

Environmental RTDI Programme 2000–2006

**EUTROPHICATION FROM AGRICULTURAL
SOURCES – Models and Risk Assessment Schemes
for Predicting Phosphorus Loss to Water**

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Final Report

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by

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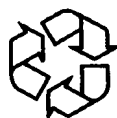
WATER QUALITY

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 this area. The reports in this series are intended as contributions to the necessary debate on water quality and the environment.

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Executive Summary

Phosphorus from agricultural sources is a component of diffuse P pollution delivered to surface waters in Ireland. Understanding the sources and pathways of P loss from grassland soils has become the central theme of much of the research undertaken at laboratory, field and catchment scales in recent years. Mechanistic and process-orientated research on soil P cycling and hydrological pathways tends to be carried out in isolation at laboratory and field scales. Catchment-scale research allows an integration of sources and pathways of P loss that provides an understanding of how these processes interact and contrive to deliver losses to water. Modelling P loss from catchments moves P research from a fundamental level to an applied level, so that results can provide a decision support for catchment managers. Recognised processes in soil P pools and hydrological pathways are combined with agricultural activities (land-use patterns, P usage, timing of applications, stocking density) to generate predictive amounts of P in surface waters. Catchment characteristics, such as arrangement of soil types, land-use patterns and rainfall, can be incorporated into some models to provide a profile of a catchment to determine losses based on the catchment's response to P sources and water movement.

In this present study, three modelling approaches were adopted to capture a range of modelling complexities and methodologies that could be applied to Irish data. Whilst the models shared a common purpose, to describe P loss from catchments and the factors controlling losses, they differed in approach. The three modelling studies captured physically based, empirical and risk assessment (multi-criteria) models. These approaches are represented by the following studies:

- i. Physically based distributed catchment models: Nasr and Bruen (2006) adapted and compared three existing models (Hydrological Simulation Program – FORTRAN (HSPF), Soil Water and Analysis Tools (SWAT) and Système Hydrologique Européen TRANsport (SHETRAN)) to predict flow and P loss from the study catchments reported by Kiely *et al.* (2006).
- ii. Empirical modelling (Daly and Mills, 2006), based on

quantifying soil-type effect and seeking the simplest relationships between catchment variables and water quality data for 84 sub-catchments.

- iii. Multi-criteria analysis or Phosphorus Ranking Scheme (Magette *et al.*, 2006), based on expert judgement informed by measured data to assign scores (risk values) to the variables, weight them according to priority (relative to other criteria), and integrate scores and weights into a single score.

The models used national data sets on land cover (CORINE), soil type (*The General Soil Map of Ireland*, Teagasc Spatial Analysis Group (SAG) soil classifications, detailed county-based soil survey) at field and catchment scales. National data sets on livestock unit density and fertiliser P use (on a District Electoral Division (DED) basis) and soil P levels were also used to varying degrees of success. Field-based data on soil P levels, application rates and timing of P were only available for the test catchment in the Phosphorus Ranking Scheme (Magette *et al.*, 2006) and were collected as part of a catchment-monitoring programme in The Three Rivers Project. Phosphorus desorption data from Daly and Styles (2005) were used in the empirical model by Daly and Mills (2006) to provide information on P chemistry in soil types. Water quality and stream flow data for the physically based models were supplied by the Clarianna, Dripsey and Oona catchment studies (Kiely *et al.*, 2006). The Lough Derg and Lough Ree Catchment Monitoring and Management System and The Three Rivers Project, Water Quality Monitoring and Management supplied water quality and stream flow data for the other two modelling studies.

The results of the modelling studies indicated that physically based catchment models (Nasr and Bruen, 2006), especially HSPF, applied to Irish conditions, can successfully simulate daily mean discharge due to the complex hydrological structure of the model that describes pathways in soils, in detail. These models also simulated P loads to an acceptable degree, but this was largely due to the models' capability in predicting the flow component used to calculate loads. Simulation of P concentrations in surface waters were unacceptable due to discrepancies between simulated and observed values,

and this was attributed to the models' generic approach to soil P and lack of suitable input data on P loadings, such as soil test P values and recorded amounts of P usage.

The empirical model (Daly and Mills, 2006) established significant correlations between flow-weighted P in surface water and soil P chemical processes (desorption) and run-off risk in soils based on % gley. A backward-stepwise regression model retained land-use categories (Unimproved Pasture and Arable) from CORINE, and P desorption and soil test P as significant ($p < 0.05$) variables that accounted for 41.4% of the variation in flow-weighted ortho-phosphate (fwOrtho-P) data across 84 sub-catchments. Sub-catchments with a predominance of soils described as high desorption risk combined with high run-off risk had significantly higher fwOrtho-P concentrations in surface water compared with sub-catchments with soils classified as low desorption and low run-off risk.

A modified Phosphorus Ranking Scheme (mPRS) (Magette *et al.*, 2006) was developed based on field data on soil drainage classification, desorption risk, soil P level, P usage and timing, transport distance and connectivity. Overall scores for fields and sub-catchments were significantly correlated with edge-of-field P losses and surface water quality. The mPRS was shown to have potential to delineate catchment 'hotspots' on a field basis and highlighted the influence of riparian zone fields in delivering P to streams.

The implications of the research conducted in this study of modelling of phosphorus loss and of the risk of phosphorus loss are combined in the context of the Water Framework Directive's (Council of the European Communities, 2000) future risk assessment of river basin districts (RBDs). The modelling research concluded that P input parameters should include soil test P level (Morgan's P) as an indicator of agricultural pressure. National soil P test data (field-scale) do not currently exist and are recommended for future risk assessment. Soil-type desorption indices derived in this study can be applied to national data sets currently being distributed to RBD managers and should be used to incorporate a soil-type effect in risk assessment. Physically based models have the capability to model daily discharge values from Irish catchments where enough monitoring data exist for model calibration and validation. For priority catchments identified in an initial risk assessment, soil hydrological risk assessment needs to be carried out on a detailed level, using either drainage classifications from detailed county-based soil survey maps or the field methodology for hydrological risk, used in the Ara catchment, and tested in the study of Magette *et al.* (2006). It is also recommended that a detailed county-based soil survey be completed for the rest of the country so that the relevant soil information can be accessed for all RBD and future studies.

