Surface and Groundwater Interactions

Location of a sub-surface remediation trench.

END OF PROJECT REPORT

RMIS 5478

Author

O.Fenton,[1]

[1] Johnstown Castle Research Centre, Wexford

Johnstown Castle Research Centre Wexford

December 2006

ISBN No. 1 84170 … .

AGRICULTURE AND FOOD DEVELOPMENT AUTHORITY

Teagasc Headquarters, Oak Park, Carlow

TABLE OF CONTENTS

SUMMARY

The Water Framework Directive aims to achieve at least “good status” of all surface and groundwater bodies by 2015. In 2009 programmes of measures to achieve this status must be implemented. In 2012 water quality response to these measures will be examined at river basin catchment level. The adoption of the Water Framework Directive from the 1st January 2007 restricts the amount of nutrients which can be applied to agricultural land. A nutrient discharge to a waterbody has a negative impact on the environment and may lead to eutrophication. A broad strategy exists at European level to minimise nutrient loss to a waterbody. This strategy examines the source/pressure, pathway and receptor approach for nutrient transport. Such nutrient management strategies try to minimise nutrient loss while maintaining productivity. Nitrogen usage is now associated with environmental degradation even at lower levels than the maximum allowable concentration (11.3 mg NO_3-N L^{-1}). A further strategy proposes that nutrient management and increased utilisation of nutrients alone will fail to recognise nutrient loss even at high levels of efficiency. This strategy attempts to use

remediation (Nitrate) and control technologies (Phosphorous) to intercept nutrients before discharge. Another function would be to further reduce concentrations presently at allowable levels. This introduces an interceptor phase into the nutrient transfer model.

Groundwater characterisation leads to a better understanding of the nutrient source and pathway to a groundwater or surface water receptor. The interactions between surface runoff, sub-surface drainage (man made) and groundwater are important when dealing with the source pathway receptor concept. Interactions between shallow groundwater and surface water should also be considered. The deeper groundwater body and surface water interactions should also be characterised.

A monitoring network incorporating surface, subsurface and groundwater elements was created on the Teagasc Environmental Research Centre, Wexford. A sub-surface drainage system was characterised and water quality monitored. Some breaches of the maximum admissible levels (MAC) of nitrate in groundwater were found in two separate locations (Dairy and Beef farms). A review of remediation options proposed a sub-surface denitrification trench to remediate excess nutrient loss on site. The location of such a permeable reactive barrier in the field to intercept a nitrate plume was investigated.

The following investigations were carried out:

- A review of “Groundwater remediation systems for the treatment of agricultural wastewater to satisfy the requirements of the Water Framework Directive” was carried out. This proposes options for Ireland.
- The groundwater characterisation of the Dairy Farm in Teagasc, Environmental Research Centre, Wexford.
- The groundwater and subsurface drainage system characterisation of a 4.2 ha field site on the Beef Farm in Teagasc, Environmental Research Centre, Wexford.
- A methodology for the location of in-field remediation techniques was established.

INTRODUCTION

The Surface Water Directive, 75/440/EEC EEC (1975), the Groundwater Directive, 80/68/EEC EEC (1980), the Drinking Water Directive, 98/83/EC EC (1998), the Nitrates Directive, 91/676/EEC EEC (1991) and the Urban Wastewater Directive, 91/271/EEC EEC (1991), combined with recent proceedings taken against the State by the EU Commission alleging non-implementation of some aspects of the directives, has focused considerable attention on the disposal of agricultural wastewaters in Republic of Ireland (henceforth termed Ireland). To address these directives, the WFD, 2000/60/EC EC (2000) came into force on 22nd December, 2000 and was transported into Irish legislation by the European Communities (Water Policy) Regulations 2003 on the 22nd December, 2003. Eight “river basin districts” (RBDs) have been established in Ireland, north and south, with the aim of achieving “good status” in all surface and ground waters by 2015. The WFD will bring about major changes in the regulation and management of Europe's water resources. Major changes include:

- a requirement for the preparation of integrated catchment management plans, with remits extending over point and non-point pollution, water abstraction and land use;
- the introduction of an EU-wide target of "good ecological status" for all surface water and groundwater, except where exemptions for "heavily-modified" water bodies are granted. Measures put in place to protect groundwater and surface water must be planned and implemented while being efficient and cost-effective.

As laid out in the Groundwater Directive groundwater is a “valuable natural resource and as such should be protected from deterioration and chemical pollution”. It is the “most sensitive and largest body of freshwater in the EU” and “protection of groundwater in some areas require a change in farming or forestry practices”.

Recent assessments of Irish waterways indicate that a significant fraction of rivers, lakes, estuaries and coastal waters will require improvements if they are to meet “good ecological status”. Water bodies identified as probably requiring improvement include: 56% of groundwater bodies, 35% of river water bodies, 20% of lake water bodies, 23% of transitional water bodies and 15% of coastal water bodies (EPA, 2004a).

In Ireland, farming is an important national industry that involves approximately 270,000 people, 6.191 million cattle, 4.257 million sheep, 1.678 million pigs and 10.7 million poultry (CSO, 2006). Agriculture utilizes 64% of Ireland’s land area (Fingleton and Cushion, 1999), of which 91% is devoted to grass, silage and hay, and rough grazing (DAF, 2003). Grass-based rearing of cattle and sheep dominates the industry (EPA, 2004a). The aquatic agri-environment is vulnerable from nutrient losses to surface and groundwater. Nutrient loss and subsequent transport may lead to nutrient interaction with surface and groundwater and may have an adverse impact on biodiversity and ecology of aquatic ecosystems (Schulte et al., 2006). A survey of 1132 rivers and streams from 2001 to 2003 (Toner et al., 2005) estimated that the percentage of pollution attributed to agriculture was approximately 32%, in the case of rivers and streams which were slightly or moderately polluted, but only 15% of serious pollution. In 2001, 56 million tones of agricultural waste were generated, of which 61.3% was from cattle manure and slurry (EPA, 2004b). Agricultural nutrient inputs are the most significant nutrient load entering receiving waters in Ireland and have been estimated to comprise 75.3% and 33.4% of the nitrogen (N) and phosphorus (P) load, respectively (RBD, 2005). Diffuse P losses from agriculture may contribute to eutrophication (Clabby et al., 1992; Bowman et al., 1996; Lucey et al., 1999; Mc Carrigle et al., 2002). Rivers and lakes have a threshold value of 0.03 mg PO_4-P L^{-1}, above which eutrophication may occur. However, the frequency of these breaches in Ireland follows a downward trend (EPA, 2004b). In their review of nutrient loss from agriculture to water, Schulte *et al.*, (2006) correlated reduced river quality to areas where P pressures coincided with transport vectors. The source-pathway receptor concept was combined with agro-meteorological factors and pressures to account for nutrient loss to water. Elevated soil P status has been identified as one of the dominant P pressures in Ireland (Tunney *et al.*, 2000). River quality trends have been correlated to population and intensity of agriculture where threshold levels are breached (EPA, 2004a). P surpluses also accumulate in the soil (Culleton *et al.*, 2000) and contribute to P loss to surface and groundwaters (Tunney, 1990).

A number of research activities, each with its discrete objectives, were established.

