Environmental RTDI Programme 2000–2006

Eutrophication from Agricultural Sources: Field- and Catchment-Scale Risk Assessment

(2001-LS-2.2.1-M1)

Synthesis Report

Main report available for download on http://www.epa.ie/download/pubs/research/water/

Prepared for the Environmental Protection Agency

by

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WATER QUALITY

The Water Quality Section of the Environmental RTDI Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in the area. The reports in this series are intended as contributions to the necessary debate on water quality and the environment.

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Preface: Overview of LS-2 Projects – Eutrophication from Agricultural Sources

This report summarises the aims, methods, results, conclusions and recommendations of the sub-project LS-2.2.1: Field- and Catchment-scale Risk Assessment. This sub-project was one of two that formed the LS-2.2 project: Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water, which aimed at developing three modelling approaches that explored the sources of phosphorus and the hydrology that transports it from land to water. The LS-2.2 project is part of the large-scale research project LS-2 – Eutrophication from Agricultural sources (Figure P.1).

The objective of this large-scale integrated research project, commissioned in 2000, was to supply scientific data to underpin appropriate actions or measures that might be used in the implementation of national policy for reducing nutrient losses to waters from agricultural sources. The research, including desk, laboratory, field plot, farm and catchment studies, was conducted by teams in Teagasc, the National Universities of Dublin, Cork and Galway; Trinity College Dublin; University of Limerick and the University of Ulster at Coleraine.

The LS-2.1 project – Three Catchments Study aimed at measuring the absolute and relative losses of phosphorus from soil, grazed pastures, slurry and fertiliser spreading and farmyards.

The LS-2.3 project – Effects of Agricultural Practices on Nitrate Leaching aimed at measuring nitrate leaching from an intensively managed dairy farm on a soil type typical of a Nitrate Vulnerable Zone.

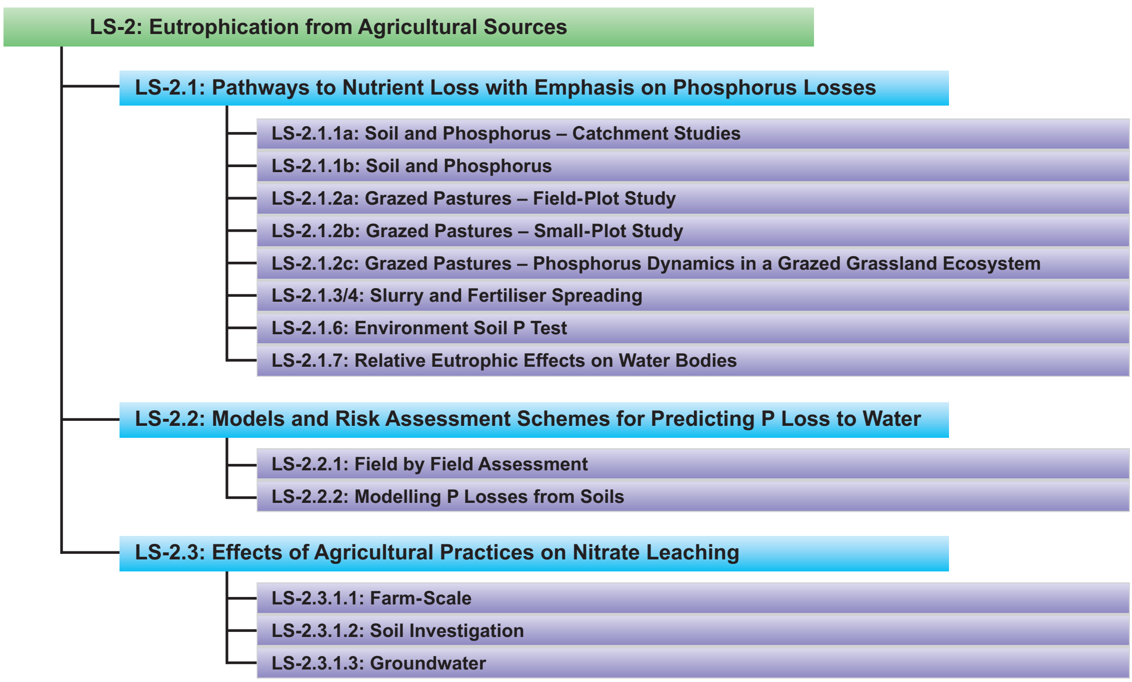

Figure P.1: Overview of LS-2 projects

Integrated synthesis for LS-2, LS-2.1, LS-2.2 and LS-2.3 projects and the individual reports from each of the sub-projects are available for download on the EPA website on http://www.epa.ie/downloads/pubs/research/water.

Executive Summary

Ambient monitoring of Ireland's water resources has identified an increase in the numbers of rivers and lakes considered to be slightly or moderately polluted. The contamination of surface waters by diffuse pollution is particularly insidious. In its recent assessment of environmental quality, the Environmental Protection Agency (EPA) determined that phosphorus (P) from agricultural sources accounts for over 70% of the total anthropogenic load to freshwaters in Ireland (EPA, 2004). As over-fertilisation of grassland is common in the Republic (EPA, 2004), this and other evidence suggests that a large proportion of the P loss to waters arising from agriculture is contributed by diffuse sources.

The European Union's Water Framework Directive (WFD) (2000/60/EC) mandates a comprehensive approach to water management. Yet, diffuse nutrient pollution from the landscape is particularly difficult to identify, and even more difficult to control (Magette, 1998). Irvine et al. (2005a) observed that risk assessment was a fundamental element of the WFD. Hand-in-hand with risk assessment is identification of those situations likely to produce environmental hazards. It is broadly accepted that strategies to address diffuse pollution will be most effective when they are targeted towards sensitive source areas of nutrients in the landscape (Sharpley et al., 1993). It follows that a procedure is needed with which to identify these sensitive areas within catchments. Magette (1998) sought to develop such a procedure, specifically for grassland areas in Ireland, which make up approximately 90% of the utilisable agricultural area in the country.

This research was commissioned to further test, and modify as appropriate, the risk-ranking procedure proposed by Magette (1998). The primary focus of the research was to be on field-scale assessments of factors that, in combination, would suggest that an area posed a particular risk of losing nutrients (especially P) that would subsequently be transported to receiving waters. The project was further intended to complement other large-scale research being conducted under a comprehensive research programme funded by the EPA and co-ordinated by Teagasc as detailed in Eutrophication from Agricultural Sources: Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water (2000-LS-2.2.2-M2) Final Report (Daly, 2006).

Magette's (1998) original ranking procedure formed the starting point for this research. The overall study plan was to first critically analyse and test the procedure more intensively than previously had been possible, and then to modify the procedure to address any deficiencies identified during the critical analysis and testing phase. In practice, testing and modification were iterative processes. Because this project was not funded to collect data, the research was dependent on the supply of appropriate data from other sources. Most of the effort was placed on developing a procedure for assessing the potential risk (meaning the relative likelihood) of losing P from areas within a landscape, and the subsequent likelihood of that P being transported to adjacent water bodies. Ideally, these sources would have been field-sized areas, but due to the limited number of data sets available at this scale in Ireland (and indeed Northern Ireland and Britain), research was also conducted at the small-catchment scale, for which considerably more data were available. The use of catchment-scale data also facilitated the examination of factors affecting the transport of nutrients from sources to the adjacent water bodies.

The output from this research is complementary to that from other nutrient-loss modelling projects funded by the EPA through the ERTDI Programme 2000–2006, each of which sought to develop a methodology that could be used to assess the potential losses of P from the landscape to water (Daly, 2006; Nasr and Bruen, 2006). On the continuum from simple to complex assessment methods, the research reported herein represents a relatively simple procedure that can be readily used by catchment managers responsible for water-quality protection and, indeed, by agricultural advisors responsible for promoting best agricultural practice with regard to nutrient management. Several distinct procedures have been developed:

- a screening tool by which catchments can be examined and areas highlighted for their propensities to transport P to water;
- a modified P ranking scheme (mPRS) and a modified nitrogen ranking scheme (mNRS) to assess the comparative potential for P and N, respectively, to be lost from landscape areas and subsequently transported to receiving waters;
- a procedure by which to qualitatively assess Irish farmyards for their potential to contribute nutrients to water resources.

More detail about this research can be found in the full final report (available on http://www.epa.ie/downloads/pubs/research/land).

1 Background and Introduction to the Project

1.1 Introduction

The latest Environmental Protection Agency (EPA) water-quality assessment (Toner et al., 2005) for Irish rivers and streams shows that 69% of river/stream length is categorised as 'unpolluted', 18% of streams are categorised as 'slightly polluted' and 12% of river channel is classified as 'moderately polluted', with a further 0.6% categorised as 'seriously polluted'. These water-quality problems extend to Irish lakes, approximately 18% of which were classified as eutrophic or hypertrophic and exhibited varying signs of pollution together with the potential impairment of their beneficial uses in the 2001–2003 period (Toner et al., 2005).

Eutrophication is the most important type of pollution associated with Irish rivers and lakes (Toner et al., 2005), and phosphorus (P) has been identified as the main limiting nutrient involved in the eutrophication process in surface waters (McGarrigle, 2001). Nitrogen (N) is an important contributory nutrient in eutrophication and also has implications for human health when present in high concentrations in surface or ground waters used as sources of supply.

McGarrigle and Champ (1999) stated that there is an urgent need for effective catchment management strategies that can reduce the P load to rivers, an observation that is especially relevant in the context of the EU's WFD 2000/60/EC (Council of the European Communities, 2000), which mandates a comprehensive approach to water management and designates large catchment areas (e.g. major river basins) as the fundamental unit of management.

The emergence of diffuse sources as the primary origin of nutrients causing eutrophication poses many difficulties to catchment managers, relevant authorities and farmers due to the disparate nature of the nutrient sources and the many factors responsible for both the loss and transport of nutrients from land to water (Table 1).

Table 1 Factors influencing nutrient losses from agriculture and the landscape (Magette, 1998)

Uncontrollable factors affecting losses of pollutants from agricultural systems
Weather
Type and history of geologic materials
Topography
Depth to ground water
Soil type
Somewhat controllable factors
Soil physical characteristics (e.g. drainage, soil loosening, cultivation)
Very controllable factors
Soil chemical characteristics (pH, nutrient levels, etc.)
Vegetation
Timing and method of agricultural operations
Pollutant characteristics (chemical formulations, etc.)

Fortunately, studies elsewhere have shown that most (as much as 90%) of the P exported from catchments on an annual basis occurs from discrete areas within catchments (as little as 5% of the total area) and during one or two storm events (Sharpley and Rekolainen, 1997; Pionke et al., 1997). Beegle (1999) identified the most important P source areas within a catchment to be those where 'P sources' and 'P transport mechanisms' overlapped, and termed these intersections 'critical source areas' (CSA). The identification of such areas, which are those most vulnerable to P loss, is fundamental to effectively managing losses of this element to water (Gburek et al., 2000).

Tools for identifying critical source areas within catchments vary from highly sophisticated deterministic models requiring a large amount of input data to relatively simple models in which most of the nutrient loss and transport processes are relegated to a 'black box'. Irvine et al. (2005b) reviewed a large number of models of varying complexity for their suitability as decision support tools for the WFD, and concluded that no single integrated model existed that could be applied universally throughout a catchment to meet all the requirements of the WFD.

