QUANTIFICATION OF PHOSPHORUS LOSS FROM SOIL TO WATER

END OF PROJECT REPORT

ARMIS 4365

Project Coordinator

Dr. Hubert Tunney
Teagasc, Johnstown Castle Research Centre,
Wexford, Ireland

Principal Project Participants and Authors
B. Coulter, K. Daly and I. Kurz, Teagasc, Johnstown Castle
C. Coxon, D. Jeffrey and P. Mills, Trinity College Dublin
G. Kiely and G. Morgan, University College Cork

Johnstown Castle Research Centre, Wexford

August 2000

ISBN 1 84170 115 7

This project was part-funded by the European Regional Development Fund throught the Operational Programme on Envinonmental Services 1994-1999

Teagasc
Agriculture and Food Development Authority

EUROPEAN UNION

European Regional
Development Fund

Teagasc, 19 Sandymount Avenue, Ballsbridge, Dublin 4.

TABLE OF CONTENTS

LIST OF FIGURES

Page No

EXECUTIVE SUMMARY

This was a joint project between three partners, Teagasc, Trinity College Dublin and University College Cork, that started in April 1996 and finished in December 1998. The project was part funded by the European Regional Development Fund (Operational Programme on Environmental Services, 1994-99) through the Environmental Protection Agency. The total cost of the project was over £0.25m, the EPA provided £0.125m and the partners provided the remainder.

The methods, results and discussion of the project are in five separate sections, 4.1) Phosphorus (P) export from agricultural grassland with overland flow and drainage water (Johnstown Castle); 4.2) Phosphorus export from farm in Dripsey catchment, Co. Cork (NMP); 4.3) Hydrometeorological aspects of farm in Dripsey Catchment (NMP); 4.4) Phosphorus desorption from Irish soils; 4.5) National phosphorus model. Most of the field and laboratory studies were carried out at Johnstown Castle, at UCC and the field site in the Dripsey catchment.

The main aim of the project was to quantify the loss of P from soil to water where point source contributions from farmyards were not high. This involved the construction of hydrologically isolated field sites where the quantity of overland flow and the P concentrations for different runoff events from the fields could be measured. In addition, 90 soil samples representative of Irish soils were collected and analysed for the different factors influencing soil adsorption and desorption of P. These results, in addition to catchment data, were used as a first attempt at developing a model that could be used to help predict P loss from soil to water at a catchment scale. The study in the Dripsey was on a farm where water flow and P levels at two points in a stream were measured. The hydrometeorology at this site was also studied. At Johnstown Castle, three overland flow sites, of the order of one hectare each, and one subsurface flow site were studied for P loss to water.

The results of this project provide information, for Irish conditions, on the factors influencing P loss from agricultural soils to water. This report provides a basis for further work and for more rational management of land resources to reduce eutrophication due to P loss from soil to water.

The details of the methods, results and discussions of the five main parts of the study are outlined in the Final Report submitted to the EPA. This End of Project Report summarises the information in the Final Report, together with overall conclusions and recommendations. Additional work on a wider range of soil and farm conditions would be necessary in order to obtain more accurate information on a national scale.

Some of the key findings from the project are summarised as follows:

(1) Soil test phosphorus (P) levels increased tenfold in Irish soils over the past 50 years. From 1980 until 1997 fertiliser P use was about 60,000 tonnes per year. However, the average soil P test continued to increase. This indicates that the quantity of P fertiliser is higher than necessary to maintain soil fertility. Fertiliser P use decreased to 49,000 tonnes in 1998, this is a positive sign both for the competitiveness of farming and for the environment. There is room for further reductions.

(2) The higher the soil test P (STP), the higher will be the potential P loss to water. Based on the limited number of sites in this study, there was a positive relationship between soil test P and P loss to water. This is in agreement with results from other countries. The results from this study indicate that, for good water quality, the STP should be at the lower end of the scale for optimum or near optimum agronomic production (Teagasc Soil Index 2).

(3) The higher the degree of P saturation in the soil, the higher the risk of P loss to water. Soils have a capacity to hold P and this varies depending on soil properties, such as organic matter, Al and Fe. For example, soils with a high content of iron and aluminium have a high capacity to bind P, while sandy and peat soils will generally have a lower capacity to bind P. Peat soils have lower sorption and desorption values than mineral soils, at broadly similar STP levels. This indicates that peat soils, with lower amounts of P binding cations (e.g. Al and Fe), are unsuitable for heavy applications of P fertiliser or manure. In this work mineral soils were up to 79 percent saturated with P, with high desorption rates at elevated STP. These soils are particularly susceptible to P loss to water.

(4) In Ireland, over 90 percent of agricultural land is devoted to

grassland. Fertiliser and animal manures are added to the soil surface each year, and most of it tends to accumulate in the top couple of centimetres (top inch). In this situation, the soil surface can easily become saturated or nearly saturated with P. In many soils, when heavy rainfall occurs, water can run over or infiltrate through this P-enriched surface soil and carry significant amounts of P with it. This, in turn, can enrich surface water and contribute to eutrophication.

(5) Water soluble P (DRP) loss to water from an intensively grazed grassland field, at Johnstown Castle Research Centre, was found to be over 4 kg P per ha per year. This field received 30 kg fertiliser P per ha per year for the past 30 years and had a soil test of 17 (mg P per litre soil). This was about six times higher than on a less intensively farmed grassland field that received very little P fertiliser in the past and had a soil test of 4. The average DRP concentration in the water from the high P site was about ten times higher than the low one.

(6) In 1997, there were several events of high summer rainfall and these events resulted in high P concentrations in the overland flow water. In general, the higher the level of overland flow the higher the concentration of P in the water. This means that high flows are coupled with high P concentrations. The P loss load is highest after a relatively small number of heavy rainfall events during the year. Most of the P loss can occur in about ten days of the year after very heavy rainfall.

(7) At one site, in Co. Cork (Dripsey), where the contribution from the farmyard was investigated, it was estimated that about 30 percent of the total P losses for the farm came from the farmyard and the remaining 70 percent came from the fields. This included losses from soil P and loss after spreading fertiliser and animal manure.

(8) Phosphorus datasets were collected for 35 river subcatchments, using water quality and stream flow data in conjunction with agricultural and land use datasets. In this initial study, which modelled P loss from soils in Ireland, there appeared to be a good relationship between catchment characteristics and measurement of P concentrations.

(9) Hydrological studies at one site (Dripsey, Co. Cork) showed 1443 mm of annual rainfall, 416 mm evapotransporation and 1081 mm of stream flow. Sub-surface flow accounted for 80 percent and surface overland flow accounted for 20

percent of the total annual streamflow. An interflow layer, mainly at a depth of between 10 and 40 cm below the soil surface, appeared to be responsible for the transport of a significant proportion of the dissolved P to the stream at this site. The shallow type of water table found in this hillslope predisposes the riparian zones (about 100 m on either side of the stream) to frequent periods of saturation. Phosphorus spread on such riparian zones is highly susceptible to being lost to streams. The assessment of the water table depth should be part of any strategy for nutrient management because of the high risk that water tables close to the surface pose for nutrient transport.

1.0 INTRODUCTION

The Environmental Monitoring, R&D sub-programme of the Operational Programme for Environmental Services (1994-1999) was allocated £2.4m by the European Regional Development Fund (ERDF) for shared cost research. The sub-programme had a number of objectives, including improving resource management, provision of more environmentally acceptable goods and services, promotion of better environmental quality, improvement in environmental monitoring to help evaluate the impact of development on the environment and sustainable development, and finally support the innovative solutions to environmental problems. This study addresses several of these objectives.

In the region of 5 percent of the £2.4m allocated was provided to help fund this project. The project was entitled Quantification of Phosphorus (P) Losses to Water due to Soil P Desorption. The contract was awarded to a multi-disciplinary study team led by Teagasc, Johnstown Castle, Co. Wexford. Work started on the project in early 1996 and was completed in 1999.

Three organisations, Teagasc, TCD and UCC, participated in the study. A number of staff in these three organisations devoted time to the study. In addition, two postgraduate students were recruited, under the Teagasc Walsh Fellowship scheme, to work at Johnstown Castle on the project and both registered with TCD for PhD degrees.

The work programme for the project is in five separate sections dealing with: 4.1) Phosphorus (P) export from agricultural grassland with overland flow and drainage water (Johnstown Castle); 4.2) Phosphorus export from farm in Dripsey catchment, Co. Cork (NMP); 4.3) Hydrometeorological aspects of farm in Dripsey Catchment (NMP); 4.4) Phosphorus desorption from Irish soils; 4.5) National phosphorus model. All five sections, A to E, with methods, results, conclusions and references are summarised in Chapter 4 of this End of Project Report. The complete details of the results are presented in the Final Report (published by the EPA) and should be consulted for further information and references to relevant publications.

Factors Influencing P Loss to Water

The chemical element phosphorus (P) is essential for plant and animal life. Many of the chemical reactions in living cells involve phosphate ions, where one atom of phosphorus is combined with four oxygen atoms. Phosphate mediates energy transformations in living cells, it is part of the semi-permeable membranes that surround cells and is also part of the genetic material of cells.

Many soils in the world, when unfertilised, are relatively low in phosphorus, and this can have adverse effects on plant and animal health. Phosphorus usually controls primary productivity in most natural ecosystems, both terrestrial and aquatic. Therefore, when P fertilisers were first developed in the last century, and increasingly used world-wide in the 20th Century, they resulted in a dramatic increase in plant and animal production and health.

When soils are low in P, in their natural state, the background loss to water is generally very low, of the order of 0.1 to 0.2 kg P per ha per year or less. As the P content of the soil increases, with the application of fertiliser and animal manures, and the highest energy binding sites are satisfied, additional added P will be held less tightly in the soil and part of this may be lost to water after rainfall. Though the quantities lost from fertilised agricultural land is generally small from an economic viewpoint, of the order of 1 kg P per ha per year, this is adequate to give increased plant (both algae and higher plants) production in rivers and lakes where P is usually the limiting nutrient. This phenomenon of increased plant production in water is referred to as eutrophication and it can have adverse effects on water quality in terms of fish and other organisms that live in water, on the amenity value of water and on the suitability of the water for drinking or industrial use, unless it receives prior treatment.

Phosphorus may be lost to water from point sources, such as municipal treatment plants in towns and cities, from septic tanks attached to dwellings in the countryside (P detergents can be an important source of P from domestic sources) and from some industrial discharges. By contrast, P loss to water from agriculture is usually considered as a diffuse source. The contribution from agriculture relative to other sources will vary depending on the contribution from domestic and industrial sources. In rural areas, most of the loss may be from agricultural sources. Most studies indicate that agriculture can be a significant source of P loss to water, perhaps of the order of 50 percent of the total in Ireland (Water Quality in Ireland, 1991-1994, EPA). If water quality is to be maintained at a high standard, it is necessary to minimise P losses from agricultural sources.