The discrete objectives were:

- to review the impact of agriculture on the environment in Ireland and to examine emerging technologies for agricultural wastewater treatment.
- to construct electronic groundwater maps for the (60.5 ha) dairy farm and a section of the beef unit in the Teagasc Environment Research Centre at Johnstown Castle, Wexford, Ireland.
- to investigate groundwater quality and characterise contamination migration and identify possible contamination sources on site
- to identify the optimal location and dimensions of a proposed field-scale, carbon-amended subsurface denitrification trench on a 4.27 ha field site at Teagasc, Johnstown Environmental Research Centre using a shallow piezometer monitoring network and electronic groundwater maps. The preliminary site investigations undertaken in this study may be used prior to the

construction of other subsurface remediation systems. Recommended preliminary tests include: soil investigation and electronic contour maps of watertable, nitrate (NO_3^--N) fluctuation, hydraulic conductivity, K_{sat}, and NO_3^-N : Chloride (Cl) ratios.

- to outline a methodology for the optimal location of a groundwater remediation system for the treatment of agricultural wastewater along a watercourse.

Emerging technologies for agricultural wastewater treatment:

European wastewater treatment strategy focuses on prevention of nutrient loss from farms by improved management practices. To address the requirements of existing legislation and the WFD, groundwater remediation of agricultural wastewater is required. The impact of agriculture on the environment in Ireland was explored. A range of options for phosphorous control were examined (buffer strips, aluminium and polyacrylamide amendments). The toxicity and aluminium usage for surface waters and in waste water treatment was examined. For nitrate removal several technologies were examined (phytoremediation, solid carbon amendment (woodchip), permeable reactive walls to intercept groundwater, water table management and willow plantations). Specifications for the implementation of these technologies on site should be developed and policy needs to change to incorporate remediation technologies. Technologies such as horizontal flow biofilm reactors, which are capable of parlour washing and soiled water remediation, should be investigated. The economic value of these improvements should also be investigated.

MATERIAL AND METHODS

Experimental site 1: Dairy Farm

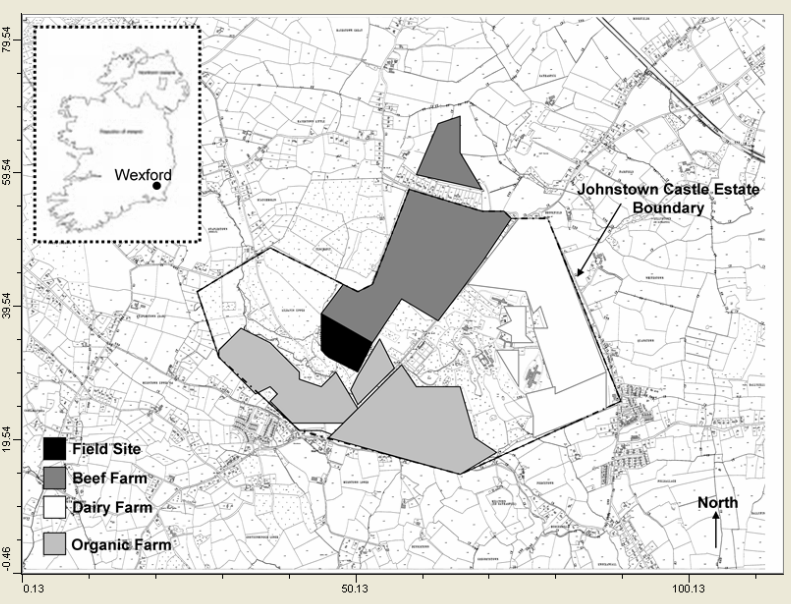


Figure 1: Johnstown Castle Environmental research centre

The Teagasc research centre at Johnstown Castle, Wexford is divided into a dairy farm (60.5 ha), a conventional beef farm (63.3 ha) and an organic beef farm (59.6 ha) (Figure 1.). The subsurface drainage system and surface water features are presented in Figure 2. The dairy farm comprises undulating slopes with grey-green shale bedrock of low permeability covered by glacial drift. The soil profile consists of fine loam to a depth of 40 cm underlain by a loam-to-clay loam subsurface soil (Culleton & Diamond, unpublished). Well to moderate drainage is

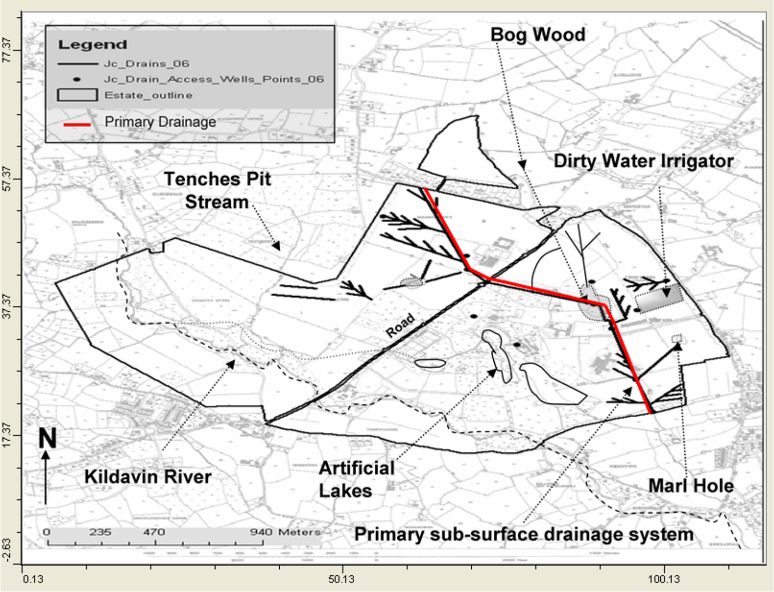


Figure 2: Sub-surface drainage system on the Dairy Farm

found centrally on the farm with poor drainage enclosing this central area. A primary subsurface collector drainage system runs the length of the farm with herring-bone secondary drains alleviating adjacent poorly drained areas (Figure 2.) the northwest and discharge to a natural woodland area (Bogwood, 0.3 ha) (Shaded area, Figure 2.). The primary drainage system conveys water below the plough layer (2 m bgl) from the secondary drains of the drainage system.

A monitoring network may be used to optimise experimental design, plot selection and orientation at any proposed study site. However, here the monitoring network was designed to construct groundwater maps. Further monitoring and a further drilling phase would be needed to isolate individual plots for experimental work. Only then can groundwater quality at a given location be justified by considering management practices at the surface. With the general groundwater maps the source of nutrient concentrations entering and leaving an area of the farm can be accounted for. Also combining this information with potential sources of contamination the monitoring network allows us to establish where the contaminate plumes exist. Bartley (1996) confirmed that groundwater flow generally mirrored topography on site. The positions of the wells DF1a, DF2A and DF3A (Figure 3.) with total drilling depths to approximately 7 m represent the shallow saturated zone, with DF2B and DF3B (Figure 3.) although deeper within the same zone. Water samples (and associated depths) from wells DF2C and DF3C (Figure 3.) represent groundwater from the grey green shale aquifer.

