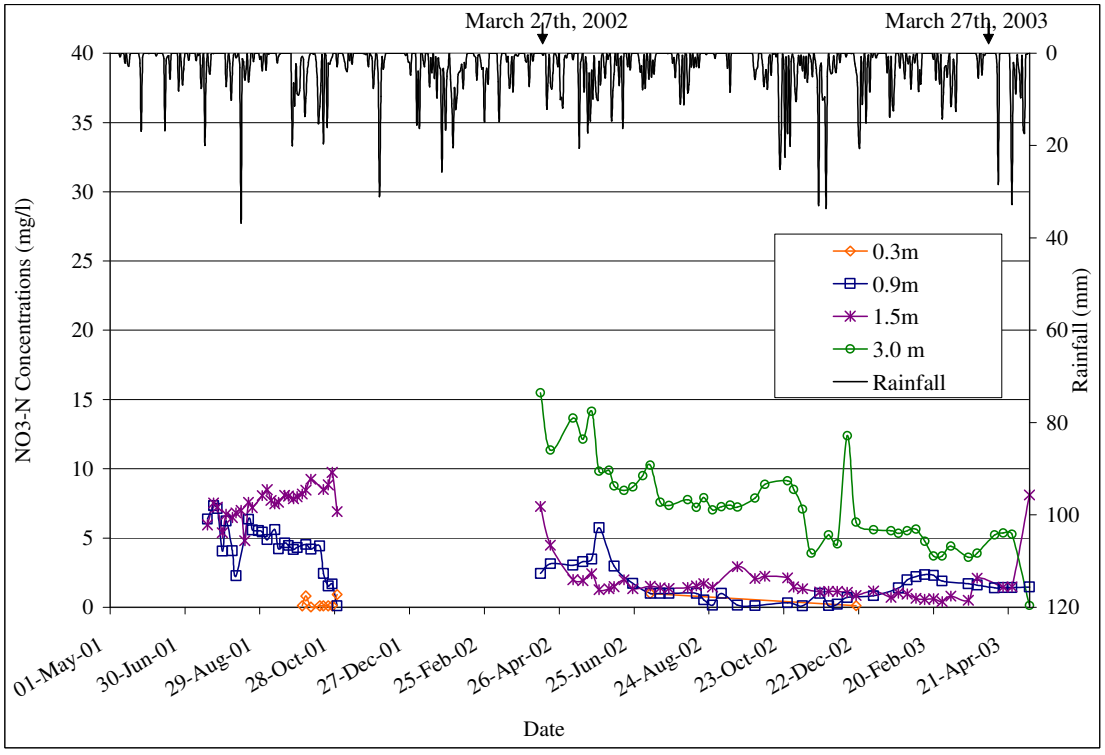

Fig. 4.25 Trends in NO_3-N concentrations for the high slurry (45 t/ha) treatment also showing daily rainfall amounts (arrows denote slurry application days)

4.6.4 Comparison of suction cups under different treatments

Ceramic cups from different plots at the same depth were compared to determine the response to different treatments. The responses of the ceramic cups to chemical fertiliser treatments are shown in Figs. 4.26 to 4.28 and responses to the dairy wastewater treatments are shown in Figs. 4.29 to 4.30.

4.6.4.1 Comparison of suction cups for different fertiliser treatments

The data in Fig. 4.26 shows the higher the application of N fertiliser the higher the up to NO_3-N concentrations are. At the 0.3 m depth, the curves are cyclical, with peaks in the January-March period, suggesting a dependence on late September and late January-early February fertilisation. This trend is repeated at 0.9 m (Fig. 4.27) which also shows increasing NO_3-N concentrations with increasing N fertiliser applications and cyclical peaks, with the median NO_3-N concentrations for the medium and high fertiliser treatments at 10.4 mg/l and 24.3 mg/l, respectively. The time taken for the 0.3m high fertiliser cup to reach its peak concentration was 49 days. The comparison of the effect of N fertiliser rate on the NO_3-N pore water concentrations at 3.0 m (Fig. 4.28) is masked by high initial and declining NO_3-N concentrations over the measurement period. The anomalous behaviour in the medium fertiliser treatment plot at 3.0 m depth is also illustrated.

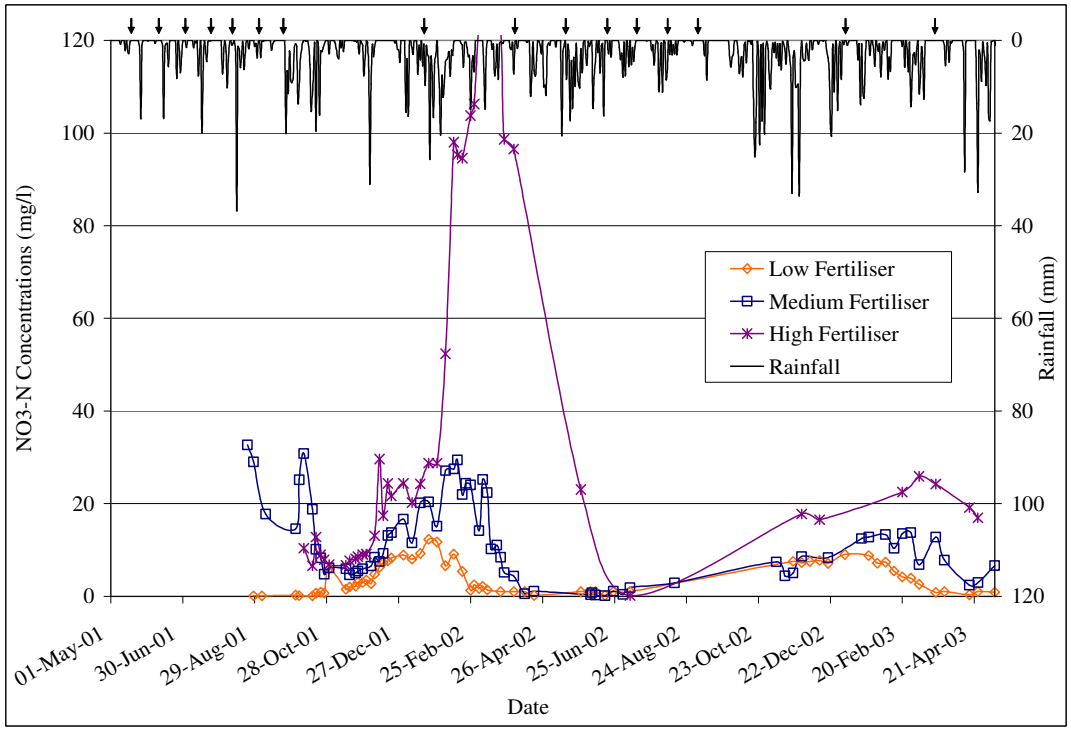

Fig. 4.26 Comparison of NO_3-N concentrations for the 0.3 m suction cups under different fertiliser application rates also showing daily rainfall amounts**.**

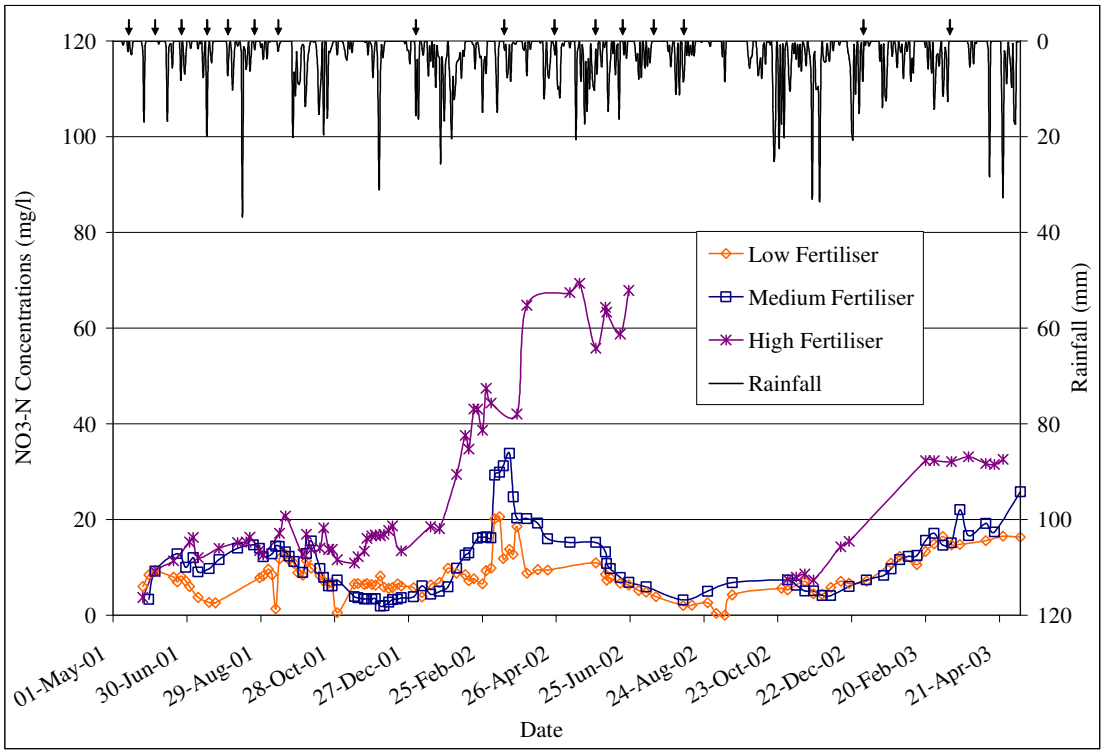

Fig. 4.27 Comparison of NO_3-N concentrations for the 0.9 m suction cups under different fertiliser regimes also showing daily rainfall amounts.

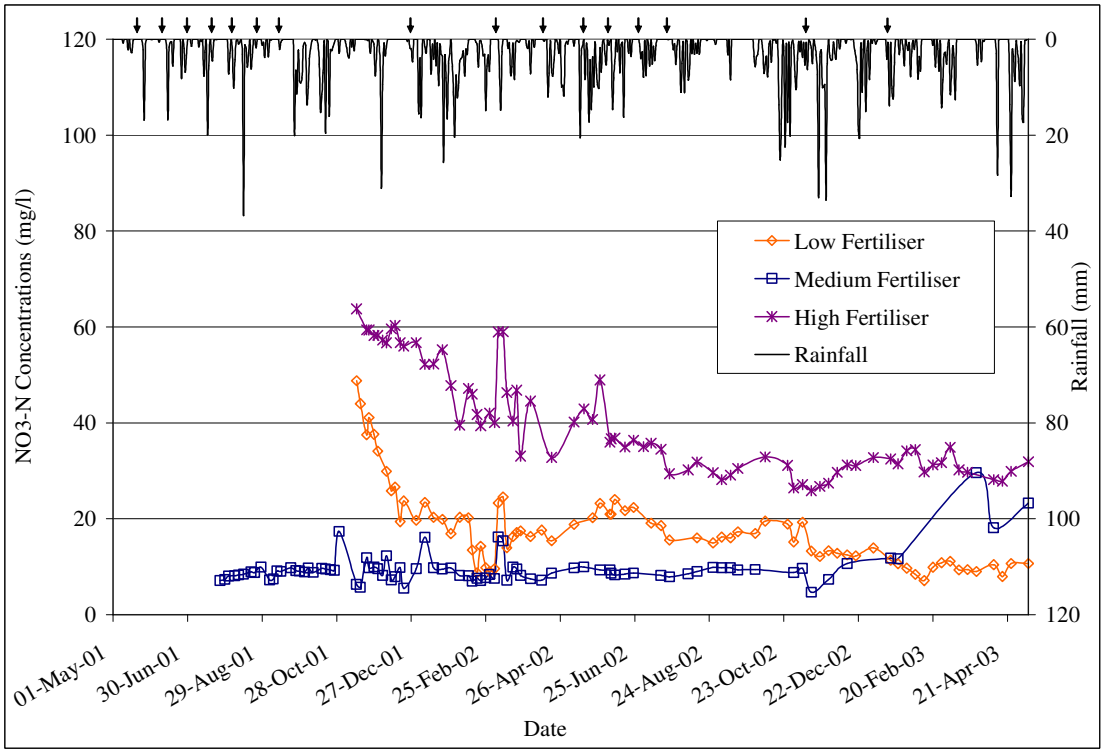

Fig. 4.28 Comparison of NO_3-N concentrations for the 3.0 m suction cups under different fertiliser regimes also showing daily rainfall amounts.

4.6.4.2 Comparison of suction cups under different treatments of dairy wastewater

The NO_3-N concentration response at the 0.3 m and 0.9 m suction cups to the different dairy wastewater applications are shown in Figs 4.29 and 4.30. The higher the application of dairy wastewater in November of both years, the higher the NO_3-N concentrations in the pore water in the upper 0.3 m layer of soil (Fig 4.29). There was no response to the summer application. At the 0.9 m there was little response to the low and medium dirty water applications. However, there was a large NO_3-N concentration response (from < 10 to 50 mg/ l) to the November application (Fig 4.30).

The very high dairy wastewater application in November illustrates the rapid but very short duration saturation of the topsoil (Fig. 4.14). This results in some water with NO_3-N moving downwards below the topsoil and beyond the reach of plant roots where it can be leached as illustrated in Fig. 4.30 at 0.9 metres depth. Subsequently, such nitrate may be driven downwards by rainfall (recharge) with attenuation.

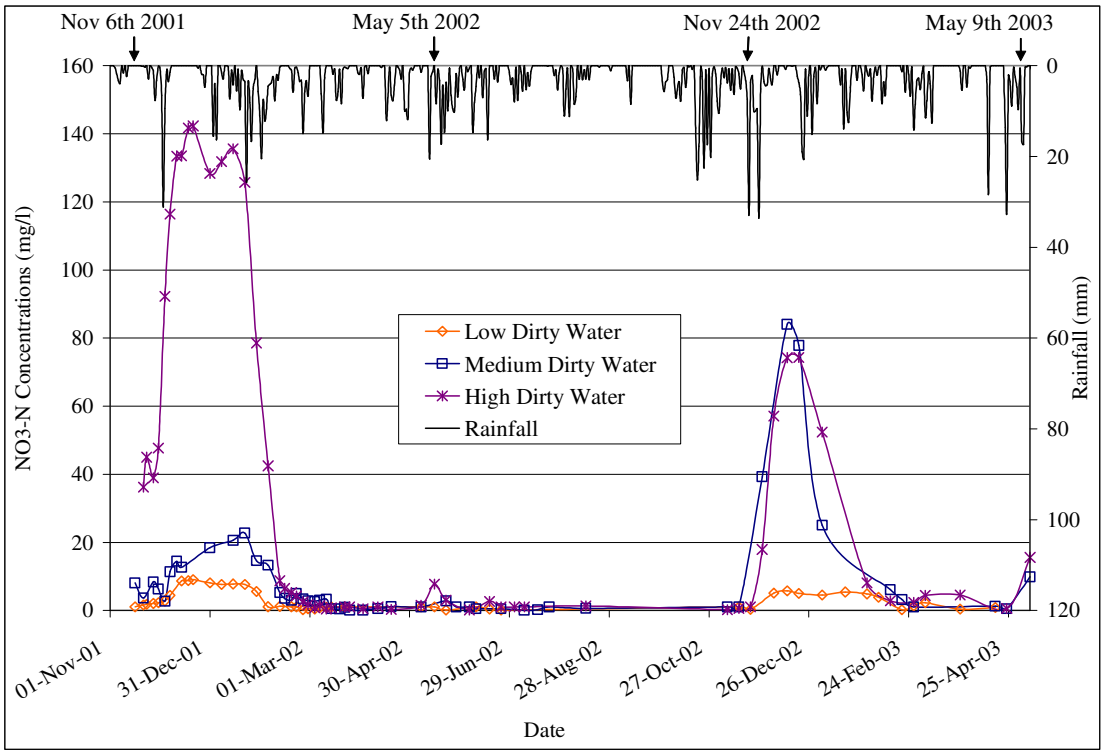

Fig. 4.29 Comparison of NO_3-N concentrations for the 0.3 m suction cups under different dairy wastewater regimes also showing daily rainfall amounts.

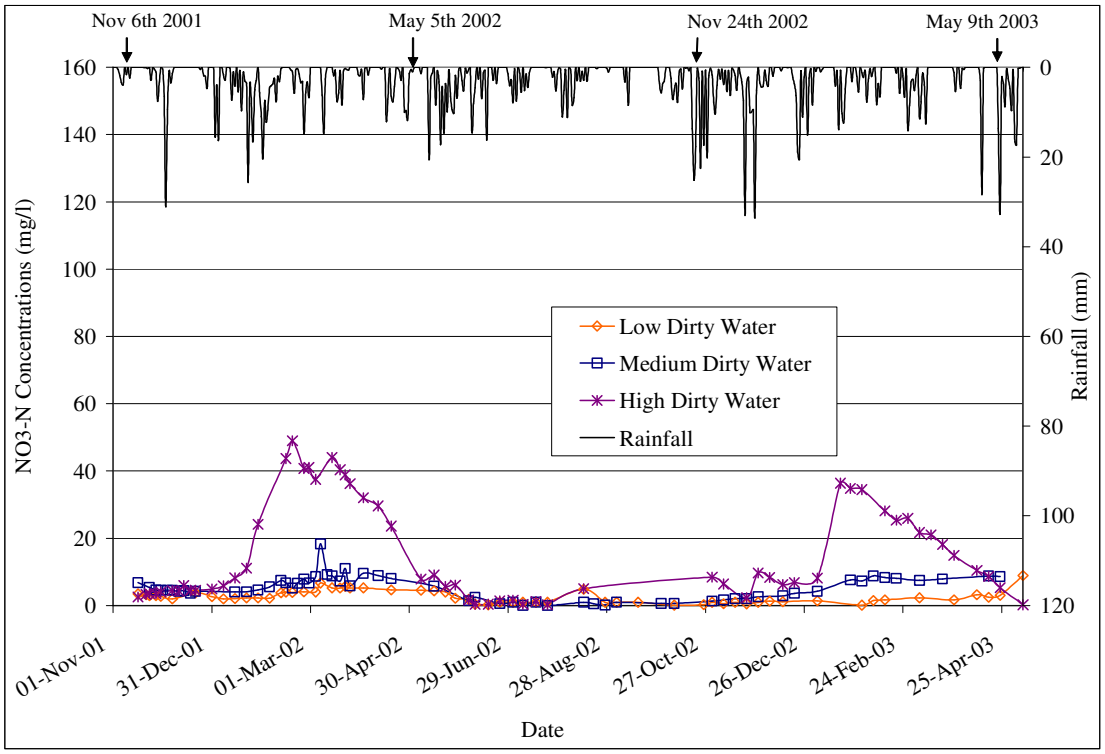

Fig. 4.30 Comparison of NO_3-N concentrations for the 0.9 m suction cups under different dairy wastewater application rates also showing daily rainfall amounts.