1.1 DIFFUSE P LOSS FROM AGRICULTURE

Phosphorus loss from agriculture may come from fields or farmyards. Direct loss from farmyards to water, either from manure storage facilities and other sources, may be significant, however, they can be corrected by good storage facilities and well managed land spreading. Loss from fields may result from heavy rain shortly after spreading fertiliser or manure, heavy rain on fields where animals are being intensively grazed and, finally, from soil P that has accumulated in the soil over many years of fertilisation. In practice, several of these sources could contribute to P loss to water during a heavy rainfall event.

There are many factors that influence the loss of P from soil to water. These include the relative size of the various P pools in the soil and the rate of exchange between them. Phosphorus pools can be summarised as follows: living biota (1), fresh organic matter (2), more stable organic matter (3), organic P in solution (4), precipitated soluble ortho-P (especially on calcareous soils) (5), ortho-P absorbed (fast) on surface of Fe/Al hydroxides (6), diffusion into soil aggregates and sorption on internal surfaces (7), on colloided material (organic or inorganic) that may be attached to soil (8), dispersed in the soil solution (9), (Wim Chardon, AB-DLO, Netherlands in a paper presented at the EU-COST 832 meeting held at the University of Cordoba, Spain, May 1999).

The main source of P lost to water is either as dissolved ortho-P (inorganic and organic) and P associated with suspended particles.

Wim Chardon (1999, see above reference) has outlined the main factors influencing reaction of P in soils and subsequent loss to water as follows: a) increasing pH can mobilise ortho P, however, on calcareous soils, decreasing pH can lead to dissolution of precipitates and release P; b) ionic strength, low ionic strengths tend to mobilise P attached to colloidal material (e.g. during heavy rainfall); c) organic acid (from plant roots or animal manures) compete with P for sorption sites and increase mobilisation of P; d) redox potential, P attached to iron oxides will be mobilised where iron is reduced from the ferric to the ferrous stage by water logging, application of animal manures etc. e) temperature can tend to mobilise soil P by increasing kinetics of ion movement, mineralisation of organic matter and dissolution of precipitated P. However, it also leads to increased biological activity with increased uptake by plants and soil organisms and increased adsorption onto particles.

The hydrological, biological and chemical processes controlling P loss to water are complex and vary both temporally and spatially. Therefore, all fields or areas within a field do not contribute equally to P loss to water in a catchment. Much of the total annual P export may come from a relatively small proportion (most hydrologically active source areas) of the catchment during a relatively small number (10 to 20) of heavy rainfall events during a year.

2.0 BACKGROUND TO THE PROJECT

The economic implications of the ongoing deterioration of water quality due to eutrophication are important for several reasons including quality food production, the risk of lost tourism revenue, and degraded water resources. This is particularly so, when, on the other side of the cost benefit analysis, it is unlikely that there are any agronomic benefits in increasing soil P values above the current level on most soils. In the region of a quarter of the agricultural area of the country have soil P levels that would be considered excessive, and levels are increasing.

National river monitoring programmes over more than 25 years have revealed a steady increase in the extent of river eutrophication. This is of particular concern in Ireland because of the presence of salmon and trout in most rivers and lakes. This situation is almost unique in Europe. Irish rivers and lakes are generally classified as salmonid waters and these fish may be at risk due to increasing eutrophication.

A number of recent studies in Ireland have highlighted the importance of agricultural P losses, for example, the Lough Conn and the Lee-STRIDE studies. Recent Teagasc publications have shown that soil P is accumulating at about 40,000 tonnes P per annum, with a steadily increasing trend in soil P test values. Teagasc has recently revised the P nutrient advice for grassland and, partly as a result of this, farmers have reduced P inputs by about 10,000 tonnes P per year in 1998 compared with 1996.

Teagasc estimated a saving of £25m per annum to farmers, based on 1996 usage, by reducing artificial P fertiliser use.

Recent evidence, from two international P workshops, one at Johnstown Castle in 1995 and one in Antrim in 1998, indicates that P loss to water is related to a number of factors. One important influence is that the soil test P levels can show a direct relationship with P loss to water. The upward trend of soil P is of concern because small increases in lake or river P concentrations can result in significant eutrophication. Losses of the order of one kg P per ha per year or about 3 percent of agricultural inputs to a catchment may cause serious eutrophication. It is recognised that other sources of inputs, municipal, industrial and septic tanks also contribute to P loss. However, in many predominantly rural areas agricultural activity is a significant or the major contributor to P loss to water. The P losses from agriculture can come from a number of sources, farmyards, fields after spreading fertiliser and animal manures, and by losses from soils that have high soil test P levels.

The increasing soil test P levels on some soils may have long-term implications for water quality, even when other sources of loss have been reduced. Though soil P desorption is only one of the possible sources of agricultural P losses to water, it is potentially the most intractable in the sense it may take many years to reduce high soil test P levels.

Quantification of Soil P Desorption and Loss Rates (Section A, B and D)

The accumulation of P in soils is a long-term source that may prove difficult to reverse. It is necessary to quantify losses due specifically to soil P desorption. However, even in small experimental catchments, it can prove difficult to distinguish between P which is desorbed from soil and P which originates from recently spread slurry, fertiliser or farmyard sources. The Lee-STRIDE study indicated losses of about 2 kg water soluble P per ha per year in a predominantly grassland mini-catchment. This level of loss is not compatible with good water quality.

It was therefore decided in the present study to select field plot catchments to obtain information of P loss from fields where there was no farmyard influence or where an attempt could be made to estimate the loss from the fields independently, of farmyard losses. In addition plots with low soil test P levels that received very little P in fertiliser or slurry were included in the study in an attempt to obtain information on background losses for comparison with intensively fertilised fields.

Soil P Desorption and National P Model (Section B and C)

Soil P desorption during heavy rainfall contributes to P loss to water. There are many aspects of soil physics, chemistry and biology that can influence P desorption and loss to water. It is important to have an understanding of how the different variables influence desorption on different soils. It appears that some soils are more susceptible to desorption than others. This work on the factors influencing P desorption on different soils should help a modelling approach to P loss from different soils on a catchment scale.

Nutrient Management Planning (Sections D and E)

Nutrient management planning (NMP) is now being implemented on many farms as part of good farming practice and is a component of the plans drawn up on farms under the Rural Environment Protection Scheme (REPS). One component of the study was to monitor P loss on a farm in order to obtain information on P loss under current farm practice, with the aim of establishing the benefits of NMP implementation in the future.

3.0 MAIN OBJECTIVES OF THE PROJECT

3.1 TO STUDY SOIL P DESORPTION RATES IN SMALL CATCHMENTS

The main aim of this part of the project was to quantify soil P desorption losses to water from a range of soils and soil P test values. The details of the methodology was decided by the project team and field-scale experimental approaches were considered more appropriate than laboratory or pot experiments.

The approaches used entailed the monitoring of small field catchments with no farm buildings. Aspects, such as, vertical distribution of nutrients and susceptibility of P to mobilisation during different periods of the year, were included as it was felt that these may have a significant bearing on P runoff. This aspect of the work is described in Section A. In addition, Sections D and E also cover part of these objectives.

3.2 PREDICTING P DESORPTION LOSSES FROM A RANGE OF REPRESENTATIVE AGRICULTURAL SOILS

A key objective of the project was to develop a generalised model, based on soil tests, using soil type, soil nutrient status etc., to help predict P loss to water over time in grassland areas. This part of the work included collecting soil samples from representative soils in the country for P sorption and desorption studies and P extraction, using a range of P extractants. This part of the work is described in Section B.

3.3 NATIONAL SOIL P DESORPTION MODEL

A third objective of the project was to make soil P desorption models derived during the project more widely available and accessible to catchment water quality managers. To this end, the project team linked in a geographical information systems (GIS) approach and the soil P desorption results to databases including: soil test P values, digitised land cover maps, river water P concentrations from selected catchments, etc. This GIS modelling approach attempted to predict river P levels and provide predictions for catchments that may lead eventually to a basis for decision making for catchment water management.

It is envisaged that such a GIS-based model may lead to the development of a tool in catchment management and for prediction of P loads to rivers and lakes in Ireland. At present, catchment management committees are faced with ongoing debate as to how much of the agricultural P load comes from farmyards, runoff after slurry and fertiliser spreading, and from soil P desorption.

The approach used should contribute to a better understanding of the importance of soil P desorption relative to the other factors. This part of the work is described in Section C.

3.4 IMPACT OF NMP ON P LOSS IN RUNOFF WATER

The final long-term objective was the possible potential of nutrient management planning (NMP) on farms to reduce P loss to water and break the link between rainfall and stream P concentration. This was approached by installing automatic samplers on carefully selected streams on a farm and measuring stream flow and P concentrations simultaneously over time. This part of the study was intended to obtain baseline information against which future NMP could be measured.

Because NMP takes time to implement and may take a number of years before measurable reductions in water P can be achieved, it was not possible in this three-year study to measure the impact of NMP on reduced P in water. However, it provides a baseline against which future improvements can be measured if NMP is implemented in this or similar catchments. This part of the work is described in Sections D and E.

4.0 METHODS, RESULTS AND DISCUSSION OF THE FIVE SECTIONS OF THE PROJECT

A brief summary of the results and discussions of the five main sections (A, B, C, D and E) is described in this section of the End of Project Report. Detailed information on this section of the study is presented in the Final Report together with a review of relevant literature. Those who are interested in more detailed information on the methods and results should consult the Final Report (available from EPA).

In this chapter (4) the results of sections A, D and E, dealing with the measurement of P loss in the field, are summarised first. This is followed by a summary of sections B and C, dealing with desorption studies in the laboratory on representative soils and national model of P loss.

4.1 PHOSPHORUS EXPORTS FROM AGRICULTURAL GRASSLAND WITH OVERLAND FLOW AND DRAINAGE WATER - JOHNSTOWN CASTLE (SECTION A)

Isabelle Kurz
TEAGASC, Johnstown Castle

Introduction

The main objective of this study was to gain information on phosphorus (P) loss with overland flow from agricultural grassland with different soil P levels. Overland flow from one field of high and one field of low soil P was measured and sampled for 16 months. The variability of the amounts and the P concentrations of overland flow, and changes of P exports during the course of a year, were studied. In addition, the amounts and P concentrations of overland flow from a field of medium soil P level were monitored for five months.