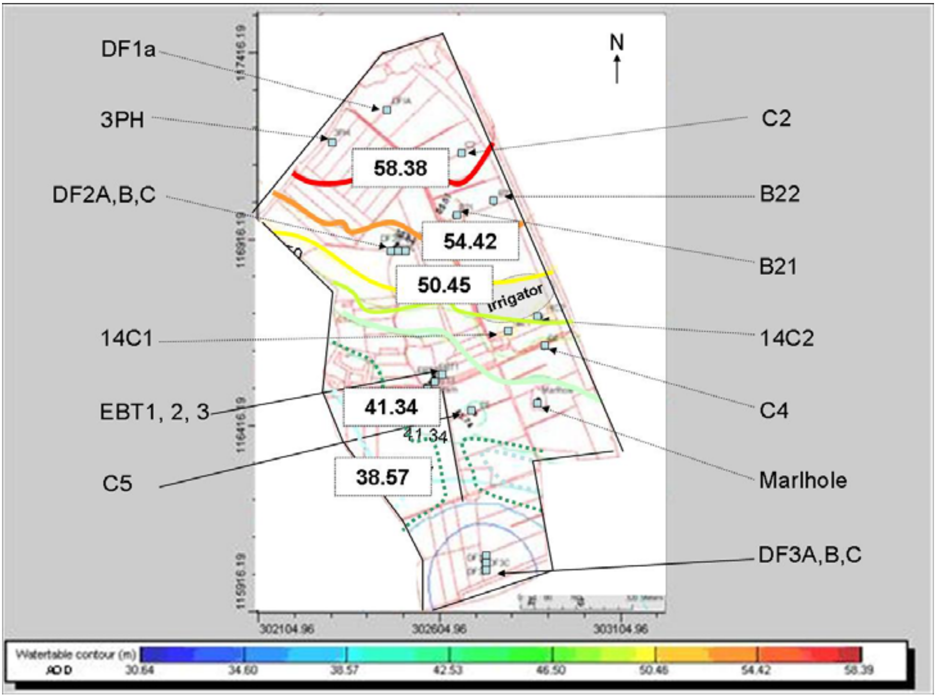


Figure 3: Dairy farm watertable contour map

Pre drilling, elevation maps were used to locate the wells. An initial phase of drilling created a network of 7 boreholes (DF1, DF2A-C, and DF3A-C) (at a density of 0.12 well ha^{-1}) (Bartley, 1996) (Figure 3). A second phase of drilling enhanced this network by installing a number of watertable observation wells (3PH, C2, B21, B22, 14C1-2, and C4) at 0.28 well ha^{-1} (Fenton & Hyde, 2006). In addition to this main network, three observational wells (EBT1-3) were installed beside an earthen lined store on a site beside the dairy farm buildings (Figure 3). The wells were levelled using TOPCON AT-G4 equipment (TOPCON Ltd, Ireland) and the locations of the wells were inputted into ArcGIS™ 9.1 (ESRI, Ireland). On the date of levelling (8th June 2006), the water level was determined using a V10/10 electric water-level indicator with acoustic and light signal (Van Walt Ltd, Surrey, U.K.).

Two dimensional groundwater data models using block kriging were generated using GW-Contour 1.0 software (Waterloo Hydrogeologic, Waterloo Ontario, Canada), which is a new data interpolation and visualisation tool. A topographic base map with field boundary overlay was generated with ArcGIS™ and merged with well location and groundwater head input files. Groundwater heads were calculated after levelling and were assigned to an input file at a given point in time and corrected for height of the well pipe above the soil surface. Surface water features such as streams, lakes, open drains and marl holes were also levelled on 8th June, 2006. Trial holes (4 m bgl) were excavated for the purposes of identifying potential sites for a further earthen lined store on the dairy farm. Soil profiles were described and each horizon was sampled for texture and Atterberg limits. This information was used to define three effective porosity zones around the farmyard. Slug tests defined hydraulic conductivity values for these zones. A dirty water irrigator (Briggs, U.K.) presently operating (Dec. 2006) with run length of 200 m is located northwest of the dairy farm. Routine photometric tests of water samples taken from the monitoring network were analysed on a water analyser, Thermo, Konelab 20 (Technical Lab Services, Ontario, Canada) for chloride, nitrite, ortho-phosphate, total organic nitrogen and potassium.

Site Description 2: Beef Farm (Section: Foals House Field)

The 4.27 ha field site (comprising of 6 isolated plots, grouped in pairs with similar area and drainage class) is located on the Beef farm in the Teagasc, Johnstown Castle Environmental Research Centre, Co. Wexford, Ireland (Figure 1). Annual groundwater temperatures on the study site range from 9.5 ºC to 10.5 ºC. It is bordered by a stream and a lagoon to the west and the Kildavin River to the south. A sub-surface drainage system is installed at 1m bgl with drain spacing of 1 m. A series of v-notch weirs are connected to this drainage system and an additional network is connected to receive runoff from the area.

The soil comprises a 15 to 40 cm-deep loam, overlying a loam-to-clay-loam subsurface soil and there is a quartzite outcrop along the eastern side of the site. The site is underlain by an impermeable layer 6-10 m below the soil surface. There is a textural transition across the site responsible for differential drainage. Six study plots, comprising 2 well-drained plots (Plots1 and 2, Figure 4.), 2 moderately-drained plots (Plots 3 and 4, Figure 4.) and 2 poorly-drained plots (Plots 5 and 6) (Figure 4.), are situated down-slope of an irrigated plot (Sandhill, Figure 4), where irrigation rates varied from 10 to 50 mm yr^{-1} prior to the study period. During the study the irrigator was not in use. Two deep, open drains with bases ranging from 71.08 m above ordnance datum (AOD) to 70.2 m AOD (Drain A, Figure 4.) and 71.10 m AOD to 70.30 m AOD (Drain B, Figure 4.) were excavated along the northern edge of the plots. Drains A and B are north of Plots 1, 2, and 3 and Plots 4, 5, and 6, respectively. A sand lens runs from the irrigated plot and under the drains rising in the middle of the six study plots. Irrigated water migrates from the Sandhill via two pathways: (1) overland flow into the drains (Drains A, B), and (2) infiltration into the sandhill. The groundwater is exposed to surface contamination in the shallow drains. Elsewhere, the watertable remains below the drains and enters the site via the sand lens. After heavy rainfall events, soiled water runs into the drains and recharges directly to groundwater.

Monitoring wells were installed at a well density of 0.22 well ha^{-1}. Each study plot has three monitoring wells, giving a total of 18 wells (Figure 4).

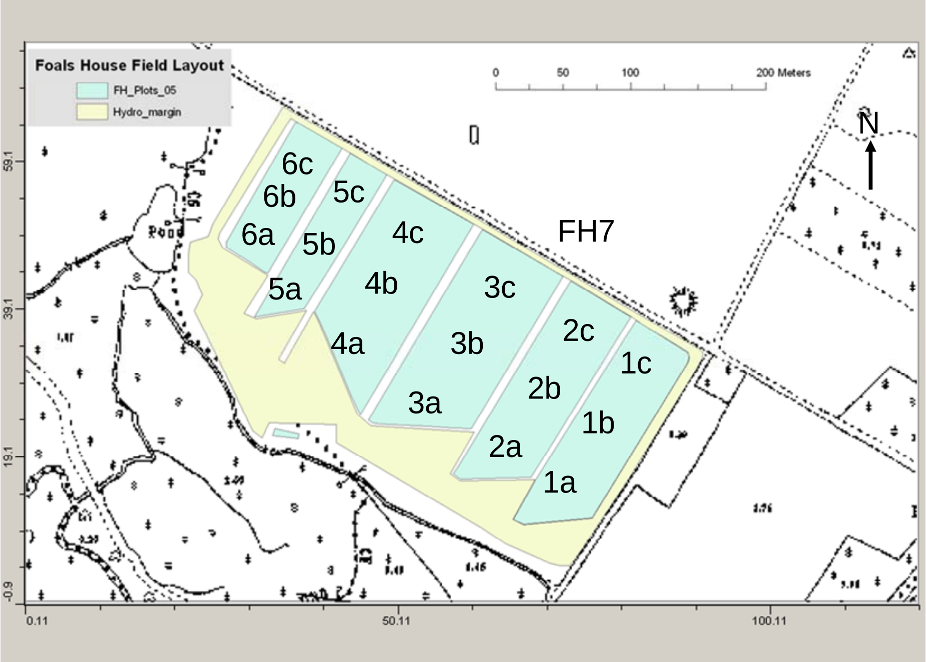


Figure 4. Field site layout and monitoring network

The elevated irrigation plot also contains a monitoring well (FH7), located down-gradient of the irrigator (Figure 4). The wells were levelled using TOPCON AT-G4 equipment (TOPCON, Ireland) and the locations of the wells were recorded using digital mapping software (ArcGIS^{TM} 9.1, ESRI, Ireland). The site and monitoring network was then digitised using DGPS antenna, MG-A1 equipment (TOPCON, Ireland). On the date of levelling (11th July, 2006), depth to water level in each monitoring well was measured using an electric water-level indicator (Van Walt Ltd, Surrey, U.K) and groundwater heads were determined using ordinance survey data. Surface water features, such as streams, drains and lagoons, were also levelled on this date. 2-dimensional groundwater data models were generated using GW-Contour 1.0 software (Waterloo Hydrogeologic, Canada). A topographic base map with a field boundary overlay was generated using ArcGIS^{TM} and merged with well location and groundwater head input files.