The P Index system first published by Lemunyon and Gilbert (1993), and indices similar to it, are toward the less complex end of the modelling continuum, and are ideally suited for use by catchment managers, agricultural advisors and farmers themselves. The premise underpinning these indices is that they can effectively determine the relative risk posed by agricultural areas to water quality, whilst being relatively easy to use and requiring only data sets which, in the main, are readily available. Generally, such indices do not attempt to make quantitative estimates of nutrient loss and transport. (Note that 'risk' in the context of this report means the propensity or relative likelihood of an area on the landscape to contribute nutrients to water.)

Irvine et al. (2005a) observed that risk assessment was a fundamental element of the EU's WFD. Djodjic et al. (2002) determined that the P Index represented 'an opportunity to identify sensitive areas within a catchment'. The P Index approach is now widely used in the USA (Sharpley et al., 2003) and has been applied to a limited extent in Europe (Magette, 1998; Bechmann et al., 2005), Canada and Australia (Melland et al., 2004). The original P Index (Lemunyon and Gilbert, 1993) was, however, developed with a caveat that it would require additional research as well as modification to account for regional variations in agricultural management practices, climate, topography, hydrology and surface-water characteristics.

1.2 Study Objectives

This project was commissioned by the EPA as part of a large-scale research programme devised to study the eutrophication of water by agricultural sources. Within this programme, this project was part of an integrated package of three research projects (ERTDI/EPA 2000-LS-2.2-M2) 'Eutrophication from Agricultural Sources – Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water'. Collectively, these projects examined three different techniques of varying complexities for assessing the loss of P from agricultural systems and its transport to water. The techniques, described by Daly (2006), were stochastic modelling, deterministic modelling and multi-criteria analysis, of which the latter was examined in the research reported herein.

The objectives of the project reported herein were to provide:

- A validated risk assessment scheme that uses a limited number of criteria to evaluate the potential losses of P and N from field-sized areas to water resources.
- A validated risk assessment scheme that uses a limited number of criteria to evaluate the potential losses of P and N from farmyards.
- A 'scanning tool' by which catchment-scale data could be used to identify catchments most likely to lose P to water.

1.3 Project Structure

Research was undertaken in distinct work packages that more or less corresponded to the three objectives. Due to the focus of the integrated project on P, most of the effort in the project reported herein was expended on developing and testing P ranking schemes (Work Packages 1, 2 and 4 below).

Work Package 1: Initial assessment of the Magette (1998) PRS at both field scale and catchment scale and the introduction of some modifications.

Work Package 2: Development of a modified PRS (mPRS) at field scale including factors for farmyard impact and detailed testing of the mPRS both at field scale and at subcatchment scale using field-scale data.

Work Package 3: Development of a modified NRS (mNRS) at field scale and testing of the mNRS at field scale using field-scale data.

Work Package 4: Assessment of catchment-scale factors and development of a 'scanning tool' for use to quickly identify catchments exhibiting a high potential to lose P to water.

Work Package 5: Assessment of farmyards as nutrient sources to water.

2 Methodology of the Project

As this project was not funded to undertake field experimentation and data collection, considerable effort was expended in searching for, and then assessing, available data that could be used to meet the project objectives. Due to the focus of the project on developing P and N loss and transport tools for Ireland, it was considered that only data sets originating in Ireland or the United Kingdom would be applicable. Limited data sets were found that were usable at the field scale; considerably more usable data sets at small-catchment scale were obtained from previously conducted catchment-monitoring and management strategy studies (Kirk McClure Morton, 2001; MCOS, 2002).

Most of the effort expended in this project was devoted to the development and testing of P ranking tools (Work Packages 1, 2 and 4 above) to discriminate between areas within catchments, based on their propensity to lose P that would be subsequently transported to receiving waters. The starting points for much of this research (Work Packages 1, 2, and 3) were the P and N ranking schemes developed by Magette (1998) (Tables 2–5).

2.1 Description of Data Sets Used in the Project

Three field-scale data sets were kindly contributed for use in this project by Irish researchers (Dr Isabelle Kurz, formerly of Teagasc Johnstown Castle Research Centre, Wexford, Ireland; Dr Catherine Watson, Agriculture, Food and Environmental Science Division of the Agri-Food and Biosciences Institute, Belfast, Northern Ireland; and Dr Pamela Bartley, Bartley and O'Suilleabhain Environmental Engineering, Galway, Ireland). The data sets are described more fully later, but consisted of the following.

Table 2 Phosphorus ranking scheme (PRS) for Ireland[1] (Magette, 1998)

		Phosphorus loss and/or transport risk (value)		
Catchment or field factor	**Weight for factor**	**Low (1)**	**Medium (2)**	**High (4)**
P usage in catchment	0.5	0–5 kg P ha^{-1}	5–10 kg P ha^{-1}	>10 kg P ha^{-1}
Condition of receiving waters	0.5	Saline waters, non-impounded waters, free-flowing rivers and streams without nutrient problems	Oligotrophic and Mesotrophic lakes	Eutrophic and Hypertrophic lakes, other special designation waters
Ratio of land to water	0.75	Ratio < 36:1	36:1 < Ratio < 44:1	Ratio > 44:1
Farmyard conditions	0.8 (0 if no animals)	See supplement (Table 4) below.		
P usage rate on site	1.0	0–5 kg P ha^{-1}	5–10 kg P ha^{-1}	>10 kg P ha^{-1}
P application time	0.9	Spring or just prior to crop needs	Late summer or early autumn	All other times
Soil-test P (based on Morgan's test)	0.8	0–6 mg P l^{-1}	6.1–15 mg P l^{-1}	>15 mg P l^{-1}
Overland flow distance	0.75	Further than catchment average	Catchment average	Less than catchment average
Run-off risk	1.0	Soil groups[2] 6a, 6b, 6c; 7a, 7b; 8, but excluding peats	Soil groups 4; 5, but excluding peats	Soil groups 1; 2; 3a, 3b, 3c, but excluding peats

[1] Final score equals the sum of all (factor risk × factor weight) products.
[2] As defined by the National Soil Survey of Ireland (Gardiner and Radford, 1980).

- Data for the Cowlands and Warren fields at Johnstown Castle, Co. Wexford (Kurz, 2000) and data from the Beef Unit and the Dairy Farm located at Johnstown Castle, Co. Wexford (Kurz, 2002).
- Data for five experimental plots at the Agri-Food and Biosciences Institute at Hillsborough, Northern Ireland (Watson et al., 2000; 2007).
- Data on N use and borehole-water quality in Co. Cork (Bartley, 2003).

In addition, catchment-scale data were used from a number of published sources. These data sets consisted of the following:

- Information on the Clarianna, Bellsgrove and Grange Rahara catchments, which are located in the River Shannon system, was collected and provided by the Derg/Ree Catchment Monitoring and Management System Project (Kirk McClure Morton, 2001).
- The Three Rivers Project (TRP) (MCOS, 2002) provided information on the Clonshanbo catchment of the River Liffy, the Yellow River and the Annesbrook catchments, and subcatchments of the Boyne River system, as well as the Clonmore, Dawn (Ballyshannock) and Ara catchments in the Suir River system.
- Data on the Dripsey 'D1' and 'D2' catchments in the south-east of Ireland (Co. Cork) were reported by Morgan et al. (2000).

Table 3 Supplemental scoring system for farmyards[1] (Magette, 1998)

Factor	Excellent (3 points each)	Good (2 points each)	Poor (1 point each)
Manure/slurry storage*	> 24 weeks	20–24 weeks	<20 weeks
Dirty water storage	≥12 weeks	More than 2, but fewer than 12, weeks	<2 weeks
Silage effluent storage	greater than 3 days	3 days	<3 days
Dirty areas**	100% covered	50% covered	<50% covered
Managerial level***	Top 5% of producers	5%<x<50%	<50%
Fatal flaw****	No		Yes

* Applicable to operations with animals only; allocate 3 points if no animals present; storage periods may require regional adjustment to take account of the shorter winter in southern compared to northern areas.

** Implies that roofed areas are fitted with gutters that divert all clean water.

*** Characteristics of exceptional managers would be attention to detail in terms of environmental as well as production issues, e.g. active use of nutrient-management planning and well-maintained equipment and facilities (e.g. non-leaking waterers), etc.

**** A 'fatal flaw' is a situation that poses an imminent pollution threat (such as a cracked slurry store, a stream running through a farmyard, or a 'clean' water drain very near a pollutant source) and is cause to assign the farmyard an overall high pollution potential, regardless of other factors.

1 Scoring – add points: 13 or more = low ranking; 8–12 = medium ranking; less than 8 = high risk.

Table 4 PRS site scores and qualitative risk assignment (Magette, 1998)

Site score	Qualitative risk
< 10.8	Low
10.8–21.6	Medium
> 21.6	High

Table 5 Nitrogen ranking scheme for Ireland (Magette, 1998)

		Phosphorus loss and/or transport risk (value)		
Catchment or field factor	**Weight for factor**	**Low (1)**	**Medium (2)**	**High (4)**
N usage in catchment	0.5	Average N use @ REPS* level	Average N use @ REPS × 1.25	Average N use > REPS × 1.25
Condition of receiving waters	For ground water: 0.5	NO_3-N < 6.0 mg l^{-1}	6.0 < NO3-N > 11.0 mg l^{-1}	NO_3-N > 11.0 mg l^{-1}
	For surface water: 0.5	Non-sensitive waters	Free-flowing waters sensitive to N	Impounded waters sensitive to N
Ratio of land to water	0.75	Ratio < 36:1	36:1 < Ratio < 44:1	Ratio > 44:1
Farmyard conditions	0.8 (or 0 if animals not utilised)	See Table 3	See Table 3	See Table 3
N usage rate	1.0	Average N use @ REPS level	Average N use @ REPS × 1.25	Average N use > REPS × 1.25
N application time	1.0	Just prior to crop needs	Early spring	All other times
Subsurface drainage	For assessing ground water: 0.9	Well-designed and operating drains	Drains in need of improvement	No drainage or drains failing
	For assessing surface water: 0.9	No drainage or drains failing	Drains in need of improvement	Well designed and operating drains
Vulnerability of ground water	1.0	Low rating by GS**	Moderate rating by GS	High or extreme rating by GS
Native riparian vegetation	For areas without subsurface drainage: 0.5	Natural stream-side vegetation intercepts most ground water discharge	Natural stream-side vegetation intercepts 50% of ground water discharge	No natural stream-side vegetation or discharge bypasses
	For areas with subsurface drainage: 0.0	Subsurface drains present	Subsurface drains present	Subsurface drains present

* REPS = Rural Environment Protection Scheme.
** GS = Geological Survey of Ireland.

2.2 Work Package 1: Initial Assessment of the PRS at Field- and Catchment-Scales with the Introduction of some Modifications

Testing of the PRS developed for Ireland by Magette (1998) was carried out at the field scale for three fields at Johnstown Castle, Wexford, Ireland (described by Kurz, 2000). Factors of the PRS pertinent only to edge-of-field P losses were evaluated against measured edge-of-field P exports using linear regression analysis. To compare edge-of-field related factors of the PRS with measured edge-of-field P losses, two truncated versions of the PRS (termed the ‘field-factor-only PRS’, or FFO PRS, and the ‘Field PRS’, respectively) were developed and evaluated.