The P concentrations in water from an artificial subsurface drainage network draining permanent grassland were also measured for five months. The drainage network under investigation had been established in the 1970s. It had not been modified for the purpose of this study. The aim of this part of the project was to estimate the P concentration in subsurface drainage water of an existing field drainage system.

Description of the Sites

The main site characteristics and the monitoring periods for the overland flow sites are summarised in Table 1.

Table 1: Site characteristics and monitoring periods of the overland flow sites at Johnstown Castle

Name	Area ha	Morgan's P mg/l	Soil type	Average slope	Monitoring Period
Cowlands	0.46	17	Gley	3°	24.11.96 to 31.3.98
Warren 1	1.54	4	Gley	3°	24.11.96 to 31.3.98
Warren 2	1.09	8	Gley	4°	8.11.97 to 31.3.98

The sites vary in size but are of similar slope. The soil profiles at the Cowlands showed a sandy loam topsoil overlying a loam. At the sites in the Warren, a sandy loam topsoil of 10-20 cm depth overlies a layer of sandy loam and loam. The catchment of the artificial subsurface drainage network monitored in this study consists of about 24.4 ha of grassland on fine to coarse loam and is classified as poorly to imperfectly drained gley. Due to the low density of drains in some parts of the area and the occurrence of overland flow, only a proportion of the precipitation falling on this 24.4 ha area will end up in the subsurface drains. A spring, caught by the drainage network, contributes groundwater to the system. The management practices at each site are outlined in the main report.

Methods

The three overland flow sites were isolated from the surrounding land from a surface water point of view. The overland flow from the sites was collected and measured with the help of tanks fitted with v-notch weirs and water level recorders.

At the Warren 1, an automatic shaft encoder with integral data logger (OTT, Thales) was used to monitor water levels. A discrete automatic sampler (SIGMA 900) took water samples.

Discrete automatic samplers with integral water level recorders (SIGMA 900 Max) were installed at the tanks in the Warren 2 and the Cowlands. A similar system, which also measures velocity, was used for flow monitoring and sampling in the concrete end pipe of the artificial subsurface drainage system.

With a view to the comparability, time-related sampling programmes were operated at the three overland flow sites. Flow-related sampling is more efficient but could not be carried out with the instrumentation at the Warren 1. At the subsurface drainage site, a flow-related sampling programme was worked out based on the information gained by time-related sampling of the first event. The sampling programmes were initiated by a water level rise in the tanks or drain.

The automated ascorbic acid reduction method was used to measure dissolved reactive P (DRP) in filtered (45 µm) samples. The laboratory takes part in the intercalibration scheme set up and run by the Environmental Protection Agency (EPA).

RESULTS AND DISCUSSION

Rainfall

There was very good agreement between the total amount of rainfall collected at the Johnstown Castle meteorological station and at the site in the Cowlands. Between 9 November 1996 and 31 March 1998, 1616.7 mm (100 percent) and 1643.4 mm (101.7 percent) of rain fell at the meteorological station at Johnstown Castle and the Cowlands, respectively. The small overall difference of 1.7 percent suggests that the distribution of rainfall over the Johnstown Castle estate was uniform during the monitoring period. Rainfall at the meteorological station is measured every day, including weekends. The rainfall records from the Cowlands, on the other hand, contain a few summary readings after missed days. The good agreement between the measurements at the two gauges makes it possible to use the more complete dataset from the meteorological station whenever necessary.

The average rainfall of years 1979 to 1995 was 1031.4 mm, the range 879.7 to 1,215.0 mm. The yearly amount of rainfall for the monitoring period at Johnstown Castle meteorological station was estimated to be 1231.8 mm (1,246.0 mm at the rain gauge in the Cowlands). This value is not only higher than the average yearly rain from 1979 to 1995 but also exceeds the maximum yearly rain of that period. Overall, the amount of precipitation during this study was therefore significantly above average.

Of the 80 rainwater samples analysed for DRP (dissolved reactive P), 63 were below the limit of detection (0.005 mg P/l). The maximum DRP concentration of 0.030 mg P/l was measured in the rain sample taken 6th January 1998. The average DRP concentration of the 17 samples above or at the limit of detection was 0.014 mg P/l. Of the 50 samples for which the TDP (total dissolved P) concentration was determined, only 5 were below the limit of detection (0.05 mg P/l). The mean of the other 45 samples was 0.14 mg P/l. The maximum concentration 0.47 mg P/l was measured in the sample collected 7th August 1997. The DRP, inputs through rain are mostly below detection and, therefore, negligible.

Flow

During the monitoring period of 493 days, 1,598 mm of rain was measured at the rain gauge in the Cowlands. For the same period, the Warren 1 produced 1,007 mm and the Cowlands 591 mm of overland flow. These figures translate into yearly amounts of 1,246 mm of rain, 795 mm of overland flow from the Warren 1 and 443 mm from the Cowlands. As December, January, February and March were monitored in two successive years, the averages of the two values for these months were used for the calculation of the yearly values. The high variability of the yearly amounts of rainfall suggests a considerable variation of the amounts of overland flow for different years.

The Warren 2 was monitored for 144 days. The rainfall amounted to 575 mm during this time, and 511 mm of overland flow ran off the Warren 1, 436 mm off the Warren 2 and 328 mm off the Cowlands.

Figure 1 illustrates the monthly overland flow for the Warren 1 and the Cowlands sites. Monthly overland flow values for the Warren 1 exceeded those for the Cowlands. Flow from the Warren 2 was invariably greater than overland flow from the Cowlands but showed no consistent relationship with overland flow from the Warren 1.

DRP Concentrations in Overland Flow

The minimum, maximum and flow-weighted averages of the DRP concentrations for the 22 overland flow events, during the monitoring period December 1996 to March 1998, are displayed in Figure 2 for the Warren 1 and in Figure 3 for the Cowlands.

The figures clearly demonstrate that the Warren 1, the low P site, normally achieved the lowest minimum DRP concentrations. The lowest DRP minima measured at that site were below detection (<0.005 mg P/l). Such low values occurred during events 1, 10, 18 and 22. The minima measured during corresponding events at the Cowlands amounted to 0.130, 0.650, 0.315 and 0.095 mg P/l. Events comparable to 18 and 22 were also monitored at the Warren 2, and DRP minima of 0.012 and 0.084 mg P/l were recorded.

Figures 2 and 3 and table 2 illustrate that the maximum and flow-weighted averages of DRP concentrations of comparable events were generally highest in overland flow from the Cowlands and lowest in overland flow from the Warren 1. The flow-weighted average DRP concentration at the Cowlands was higher than 0.3

mg P/l during all but three events. The flow-weighted average DRP concentrations at the Warren 1, on the other hand, only exceeded 0.3 mg P/l for events 12, 15 and 20 and event 20 consisted of just one sample. The high DRP concentrations of the other two events are likely to be a result of the presence of grazing animals shortly before rainfall. The Warren 1 was grazed for two periods in summer 1997. Events 12 and 15 were the first overland flow events following those periods. There were 13 days of no flow between the removal of the animals and the beginning of event 12, whereas event 15 started the day the bullocks left the site. The presence of grazing animals during or shortly before heavy rainfall may have an important effect on P loss to water.

Table 2: The range of average flow-weighted and maximum DRP concentrations at the Warren 1, the Cowlands and the Warren 2

	Warren 1	Cowlands	Warren 2
Range of average flow-weighted DRP concentrations 24.11.96 to 31.3.98 (mg P/l)	0.011 to 1.050	0.122 to 5.102	
Range of maximum DRP concentrations 24.11.96 to 31.3.98 (mg P/l)	0.011 to 1.385*	0.173 to 6.852	
Range of average flow-weighted DRP concentrations 8.11.97 to 31.3.98 (mg P/l)	0.013 to 0.049	0.122 to 0.697	0.050 to 0.208
Range of maximum DRP concentrations 8.11.97 to 31.3.98 (mg P/l)	0.048 to 0.471	0.173 to 0.721	0.078 to 0.324

* Excessive values due to dirty drain excluded (see main report for details)

The comparison of the DRP minimum, maximum and average flow-weighted DRP concentrations measured in samples from the three sites shows a clear increase of DRP concentrations from the Warren 1 to the Warren 2 to the Cowlands. This trend was broken during the last recorded event (24th to 31st March 1998). The highest maximum DRP concentrations of this event were found in samples from the Warren 1 and the lowest maximum DRP concentrations in samples from the Cowlands. Furthermore, the flow-weighted average DRP concentrations were higher in overland flow from the Warren 2 than from the Cowlands for this event.

DRP levels at the Warren 1 were often high at or near the beginning of events and decreased during the course of events.

There was a similar but less distinct tendency for the Cowlands and the Warren 2.

There were indications of seasonal trends in the DRP concentrations at the Cowlands and the Warren 1. The DRP levels at the Cowlands were higher for the period May 1997 to middle of November 1997 than for the rest of the monitoring period. The concentrations, furthermore, increased from May to the end of August and then dropped again. The trend at the Warren 1 was less clear. However, DRP concentrations were more likely to be high for November to late December 1996, April to early November 1997 and late March 1998 than for other sampling dates.

The elevated DRP concentrations at both sites during late spring, summer and early autumn were at least partly due to the presence of grazing animals. However, the DRP concentrations at the Warren 1 were generally higher for April to June 1997 than for January and February of the same year, even though bullocks were first introduced to that site in July 1997. This and the elevated DRP concentrations at the Warren 2 towards the end of March 1998 point to an additional seasonal influence on DRP concentrations.

Scatterplots of the flow and P data for each site revealed no clear relationships between the two parameters. Scatterplots of P concentrations against flow were then drawn up for samples within every single event. No pattern became apparent in plots from the Cowlands. The only recognisable trend was that the minimum concentration of an event usually occurred at very low flow.

DRP Concentrations in Sub-Surface Drainage Water

In artificial subsurface drainage water, the P concentrations at low flow were invariably below the limit of detection of the analyses. Thus, a negligible quantity of P was imported into the subsurface drainage site by groundwater contributing the spring caught by the drainage network. The maximum DRP levels in subsurface drainage water ranged from 0.015 mg P/l to 1.650 mg P/l and were thus very high at times. Highest concentrations were measured during the first event (November 1997), and after slurry spreading (February 1998).

The scatterplot of the P concentrations against the rates of flow displayed no overall relationship between the P fractions and flow but samples taken at low flow had consistently low P values.

Plots of P concentrations versus flow rates for single events revealed relationships between the two parameters in some cases. Thus the rate of flow had a greater influence on P concentrations in subsurface drainage water than on P concentrations in overland flow.