1 Introduction

The Water Framework Directive (WFD) has been cited as one of the most comprehensive and complex pieces of water-related legislation from the EU. The Directive requires all waters to achieve good status by 2015 by providing a legislative framework for the protection and improvement of water quality, the main unit of which is the River Basin District (RBD). A wide range of tasks have been assigned to the Irish EPA in the implementation of the WFD and the most recently completed characterisation and risk assessment document (Article 5) was submitted to the EU in March 2005. This document outlined a proposed methodology for diffuse pollution risk assessment for RBDs and authorities responsible for implementing the WFD in Ireland. This methodology was designed to use nationally available data sets that could be utilised by each RBD. The 'water body' (which included all streams except 1st-order streams $<10 \text{ km}^2$) was defined as the unit of assessment. Four categories of risk were decided upon, into which water bodies could be placed using a 'Pressures' and 'Impacts' analysis of all water bodies. The risk categories were:

- 1a at risk
- 1b probably at risk
- 2a probably not at risk
- 2b not at risk.

Agriculture is one of many sources of diffuse pollution identified and the 'Driver' or 'Pressure' identified for agriculture was listed as "nutrients from organic and inorganic fertilisers, pesticides, siltation from grazing, ammonia from silage or slurry, agricultural fuel oil". The 'Impact' data included the water quality status of water bodies, and the general methodology for diffuse pollution risk assessment involves assessing the data on pressures in conjunction with available water quality data for each water body.

A risk assessment of general diffuse pollution (i.e. not specifically agriculture) has been carried out by the EPA and a predictive model to estimate the likelihood of a water body achieving 'good status' (by 2015) has been developed using CORINE land-cover classes: Pasture,

Arable and Urban. From this model, threshold % land-cover classes in each catchment have been calculated, above which water bodies had a >0.75 probability of not achieving Q4 status. For grassland and arable land-cover categories, the % coverage thresholds were 37% and 1.3%, respectively.

Consultancies appointed to undertake River Basin Management projects will be responsible for risk assessment in each RBD and will use nationally available data sets to do so. In terms of diffuse pollution, some of these data include CORINE 2000, Teagasc, Spatial Analysis Group (SAG) soils and subsoil classifications, a national digital terrain map (that was developed and described by Daly and Mills (2006)), livestock unit density (Department of Agriculture Food and Forestry) and Central Statistics Office (CSO) data on fertiliser N and P use on a District Electoral Division (DED) basis.

Modelling diffuse sources of P has embraced hydrological pathways and sources of P from land to water. It is recognised that water movement is the transport agent for P transfer to water, whilst the influence of soil and agronomic practices are considered as the source compartment. There are two main approaches to modelling the relationship between physical characteristics of the catchment and the water quality of the run-off from the catchment: (i) empirical (data-derived) relationships and (ii) physically based (or process-based or mechanistic) modelling. Both are quite different. The empirical approach seeks the simplest relationship between the relevant variables, while the physically based approach seeks to build up an understanding of what is happening and where in the catchment. They are complementary in terms of purpose and usefulness. The empirical equation approach may be best used for assessing or classifying catchments according to their water quality risk in addition to identifying factors controlling diffuse P losses. The approaches are also complementary in terms of the appropriate time and space scales at which they can be used. Both the empirical and physically based approaches are summarised and their results integrated in conclusions and recommendations in this document.

The research reported here developed models that explored the sources of P and the hydrology that transports P to water. Three approaches were adopted and are briefly described as follows.

- i. Physically based distributed catchment models: Nasr and Bruen (2006) adapted and compared three existing models (Hydrological Simulation Program – FORTRAN (HSPF), Soil Water and Analysis Tools (SWAT) and Système Hydrologique Européen TRANsport (SHETRAN)) to predict flow and P loss from the study catchments monitored in Kiely *et al.* (2006).
- ii. Empirical modelling (Daly and Mills, 2006), based on quantifying soil-type effect and seeking the simplest relationships between catchment variables and

water quality data for 84 sub-catchments.

- iii. Multi-criteria analysis or Phosphorus Ranking Scheme (Magette *et al.*, 2006), based on expert judgement informed by measured data to assign scores (risk values) to the variables, weight them according to priority (relative to other criteria), and integrate scores and weights into a single score.

This document provides an overview of the approaches and results from each of the above three modelling studies. The modelling studies are discussed and compared in terms of their overall predictability and understanding of source and transport processes. The applicability of the modelling approaches is then discussed in the context of the WFD and conclusions and recommendations are incorporated into that discussion.

2 Physically Based Modelling – A Comparison of SWAT, HSPF and SHETRAN/GOPC Phosphorus Models for Three Irish Catchments (Nasr and Bruen, 2006)

2.1 Approach

The physically based modelling approach selected three readily available models and applied them to the three mini-catchment areas monitored by Kiely *et al.* (2006). The models were SWAT, HSPF and SHETRAN. The approach adopted here assumes that non-point P loss is described by three components: water, sediment and P. Any given catchment may contain several different soil types and land-use patterns, the physically based model breaks up a catchment into uniform spatial units, known as hydrologic response units (HRUs) which are described by only soil type and land use. The number of HRUs depends on the extent of variation of soil type and land-use patterns across a catchment.