A detailed assessment of the PRS to determine its effectiveness in identifying the risk of P loss to surface water was carried out at the catchment scale by using the available catchment-scale data to assign values to the factors used in the PRS. Following this initial assessment, a number of modifications were introduced to the Magette PRS in an attempt to improve its functionality and usability at the catchment scale. The result was termed ‘Catchment PRS’. Linear regression analysis was used to evaluate the PRS against median in-stream molybdate reactive phosphorus (MRP). In addition, Spearman's rank correlation was used to measure the association between the total Catchment PRS value and the median in-stream MRP (SAS, 1985).

2.3 Work Package 2: Development and Testing of a Modified PRS at Field Scale

Following an exhaustive review of the scientific literature to assess international best practice in regard to P indices, a radically altered and more compartmentalised index was developed and called 'modified PRS' (mPRS) (Tables 6–8). Compared to the original PRS (Magette, 1998), the main features of mPRS were:

- Restructuring into source and transport factors.
- Adoption of a multiplicative approach for site scoring.
- Inclusion of 'distance from stream'.
- Use of open-ended categorisation.
- Development of optimised factor weightings.

The mPRS was assessed at the field and catchments scales by linear regression analysis between mPRS scores and measured edge-of-field and in-stream water quality (generally MRP concentration), respectively. An optimisation analysis was also undertaken using the Ara data set to determine the most effective weightings for factors in mPRS. Then, to critically examine the validity of the mPRS complete with optimised weightings, mPRS scores arising from using the optimised weightings were tested on the Clonmore catchment data. Linear regression analysis was utilised to evaluate the correlation between mPRS site scores and in-stream annual average MRP concentrations.

2.4 Work Package 3: Development and Testing of a Nitrogen Ranking Scheme

A modified nitrogen ranking scheme (mNRS) was developed (Tables 9 and 10). As with the mPRS, 'source factors' and 'transport factors' are calculated separately and then combined by multiplication to generate a site score.

The mNRS was assessed using groundwater-quality data from nine boreholes at Teagasc's Moorepark Research and Development Centre (Curtin's Farm) in Fermoy, Co. Cork. These data were kindly supplied by Dr Pamela Bartley and were generated in her work leading to a PhD entitled 'Nitrate Responses in Ground water under Grassland Dairy Agriculture' (Bartley, 2003), under sponsorship by the EPA through the ERTDI research programme 2000–2006. Field-scale data were available for 19 fields at the farm, as were detailed data on nutrient applications to each field and on the agricultural activity undertaken on each field. An mNRS score was generated for each field within the farm, and these scores were compared to measured borehole-water quality by regression analysis.

Table 6 Modified PRS

Factor	Description	Weighting	Low risk (1)*	Medium risk (2)*	High risk (4)*
S1	P usage rate	1	Teagasc P Index 1 or 2, or 0–5 kg P ha^{-1} added	Teagasc P Index 3, or 5–10 kg P ha^{-1} added	Teagasc P Index 4, or > 10 kg P ha^{-1} added
	P application timing	0.9	See Table 7	See Table 7	See Table 7
S2	Soil P (by Morgan's test)	0.8	0–6 mg P l^{-1}	6.1–10 mg P l^{-1}	> 10 mg P l^{-1}
	Desorption risk	1	Low	Moderate	High
S3	Farmyard risk	0.8	Good	Moderate	Poor
T1	Transport distance	0.75	> 500m	200–500m	0–200m
T2	Connectivity, see also Table 8	0.75	Low risk due to subsurface drainage or surface drainage	Moderate risk due to subsurface drainage or surface drainage	High risk due to subsurface drainage or surface drainage

Calculations
S1 (Risk of P loss from P applications) = P applications x P application timing
S2 (Risk of P loss due to soil P concentration) = soil-test P x desorption risk
mPRS source subscore = S1 + S2 + S3, where S3 is farmyard risk
mPRS transport subscore = T1 × T2
Site score = source subscore × transport
* Numerical value corresponding to qualitative risk level

Table 7 Assessment of risk (i.e. value) for P application factor in mPRS

P application timing	P application timing factor value		
	Hydrologically low-risk soils	Hydrologically moderate-risk soils	Hydrologically high-risk soils
Between May 1 and Sept 1	1	1	2
Between 15 Jan and 1 May	1	2	4
Application at other times	1	4	4

Due to uncertainty about which field or fields might be affecting a specific borehole, two scenarios, consisting of alternate combinations of field-scale data, were used to generate mNRS scores for each borehole. Scenario A assumed that a borehole was impacted by the field in which it was located. Scenario B combined the mNRS scores (by averaging) from the fields which were up-gradient from a borehole, in terms of ground water flow direction.

Table 8 Assignment of mPRS T2 factor values relative to field drainage

Drainage system	Low risk (1)*	Medium risk (2)*	High risk (4)*
Subsurface drainage	No subsurface drainage	Subsurface drainage, but no direct link to river channel	Subsurface drainage with a direct link to river channel
Field drains	No field drains	Field drains but no direct link to river channel	Field drains present with a direct link to river channel

* Numerical value corresponding to qualitative risk level

Table 9 The mNRS for assessing the potential for nitrate losses to ground water

	Nitrogen loss and/or transport risk (value)		
Factor description	High (4)*	Moderate (2)*	Low (1)*
Nutrient application (A)			
Application rate (NA)	> 1.25 times crop requirements	≤ 1.25 times crop requirements	< crop requirements
Application timing (NT)	Outside growing season	During growing season	Just prior to growing season
Dirty water applications (DW)	Made outside of growing season	Made during growing season only	Reduced applications during growing season but reduced due to farmyard management
Cropping system (C)	Arable, or grassland grazed all year	Grassland grazed during growing season only	Grassland, no grazing
Farmyard risk (FR)	Poor farmyard management	Good farmyard management	Excellent farmyard management
Aquifer vulnerability (where classification is available) (AV)	High or extreme	Moderate	Low
Transport pathways (T)			
Subsoil type (SS)	Sand/Gravel	Sandy clay	Clayey/Silty
Hydrological risk (runoff risk) (HR)	Low	Moderate	High
Preferential flow paths (including subsurface drains)	Present and functioning	Present, but not functioning well	Not present

Calculations
$A = (NA \times NT) + DW$
(1) If AV is available, mNRS site score = $(A + C + FY) \times AV$
(2) If AV is not available, mNRS site score = $(A + C + FY) \times T$, where $T = SS \times PP$; or, if SS is unavailable, $T = HR \times PP$
* Numerical value corresponding to qualitative risk level

Table 10 The mNRS for assessing potential for nitrate losses to surface water

	Nitrogen loss and/or transport risk (value)		
Factor description	**High (4)***	**Moderate (2)***	**Low (1)***
Nutrient application (A)			
Application rate (NA)	> 1.25 times crop requirements	≤ 1.25 times crop requirements	< crop requirements
Application timing (NT)	Outside growing season	During growing season	Just prior to growing season
Dirty water applications (DW)	Made outside of growing season	Made during growing season only	Reduced applications during growing season, but reduced due to farmyard management
Farmyard risk (FR)	Poor farmyard management Good farmyard management	Excellent farmyard management	
Transport pathways (P)			
Hydrological risk (run-off risk) (HR)	High	Moderate	Low
Preferential flow paths (including subsurface drains)	Not present	Present, but not functioning well	Present and functioning

Calculations
A = (NA × NT) + DW
mNRS site score = (A + FY) × T, where T = HR × PP
* Numerical value corresponding to qualitative risk level

2.5 Work Package 4: Development and Testing of a Catchment-Scale Screening Tool

This part of the research was conducted using data from two catchments in western Ireland, the Lough Conn catchment and the Lough Mask catchment. A number of catchment-scale (or larger) data sets were used to examine relationships between selected catchment characteristics and water quality for the Lough Conn and Lough Mask catchments using linear regression analysis. The data sets used were: land-use data derived from the CORINE (Co-ordination of Information on the Environment) data set, in which the 44 land-cover types were divided into four risk categories that reflected the presumed likelihood that P would be lost and transported from these areas, a presumption that was based on the intensity of the land use; soil-test phosphorus (STP), as provided by Teagasc; P desorption potential, generated by combining the soil characterisations in the General Soil Map of Ireland (Gardiner and Radford, 1980) with soil P desorption categories devised by Daly (2000); soil drainage, described by Gardiner and Radford (1980).

To investigate the importance of critical source areas (CSA) in the transfer of P from diffuse agricultural sources, an analysis was undertaken in which, instead of using entire catchment areas to determine the various factors, only those areas within 100m, 200m and 500m of the main stream channel were used. These factors were then regressed against measured water quality for each catchment.

Water-quality data (total P (TP) concentration) resulting from weekly grab sampling (supplemented by limited automatic sampling) were available for five- and four-year periods from records for the Lough Conn and Lough Mask catchments, respectively. In addition to annual mean TP concentrations, seasonal mean TP concentrations were calculated for each of three periods within the year:

- May 1 – August 30 (summer).
- September 1 – January 31 (winter).
- February 1 – April 30 (spring).

2.6 Work Package 5: Development of a Farmyard Assessment Procedure

As this project was not funded to collect/generate new data, the scientific literature served as a fundamental resource to guide development of the rating procedure. In addition, an ad hoc expert panel was established to serve as a technical resource. The panel consisted of four research scientists from Teagasc, one from the Environmental Protection Agency, one from University College Dublin and a research/advisory scientist from ADAS in the UK. For this portion of the research, a fundamental assumption was that the 'risk' (i.e. the likelihood) of P and N transport from farmyards to water is directly proportional to the mass of pollutants at the source that are available for transport, and inversely proportional to the distance between a farmyard and the water resource.

3 Results

3.1 Initial PRS Evaluation

Results from the application of the PRS developed by Magette (1998) to the Johnstown Castle field (Kurz, 2000) are given in Table 11.

The PRS numeric score rank corresponded directly to the rank according to measured edge-of-field P loss over the period of monitoring. However, the final PRS categorisation of 'medium' P loss risk for all sites indicated that the PRS did not distinguish between sites, despite the difference in edge-of-field P export rates and STP values. This may have been due to the mathematical procedure used to translate numerical scores into qualitative risk descriptions, or to a more serious deficiency in the PRS itself. For example, comparing the Warren 1 to the Warren 2 results, the PRS scores differed in magnitude by 29% whereas the normalised edge-of-field P losses differed by 22%. However, comparing the Warren 2 to the Cowlands results, the percentage differences in PRS scores and normalised P loss were 5% and 452%, respectively.

Similar results were found when the PRS was applied to the three fields under various hypothetical scenarios about the overland flow distance to receiving waters. The main reasons for this apparent inability of the PRS to classify the fields correctly (relative to edge-of-field P losses) are as follows:

- Four of the nine factors in the PRS (catchment P usage rate, condition of receiving waters, ratio of land to water and farmyard conditions) were assigned the same values for all three fields. Due to their relatively large contribution to the final PRS score, these factors masked differences in factors such as STP and field P usage.
- The risk assigned for both the P application time and rate factors to a field that receives no P additions was the same value ('low') as for a field that receives 0–5kg P ha^{-1} applied in the spring or just prior to crop needs.
- Lack of data precluded the full application (i.e. incorporation of all factors) of the PRS.