From March, 2005 to December, 2006, water levels were measured weekly in each monitoring well and NO_3-N and Cl^- concentrations within each well were measured every 2 weeks. Both NO_3^- and Cl^- are negative ions and do not adsorb to the soil matrix. However NO_3^- concentrations are reduced by biochemical processes. Using the NO_3^-/Cl^- ratio, the groundwater flow pathway may be identified (Obenhuber & Lowrance, 1991; Agriculture and Agri-Food Canada, 2002).

Daily weather data was recorded at the Johnstown Castle Weather Station. Daily soil moisture deficit (SMD), potential evapotranspiration (PE), actual evapotranspiration (AE) and effective drainage were calculated using the AgMet model (Schulte *et al.*, 2005) under moderately drained soil conditions. Effective drainage occurred when the SMD=0. Prior to the study, undisturbed soil samples were excavated using an Edelman auger (Van Walt Ltd., Surrey, UK) and sampled for texture, porosity and Atterberg limits. Hydraulic conductivity falling head slug tests were carried out by an instantaneous injection of 1 L of water into each well (Bouwer and Rice, 1976; Horslev, 1951). Watertable changes and groundwater temperatures were recorded using CTD divers (Van Walt Ltd, Surrey, U.K.)

RESULTS AND DISCUSSION

Results for experimental site 1

As a result of the second phase of drilling (0.28 well ha^{-1}), groundwater flow across the farmyard and in specific areas of interest may be assessed. The watertable map of the dairy farm is presented in Figure 3. The drainage system causes the contours to break (dashed lines Figure 3.) across this area and groundwater flow changes to accommodate drainage. Depth to bedrock varies (from 12 m to > 20 m).

A mean annual nitrate fluctuation map using data from the first and second drilling phases is shown in Figure 5. Highest fluctuations occur south of the farmyard and to the southwest mirroring groundwater flow direction. Nitrate/chloride ratios in this region are also high (C5, 14C1 and 14C2) and low elsewhere (C4).

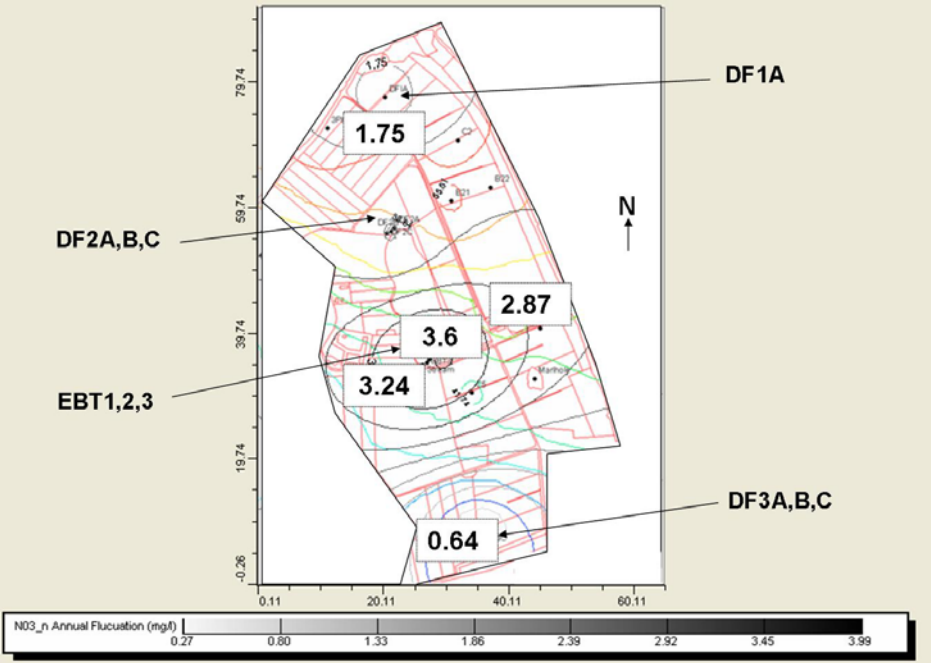


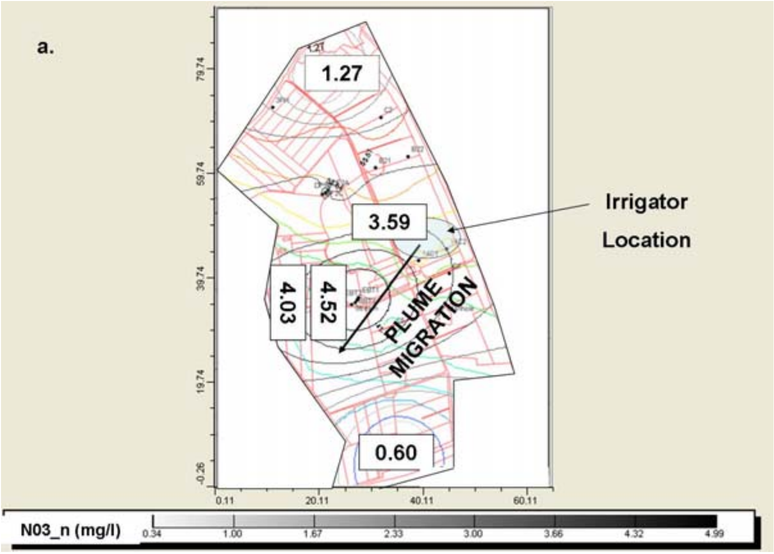
Figure 5. Mean annual Nitrate fluctuations from December 2004 to January 2006

Nitrate fluctuations may be divided into three regions:

1) DF1A where a contaminant source enters the farm from the north. Groundwater flow direction is towards the farm from outside. The soil here at depth is very permeable (running sands were encountered during drilling and soil profile excavation).

2) An intermediate zone around the farmyard and soiled water irrigator. Groundwater direction flow south west across this area. Land spreading north of this area may have an effect on nitrate fluctuations.

3) DF3A very small fluctuations, groundwater flow is away from this area and also dilution from the lake system occurs in this zone.