Phosphorus Export with Overland Flow

Phosphorus loadings are calculated by multiplying the total flow of a time interval by the P concentration measured during that period. Factors leading to variability in the flow and/or P concentration data will therefore also affect P loadings. The result of the interactions between the trends of the flow and P concentration data is a new dataset with its own particular variability and trends.

The DRP export measured during the 493 days of monitoring amounted to 778 g/ha for the Warren 1 and 5,299 g/ha for the Cowlands. This translates into yearly export rates of 698 g/ha and 4,764 g/ha.

The amounts of DRP lost from the sites within the 144 days of monitoring at the Warren 2 were 111 g/ha for the Warren 1, 300 g/ha for the Warren 2 and 1,162 g/ha for the Cowlands.

The calculated TDP exports for the 493 day and 144 day monitoring periods wre 1,290 g/ha and 339 g/ha for the Warren 1 and 6,556 g/ha and 1,600 g/ha for the Cowlands. The TDP export at the Warren 2 (144 days) was estimated to be 465g/ha.

Provided that there was overland flow at the Cowlands, monthly DRP exports from that site were consistently higher than those from the other sites (Figure 4). Greater monthly amounts of DRP flowed off the Warren 2 than the Warren 1.

The maximum DRP export in August 1997 at the Cowlands dwarfs both exports during all other months and losses from the Warren 1. August 1997 was also the month of maximum flow at the Cowlands but the value is similar to the amount of overland flow in November 1997 and January 1998. Furthermore, considerably more water ran off the Warren 1 than the Cowlands in August 1997. Most of the rainfall and overland flow, for August 1997, occurred during an exceptional rainfall event in the first few days of the month. The high DRP concentrations in overland flow from the high soil P site (Cowlands) during times of high P availability therefore have an enormous effect on DRP exports.

Phosphorus Export with Subsurface Drainage Water

From 4 November 1997 to 31 March 1998, about 10 kg of DRP were lost via drains from the subsurface drainage catchment area.

Area export rates were estimated to allow a rough comparison of P losses from the overland flow and the subsurface drainage sites. During the monitoring period at the subsurface flow site, an estimated 412 g P/ha were lost as DRP via the subsurface drains. DRP losses with overland flow from the Warren 1 and the Cowlands for the same time interval amounted to 150.2 g P/ha and 1,255 g P/ha. Phosphorus loss per ha via the subsurface drainage network at the Beef Unit was therefore greater than the P export with overland flow from the Warren 1 but less than by the export at the Cowlands.

CONCLUSIONS

The amounts and concentrations of P in overland flow were affected by the hydrological and management characteristics of the sites, and by climatic variables. The estimated P area export rates are therefore specific to the particular sites monitored in this study and they reflect the weather conditions during the monitoring period.

Despite the great temporal variation of the amount of flow and the P levels, the data illustrate that even though the Warren 1 (low soil P) produced the most overland flow and the Cowlands (high soil P) the least, DRP exports during the monitoring period were nearly seven times higher from the Cowlands than the Warren 1. Clearly, the increase of DRP concentrations in overland flow from the Warren 1 to the Warren 2 (medium soil P) and the Cowlands was responsible for the same trend in DRP exports. The between-plot difference in soil P levels is the most likely cause of the changing DRP concentrations.

The subsurface flow at the tree overland sites would have carried some P with it, but it was not quantitatively estimated in this study. Therefore, the P export losses calculated are likely to be an underestimate of the actual P loss.

The information on the subsurface drainage site at the Beef Unit, Johnstown Castle, indicates that the P concentrations in subsurface drainage water at this particular site were substantial at times.

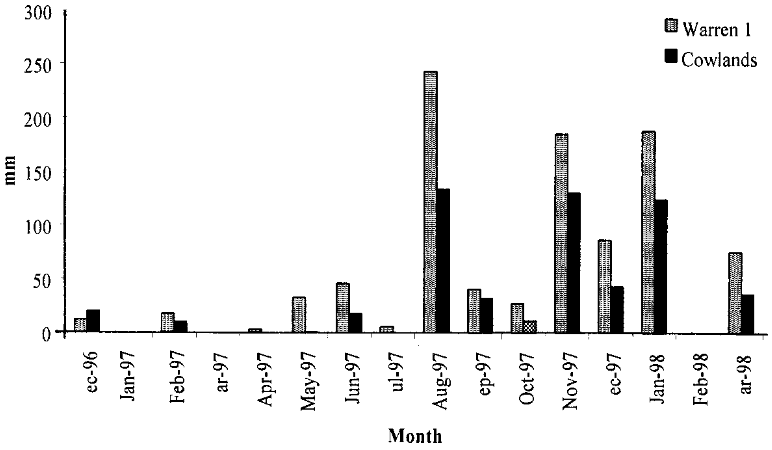


Figure 1: Monthly Overland Flow at the Warren 1 and the Cowlands

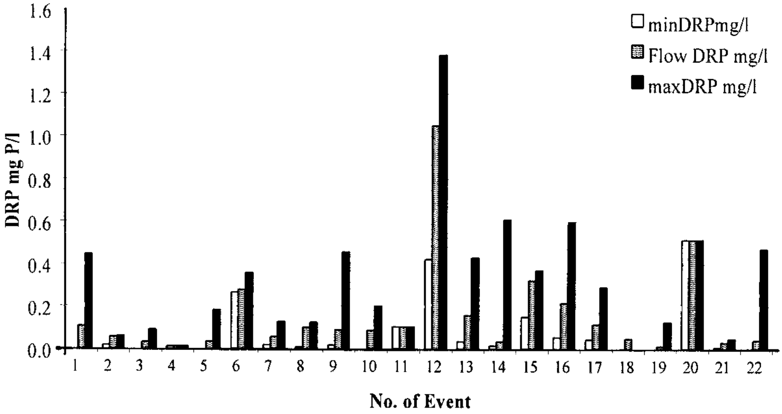


Figure 2: Minimum, Maximum and Flow Weighted Average DRP Concentrations at the Warren 1

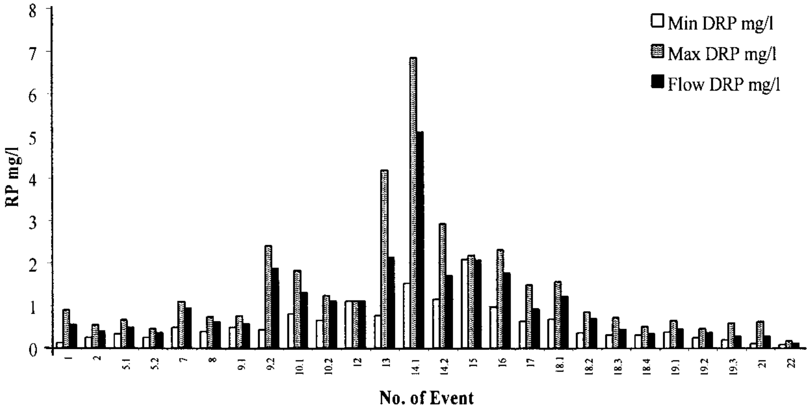


Figure 3: Minimum, Maximum and Flow Weighted Average DRP Concentrations at the Cowlands

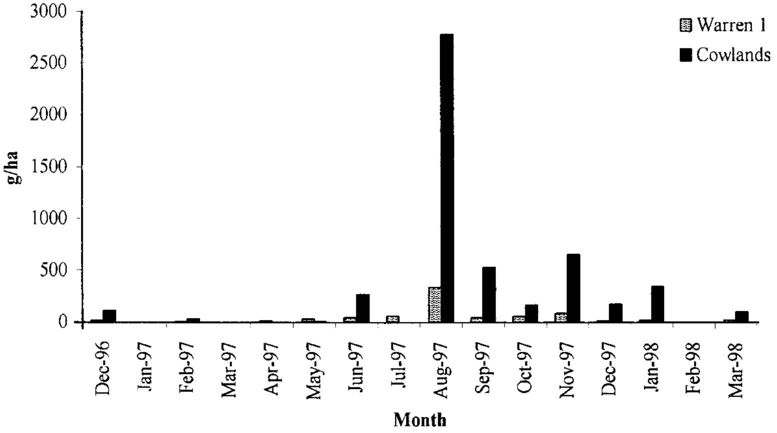


Figure 4: Monthly DRP Exports from the Warren 1 and the Cowlands

4.2 PHOSPHORUS EXPORT FROM FARM IN DRIPSEY CATCHMENT, CO. CORK (NMP) (SECTION D)

Ger Morgan, Quishi Xie, Martin Devins
Aquatic Services Unit, University College Cork

Introduction

The Nutrient Management Planning (NMP) - Small Catchments Portion of the Soil-P Desorption Research Project was undertaken in part of a single farm unit in the River Dripsey Catchment in Co. Cork. The farm is situated near the village of Donoughmore, Co. Cork. The small stream, which drains the farm, is part of the eastern sub-catchment of the Dripsey, which in turn drains to the Inniscarra Reservoir on the main channel of the River Lee. The reservoir is a major source of domestic and industrial water abstraction for the city of Cork and its environs.

The study area (D2) is approximately 23 ha in extent and comprises the dairying section of a 38.3 ha farm. Within D2, a second catchment (D1), of approximately 14.5 ha, is delineated on its western boundary by a north-south flowing stream. A farmyard and family-farm dwelling are present in D2 and contaminated surface water from the farmyard (0.5 ha) runs directly to the north-south flowing stream, which marks the western boundary of D1.

The full catchment, that is the study area (D2), drains to a point on the east-west running stream toward the southern boundary of the catchment. At this point, designated as D2, flow and water quality equipment is installed. Further upstream, the smaller catchment (D1) drains to a sampling point on the same stream designated as D1. The latter sub-catchment does not receive point source run-off.

Methods

The main thrust of the study was centred on the two stream monitoring sites, D1 and D2, situated on a small stream draining the study area. At both these sites, stream flow was measured continuously at 'v' notch weirs and automatic water samplers, which were programmed to sample intensively during periods of elevated flow.

Water samples were collected at the stream sampling points D1 and D2, corresponding to catchments D1 and D2, beginning in December 1996 and continuing almost without interruption until mid-March 1997. There followed a three-month gap in sampling until about mid-June, when one peak flow event was monitored between the 20th and 25th. This was followed by another month's gap until mid-July when another small event was sampled between the 11th and 15th. The final samples were taken in early August when the tail end of a run-off event was sampled between the 3th and the 8th. Within the periods outlined above, the sampling effort was concentrated almost exclusively on peak flow events, the only exception being December (1996) when detailed low-flow sampling was carried out. In all, 19 peak-flow events were sampled. Between periods of peak flow, grab samples were taken, normally at weekly intervals. The latter, however, didn't extend into the mid-March to mid-June sampling pause mentioned above, or to the gaps between the June, July or August sampling periods.