4.6.4.3 Residence time of NO_3-N in solution at depth

Elements of water containing NO_3-N in solution passing through soil take different routes and hence different lengths of time to reach a given depth. The distribution of these times is called the residence time distribution (RTD) of the NO_3-N solution. The NO_3-N concentrations in the dairy wastewater treatments applied in November 2001 show that the mean residence time of NO_3-N in the application was about 120 days for a depth of 0.9 m below ground surface. The irrigation rates were 10, 25 and 50 mm. During that period the effective rainfall was 317 mm and adding the medium application rate, the effective recharge was 342 mm, which travelled through the water-filled pores that amounted to 0.37 of the soil volume. The average recharge rate was 2.9 mm/day and the average pore velocity was 7.7 mm/day. Dividing the recharge over the 120 days by the water filled porosity gives the depth of penetration, which is 0.92 m. This is close to the depth at which the measurements were taken i.e. 0.90 m. Similar agreement was obtained for 13 measured and calculated NO_3-N mean travel times at depths less than 1.5 m. This confirms that the mean residence time is determined by the recharge (effective rainfall and irrigation) rate and the water-filled pore space, and not by the saturated hydraulic conductivity that is in the range of 160-1130 mm/day, which is at least 40 times greater than the mean rainfall rate of 3- 4 mm/day during the winter season. These results indicate that the mode of flow is convection-dispersion at the experimental plots.

4.6.4.4 Laboratory comparison of suction cups from Farm Scale and Soil Investigation work packages

Two types of ceramic pore water samplers were employed in the nitrate leaching study. For the Farm Scale work package (Ryan *et al*., 2006), small ceramic cups (25 mm outside diameter), labelled Ryan cups in Figs. 4.31–4.34, were placed in the soil at 1.0 m depth and connected by 8 m of capillary tube to a conical flask under a

vacuum of 5 m resting on the ground surface. For the present study - the Soil Investigation – larger ceramic cups, 50 mm outside diameter attached to PVC tubes 1.0 m long (Fig 3.9) and labelled ceramic cup in Figs. 4.31–4.34 were used and placed in the soil under a 1.0 m vacuum. Both cups were compared in a tank of silty sand to determine if they collected pore water samples of similar concentrations of NO_3-N and bromide (Br^-).

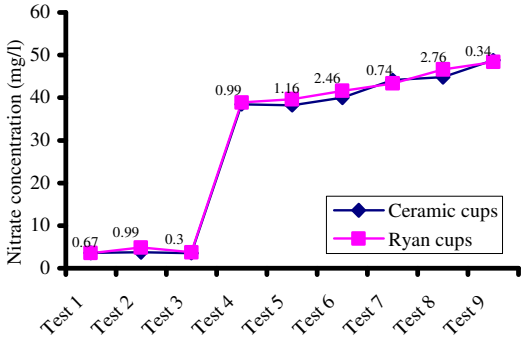

Figure 4.31. Nitrate concentrations in leachates with STDEV on top for two cup samplers under field-saturated conditions

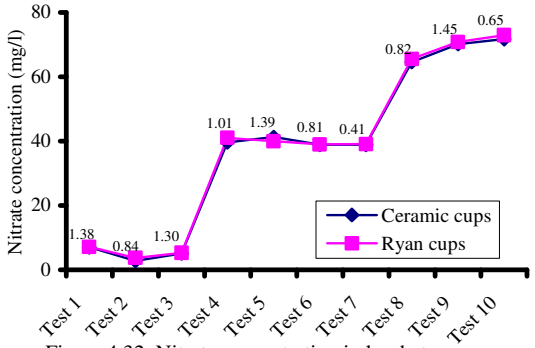

Figure 4.32. Nitrate concentration in leachates with STDEV on top for two cup samplers under unsaturated conditions

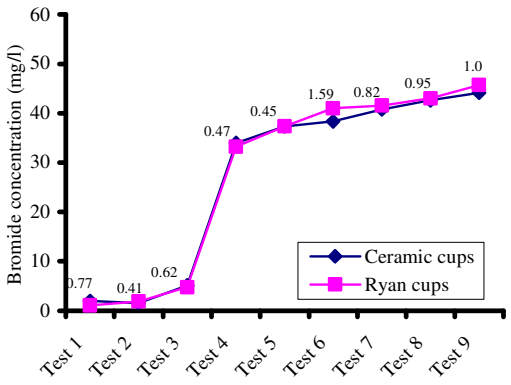

Figure 4.33. Bromide concentrations in leachates with STDEV on the top for two cup samplers under field-saturated conditions

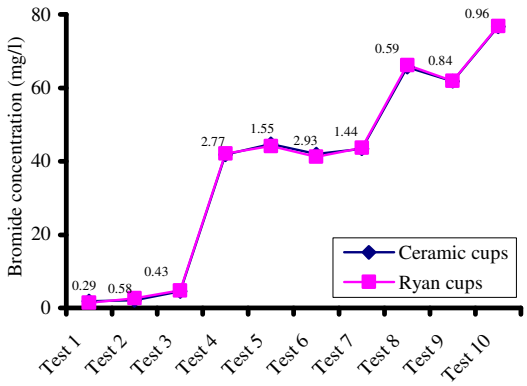

Figure 4.34. Bromide concentrations in leachates with STDEV on the top for two cup samplers under unsaturated conditions

The ceramic cup samplers were tested under field-saturated and unsaturated conditions. Three loadings, i.e. 10, 40 and 80 mg/l of NO_3-N solutions, were used for the field-saturated and unsaturated tests. The concentrations of NO_3-N in leachate collected by the large and small cup samplers for different test runs are shown in Figs. 4.31 and 4.32. These graphs show that both samplers yielded similar NO_3-N concentrations regardless of concentration loadings, under both field-saturated and unsaturated conditions. In order to assess the differences between the two sampler types, the standard deviation for each test run was calculated. It ranged between 0.3 and 2.76 mg/l for different test runs and revealed no significant differences between sampler types. The experiments were repeated using three loadings (i.e. 10, 40 and 80 mg/l) of bromide concentrations to check the reliability of samplers. The bromide concentrations observed in the leachate are shown in Figs. 4.33 and 4.34. Both samplers yielded similar bromide concentrations under low and high loadings in field-saturated and unsaturated conditions. The standard deviation ranged between 0.41 and

1.59 mg /l for the different test runs showing no significant differences between the sampler means.

4.6.4.5 Decline in nitrate-nitrogen concentrations at depths greater than 1.5 m during the study period.

The NO_3-N concentrations at 2.0, 2.5 and 3.0 m in the medium dairy wastewater treatment declined during the study period (Fig 4.35). The high concentrations of NO_3-N recorded in all four plots at depths of 1.5 m and greater, declined steadily below the 11.3 mg/l over a period of 12 to18 month measurement period indicating that high initial NO_3-N values in soil pore-water are leached out by the high net annual recharge (600 mm).

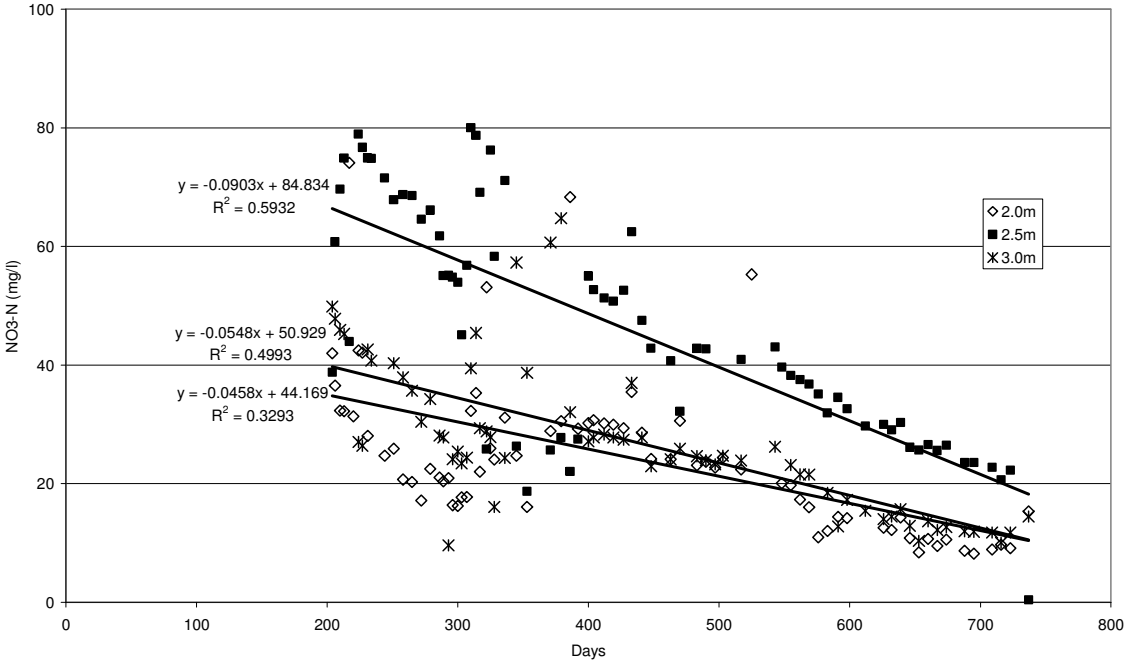

Fig.4.35. The decline in NO_3-N concentrations in the soil water at 2, 2.5 and 3 m with time as high NO_3-N soil solutions were driven downwards by recharge in the medium dairy wastewater treatment. The high values of NO_3-N were not caused by the 25 mm dairy wastewater application on Day 189.

4.7 Summary

Chapter 4 presented the results from the field and laboratory tests and experiments. They include:

1. Description, classification and physical properties of the soil
2. Hydraulic conductivities
3. Pore water characteristic curves
4. Nutrient application rate treatments on plots
5. NO_3-N analyses of pore water samples from different depths in the various treatments indicating convection-dispersion flow
6. Hydraulic potentials and contents of soil pore water
7. Estimation of NO_3-N travel times in the soil
8. A comparison of two porous ceramic samplers used on site.
9. Evidence of a decline in NO_3-N concentrations in the soil below 1.5 m.

CHAPTER FIVE

Mathematical Modelling

5.1 Introduction

Mathematical modelling is a widely accepted form of estimating solute transport in soils and groundwater. There are a wide variety of models available and these models vary in complexity. Deterministic mechanistic models of solute movement based upon miscible displacement theory, diffusion and Darcy's law (Nielsen and Biggar, 1962) have been widely used in soil science over the last 30 years. Models can be used to predict solute movement through soils, such as nitrates, and how different agricultural practices may affect this movement. Mathematical models presume that a given set of physical and chemical events leads to a uniquely definable water or solute distribution in the soil profile (Hutson, 2001)

5.2 LEACHM modelling

LEACHM is a general acronym for Leaching Estimation and Chemistry Model. It was developed by R.J. Wagenet and J.L. Hutson of Cornell University, USA in 1987. It contains five different modelling versions for describing solute and water transport through unsaturated soils:

- LEACHN describes N and P transport using biological and chemical transformations
- LEACHP describes pesticide displacement and degradation
- LEACHC describes the movement of inorganic ions
- LEACHW describes the water regime
- LEACHB describes microbial population dynamics in the presence of a single growth supporting substance (not available on newer versions)

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5.3 Theory

5.3.1 Water retention and conductivity functions

Retentivity equations are equations which relate volumetric water contents (θ) to matric potential (h). Conductivity functions relate volumetric water contents (θ) to hydraulic conductivities (K). LEACHN uses functions proposed by Campbell (1974). Campbell's water retention equation (1974) is:

$$h = a\,(\theta/\theta_s)^{-b} \qquad \textbf{(5.1)}$$

where
h is pressure potential (kPa)
θ_s is volumetric water content at saturation
θ is volumetric water content
a and b are constants

Hutson and Cass (1987) modified Equation 5.1 by defining a parabolic section expressed in terms of the constants a and b. For pressure potentials between zero and h_c,

$$h = \frac{a(1-\theta/\theta_s)^{1/2}(\theta_c/\theta_s)^{-b}}{(1-\theta_c/\theta_s)^{1/2}} \qquad \textbf{(5.2)}$$

where (h_c,θ_c) is the point of intersection of the exponential and parabolic curves, and

$$h_c = a[2b/(1+2b)]^{-b} \qquad \textbf{(5.3)}$$

and

$$\theta_c = 2b\theta_s/(1+2b) \quad \textbf{(5.4)}$$

By applying a capillary model to Equation 5.1 Campbell (1974) derived a conductivity equation,

$$K(\theta) = K_s(\theta/\theta_s)^{2b+2+p} \quad \textbf{(5.5)}$$

where
$K(\theta)$ = hydraulic conductivity (mm/d) at a water content θ
K_s = hydraulic conductivity at saturation θ_s
p = a pore interaction parameter

5.3.2 Water uptake by roots

Following Nimah and Hanks (1973), the rate of water absorption by plant roots at node i during the time interval j-1 to j can be estimated by:

$$U_i^{j-½} = [H_{root} + z_i(1+R_c) - h_i^{j-½} - s_i^{j-½}] [RDF_i^{j-½} K_i^{j-½}/\Delta x\Delta z] \quad \textbf{(5.6)}$$

where
$U_{i,j-½}$ = the transpiration sink term (day^{-1}) for node i
H_{root} = an effective water potential in the root at the soil surface (mm)
$(1+R_c)$ = a root resistance term
h_i = soil water matric potential (mm)
s_i = osmotic potential (mm)
RDF = the fraction of total active roots present in depth increment i
K_i = hydraulic conductivity (mm/d)
z_i = depth to node i (mm)
Δx = the distance from a point in the soil where $h_i^{j-½}$ and $s_i^{j-½}$ are measured, to the plant root (currently specified in the code to be 10 mm)
Δz = thickness of the soil profile

5.3.3 Richards Equation

LEACHN uses a finite-difference one-dimensional form of the Richards equation as a means of predicting water contents, fluxes and potentials. Richards' equation, the soil water flow equation for transient vertical flow derived from Darcy's law and the equation of continuity, is:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\frac{\delta H}{\delta z}\right] \pm U(z,t) \quad \textbf{(5.7)}$$

where
θ = volumetric water content (m^3m^{-3})
H = hydraulic head (mm)
K = hydraulic conductivity (mm/d)
t = time (d)
z = depth (mm) positive downwards
U = a source or sink term (d^{-1})

The differential water capacity, $C(\theta)$, is defined as:

$$C(\theta) = \delta\theta/\delta h \quad \textbf{(5.8)}$$

where h is the matric potential

Substituting Equation 5.8 into 5.7 yields Equation 5.9

$$\frac{\delta h}{\delta t} C(\theta) = \frac{\delta}{\delta z}\left[K(\theta) \frac{\delta H}{\delta z} \right] - U(z, t) \qquad \textbf{(5.9)}$$

where the pressure potential is the only dependent variable.
The first-order partial on the left-hand side of Equation 5.9 may be approximated as:

$$\frac{\delta h}{\delta t} = \frac{h_i^j - h_i^{j-1}}{\Delta t} \qquad \textbf{(5.10)}$$

The second-order partial differential term on the right hand side of Equation 5.9 can be approximated as:

$$\frac{\delta}{\delta z}\left[K(\theta) \frac{\delta H}{\delta z} \right] = \frac{\delta}{\delta z}\left[K(\theta) \frac{\delta h + \delta z}{\delta z} \right]$$

$$\approx \frac{K_{i-1/2}^{j-1/2}}{\Delta z_3 \Delta z_1}\left(h_{i-1}^{j-1} + h_{i-1}^{j} - h_i^{j-1} - h_i^{j} + 2\Delta z_1 \right) \qquad \textbf{(5.11)}$$

$$- \frac{K_{i+1/2}^{j-1/2}}{\Delta z_3 \Delta z_2}\left(h_i^{j-1} + h_i^{j} - h_{i+1}^{j-1} - h_{i+1}^{j} + 2\Delta z_2 \right)$$

where
$\Delta z_1 = z_i - z_{i-1}$
$\Delta z_2 = z_{i+1} - z_i$
$\Delta z_3 = z_{i+1} - z_{i-1}$ (From Fig. 5.2)
and $K_{i+½}^{j-½}$ and $K_{i-½}^{j-½}$ are hydraulic conductivities representative of the depth interval i - ½ to i + ½, of thickness Δz.

Substituting Eq. 5.10 and 5.11 into Eq. 5.9 gives

$$C(\theta)_i^{j-1/2} \frac{(h_i^j - h_i^{j-1})}{\Delta t}$$

$$\approx \frac{K_{i-1/2}^{j-1/2}}{\Delta z_3 \Delta z_1}\left(h_{i-1}^{j-1} + h_{i-1}^{j} + 2\Delta z_1 - h_i^{j-1} - h_i^{j} \right)$$

$$- \frac{K_{i+1/2}^{j-1/2}}{\Delta z_3 \Delta z_2}\left(h_i^{j-1} + h_i^{j} + 2\Delta z_2 - h_{i+1}^{j-1} - h_{i+1}^{j} \right) - U_i^{j-1/2} \qquad \textbf{(5.12)}$$

Equation 5.12 describes the change in water content at node i during the time interval j-l to j

5.3.4 Characteristics of LEACHN

- LEACHN is a deterministic mechanistic model for predicting nitrate movement in unsaturated soils
- it uses equal depth increments
- it does not take account of surface runoff
- all flow is assumed to be one dimensional

5.4 Input and output files in LEACHN

Fig. 5.1 shows the major components and pathways used in LEACHM.