Table 11 Phosphorus ranking scheme (Magette, 1998) applied to Johnstown Castle field sites (Kurz, 2000)

		Factor value: low = 1, medium = 2, high = 4		
Catchment or field factor	**Weight for factor**	**Warren 1**	**Warren 2**	**Cowlands**
P usage in catchment	0.5	4	4	4
Condition of receiving waters	0.5	1	1	1
Ratio of land to water	0.75	2	2	2
Farmyard conditions	0.8 (0 if no animals)	1	1	1
P usage rate	1.0	1	4	4
P application time	0.9	1	1	1
Soil-test P (based on Morgan's test	0.	1	2	4
Overland flow distance	0.75	2	2	1
Run-off risk	1.0	4	4	4
Final score*		13.0	16.8	17.7
Qualitative risk assignment**		Medium	Medium	Medium
Measured field P loss***		778 g ha^{-1} (16 months)	300 g ha^{-1} (5 months)	5,300 g ha^{-1} (16 months)
Normalised P loss (g ha^{-1} $month^{-1}$)		49	60	331

* Final score equals the sum of all (factor risk × factor weight) (Magette, 1998).
** Final rank was categorised as high, medium or low, based on the procedure used in Magette (1998).
*** From Kurz (2000).

3.2 Edge-of-Field PRS Factor Evaluation

The results from the assessment using only the edge-of-field factors from the PRS (Magette, 1998) showed more promise in differentiating between sites based on edge-of-field P losses (Table 12). The Cowlands site, with high P losses, was ranked as 'high' risk for P loss. Both the Warren 1 and Warren 2 sites were ranked 'medium' risk. As with the original PRS, the FFO PRS does not distinguish between situations where no P is applied and where P is applied at the recommended time, requiring a 'low' P application time risk for both scenarios. Thus, the P usage rate for the Warren 1 site constitutes 15% of the final score, even though no P was applied to this site.

3.3 Assessment of Field PRS

Results from applying Field PRS to the Kurz (2000) fields were similar to those for FFO PRS. However, this scheme categorised both the Cowlands and Warren 2 fields as 'medium' risk, while the Warren 1 field was 'low' risk for P loss.

3.4 Assessment of PRS (Magette, 1998) Using Catchment-Scale Data

Of the 31 catchments analysed, two ranked 'high', none ranked 'low', and 29 ranked 'medium' for overall risk. Average median MRP for 'high' and 'medium' risk subcatchments were 66 and 39µg l^{-1}, respectively. Both catchments in the 'high' risk categorisation had correspondingly unacceptable in-stream median MPR concentrations according to the MRP criterion of Bowman et al. (1996). For the 'medium' risk catchments, 45% of the corresponding water-quality rankings were unacceptable, while 55% were acceptable.

Evaluation of the results from the 31 catchments highlights both the strengths and the limitations of the PRS. Overall for the 31 catchments, the PRS rank score was positively correlated with in-stream median MRP, despite several anomalous catchments where the final rank score was not closely correlated with in-stream P. There are a number of possible reasons for the anomalies with respect to PRS rank and in-stream median MRP.

The use of only one parameter (such as median MRP) as the benchmark against which to compare PRS performance may be inadequate. For example, P loading may have been a better measure of the P losses from the landscape as hydrological differences between streams can cause major anomalies between the actual P loadings carried in a stream, even though the MRP concentrations in the streams may be very similar.

The water-quality rank used in this analysis of the PRS was based on discharge median MRP and did not account for inflow P. Water quality in 'downstream' catchments is most certainly impacted by inflow water quality, but this influence could not be accommodated in the PRS.

Table 12 FFO PRS (based on Magette, 1998) applied to the Kurz (2000) field sites

		Factor value: low = 1, medium = 2, high = 4		
Catchment or field factor	**Weight for factor**	**Warren 1**	**Warren 2**	**Cowlands**
P usage rate	1.0	1	4	4
P application time	0.9	1	1	1
Soil-test P (based on Morgan's test)	0.8	1	2	4
Run-off risk	1.0	4	4	4
Final score*		6.7	10.5	12.1
Final rank**		Medium	Medium	High
Measured field P loss***		778 g ha^{-1} (16 months)	300 g ha^{-1} (5 months)	5,300 g ha^{-1} (16 months)
Normalised P loss (g ha^{-1} $month^{-1}$)		49	60	331

* Final score equals the sum of all (factor risk × factor weight) (Magette, 1998).
** Final rank was categorised as high, medium, or low, based on the procedure used in Magette (1998), and are categorised as follows: < 5.5 = 'low', 5.5–11.1 = 'medium' and > 11.1 = 'high' risk of P loss from the site.
*** From Kurz (2000).

The PRS does not account for point source P loading (with the exception of that arising from farmyards). Although the catchments were rural and primarily agricultural, there could have been P contributions from ‘point’ sources such as failing onsite wastewater treatment systems.

Another problem observed in evaluating the PRS at the catchment scale was related to the P application timing factor. Except for the Dripsey catchments in Co. Cork, and the Beef Unit and Dairy Farm catchments at Johnstown Castle in Co. Wexford, information by which to assess the P application timing factor was not available. Thus, assumptions had to be made to assign scores for this factor in most of the catchments examined.

Also, the relative lack of synchronous land-use and water-quality data (i.e. water-quality data collected simultaneously with significant land-management operations, such as when slurry and fertiliser spreading were occurring) prevented a more comprehensive evaluation of PRS over a wider geographic area.

3.5 Assessment of Catchment PRS

Results indicated that the performance of Catchment PRS was similar to that of the PRS with respect to both predictive capability and limitations. The use of a single parameter (median MRP concentration) for ranking of P status in streams, as well as basing this rank on outflow water quality irrespective of inflow water quality, limited the precision of the comparisons between assessed P loss risk and measured in-stream water quality, as discussed in Section 3.4. The relative lack of synchronous land-use and water-quality data (i.e. both types of data collected at the same points in time) prevented a more comprehensive evaluation of both PRS and Catchment PRS over a wider geographic area. As in the catchment-scale analysis of PRS, it is possible that an unidentified point source resulted in an inaccurate Catchment PRS rank for some catchments.

3.6 Assessment of mPRS with Field/Plot Scale Data

The field-scale data sets allowed analysis of two of the three ‘source factors’ of the mPRS (S3, farmyard risk, could not be assessed), but neither of the transport factors. So, for this assessment, the mPRS used is described as a ‘partial mPRS’.

3.6.1 Analysis of Hillsborough Data

The linear regression of partial mPRS scores against the mean MRP concentrations in run-off from the five plots was highly significant ($R^2 = 0.90$, $p = 0.013$, $n = 5$), as shown in Figure 1. There was also a similarly strong relationship (not shown) between MRP loads and partial mPRS scores.

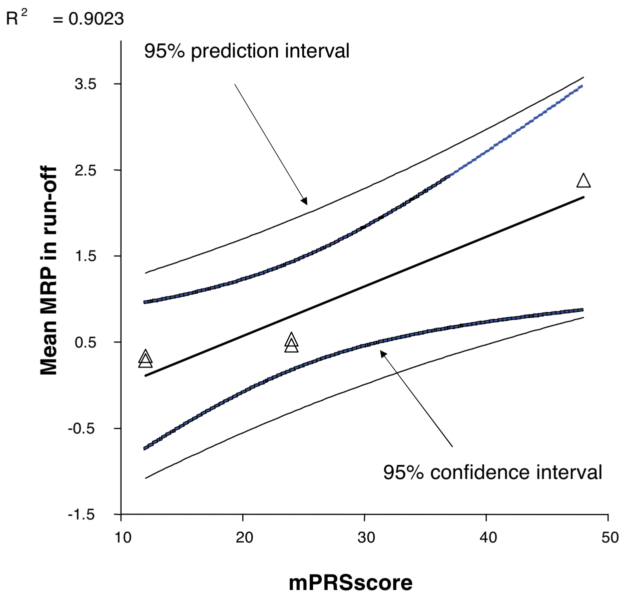

Figure 1: Regression of mean MRP concentration (mg l^{-1}) in run-off versus partial mPRS scores for Hillsborough sites (n = 5) (95% confidence interval, 95% prediction interval)

The regression was even more impressive when the TP concentration was regressed against the partial mPRS (R^2 = 0.93, p = 0.008). For TP loading in run-off water versus partial mPRS, the regression was also very good (R^2 = 0.93, p = 0.025), indicating that the partial mPRS can effectively estimate the risk of P loss occurring from these plots (as defined by the measured edge-of-field water quality).

3.6.2 Analysis of Johnstown Castle Data

In like fashion to those at Hillsborough, the three sites at Johnstown Castle were assessed to examine relationships between the partial mPRS scores and the measured edge-of-field water quality. The regression analysis showed very good agreement between the partial mPRS scores and the actual P lost via overland flow as defined by measured edge-of-field water quality (R^2 = 0.94 for MRP, and R^2 = 0.90 for total dissolved phosphorous [TDP]). However, the confidence intervals in the regressions were low, reflecting the small size of the data set. The rank order of the partial mPRS scores also matched the rank order of the edge-of-field P loads.

3.6.3 Comparison of mPRS, PRS and Field PRS

Using data from five sites at Hillsborough, a comparison was conducted using the original PRS (Magette, 1998), its evolved form represented by Field PRS (Hughes, 2004) and the significantly modified form represented by Partial mPRS to determine which might be most effective at ascribing the risk of losing P in run-off from the fields.

Scores from each PRS were assessed using linear regression against both mean MRP concentration and annual MRP loading measured in run-off at the edges of the fields. The analysis showed that each PRS gave a good fit between PRS score and edge-of-field water quality. However, the mPRS provided the best fit for both MRP concentration and MRP loading (Table 13).

3.6.4 Analysis of mPRS Factors

A detailed analysis using data from the Hillsborough sites was carried out whereby each of the partial mPRS source factors was regressed against MRP concentration and MRP loading in order to determine the relationship between these factors and edge-of-field water quality. The S1 source factor showed good correlations (R^2 = 0.9) with both mean MRP concentration and annual MRP loading.

There were equally good correlations between S2 and both MRP concentration (R^2 = 0.9) and MRP loading (R^2 = 0.9). Undoubtedly, these regressions were limited by the small size of the Hillsborough data set (n = 5). When the Johnstown Castle data set were analysed jointly with the Hillsborough data, the correlation between S1 and edge-of-field water quality (MRP concentration) was much lower (R^2 = 0.34). (Note that in this analysis, one extreme outlying data point in the Johnstown Castle data set was eliminated.)

Despite the small data set represented by the Hillsborough and Johnstown Castle data, these regression results indicate that there are good relationships between the mPRS source factors and edge-of-field water quality, i.e. that the source factors used in mPRS are important.