Supporting data about the farm were also obtained, including, stocking rates, fertiliser and slurry spreading rates, milk production and Morgan's P levels in the soil etc.

Samples were analysed using standard methods for dissolved reactive phosphorus (DRP), total dissolved phosphorus (TDP), total phosphorus (TP), suspended solids (SS), potassium (K) and total oxidised nitrogen (TON, i.e. nitrate plus nitrite). Dissolved organic phosphorus (DOP) and particulate phosphorus (PP) were calculated as the difference between TDP and DRP, and TP and TDP respectively, and results for both are available for samples for which the three main P fractions were analysed. Load estimations were made for 19 separate hydrograph peaks and for 16 accompanying baseflow or elevated baseflow periods during the January to August sampling period.

In order to facilitate inter-comparison of the Dripsey results with those for Johnstown Castle Small Catchments Study (Section A) as well as previous Dripsey and other studies, an annual DRP export load for the study area was estimated. This was achieved by the examining the loads calculated for the study periods (January to August 1997) and applying them to the remaining four months of the year and those periods within the January-August period for which flow data only were available.

Essentially, a range of flow-weighted average concentrations (FWAC) was calculated for all the peak-flow and baseflow events within the study period for which both water chemistry and flow data were available. These were then classified according to the type of flow event, i.e. whether it was a once-off event or a one of a series of events, whether it was a summer, autumn or a winter event, whether it was a large or small event etc. Using these criteria to classify the flow-only data, the appropriate FWAC was applied to them and an annual DRP load for D1 and D2 was estimated.

Estimation of Farmyard Contributions

The contribution of the farmyard to the overall nutrient export from the 38.3ha farm area was assessed as the difference in the export from D1 and D2 normalised for flow and area. The two main assumptions made in this approach, were (i) that the rate of nutrient export and run-off rates from D1 were the same in the remaining farmland area and (ii) that all of the waste derived from the farmyard reached the D2 sampling point (i.e. without attenuation en route). The following formulae were employed to assess the percent contribution (DRP & K), on an event by event basis, of the farmyard to the total farm export (i.e. farmyard + farmland). For these calculations, the area of D1 was taken to be 14.5 ha, D2 outside D1 (i.e. D2-D1) as 8.5 ha, and the remaining farmland area as 15.3 ha. The latter is also grassland (immediately east of D2) and is used for dry stock rearing:

Flow-Weighted Formula:

Farmyard Load (A)= ((D2 Load - D1 Load) - (D1 Load ÷ D1 Flow) *
(D2 Flow-D1 Flow))
Total Farm Land Load (B) = Total Farm Area (38.3ha) * (D1 Load ÷ D1 Area)
Farmyard Contribution as percent of the Full Farm Are= (A ÷ (A+B))*100.

Area-Weighted Formula:

Farmyard Load (A)= ((D2 Load - D1 Load) - (D1 Load ÷ D1 Area) *
(D2 Area-D1 Area))
Total Farm Land Load (B)= Total Farm Area (38.3ha) * (D1 Load ÷ D1 Area)
Farmyard Contribution as percent of the Full Farm Area= (A ÷ (A+B))*100.

Results

Farm Activity and Soil P Levels

The study area forms the dairying section of a grassland farm. It caters for 40 cows and an equivalent number of calves, i.e. a stocking density of 1.7 cattle per ha (not including calves). Annual milk production ranges from 170-180,000 litres. All fields have been under grass for over five years. Silage is cut from several fields, usually as just one cut in May or June. Dry cattle (from other areas of the farm) and dairy animals are housed in slatted units and sheds during the winter and fed silage and concentrates. The latter are used at the rate of about 4.6 kg/cow/day during the winter and when cows are on the land they receive a reduced rate of 1.4 kg /cow/day. The remaining land on the farm (15.3 ha), i.e. outside the immediate study area, is used to rear about 40 dry cattle.

Slurry is spread early in the year and after the first cut of silage depending on ground conditions, availability, etc.; it is also spread again in autumn. Grassland fertiliser, mainly Cut Sward (N:P:K, 24:2.5:10) for silage fields and Pasture Sward (N:P:K, 27:2.5:5) on non-silage fields or after silage, is spread up until about September.

Soil P levels (Morgan's, 0-10cm) were analysed over the greater part of the study area in January and February 1997. Based on these figures, area-weighted soil-P values (mg P per litre soil) calculated for each section of the study area were very similar as follows: D2 (9.6), D1 (9.5), and D2 outside D1 (9.9). The range was 7.0-15.7 mg, P per litre soil.

Table 3: Annual summarised slurry and fertiliser usage - D1 and D2 (1996 and 1997)

	Slurry (m^3)	Fertiliser (kg)	Total N (kg)	Total P (kg)	Nitrogen (kg/ha)	Phosphorus (kg/ha)
1996	341	22875	7383	790	398	42.6
1997	239	8525	3278	366	177	22.9

Stream Water Quality Data (General)

Phosphorus

During the winter and spring period, all phosphorus fractions reached their highest concentration on 17th and 18th January during the first main run-off events of the year (Figs 5 and 9). During this event, DRP and TP reached a concentrations of 1.3

and 1.7 mg/l, P, respectively, at D1 and at D2 were 1.1 and 4.4 mg/l, P. Thereafter, concentrations slowly began to decline in relative terms until the first week in March when DRP and TP were 0.17 and 0.24 mg/l, P, respectively, at D1 and 0.29 and 0.82 mg/l, P, respectively, at D2. This rather marked decline is thought to relate to several factors, including the succession of small to medium sized peak flow events (about 15 in all) which occurred in the interim (February). The latter are believed to have gradually reduced the residual slurry which had been spread in late December and early January and part may have been washed out by the two January floods. Furthermore, there were no cattle on the land since early to mid-December so the influence of their droppings etc. was probably at a minimum. Finally, there had been no slurry or fertiliser spread on the land during the same period.

As no samples were taken in April or May, it isn't possible to say when the changeover to high nutrient run-off began again. In June, however, during a relatively minor flood event (20 l/s at D1 and 30 l/s at D2), the highest levels of DRP for the study were measured at both sampling sites (2.2 mg/l, P). Farm records indicated that grassland fertiliser was spread (about 3.1kg, P/ha) in several fields in both parts of the catchment immediately prior to the event. Whether this was the reason for all or just part of the occurrence is not known, although it seems safe to assume that it was significant. Other factors may have included the presence again of cattle on the land since April and the residual impact of fertiliser spreading in April, May and early June, which could have resulted in a seasonal accumulation of phosphorus on the soil surface or in the shallow subsurface.

Again in August, fertiliser was spread, this time in one field just next to stream, immediately prior to a significant run-off event. It is very likely that run-off from the south-eastern corner of this field also contributed to the high P levels measured at D2 during this event. Small surface samples of overland flow taken directly from the field at this point had TP concentrations of between 2 and 6 mg/l, P. These figures would point strongly to incidental losses associated with fertiliser spreading immediately in advance of rain. It is likely that the levels measured in the stream at the time (1.2 mg/l, DRP), would have been significantly higher if the main section of the event, rather than its tail, had been caught.

Suspended Solids

Suspended solids levels were generally quite low at D1 throughout most of the study, in line with the grassland nature of the site (Figs 7 & 11). At D2, the levels, which were much higher, were in line with those previously measured during peak floods at the Mini-Catchment (around 400 mg/l). Solids, however, relate to many in-channel processes quite apart from what's happening on the land (e.g. bank erosion and streambed re-suspension), and these combined with solids from the farmyard and a farm passageway are believed to be influencing the higher solids levels at D2. Potassium was generally higher at D2 (Figure 6).

Total Oxidised Nitrogen

Concentrations of TON (mainly nitrate) were quite similar at both D1 and D2 for most of the study although concentrations at D2 were generally slightly lower than at D1, especially during low flows (Fig 8). TON concentrations were within the range previously measured in the area during two earlier studies (STRIDE and LIFE studies). During most flood events, TON followed a pattern commonly seen during the STRIDE and again during the LIFE study, i.e. with concentrations directly inverse to flow levels, indicating a dilution effect. Only during June and July was this pattern briefly reversed when TON peaked in concentration, at or immediately post the hydrograph peak. The June D1 peak of nearly 9 mg/l, N may also be associated with fertiliser spread at the time.

Water Quality Conclusions

During the present study, water quality varied in a manner, and generally to an extent, which would have been anticipated by the two previous studies in the catchment. The study confirms the high levels of phosphorus in receiving waters during and immediately succeeding many run-off events. There is also evidence to indicate that farm activity, particularly in the form of slurry and fertiliser spreading when it is followed by heavy rain, is contributing to these losses. It may also be the case, because of the intensive nature of the land management in high yield dairy farms, that summer losses of phosphorus are inevitably likely to be high if there is sustained or intermittent heavy rain during this season.

Dissolved Reactive Phosphorus (DRP) And Potassium (K) Export Loads

Nineteen separate events between January and August were analysed for dissolved phosphorus and potassium loss. In addition, the losses, which occurred during sixteen baseflow or elevated baseflow periods, were also calculated.

Total Exports per Event

The importance of total flow as a key driving force behind DRP exports can be seen clearly when the variation in total export loads per event is compared with the total run-off for the same periods. This is most apparent for events 1-15 inclusive, where each successive change in run-off prompts a response in terms of increased DRP load. However, the degree of this response is not the same for run-off events of the same magnitude. This is particularly clear when events 1 and 2 from mid-January are compared with events 10 and 11 from the second half of February. It is considered likely that slurry spreading in late December and early January contributed to the relatively much higher rates of DRP loss in January. In the June and August events (16 and 19), incidental losses have also been implicated along with seasonally changing activity on the land, as discussed in the foregoing section on stream water quality.

Exports per Unit Flow

DRP: When loads are converted to unit flow on an area basis, i.e. g/mm/ha (Fig. 12), which is the same as flow-weighted average concentration (FWAC) by 10, the data appear to be less variable. Firstly, there appears to be a fairly sharp drop in loss rates between the first two events and the next two. Thereafter, there follows a steady, very slow decline, which may be bottoming out between events 11 and 15. Everything changes dramatically again in June, July and August (nos. 16-19) when flow-weighted exports reach their highest levels of the study. The fact that the July rate at D2 is much higher than at D1 is thought mainly to relate to the very low flow at D1 at the time, probably even too low to re-suspend material from the stream bed or drains.