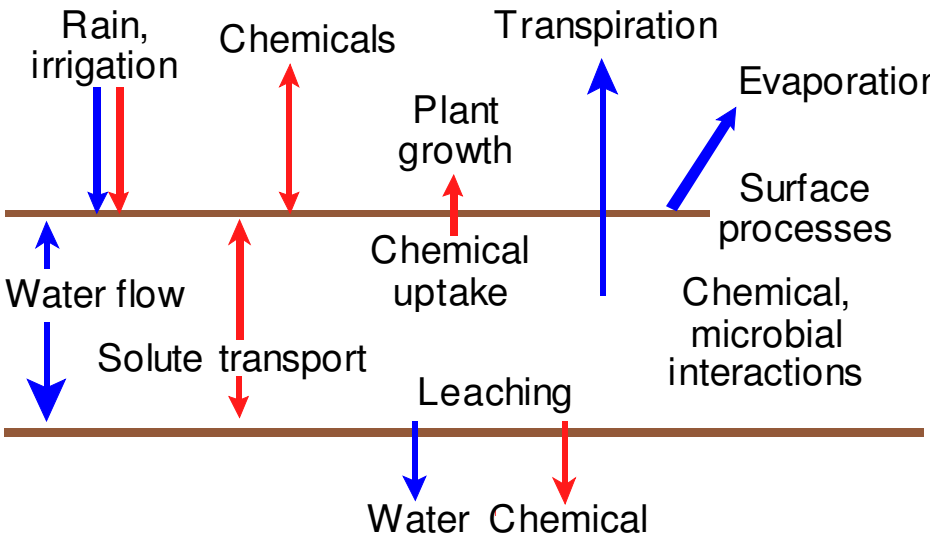

Fig. 5.1 Major components and pathways of LEACHM

LEACHM divides the soil into a number of horizontal segments of equal thickness (Fig. 5.2). There are two nodes; one above the profile surface and one below the profile depth that are used to maintain the boundary conditions.
Among the boundary conditions that can be simulated are:

Upper boundary

- ponded infiltration
- non-ponded infiltration
- evaporation
- zero-flux

Lower boundary

- fixed water table depth
- free drainage
- zero flux
- lysimeter
- fluctuating water table

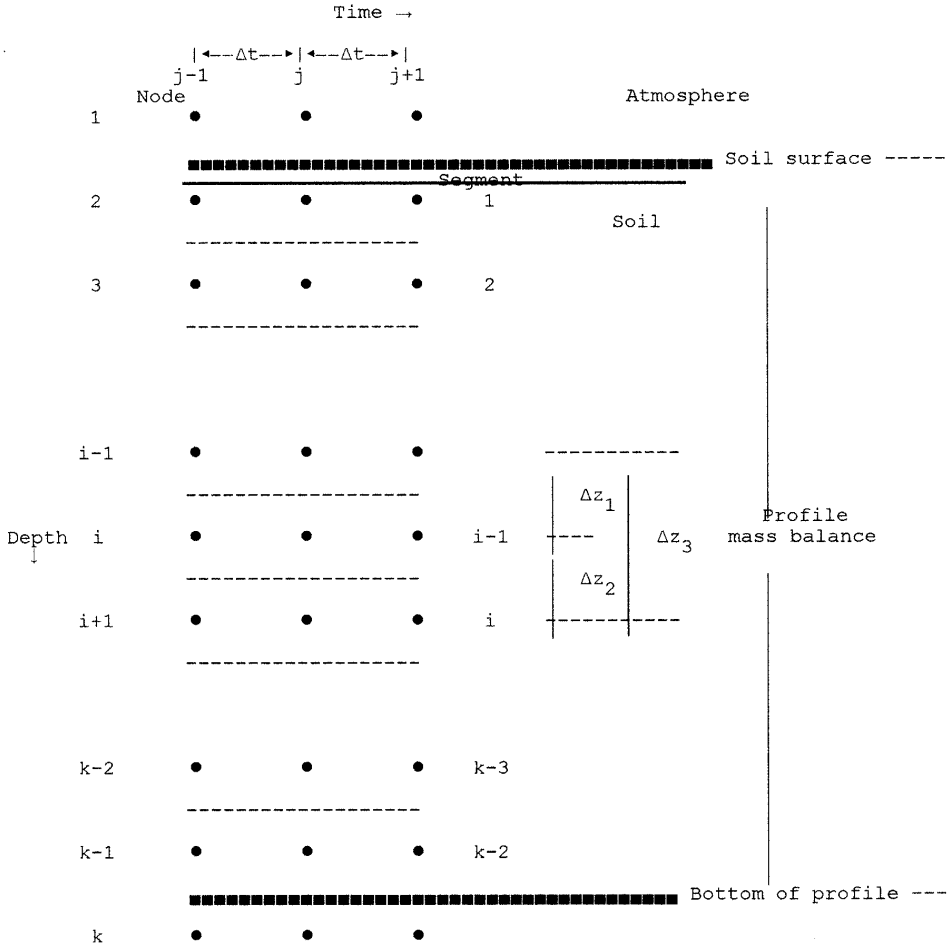

Fig. 5.2 Definition of nodes and segments in LEACHM. Two boundary nodes (1 and k) are outside of the profile and are not included in profile mass balance calculations.

LEACHN requires the following inputs:

1. General information
   - Date format (DDMMYYY or MMDDYYY)
   - Dates of study
   - Profile depth
   - Segment thickness
   - Equation for water flow (Richards, Addiscott, etc)

2. Output information
   - Units (some fields are fixed)
   - Files to be generated
   - Type of information to be returned
     - Pore water concentrations
     - Mass of nutrients leached
     - Hydraulic conductivities
   - Cumulative data
   - Dates for output data

3. Soil properties and initial conditions for each input
   - Clay, silt, organic carbon percentages
   - Potentials or water contents
   - Root percentages
   - Particle density: clay, silt and sand, organic matter
   - Parameter values for Addiscott or Campbell equation
   - Bulk density
   - Hydraulic conductivity
   - Dispersivity values
   - Runoff parameters : curve number and % slope

4. Crop data
   - Number of crops
   - Wilting point and minimum root water potential
   - Root resistance
   - Crop uptake (N,P)
   - N fixed
   - Harvested fraction

5. Initial N, P, and C pools in soil profile
   - Concentrations of NH_4, NO_3 and P
   - Concentrations of Urea, NH_4, NO_3, Residue-(N,P,C), Manure-(N,P,C), Labile-P
   - Depth of water in mixing cell

6. Chemical Properties
   - K_d constants for manure and residue organic sources for N, P, C
   - Molecular diffusion coefficients

7. Nitrogen transformations
   - Efficiency factor
   - Humification fraction
   - Relation C/N and C/P
   - Temperature
   - High and low water potentials
   - Transformation rates at saturation
   - Rate constants: Hydrolysis Urea, NH_4-NO_3, NO_3-N_2, mineralization constants for residue, manure, humus
   - Ammonia volatilization from surface
   - Denitrification half-saturation rate
   - Limiting ratio NH_4/NO_3 for nitrification

8. Nutrient applications (N, P, C)
   - Number the segments affected
   - Amounts of the fertilizers of N, P and C in their correspondent forms
   - Cultivation depth

9. Weather information
   - Daily rainfall, surface flux density and concentrations of Urea, NH_4, NO_3, and P

- Weekly evapotranspiration, mean temperature, temperature amplitude

LEACHN generates four output files:

1. .OUT file
   - Predicted conductivity and retentivity
   - Mass balance for water, urea, NH_4, NO_3, residual N, manure N, humus N, residue C, manure C, humus C, CO_2, N_2 and their sources (losses or additions)
   - Detailed data per node of depth: water content, hydraulic potential and pore water concentrations
   - Crop information per node: uptakes of NH_4, NO_3, transpiration, temperature, root potential

2. .SUM file
   The .SUM file is a summary file that predicts solute concentrations of nitrogen and phosphorus at three specified depths during the specified dates of the project

3. .BTC file
   - Time, year, month where the leaching is produced, cumulative leached water, cumulative pore volumes, flux-averaged concentrations for Urea, NH_4, NO_3 and P, cumulative mass of solute species leached

4. .P file
   For each selected date:
   - Mass balance for water, Fert-P, Labile-P, Residue-P, Humus-P, Manure-P, Bound-P (losses or additions)
   - Detailed data per node of depth: water content, potential, flux and nutrient information
   - Crop information per node: root fraction, temperature, transpiration, uptake by plants, labile-P

5.5 Input parameters for the LEACHN input file

The input parameters for the model were based on measured physical and chemical soil properties of the Curtin's farm soil. A 3.0 m soil profile was used in the model and was divided into 20 segments. There were five layers in the soil (Table 4.1) and there was a number of 150 mm segments assigned to each layer. The input parameters are shown in Table 5.1.

Table 5.1 Input parameters for LEACHN input file

Segment No.	Soil Depth	Clay	Silt	Air entry value	Campbell's *b*	Permeability
	cm	%	%	kPa		mm/day
1	0 - 13	6	38	-1.0	3.0	320
2 - 3	14 - 35	11	41	-1.0	3.5	320
4 - 6	36 - 80	12	36	-1.5	4.5	250
7 - 10	81 - 150	11	29	-2.2	6.7	200
11 - 20	151 - 300	16	35	-2.4	7.0	200

5.6 Results of mathematical modelling

Dairy wastewater was the only fertiliser modelled since chemical fertiliser was applied in granular form and it would have to be dissolved before it could move down the soil profile, and slurry did not give rise to any soil contamination problems. The sequence of results in LEACHN is presented in Table 5.2.

Table 5.2 LEACHN results layout

Experiment	Fig. No.
Low dairy wastewater	5.3
Medium dairy wastewater	5.4
High dairy wastewater	5.5

5.6.1 Low dairy wastewater (Fig. 5.3)

The model values at 0.3 and 0.6 metres compared well with the field data. Field results at the 0.6 m depth were low (<5 mg NO_3-N /l) and this was reflected in the model data. At 1.2 m and 1.5 m depths (day 200), the model showed higher concentrations of NO_3-N than the field data initially, but the concentrations reduced to values similar to the field data with time.

5.6.2 Medium dairy wastewater (Fig. 5.4)

The model gave good agreement with the field nitrate concentrations at the 0.3 and 0.6 metre depths. At 1.5 m depth there was fair agreement between the model and field results.

5.6.3 High dairy wastewater (Fig. 5.5)

The model NO_3-N concentrations compared reasonably well with the field data in the high dairy wastewater treatment.

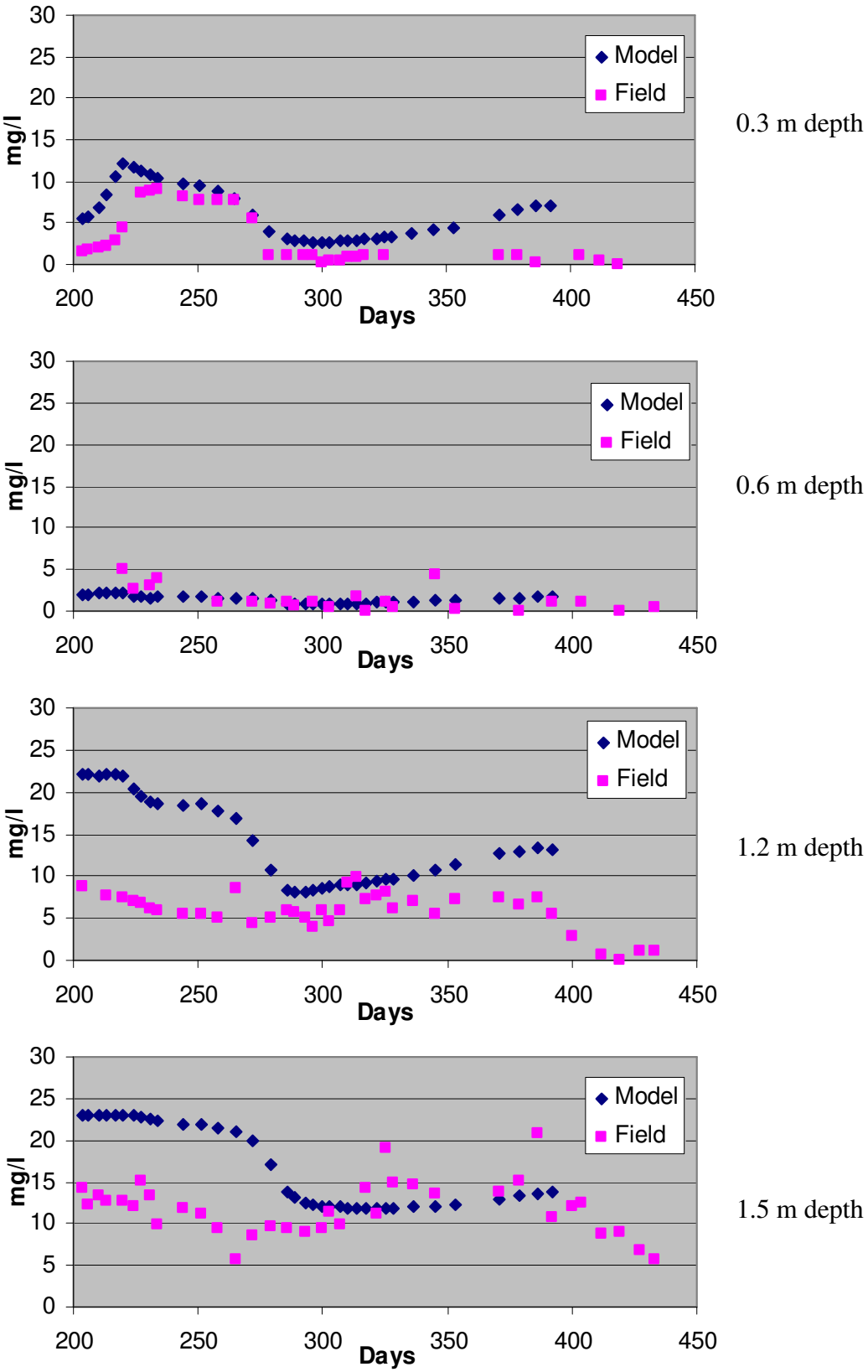

Fig. 5.3 NO_3-N concentrations for the low dairy wastewater plot compared with the model for depths of 0.3, 0.6, 1.2 and 1.5 m (days after May 1st, 2001)

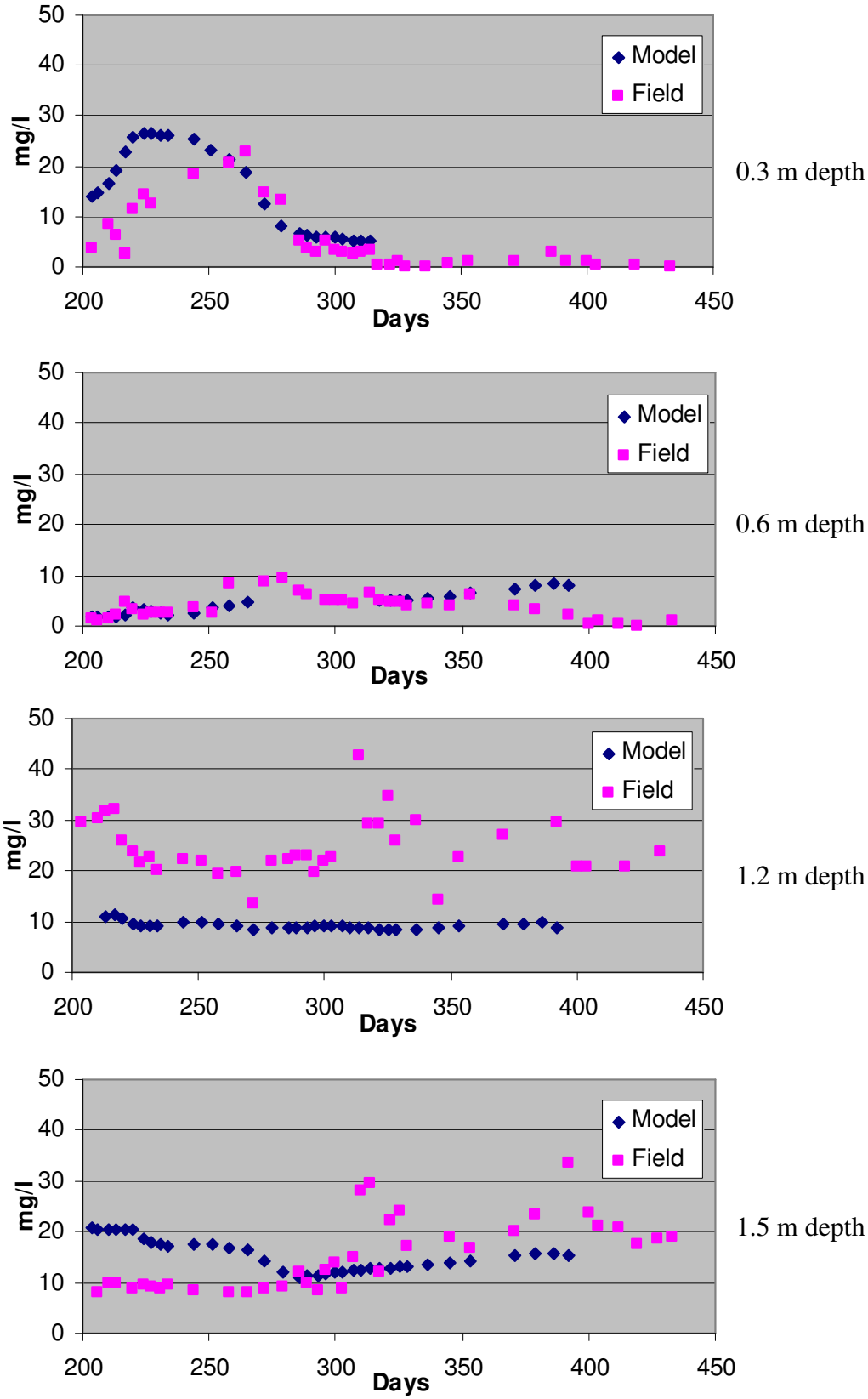

Fig. 5.4 NO_3-N concentrations for the medium dairy wastewater plot compared with the model for depths of 0.3, 0.6, 1.2 and 1.5 m (days after May 1st, 2001)

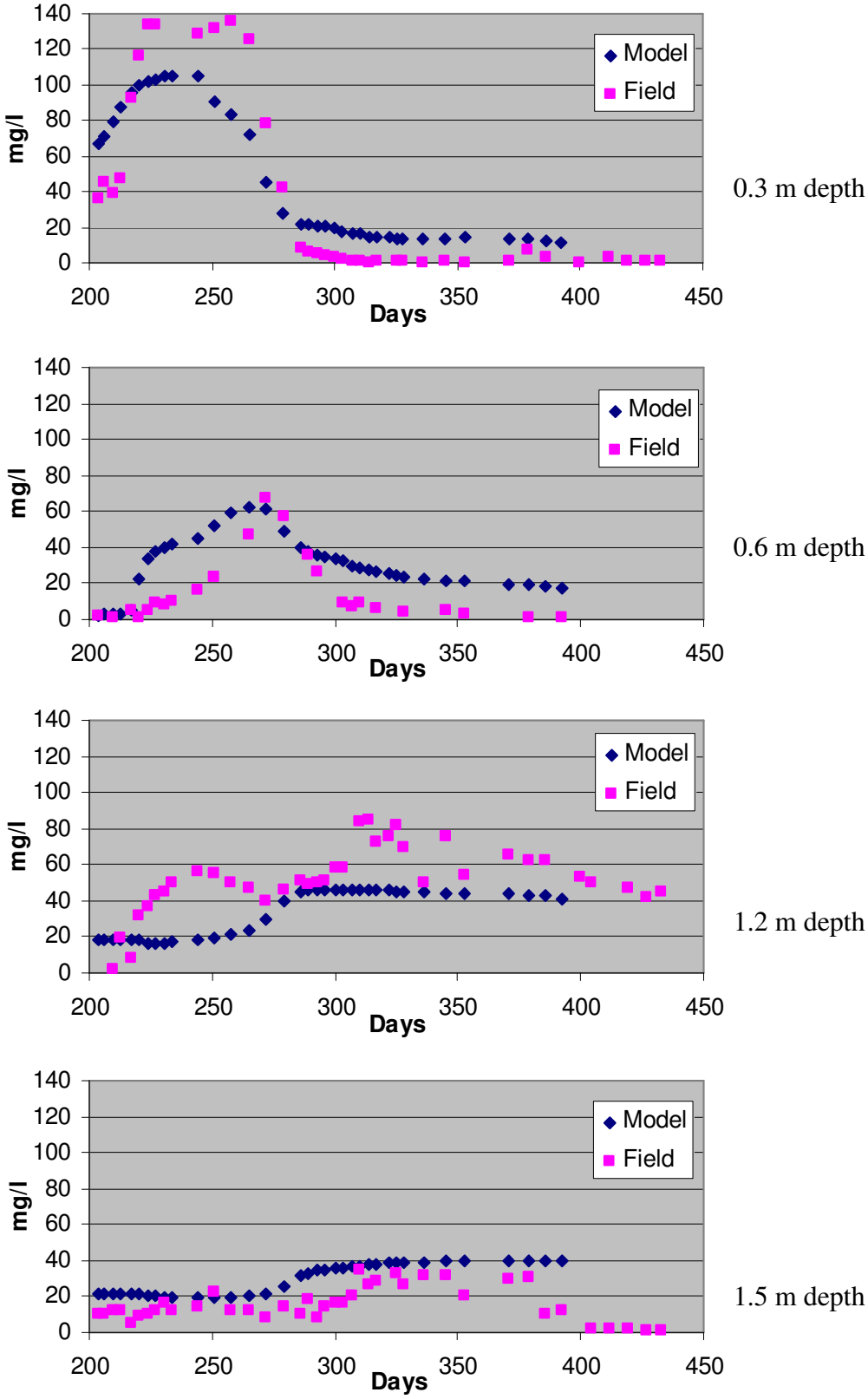

Fig. 5.5 NO_3-N concentrations for the high dairy wastewater plot compared with the model for depths of 0.3, 0.6, 1.2 and 1.5 m (days after May 1st, 2001)

5.7 Conclusions from model results

The modelling of dairy wastewater worked reasonably well. The model gave fair agreement with the nitrate concentrations for all dairy wastewater treatments. Further experimental work would need to be carried out to model the solubilisation and movement of NO_3-N derived from chemical fertilisers.