3.7 Testing of mPRS Using Field Data at Catchment Scale

3.7.1 Ara Catchment Analysis

Initial testing of the mPRS indicated that there were poor correlations between the mPRS site scores and the annual average in-stream MRP concentration (R^2 = 0.05). Introduction of an altered S1 factor (S1var1), resulted in a slightly improved correlation between the mPRS and MRP concentration (R^2 = 0.13). However, this regression was still poor.

Table 13 Coefficients of linear correlation between scores from three different PRS versus edge-of-field mean MRP concentration (mg l^{-1} P) and annual MRP load (kg ha^{-1}), Hillsborough Agricultural College fields (n = 5)

PRS version	MRP concentration	MRP load
PRS (Magette, 1998)	0.81	0.82
Field PRS (Hughes, 2004)	0.77	0.80
Partial mPRS (this research)	0.90	0.90

In an attempt to address the variability in the availability of data among subcatchments, only those subcatchments having greater than 30% of the subcatchment area represented in the data set were used. The resultant correlation between mPRS scores and in-stream water quality (average annual MRP concentration) was considerably improved ($R^2 = 0.73$) (Figure 2).

Nevertheless, results from the analysis of individual mPRS factors for the Ara catchment were generally disappointing, as coefficients of linear correlation were generally low. A good correlation ($R^2 = 0.52$) was found between S2 × distance and MRP concentration, probably reflecting the effectiveness of the S2 factor, as suggested by the field-scale testing.

Despite the generally low correlations, some interesting relationships were noted. The first of these is the importance of the S2 factor (soil P × desorption factor) in the mPRS. Of all the mPRS factors tested, S2 is the one most strongly correlated with annual average in-stream MRP concentration. This relationship was also true in the field-scale analyses. The second important result from the analysis of Ara subcatchments was the need for good quality 'field' data representing a good proportion (at least 30%) of a catchment. When subcatchments having less than 30% of catchment coverage were excluded from the analyses, all correlations (between the mPRS as well as its factors and measured water quality) improved considerably.

3.7.2 Clonmore Catchment Analysis

The initial regressions between the mean mPRS scores and the annual average in-stream MRP concentration (mg l^{-1}) indicated poor correlation ($R^2 = 0.08$).

The strengths of the correlations between individual mPRS factors and annual average MRP concentration were mixed, as was the case in the Ara catchment. Both the S1 factor ($R^2 = 0.07$) and the S3 factor ($R^2 = 0.02$) were poorly correlated with the annual average in-stream MRP concentration. However, as was the case with the Ara catchment (and in field-scale testing), the S2 factor (soil P concentration × desorption risk) was strongly correlated with the MRP concentration ($R^2 = 0.60$).

3.7.3 Optimisation of mPRS Weightings

The optimisation process was very successful at generating weightings that greatly improved the positive correlations between mPRS scores and average annual in-stream MRP concentrations measured in the Ara subcatchments. The best-fit set of weightings was generated using an optimisation procedure with no

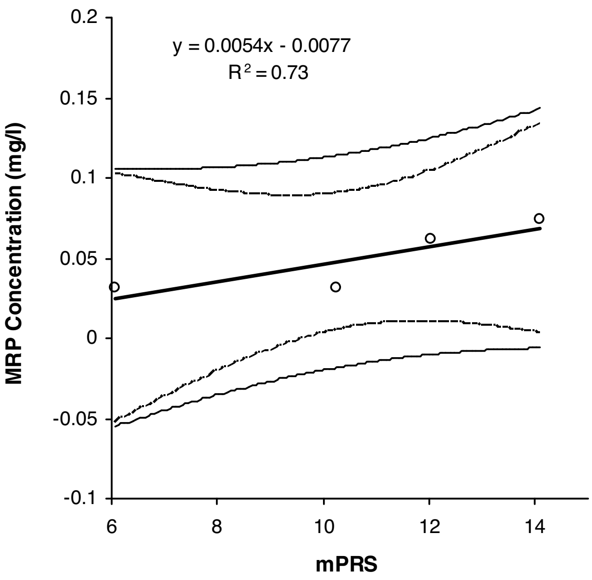

Figure 2: Linear regression of annual average MRP concentration (mg l^{-1}) versus mPRS score for four Ara subcatchments having greater than 30% catchment coverage with field data (95% confidence interval, 95% prediction interval)

constraints (R^2 = 0.76). These unconstrained weightings varied quite widely, between –11.23 and 16.24. Interestingly, the presence of the negative weightings for the P application factor (S1 subfactor) and the farmyard risk factor (S3) indicate that these two factors did not effectively represent the contribution of P applications and farmyard risk, respectively, to the description of (i.e. correlation with) annual average MRP concentrations in the Ara subcatchments. This finding corroborated the results of examining the correlations between individual factor scores and annual average MRP concentrations. In those analyses (both for the field-scale data and the Ara and Clonmore data) only the S2 factor appeared to be well correlated to in-stream MRP concentrations.

Use of the optimised weightings in the mPRS applied to the Clonmore data set showed that the weightings improved the correlation between the mPRS scores and annual average MRP concentration (R^2 = 0.63 versus R^2 = 0.25).

3.8 Assessment of mNRS

Analyses to assess the performance of mNRS were undertaken separately for the year 2002 and for the year 2003. As part of these analyses, a number of variations of the nitrogen application (NA) and nitrogen application timing (NT) subfactors were also assessed. Three separate variations on the NA factor were examined:

1 Nitrogen applications including dirty water applications.

2 Slurry and fertiliser nitrogen applications only.

3 All nitrogen applications including nitrogen deposited by grazing animals.

Each of the three alternative calculations (1), (2) and (3) for the nutrient application subfactor was then combined with the remaining mNRS factors to generate three separate mNRS scores, referred to as $mNRS_1$, $mNRS_2$ and $mNRS_3$. Each of these scores was generated for the mNRS(A) and mNRS(B) scenarios (described in Section 2.4). Thus, for mNRS(A), three mNRS scores were generated: $mNRS_1$(A), $mNRS_2$(A) and $mNRS_3$(A). Likewise for mNRS(B), three scores were generated: $mNRS_1$(B), $mNRS_2$(B) and $mNRS_3$(B).

3.8.1 Results for 2002

Analysis of the mNRS for the 2002 data set from Curtin's Farm identified the difficulty in relating field-based parameters (and resultant scores) to groundwater-quality data. The regression analysis resulted in generally poor correlations between all mNRS scores and the average measured $N0_3$-N concentrations for each of the boreholes. For $mNRS_2$, which accounted for the application of N via artificial fertiliser and slurry only, the correlations were very poor, indicating that the resultant mNRS score did not effectively estimate the risk of nitrogen losses to ground water (as measured by $N0_3$-N concentration).

The correlations between mNRS scores and borehole $N0_3$-N concentration were similarly poor when the NA subfactor included 'dirty water' applications: $mNRS_1$(A) versus $N0_3$-N (R^2 = 0.03) and $mNRS_1$(B) versus $N0_3$-N (R^2 = 0.04). By comparison, correlations between $mNRS_3$ (mNRS score generated using all nitrogen applications in the NA subfactor, including nitrogen deposited by livestock) and borehole $N0_3$-N concentration, were much improved (R^2 = 0.36 and 0.38 for Scenarios A and B, respectively).

The regression analysis undertaken for the 2002 data set indicated that the mNRS did not effectively estimate the risk of nitrogen losses to ground water arising from the fields on Curtin's Farm for the hydrological year 2001–2002. However, by including applications of N directly deposited by livestock in the scoring of the NA subfactor, the mNRS ($mNRS_3$) was fairly correlated (R^2 = 0.37) to average borehole $N0_3$-N concentrations. While the correlation was not particularly strong, it was much improved over those when N applications were attributed either only to fertiliser or to fertiliser and dirty water. This indicates the importance of including all nitrogen applications, not just the applications of fertiliser and slurry, when attempting to determine the risk of nitrogen losses to ground water using mNRS.

3.8.2 Results for 2003

As with the 2002 data set, there was no correlation between either the $mNRS_2$(A) or $mNRS_2$(B) score and the average 2003 borehole $N0_3$-N concentrations. These scores considered fertiliser and slurry to be the only N sources.

However, by including additional sources of N in the NA subfactor (i.e. $mNRS_1$ and $mNRS_3$), correlations between mNRS scores and average borehole $N0_3$-N concentration were generally good. Correlations between $mNRS_1$ and the average $N0_3$-N concentration in the boreholes were very good for both scenarios $mNRS_1$(A) (R^2 = 0.51) and $mNRS_1$(B) (R^2 = 0.56). Reasonable correlations also existed between $mNRS_3$ scores and average borehole $N0_3$-N concentrations: $mNRS_3$(A) versus $N0_3$-N (R^2 = 0.40) and $mNRS_3$(B) versus $N0_3$-N (R^2 = 0.44). These results (and those for 2002) highlight the importance of including all sources of nitrogen in the scoring of the NA subfactor in the mNRS.

3.8.3 Combined Results for 2002/2003 and Summary

A comparison of mNRS scores (assuming Scenario B and application alternative 1) against the average borehole $N0_3$-N concentrations for the combined 2002/2003 period is shown in Figure 3.

Of the two scenarios for testing the mNRS against borehole-water quality, Scenario B (which assumed that fields up-gradient of a borehole influenced water quality in the borehole) generally yielded the stronger correlations to both the 2002 and 2003 data. Likewise, the inclusion of N from dirty water applications, slurry and fertiliser in the scoring of the NA subfactor (alternative 1) seemed generally to be the superior alternative. For both the 2002 and 2003 data sets, the mNRS(B) score tended to be better correlated with the average $N0_3$-N concentrations than the mNRS(A) score. This indicates that the land area of influence is generally extended beyond the area of just one field (of the sizes in this study). The area of influence around a borehole is dependent on a number of hydrological factors and most certainly varies among sites. However, for this farm, areas up-gradient from boreholes by at least 100m seem to affect borehole $N0_3$-N concentrations.

3.9 Catchment Screening Tool

Correlations between selected catchment characteristics and water-quality data for the Lough Conn and Lough Mask catchments showed that catchment-scale data sets can be good indicators of water quality, particularly as measured by mean concentrations of TP, and therefore serve as useful screening tools by which to assess catchments for their propensities to lose P to surface water. The results also highlighted a number of problematic issues in regard to the spatial and temporal losses of P occurring from the catchments analysed in this study.