Nutrient Management Planning (NMP) Baseline

Given the extreme variability in stream phosphorus concentrations observed in rivers and streams, such as those in the present study, attempting to set a baseline concentration against which to asses future changes in farm NMP would appear to be impossible. However, the stabilising (or near stabilising) of the DRP FWAC's, as observed for the long series of February/March floods at D1 and D2, may provide a limited solution to this problem. Thus, at a time of the year when all farmland activity would have ceased, and a few antecedent floods would have removed the bulk of surface held applications or loosely bound soil P reservoirs, subsequent floods, when analysed quantitatively, might provide the best indication of baseline soil-P run-off rates. One might expect the latter to reflect mainly the soil-P levels on the land at the time, separated from incidental and other losses.

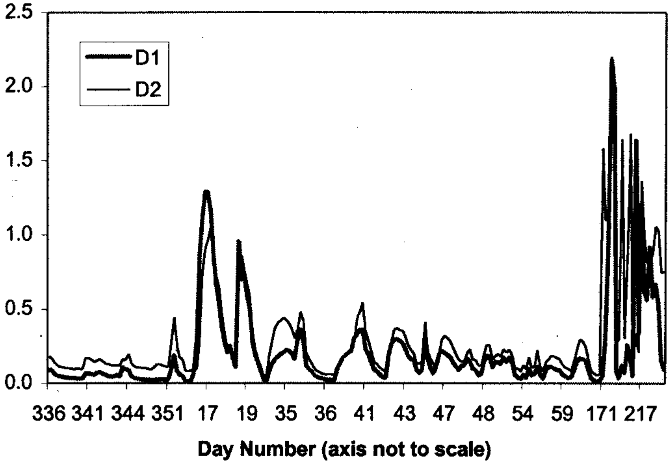


Figure 5: DRP - Sample Concentration (mg/l, P), Dec 1996-Aug 1997

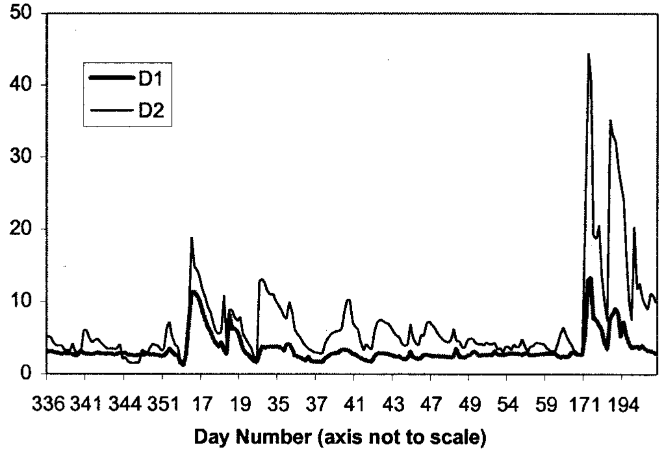


Figure 6: Potassium - Sample Concentration (mg/l, K), Dec 1996-Aug 1997

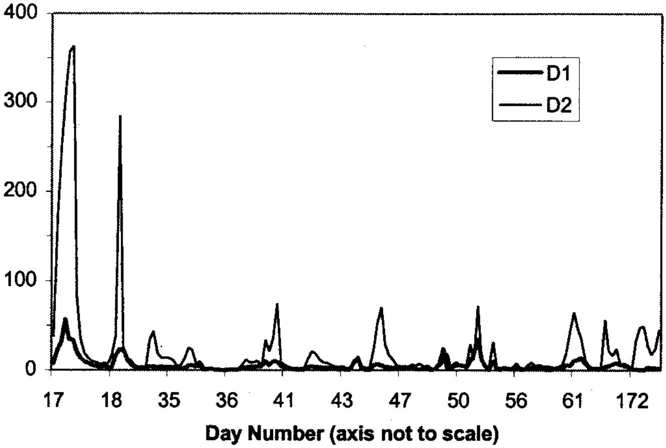


Figure 7: Suspended Solids - Sample Concentration (mg/l), Jan-July 1997

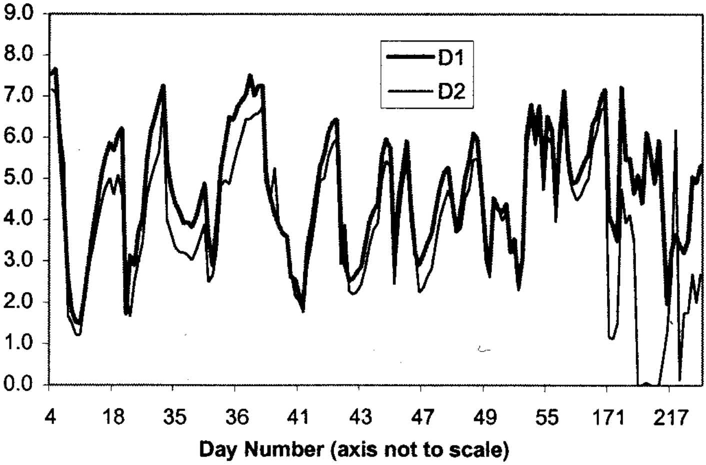


Figure 8: TON - Sample Concentration (mg/l, N), Jan-Aug 1997

Estimated Annual Unit-Area DRP Losses

Estimated annual export rates of dissolved phosphorus were high, in the region of 1.61-1.64 kg/ha/yr for D1 and 2.74 kg/ha/yr for D2. The D1 figure is roughly in line with the estimate of 1.9 kg/ha/yr measured for the Mini-Catchment during the STRIDE study in 1993/94. However, the D2 figure seems particularly high and may be due to the high FWAC's of floods 16-19 (June to July) which may be having a disproportionate influence on this estimate. If these are excluded from the calculation, the resultant export decreases to

2.1kg, P/ha. The higher export rate at D2 is not unexpected, given the presence of the farmyard in this section of the catchment.

It is noteworthy that an oft-quoted feature of non-point source exports, i.e. the fact that the bulk of it tends to occur during small numbers of short duration events, is supported by the data in Table 4. Those indicate that 94 percent of the estimated DRP export from D1 took place in just 32 percent of the time.

Table 4: Method 1 estimated annual (1997) DRP export loads from D1

Method 1	Flow m^3	% Time	% Load	Total Load (g)
A (Peak Flows)	55,547	18	75	17,775
B (Elevated Baseflows)	32,056	14	19	4,602
C (Baseflow)	63,888	68	6	1,456
Annual Totals	*151,491*	*100*	*100*	*23,833*

Table 5: Annual (1997) unit area export loads for DRP

Study	DRP Export Load Method 1 (kg/ha/yr)	DRP Export Load Method 2 (kg/ha/yr)
D1 (present study)	1.64	1.61
D2 (present study)		2.74 - *2.10
Mini-Catchment (STRIDE)	1.9	

* D2 estimated using FWAC for just 15 of the 19 flood events (i.e. excluding the high summer concentrations)

Farmyard Contribution to DRP and K Losses

The very influential effect of the farmyard on the water quality at the D2 sampling point is beyond argument. The results indicate that the contribution from the farmyard can be very variable, ranging from less than 5 percent to greater than 90 percent of the total farm export for different events. The lowest relative contributions (i.e. during January and June) coincided with times when peak flow events followed recent spreading of slurry or fertiliser, thus increasing the relative contribution of the land. Conversely, during July, when very little drainage appears to have come from the land (due to high soil moisture deficits), the farmyard contribution became relatively more significant following a rainfall event. Silage liquor contamination of the farmyard surface is also thought to have been a contributory factor on the latter occasions (events 17 & 18). On average, the farmyard DRP contribution amounted to around 25-35 percent during the flood events and around 35-45 percent during base flow events, whereas, roughly the reverse applied to the potassium contributions with the higher levels occurring during flood conditions (see Table 6).

When the DRP losses for D1 and D2 are summed for the 19 flood and 16 baseflow periods analysed in the January - August period, the total farmyard losses can be estimated for the same period using the area-weighted formula on these totals. This exercise indicates that D1 contributed 5.3 kg (P), i.e. 27 percent of the full farm export, D2 (external to D1) contributed 3.1 kg, P (16 percent), the remaining farmland outside the study area (15.3 ha) contributed an estimated 5.8 kg, P (28 percent) and the farmyard contributed 5.3 kg, P (27 percent).

These findings suggest that on-average farmyard losses can constitute a significant proportion of total farm nutrient exports, and that 'leakage' from farmyards in the summer can constitute a significant proportion of farm P losses even when exports from general land area may be relatively small. It should be remembered also, however, that the farmyard surveyed in this study may be more typical of 'high risk' farmyards, i.e. those more likely to contaminate surface waters.

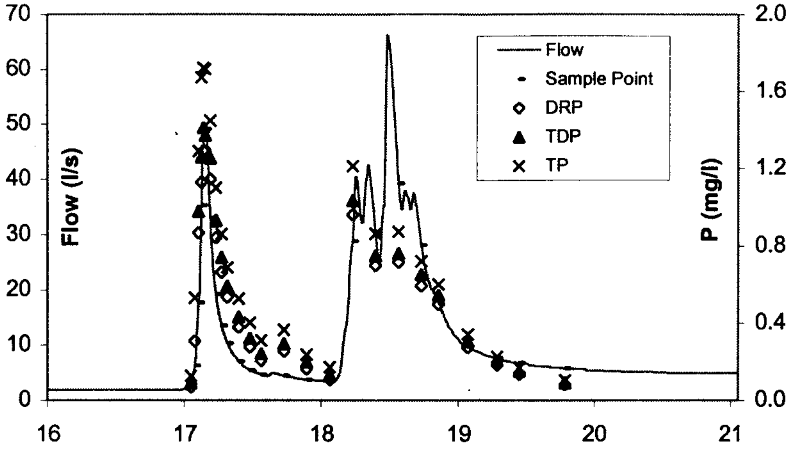


Figure 9: Variation of Phosphorus with Flow - D1 (Jan 16-21, 1997)

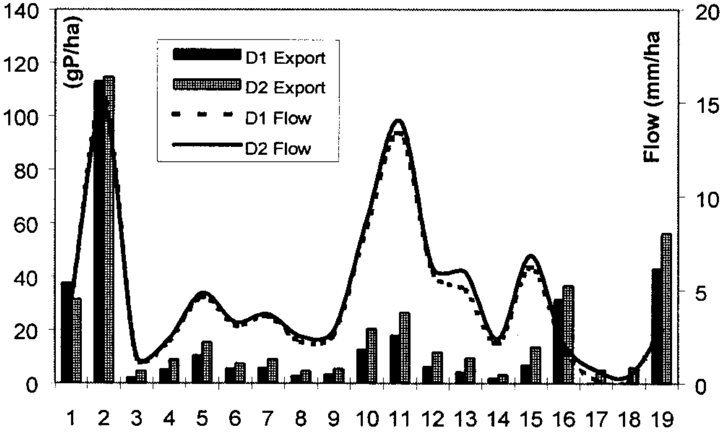


Figure 10: DRP Export (g/ha) for 19 Flood Peaks (Jan-Aug 1997)