5.8 Summary

Chapter 5 discusses the different processes involved in LEACHN. The dairy wastewater treatments were modelled and results are presented in graphical format

CHAPTER SIX

Conclusions and Recommendations

6.1 Introduction

The objective of the study was to measure the effects of high, medium and low applications of chemical N fertilisers, cow slurry and dairy wastewater on the NO_3-N concentrations in a deep, unsaturated, free draining soil typical of a nitrate vulnerable zone. The study involved setting up 8 m x 8 m experimental plots equipped with tensiometers, neutron access tubes and pore water samplers. The soil was characterised physically to assess its vulnerability to leaching. Fertiliser, slurry and dairy wastewater were applied at various times throughout the year to simulate farming practices. Soil pore water samples were extracted for NO_3-N concentration analysis throughout the two years of the study. A finite difference mathematical model was used to simulate solute movement through the soil.

6.2 Main conclusions from field experiments

- The soil is a free-draining gravelly sandy SILT (sandy loam) of low plasticity down to 1.5 m depth, underlain by a free-draining gravelly clayey sandy SILT (clay loam) of low plasticity down to about 3.0 m depth. Beneath the topsoil the soil has high dry bulk density, low porosity and a field-saturated hydraulic conductivity of 160-1130 mm/day. The soil below the topsoil (subsoil) has a good uniform structure with no evidence of fissures, cracks or other macropores. The soil has a wide use range for agriculture and is thought to represent about 13% of the soils of the Republic of Ireland.
- In general, the NO_3-N concentrations at depths greater than 1.5 m declined from initially high values over the 24 month study period. For example, the decline was measured in 9 of the 10 treatment plots (including the control) at 3-m depth. These initial high concentrations of NO_3-N were not caused by the treatments imposed in this investigation since high concentrations (up to 21.4 mg/l) were also measured in the control plot at depths greater than 1.5 m. The declines suggest that due to the high recharge in Irish conditions, high levels of pore water NO_3-N concentrations in soils can reduce to low levels over relatively short periods of time - of the order of 12 to 24 months - following reductions in N applications and/or rescheduling of late autumn – late winter/early spring chemical N applications and/or reduction in irrigation rates of dairy wastewater especially in winter and/or proper operation of a rotational schedule of irrigation.
- The measurements on the dairy wastewater plots applied in November 2001 showed that the mean residence time of NO_3-N was about 120 days for a depth of 0.90 m below ground surface. The irrigation rates were 10, 25 and 50 mm. During that period the effective rainfall was 317 mm and adding the medium irrigation rate, the effective recharge was 342 mm, which travelled through the water-filled pores that amounted to 0.37 of the soil volume. The average recharge rate was 2.9 mm/day and the average pore velocity was 7.7 mm/day. Dividing the recharge over the 120 days by the water filled porosity gives the mean depth of travel, which is 0.92 m and is close to the depth at which the measurements were taken i.e. 0.90 m. Similar agreement was obtained for 13

measured and calculated NO_3-N mean travel times at depths less than 1.5 m. This confirms that the mean residence time is determined by the recharge (effective rainfall and irrigation) rate and the water-filled pore space, and not by the saturated hydraulic conductivity that is in the range of 160-1130 mm/day, which is at least 40 times greater than the mean rainfall rate of 3-4 mm/day during the winter season. These results show that the downward recharge was in convection-dispersion flow mode.

- Over the 24 month period of measurement in the control treatment, the NO_3-N concentrations in the pore water were in general below 10 mg /l. At the 3.0 m depth, the NO_3-N concentrations in the pore water declined from an initial value of 19 mg/l to less than 10 mg /l over a period of 5 weeks in November-December 2001 and remained low thereafter.
- Over the 24 month period of measurement in the low N fertiliser treatment (174 kg/ha), the NO_3-N concentrations in the pore water were, in general, below 10 mg/l. At the 3.0 m depth, the NO_3-N concentrations declined from an initial value of 50 mg/l to less than 10 mg /l in 18 months.
- Over the 24 month measurement period in the medium N fertiliser plot (286 kg/ha), the NO_3-N concentrations in the pore water were, in general, about 10 mg/l. It appears that the values in excess of 10 mg /l were caused by the mid-late September N applications and late January-early February urea-N applications. The timing and rates of these applications should be reviewed. Summer N fertiliser applications did not appear to cause a significant rise in the NO_3-N concentrations in the pore water.
- Over the 24 months of measurements in the high N fertiliser plot (387 kg/ha), the NO_3-N concentrations in the pore water were, in general, over 10 mg/l indicating that this rate is excessive, especially in spring. This result again emphasizes the necessity to review the timing and rates of the late and early season N applications.
- The NO_3-N concentrations in the pore water of the low dairy wastewater treatment (10 mm irrigation) were low and never exceeded 10 mg/l at 0.3 and 0.9 m. At 1.5 and 3.0 m, the NO_3-N concentrations were initially above 10 mg/l but declined with time.
- In the medium dairy wastewater treatment in November (25 mm irrigation), the NO_3-N concentrations at 0.3 m depth responded slowly in 2001 when rainfalls were low and quickly in 2002 when the soil was wet due to heavy rainfall. While no NO_3-N concentrations response was obtained to the summer application at any depth, there appeared to be a response of > 10 mg/l to the November applications at 1.5 m depth. Responses at all depths were in accordance with convection-dispersion theory.
- The NO_3-N concentrations in the high dairy wastewater treatment were above 10 mg/l at all depths as a result of the 50 mm application of dirty water in November, 2001 and 2002 indicating that this application rate in winter is excessive. The application of high dirty water in May 2002 did not cause NO_3-N concentrations to rise at any depth.
- Field saturation developed in the top 0.9 m soil following medium and heavy hydraulic irrigation in November 2002 for less than a day. These conditions are reflected in the high pore water NO_3-N concentrations at 1.5 m (May 2002) in the medium load plot, and at 0.3, 0.9 and 1.5 m in the heavy load plot.

- Hydraulic loads in excess of 25 mm wastewater should not be applied at any time of the year and loads in excess of 10 mm should not be applied in winter.
- The frequency of irrigation should not be more than twice per year. This would require that 15-20% of the farm area be dedicated to irrigation. On a 100 cow, 40 ha farm, the dirty water could be irrigated, for example, on 6 ha (15 % of the farm area) as follows:
  during the period mid-October to mid-February inclusive, irrigate at 100t/ha (10 mm); during the rest of the year, irrigate at a maximum of 250 t/ha (25 mm)
- Concentrations in all of the slurry plots were lower than 10 mg/l NO_3-N at all depths down to and including 1.5 m. The shallower ceramic suction cups did not show an increase in NO_3-N concentrations as a result of application of slurry.
- High initial NO_3-N concentrations at the 3.0 m depth in the three slurry plots declined from above 10 mg/l to below 10 mg/l over a 12 month period. These initial high concentrations of NO_3-N were not caused by the treatments imposed in this investigation.
- The LEACHN model gave fair agreement with field data for the dirty water treatments. Further research is required on this model before it can be used to predict nitrate movement following chemical fertilizer application.

6.3 Recommendations for further research

Further study is recommended on the site since it is now well instrumented and well characterised:

1. Further research should be carried out on the timing and rates of chemical N fertiliser applications, especially late and early season applications.
2. Since NO_3-N concentrations at depths below 1.5 m have declined below 10 mg/l, the effects of applications of chemical N fertiliser and dirty water on pore water NO_3-N concentrations at depths of 1.5 m and greater should be investigated by continuing to sample and analyse the soil pore water.
3. Studies on the combined effect of chemical N fertiliser and dairy wastewater on NO_3-N pore water concentrations are recommended.

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APPENDIX A –
NITRATE CONCENTRATIONS

NO_3-N concentrations for the control plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
114	0.1	114	0.2	24	3.9	24	2.5
119	0.1	119	0.1	29	12.3	34	9.8
129	0.1	129	0.1	34	6.4	38	8.7
157	0.0	132	0.0	49	6.7	49	9.2
161	0.1	135	0.3	59	8.8	52	12.1
168	0.1	140	0.1	62	10.7	55	13.5
171	0.1	147	0.1	65	9.9	59	12.8
175	0.1	154	0.2	69	8.2	62	14.0
178	0.1	157	0.3	78	8.2	65	13.5
182	0.1	161	0.0	86	9.4	69	9.4
196	0.1	171	0.1	101	13.8	73	9.8
199	0.2	175	0.1	114	9.1	78	8.9
204	0.2	178	0.1	119	11.1	83	12.1
206	0.7			122	12.5	86	12.7
210	0.7	213	5.0	132	13.0	90	9.7
213	0.8	217	2.5	135	13.0	93	11.5
217	0.8	220	1.8	140	12.2	98	12.8
220	0.6	224	2.0	143	11.4	101	12.9
224	0.6	227	2.3	147	11.8	105	12.9
227	0.6	231	2.4	154	8.6	108	8.5
231	1.1	234	3.1	157	11.7	111	11.2
234	0.7	244	2.6	161	8.0	122	10.4
244	1.0	251	3.0	168	8.8	126	6.3
251	1.4	258	3.3	171	4.8	129	9.6
258	1.3	265	3.8	175	6.3	132	12.2
265	1.3	272	3.6	178	6.3	135	12.4
272	0.5	279	3.5	196	6.2	140	12.5
279	0.2	286	3.1	199	5.9	143	11.6
286	0.0	289	2.0	204	5.5	147	11.9
289	0.4	293	3.0	206	5.5	150	9.0
293	0.3	300	3.0	210	5.3	154	8.2
296	0.1	303	2.8	213	5.5	157	13.8
300	1.0	307	2.1	217	4.1	157	10.1
303	1.0	310	4.3	220	4.1	161	7.6
307	1.0	314	4.6	224	4.3	168	7.0
310	0.3	322	4.0	227	4.5	171	9.6
314	0.3	325	3.4	231	4.2	175	7.0
317	0.3	328	3.5	234	4.2	178	9.6
322	1.0	336	0.9	244	4.2	182	6.9
325	1.0	353	2.2	251	4.5	196	9.1
336	1.0	371	1.3	258	4.2	199	9.9
353	0.6	379	0.8	265	4.5	204	8.6
392	1.0	392	0.2	272	7.2	206	7.7
400	0.2	400	1.2	279	5.7	210	7.7
401	1.0	404	1.2	286	5.6	213	7.4
404	0.2	412	0.8	289	3.7	217	6.6

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	NO3-N	Days after May 1st	NO3-N	Days after May 1st	NO3-N	Days after May 1st	NO3-N
	mg/l		mg/l		mg/l		mg/l
412	0.1	419	0.8	293	5.6	220	6.2
419	0.1	427	0.1	296	5.3	224	6.3
427	1.3	433	1.0	300	5.5	227	6.4
433	1.0	441	0.2	307	6.1	231	6.2
470	1.0	448	2.3	310	9.3	234	6.4
562	1.0	470	1.0	317	7.1	251	6.8
576	1.0	548	1.0	322	7.7	265	7.2
583	0.1	555	0.5	325	7.3	272	7.5
591	0.4	562	1.0	328	6.8	279	6.6
598	0.4	569	1.0	336	7.0	286	7.0
612	1.2	576	1.0	353	6.9	289	4.9
626	1.4	583	0.4	371	7.2	293	6.6
632	2.6	598	1.1	392	5.4	296	7.0
639	2.2	612	0.4	400	3.5	300	7.1
646	2.5	626	2.0	401	3.9	303	7.7
653	0.7	632	1.6	404	3.5	307	7.6
660	1.3	639	2.1	412	2.8	310	14.1
723	1.2	646	2.0	419	2.5	314	15.2
		653	1.7	433	0.5	317	9.5
		660	1.1	441	0.5	322	8.5
		667	0.9	448	0.3	325	7.5
		695	0.1	470	3.0	328	8.1
		709	7.5	476	3.5	336	8.7
		716	1.0	483	3.8	353	8.4
		723	0.2	490	4.3	371	9.6
		737	0.4	503	5.6	379	9.7
				517	6.0	392	8.6
				543	5.7	400	7.6
				548	3.8	401	7.6
				555	3.8	404	7.6
				562	4.4	412	6.7
				569	4.4	419	6.2
				576	4.0	427	5.7
				583	4.9	433	3.3
				591	4.9	441	1.9
				598	4.7	448	1.4
				612	2.6	463	0.6
				632	8.0	470	0.6
				639	7.7	483	0.8
				646	9.6	490	0.5
				660	9.2	497	0.2
				667	8.9	503	1.1
				674	6.3	517	2.0
				709	5.9	525	2.9
				737	0.5	543	4.3
						548	4.4
						555	3.9
						562	8.4

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
						569	4.1
						576	3.6
						583	4.0
						591	4.4
						598	
						612	4.0
						626	4.1
						632	3.9
						639	3.9
						646	4.9
						653	4.8
						667	4.9
						681	5.6
						695	6.5
						709	5.7
						716	7.6
						723	7.5
						737	9.8

NO_3-N concentrations for the control plot (1.5, 2.0, 2.5 and 3.0 m)

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
24	2.8	196	21.4	98	1.9	196	15.6
31	9.3	199	16.7	101	2.4	199	18.3
34	5.7	204	15.4	105	2.4	204	16.8
38	5.2	206	18.4	111	3.6	206	17.7
49	4.8	210	18.7	114	3.7	210	17.4
52	6.6	213	16.8	119	3.9	217	14.9
55	8.3	217	14.6	122	4.4	220	13.6
59	5.6	220	11.8	126	4.0	224	13.2
62	6.1	224	12.1	129	4.3	227	12.3
65	5.9	227	12.7	132	4.3	231	13.4
69	5.2	231	13.6	135	4.3	234	9.8
73	5.1	234	9.5	140	4.4	244	11.3
78	5.2	244	12.1	143	4.7	251	7.4
83	5.9	251	4.4	147	4.6	258	10.8
86	6.2	258	9.7	150	6.0	265	10.7
90	5.1	265	8.7	154	4.6	272	7.9
93	5.6	272	5.9	157	5.2	279	7.1
98	5.4	279	6.6	161	5.4	286	9.8
101	6.4	286	8.8	168	5.5	289	6.7
108	13.1	289	5.3	171	5.7	293	8.3
114	8.3	293	7.8	175	5.7	300	6.7
119	7.0	296	7.2	178	5.8	303	7.8
122	8.3	300	7.4	182	6.8	307	8.2
126	7.6	303	8.4	196	6.3	310	16.2
129	6.9	310	17.1	199	7.0	314	16.8
132	6.9	314	17.2	204	6.7	317	9.3
135	7.1	317	9.5	206	6.5	325	6.8
140	7.7	322	8.4	210	6.7	328	8.7
143	8.3	325	8.6	213	15.1	336	6.6
147	7.6	336	9.6	217	6.6	353	9.0
150	8.7	353	9.8	220	7.0	371	9.6
154	7.9	371	6.8	224	7.2	379	9.2
157	8.5	379	7.5	227	7.5	386	7.1
161	8.6	386	8.0	231	6.9	392	8.6
168	8.1	392	10.2	251	10.6	400	9.0
171	6.9	400	9.7	272	8.2	404	9.0
175	6.4	401	9.6	279	6.9	412	8.3
178	6.4	404	9.7	286	5.5	419	8.0
182	9.1	412	8.8	289	4.4	427	9.0
196	6.3	419	8.9	293	6.2	433	9.2
199	6.1	427	9.2	296	6.2	441	7.4
204	7.0	433	9.4	300	7.1	448	7.7
206	7.3	441	7.5	303	6.9	470	8.6
210	7.1	470	8.4	307	7.6	483	9.1
213	6.4	483	8.7	310	14.5	490	8.9
217	5.1	490	8.6	317	8.8	497	9.0

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
220	4.6	497	8.7	322	8.0	503	9.1
224	4.8	503	8.7	325	8.7	517	8.4
227	5.0	525	9.4	328	7.9	525	8.9
231	4.6	543	9.2	336	9.1	543	9.3
234	4.6	548	8.6	353	7.9	548	9.7
244	4.7	555	8.2	371	8.7	555	9.2
251	4.5	562	4.5	379	8.8	569	10.0
265	4.5	569	8.1	400	6.8	576	9.5
272	3.1	576	7.4	401	8.1	583	9.8
279	3.0	583	7.2	404	6.8	591	9.1
286	2.8	591	6.7	412	7.4	598	8.4
289	2.1	598	6.4	419	7.6	612	7.6
293	2.7	612	5.7	427	8.1	626	8.2
296	2.5	626	6.1	441	7.1	632	8.3
300	2.5	632	5.7	448	7.3	639	7.4
303	2.4	639	5.2	470	7.8	646	9.1
307	2.6	646	6.1	483	8.2	653	7.9
310	3.9	653	5.2	490	8.1	660	6.7
317	3.4	660	4.1	497	8.5	667	6.7
322	3.5	667	3.9	503	8.2	674	6.5
325	3.5	674	3.6	525	8.4	681	6.1
328	3.0	681	4.5	543	8.3	688	8.6
336	3.7	688	6.3	548	7.6	695	5.7
353	4.8	695	4.6	555	7.4	709	6.5
371	4.4	709	6.3	562	7.6	716	6.8
392	5.9	716	6.0	569	7.0	723	6.9
400	5.9	723	5.9	576	5.3	737	7.0
401	5.5	737	5.2	583	5.1		
404	5.9			591	5.9		
412	4.6			598	5.8		
419	3.9			612	4.6		
427	3.9			626	6.2		
433	3.5			632	5.9		
441	2.4			639	5.9		
463	2.4			646	7.1		
470	0.6			653	6.3		
476	2.1			660	5.3		
483	1.4			667	5.6		
497	1.8			674	4.8		
503	1.8			681	5.2		
517	3.4			688	7.0		
543	4.4			695	5.4		
548	4.2			709	6.5		
562	3.6			716	6.7		
569	3.8			723	6.8		
576	2.7			737	5.8		
583	2.5						
591	3.0						