To implement the models on the three catchments, spatial data on land use, soil type and topography were used. Land-use classes for the catchments were extracted from the CORINE database, soil type represented by soil associations from the General Soil Map of Ireland (GSM) and the digital elevation map (DEM; described by Daly and Mills (2006)) was used to describe slope and main channel length. Physical properties of each soil association, namely, soil texture, taken from the explanatory bulletin to the GSM, were related to properties tabulated in the model that included saturated hydraulic conditions, soil hydrolic group, porosity, water content at field capacity and wilting point. In addition to these data on soil type, land use and topography, the models also required meteorological data on rainfall, temperature, wind speed, relative humidity and solar radiation that were collected from weather stations at or near the mini-catchments. These data were used to predict daily discharge for each of the mini-catchments. The models used fertiliser P application to predict P concentrations in surface water. The annual P application rate was assumed to be 15 kg/ha for the Clarianna and Dripsey. The models converted fertiliser P (using equations) into soil P fractions, from which soluble and particulate P in overland flow were computed. Stream P

concentrations (soluble and particulate) were then derived from P in overland flow. Phosphorus loads (concentration \times flow) were calculated for each catchment using predicted flow and P concentrations. The models simulated these data on a daily basis for each catchment and the outputs from the models included average daily discharge, average daily total P concentrations and loads, average daily dissolved reactive P concentrations and loads.

2.2 Summary of Results

In general, the models simulated daily mean discharge values comparable to observed flow data collected from the three catchments monitored by Kiely *et al.* (2006) and HSPF was the better model in simulating flow data. The SWAT flow simulations were generally acceptable but SHETRAN showed some deficiencies in simulating flow that were attributed to the structure of the model and its sensitivity to parameters and spatial scale. The R^2 values calculated for simulated flow were high and ranged from 0.74 to 0.95 across the three mini-catchments. The best total phosphorus (TP) loads (using simulated flow data) for the Clarianna and Oona catchments were derived from SWAT, whilst the grid-oriented P component (GOPC) written for SHETRAN simulated best the results for the Dripsey. The best R^2 values for TP loads ranged from 0.51 to 0.59 across the three mini-catchments. Dissolved reactive P (DRP) loads simulated by the models showed large discrepancies with observed data from the catchments and model results for DRP loads were unacceptable. In addition, the models failed to simulate acceptable concentrations for TP and DRP showing large discrepancies between observed P concentrations and model predictions.

Table 2.1 provides a summary of the best R^2 coefficients from the results of applying SWAT, HSPF and SHETRAN/GOPC to the study catchments used in Kiely *et al.* (2006), i.e. the Dripsey, Clarianna and Oona catchments.

Table 2.1. Summary of the best Nash–Sutcliffe coefficients (R^2) obtained from results of applying SWAT, HSPF, and SHETRAN/GOPC models to the Clarianna, Dripsey and Oona catchments.

	Clarianna catchment		Dripsey catchment		Oona catchment					
	Calibration		Calibration		Calibration		Validation (first period)		Validation (second period)	
	Best model	R^2	Best model	R^2	Best model	R^2	Best model	R^2	Best model	R^2
Discharge	HSPF	0.95	HSPF	0.74	HSPF	0.91	HSPF	0.90	SHETRAN	0.80
Average daily TP* load	SWAT	0.59	GOPC	0.51	SWAT	0.56	HSPF	0.59	HSPF	0.77
Average daily TP concentration	SWAT	0.55	–	No useful value	–	No useful value	–	No useful value	–	No useful value
Average daily DRP* load	HSPF	0.70	GOPC	0.46	GOPC	0.56	GOPC	0.39	–	No useful value
Average daily DRP concentration	–	No useful value	–	No useful value	–	No useful value	–	No useful value	–	No useful value

*TP, total phosphorus; DRP, dissolved reactive phosphorus.

3 Empirical Modelling – Relating Catchment Characteristics to Phosphorus Concentrations in Irish Rivers (Daly and Mills, 2006)

3.1 Approach

This approach sought to model surface water flow-weighted P concentrations using soil classifications, land-use and agricultural management data at multi-catchment scale. Soil processes that characterise P mobilisation from soil to water were incorporated into soil classification databases, so that soil types in catchments could be described not just in terms of their pedogenic classifications but also in terms of their P chemistry and hydrology. Thus, modelling took place at two different scales: laboratory scale and catchment scale. At laboratory scale (Daly and Styles, 2005) data from P sorption isotherms and desorption extractions were used to describe differences in P desorption in a range of soil classifications. These data were used to weight soil classifications relative to each other so that soils could be ranked in terms of P desorption risk.

Quantifying the desorption process at laboratory scale identified other soil chemical factors (in addition to Morgan's P level) such as % organic matter (OM) and soil pH, that influenced the amount of P desorbed to solution. Therefore, at similar Morgan's P levels, P desorption varied according to soil type, and the soil-type factors responsible were %OM and pH. Separating soil types into categories of desorption involved observing P desorption at similar soil test P (STP) values in different soil groups.

Firstly, peat soils represented soils with lowest P desorption to solution owing to their inability to chemically bind P and build up P pools and reserves. Where P reserves do not exist, this provides little opportunity for desorption to solution to occur and this may explain the significantly lower desorption rates in these soils compared to mineral soils. However, the lack of sorption capability in these soils does indicate a vulnerability to P loss if fertiliser and manure P are applied outside the growing season; therefore these soils are vulnerable due to a lack in sorption capability rather than high rates of desorption to solution. For the purposes of this study, soils are risk ranked based on desorption rates over similar

ranges of STP and, due to a lack of P storage and reserves, with lowest desorption rates, peat soils are ranked as lowest risk.

Secondly, among mineral soils, non-calcareous and calcareous soils showed a significant difference in P desorption, such that non-calcareous soils desorbed more P to solution than calcareous soils, at high Morgan's P levels. Furthermore, non-calcareous soils displayed highest sorption capacities and highest desorption rates compared to calcareous mineral soils. High sorption capacities (with high Al and Fe) indicate a greater potential for P storage and build-up of P reserves, that presents a greater likelihood of P release to water at high STP levels, during periods of overland flow. Gburek *et al.* (2000) suggest that most soil P losses originate from relatively small critical source areas where high soil P levels coincide with high hydrological connectivity. Data from this study showed that high Morgan's P soils from non-calcareous soils desorbed more P than high Morgan's P soils from calcareous soils, which suggests more intense critical source areas in non-calcareous soils compared to calcareous soils. The relationship between Morgan's P and P desorption derived for each soil category of soil (peat, non-calcareous and calcareous mineral soil) was used to quantify their relative risk of P desorption and weight each soil group in terms of risk of P loss by desorption. These weights were applied to the SAG soil classifications, namely, acidic mineral, basic mineral and peat soils. However, regardless of these differences between soil categories, Morgan's P alone remained a good predictor of P desorption from soil to solution, confirming that high STP generates high P desorption (and potential for loss) to solution. This concurs with earlier work by Daly and Casey (2003) which concluded that Morgan's P to 10 cm was a good indicator of risk of P loss from soils.