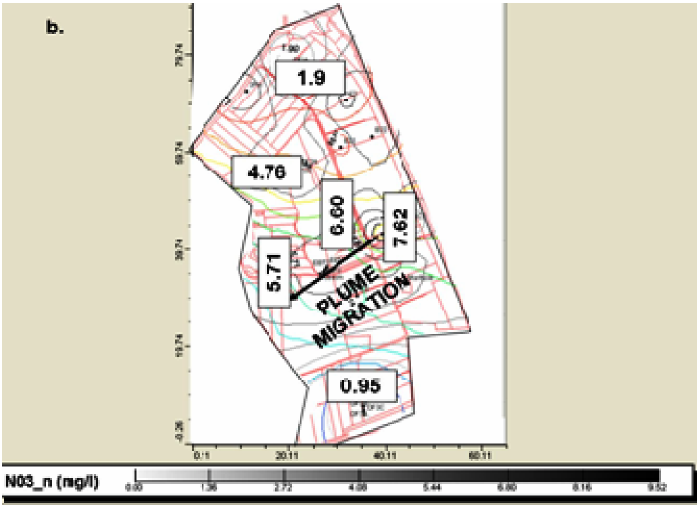


Figure 6: NO_3-N status for initial monitoring network (a) and final network (b

Despite topography, groundwater flow northwest of the farmyard flows in two different directions (irrigated area shown in Figure 5.). An area is identified where nutrient status from the irrigator source develops in the direction of groundwater flow. This helps to distinguish the nitrate plume. Surrounding wells not in direct groundwater flow (C4, 14C2) as shown in (Table 1.) have lower nitrate concentrations. Boreholes B2 (1) and B2 (2) receive groundwater up gradient from the irrigated area (Figure 5.) (Fenton & Hyde, 2006).

When all wells are used in the NO_3-N status contour map a plume is seen consistent with groundwater flow direction across the farmyard (Figure 6.). This can be combined with the nutrient fluctuation map to interpolate groundwater concentration ranges at a point in time.

The velocity vector map for a dirty water irrigation area is presented in Figure 7. Deflections in groundwater flow come predominantly from the artificial lake system to the west and surface water features. Surface and groundwater interactions due to the elevation of the artificial lakes have been altered. Instead of a groundwater sink the lakes recharge to groundwater. The lower lake is situated adjacent to the Castle (T02329 16328) and is connected to the middle lake by a small inflow stream. Two streams flow out of lower lake re-entering the Kildavin stream, at Piercetown, South of Johnstown Castle. It is the largest of the lakes (11.9 acres). A maximum depth of 3.8m was recorded. Algal mats and an algal bloom were noted on the surface of the lake (July 2006). Water samples from the lake confirm the algal mats extended down through the water column to the lake bottom and covered around 30% of the lakes surface. Many fish and the Common blue damselfly (*Enallagma cyathigerum*) were observed. Water samples were collected for nutrient analysis (TP, Orthophosphate, TN and dissolved nutrients) and for Chlorophyll analysis (lakes only). Phytoplankton samples were also collected at all three lakes. Temperature, Calcium, Potassium, Sodium, Chloride, Sulphate and Fluoride results were within the range expected for waters influenced by a calcareous geology.

A more natural sink occurs on the farm where the marl hole is situated (shaded area, Figure 2.). This has important implications for nutrient concentrations in the vicinity of the lake system.

Large differences in elevation exist between the boreholes DF (1), DF (2) and DF (3) (Table 2.). The base of DF2C (37.21 m AOD) is above the ground elevation at DF3A (33.3 m AOD). The boreholes DF2C and DF3C were drilled to below the bedrock at 34.7 m AOD and 21.3 m AOD, respectively (Bartley, 1996). Two scenarios exist with groundwater stratification. For boreholes DF2A ands DF2B the watertable level on 8th June, 2006 was at 52.79 m AOD whereas the borehole DF2C was at 52.35 m AOD. Total depths indicate downward movement of groundwater (Table 2.). Nutrient concentrations appear stratified in these multi level wells (Table 1). The reverse is true for the relationship between boreholes DF3A and DF3B (30.63 m AOD) and borehole DF3C (30.93 m AOD) (Table 2.).

Table 1: Nitrate (NO_3-N) concentration mg L^{-1} over the study period

Well	Aug 04	Sep	Oct	Nov	Dec	Jan05	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan06	Feb	Mar
DF1A	1.07		0.99	2.21	2.09	1.83	1.00		0.90		0.81	0.94	0.58	0.66		2.07	0.75	0.70		
DF2C	1.79		1.32	2.16	2.37	2.81	2.01		2.54		2.03	3.49	0.41	2.56		2.74	2.82	2.94		
DF2B								5.11	4.58		4.41	5.32	4.01	4.17		4.54	4.61	4.99		
DF2A								5.11	4.58		2.94	4.45	3.07	2.63		3.32	3.37	3.50		
EBT1			4.07	3.87	1.71	5.07	4.85		5.07		4.85	5.70	5.05	4.85		4.78	4.82	4.86		
EBT2			4.37	4.11	3.39	6.13	2.69		4.80		4.99	5.84	4.78	4.54		4.38	4.68	4.98		
EBT3			5.09	4.49	4.01	6.25	2.71		5.15		4.64	6.01	5.18	5.10		5.12	5.34	4.92		
DF3C	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL		<DL	<DL	<DL		
DF3B	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL		<DL	<DL	<DL		
DF3A	0.70	0.67	1.29	1.40	1.73	1.17		1.84	1.42	1.31	1.05	0.81	1.86	1.86		1.86	1.86	1.86		
3PH										10.71		6.38	7.76		8.12		9.60	10.49	9.61	11.77
C2										6.63		6.86	0.95		1.87		1.68	2.08	1.68	2.50
B2 (1)																	8.92	7.86	8.62	4.65
B2 (2)										5.36		6.03	4.18		1.11		9.23	7.58	10.09	10.57
14C (1)										12.14		9.52	8.73		8.03		15.76	17.38	15.32	19.68
14C (2)										1.04		1.58	2.64		2.36		1.26	2.11	7.42	4.31
C4										<DL		<DL	<DL		0.09			0.08	0.02	0.01
C5										5.93		6.53	6.54		7.22		8.11	7.92	6.05	11.55

Groundwater is shown to move upwards in this area from depth diluting the shallower unsaturated zone water (Table 1.). Consequently nutrient concentrations at borehole DF3B may be diluted by the lake system and upward seepage from the bedrock aquifer. The reverse can be seen for boreholes DF2 A-C where nutrient concentrations increase with depth

Table 2: Well and map parameters for 8th June 2006

Well	Elevation m AOD	Total Depth m bgl	Watertable height m AOD
3PH	63.2	4.68	58.3
DF1A	59.7	6.94	58.1
C2	62.8	8.23	56.9
DF2C	54.2	16.5	52.3
DF2B	54.2	12	52.7
DF2A	54.1	6.56	52.7
B2(1)	59.4	3.2	56.1
B2(2)	57.6	6.61	53
14C(1)	52.1	3.25	50.8
14C(2)	52.3	4.81	50.7
EBT1	47.2	5.46	44.2
EBT2	46.3	5.95	42
EBT3	45.9	5.95	42.5
C4	47.5	3.33	46.1
C5	45.9	8	41.2
DF3C	33.3	16.6	30.9
DF3B	33.3	11.93	30.6
DF3A	33.3	5.95	30.6
MarlHole	42.5	-	-
Stream	42.1	-	-
Irrigator	52.5		

Higher groundwater nutrient concentrations in this area may be explained due to a depression around borehole C5 where a continuous sand lens connects the area around the farmyard down gradient to the southwest. However borehole C4 receives lower concentrations along the dilution front of groundwater flow. In the northeast of the farm borehole 3PH has high groundwater nutrient concentrations whereas DF1A and C2 have lower concentrations due to the fact a point source is orientated to the northwest (Table 1.). The area surrounding DF1A has a soil thickness of greater than 20 m with low permeability zones at depths greater than 7 m. Zones 1 and 3 have fine loamy and coarse loamy over fine loamy textures and are moderately drained. Zone 2 has a sand texture (flowing sands in places) and is well drained. Each zone was allocated an effective porosity (Zone 1 (0.25), Zone 2 (0.35) and Zone 3 (0.20). Each zone was also allocated a hydraulic conductivity from slug test results (Zones 1 and 2 (10^{-3} cm s^{-1}) and Zone 3 (10^{-4}cm s^{-1}). Blue arrows of different lengths and direction show the general plume migration direction. However more detailed studies using a grid are needed to generate a clearer picture. This first estimate mirrors that of the groundwater map direction.