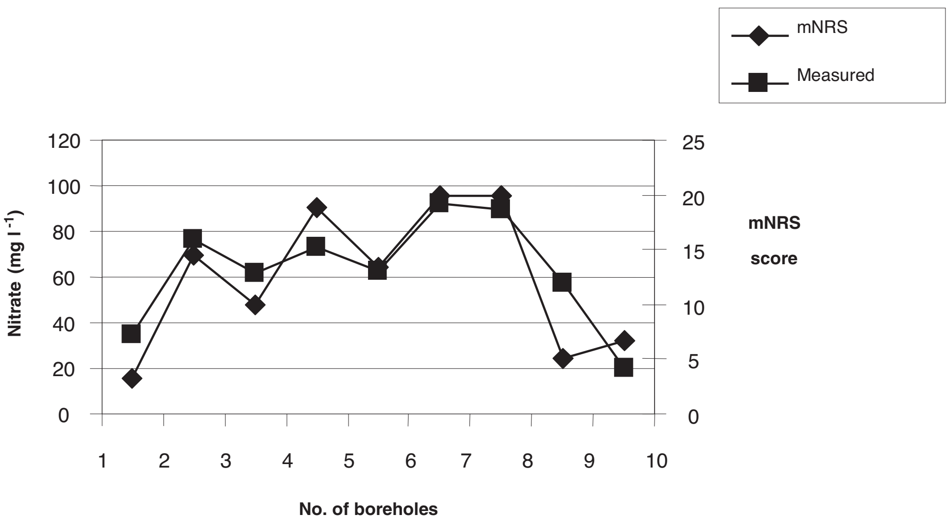

Figure 3: mNRS scores versus mean borehole $N0_3$-N concentration (mg l^{-1}) for 2002/2003 for Scenario B with dirty applications included in the scoring of the NA subfactor (alternative 1)

3.9.1 Phosphorus Desorption Properties of Soils

There was a strong negative correlation between Des2 (desorption category 2: soils with low sorption capacity) and the TP concentration in rivers, with a linear correlation coefficient between the two factors of $R^2 = 0.41$. Des1 and Des3 category soils showed no significant linear correlations with the in-stream TP concentration. This is primarily because soils of this quality are very scarce within these catchments and so are likely to have very little influence.

As with Des2 category soils, those in the Des4 category exhibited a reasonable linear correlation with TP concentration ($R^2 = 0.53$). This category includes soil types with a relatively high desorption capacity that are generally well drained and suitable for productive agriculture. This regression is positive, indicating that TP concentration within these catchments increases with increasing area of Des4 land.

Each category of the P desorption coverage was calculated over the whole catchment as well as over areas that were limited to 500m, 200m and 100m from the river channel. For the Des4 category, there were considerable variations in the correlations, with the whole catchment coverage resulting in the best linear correlation with average TP concentration ($R^2 = 0.53$) (Table 14). These results indicate that the desorption factor is a more effective indicator of water quality in these catchments when considered over the entire catchment than when considered only over areas nearer to the streams. This result is somewhat surprising, as the importance of P transfer from riparian zones has been highlighted throughout the literature, with particular reference to the critical source area theories and the variable source area theories. It may be the case, however, that the results found in the research reported herein are influenced by the scale (and therefore sensitivity) of the data set.

The strongest correlations between the in-stream TP concentrations and all desorption categories occurred during the winter period, when most TP would be expected to be lost in run-off. For this time period the regression between the seasonal average TP concentration and the Des4 factor showed an improved correlation ($R^2 = 0.58$) over that exhibited when the annual average data were used.

3.9.2 Drainage

The coverage of soils in the excessive drainage category was somewhat negatively correlated to the annual mean TP concentration ($R^2 = 0.36$). The percentage of soils exhibiting good drainage within the catchments was positively correlated with the TP concentrations ($R^2 = 0.47$). This positive relationship is probably due to the fact that these soils facilitate more intensive agricultural practices to be undertaken than do excessively drained soils, with the associated increased rates of the P applications associated with intensive agricultural production. This correlation between mean annual TP concentration and soil drainage is further improved ($R^2 = 0.52$) when the coverage of good drainage soils are combined with the coverage of moderately drained soils.

As with the desorption factor, there were only minor differences among the correlations for a given soil drainage category and the areal coverage in riparian zones. However, for the ‘good’ soil drainage category, the percentage coverage in the area of catchments within 500m from the river channel was best correlated ($R^2 = 0.45$) with the mean annual TP concentration measured in the streams. The combined areas of good and moderately drained soils within 500m of the stream channel showed a relatively strong correlation ($R^2 = 0.47$) with annual average TP concentration.

Table 14 Linear correlation coefficients between annual average in-stream TP concentration (µg l^{-1}) in 16 catchments and soils in the Des2 and Des4 categories over the full catchment and over partial catchment areas (adjacent to streams)

	Whole catchment	500m	200m	100m
Des2	0.42	0.42	0.40	0.40
Des4	0.53	0.29	0.40	0.39

The mean TP concentrations for the winter period, from September through January, were marginally better correlated to the coverages of most of the soil drainage categories than were the other seasonal averages. The 'poor', 'imperfect' and 'moderate' soil drainage categories were not correlated to the seasonal TP concentrations.

3.9.3 Soil-Test Phosphorus

None of the soil-test P (STP) categories (or combinations of categories) were strongly correlated to mean annual in-stream TP. Correlations between annual average in-stream TP concentration and STP categories within selected distances from the river channel were also weak.

The results from this analysis are somewhat surprising, as STP has been cited widely in the literature as one of the most significant indicator factors for P loss from agriculture. However, the data set for this analysis comprised a national map showing average soil P levels in four categories on a 10km^2 grid. It is likely that this data set is not truly representative of the STP concentrations; in addition, the spatial resolution of the data set is poor. The limitations of the data set may, therefore, have masked relationships between STP and in-stream TP.

3.9.4 CORINE Land Use

The class CORINE 2 (high presumed risk for P loss), which includes land uses ranging from mineral extraction to arable crop production, exhibited a very strong correlation with the annual average TP concentration (R^2 = 0.75, Figure 4). This was the best correlation of any of the factors examined against mean TP concentration. The class CORINE 2 represents the more intensive agricultural land uses in the catchment, such as the 'improved pasture' category and arable land uses; these were the dominant categories in the class CORINE 2 areas in the Conn and Mask catchments. This result agrees with results presented by others in the literature, i.e. the more land within a catchment occupied by relatively intensive agriculture, the greater will be the losses of TP to water.

There were no significant correlations between mean in-stream TP concentration and either the CORINE 1 or the CORINE 3 land-use classes, considered individually. The areal extent of these classes in the catchments was, however, small. The land-use class CORINE 4 (low risk) exhibited a negative correlation (R^2 = 0.27) with average annual in-stream TP concentration.

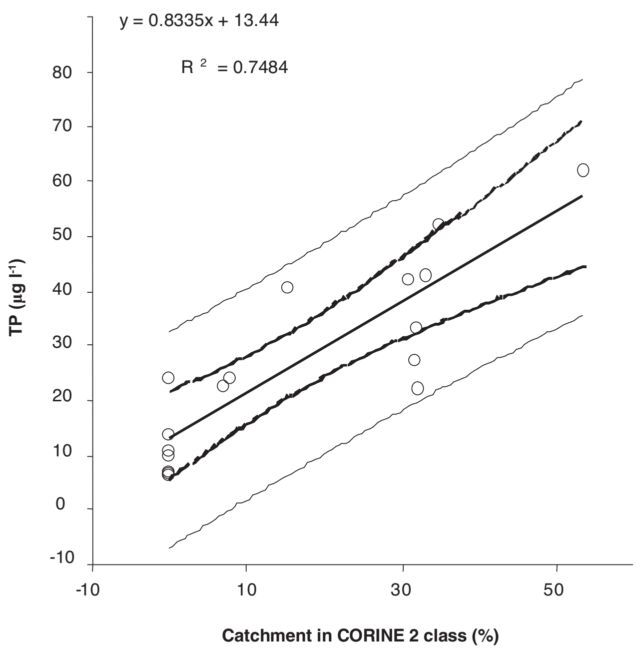

Figure 4: Linear regression between percentage of the catchment area occupied by the CORINE 2 class and the annual average in-stream TP concentration (µg l^{-1}), 16 catchments (95% confidence interval, 95% prediction interval)

The use of the 'partial catchment' areas (riparian zones of various widths) did not improve the strength of correlations between mean TP concentrations and CORINE land-use class compared to the use of 'whole catchment' coverage. For the CORINE 2 land-use class, the partial catchment area located 100m from the stream channel exhibited the best fit (R^2 = 0.71) and was nearly as good as that for the relationship with CORINE 2 land-use class over the whole catchment.

Temporal variations were observed in the correlations between the CORINE land-use classes and mean in-stream TP concentration. As with soil P desorption, STP and soil drainage, water-quality data from 1995 were least correlated with CORINE land-use class, and this is assumed to be the result of unusually low rainfall during 1995. For the CORINE 2 land-use class, the best correlation was with the mean TP concentrations in 1998 (R^2 = 0.77). In common with the other factors assessed, the best-fit period was the winter for all years. The regression of winter seasonal average TP concentration against CORINE 2 land-use class was slightly better (R^2 = 0.81) than that for the regression with the annual average TP concentration (R^2 = 0.75).

3.9.5 Combination of Factors

The analyses described previously indicated that, in general for the two catchments, the whole-catchment data sets were best correlated to in-stream TP concentrations, and therefore to the risk of P loss occurring to water. This may be contrary to findings elsewhere, where the importance of limited subcatchment areas known as 'critical source areas' has been identified (Poinke et al., 2000). However, it is considered that the main reason for the findings here is the fact that the data sets used in this study are at such a large scale that the data cannot differentiate between variations in factor categories/classes over small areas and that this may have led to some bias in the proportioning of these categories/classes over the total catchments.

Three of the four factors analysed exhibited fair to good correlations with TP concentrations. Based on these, a screening tool was developed comprised of the factors:

- CORINE land-use class 2 (C2).
- Good and moderate drainage, combined (GMD).
- Desorption class 4 (Des4).

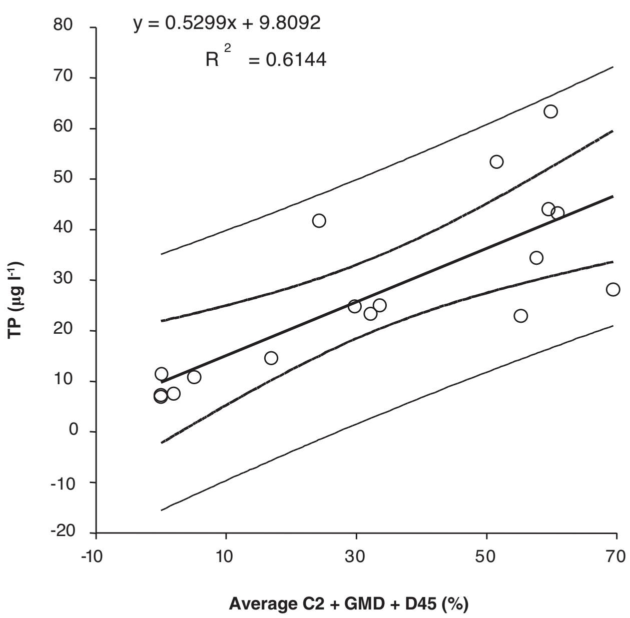

Figure 5: Linear regression between the combination of best-fit factors C2, GMD and D45 (arithmetic average of percentages of each factor in the catchments) and the annual average in-stream TP concentration (µg l^{-1}), 16 catchments (95% confidence interval, 95% prediction interval)

When regressed against TP concentrations, the combined factors were fairly well correlated ($R^2 = 0.61$, Figure 5). However, it must be noted that the regression is poorer than that for the CORINE 2 land-use category on its own. Multiple linear regression analysis was undertaken to develop a single equation containing the three factors C2, GMD and D4 against TP concentration. The resulting equation

$$y = 12.7735 + (C2 \times 0.7822) + (GMD \times -0.1261) + (Des4 \times 0.1577),$$

in which y is the predicted TP concentration, produced excellent correlations with average annual in-stream TP concentration ($R^2 = 0.75$) and indicated that the CORINE 2 land-use class is easily the most significant factor ($p = 0.0051$). The screening tool suggests, therefore, that the percentage of a catchment occupied by the CORINE 2 land-use class is by far the single most significant predictor of in-stream TP concentration in these catchments. The use of this single factor as a screening tool for the risk of losses of P from diffuse agricultural sources at catchment level would appear to be justified.