At catchment scale, the study collected water quality data from catchment studies such as the Lough Derg and Lough Ree Catchment Monitoring and Management System and the Three Rivers Project, Water Quality

Monitoring and Management. One hundred and sixty-one sub-catchments were identified and suitable stations used to calculate flow-weighted ortho-phosphate (fwOrtho-P) concentrations on an annual basis, averaged over a 4-year monitoring period. However, in the final analysis, 84 sub-catchments were used since areas without 100% SAG soils coverage and identified point sources were screened out of the data set. For each sub-catchment area, land-cover data from CORINE were extracted and categories such as % land-cover classes such as Arable, Improved Pasture, Unimproved Pasture, Semi-natural Areas and Peat were extracted from a GIS. Agricultural management data on livestock unit density (LUD) and fertiliser P use were collected from the Department of Agriculture, Food and Rural Development and Teagasc, respectively. Soil test P data (Morgan's P) from a Teagasc client Morgan's P database were used to represent soil P levels in sub-catchments. These data, originally on a 10 x 10 km grid basis, were geo-coded to the nearest town and village using address fields in the database. Soil P levels, representing Morgan's P levels in categories 0–6, 6.1–10 and >10 mg/l, were used such that % sub-catchment in each category was extracted for each sub-catchment.

Soil types in sub-catchments were extracted using all existing soil survey databases available in Ireland for each sub-catchment; these included the GSM, the National Soil Survey on a county basis (detailed soil survey) and the SAG Soil Classifications (Teagasc). Each of these soil databases was used for a different purpose. Broadly, the SAG soils delineate soils into mineral and peat soils, and mineral soils are further divided into categories based on parent material (i.e. mineral soils derived from acidic and basic parent material). There are further categories depicting depth and drainage classification, but for the purposes of applying a desorption weighting the SAG soils were divided into three classes (Acidic mineral, Basic mineral and Peat) and each assigned a desorption weighting from the laboratory-scale modelling. For each sub-catchment, an area-weighted phosphorus desorption index (PDI), was calculated based on the sum of area x desorption weight for each soil classification, divided by the total area of the sub-catchment. This provided a single index for each sub-catchment that amalgamated desorption risk over a range of soil types.

The GSM was used to derive a run-off risk class of soil associations based on their % gley. Four run-off risk classes were identified to represent 5–10, 15–25, 50, and

>75% gley in a soil association. An area-weighted run-off risk index (RRI) was calculated for each sub-catchment using the same method as used for the PDI. The detailed soil survey maps were not used in the model but were used for comparative purposes, to compare the extent of poorly drained soil in the SAG data derived run-off risk classes from the GSM with the extent of gleys from the detailed soil survey maps. Similarly, the STP categories were used to calculate a single value or soil P index (SPI) for each sub-catchment.

3.2 Summary of Results

A backward-stepwise regression model of fwOrtho-P in sub-catchments retained Arable, Unimproved Pasture, PDI and SPI as significant variables that accounted for 41.4% of the variation in fwOrtho-P concentrations across 84 sub-catchments. Whilst the regression model accounted for only 41.4% of the variation in fwOrtho-P concentrations, it highlighted some of the soil-type characteristics, namely, desorption and run-off risk, that were positively associated with increasing fwOrtho-P concentrations. The highly significant correlations between fwOrtho-P and PDI ($r = 0.42^{***}$) and RRI ($r = 0.41^{***}$) also suggested that the initial modelling and risk assessment of soil classifications into categories of desorption and run-off risk, whilst not accounting for all of the variation in fwOrtho-P data, were, in principle, correct. The agricultural management data (LUD and fertiliser P use) were not significantly correlated with fwOrtho-P data, and the only management-type variable retained by the backward-stepwise regression model was STP level.

Since each sub-catchment was represented by a single area-weighted index that represented soil P desorption and run-off risk, the critical source areas approach was then adapted by combining desorption risk with run-off risk in an attempt to find sub-catchments with both high PDI and RRI. Although the critical source areas concept typically uses the combined risk of high P loading on soils that are described as high run-off risk, the non-significant correlation between P loading data (LUD and fertiliser P use) suggested that these data may not be accurate enough for use in risk assessment at these scales. The STP data retained in the regression model correlated significantly with fwOrtho-P ($r = 0.29^{**}$) but since these data were based on 1996 soil P results and the geocoding method does not explicitly record the exact farm location, it was decided for the purposes of this approach not to use these data and to consider the process-driven variable

describing desorption risk instead. Since the PDI weighting factors were based on relative desorption rates at high soil P levels, the PDI variable generated for each sub-catchment was used to represent high P loading (or high STP) on soils with a high desorption risk. This approach is represented conceptually in Fig. 3.1 and four categories of risk from low (low PDI + low RRI) to very high (high PDI + high RRI) risk, based on the combination of desorption risk with run-off risk were generated and assigned to each sub-catchment based on this combination of soil properties. These sub-catchments and their assigned risk class are shown in Fig. 3.2. A comparison of fwOrtho-P values in sub-catchments within each risk class confirmed significant ($P < 0.05$) differences between risk classes, with highest fwOrtho-P values in the highest risk class (high PDI + high RRI) and lowest values associated with the low -risk class (low PDI + low RRI). The distribution of fwOrtho-P values between risk classes is represented in Fig. 3.3. A significant positive correlation ($r = 0.46^{***}$) between fwOrtho-P in sub-catchments and risk class confirmed that the combined risk of high desorption potential on soils with high run-off risk was associated with highest values of fwOrtho-P in the surface waters of these sub-catchments.