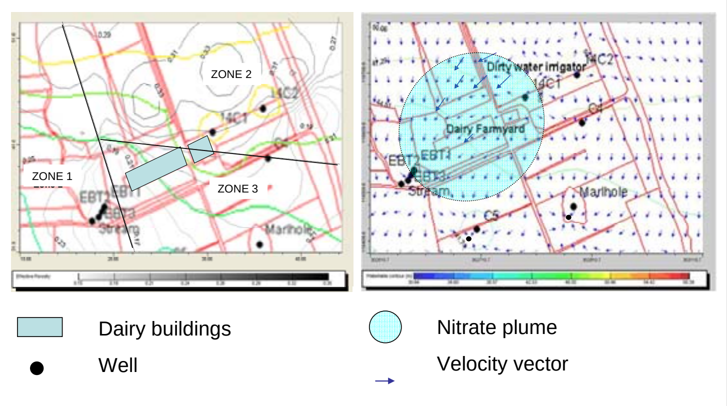


Figure 7. Effective porosity zones and plume migration across the dairy farmyard, blue arrows are of different lengths.

Some wells are seen to exert great influence over the model (C5) and in such cases flow direction (where no abstraction takes place) should be directed past the well.

Results for experimental site 2

Method 1

Well parameters and associated watertable and NO_3^-N fluctuations are presented in Table 3. Over the study period, the site received an annual precipitation of 1046 mm (44689.8 m^3) of which 553 mm (23613.1 m^3)

drained through the root zone in a process known as effective drainage. Effective drainage occurred on 178 days within the study period, giving an average recharge rate of 3.11 mm d^{-1}. From laboratory testing of undisturbed soil samples, the average soil porosity was 32.2%. Using this data, the average pore velocity was estimated to be 9.7 mm d^{-1}, giving an approximate mean travel depth of 1.7 m in a moderately drained soil over the study duration. If the average irrigation rate is added to the effective rainfall, mean depth of travel on the irrigated site was approximately 1.8 m. The average watertable bgl depth was 2.2 m within the six plots (Table 3.).

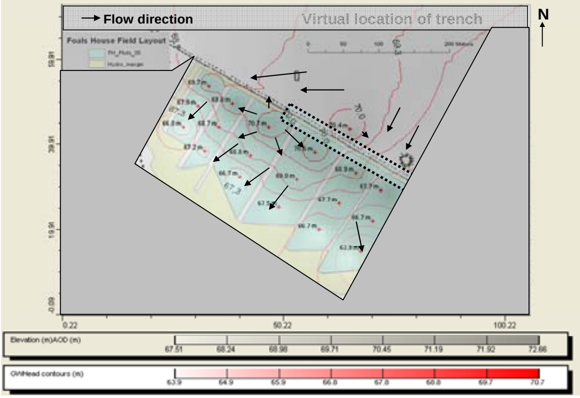


Figure 8. Groundwater map for 6 plots with general flow directions

NO_3-N concentrations were highest in August for Plots 1 and 2 and in July for Plots 3 and 4, respectively. The variation in NO_3-N concentration in the monitoring wells throughout the study period is illustrated in Figure 9. NO_3-N concentrations were below the maximum allowable concentration (MAC) of 11.3 mg NO_3-N L^{-1} during December and rose again in January and February. An elevated watertable at 4c (70.7 m AOD) created a boundary between Plots 3 and 5, forcing groundwater flow around this area (Figure 8). The K, watertable and NO_3-N fluctuations present Drain A as a suitable site for a proposed denitrification trench (Figure 8). Based on the study findings, a 175 m-length trench, extending from Plot 1 to the end of Plot 3, should be used. This would involve deepening Drain A to intercept the sand lens, backfilling with a C-rich media and then capping with topsoil and re-seeding. Allowing for seasonal watertable variations, the trench should at least be 3 m deep and extend into the elevated groundwater area of Plot 4; this would act as a boundary wall forcing groundwater into the trench. The parameters of the subsurface drainage in Foals House are presented in Table 4. The equation uses recharge, saturated hydraulic conductivity above (K_a) and below (K_b) the drainage system, the depth to impermeable zone (D), the drain level (in our case 1m) to calculate a desired watertable depth .

Table 3: Well elevations in (n AOD), total depth (m bgl), NO_3-N mg L^{-1} fluctuations, watertable fluctuations (m) and K_{sat}

Well	Elevation m AOD	Total Depth m bgl	Watertable fluctuation m	NO_3-N fluctuation mg L^{-1}	K m day^{-1}
1c	72.10	4.97	2.48	10.02	0.01
1b	70.20	4.51	2.56	19.98	0.01
1a	76.80	4.29	1.33	15.50	0.007
2c	72.00	4.65	2.15	9.19	0.015
2b	70.00	2.62	0.72	10.00	0.018
2a	67.60	3.53	0.95	10.85	0.001
3c	71.73	4.10	0.41	5.07	0.01
3b	70.07	3.28	0.76	14.95	0.01
3a	68.24	4.2	0.85	17.26	0.015
4c	71.82	3.35	0.29	9.25	0.01
4b	69.50	3.53	0.31	0.41	0.013
4a	67.75	3.11	0.24	0.58	0.012
5c	72.02	4.65	0.95	15.60	0.01
5b	69.40	3.46	0.45	15.60	0.01
5a	67.73	2.25	0.32	7.71	0.006
6c	71.14	3.48	0.85	4.63	0.012
6b	68.48	3.58	0.43	3.85	0.01
6a	67.43	3.44	0.55	3.82	0.002
FH7	72.68	4.40	1.20	9.62	0.002

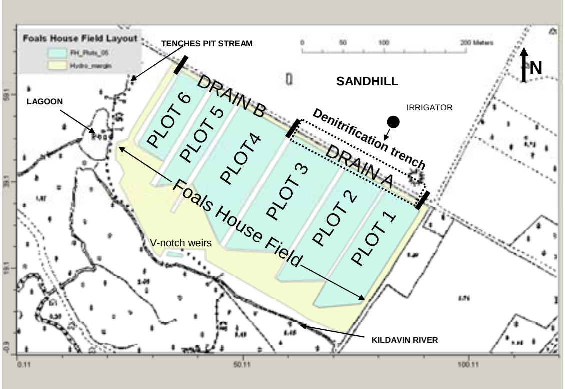


Figure 9: Denitrification trench location

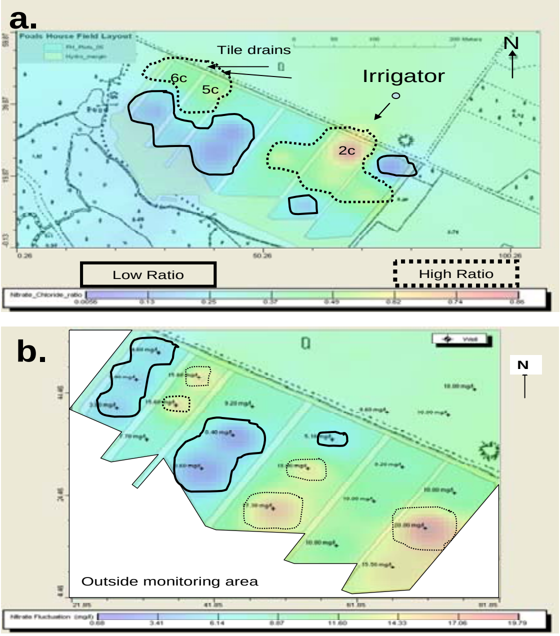


Figure 10. (a) nitrate/chloride ratio and (b) NO_3-N fluctuation

(Depth wt) and drain pipe inner radius (Drain radius). This calculates the drain spacing needed to maintain the watertable at the desired depth. This is usually below the rooting zone. Due to the fact the sub-surface system was already in the ground, known values were used to calculate unknowns.