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
598	2.5						
612	3.1						
632	3.5						
639	3.1						
646	3.8						
653	3.5						
660	2.2						
667	3.3						
674	6.3						
681	3.7						
688	5.6						
695	3.7						
709	6.4						
716	4.4						
723	5.3						
737	7.3						

NO_3-N concentrations for the high fertiliser plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
161	10.4	24	2.9	24	3.7	24	8.1
168	6.6	29	8.4	34	9.1	29	6.5
171	12.8	34	9.7	49	11.3	38	16.4
175	9.0	49	9.5	62	15.3	49	19.8
178	7.9	129	7.7	65	16.2	52	48.0
182	6.8	168	7.9	69	12.0	55	35.6
196	6.7	171	9.0	86	14.0	65	26.3
199	7.7	175	12.0	101	15.2	69	21.7
204	8.1	178	10.5	108	15.3	78	22.4
206	8.6	182	6.2	111	16.3	83	25.0
210	9.0	196	9.6	119	13.5	86	4.5
213	9.1	199	10.0	122	12.6	90	20.0
220	13.1	204	9.8	135	17.1	98	23.5
224	29.6	206	13.5	140	20.7	108	4.5
227	17.4	210	12.1	154	12.7	161	7.0
231	24.4	213	14.7	157	16.9	168	29.2
234	21.7	217	13.9	161	13.7	171	28.9
244	24.4	220	12.4	168	14.0	175	37.0
251	20.3	224	16.9	171	18.2	178	37.0
258	24.3	231	15.4	175	13.7	182	11.5
265	28.7	234	15.7	178	13.7	196	28.2
272	28.7	244	15.4	182	11.6	199	27.7
279	52.3	258	18.8	196	10.9	204	25.9
286	98.1	265	29.1	199	12.2	206	28.9
289	95.3	272	35.0	204	13.4	210	29.1
293	94.6	279	47.8	206	16.0	213	28.4
300	103.8	286	38.0	210	16.6	217	15.8
303	106.3	289	56.2	213	16.7	220	17.2
310	137.6	300	43.6	217	16.6	224	14.3
314	137.6	303	45.7	220	16.9	227	19.1
317	133.9	307	49.9	224	17.7	231	19.8
325	122.7	317	45.2	227	18.6	234	16.1
328	98.7	322	60.7	234	13.5	244	19.8
336	96.6	325	66.0	258	18.5	251	17.7
392	23.0	328	60.3	265	18.1	258	15.4
433	0.1	336	67.2	279	29.4	265	14.6
576	17.8	353	52.1	286	37.6	272	9.5
591	16.5	371	66.2	289	34.7	279	14.5
660	22.5	392	23.7	293	43.0	286	19.2
674	25.9	401	12.2	296	43.0	289	9.6
688	24.2	404	6.8	300	38.7	293	21.8
716	19.1	412	4.5	303	47.4	296	21.6
723	16.9	419	3.6	307	44.4	300	20.7
		448	1.2	328	42.0	303	13.3

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
		548	52.7	336	64.8	307	18.6
		555	49.1	371	67.4	310	41.0
		562	44.4	379	69.4	314	41.0
		569	37.5	392	55.8	317	34.6
		576	31.2	400	64.3	322	36.0
		583	13.6	401	63.4	325	38.9
		612	17.8	412	58.8	328	42.0
		626	18.7	419	67.8	336	40.3
		632	19.5			371	44.0
		653	20.2	503	59.6	379	51.9
		660	21.0			392	56.4
		667	23.3	548	7.5	401	44.4
		674	21.6	555	7.9	404	47.9
		681	19.1	562	8.6	412	44.9
		688	19.4	569	7.3	419	44.5
		695	19.3	591	14.3	427	44.6
		709	21.9	598	15.4	433	46.9
		723	19.4	660	32.3	441	47.5
				667	32.3	448	39.0
				681	32.1	470	44.2
				695	33.1	483	37.2
				709	31.7	490	33.1
				716	31.5	503	35.3
				723	32.6	517	37.6
						525	59.3
						543	43.3
						548	29.7
						576	17.0
						591	21.8
						612	21.9
						626	22.2
						639	24.6
						646	25.0
						653	22.6
						660	24.4
						667	25.6
						674	25.6
						681	24.9
						688	25.0
						709	27.1
						716	25.3
						737	24.5

NO_3-N concentrations for the high fertiliser plot (1.5, 2.0, 2.5 and 3.0 m)

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
24	6.3	98	4.5	196	62.6	196	63.8
31	2.0	101	8.8	199	58.1	204	59.4
34	2.8	108	12.9	204	55.7	206	59.4
38	3.3	111	10.6	206	56.0	210	58.2
49	3.6	114	8.5	210	54.9	213	58.2
52	4.2	119	8.2	213	54.2	217	57.3
55	4.7	122	0.1	217	50.9	220	56.7
59	4.7	126	8.5	220	46.1	224	59.6
62	4.8	129	7.3	224	46.3	227	60.3
65	5.0	132	9.3	227	46.2	231	56.7
69	4.1	135	8.9	231	44.6	234	56.0
73	4.2	371	19.0	234	47.3	244	56.7
78	4.6	379	21.2	244	44.6	251	52.2
90	1.2	386	20.9	251	41.2	258	52.3
93	3.0	392	25.1	258	38.5	265	55.3
98	4.1	401	28.0	265	35.0	272	47.8
101	5.3	404	25.8	272	28.2	279	39.5
105	5.9	412	24.4	279	36.7	286	47.2
122	6.0	419	26.4	286	26.9	289	46.0
132	6.1	427	26.4	289	31.1	293	41.7
143	7.0	433	28.1	293	9.5	296	39.3
147	7.0	441	29.3	296	28.4	303	42.0
150	7.1	463	7.2	300	30.0	307	40.0
154	6.7	470	33.3	303	32.8	310	59.0
157	7.8	483	25.1	307	28.7	314	59.0
161	7.9	490	25.3	310	47.1	317	46.3
168	6.6	497	23.1	314	47.1	322	40.4
171	6.7	503	23.9	317	40.0	325	46.8
175	7.4	517	23.4	322	46.7	328	33.1
178	7.4	525	47.6	325	39.7	336	44.5
196	6.6	543	28.8	328	34.9	353	32.8
199	6.6	548	26.9	336	37.8	371	40.2
204	13.3	555	27.1	353	28.2	379	42.9
206	6.5	562	25.6	371	36.0	386	40.7
210	6.7	569	26.0	379	38.7	392	49.0
213	6.7	576	27.5	392	43.2	400	36.0
217	6.8	583	28.8	400	33.6	401	36.7
220	6.4	591	29.3	401	32.8	404	36.8
224	6.7	598	29.2	404	33.3	412	35.0
231	6.7	612	32.5	412	30.9	419	36.4
234	7.0	626	33.8	419	32.3	427	35.0
244	6.7	632	34.2	427	30.0	433	35.8
251	6.7	639	36.4	433	34.3	441	34.5
258	7.2	646	38.8	441	32.8	448	29.4

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	NO3-N	Days after May 1st	NO3-N	Days after May 1st	NO3-N	Days after May 1st	NO3-N
	mg/l		mg/l		mg/l		mg/l
265	7.0	653	34.5	448	29.2	463	30.2
272	7.7	660	36.2	470	36.3	470	31.8
286	8.7	667	36.2	483	32.4	483	29.6
289	6.4	674	36.8	490	21.4	490	28.1
293	8.7	681	35.6	497	29.7	497	29.1
296	7.4	688	36.1	503	30.4	503	30.5
300	12.1	709	35.3	517	29.1	525	32.9
307	14.7	716	35.1	525	58.6	543	31.1
310	28.1	723	45.6	543	32.0	548	11.7
314	28.1	737	23.4	548	27.5	555	27.1
317	21.9			555	26.1	562	25.9
325	23.7			562	23.4	569	26.8
328	24.0			569	24.6	576	27.4
336	15.7			576	25.0	583	29.7
371	25.7			583	26.7	591	31.2
386	26.3			591	26.8	598	31.1
392	29.9			598	27.2	612	32.7
401	25.3			612	28.8	626	32.4
412	26.2			626	30.7	632	31.4
419	24.5			632	30.1	639	34.1
433	21.5			639	30.7	646	34.4
470	25.4			646	32.7	653	29.7
476	21.8			653	28.6	660	31.2
483	18.0			667	31.0	667	31.7
503	18.5			674	31.8	674	34.9
543	22.4			681	29.7	681	30.2
548	17.9			688	29.4	688	29.7
555	20.2			709	29.0	709	28.1
562	13.9			716	29.9	716	27.8
569	13.7			723	32.8	723	29.9
576	14.9			737	35.1	737	31.9
583	15.0						
591	17.3						
598	18.3						
612	22.4						
626	22.5						
639	25.3						
646	22.8						
653	21.0						
660	22.6						
667	23.9						
674	24.4						
681	22.5						
695	23.1						
709	25.1						
716	21.3						
723	23.1						
737	26.5						

NO_3-N concentrations for the medium fertiliser plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
114	32.7	161	13.0	29	3.3	29	10.1
119	29.0	168	9.0	34	9.2	34	4.3
129	17.7	171	12.3	52	12.8	38	4.5
154	14.6	175	18.8	59	10.0	49	4.9
157	25.1	178	21.2	65	12.0	52	8.8
161	30.8	182	4.5	69	9.0	55	9.4
168	18.8	196	20.4	78	9.7	59	6.3
171	10.1	199	22.6	86	11.6	62	6.4
175	8.3	204	18.3	101	14.0	65	6.5
178	4.7	206	21.2	114	14.7	69	5.3
182	6.1	210	20.4	119	14.0	73	5.1
196	5.9	213	20.5	122	12.2	78	5.0
199	4.7	217	18.5	129	12.8	83	5.0
204	5.0	220	16.4	132	14.4	86	5.5
206	5.4	224	18.4	135	14.4	90	4.8
210	5.9	227	18.0	140	13.2	93	6.7
217	6.5	234	17.3	143	12.3	98	5.1
220	8.4	244	18.4	147	11.2	101	5.6
224	7.5	251	26.3	154	9.0	105	5.7
227	9.2	258	20.6	157	12.9	108	6.0
231	13.1	265	26.0	161	15.5	119	6.5
234	13.7	272	32.1	168	9.8	122	6.5
244	16.6	279	30.9	171	7.9	126	6.5
251	11.5	286	36.2	175	6.1	129	6.8
258	20.2	289	33.5	178	6.1	132	6.2
265	20.3	293	33.7	182	7.3	135	6.4
272	15.2	296	34.3	196	3.9	140	6.4
279	27.1	300	33.4	199	3.6	143	6.7
286	27.5	303	34.1	204	3.4	147	6.5
289	29.4	307	34.0	206	3.5	150	6.8
293	22.0	310	52.6	210	3.3	154	6.6
296	24.4	314	53.1	213	3.4	157	7.4
300	24.0	317	38.3	217	1.9	161	7.0
307	14.2	322	42.4	220	1.9	168	5.3
310	25.2	325	44.6	224	2.7	175	2.5
314	22.4	328	39.9	227	3.3	178	2.5
317	10.2	336	48.9	231	3.3	182	5.4
322	11.1	345	41.2	234	3.6	196	4.4
325	8.4	353	35.4	244	3.8	199	5.0
328	5.1	371	43.1	251	6.1	204	4.3
336	4.3	386	17.7	258	4.4	206	4.5
345	0.5	392	33.1	265	5.0	210	4.6
353	1.1	400	13.4	272	5.9	213	4.6
400	0.3	401	8.4	279	9.8	217	3.8

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
401	0.8	404	5.0	286	12.5	220	3.7
404	0.3	412	3.8	289	13.0	224	4.4
412	0.13	419	3.8	296	16.1	227	4.7
419	1.09	427	1.8	300	16.3	231	4.7
427	0.41	433	5.0	303	16.3	234	5.2
433	1.9	441	1.5	307	16.1	244	4.4
470	2.9	470	4.0	310	29.3	251	3.9
555	7.4	476	4.4	314	29.8	258	7.0
562	4.4	497	5.3	317	31.2	265	8.6
569	5.0	503	5.9	322	33.8	272	11.5
576	8.6	548	9.7	325	24.7	279	20.0
598	8.3	555	9.4	328	20.3	286	9.6
626	12.5	562	3.7	336	20.2	289	8.3
632	12.8	569	1.0	345	19.2	296	18.2
646	13.3	576	8.8	353	16.0	300	18.9
653	10.3	583	9.4	371	15.2	303	19.6
660	13.5	591	12.1	392	15.2	307	20.4
667	13.7	598	12.9	400	13.2	310	33.7
674	6.8	612	14.3	401	10.8	314	35.0
688	12.8	626	12.1	404	9.7	317	14.6
695	7.8	632	14.7	412	7.9	322	27.7
716	2.4	639	15.4	419	6.8	325	29.6
723	2.9	646	16.2	433	5.9	328	13.9
737	6.6	653	15.9	463	3.2	336	24.3
		660	18.6	483	5.0	345	23.0
		667	18.6	503	6.8	353	0.0
		681	20.7	548	7.4	379	21.1
		695	22.8	555	6.2	400	8.4
		709	24.5	562	5.0	401	11.1
		716	24.5	569	5.1	404	13.3
		723	25.8	576	4.1	419	6.5
		737	3.2	583	4.1	427	5.5
				598	6.0	433	32.3
				612	7.4	441	5.5
				626	8.3	470	4.0
				632	9.6	483	9.3
				639	11.6	503	10.8
				646	12.2	476	
				653	12.5	543	7.6
				660	15.6	548	6.0
				667	17.1	562	5.9
				674	14.6	569	6.5
				681	15.1	576	5.407
				688	22.0	583	7.382
				695	16.6	632	11.617
				709	19.2	646	16.204

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
				716	17.362	653	13.3
				737	25.774	667	17.8
						674	18.1
						681	16.3
						688	20.3
						695	17.3
						709	21.0
						723	18.3
						737	19.7

NO_3-N concentrations for the medium fertiliser plot (1.5, 2.0, 2.5 and 3.0 m)

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
31	4.9	196	35.4	98	24.0	86	7.1
38	6.3	199	30.4	101	23.7	90	7.4
49	6.9	204	28.8	105	22.5	93	8.0
52	8.5	206	30.7	111	20.7	98	8.1
55	8.3	210	29.2	114	21.4	101	8.3
59	8.4	213	26.8	119	22.5	105	8.4
62	8.6	217	23.9	126	23.9	111	8.9
65	8.6	220	24.5	129	21.0	114	8.8
69	7.3	224	22.2	132	23.2	119	9.9
73	7.4	227	29.8	135	23.5	126	7.2
78	7.7	231	18.5	140	24.2	129	7.4
83	7.6	234	15.3	143	22.0	132	9.1
86	7.6	244	16.9	147	23.6	135	9.0
90	7.0	258	15.7	150	23.4	143	9.8
93	7.9	265	13.9	154	19.4	147	9.2
98	8.0	272	10.3	157	19.4	150	9.1
101	7.9	279	8.9	161	23.9	154	8.9
105	7.5	286	14.7	168	23.7	157	9.7
108	8.4	289	7.4	171	23.8	161	8.8
111	9.5	296	13.3	178	23.4	168	9.6
114	8.8	300	14.0	182	8.3	171	9.5
119	6.6	303	8.2	204	15.1	175	9.4
122	9.4	307	14.5	206	17.5	178	9.2
126	7.0	310	28.2	210	16.7	182	17.4
129	7.6	314	28.5	213	17.3	196	6.3
132	9.3	317	17.1	217	17.4	199	5.7
135	9.0	322	23.8	220	16.5	204	11.9
140	9.4	325	15.2	224	15.1	206	9.8
143	9.5	328	21.9	227	14.2	210	9.9
147	9.2	336	22.2	231	15.2	213	9.6
150	9.1	345	24.5	234	12.3	217	8.2
154	9.6	353	19.0	244	14.9	220	12.3
157	9.8	371	25.7	251	6.7	224	7.2
161	9.6	379	25.1	258	12.4	227	7.9
168	9.1	386	26.8	265	11.8	231	9.8
171	7.8	392	31.2	272	9.9	234	5.5
175	8.1	400	27.3	279	8.9	244	9.6
178	8.1	401	25.2	286	8.9	251	16.1
182	3.2	404	27.9	289	5.2	258	9.8
196	7.7	412	27.1	293	7.9	265	9.5
199	8.0	419	27.5	296	8.3	272	9.7
204	7.5	427	26.5	300	8.4	279	8.2
206	7.4	433	11.4	303	8.2	286	8.1
210	7.4	441	27.3	307	9.0	289	7.0

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
213	7.4	448	24.1	310	19.1	293	7.6
217	7.1	463	24.7	314	20.2	296	7.1
220	5.7	470	30.6	317	10.3	300	7.6
224	6.5	483	28.0	322	8.6	303	8.4
227	6.9	490	25.8	325	12.3	307	7.5
231	6.6	497	24.1	328	11.1	310	16.2
234	6.8	503	24.9	336	9.4	314	15.4
244	6.8	517	26.2	345	11.3	317	7.2
251	5.8	525	26.6	353	9.9	322	9.9
258	6.7	543	28.1	371	12.3	325	9.5
265	6.5	548	24.3	379	11.2	328	8.2
272	12.1	555	25.1	386	11.9	336	7.5
279	13.1	562	18.7	401	12.8	345	7.2
286	12.1	569	19.0	404	14.0	353	8.6
289	7.1	576	18.3	412	14.6	371	9.7
293	9.3	583	17.8	419	13.8	379	9.9
296	11.1	591	18.8	427	9.3	392	9.3
303	11.3	598	19.2	433	9.2	400	9.3
307	12.9	612	21.0	448	11.2	401	8.6
310	27.3	626	21.5	463	12.4	404	8.3
314	30.7	632	20.3	470	16.1	412	8.4
317	13.7	639	20.7	483	9.3	419	8.7
322	22.4	646	22.3	490	12.3	441	8.2
325	23.7	653	19.9	497	16.8	448	7.9
328	23.2	660	21.3	503	14.5	463	8.5
336	23.0	667	23.6	517	14.5	470	9.0
353	19.6	674	17.5	525	16.6	483	9.8
371	26.7	681	22.3	543	17.4	490	9.8
379	28.8	688	28.4	548	10.6	497	9.8
386	29.1	695	21.6	555	11.9	503	9.3
400	31.2	723	23.6	569	7.4	517	9.4
404	32.4	737	23.1	576	8.6	548	8.8
412	31.4			583	8.6	555	9.6
419	32.7			591	10.2	562	4.7
433	26.8			598	10.2	576	7.3
441	27.6			612	14.8	591	10.7
470	25.8			626	14.1	626	11.8
476	26.7			632	13.7	632	11.6
503	28.0			639	14.3	695	29.6
517	27.0			646		709	18.1
525	25.8			653	12.3	737	23.3
543	29.1			660	14.7		
548	20.1			667	16.6		
555	19.7			674	23.4		
569	14.3			681	16.3		
576	9.9			695	15.9		