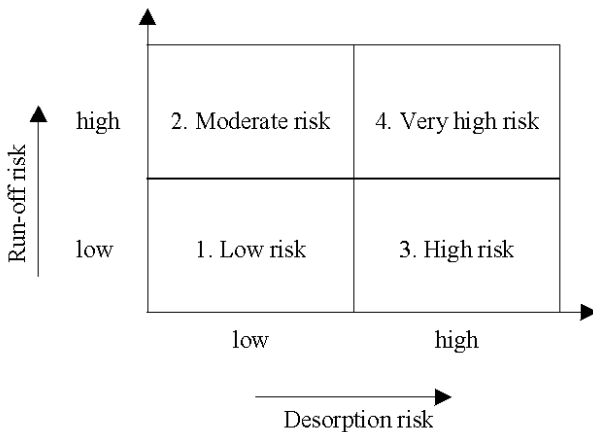


Figure 3.1. Phosphorus desorption risk by run-off risk for sub-catchment soil types.

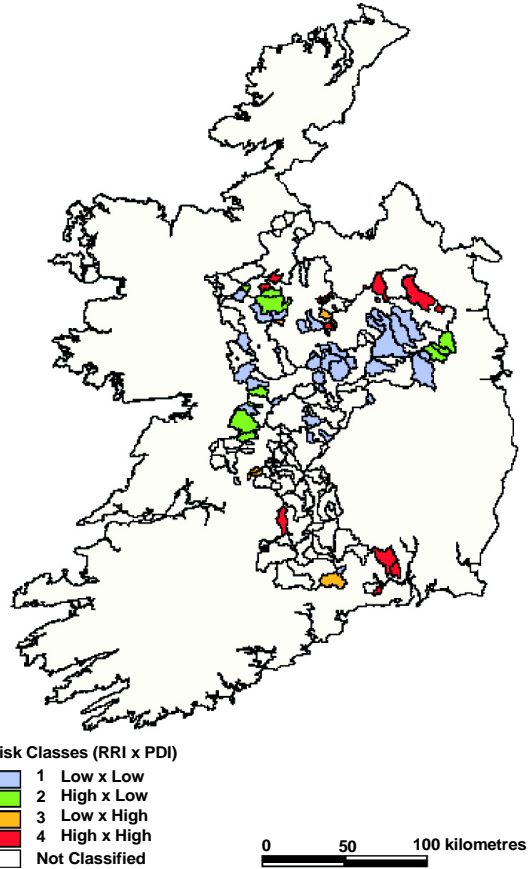


Figure 3.2. Map of sub-catchment areas with assigned risk classes (1–4) based on combined risk of P desorption and run-off in soils.

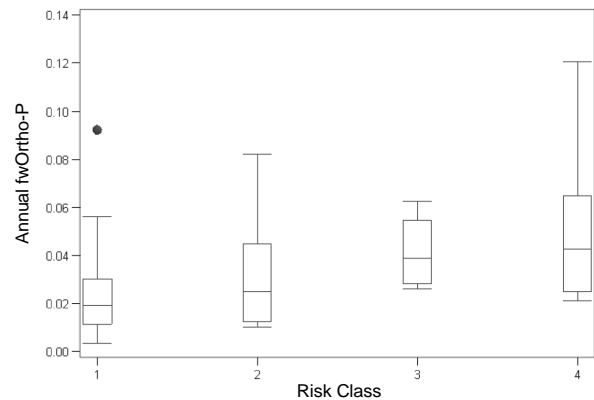


Figure 3.3. Box and Whisker plot showing the distribution of average annual fwOrtho-P values among sub-catchments divided into four risk classes.

4 Ranking schemes – Field-by-Field Risk Assessment (Magette *et al.*, 2006)

4.1 Approach

The field-by-field risk assessment scheme was applied to field and sub-catchment-scale data in Ireland. This approach was originally derived by Magette (1998) for grassland fields in Ireland and uses a common-sense approach to modelling that takes risk factors identified in the literature that contribute to nutrient (N and P) loss from fields. The factors listed rely on STP data (Morgan's P) and P application rate and timing and soil run-off risk based classifications from the GSM.

Initial testing of the original Magette PRS scheme (denoted as Magette PRS) indicated that some adjustments to the scheme were necessary and that more field data were required for further validation. Difficulties identified with the original scheme were addressed by further development of the procedure and a modified PRS (mPRS) was derived. The same concept of listing and weighting factors was applied, but used a more compartmentalised approach whereby field characteristics were partitioned into source and transport factors.

The factors used in the mPRS were divided into source factors and transport factors; these 'compartments' were further divided to represent field-scale processes, which lead to elevated phosphorus loss to water. Besides

structural changes to the mPRS, other alterations also included variation in the factors used in the Magette PRS. The factors included in the mPRS were also combined by way of multiplication and addition as opposed to addition used in the original Magette PRS. The mPRS is detailed in [Tables 4.1 to 4.4](#).

In an attempt to address soil processes identified as contributing factors in P mobilisation from soil, the mPRS incorporated physical soil properties to describe hydrological risk, and soil chemical soil properties were used to describe desorption risk. However, the desorption criteria that Magette *et al.* (2006) have used in this instance are based on previous desorption indices derived by Daly *et al.* (2002) that were applied to the soil associations from the GSM. These desorption classifications divided soil types based on %OM on the basis of previous laboratory work that ranked soil types based on P desorption risk. Daly and Mills (2006) have since updated desorption classification for Irish soils that delineates organic soils from mineral soils and soils derived from acidic and basic parent material, and these have been applied to SAG soils. The desorption risk in Magette *et al.* (2006) was combined with a soil P risk factor by way of multiplication risk to determine the risk of phosphorus loss arising from elevated soil P levels (S2).

Table 4.1. Structure of the mPRS.