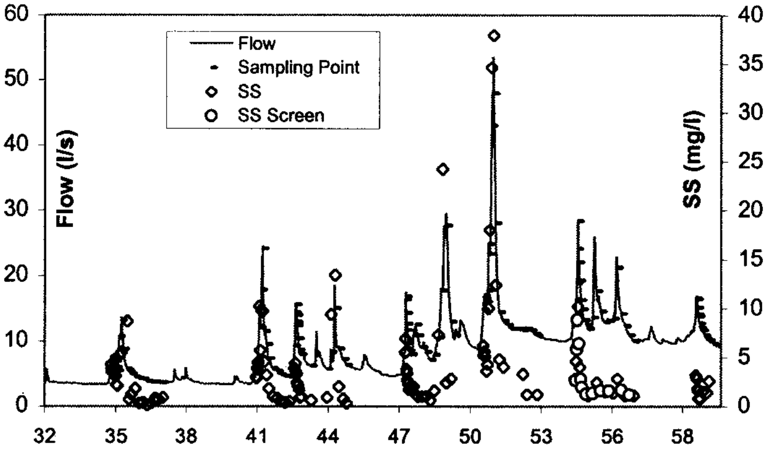


Figure 11: Variation of Suspended Solids with Flow - D1 (Feb 1-28, 1997)

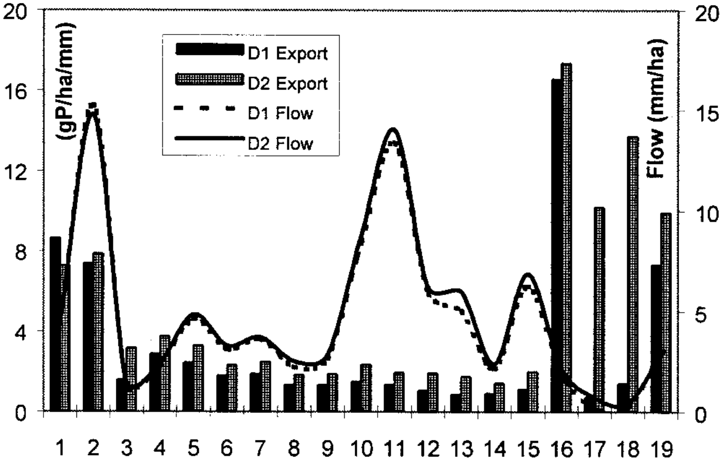


Figure 12: DRP Export (g/ha/mm) for 19 Flood Peaks (Jan-Aug 1997)

Table 6: The estimated percentage contribution of the farmyard losses of DRP and K to the overall farmland (38.3 ha) losses; mean and median of 19 flood events and 15 baseflow events calculated by two slightly different formulae.

	Flow-Weighted Estimate		Area-Weighted Estimate	
	Mean	Median	Mean	Median
DRP (floods)	30	22	35	30
DRP (baseflows)	41	37	45	42
K (floods)	43	42	46	44
K (baseflows)	35	34	40	37

Overall Conclusions - Dripsey Small Catchment Study

The main conclusion to be drawn from this portion of the study is that the total annual losses of DRP from the farmland section of the study area are high (1.6 kg/ha/yr). Also, they are in line with high dissolved P levels measured in the same area (Mini-Catchment site) during the STRIDE Lee Valley study in 1993/94. The water quality data measured during the present study are also comparable with another winter/spring study, carried out under the LIFE programme in 1995/96 at exactly the same site.

An examination of the variation of water quality with flow throughout the period of the study strongly suggests that incidental losses of P associated land applications of both slurry and fertilisers contributed significantly to farmland losses.

The existence of increased summer loss rates of P is inferred from the data, but the number of sampling runs for which data are available is insufficient to distinguish such an effect from incident-related losses for this study.

The farmyard contributes significantly to P losses from D2, and when set against the estimated figure for losses from the full farm area, constitute about 27 percent on average of the total. During periods of low flow, the relative contribution of the farmyard increases to between 35-45 percent on average, of the total farm exports.

It is suggested that as a baseline against which to test the impact of improvements in farm NMP, the average flood-FWAC's of the later winter-spring events, i.e. 0.1- 0.2 mg/l, P should be used. This figure should only be applicable for the present study area until further research at the site either improves the precision of this estimate or discounts the value of setting one.

4.3 HYDROMETEOROLOGICAL ASPECTS OF FARM IN DRIPSEY CATCHMENT (NMP) (SECTION E)

Gerard Kiely
Civil & Environmental Engineering, University College Cork

Introduction

Without understanding the physics of water and solute transport in catchments, it is not possible to evolve a scientifically based nutrient management plant (NMP) for grassland catchments. This section deals with an experimental and modelling investigation on hillslope hydrology with the objective of identifying the significant physical flow and transport mechanisms at the plot and field scale on the farm.

The hydrological cycle represents the continuum of water movement at the earth, ocean and atmosphere interfaces. Of relevance to this study are the three components of the annual water balance, namely: precipitation, evapotranspiration and stream runoff.

The energy cycle is another closed system representing the continuum of the sun's energy as it arrives at the earth's surface. The net radiation at the earth's surface partitions itself into: sensible heat (the energy required to heat the air), latent heat (the energy used for evaporation) and soil heat (energy absorbed by the soil surface.).

The hydrological cycle and the energy cycle have the process of evaporation in common. Without radiation, evaporation is much diminished. Without water at the earth's surface or just below the earth's surface there is no evaporation. So the two cycles are coupled. This is relevant in this study as it deals with the partitioning of rainfall into streamflow and evaporation. High rates of evaporation (if driven by radiation) create soil moisture deficits leading to less likelihood of phosphorus runoff to streams.

Hillslope experiments have been used to define particular types of surface runoff: Hortonian overland flow; saturation-excess overland flow; macropore flow or groundwater flow.
Figure 13 is a schematic representation of the physical process of

water transport in a hillslope. This Figure represents the potential processes in the Dripsey field (14.5 ha). The hillslope is shown with a length of about 500 m with a gradient in the upper end of about 5 percent and at the lower end of about 3 percent. At the downstream end there is a stream. The depth of the water table is approximately 3 m at the upper end and 1 m at the lower end. The precipitation after landfall has several different potential routes to travel before arrival at the stream.

Description of field and plot experiments

Field Site (14.5 ha)

The 14.5 ha grassland field is at the headwater of the 98 km^2 Dripsey catchment, 25 km northwest of the city of Cork. The study site is a hillslope about 500 m long and 300 m wide, sloping at between 5 percent and 3 percent to a small stream. The water table is at 1 to 3 m below the surface. The unsaturated zone is composed of sandy gravel with a porosity of approximately 50 percent and with the gravel size and boulder size increasing with depth. The underlying rock is sandstone. The area is well known for sand and gravel quarries. The instrumentation includes a micro-meteorological station consisting of: a net radiometer, a wind anemometer and wind vane, precipitation gauges, an air temperature and relative humidity sensor, soil heat flux plates, soil temperature sensors and an infra-red surface temperature sensor. In addition, there were streamflow recorders and a class A pan evaporation device. Water table was recorded using piezometers at 10 locations within the field on a weekly basis and at one location (near the meteorological station) at twenty-minute intervals. A profile was also obtained for 9 Time Domain Reflectometers (TDRs) near the weather station.

Plot Study Site (100 m^2 Plot)

The 100 m^2 grassland plot is part of the 14.5 ha hillslope research field. The research field is agricultural grassland, typical of the land-use and vegetation in this part of the country. The grassland type is moderately high quality pasture and meadow, with perennial ryegrass being the dominant plant species. The bedrock geology is Devonian Sandstone at approximately 2 to 4 m below the surface. The soil profile is characterised by a top 5 cm humus layer overlying a dark brown A-horizon of sand texture to a depth of about 20 cm. The yellowish-brown B-horizon of sand texture grades into a brown gravelly sand parent material at about 30 cm. The site has a gentle slope of 5 percent and drains into a small nearby stream which runs along two sides of the 14.5 ha field.

The 100 m^2 (20 m by 5 m) plot was hydraulically isolated from the rest of the 14.5 ha field by excavating a 1.2m deep trench on the four sides. A 3 mm thick HDPE sheet was installed, to a depth of 1.2m on three sides of the four-sided trench. On the fourth side (the downstream end), the trench was filled with gravel and a surface runoff recorder and a subsurface (at 1.2 m) recorder were installed. The experimental plot was also instrumented with six soil moisture access tubes (FDR method, i.e. Frequency Domain Reflectometry, Institute of Hydrology, UK.) and eight tensiometers. At six locations in the plot, vertical profiles of soil moisture were recorded at approximately 4 cm depth increments on a weekly basis. For the modelling study, we used the physically based, 2-D distributed modelling system HILLFLOW using insitu measured dataset (Case A) and also dataset adopted from the literature (Case B).

Results

Soil Parameters

The saturated hydraulic conductivity of the soil measured from the falling head laboratory test, is shown in Table 7. The average of 4 tests was $2.2*10^{-6}$ m/sec. In the field, double ring infiltrometer tests were carried out. The field estimate of saturated hydraulic conductivity was approximately 90 mm/hour or about $2.5*10^{-5}$ m/sec. It is relevant to note that the field value is approximately an order of magnitude 'faster' than the laboratory tests. This is due to the presence of macropores in the field. Precipitation anything close to 90 mm/hour is impossible in the Irish climate, (highest hourly record in Dripsey in 1997 was 11.6 mm/hour). This suggests that unless the soil saturates from below, then most precipitation can infiltrate and Hortonian overland flow is unlikely.

Other soil properties are shown in Table 8, for three different depths, 0-30 cm, 30-60 cm, and 60-100 cm. The porosity for all depths is approximately 50 percent. Saturated water content decreases from about 46 percent near the surface to about 36 percent at the lower depths. Saturated water content is typically a few percent less than the porosity. The field capacity decreases with depth from about 36 percent at the upper layer to 29 percent at the lowest layers.