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
583	12.5			709	22.5		
591	15.5			716	15.3		
598	15.8			723	17.7		
639	21.6			737	18.3		
646	21.9						
653	20.7						
660	21.5						
667	23.8						
681	23.5						
709	26.2						
737	16.9						

NO_3-N concentrations for the low fertiliser plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
119	0.1	114	0.0	24	6.0	24	7.9
126	0.1	126	0.1	29	8.4	29	4.8
154	0.3	135	0.3	34	9.3	34	17.2
157	0.1	154	1.3	49	7.9	38	17.5
168	0.1	157	0.2	52	6.9	49	21.1
171	0.7	161	0.1	55	8.1	52	26.5
175	0.9	168	0.2	59	7.1	55	26.3
178	0.7	171	0.2	62	6.0	62	26.6
182	5.9	175	0.3	69	3.7	65	26.4
196	1.5	178	1.0	78	2.6	69	21.4
199	2.0	182	0.8	83	2.5	73	20.3
204	2.2	196	1.2	119	7.8	83	21.8
206	3.0	199	1.0	122	8.2	86	24.0
210	3.0	204	1.7	126	9.6	90	20.6
213	3.5	206	1.6	129	8.4	93	22.9
217	2.7	210	1.6	132	1.3	98	24.6
220	4.8	213	1.6	135	11.8	101	24.6
224	6.3	217	6.4	140	12.7	105	20.7
227	7.2	220	2.5	143	11.6	108	22.3
231	7.7	224	2.6	147	10.8	111	20.9
234	8.3	227	2.8	150	8.9	114	22.9
244	8.9	231	3.0	154	8.3	119	23.0
251	8.0	234	3.0	157	11.3	122	22.8
258	9.2	244	3.5	161	9.8	126	23.7
265	12.3	251	10.0	168	8.3	129	23.6
272	11.7	258	5.0	171	7.1	132	11.8
279	6.6	265	5.8	175	6.7	135	25.5
286	9.1	272	9.0	178	6.7	140	26.5
293	5.4	279	6.5	182	0.5	143	23.0
300	1.3	286	6.8	196	6.5	147	25.3
303	2.4	289	7.4	199	6.6	150	22.3
307	1.7	293	7.2	204	6.4	154	20.8
310	2.2	296	7.5	206	6.6	157	23.9
314	1.4	300	6.2	210	6.4	161	7.6
325	1.0	303	8.8	213	6.2	168	6.9
336	1.0	307	8.8	217	8.2	171	7.2
345	1.0	310	8.6	220	5.8	175	7.8
353	0.2	314	17.9	224	5.6	178	14.1
392	1.0	317	7.2	227	5.8	182	7.1
400	1.0	322	8.2	231	6.5	196	10.8
401	0.3	325	9.1	234	6.1	199	10.3
404	1.0	328	7.6	244	5.7	204	9.4
412	0.2	336	7.7	251	3.8	206	13.3
419	1.0	345	6.5	258	6.3	210	10.8

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
433	1.0	353	5.7	265	6.8	213	12.4
569	7.5	392	2.0	272	9.8	217	5.5
576	7.262	400	1.0	279	8.8	220	8.3
583	7.496	401	0.6	286	8.5	224	7.8
591	7.725	404	1.0	289	7.2	227	6.7
598	7.1	412	0.4	293	7.6	231	9.6
612	9.0	419	0.3	300	6.5	234	7.0
632	8.8	427	1.0	303	9.3	244	9.9
639	7.1	433	1.0	307	9.8	251	6.2
646	7.4	441	1.0	310	20.1	258	9.9
653	5.4	470	1.0	314	20.6	265	8.9
660	4.2	497	1.0	317	11.8	272	8.9
667	3.9	503	0.2	322	13.8	279	9.1
674	2.6	548	1.0	325	12.7	286	9.9
688	0.8	555	0.3	328	18.5	289	9.2
695	1.0	562	1.0	336	8.7	293	29.8
716	0.3	569	0.1	345	9.5	296	10.1
723	1.0	576	0.7	353	9.4	300	9.1
737	0.9	583	1.7	392	10.9	303	16.6
		591	2.6	400	8.5	314	25.4
		598	3.4	401	7.3	371	18.3
		626	8.0	404	7.8	379	19.9
		639	9.9	412	6.6	392	22.7
		653	9.9	419	6.3	314	25.4
		660	10.9	427	5.2	317	14.4
		667	11.9	433	4.8	322	19.8
		688	9.0	441	3.9	325	19.4
		695	6.1	463	2.0	328	19.5
		709	3.8	470	2.1	336	16.0
		716	2.0	483	2.6	345	16.2
		723	3.3	490	0.4	371	18.3
		737	4.3	497	0.0	379	19.9
				503	4.2	392	22.7
				543	5.6	400	20.1
				548	5.3	401	20.3
				562	7.1	404	20.8
				569	4.5	412	19.5
				576	4.3	419	15.9
				583	5.8	427	9.3
				591	7.1	433	6.6
				598	6.6	441	4.3
				612	7.1	448	2.2
				632	10.9	470	0.2
				639	12.2	483	0.5
				653	10.6	490	2.8
				660	13.3	503	1.2

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
				667	14.9	543	5.7
				674	16.4	548	6.5
				681	14.7	555	6.8
				688	14.8	562	5.4
				709	15.6	569	6.5
				723	16.5	576	6.5
				737	16.3	583	7.3
						626	9.9
						639	8.8
						653	7.6
						660	10.8
						667	12.8
						681	12.0
						688	13.1
						709	14.6
						716	12.4
						737	14.8

NO_3-N concentrations for the low fertiliser plot (1.5, 2.5 and 3.0 m)

1.5m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**
24	9.7	196	36.3	196	48.8
31	5.9	199	35.6	199	44.0
34	2.9	204	31.5	204	37.5
38	3.0	206	33.9	206	41.1
49	3.7	210	31.7	210	37.6
52	5.1	213	30.8	213	34.1
55	5.7	217	32.3	220	29.9
59	5.9	220	22.8	224	25.8
62	5.8	224	29.2	227	26.6
65	6.3	227	21.0	231	19.4
69	4.4	231	25.9	234	23.7
73	4.7	234	18.5	244	19.7
83	4.8	244	28.6	251	23.4
86	5.8	258	14.3	258	20.3
90	5.2	265	13.6	265	19.9
93	5.7	272	10.6	272	16.9
98	5.2	279	7.0	279	20.3
101	5.2	286	9.0	286	20.2
105	5.8	289	8.9	289	13.4
108	6.9	293	19.0	293	8.7
111	6.5	296	9.0	296	14.3
119	7.3	300	14.1	300	9.8
122	6.9	303	14.7	303	8.9
126	7.0	307	15.0	307	9.6
129	7.6	310	28.0	310	23.3
135	5.8	314	30.0	314	24.5
140	6.1	317	18.2	317	13.9
147	6.4	322	21.1	322	16.2
150	7.6	325	22.8	325	17.2
154	6.5	328	9.5	328	17.5
157	7.6	336	15.7	336	16.3
161	21.6	345	15.7	345	17.6
168	19.6	353	18.5	353	15.4
171	14.7	371	20.8	371	18.8
175	14.1	400	21.7	386	20.2
178	7.8	401	23.1	392	23.2
182	15.6	404	22.6	400	20.9
196	6.2	412	21.8	401	20.9
199	5.3	419	21.5	404	24.0
204	6.2	427	21.2	412	21.7
206	5.8	433	21.4	419	22.3
210	5.8	448	18.6	433	19.1
213	5.7	463	21.0	441	18.6
220	4.9	470	27.9	448	15.6

1.5m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**
224	5.3	483	17.3	470	16.0
227	5.0	490	19.8	483	14.9
234	5.4	497	5.6	490	16.2
244	4.7	503	20.5	497	16.0
251	9.5	517	20.8	503	17.3
272	3.7	525	40.6	517	16.9
279	3.1	543	22.0	525	19.5
286	3.3	548	18.8	543	18.9
289	3.2	555	16.5	548	15.1
293	2.9	562	10.9	555	19.2
296	3.6	569	13.9	562	13.2
303	3.9	576	14.2	569	12.1
307	2.9	583	11.6	576	13.3
310	4.7	591	10.7	583	12.8
314	5.0	598	12.3	591	12.4
317	3.5	612	14.3	598	12.2
322	4.3	626	9.4	612	13.9
325	3.8	632	9.7	626	11.4
328	3.2	639	8.8	632	10.6
336	3.8	646	6.9	639	9.7
345	3.7	653	9.4	646	8.4
353	3.9	660	8.7	653	7.1
379	4.8	667	9.3	660	9.9
386	4.7	674	9.5	667	10.8
392	4.4	681	8.1	674	11.1
400	3.8	688	7.8	681	9.3
401	3.4	695	7.9	688	9.4
404	3.8	709	9.1	695	9.0
412	4.9	716	9.9	709	10.4
419	4.7	723	9.8	716	8.0
427		737	9.4	723	10.6
433	4.5			737	10.6
441	4.6				
448	3.7				
463	4.7				
470	5.9				
483	5.4				
517	6.1				
525	5.1				
562	3.1				
569	4.9				
576	3.5				
598	3.4				
653	6.1				
660	5.8				
674	7.9				

1.5m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**
688	7.9	709	22.5		
709	10.1	716	15.3		
716	10.8	723	17.7		
723	10.7	737	18.3		
737	10.8				

NO3-N concentrations for the low dirty water plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
199	1.0	199	1.9	199	3.5	199	9.1
204	1.6	220	5.0	204	3.2	204	8.7
206	1.8	224	2.7	206	3.0	213	7.8
210	2.1	231	3.1	210	2.9	220	7.5
213	2.3	234	3.9	213	2.8	224	6.9
217	2.8	258	1.0	220	1.9	227	6.8
220	4.4	272	1.0	234	3.8	231	6.2
227	8.7	279	0.9	244	2.6	234	6.0
231	8.8	286	1.0	251	2.0	244	5.6
234	9.1	289	0.7	258	2.1	251	5.5
244	8.1	296	1.0	265	2.3	258	4.9
251	7.6	303	0.5	272	2.3	265	8.6
258	7.8	314	1.7	279	2.2	272	4.4
265	7.7	317	0.1	286	3.8	279	5.0
272	5.6	325	1.1	289	4.0	286	5.9
279	1.1	328	0.4	293	4.0	289	5.6
286	1.2	345	4.3	300	4.1	293	5.1
293	1.1	353	0.1	307	4.0	296	4.0
296	1.0	379	0.0	310	6.7	300	5.9
300	0.3	392	1.0	317	5.2	303	4.6
303	0.5	404	1.0	322	5.2	307	5.9
307	0.4	419	0.1	325	5.7	310	9.3
310	0.9	433	0.4	328	5.3	314	9.9
314	1.0	448	1.0	336	5.3	317	7.3
317	1.0	503	0.1	353	4.7	322	7.7
325	1.0	548	1.0	371	4.6	325	8.0
371	1.0	576	0.7	379	4.4	328	6.1
379	1.0	583	0.6	386	4.1	336	7.1
386	0.1	591	1.3	392	2.2	345	5.5
404	1.0	632	1.6	400	1.9	353	7.2
412	0.4	688	1.0	404	0.4	371	7.4
419	0.1	695	0.1	412	0.3	379	6.7
562	1.0	723	0.2	419	1.0	386	7.5
569	0.3	737	6.4	427	1.0	392	5.4
583	5.1			433	1.0	400	2.8
591	5.8			441	1.0	412	0.6
598	5.0			448	1.0	419	0.1
612	4.5			470	4.9	427	1.0
626	5.4			483	1.0	433	1.0
639	4.9			490	1.0	441	1.0
646	3.9			503	1.0	448	1.0
660	0.2			525	0.1	463	1.0
667	1.3			543	0.3	470	1.0
674	2.3			548	1.0	476	3.4
695	0.4			555	0.6	483	1.0
716	0.8			562	1.0	490	0.2

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
				569	0.5	497	1.0
				576	1.0	503	0.5
				583	1.3	517	0.2
				591	1.1	525	0.4
				612	1.4	543	0.3
				639	0.1	548	1.0
				646	1.5	562	1.0
				653	1.7	569	0.1
				674	2.3	576	1.4
				695	1.7	583	5.9
				709	3.3	591	1.4
				716	2.5	598	1.4
				723	3.0	626	2.9
				737	8.9	632	2.7
						639	0.3
						646	3.2
						653	3.1
						660	2.7
						667	2.5
						674	3.3
						688	3.4
						695	3.4
						709	4.0
						716	4.4
						723	4.5
						737	8.0

NO_3-N concentrations for the low dirty water plot (1.5, 2.0, 2.5 and 3.0 m)

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
199	12.8	204	21.7	199	66.5	199	35.8
204	14.2	206	20.6	204	31.8	210	24.3
206	12.4	210	19.5	206	27.2	213	26.5
210	13.5	213	21.6	210	42.4	217	31.0
213	12.7	217	18.9	213	22.0	220	27.7
220	12.7	220	19.0	220	16.2	224	23.3
224	12.0	227	23.8	224	16.1	227	15.1
227	15.2	231	19.3	227	25.4	231	21.1
231	13.4	251	18.2	231	14.9	234	16.1
234	9.8	258	16.0	234	11.7	244	20.4
244	11.7	265	13.3	244	14.4	251	22.4
251	11.1	272	13.1	251	14.6	258	17.1
258	9.4	279	17.3	258	11.3	265	15.5
265	5.6	286	16.5	265	11.0	272	12.9
272	8.6	289	8.3	272	8.3	279	15.8
279	9.6	293	8.1	286	9.5	286	16.2
286	9.5	296	8.8	289	8.3	289	17.3
293	9.1	300	9.5	293	8.0	293	6.7
300	9.4	303	9.5	296	8.4	296	13.8
303	11.5	307	8.8	300	14.8	300	14.0
307	10.0	310	20.1	303	13.9	303	12.6
317	14.2	314	23.4	307	14.6	307	13.7
322	11.2	317	9.6	310	28.9	310	27.1
325	19.2	322	12.7	314	29.7	314	29.3
328	15.0	325	15.8	317	18.4	317	16.5
336	14.8	328	12.2	322	21.0	322	19.6
345	13.7	336	8.9	325	23.8	325	15.9
371	13.7	345	19.5	336	10.9	328	17.8
379	15.1	371	12.1	345	19.5	336	9.4
386	20.9	379	12.6	371	12.1	353	20.6
392	10.7	386	18.5	379	12.6	371	26.5
400	12.1	392	11.5	386	18.5	379	27.9
404	12.5	400	12.7	392	11.5	386	28.1
412	8.7	404	13.7	400	16.8	392	23.8
419	9.0	412	16.0	404	16.8	400	23.4
427	6.8	419	14.8	412	18.3	404	24.5
433	5.8	427	11.2	419	17.1	412	28.0
441	4.6	433	12.3	427	13.7	419	29.7
448	4.3	441	13.7	433	13.0	427	29.5
463	2.8	448	10.0	441	11.7	433	26.8
470	2.0	483	12.4	448	11.6	441	27.7
483	1.5	490	7.0	463	11.7	448	27.3
503	1.6	497	11.5	476	13.4	463	32.5
543	2.4	503	12.9	483	12.9	476	33.3
548	2.9	517	12.4	490	10.8	483	33.3
555	4.5	525	26.4	497	11.6	490	32.8

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
562	5.2	548	12.4	503	13.1	497	37.6
569	5.6	555	10.2	517	12.8	503	36.3
576	5.6	562	8.2	525	30.4	517	25.5
583	8.0	569	8.0	543	14.0	548	22.9
591	8.0	576	9.3	548	11.4	548	32.0
598	7.5	583	8.3	555	9.0	555	39.3
632	6.6	591	9.0	562	7.4	562	36.1
639	2.9	598	9.4	569	7.0	569	33.9
646	7.6	612	8.9	576	7.3	576	33.5
653	7.2	626	9.2	583	28.4	583	28.0
660	6.4	632	8.8	591	9.4	591	27.4
667	6.3	639	8.3	598	8.7	598	26.9
674	7.3	646	9.4	612	7.8	612	26.4
688	7.1	653	8.4	626	8.2	626	25.8
695	6.8	660	8.3	632	8.1	632	25.4
709	8.8	667	7.3	639	7.4	639	24.9
716	8.3	674	8.4	646	8.8	646	22.8
737	20.5	688	7.8	653	7.6	653	19.8
		695	7.6	660	7.1	660	19.8
		709	9.1	667	6.8	667	18.8
		716	9.5	674	7.4	674	18.8
		723	9.7	688	6.9	688	16.6
		737	7.8	695	6.9	695	16.3
				709	8.2	709	18.5
				716	8.3	716	15.6
				723	8.4	723	18.9
				737	0.2	737	0.3
						723	10.4
						737	10.5