Factor	Description	Weighting	Low risk (1)	Medium risk (2)	High risk (3)
S1	P usage rate	1	If P added to Index 1 or 2 soils	If P added to Index 3 soils	If P added to Index 4 soils
	P application timing ¹	0.9	See Supplemental Table 4.2	See Supplemental Table 4.2	See Supplemental Table 4.2
S2	Soil P	0.8	0–6 mg P/l	6.1–10 mg P/l	>10 mg P/l
	Desorption risk	1	Low	Moderate	High
S3 ²	Farmyard risk	0.8	Good	Moderate	Poor
T1	Transport distance	0.75	0–200 m	200–500 m	>500 m
T2 ³	Connectivity	0.75	Low risk due to subsurface and surface drainage	Moderate risk due to subsurface and surface drainage	High risk due to subsurface and surface drainage

¹From [Table 4.2](#).

²From [Table 4.3](#).

³From [Table 4.4](#).

Table 4.2. Supplemental factors for P application factor.

Factors	Low-risk soils	Moderate-risk soils	High-risk soils
Application between 1 May and 1 Sept	1	1	2
Application between 15 Jan and 1 May	1	2	4
Application at other times	1	4	4

Table 4.3. Supplemental scoring system for farmyards.

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	12 weeks>x>2 weeks	<2 weeks
Silage effluent	>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

Table 4.4. Supplemental factors for T2.

Factors	Low risk (1)	Medium risk (2)	High risk (4)
Sub-surface drainage	No sub-surface drainage	Sub-surface drainage, but no direct link to river channel	Sub-surface 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

The hydrological risk of soils was based on drainage classifications from detailed county-based soil survey maps where that information was available. For areas where no detailed soil survey was available, a field-based methodology that observed the extent of mottling in a soil core to 50 cm was used to derive a drainage class. This method was originally used in the National Soil Survey to derive drainage classifications for soil series for detailed soil survey on a county basis in Ireland and identified gley soils in detailed soil survey maps. The field-based methodology was applied to the Ara mini-catchment during the Three Rivers Project to generate a hydrological risk assessment for fields and the results were used in this present study for the Ara mini-catchment. Fields in the Ara mini-catchment were divided into three hydrological risk categories that were described as low, moderate and high risk. This hydrological risk assessment was used in conjunction with the timing of P fertiliser and slurry applications to determine the risk arising from ‘P application timing’. The timing of P applications was categorised based on the time of year when P applications were made. Three categories were determined as follows: applications from May to September, applications from January to May, and applications at other times of the year (September to

January). The P application timing categories were then combined with the hydrological risk categories by way of a simple matrix grid to determine P application timing risk (see Table 4.2). This allowed for P applications during the growing season to be ranked as low risk, relative to the other two time periods. Risk factors associated with the time period used were linked with soil hydrological risk, i.e. the highest risk is described as P applied during high-risk periods (January to May and other times) on soils classified as high hydrological risk, and lowest risk is attributed to P applied between May and September on soils of low hydrological risk. The P application timing risk factor was combined by multiplication with the P application factor to derive an overall factor (S2) for risk of phosphorus loss arising from excessive P applications.

Overall, the source compartment of the mPRS consisted of P usage rate, P application timing (based on hydrological risk of soils), STP and desorption risk. The transport components of the mPRS consisted of transport distance and connectivity. Transport distance is described as the distance between field and stream to gauge how far nutrients must travel to reach a watercourse, whilst connectivity is used to describe the presence (or absence) of subsurface drainage, linking a field to a stream by field drains.

4.2 Summary of Results

The mPRS was tested at sub-catchment scale by dividing the Ara mini-catchment into 12 sub-catchments and applying an mPRS score to each field in a sub-catchment. Since edge-of-field data were not available on a field-by-field basis, the scores for each field were combined to generate an average mPRS score for each sub-catchment. The data used in this analysis were combined by way of ArcGIS, which allowed for the different data sets to be combined on a spatial level, resulting in the generation of 3440 plots with unique mPRS scores. The scores for each of these plots were averaged for the 12 Ara sub-catchments to give an average mPRS score for each sub-catchment. These scores were positively correlated with MRP concentrations at each sub-catchment ($R^2 = 0.28$). Whilst these correlations indicated a good relationship between mPRS scores and measured MRP concentrations, there remained a large amount of unaccounted-for variation in MRP concentrations. It was noted that field-scale data were not uniformly available for each sub-catchment and, for this reason, data were then filtered to remove sub-catchments for which less than 30% of fields had available data. This process improved the relationships between MRP concentrations and mPRS very significantly ($R^2 = 0.59$). A minor alteration was also made to the mPRS, whereby the S1 factor was calculated by way of addition rather than multiplication. This resulted in a dramatic improvement in the regression between the mPRS and the MRP ($R^2 = 0.38$). When this analysis was carried out for sub-catchments having field-

scale data for >30% of the catchment by area the regression improved even further ($R^2 = 0.75$). The regression for the mPRS source factors alone was in general poor and improved greatly with the inclusion of the transport factor (distance), which indicates the importance of the distance from a stream as a factor in determining the risk of phosphorus loss to water.

At field scale, edge-of-field studies carried out at Greenmount Agricultural College, Northern Ireland, supplied data 8 fields and site characteristics and field data were used to calculate an mPRS score for each field. At this scale, soil type was uniform across the study plots; therefore, desorption risk and hydrological risk did not vary between the sites and were not included in the field scores. Differences between field characteristics were observed in STP values and P application rates and field mPRS scores were calculated for each field based on these data. A comparison between mPRS scores and mean DRP ($R^2 = 0.90$) and TP ($R^2 = 0.93$) concentrations in run-off indicated that the predicted risk scores were in agreement with observed run-off data. Similarly, when DRP and TP loads were compared against mPRS scores, there was good agreement between risk scores and observed loads measured at edge-of-field from these sites. The same procedure was repeated for field data collected at sites in Johnstown Castle, Wexford, and mPRS scores (using STP and P usage) correctly predicted the relative export rates of DRP ($R^2 = 0.94$) and total dissolved phosphorus ($R^2 = 0.90$) between the sites.