Table 4: Model used to calculate the drain spacing (L)

Parameter	Input Value	Units	Calculated
Recharge	13	mm day^{-1}	
Ka	0.2	m day^{-1}	
Kb	0.01	m day^{-1}	
D	10	m	
Drainlevel	1	m	
Depth WT	0.9	m	
Drain (r)	0.0726	m	
h	0.1	m	
d	0.64	m	
(x)	12.57		
F(x)	0.64		
L			1m

By investigating the position of the watertable two scenarios have been identified:

Scenario 1:

The watertable is maintained above the subsurface drainage system to a specific level at all times to monitor groundwater.

This is the design specification of the subsurface system. The drain spacing of the system was used to calculate the optimal recharge rate needed to maintain the watertable above the drainage system. For a system with 0.0762 m (6 inch equivalent) inner diameter piping installed at 1m bgl and 1m drain spacing an optimal mean recharge rate of 13 mm day^{-1} was calculated. This would maintain the watertable at 0.9 m bgl. At this level groundwater would be monitored. The idea of designing the system for high recharge rates is obvious when we look at the mean annual recharge rate of 2.85 mm day^{-1}. At this rate the watertable would drop below the drainage system and the monitoring would now switch to infiltrating drainage water from the surface. However where the recharge rate is above this 13 mm day^{-1} specification the watertable rises again and the system monitors both groundwater and infiltrating drainage.

Scenario 2:

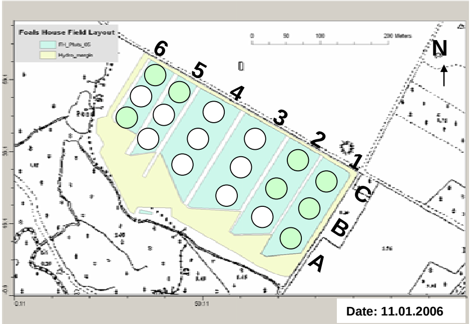
The watertable is maintained under the subsurface drainage system to monitor infiltrating water from the unsaturated zone.

With a mean annual recharge of 2.85 mm day^{-1} the drain spacing required would be 1.0m with drain radius of 0.0762 m (6inch equivalent). Therefore the drain spacing in place is more than adequate to maintain the watertable below the 1 m mark under average conditions. Therefore all water flowing through the subsurface drainage system should in fact be infiltrating water in the unsaturated zone. However, above this average the drain spacing required would fall below the present 1m. Therefore for months January, April, July, October, and November (2005) the mean monthly recharge is above the mean annual recharge level and the watertable will begin to rise. When this occurs the system is controlled by scenario 2. The sub surface drainage system now monitors the groundwater.

A constant watertable monitoring system would need to be put in place at all wells to allow the distinction between groundwater and infiltrating drainage water at the v-notch weirs. The flows on the weirs would need to be set at the interval time on the diver in each well. Then for each well at three locations in a plot a watertable height would be known and a flow rate. The volume of flow could then be assigned to groundwater or drainage.

Table 5: Well elevations in (n AOD) for selected dates in 2006

Well	11.01	18.01	24.01	31.01	7.02	14.02	22.02	28.02	7.03	14.03	21.03
1c	-3.38	-3.38	-3.38	-3.38	-3.38	-3.38	-3.38	-3.38	-3.38	-2.38	-3.38
1b	-1.62	-1.42	-1.47	-1.92	-1.72	-3.62	-3.62	-3.62	-2.77	-3.62	-2.62
1a	-2.45	-2.80	-2.65	-3.15	-2.95	-2.85	-2.70	-2.95	-2.95	-2.25	-2.75
2c	-2.43	-1.78	-2.03	-2.38	-2.68	-2.73	-2.93	-3.03	-3.18	-2.88	-2.23
2b	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00
2a	0.29	0.49	0.34	0.19	0.04	0.04	0.04	0.04	-0.01	-0.11	0.14
3c	0.46	0.51	0.26	0.01	-0.09	-0.04	-0.04	0.01	-0.09	0.46	-0.14
3b	0.21	0.11	0.01	-0.14	-0.24	-0.09	-0.09	-0.09	-0.09	-0.09	-0.09
3a	0.15	0.40	0.25	0	0	-0.05	-0.05	-0.05	-0.15	0.25	0.25
4c	0.06	0.06	-0.04	-0.19	-0.24	-0.24	-0.34	-0.24	-0.24	0.06	-0.14
4b	0.39	0.39	0.29	0.24	0.19	0.19	0.19	0.19	0.14	0.19	0.29
4a	0.11	0.11	0.06	0.06	0.06	0.06	-0.04	0.06	-0.19	0.06	-0.09
5c	-1.18	-0.88	-1.18	-1.38	-1.53	-1.48	-1.43	-1.43	-1.53	-0.93	-1.18
5b	0.23	0.53	0.38	0.28	0.23	0.23	0.23	0.23	0.23	0.23	0.33
5a	0.60	0.60	0.45	0.35	0.30	0.25	0.25	0.40	0.50	0.65	0.45
6c	-0.33	-0.13	-0.38	-0.63	-0.73	-0.63	-0.63	-0.63	-0.83	-0.23	-0.43
6b	0.6	0.75	0.65	0.45	0.50	0.40	0.40	0.55	0.55	0.70	0.40
6a	-0.20	0.19	0.14	-0.005	-.005	-0.055	-0.155	0.04	0.04	0.09	-0.40



🟢 **WT below SSDS = Infiltrating water**

○ **WT above SSDS = Groundwater**

Figure 6. Plots 1 to 6 with watertable heights (subsurface drainage system at 1 m bgl).

The complexity of the system can be seen from Table 5. where the watertable can be seen to be above or below the subsurface drainage system on the same date. This occurs throughout the site but also with plots. As there is only one outlet at 1m bgl for each plot, both infiltrating drainage water and groundwater can pass through the v-notch weir system as a mixed sample. By only looking at the scenario where groundwater is above the sub surface drainage system the plots exhibit some sort of pairing (from 20.10.2003 to 21.03.2006 on 63 water level dipping events). The total drainage due to groundwater on these dates was 8.38, 37.69, 173.3, 241, 109 and 104 m^3 for plots 1, 2, 3, 4, 5 and 6 respectively. These patterns mirror the average watertable heights taken over the same period when plots are taken in pairs: plots 1 and 2 having an average watertable height of 2.7 m bgl (below the subsurface drainage system), plots 3 and 4 have an average watertable height of 0.87 m bgl (above the drainage system) and plots 5 and 6 have an average watertable height of 1m (same height as drainage system). When area is taken into consideration plots 3, 4, 5, 6 are very similar with plots 1 and 2 significantly different. Therefore the assumption that differential drainage across the site in accordance with pairs holds true.

Plots 5 and 6 contribute more drainage from groundwater than plots 3 and 4 who in turn exhibit more than plots 1 and 2. The next step here is to differentiate the drainage from groundwater and that of infiltrating effective drainage water and then look at the percentage of the water balance attributed to runoff (incorporated in our 9.5 mm). To achieve this, the wells would need to be dipped on a continual basis with the use of electronic dippers.