NO3-N concentrations for the medium dirty water plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
199	8.1	199	3.0	199	6.8	199	17.6
204	3.6	204	1.5	206	5.4	204	29.7
210	8.4	206	1.1	210	4.6	210	30.2
213	6.3	210	1.6	213	4.6	213	31.8
217	2.7	213	2.0	217	4.6	217	32.2
220	11.3	217	4.6	220	4.6	220	25.8
224	14.4	220	3.1	224	4.3	224	23.7
227	12.7	224	2.1	227	4.5	227	21.7
244	18.4	227	2.7	231	3.7	231	22.8
258	20.6	231	2.4	234	4.3	234	20.0
265	22.7	234	2.7	258	4.0	244	22.4
272	14.6	244	3.7	265	4.1	251	22.0
279	13.3	251	2.7	272	4.6	258	19.2
286	5.2	258	8.3	279	5.5	265	19.7
289	3.5	272	8.8	286	7.4	272	13.5
293	3.0	279	9.5	289	6.7	279	21.8
296	5.0	286	6.8	293	5.2	286	22.2
300	3.4	289	6.2	296	6.6	289	23.1
303	2.9	296	4.9	300	7.9	293	23.0
307	2.7	300	5.1	303	6.7	296	19.8
310	3.0	303	4.9	307	8.7	300	21.7
314	3.3	307	4.5	310	18.3	303	22.6
317	0.5	314	6.6	314	9.3	314	42.6
322	0.4	317	5.1	317	8.8	317	29.1
325	0.9	322	4.9	322	7.3	322	29.2
328	0.1	325	4.8	325	11.0	325	34.8
336	0.1	328	4.0	328	5.9	328	25.8
345	0.6	336	4.3	336	9.6	336	29.8
353	1.2	345	3.9	345	8.9	345	14.4
371	1.0	353	6.3	353	8.0	353	22.5
386	2.8	371	4.1	379	5.8	371	27.1
392	1.0	379	3.3	400	1.4	392	29.6
400	1.0	386	36.2	404	2.5	400	20.8
404	0.5	392	2.2	419	0.6	404	21.0
419	0.5	400	0.3	427	1.0	419	20.9
433	0.1	404	1.0	433	0.1	433	23.7
441	0.2	412	0.3	441	1.0	463	17.5
448	1.0	419	0.0	448	0.0	483	6.6
470	0.6	433	1.0	470	1.0	503	21.4
555	1.0	503	0.3	476	0.5	517	19.5
562	1.0	548	1.0	483	0.2	525	41.3
576	39.3	576	4.8	490	1.0	548	16.7
591	84.1	583	3.6	517	0.6	555	13.6
598	77.8	591	3.8	525	0.6	562	9.7
612	25.0	598	7.7	548	1.3	569	

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
653	6.1	612	7.0	555	1.7	576	7.1
660	3.2	632	9.4	562	2.1	583	10.0
667	1.0	639	4.7	569	2.1	598	8.7
716	1.3	653	1.6	576	2.6	612	6.8
723	0.5	695	1.0	591	2.9	632	10.9
737	9.8	709	1.0	598	3.6	639	13.6
		737	22.4	612	4.3	646	10.3
				632	7.6	660	13.3
				639	7.3	667	12.8
				646	8.8	674	16.3
				653	8.3	737	12.0
				660	8.1		
				674	7.5		
				688	7.9		
				716	8.8		
				723	8.6		

NO_3-N concentrations for the medium dirty water plot (1.5, 2.0, 2.5 and 3.0 m)

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
199		204	42.0	204	38.8	204	49.9
204		206	36.6	206	60.8	206	47.8
206	7.9	210	32.4	210	69.7	210	45.9
210	9.7	213	32.2	213	74.9	213	45.3
213	9.9	217	74.1	217	44.0	224	27.0
220	8.7	220	31.4	224	79.0	227	26.4
224	9.5	224	42.5	227	76.7	231	42.7
227	9.2	227	42.1	231	75.0	234	40.8
231	8.8	231	28.1	234	74.8	251	40.3
234	9.6	244	24.8	244	71.6	258	37.9
244	8.5	251	25.9	251	67.9	265	35.7
258	8.0	258	20.7	258	68.8	272	30.4
265	7.9	265	20.3	265	68.6	279	34.3
272	8.6	272	17.1	272	64.6	286	28.2
279	9.1	279	22.5	279	66.1	289	27.8
286	12.2	286	21.1	286	61.8	293	9.6
289	9.9	289	20.4	289	55.1	296	24.1
293	8.3	293	21.0	293	55.2	300	25.4
296	12.5	296	16.4	296	54.8	303	23.4
300	13.8	300	16.3	300	54.0	307	24.4
303	8.8	303	17.7	303	45.1	310	39.5
307	14.9	307	17.8	307	56.8	314	45.4
310	28.1	310	32.3	310	80.0	317	29.4
314	29.5	314	35.3	314	78.7	322	28.8
317	11.9	317	22.0	317	69.1	325	27.9
322	22.3	322	53.1	322	25.9	328	16.1
325	24.0	325	25.9	325	76.3	336	24.3
328	17.1	328	24.1	328	58.3	345	57.3
345	19.1	336	31.1	336	71.1	353	38.7
353	16.8	345	24.8	345	26.3	371	60.7
371	20.1	353	16.1	353	18.7	379	64.8
379	23.2	371	28.9	371	25.7	386	32.1
392	33.6	379	30.6	379	27.8	400	27.2
400	23.7	386	68.4	386	22.1	404	27.8
404	21.2	392	29.3	392	27.5	412	28.3
412	20.7	400	30.2	400	55.0	419	27.8
419	17.7	404	30.7	404	52.7	427	27.4
427	18.4	412	30.2	412	51.3	433	37.0
433	19.2	419	29.9	419	50.8	441	27.8
441	14.5	427	29.4	427	52.6	448	23.0
463	9.9	433	35.5	433	62.5	463	24.1
470	12.2	441	28.6	441	47.6	470	25.9
483	7.9	448	24.2	448	42.9	483	24.6
490	7.9	463	24.1	463	40.7	490	24.0
503	7.1	470	30.6	470	32.2	497	23.3

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
525	9.3	483	23.1	483	42.8	503	24.7
543	8.0	490	23.7	490	42.7	517	23.9
548	9.3	497	22.7	517	40.9	543	26.2
555	9.0	503	24.4	543	43.1	555	23.2
562	7.0	517	22.4	548	39.6	562	21.6
569	5.8	525	55.3	555	38.2	569	21.5
576	7.1	548	20.1	562	37.6	576	
583	6.6	555	19.8	569	36.8	583	18.5
598	9.8	562	17.3	576	35.1	591	12.8
612	13.0	569	16.0	583	32.0	598	17.3
632	12.5	576	11.0	591	34.6	612	15.5
639	14.4	583	12.0	598	32.6	626	14.0
646	11.9	591	14.4	612	29.7	632	14.5
653	10.8	598	14.2	626	30.0	639	15.7
667	13.8	626	12.6	632	29.1	646	12.9
695	14.4	632	12.2	639	30.3	653	10.4
709	8.3	639	14.3	646	26.2	660	13.7
716	12.8	646	10.8	653	25.7	667	12.2
723	14.2	653	8.4	660	26.6	674	12.7
		660	10.7	667	25.6	688	12.0
		667	9.5	674	26.5	695	11.9
		674	10.6	688	23.6	709	11.8
		688	8.7	695	23.6	716	10.0
		695	8.2	709	22.8	723	11.8
		709	8.9	716	20.7	737	14.4
		716	9.7	723	22.3		
		723	9.1	737	0.4		
		737	15.3				

NO3-N concentrations for the high dirty water plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
204	36.3	204	1.8	199	2.6	199	0.1
206	45.0	210	0.9	204	3.3	210	1.6
210	38.9	217	4.8	206	3.6	213	19.9
213	47.7	220	1.3	210	3.5	217	8.6
217	92.3	224	5.1	213	4.1	220	32.1
220	116.4	227	8.8	220	4.4	224	36.9
224	133.4	231	8.7	224	4.3	227	43.4
227	133.5	234	9.8	227	5.9	231	44.6
231	141.7	244	16.7	231	4.6	234	49.6
234	142.3	251	23.6	234	4.5	244	56.0
244	128.4	265	47.1	244	4.9	251	55.5
251	131.8	272	67.5	251	5.9	258	50.0
258	135.6	279	56.9	258	8.2	265	46.8
265	125.7	289	35.6	265	11.1	272	39.5
272	78.6	293	26.8	272	24.1	279	46.0
279	42.5	303	9.2	289	43.7	286	50.9
286	8.7	307	7.0	293	49.0	289	49.2
289	6.4	310	9.7	300	40.8	293	50.5
293	5.3	317	6.6	303	41.1	296	51.3
296	4.3	328	3.8	307	37.6	300	58.3
300	2.6	345	5.4	317	44.0	303	58.5
303	1.7	353	2.9	322	40.4	310	84.0
307	0.8	379	0.9	325	38.9	314	84.4
310	1.4	392	1.1	328	36.3	317	72.9
314	0.5			336	32.1	322	75.3
317	0.8			345	29.6	325	81.7
325	1.0			353	23.6	328	69.4
328	1.0			371	7.9	336	49.7
336	0.5			379	9.1	345	76.1
345	1.0			386	5.7	353	54.2
353	0.3			392	6.1	371	65.0
371	1.5			400	1.7	379	62.5
379	7.7			404	0.4	386	62.3
386	3.0			412	0.4	400	53.2
400	0.2			419	1.4	404	50.6
412	2.7			427	1.6	419	46.9
419	1.0			433	0.3	427	42.3
427	1.0			441	1.2	433	44.5
433	1.0			448	0.3	441	39.4
470	1.3			470	5.0	448	34.4
555	0.2			548	8.4	463	30.8
562	0.6			555	6.4	470	35.9
569	1.0			569	2.4	503	31.4
576	17.9			576	9.7	517	31.6
583	57.1			583	8.4	525	54.8

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
591	74.2			591	6.2	543	34.2
598	74.3			598	6.8	548	30.4
612	52.4			612	8.1	555	18.9
639	8.1			626	36.4	562	21.2
653	2.9			632	34.8	569	17.2
667	2.4			639	34.5	576	8.6
674	4.4			653	28.2	583	9.5
695	4.5			660	25.4	591	10.6
723	0.6			667	25.9	598	9.8
737	15.6			674	21.7	612	9.4
				681	21.0	626	11.1
				688	18.2	632	10.2
				695	14.9	646	10.0
				709	10.4	653	9.0
				716	8.7	667	14.2
				723	5.3	674	14.8
				737	0.2	681	14.5
						688	15.7
						695	15.4
						709	17.6
						716	15.4
						723	20.8
						737	2.4

NO_3-N concentrations for the high dirty water plot (1.5, 2.0, 2.5 and 3.0 m)

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
199	5.0	199	0.9	199	27.5	199	30.5
204	10.6	204	2.8	204	31.2	204	21.6
206	10.1	210	3.9	206	27.8	206	16.1
210	11.9	213	4.4	210	27.3	210	15.4
213	12.7	217	23.9	213	25.8	213	13.3
217	4.7	220	5.3	217	11.7	217	3.3
220	9.4	224	5.5	220	21.9	220	11.0
224	10.3	227	6.3	224	19.5	224	10.6
227	12.4	231	6.0	227	32.5	227	13.2
231	16.4	234	6.5	231	17.8	231	10.6
234	12.2	244	6.9	234	17.6	234	7.5
244	14.4	251	6.7	244	19.6	244	10.9
251	22.2	258	16.0	251	18.7	251	10.6
258	12.0	265	7.2	258	7.0	258	8.6
265	12.0	272	7.4	265	15.5	265	8.6
272	8.3	279	6.8	272	17.5	272	6.1
279	13.9	286	6.7	279	8.5	279	8.0
286	9.9	289	6.7	286	7.6	286	7.7
289	18.6	293	7.0	289	9.6	289	8.4
293	8.3	296	7.1	293	9.7	293	7.8
296	14.3	300	7.1	296	12.9	296	8.8
300	16.1	303	8.8	300	14.9	300	25.4
303	16.7	307	8.6	303	13.9	303	9.2
307	20.7	310	16.6	307	15.2	307	8.1
310	34.7	314	17.3	310	29.1	310	23.9
314	26.7	317	6.0	314	30.5	314	25.1
317	28.5	322	12.0	317	21.1	317	14.7
325	32.5	325	7.6	322	23.3	322	17.5
328	26.8	328	8.9	325	25.4	325	18.8
336	31.6	336	7.5	328	21.0	328	15.3
345	31.9	345	7.9	336	23.1	336	15.5
353	20.8	353	9.8	345	21.3	345	11.7
371	29.2	371	9.4	353	1.0	353	13.9
379	30.3	379	6.7	371	26.5	371	17.9
386	10.3	386	28.0	379	27.5	379	19.6
392	12.4	392	17.6	386	18.9	386	4.6
404	1.6	400	14.1	400	27.2	392	27.5
412	1.6	404	14.3	404	26.7	400	21.4
419	1.7	412	14.8	412	27.0	404	21.4
427	1.2	419	13.6	419	26.9	412	23.0
433	0.9	427	9.6	427	25.7	419	22.5
441	0.4	433	9.9	433	26.7	427	20.8
448	0.1	441	9.5	441	28.4	433	19.3
463	8.7	448	8.2	448	24.3	448	17.0
470	2.0	463	10.3	463	24.6	463	18.8

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
483	2.5	470	5.9	470	24.0	470	25.8
490	3.1	483	1.0	483	23.8	483	17.9
503	2.9	490	8.5	490	17.2	503	19.8
517	2.0	497	3.9	503	25.6	517	18.6
525	2.2	503	3.8	543	2.4	525	21.1
548	3.6	517	2.1			543	20.1
555	4.8	525	1.4			548	17.7
569	7.0	543	22.1			555	17.4
576	6.0	548	4.1			562	8.6
583	7.1	555	5.8			569	14.8
591	8.0	562	7.2			576	
598	8.4	569	7.4			583	16.0
612	7.2	576	6.9			591	14.6
632	8.1	583	7.7			598	12.7
639	8.2	591	8.8			612	1.2
646	7.8	598	9.7			626	9.7
653	8.7	612	7.7			632	10.4
660	12.8	626	9.5			639	9.9
667	9.0	632	8.6			646	9.2
674	9.6	639	7.5			653	7.2
681	9.8	646	9.7			660	9.3
688	9.2	653	8.2			667	9.6
695	10.0	660	8.0			674	9.7
709	11.2	667	7.3			681	9.2
716	10.0	674	8.7			688	9.3
737	13.8	681	7.4			695	9.2
		688	7.8			709	10.3
		695	6.8			716	7.8
		709	6.2			723	10.4
		716	5.7			737	10.5
		723	4.8				
		737	4.3				

NO3-N concentrations for the low slurry plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
154	0.1	114	0.3	78	1.4	78	4.2
157	0.1	119	0.1	83	1.4	83	4.5
161	0.1	122	0.1	86	1.0	90	4.2
171	0.1	126	0.1	90	1.7	93	3.9
175	0.1	129	0.1	93	1.6	98	3.9
178	0.1	132	0.1	98	2.0	101	3.9
182	0.1	135	0.1	101	1.8	108	1.7
		140	0.1	108	2.4	111	3.6
345	1.0	143	0.1	111	1.9	114	3.9
353	1.0	147	0.1	114	1.5	119	4.0
386	0.1	150	0.1	119	1.2	122	4.0
404	1.0	154	0.1	122	1.1	126	0.1
412	0.1	157	0.1	126	1.2	129	1.5
427	1.0	161	0.0	129	0.1	132	3.8
433	1.0	168	1.1	132	1.4	135	4.0
441	1.0	171	0.1	135	1.4	140	4.1
470	1.0	175	0.1	140	1.5	143	3.6
555	1.0	178	0.1	143	1.8	147	3.3
569	1.0	182	0.1	147	1.3	150	3.3
576	1.0			150	1.4	154	3.2
583	1.0	345	1.6	154	1.3	157	3.2
598	1.0	353	0.6	157	1.3	161	2.9
612	0.3	371	1.0	161	0.7	168	6.4
626	1.0	379	1.0	168	2.0	171	1.5
632	0.1	392	1.0	171	0.1	175	0.9
646	0.1	404	0.3	175	0.0	178	1.0
653	0.1	412	0.3	178	0.1	182	0.8
660	0.1	433	1.0	182	0.1		
667	0.1	441	1.0			345	3.3
674	0.1	463	1.0	345	0.4	353	1.7
688	0.1	470	1.0	353	1.0	386	1.6
695	0.1	476	0.2	379	1.0	392	0.7
716	0.1	497	1.0	386	1.0	404	1.0
737	0.1	548	1.0	392	1.0	412	1.3
		555	1.0	400	1.0	419	1.3
		562	1.0	404	1.0	427	1.2
		569	1.0	412	1.0	433	0.7
		576	1.0	419	1.0	441	0.7
		583	1.0	441	1.0	448	0.6
		612	0.3	448	1.0	463	1.0
		626	1.0	463	1.0	470	0.9
		632	0.2	470	1.0	476	0.9
		639	0.1	476	0.2	483	0.9
		646	0.1	483	1.0	490	0.6

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
		653	0.1	490	1.0	497	0.5
		660	0.1	497	1.0	503	1.0
		667	0.1	503	0.2	517	0.5
		695	0.1	517	1.0	525	0.5
		709	0.1	525	0.1	543	7.4
		716	0.1	543	1.0	548	6.6
		723	0.1	548	0.3	555	0.2
		737	0.3	548	0.3	562	1.0
				555	1.0	569	1.0
				576	1.0	576	1.0
				583	1.0	583	0.3
				612	0.4	598	0.6
				632	0.7	612	1.1
				639	1.9	626	1.7
				646	0.7	632	2.2
				653	0.4	639	3.1
				660	1.0	646	3.2
				667	0.4	653	3.6
				674	0.2	660	3.5
				688	0.2	667	3.2
				695	0.1	674	3.4
				716	0.1	688	2.3
				723	0.2	695	1.7
				737	2.6	716	3.0
						723	2.6
						723	5.7

NO_3-N concentrations for the low slurry plot (1.5, 2.0, 2.5 and 3.0 m)

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
78	4.0	345	54.6	470.0	19.7	108	6.0
83	5.5	353	37.0	476.0	20.9	111	12.3
90	4.8	371	27.0	483.0	21.4	114	10.7
93	5.0	386	27.7	490.0	22.0	122	10.9
98	5.0	392	22.3	497.0	20.9	126	11.6
108	5.1	404	20.9	503.0	21.8	129	5.5
111	6.7	412	24.3	517.0	19.4	132	13.4
122	7.6	419	22.7	548.0	0.6	135	13.3
126	6.9	427	19.6	555.0	0.9	140	12.3
129	6.1	433	17.5	562.0	3.9	143	12.8
132	5.7	441	15.4	569.0	2.9	147	11.0
135	6.5	448	15.9	576.0	3.5	154	9.5
140	6.3	463	14.3	583.0	3.8	157	13.8
143	5.8	470	15.5	598.0	4.0	161	12.7
147	5.8	476	13.9	612.0	2.8	171	9.7
150	6.1	483	8.7	626.0	4.7	175	13.8
154	5.8	490	9.8	632.0	4.6	178	10.6
157	6.1	497	7.9	639.0	5.0	182	7.5
161	6.4	503	3.8	646.0	4.8		
168	6.6	517	1.0	653.0	4.4	345	9.0
171	6.0	525	1.6	660.0	3.4	353	6.3
175	6.5	543	18.1	667.0	3.4	371	5.1
178	6.4	548	15.7	674.0	3.2	379	5.1
182	5.4	548	15.7	688.0	2.0	392	5.5
		555	11.8	695.0	2.1	400	4.9
345	5.6	562	1.2	709.0	2.5	412	4.9
353	5.7	569	8.9	716.0	1.5	419	5.5
371	7.4	576	7.1	723.0	0.6	427	4.6
386	7.5	583	9.0	737.0	0.3	433	4.7
392	6.4	598	7.8			441	4.0
404	5.8	612	4.3			448	4.3
427	4.0	626	6.8			463	4.5
463	3.8	632	6.3			470	4.5
483	7.0	639	6.2			476	4.2
503	6.8	646	5.8			483	3.8
525	7.8	653	5.0			490	4.5
555	5.4	660	3.8			497	4.3
576	2.7	667	3.6			503	4.3
583	2.4	674	4.0			543	5.2
598	2.0	688	4.0			548	4.9
626	2.1	695	3.6			555	4.4
632	2.0	709	5.0			569	3.6
646	2.1	716	5.1			576	3.4
653	2.0	723	5.2			583	3.3