5 Discussion

5.1 Model Predictability and Understanding the Processes Involved

Whilst the three studies outlined above used different approaches to modelling, they were attempting to address the same problem, i.e. identifying factors controlling P loss from soils so that areas at risk could be identified for future mitigation strategies. One of the objectives of any P model is the ability to predict P loss or simulate observed values. The benefit of developing a model that can predict or simulate P loss is that it identifies areas or factors contributing to high values that might be a cause for concern for water quality managers. In this study, all three modelling approaches endeavoured to predict P loss from catchments. Nasr and Bruen (2006) used three physically based models applied to Irish conditions and successfully simulated the flow component of diffuse P loss from three study catchments in Kiely *et al.* (2006). This was in part due to the detailed hydrological structure of the models that defined pathways of water movement to predict surface, subsurface and return flow that contributed to stream flow. This depended on soil texture from soil associations and meteorological data as inputs to predict flow on a daily basis from catchments. In contrast, the flow component in the modelling study by Daly and Mills (2006) assumed a less detailed approach but, similar to Nasr and Bruen (2006), also used soil association properties as soil-type input parameters. In this study, an RRI was generated on a sub-catchment basis that used % gley in each soil association. These area-weighted indices were generated for 84 sub-catchments and correlated positively with fwOrtho-P concentrations in surface waters. The authors did not relate RRI to flow data exclusively but considered it as a soil-type effect that would contribute to elevated P concentrations in surface waters. Similar to this approach, Magette *et al.* (2006) ranked soils in terms of hydrological risk but, in contrast to Daly and Mills (2006), used drainage classifications from detailed county-based soil surveys to derive a hydrological risk factor that was more detailed and capable of delineating this risk on a field-by-field basis. In contrast to the Nasr and Bruen (2006) approach to modelling of the flow component, both Daly and Mills (2006) and Magette *et al.* (2006) did not relate the hydrological aspects of soils exclusively to flow data, nor

could their hydrological risk assessment predict or simulate flow without the complex structure that the physically based models provided. Therefore, the physically based models can describe the hydrological processes and pathways, thus leading to a greater understanding of catchment hydrology. However, by using the physical properties of soils as input variables (soil texture, drainage class or % gley), all three modelling studies recognised the effect of different soil types on soil hydrology and the potential impact on the transport of nutrients to surface waters.

The P component of modelling diffuse P loss, referred to as the 'Source' compartment by Magette *et al.* (2006) in their field-by-field risk assessment, varied considerably across the three modelling studies. Nasr and Bruen (2006) used estimates of fertiliser P use, not based on actual amounts used but rather on estimates derived from recommended fertiliser P application rates for grassland based on Teagasc advice. In contrast to the other two modelling efforts, STP levels, livestock unit density or fertiliser and manure P use were not considered as P loading factors, despite conclusions in literature from Ireland and elsewhere that these variables, especially STP, are recognised indicators of agricultural intensity. In addition, the Nasr and Bruen (2006) models adopted a generic approach to soil P processes (sorption and desorption) and, as such, did not consider the variation in soil P chemistry that exists in Irish soil types. The models failed to simulate P concentrations in surface waters satisfactorily, possibly due to the lack of P input data on actual applications and soil P levels, and the soil-types response to P loading in terms of desorption risk. The models predicted P loads to an acceptable degree from the three study catchments (Kiely *et al.*, 2006) although this was due to the good simulation of daily flow values from three catchments with varying hydrological characteristics and soil types.

Phosphorus processes in soils were represented in both Daly and Mills (2006) and Magette *et al.* (2006) by using P desorption characteristics of soil types that provided a second soil-type effect, alongside hydrological risk, that contributes to potential P losses from soils. In terms of understanding the P processes in soils, a separate

laboratory study (Daly and Styles, 2005) formed the basis for modelling P desorption in Irish soil types and, when applied to soil classifications (SAG soil map), this proved to be a significant variable in the regression model described by Daly and Mills (2006).

Magette *et al.* (2006) examined the relationship between their source variables (S1 = P usage + timing; S2 = soil P + desorption) and P in overland flow at field scale. Since soil type did not vary across their sites, the main source factors correlating with MRP concentrations and loads in overland flow were STP and P usage. At field scale, Magette *et al.* (2006) linked their source factors, exclusively, to edge-of-field losses of P, further validating the use of agronomic soil P tests as an environmental indicator of risk of P loss from field, which concurs with work carried out by Daly and Casey (2003).

5.2 Combining Risks to Find Hotspots

The three modelling studies discussed here share the common theme of using soil classifications, either from the GSM, detailed soil survey or the recently derived SAG soils classifications as input variables. The studies used the variation in hydrological and chemical properties of soils, in conjunction with other variables, to model P loss at field and catchment scale. Across these studies (and in agreement with findings from Kiely *et al.*, 2006) it is broadly accepted that variation in soil type leads to variation in losses between catchments and indeed from within catchments. Whilst the land-cover area over which agricultural practices occur is a potential source of P loss to water, some areas will present more risk than others. This variation in risk can be attributed to differences in soil types. Magette *et al.* (2006) address this issue in their field-by-field risk assessment by combining their source (P loading) factors with transport factors to generate an overall score for fields within a catchment, thus allowing high-risk areas to be identified on a field basis. In addition, Magette *et al.* (2006) incorporated the risk of timing P applications outside the growing season to soils of varying hydrological risk (low, moderate and high) based on drainage classifications. This allows for a more soil-type-

specific P loading factor to be assessed in a model, by recognising that the timing of P applications on certain soils may not pose a risk, and removes the generic use of a P application factor in a risk assessment approach. In terms of predicting P loss based on combining source and transport risk, the mPRS of Magette *et al.* (2006) was tested on 12 sub-catchments within the Ara catchment and showed good agreement with MRP concentrations, although the paucity of field data for some sub-catchments may have affected their model's performance, only accounting for 27–38% of the variation in MRP concentrations. It should be noted, however, that the model's performance was improved dramatically ($R^2 = 0.59-0.75$) when sub-catchments were excluded from analysis if <30% of the catchment area was described by actual field-scale data. Results from this analysis also highlight the importance of the distance of the fields from the river channel, as the inclusion of the transport factor in the mPRS improved the regressions dramatically.