CONCLUSIONS

A groundwater map may be used to interpolate nutrient concentrations at a study site. A monitoring network that is designed with a map as its primary objective, and which is used as a reference for site suitability, plot location and orientation can attempt to account for nutrient concentrations in different areas. A monitoring network of high density and coverage attempts to define nutrient transport to certain areas of the farm and decreases the bias related to interpretation. Therefore outside influences are monitored by a peripheral well network, which then extends internally to form a grid. A monitoring network design should precede experimental design and include surface water features and subsurface drainage system. The influence of this drainage system must be accounted for whilst constructing any watertable maps.

The type, extent and function of these drains must be taken into account. A clearer understanding of the groundwater flow pathways may lead to a better understanding of nutrient concentration at monitoring wells. Groundwater entering and leaving the farm and nutrient migration may be monitored. Areas where upward or downward seepage should also be identified and the connection between surface and groundwater defined. Longer term monitoring will produce watertable fluctuation, head differences and groundwater quality maps. The use of automatic loggers will enable accurate watertable fluctuation maps to be constructed seasonally/annually aiding experiments relating to groundwater response to certain agricultural practices. Now that the basic hydrogeology of the site is understood, more detailed studies could be carried out by dividing the farm into hydraulic conductivity zones.

The isolated plot study illustrated the preliminary steps to be taken in advance of the installation of a groundwater remediation system. The success of such a system depends on a thorough and long-term site investigation carried out prior to its installation. A preliminary site investigation may include:

1. the identification of the groundwater flow direction;
2. the measurement of the watertable depth and its seasonal fluctuation;

the identification of soil type, hydraulic conductivity, watertable and nutrient fluctuations, as well as watertable contour maps. A distinction between groundwater and unsaturated zone monitoring must be clearly defined when designing a subsurface drainage system taking annual fluctuations into account. Important to note is the monitoring needs of a subsurface drainage analysis. Two sources (groundwater and drainage water from the unsaturated zone) of subsurface water from one outlet must be distinguishable. This may only be achieved by monitoring the watertable at three locations (a, b and c) within each plot.

ACKNOWLEDGEMENTS

The author wishes Alan Cuddity (field data collection), Denis Brennan (Water analysis) and Eddie McDonald for ArcGIS work.

REFERENCES

Agriculture and Agri-Food Canada. 2002. *In-situ* remediation of nitrate in groundwater. Phase 1: Site Characterization

Bartley, P. 1996. Groundwater Investigation at Johnstown Castle. M.Sc. Thesis, Trinity College, Dublin

Bouwer, H., Rice, C. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating walls. Water Resources Research 12: 423-428.

CSO. 2006. Livestock survey. February, 2006. www.cso.ie

Culleton, N., Liebhardt, W.C., Murphy, W.E., Cullen, J., Cuddity, A. 2000. Thirty years of phosphorous fertilizer on Irish pastures: animal-soil-water relationships. Rmis 4231-A, Teagasc, Wexford. www.teagasc.ie

Culleton, E & Diamond, S. (in press). Soils of Johnstown Castle Estate, Soil Survey Bulletin. Teagasc, Johnstown Castle. www.teagasc.ie

DAF. 2003. Compendium of Irish agricultural statistics. Department of Agriculture and Food.

EEC. 1975. Council Directive (75/440/EEC) of 16th of June 1975 concerning the quality required of surface water intended for the abstraction of drinking water in the Member States. Official Journal of the European Communities, No. L194, pp 26-31; 25th July 1975.

EEC. 1980a. Council Directive (80/68/EEC) of 17th December 1979 on the protection of groundwater against pollution caused by certain dangerous substances. Official Journal of the European communities No. L20, pp 43-48; 26th January 1980. Brussels, Belgium.

EEC. 1986. Council Directive (86/278/EEC) of 12th June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. Official Journal of the European Communities. Brussels, Belgium.

EEC. 1991a Council Directive (91/271/EEC) of 12th December 1991 concerning the protection of waters caused by nitrates from agriculture sources. Official Journal of the European Communities L375/1. Brussels, Belgium.

EEC. 1991b. Council Directive (91/271/EEC) of 21st May 1991 concerning urban wastewater treatment. Official Journal of the European Communities L135/40. Brussels, Belgium.

EC. 2000. Water Framework Directive (2000/60/EC) establishing a framework for community action in the field of water policy. http://www.wfdireland.ie/

EC. 1998. Council Directive (98/83/EC) of 3^{rd} November 1988 on the quality of water intended for human consumption. Official Journal of the European Communities L220/32. Brussels, Belgium.

EPA. 2004a. Biological survey of river quality - results of the 2003 Investigations. EPA report, Johnstown Castle, Co Wexford, Ireland.

EPA. 2004b. Ireland’s environment. EPA, Johnstown Castle, Co. Wexford, Ireland. 315pp.

Fenton, O and Hyde, B.2006. Electronic watertable contour mapping and improved groundwater nitrate interpolation of the Dairy Farm in Teagasc, Johnstown Castle, Wexford. Journal of Environmental Hydrology. Vol 14, Paper 27.

Fingleton, W.A., Cushion, M. 1999. Irish agriculture in figures 1998. Teagasc, Agricultural and Food Development Authority.

Hvorslev, M.J. 1951. Time lag and soil permeability in groundwater observations. U.S. Army Corps of Engineers Waterway Experimental Station, Bulletin 36, Vicksburg, Mississippi, USA.

Lucey, J., Bowmann, J.J., Cunningham, P., Lehane, M., Mac Carthaigh, M., McCarrigle, M.L., Toner, P.F. 1999. Water quality in Ireland 1995-1997. EPA, Ireland.

McGarrigle, M.L., Bowman, J.J., Clabby, K.J., Lucey, J., Cunningham, P., MacCarthaigh, M., Keegan, M., Cantrell, B., Lehane, M., Clenaghan, C and Toner, P.F. 2002. Water Quality in Ireland 1998-2000. EPA, Wexford.

RBD. 2005. The characterisation and analysis of Ireland's river basin districts in accordance with Section 7 (2&3) of the European communities (Water Policy) regulations 2003 (SI 722 of 2003). National summary report (Ireland), May 2005. 117 pp.

Schulte, R.P.O., Diamond, J., Finkele, K., Holden, N.M., Brereton, A.J. 2005. Predicting the soil moisture conditions of Irish grasslands. Irish Journal of Agricultural and Food Research 44: 95-110.

Schulte. R.P.O., Richards, K., Daly, K., Kurz, I., McDonald, E.J., Holden, N.M, 2006. Agriculture, Meterology and Water Quality in Ireland: A Regional Evaluation of Pressures and Pathways of Nutrient loss to water. Biology and Environment: Proceedings of the Royal Irish Academy. 106B, 2, 117-133.

Toner, P., Bowman, J., Clabby, K., Lucey, J., McGarrigle, M., Concannon, C., Clenaghan, C., Cunningham, P., Delaney, J., O'Boyle, S., MacCarthaigh, M., Craig, M. and Quinn, R. 2005. Water quality in Ireland 2001-2003. Irish Environmental Protection Agency, Wexford, Ireland. 164 pp + appendices.

Toner, P., Bowman, J., Clabby, K., Lucey, J., McGarrigle, M., Concannon, C., Clenaghan, C., Cunningham, P., Delaney, J., O'Boyle, S., MacGarthaigh, M., Craig, M., Quinn, R. 2005. Water quality in Ireland. Environmental Protection Agency, Co. Wexford, Ireland.

Tunney, H., Coulter, B., Daly, K., Kurz, I., Coxon, C., Jeffery, D., Mills, P., Kiely, G and Morgan, G. 2000 Quantification of phosphorus loss to water due to soil P desorption. Final report. Environmental Monitoring R&D Report Series No.6. Wexford. EPA.