3.10 Farmyard Risk Assessment Scheme

Using data collected in the Teagasc farmyard survey, advice on good agricultural practice and input from the expert panel, a farmyard risk assessment scheme (FRAS, Tables 15–19) was developed. The FRAS is comprised of five sections, each of which addresses a significant potential source of water pollutants, viz. storage facilities for slurry, dungstead manure, farmyard manure, silage effluent and dirty water. As illustrated in Table 15, a section contains several elements that contribute to the overall integrity of the given storage facility, and the importance of each element is assigned an 'intra-section' weighting according to its relative contribution to the overall risk of the storage facility. Each element is assigned a risk score depending on its status. An 'inter-section' weighting reflects the relative contribution of a given section to the risk of the entire farmyard. The assignment of inter-section and intra-section weightings, as well as risk scores for elements within each section, was developed by consensus with the Expert Panel.

While the FRAS described by Tables 15–19 was designed to be logical, simple, straightforward and intuitive, the absence of measured data on nutrient losses from farmyards made it impossible to actually verify the scheme. There were no data available to the research team concerning the measured losses of P and N leaving farmyards relative to the various elements included in the FRAS. Nor was it possible to extrapolate what effect the surveyed farmyards might have had on nearby in-stream water quality because the physical locations of the surveyed farms were not revealed in the survey due to data protection constraints. In short, there were no benchmarks against which to compare risk scores arising from application of the FRAS and the validity of the scheme remains untested.

Table 15 Section A of FRAS, addressing risks associated with slurry storage facilities

Section A: Slurry storage facility			
Intra-section weighting multiplier		**Weighting multiplier between sections: 2**	**Risk score**
2	What type of slurry storage?	Underground concrete/steel	0
		Overground concrete/steel	0
		Lined earthen	40
		Unlined earthen	100
1	Is it covered?	Yes	0
		No	100
4	In what condition is the slurry storage?	Good	0
		Average	20
		Poor	100

Table 16 Section B of FRAS, addressing risks associated with dungstead storage facilities

Section B: Dungstead storage facility			
Weighting multiplier within the section		**Weighting multiplier between sections: 1.7**	**Risk score**
1	In what condition are the dungstead stores?	Good	0
		Average	20
		Poor	100
3	In what condition is the seepage storage?	Good	0
		Average	20
		Poor	75
		None present	100

Given such difficulties as those just described with the FRAS (and similar farmyard assessment strategies), an even simpler evaluation tool may be worth considering, at least as a screening procedure. For such a tool, it is considered that the single measure of manure storage capacity relative to manure production would be an easy and unequivocal assessment that requires no qualitative judgements. Indeed, this simple measure has been used elsewhere as a means to prioritise assistance for pollution control. While the capacity of manure storage does not encompass the many pollution sources around a farmyard, as the FRAS does, it would lend significant insight into the fundamental polluting potential of farmyards.

Table 17 Section C of FRAS, addressing risks associated with farmyard-manure (dry) storage facilities

Section C: Farmyard-manure storage facility			
Weighting multiplier within the section		**Weighting multiplier between sections: 1.5**	**Risk score**
1	In what condition are the farmyard manure stores?	Good	0
		Average	20
		Poor	100
3	In what condition is the seepage storage?	Good	0
		Average	20
		Poor	75
		None present	100

Table 18 Section D of FRAS, addressing risks associated with silage storage facilities

Section D: Silage storage facility			
Weighting multiplier within the sectionn		**Weighting multiplier between sections: 2**	**Risk score**
2	Does the pit have a concrete base?	Yes	5
		No	100
1	Does the pit have a sealed concrete base?	Yes	0
		No	100
	Is the silage pit roofed?	Yes	0
		No	100
3	What is the overall condition of the silage pit?	Good	0
		Average	20
		Poor	100
4	What is the condition of the effluent collection system?	Good	0
		Average	20
		Poor	75
		None present	100
1	Are there silage bales on the farmyard?	Yes	100
		No	0
	Are the silage bales made from wilted grass?	Yes	0
		No	100

Table 19 Section E of FRAS, addressing risks associated with dirty-water storage facilities

Section E: Dirty-water storage facility			
Weighting multiplier within the section		**Weighting multiplier between sections: 3**	**Risk score**
3	What is the condition of the parlour washings and collecting yard dirty water storage?	Good	0
		Average	20
		Poor	75
		None present	100
2	What is the condition of the dirty yard water storage?	Good	0
		Average	20
		Poor	75
		None present	100
4	What is the condition of the complete dirty water storage? (Includes parlour and collecting yard and dirty yard water.)	Good	0
		Average	20
		Poor	75
		None present	100
1	How is clean water managed?	Diverted to watercourse/drain	0
		Diverted to storage tank	20
		Diverted to a soak pit	0
		Not diverted or stored	100
1	What is the condition of the guttering and drainage?	Good	0
		Average	20
		Poor	75
		None present	100

4 Conclusions

This project successfully accomplished all its objectives, save for the validation of a farmyard ranking system. Although it may sound like the classic scientist's lament to say that a lack of appropriate data severely constrained the conduct of this research, it is in fact true that the dearth of small-scale data on water quality and land/farm management precluded more rigorous analyses in this research. Nevertheless, the results of this research support the following conclusions.

4.1 Field PRS Evaluation

Results from this evaluation indicated that the Field PRS has the potential to identify critical source areas for P loss in catchments, although the data available for evaluation were very limited. Features incorporated into the Field PRS improved on the assessment capability of the original PRS proposed by Magette (1998) for field-scale application.

4.2 Performance of PRS at Catchment Scale

Although it is important to acknowledge problems (in terms of data availability) with the PRS proposed by Magette (1998), the PRS rank scores from this scheme were positively correlated with median in-stream MRP associated with 31 catchments in Ireland. Unfortunately, the PRS did not discriminate well among sites scored as having a 'medium' propensity for losing and transporting P. This suggests that the scale used in the PRS for assigning qualitative indicators needs additional modification.

4.3 Catchment PRS

In the modification of the PRS called 'Catchment PRS', elimination of the overland flow distance, P application time and field P usage rate did not diminish (relative to PRS) the accuracy of assessed P loss based on comparisons with measured in-stream MRP, but improved the practical application of this ranking scheme.

4.4 Modified PRS

Using measured edge-of-field P losses as the benchmark, the mPRS was very successful in assessing the risk of P loss to water from the study sites in Hillsborough, Northern Ireland. However, it is important to note that for a number of factors there was no difference in value between the different plots, i.e. each of the plots had the same 'run-off risk' as they are all categorised as the same soil type. Thus, whilst this testing confirmed mPRS to be a successful site assessment tool, further testing will be required at a range of different sites which have much more variability in their characteristics.

In general, this research indicated that the mPRS is an effective tool in assessing the risk posed at field level to surface waters, but it also indicated that there may be issues relating to varying hydrology at different sites that are not being represented by the mRPS. It is true to say that the number of fields available for assessment in Ireland is very low, and as a result it is necessary for further field testing to occur over a larger number of fields representing varying soil types, P management regimes, hydrological conditions and meteorological conditions in order to fully assess the usefulness of the mPRS.

In summary, the results from this part of the research project provide a valid method by which to assess, a priori, the relative risk, or potential, for P to be lost from field-size areas of grassland in Ireland and transported to receiving waters. Through the use of the methodology developed in this research, areas within catchments that pose particularly high risks in terms of P loss and transport can be identified and targeted with focused intervention efforts. Likewise, agricultural advisers can use the technique to identify specific fields to which particular attention in terms of nutrient management planning should be given. Both uses of these research results will ultimately lead to better environmental quality by reducing the loss of P from the landscape to surface water.

4.5 Conclusions Regarding the mNRS

Considering the very complex set of interactions that govern the loss of nitrates to ground water from agricultural sources, it is considered that the mNRS functioned well. However, the mNRS was not able to consider the temporal variations in ground-water quality, which were believed to be due to differences in annual rainfall. This is an issue for all simplified ranking procedures and can be addressed only through the use of long-term contemporaneous databases of water quality (including ground water) and land management for development and testing. Unfortunately, these databases do not exist in Ireland.

The testing of the mNRS also highlights the importance of considering all N applications, and not just the inorganic fertiliser applications, when assessing the risk of nitrate leaching. Dirty-water applications seem to be particularly important, for when they are removed from the mNRS, the correlation between mNRS scores and ground water quality becomes much weaker.

4.6 Conclusions Regarding the Development and Testing of the Catchment-Scale Screening Tool

Three of the four catchment characteristics (CORINE land use, soil P desorption and soil drainage) examined in this research showed potential to identify P ‘hotspots’ as evidenced by their correlation with average annual in-stream TP concentrations in the 16 catchment areas assessed in this study. While no effective correlations were evident between the soil-test P data set and in-stream TP concentrations, this is believed to reflect the lack of spatial detail in the data set rather than the absence of a relationship between the two parameters.

Among the four factors evaluated, the CORINE 2 land-use class factor, encompassing, inter alia, the proportion of a catchment devoted to more intensive farming, was the factor most strongly correlated with the TP concentrations occurring in the catchment streams (R^2 = 0.75). When the three best-fit factors (CORINE land use, soil P desorption and soil drainage) were combined into an algorithm that might serve as a ‘screening tool’ by which to identify areas based on their potential to lose and transport P to surface water, the resultant correlations with in-stream TP concentrations were also good (R^2 = 0.61). However, it is considered that the use of the ‘CORINE 2’ factor alone would be the most effective method of screening catchments for the identification of P loss ‘hotspots’.

4.7 Conclusions Regarding the Identification of Farmyard Pollution Potential

The potential for point sources such as farmyards to contribute polluting materials to water is controlled by a variety of interacting factors. Among these are the structural integrity and capacity of storage structures, and the associated appurtenances that convey polluting materials, the proximity of farmyards to water resources, and the managerial expertise of farm managers. Through this research a comprehensive farmyard risk assessment scheme (FRAS) was developed that can integrate the various factors affecting the polluting potential of farmyards and yield a single score with which relative comparisons among a variety of farmyards can be made. While the FRAS encompasses the best professional judgement of practitioners in the fields of agricultural and environmental management, a lack of measured data concerning, inter alia, P and N transport from a variety of farmyards prevented the validity of the FRAS from being tested.