Daly and Mills (2006) used a similar concept by combining run-off risk with desorption risk, but on a whole sub-catchment basis as opposed to a field basis. Soil classifications and associations were used to derive a single areas-weighted desorption index and run-off risk index, respectively, for each sub-catchment. These were combined in a matrix to identify four possible combinations of low/high run-off risk coinciding with low/high desorption risk. Four risk categories emerged and the fwOrtho-P data for sub-catchments in each risk class confirmed that sub-catchments with a high desorption and high run-off risk index had significantly higher fwOrtho-P concentrations. This method allows for combined risk assessment on a sub-catchment basis and could only identify hotspots within a catchment where the soil information is at a more detailed level than that available using the GSM. However, similar to the mPRS for catchments of Magette *et al.* (2006), a single risk class was generated based on the unique composition of soils in each sub-catchment that contrived to deliver diffuse P to surface waters.

6 Conclusions and Implications

The overall conclusions integrated from the three studies modelling P loss from soils can be summarised as follows:

- Physically based models, specifically HSPF, can be adapted to Irish catchments and used successfully to simulate daily mean discharge; however, these models need more input parameters related to soil sorption and desorption processes in order to simulate acceptable P concentrations in surface waters.
- The mPRS field-by-field risk assessment appeared to be an effective tool at field scale and has the potential to make assessments at catchment scale, provided that sufficient detailed information on soil type (hydrology) exists or can be assessed using a field methodology for drainage classification. At catchment scale, this risk assessment approach should be tested on a broader range of catchment areas for more robust validation.
- The mPRS has the potential to identify catchment hotspots on a field basis and identify a riparian zone influence on surface water quality, provided that a comprehensive field data set is collected for all fields.
- The modelling approaches of Magette *et al.* (2006) and Daly and Mills (2006) identified the importance of STP levels and desorption characteristics of soil types on modelling P loss from soils. However, it is recommended that future field-by-field risk assessment includes updated desorption criteria for soils based on Daly and Styles (2005) applied to soil classifications from the SAG soil map.
- Risk assessment, either at field scale or sub-catchment scale, that included combined risk of soil hydrology, desorption, or P usage can delineate field or sub-catchments at highest risk.

6.1 Implications for Risk Assessment under the Water Framework Directive

Future risk assessment carried out under the WFD will have to address agricultural P inputs to surface waters using nationally available data sets. The methodology

recently submitted to the EU under Article 5 will use a classification system to initially highlight situations where problems meeting the requirements for good water quality are likely to occur. Water bodies falling into the 'at risk' or 'probably at risk' categories will then be singled out as priority areas for follow-up studies.

The results from modelling studies reported here have implications for future RBD risk assessment of diffuse P loss from agriculture. Risk assessment adopted by each RBD should consider the effects of soil types outlined in this study, in conjunction with pressures. Agriculture pressures defined as P inputs (stocking rate and fertiliser P use) used exclusively in a risk assessment assumes that all soil types (including transport pathways) are the same across a catchment. Soils vary in their response to rainfall and P inputs, using soil hydrology and P desorption processes from soil to solution. Soil characteristics such as drainage classification, STP level, %OM and soil pH have been identified by laboratory-, plot- and field-scale studies carried out on Irish soils as soil properties that contribute to potential P loss from different soil types (Daly and Casey, 2003; Daly and Styles, 2005; Doody *et al.*, 2006; Kiely *et al.*, 2006; Kurz and O'Reilly, 2006). Therefore, it is essential that future P modelling and risk assessment studies carried out in Irish catchments incorporate all existing soil information and data that contribute to potential losses to water.

The national database on soils, which currently exists in Ireland, includes a classification system from the SAG on acidic mineral, basic mineral and peat soils that can be utilised and quantified in terms of their relative risk of P desorption. Detailed county-based soil survey maps exist for 44% of the country and have been shown in this study to provide drainage classifications for soils that can be applied to fields and catchments. Therefore, any initial classification or 'flagging' of water bodies, that may not achieve good quality, should incorporate as much soils information as possible, in conjunction with P data, to identify priority areas for follow-up studies. It is recommended that the detailed soil survey is completed for the remainder of the country to provide essential soils information for reliable risk assessment and a reliable programme of measures that will ensue. Furthermore,

detailed soil information should be used in conjunction with P data and meteorological data to assess the soil-type response to these variables and to provide a framework for a programme of measures based on soil type and local conditions.

The results from the studies reported here provide the criteria for desorption and hydrological risk that can accompany nationally available data on soils in Ireland. In terms of pressure or source factors, the agronomic soil P test can be used as an indicator of potential P loss from soils, at field (Daly and Casey, 2003; Magette *et al.*, 2006) and catchment scale (Daly and Mills, 2006; Magette *et al.*, 2006). Therefore, STP levels, on a field basis, should be incorporated as a 'pressure' factor in RBD risk assessment for P loss to water. However, since reliable data on STP values do not exist on a national scale, a national soil P testing programme should be developed as an additional data set that can be disseminated to each RBD. The link between STP levels and risk of P loss from soils is now so well established that it would provide a more scientific basis as a P 'pressure' than fertiliser use

and livestock density reported from surveys on a DED basis. Furthermore, since difficulties in using national data sets recorded at DED levels for livestock density and fertiliser P use at catchment level have already been identified in this work (and noted by the EPA in their surface water guidance documents under Article 5), the inclusion of accurate and reliable STP data is a fundamental component of P risk assessment. A national soil P testing survey is recommended not only as a basic data set for risk assessment in RBD but also to identify excessively high soil P areas on high-risk soils. Soil test P levels are essential, not only as an indicator of risk *per se* but, coupled with information on soil type (drainage classification and chemistry), the most intense areas of loss within a catchment could be identified as soils carrying high hydrological and P desorption risk at excessively high STP levels. A national soil P testing survey should consider testing on a field-by-field basis, so that the information could be compatible with field-by-field risk assessment schemes (Magette *et al.*, 2006) and provide some detailed agronomic information to farmers.

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