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
660	1.8	737	5.5			598	2.6
667	2.0					612	0.6
674	2.2					626	2.5
695	2.3					632	2.6
716	4.4					639	1.1
723	4.3					646	2.1
737	4.4					653	1.9
						660	1.4
						667	1.4
						674	1.3
						688	1.2
						695	1.2
						709	1.8
						716	1.8
						723	2.2
						737	2.1

NO3-N concentrations for the medium slurry plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
114	0.1	114	3.6	90	5.3	78	5.5
119	0.1	119	2.5	114	6.9	83	5.9
126	0.1	122	1.8	119	6.6	86	6.0
154	0.1	126	2.0	122	6.4	90	4.8
157	0.3	135	0.1	126	9.2	93	4.6
161	0.0	140	0.1	135	5.9	98	4.3
168	0.3	147	0.1	140	6.3	105	3.7
171	0.1	154	0.1	143	6.1	108	0.3
175	0.7	157	0.2	147	6.1	111	4.2
178	0.1	161	0.2	150	6.2	114	4.0
182	0.1	168	4.9	154	6.7	119	3.7
		171	0.3	157	6.3	122	3.1
345	0.6	175	0.3	161	6.5	126	3.1
353	0.1	178	3.0	168	5.0	129	0.0
386	1.0	182	0.6	171	4.0	135	3.0
392	1.0			175	3.0	140	1.7
400	1.0	345	6.1	178	1.5	143	3.0
404	1.0	353	4.8	182	2.3	147	3.0
412	0.0	371	3.4			150	2.8
419	1.0	379	1.4	345	3.3	154	2.9
441	1.0	386	1.0	353	1.8	157	3.3
448	1.0	392	1.0	371	1.0	161	3.1
470	1.0	400	1.0	379	0.0	168	3.1
555	1.0	404	1.0	386	1.0	171	2.1
562	1.0	412	0.0	392	1.0	175	1.7
569	1.0	419	1.0	400	0.2	178	4.9
576	1.0	427	1.0	404	0.2	182	1.3
583	1.0	433	1.0	412	0.3		
591	1.0	441	1.0	419	0.6	345	2.6
598	1.0	448	1.0	433	1.0	353	1.5
612	0.5	470	0.1	441	1.0	371	0.7
626	1.0	476	0.2	448	1.0	379	0.3
632	0.3	497	1.0	463	1.0	392	1.0
639	0.2	503	0.5	470	1.0	400	1.0
646	0.1	555	1.0	476	0.4	404	1.0
653	0.1	562	1.0	483	0.1	412	0.1
660	0.1	569	1.0	490	0.2	419	1.0
667	0.1	576	0.8	497	1.0	433	1.0
674	0.1	583	1.1	503	0.3	441	1.0
688	0.1	591	1.7	517	0.2	448	1.0
695	0.1	598	2.5	525	0.8	463	1.0
716	0.1	612	2.8	543	1.0	470	0.2
723	0.1	626	3.6	548	0.6	476	0.8
737	0.1	632	3.7	555	1.1	483	1.1

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	NO3-N	Days after May 1st	NO3-N	Days after May 1st	NO3-N	Days after May 1st	NO3-N
	mg/l		mg/l		mg/l		mg/l
		646	1.9	562	1.1	497	0.3
		653	0.6	569	1.2	503	0.6
		660	0.3	576	1.2	517	0.4
		667	0.1	583	1.3	525	1.3
		674	0.1	591	1.7	543	1.1
		688	0.1	598	1.8	548	0.9
		695	0.1	612	1.9	555	1.0
		716	0.1	626	3.0	569	1.3
		723	0.2	632	3.1	576	1.3
		737	0.2	639	3.7	583	1.5
				646	4.4	591	1.5
				653	4.3	598	1.6
				660	3.5	612	2.0
				667	4.7	626	2.4
				674	3.9	632	2.9
				688	3.8	639	3.1
				695	3.1	646	3.4
				709	2.2	653	3.5
				716	1.4	660	3.2
				723	1.3	667	4.5
						674	4.0
						688	4.9
						695	4.2
						709	5.9
						716	5.8
						723	5.7

NO_3-N concentrations for the medium slurry plot (1.5, 2.0, 2.5 and 3.0 m)

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
78	2.1	345	13.0	555.0	14.5	345	67.2
86	2.7	353	15.6	562.0	11.6	379	63.9
90	2.5	371	18.8	569.0	10.9	386	53.7
93	2.2	386	20.7	576.0	11.1	392	42.9
98	2.3	404	14.9	583.0	11.3	404	36.1
101	2.7	412	14.8	591.0	10.9	412	36.1
105	2.5	419	13.1	612.0	8.5	419	34.3
108	3.6	427	8.4	626.0	8.7	427	32.7
111	2.7	433	13.6	632.0	7.9	433	30.1
114	2.9	463	16.0	639.0	7.6	441	26.4
126	3.1	470	19.2	646.0	8.3	448	26.4
129	2.8	476	18.6	653.0	7.2	463	23.7
135	3.6	483	17.6	660.0	6.4	470	24.8
143	4.3	490	15.6	667.0	7.9	476	18.3
147	4.2	497	15.4	674.0	9.9	483	21.4
150	3.9	503	16.6	688.0	6.1	490	19.0
154	3.9	517	16.5	695.0	5.2	497	20.4
157	3.9	525	32.6	709.0	6.9	503	21.5
161	4.8	543	14.0	716.0	6.8	517	23.4
171	4.8	548	18.2	723.0	6.6	525	25.3
175	5.1	555	9.6	737.0	6.1	543	24.2
178	3.9	562	9.1			548	33.7
182	4.5	569	8.2			555	24.8
		576	8.5			562	20.8
345	6.6	583	8.8			569	19.0
353	9.3	591	7.4			576	11.0
371	9.1	598	6.3			583	12.2
386	9.5	612	5.7			591	13.2
392	9.3	626	6.0			598	12.8
400	7.3	632	5.7			612	10.6
404	5.5	639	5.8			626	9.4
412	4.4	646	6.3			632	12.9
419	4.5	653	5.7			639	12.8
433	3.6	660	4.5			646	9.2
441	2.8	667	5.8			653	7.2
448	2.8	674	4.4			660	9.4
463	2.0	688	5.2			667	11.6
470	1.6	695	4.7			674	6.5
476	1.1	709	6.3			688	9.4
483	1.8	716	6.5			695	8.1
503	3.8	723	6.3			709	9.9
517	4.4	737	4.9			716	10.0
525	5.7					723	10.2
543	5.7					737	6.3

1.5m		2.0m		2.5m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
548	5.5	723	7.9			723	5.3
555	4.6	737	5.4			737	0.1
576	4.3						
583	3.6						
591	3.1						
598	2.7						
612	3.7						
626	4.5						
632	4.4						
639	4.0						
646	4.2						
653	3.8						
660	3.5						
667	4.5						
674	3.2						
695	4.0						
709	5.0						
723	5.2						
737	5.5						

NO3-N concentrations for the high slurry plot (0.3, 0.6, 0.9 and 1.2 m)

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
154	0.1	78	9.2	78	6.4	78	4.1
157	0.8	108	11.2	83	7.3	83	5.3
161	0.0	114	4.7	86	7.1	86	4.7
168	0.1	122	2.5	90	4.1	90	7.3
171	0.1	126	2.3	93	6.2	93	3.9
175	0.1	129	1.9	98	4.1	98	8.0
178	0.1	132	0.7	101	2.3	101	4.4
182	0.9	135	1.5	111	6.4	108	8.4
		140	1.6	114	5.6	111	4.6
433	1.0	143	1.3	119	5.5	114	4.7
598	0.1	147	0.8	122	5.4	122	4.3
		150	0.8	126	4.9	126	4.3
		154	4.4	132	5.6	129	3.8
		157	0.4	135	4.2	132	2.8
		161	0.4	140	4.6	135	4.2
		168	3.6	143	4.5	140	4.3
		171	0.1	147	4.2	143	4.3
		175	0.1	150	4.3	147	4.4
		178	0.1	157	4.5	150	4.3
		182	0.2	161	4.2	154	4.2
				168	4.4	157	4.6
		345	0.2	171	2.4	161	5.4
		353	1.0	175	1.5	168	8.3
		379	1.0	178	1.7	171	3.9
		386	0.1	182	0.1	175	2.6
		404	0.2			178	1.7
		412	0.2	345	2.4	182	1.7
		419	0.1	353	3.1		
		427	1.0	371	3.0	345	2.1
		433	1.0	379	3.3	353	2.4
		441	1.0	386	3.5	371	1.9
		448	1.0	392	5.7	379	1.8
		503	1.0	404	3.0	386	2.4
		562	1.0	419	1.7	392	2.0
		569	1.0	433	1.0	400	1.9
		576	1.0	441	1.0	404	1.9
		583	1.0	448	1.0	412	2.1
		591	4.8	470	1.0	419	1.9
		598	0.1	476	0.5	433	2.3
		612	0.2	483	0.1	441	1.8
		626	1.0	490	1.0	448	2.0
		639	0.1	503	0.2	463	2.4
		653	0.1	517	0.1	470	2.6
		660	0.1	543	0.3	476	2.7

0.3m		0.6m		0.9m		1.2m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**		**mg/l**
		667	0.1	555	0.1	483	2.7
		674	0.1	569	1.0	490	2.8
		688	0.1	576	0.1	497	2.6
		695	0.1	583	0.2	503	2.9
		709	0.1	591	0.7	517	3.0
		716	0.1	612	0.8	525	3.4
		723	0.2	632	1.4	543	3.7
		737	2.6	639	2.0	548	2.7
				646	2.2	555	1.7
				653	2.4	562	1.0
				660	2.3	569	0.7
				667	1.9	576	0.8
				688	1.7	583	0.6
				695	1.6	591	1.1
				709	1.4	598	0.7
				716	1.4	612	0.9
				723	1.4	639	1.7
				737	1.5	646	1.9
						653	2.1
						660	2.1
						667	1.9
						674	2.1
						688	1.7
						716	2.6
						723	2.6

NO_3-N concentrations for the high slurry plot (1.5, 2.0 and 3.0 m)

1.5m		2.0m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**
78	6.0	345	52.3	345	15.5
83	7.5	371	12.1	353	11.4
86	7.2	379	9.3	371	13.7
90	5.4	386	9.1	379	12.1
93	6.7	392	9.5	386	14.2
98	6.5	400	8.8	392	9.8
101	6.8	404	8.7	400	9.9
105	7.0	412	7.9	404	8.8
108	4.8	419	8.4	412	8.4
111	7.6	427	8.6	419	8.7
114	7.2	433	9.5	427	9.5
122	8.1	441	9.7	433	10.3
126	8.5	448	9.8	441	7.6
129	7.7	463	8.1	448	7.4
132	7.5	470	7.9	463	7.8
135	7.6	476	7.3	470	7.2
140	8.1	483	7.3	476	7.9
143	8.0	490	7.0	483	7.0
147	7.8	497	8.0	490	7.2
150	8.0	503	7.1	497	7.4
154	8.2	517	7.9	503	7.2
157	8.5	525	8.8	517	7.9
161	9.2	543	8.4	525	8.9
171	8.5	548	7.0	543	9.1
175	8.8	555	6.1	548	8.5
178	9.7	562	1.2	555	7.1
182	6.9	569	7.1	562	3.9
		576	8.6	576	5.2
345	7.3	583	8.1	583	4.6
353	4.5	591	15.5	591	12.4
371	2.0	598	5.7	598	6.1
379	1.9	612	5.2	612	5.6
386	2.4	626	5.9	626	5.5
392	1.3	632	5.7	632	5.3
400	1.3	639	6.6	639	5.5
404	1.5	646	6.5	646	5.6
412	2.0	653	5.9	653	4.8
419	1.3	660	5.1	660	3.7
433	1.5	667	5.1	667	3.7
441	1.4	674	5.4	674	4.4
448	1.4	688	6.1	688	3.6
463	1.4	695	6.2	695	3.9
470	1.5	709	7.8	709	5.2
476	1.7	716	8.2	716	5.4

1.5m		2.0m		3.0m	
Days after May 1st	**NO3-N**	**Days after May 1st**	**NO3-N**	**Days after May 1st**	**NO3-N**
	mg/l		**mg/l**		**mg/l**
483	1.5	723	7.9	723	5.3
503	2.9	737	5.4	737	0.1
517	2.1				
525	2.2				
543	2.1				
548	1.5				
555	1.3				
569	1.1				
576	1.2				
583	1.1				
591	1.1				
598	0.8				
612	1.2				
626	0.7				
632	1.0				
639	1.0				
646	0.6				
653	0.6				
660	0.6				
667	0.4				
674	0.8				
688	0.5				
695	2.1				
716	1.4				
723	1.5				
737	8.1				

APPENDIX B –
MOISTURE CONTENT READINGS

Moisture Content Readings

Control		0.3	0.6	1.0	1.5	2.0	3.0
01-Nov-01							
02-Nov-01	0	0.346	0.290	0.361	0.362	0.380	0.393
13-Nov-01	11	0.351	0.293	0.355	0.362	0.362	0.331
16-Nov-01	14	0.349	0.290	0.359	0.362	0.371	0.343
23-Nov-01	21	0.345	0.292	0.356	0.359	0.371	0.389
27-Nov-01	25	0.344	0.288	0.357	0.359	0.371	0.390
04-Dec-01	32	0.360	0.324	0.364	0.364	0.373	0.394
07-Dec-01	35	0.364	0.325	0.360	0.370	0.374	0.397
11-Dec-01	39	0.346	0.300	0.359	0.364	0.370	0.401
14-Dec-01	42	0.348	0.293	0.356	0.360	0.369	0.399
18-Dec-01	46	0.347	0.291	0.355	0.359	0.369	0.401
21-Dec-01	49	0.346	0.288	0.355	0.360	0.368	0.403
29-Jan-02	88	0.357	0.299	0.361	0.361	0.373	0.410
04-Feb-02	94	0.368	0.304	0.363	0.365	0.377	0.413
11-Feb-02	101	0.362	0.303	0.361	0.365	0.375	0.412
14-Feb-02	104	0.354	0.298	0.358	0.366	0.372	0.414
21-Feb-02	111	0.354	0.300	0.352	0.359	0.370	0.402
01-Mar-02	119	0.359	0.297	0.358	0.362	0.370	0.411
04-Mar-02	122	0.354	0.300	0.363	0.364	0.373	0.414
11-Mar-02	129	0.358	0.302	0.363	0.363	0.370	0.412
14-Mar-02	132	0.340	0.302	0.353	0.358	0.364	0.404
19-Mar-02	137	0.360	0.311	0.365	0.366	0.377	0.413
25-Mar-02	143	0.357	0.311	0.367	0.368	0.372	0.414
02-Apr-02	151	0.340	0.313	0.355	0.364	0.366	0.402
08-Apr-02	157	0.344	0.298	0.363	0.364	0.366	0.405
19-Apr-02	168	0.335	0.296	0.355	0.366	0.370	0.406
23-Apr-02	172	0.350	0.306	0.356	0.363	0.370	0.407
30-Apr-02	179	0.357	0.314	0.360	0.365	0.368	0.406
07-May-02	186	0.345	0.306	0.359	0.366	0.368	0.408
13-May-02	192	0.341	0.300	0.355	0.364	0.370	0.408
28-May-02	207	0.363	0.311	0.361	0.367	0.367	0.407
05-Jun-02	215	0.354	0.305	0.357	0.365	0.372	0.411
11-Jun-02	221	0.355	0.308	0.362	0.364	0.366	0.409
18-Jun-02	228	0.358	0.306	0.361	0.363	0.370	0.409
24-Jun-02	234	0.344	0.303	0.360	0.364	0.367	0.407
01-Jul-02	241	0.339	0.298	0.357	0.365	0.368	0.410
08-Jul-02	248	0.340	0.295	0.356	0.362	0.365	0.403
16-Jul-02	256	0.343	0.296	0.354	0.364	0.366	0.405
23-Jul-02	263	0.326	0.292	0.354	0.362	0.365	0.385
30-Jul-02	270	0.322	0.288	0.350	0.358	0.361	0.389
08-Aug-02	279	0.310	0.274	0.337	0.347	0.352	0.374
09-Aug-02	280	0.327	0.277	0.335	0.347	0.349	0.369
14-Aug-02	285	0.339	0.291	0.346	0.356	0.358	0.381
21-Aug-02	292	0.333	0.282	0.344	0.358	0.360	0.376
03-Sep-02	305	0.322	0.285	0.348	0.357	0.357	0.377
10-Sep-02	312	0.296	0.267	0.330	0.345	0.346	0.366
16-Sep-02	318	0.291	0.257	0.321	0.334	0.335	0.350
29-Sep-02	331	0.297	0.267	0.335	0.354	0.355	0.372
08-Oct-02	341	0.302	0.270	0.334	0.352	0.351	0.370
26-Oct-02	359	0.320	0.282	0.329	0.335	0.334	0.365

Control		0.3	0.6	1.0	1.5	2.0	3.0
31-Oct-02	364	0.321	0.284	0.328	0.334	0.333	0.360
07-Nov-02	371	0.324	0.281	0.322	0.331	0.333	0.355
14-Nov-02	378	0.327	0.284	0.326	0.331	0.333	0.356
28-Nov-02	392	0.329	0.287	0.330	0.330	0.332	0.367
05-Dec-02	399	0.322	0.283	0.321	0.338	0.324	0.366
13-Dec-02	407	0.319	0.278	0.313	0.321	0.322	0.359
20-Dec-02	414	0.310	0.275	0.313	0.321	0.322	0.359
04-Jan-03	429	0.315	0.273	0.312	0.322	0.324	0.351
10-Jan-03	435	0.299	0.266	0.305	0.310	0.314	0.338
16-Jan-03	441	0.305	0.266	0.306	0.316	0.313	0.343
24-Jan-03	449	0.350	0.312	0.357	0.375	0.374	0.411
30-Jan-03	455	0.343	0.296	0.338	0.356	0.351	0.392
06-Feb-03	462	0.336	0.299	0.336	0.347	0.339	0.391
13-Feb-03	469	0.331	0.290	0.328	0.333	0.329	0.370
06-Mar-03	490	0.319	0.284	0.324	0.326	0.328	0.361
13-Mar-03	497	0.348	0.304	0.351	0.357	0.360	0.404