4.8 General Conclusions about Simplified Approaches to Pollution Risk Identification

This research formed an important element of a comprehensive study of mechanisms by which to assess, a priori, the transport of P (and for this project, N) from land to water (2000-LS-2-M2). Although the alternative strategies investigated as part of 2000-LS-2-M2 share a similar purpose, it would be erroneous to compare them by the same criteria and to expect all to produce similar guidance. The techniques investigated in the research reported herein are at the less complex end of the continuum from simple to complex pollution-assessment approaches. It is important to emphasise that these simplified techniques, which are essentially multi-criteria ranking procedures, are not intended to yield quantifiable predictions of P or N loss and transport. Instead, these procedures endeavour to simplify what are in reality very complex interrelationships about the natural environment in an attempt to facilitate managerial decisions. Such decisions may take a variety of forms (such as where to target specialist environmental-management programmes or what nutrient management strategies to undertake), but all are facilitated by a rational mechanism that can facilitate relative comparisons. Fundamentally, this is the intended use of the techniques investigated in this research.

As rational methods by which to make relative comparisons, the principal outputs from this research (Field PRS, Catchment PRS, mPRS, mNRS and the catchment screening tool) have each been tested against the best sets of measured data that are available in Ireland and have been shown to provide valid decision criteria. While not validated, it is believed that the farmyard risk assessment scheme, FRAS, also can produce defensible comparisons of farmyard pollution potential.

5 Recommendations

1 As the development, testing and validation of predictive risk assessment techniques (even relatively simple approaches investigated in this research) are constrained by the quality of appropriate data sets, an integrated programme of land-use activity monitoring, edge-of-field water-quality monitoring and simultaneous in-stream water-quality monitoring should be implemented on as widespread a scale as possible, but at least to allow coverage in Ireland's major agri-hydrological regions. Such an environmental-monitoring approach would facilitate the development of procedures such as mPRS, mNRS and FRAS and enhance the confidence in implementing these. The need for monitoring of farmyards for pollutant losses is particularly acute.

2 Because land-use (including farmyards) monitoring involves issues of privacy associated with private property, mechanisms need to be enacted by government/local authorities to (a) indemnify participating landowners from prosecution for environmental offences (if, indeed any are identified) and/or (b) reimburse landowners financially or use other incentives to encourage them to participate in the data-collection programmes that would be necessary for a simultaneous land-use and water-quality monitoring programme to be successful.

3 The mPRS and catchment screening procedures should be implemented, perhaps on a trial basis and possibly via a geographical information system (GIS), in a selected number of river-basin districts as a tool to assist in catchment water-quality management planning. Despite the prudence of further testing of the mPRS and mNRS (and FRAS) with more extensive data sets, these procedures should be implemented in their present formats where data sets are available to provide rational, relative measures of the likelihood that N and P will be lost from the landscape and transported to receiving waters.

4 A concerted research programme should be undertaken, possibly using rainfall simulation, to develop appropriate field-scale management strategies to correspond with particular mPRS, mNRS and FRAS rank scores.

References

Bartley, P., 2003. Nitrate Responses in Groundwater under Grassland Dairy Agriculture. PhD thesis, Department of Civil Structural and Environmental Engineering, University of Dublin, Trinity College Dublin, Ireland.

Bechmann, M.E., Krogstad, T. and Sharpley, A.N., 2005. A phosphorus index for Norway, *Acta Agriculturae Scandinavica, Section Soil and Plant Sci*. 55(3): 205–13.

Beegle, D.B., 1999. Soil Fertility Management. In: Serotkin, N. and Tibbetts, S. (eds) *The Agronomy Guide 1999–2000*, Pennsylvania State University, Publications Distribution Center, University Park, Pennsylvania, USA. pp. 19–46.

Bowman, J., Clabby, K., Lucey, J., McGarrigle, M., and Toner, P., 1996. *Water Quality in Ireland: 1991–1994*. Environmental Protection Agency, Wexford, Ireland.

Council of the European Communities, 2000. Directive 2000/60/EC of October 2000, establishing a framework for community action in the field of water policy. *Official Journal of the European Communities* L327/1 2000.

Daly, K., 2000. Phosphorus desorption from Irish soils. In: *Quantification of Phosphorus Loss from Soil to Water: Final Report and Literature Review*. Environmental Protection Agency, Wexford, Ireland.

Daly, K., 2006. *Eutrophication from Agricultural Sources: Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water (2000-LS-2.2.2-M2)* Final Report. Environmental Protection Agency, Wexford, Ireland.

Djodjic, F., Montas, H., Shirmohammadi, A., Bergström, L., and Ulén, B., 2002. A decision support system for phosphorus management at a watershed scale. *J. Environ. Qual*. 31: 937–45.

EPA. 2004. *Ireland's Environment 2004*. Environmental Protection Agency, Wexford, Ireland.

Gardiner, M. and Radford, T., 1980. *Soil Associations of Ireland and Their Land Use Potential*. National Soil Survey of Ireland, An Foras Taluntais, Dublin, Ireland.

Gburek, W.J., Sharpley, A.N., Heathwaite, L. and Folmar, G.J., 2000. Phosphorus management at the watershed scale: A modification of the phosphorus index, *J. Environ Qual*. 29(1): 130–44.

Hughes, K. 2004. *Evaluation of the Magette Phosphorus Ranking Scheme: a Risk Assessment Tool for Ireland*. MEngSc thesis, Department of Biosystems Engineering, University College Dublin, Ireland. 184pp.

Irvine, K., Boelens, R., Fitzsimmons, J., Kemp, A. and Johnston, P., 2005a. *Review of Monitoring and Research to Meet the Needs of the Water Framework Directive (2000-DS-5-M1)*. Environmental Protection Agency, Co. Wexford, Ireland.

Irvine, K., Mills, P., Bruen, M., Walley, W., Hartnett, M., Black, A., Tynan, S., Duck, R., Bragg, O., Rowan, J., Wilson, J., Johnston, P., and O'Toole, C. 2005b. *Water Framework Directive: An Assessment of Mathematical Modelling in its Implementation in Ireland (2002-W-DS-11)*. Environmental Protection Agency, Co. Wexford, Ireland.

Kirk McClure Morton., 2001. *Lough Derg and Lough Ree Catchment Monitoring and Management System: Final Report*. Elmwood House, 74 Boucher Road. Belfast, BT12 6RZ, UK, 223pp.

Kurz, I., 2000. Phosphorus exports from agricultural grassland with overland flow and drainage water (Johnstown Castle). In: Quantification of Phosphorus Loss from Soil to Water: Final Report and Literature Review. Environmental Protection Agency, Co. Wexford, Ireland.

Kurz, I., 2002. Phosphorus Export from Agricultural Grassland with Overland Flow and Surface Drainage Water. PhD thesis, Trinity College Dublin, Ireland.

Lemunyon, J.L. and Gilbert R.L., 1993. The concept and need for a phosphorus assessment tool. *J. Prod. Agric*. 6: 483–6.

Magette, W.L. 1998. Factors affecting losses of nutrients from agricultural systems and delivery to water resources. In: O.T. Carton (ed.) *Draft Guidelines for Nutrient Use in Intensive Agricultural Enterprises*, Teagasc, Johnstown Castle Research and Development Centre, Wexford, Ireland, pp. 6–31.

McGarrigle, M.L. and Champ, W.S.T. 1999. Keeping pristine lakes clean, Loughs Conn and Mask, Western Ireland. *Hydrobiologia*, 395/396: 455–69.

McGarrigle, M.L. 2001. Eutrophication of Irish waters – From science to legislation and management. Went Memorial Lecture, *Occasional Papers in Irish Science and Technology*, 24: 1–18.

MCOS, 2002. *Three Rivers Project: Final Report*. M.C. O'Sullivan Consulting Engineers, Dun Laoghaire, Co. Dublin, Ireland. (Now part of RPS Ireland.)

Melland, A.R., Gourley, C.J.P., Smith, A.P., Tarbotton, I.S.and Peverill, K.I., 2004. *Developing a Farm Nutrient Loss Index for Grazed Pastures in Australia. Supersoil 2004, 3rd Australian New Zealand Soils Conference, 5–9 December 2004*, University of Sydney, NSW, Australia.

Morgan, G., Xie, Q. and Devins, M., 2000. Small catchments – NMP (Dripsey)-water quality aspects. In: *Quantification of Phosphorus Loss from Soil to Water: Final Report and Literature Review*. Environmental Protection Agency. Co. Wexford, Ireland.

Nasr, A.E. and Bruen, M. 2005. *Eutrophication from Agricultural Sources: A Comparison of SWAT, HSPF and SHETRAN/GOPC Phosphorus Models for Three Irish Catchments. (2000-LS2.2.2-M2) Final Report*. Environmental Protection Agency, Co. Wexford, Ireland.

Pionke, H.B., Gburek, W.J., Sharpley, A.N, and Zollweg, J.A., 1997. Hydrological and chemical controls on a phosphorus loss from catchments. In: *Phosphorus Loss from Soil to Water*. H. Tunney, O.T. Carton, P.C. Brookes and A.E. Johnston (eds), Centre for Agriculture and Biosciences International, Oxon, England. pp. 225–42.

SAS (Statistical Analysis System), 1985. *SAS User's Guide: Statistics 5th Ed*. SAS Institute, Cary, North Carolina, USA.

Sharpley, A.N., Daniel, T.C. and Edwards, D.R. 1993. Phosphorus movement in the landscape. *J. Prod. Agric*., 6(4): 492–500.

Sharpley, A.N. and Rekolainen, S., 1997. Phosphorus in agriculture and its environmental implications. In: H. Tunney, et al. (eds.) *Phosphorus Loss from Soil to Water*, Center for Agriculture and Biosciences International, Oxon, England, pp. 1–54.

Sharpley, A.N., Weld, J.L., Beegle, D.B., Kleinman, P.J. A., Gburek, W.L., Moore, Jr., P.A. and Mullins, G. 2003. Development of phosphorus indices for nutrient management planning strategies in the US *J. Soil Water Conserv*., 58: 137–52.

Toner, P., Bowman, J., Clabby, K., Lucey, J., McGarrigle, M., Concannon, C., Cleneghan, C., Cunningham, P., Delaney, J., O Boyle, S., McCarthaigh, M., Craig, M., and Quinn, R., 2005. *Water Quality in Ireland, 2001–2003*. Environmental Protection Agency, Co. Wexford, Ireland.

Watson, C.J., Jordan, C., Lennox, S.D., Smith, R.V. and Steen, R.W.J., 2000. Nitrogen in drainage water from grazed grassland in Northern Ireland. *J. Environ. Qual*. 29: 225–32.

Watson, C.J., Smith, R.V. and Mathews, D.I., 2007. Increase in phosphorus losses from grassland in response to Olsen-P accumulation. *J. Environ. Qual*. (in press).

Acronyms

CORINE	Co-ordination of Information on the Environment
CSA	critical source area
Des	desorption category
EPA	Environmental Protection Agency
ERDTI	Environmental Monitoring Research Technological Development and Innovation Programme
FFO PRS	field-factor-only PRS
FRAS	farmyard risk assessment scheme
mNRS	modified nitrogen ranking scheme
mPRS	modified phosphorus ranking scheme
MRP	molybdate reactive phosphorus
NA	nitrogen application rate subfactor
NO_3-N	nitrogen as nitrate
NRS	nitrogen ranking scheme
PRS	phosphorus ranking scheme
REPS	Rural Environment Protection Scheme
WFD	Water Framework Directive