Table 7: Saturated hydraulic conductivity K_s determined by the laboratory falling head method

Date of Experiment	Saturated hydraulic conductivity K_s [m/s]
March 3 1997	$1.8 * 10^{-6}$
April 4 1997	$1.9 * 10^{-6}$
May 5 1997	$1.8 * 10^{-6}$
June 8 1997	$3.2 * 10^{-6}$
Average	$2.2 * 10^{-6}$

Table 8: Parameters for the van Genuchten function and soil moisture values of permanent wilting point and field capacity

depth [cm]	θ_r residual water Content [vol.-%]	θ_s saturated water Content [vol.-%]	a van Genuchten Papameter [l/m]	N van Genuchten Parameter [-]	θ_{wp} wilting point [vol.-%]	θ_{fc} field capacity [vol.-%]
0-30	2.0	46.0	2.10	1.23	13.0	36.0
30-60	1.0	42.0	3.19	1.18	12.0	33.0
60-100	1.0	36.0	2.13	1.19	12.0	29.0

Weather Variables

The twenty-minute averaged relative humidity (RH) was generally greater than about 80 percent. Even instantaneous values rarely dip below 50 percent. In mid-summer the RH averages about 80 percent rising to close on 100 percent in December. These high values relate to the propensity for frequent rain events. One of the three variables of long-term water balance, evaporation, is inversely proportional to relative humidity or proportional to its surrogate, vapour pressure deficit.

During cloudless summer days, instantaneous net radiation highs of close to 700 W/m^2 were experienced. However, it is more common in summer to see instantaneous net radiation highs of about 250 to 500 W/m^2. Of course, at night the net radiation is of order 20 W/m^2 negative as the soil emits longwave radiation. Also, in winter, the instantaneous net radiation was commonly less than 50 W/m^2 during cloudy days. Evaporation is directly proportional to net radiation.

The wind speed was moderate at this site at about 4 m/sec with a standard deviation of about 2 m/sec. The highest wind speed experienced (twenty-minute average) was 20.5 m/sec on 24 December 1997. The low average wind speed of approximately 4 m/sec indicates that the site of the meteorological station is protected by virtue of being sited near the bottom of the hillslope.

The vapour pressure deficit (VPD) was of the order 0.5 KPa in summer and as low as 0.05 KPa in winter. The higher the VPD, the greater the potential for evaporation.

Daily evapotranspiration, estimated from the Penman-Monteith equation, ranges from a high of approximately 4 mm/day in summer to a low of 0.1mm/day in winter. There is also a diurnal cycle to the evapotranspiration, with highest evapotranspiration rates after midday and lowest close to midnight. Evapotranspiration rates are a function of many factors: e.g. VPD, net radiation, wind speed, availability of soil moisture, crop type. In this wet climate, the limiting factors for evapotranspiration rates are meteorological since there is generally no deficit in soil moisture. This means that evapotranspiration is generally at its potential, most of the year.

Precipitation and Stream Runoff

The total 1997 annual rainfall at the site was 1443 mm by comparison with 1272 mm at Cork Airport. The maximum daily rainfall was 74 mm on 3rd August. February was a particularly wet month with only three non-rain days. March and April were exceptionally dry with light rain in May and June. August was exceptionally wet with 3rd August supplying 74 mm and 31st August supplying 45 mm. The stream hydrograph showed the highest flows were not in the winter time but in August. Statistically, the most extreme rain events occur in the three-month period of August, September and October, with corresponding high stream-flows. High summer rains and runoff implications for all year round phosphorus loss. Streamflow ranges from 0.5 l/sec to 180 l/sec. The low value of 0.5 l/sec is groundwater baseflow or the contribution from groundwater at its lowest levels with no flow from the unsaturated zone. The highest flow of 180 l/sec occurred in August in response to a continuously high rainfall over a three-day period (greater than 30 mm per day for more than three days).

The summary statistics of precipitation at Cork airport are: mean annual of 1207 mm with a standard deviation of 140 mm; mean monthly precipitation of 100 mm with a standard deviation of 59 mm. Dripsey experienced in 1997 an annual value of 1443 mm with a monthly average of 120 mm. The Dripsey values are slightly higher than for Cork Airport. In August 1997, Dripsey experienced 261 mm while the long term August value for Cork is 90 mm. The year 1997 was wetter than normal (but not an extremely wet year) and summer precipitation in the Cork area was not much less than winter. This indicates the need for careful nutrient management, not only in the winter but on an all-year-round basis. Precipitation in the Cork area is not only a winter phenomenon and extreme precipitation can also occur in the summer months. August 1986, August 1997 and August 1998 are particular examples of extreme precipitation months.

The Penman-Monteith formula was used to estimate the potential evapotranspiration of 416 mm. The evapotranspiration calculated from the annual water balance was 399 mm (28 percent of annual precipitation). The Penman-Monteith factor to get from potential evapotranspiration to actual evapotranspiration is 0.96. This is a typical factor for our humid climate. Approximately 72 percent (1044 mm) of annual precipitation became streamflow, while about 28 percent evaporated.

Water Table Depth

Figure 14 shows the time series of the water table from two piezometers: one at the top of the hillslope (P10) and the second at the bottom of the hillslope (P1, near the stream). The weekly time series of precipitation for 1997 are also shown. At the top of the hillslope, the water table depth ranges between about 1.3 m and 1.9 m. At the bottom of the hillslope the water table depth ranges between about 0.4 m and 1.1 m. Water table levels are recorded at twenty minute intervals by the water table sensor at the bottom of the hillslope. This indicates the water level diurnal fluctuations of about 0.15 m which is due to the capillary rise.

So, examining Figure 14, some of the variations in the water table depth are due to measurements taken at different times of the day. Furthermore, during 1997, the water table depth was measured at weekly or less regular intervals and did not 'catch' every fluctuation of the water table. Some of the fluctuations of the water table at the bottom of the hillslope can be explained by the requirements of root water uptake by the plants (grass for silage). It was observed, on site, that the rooting depth in some areas penetrated to as much as 1 m below the surface. The water table at the top of the hillslope is about 0.5 m deeper than the water table at the bottom of the hillslope. The shallow depth of the water table, particularly at the bottom of the hillslope predisposes the riparian zone (about 100 m on either side of the stream) to frequent periods of saturation. This facilitates easy transport of phosphorus to the stream.

Baseflow

Baseflow is defined as any flow that arrives at the stream that did not arrive via surface overland flow. In other words, baseflow is made up of a groundwater contribution and an unsaturated zone contribution. A numerical technique was used to separate baseflow from overland flow, 79.6% of the total annual flow was baseflow or, in general terms, this catchment has a baseflow index (BFI) of 0.796. For 1998 the BFI was 80.2%. Baseflow is not a constant flow over the year. The range of streamflow was from 0.5 l/sec to 180 l/sec. Baseflow increased with precipitation as the unsaturated zone began to contribute flow to the stream. For instance, in February 1997 the baseflow increased from about 4 l/sec at the beginning of February to about 10 l/sec at the end of February. The increase in baseflow was due to both a rise in the water table and an increase in the degree of saturation of the unsaturated zone. The increasing saturation of the unsaturated zone produces horizontal flow in the direction of the stream. This is called interflow, and it occurs at a depth of about 10 cm to 50 cm below the land surface. This interflow layer is highly relevant to the transport of phosphorus, particularly dissolved phosphorus. Furthermore, a high baseflow index, implies that most rainwater gets to the stream via subsurface routes. It is, therefore, likely that the most common form of phosphorus found in the streamflow should be of dissolved form and accompanied with low suspended solids. The accompanying water chemistry report in the previous section (Section D) bears this out.

2-D Soil Moisture and the Interflow Layer

Figure 15 is a picture of the two dimensional soil moisture behaviour in the 100 m^2 plot on 31st May 1997. Prior to this day, there was a week of dry weather so the soil profile was drying out. Figure 15 shows an overall soil profile depth of 60 cm. The longitudinal length of the plot shown is 16 m. The soil moisture legend shows a range of about 5% to 30%. The porosity of the soil is 50% with a field capacity of 36% and a wilting point of 13%. In Figure 15 (looking at the downstream end of the plot) a surface layer, of about 15 cm in depth, can be seen with moisture content of less than 15%. In other words this surface layer has moisture content close to wilting point. However, at that time in May/June 1997, the grass and silage was far from wilting. It was getting its moisture from depths. Also in Figure 15, the next layer, from a depth of 15 cm to a depth of 45 cm shows moisture content of about 22% to about 32%. This level of moisture supports grass/silage growth but does not support interflow. The latter will tend to occur only when this interflow layer achieves moisture contents close to or above field capacity. The lowest layer, 45 cm to 60 cm in Figure 15, indicates a moisture content of about 15%. From this Figure, it is clear that there is no surface overland flow. Neither is there active interflow. The grass/silage receives its moisture from the interflow layer and has 'a first call' on the moisture in this layer before any interflow can be supported.

Figures 16 and 17 show the 2-D soil moisture profiles at 11.30 am and at 4.30 pm on 12th July 1997. The previous 10 days were dry and warm with high evaporation. Rain began in the early hours of the 12th July and persisted throughout the day with a total daily rainfall of 32.2 mm. We recorded the soil moisture in the field just before noon and again at 4.30 pm. In Figure 16 (at 11.30 am) we see the growth of the interflow layer with soil moisture pockets as high as 35% can be seen. At the upstream end of the plot, there appears to be two interflow layers. In Figure 17 (at 4.30 pm) we see that the two layers have almost joined. At the downstream end, we see an interflow layer from about 5 cm to 40 cm, with a very wet core of moisture content at about 36 % or at field capacity. We recorded continuous flow from the sub-surface collector (interflow) on this occasion but there was no surface runoff. Also visible in this Figure, at the lower depth of about 60 cm, is a layer with moisture content less than about 18%. This appears to be a capillary barrier, restricting vertical percolation to depths than 60 cm.

In Figure 18, a typical vertical profile of soil moisture for 28th June 1997 is presented. There were three dry days preceding the 28th but there were six wet days preceding the 24th (total rainfall 18th-24th June was 57.4 mm). At the downstream end of the plot (access tube 3) there is an interflow layer with its centre at a depth of about 15-20 cm and at the centre the moisture content was measured at 35 %. At the upstream end of the plot (access tube 1), there were two distinct interflow layers, one centred at about 15 cm and the second centred at about 40 cm. This is also clearly visible in the colour pictures. The 2-D modelling results are also shown in Figure 18. The model estimates the soil moisture well if we consider the full depth of 60 cm. However, it under-predicts the soil moisture in the interflow layers.

CONCLUSIONS

❶ The water balance over the calendar year 1997 in Dripsey showed 1443 mm of precipitation, 416 mm of evaporation and 1081 mm of streamflow. Evaporation constitutes about 28 % of total annual rainfall.

❷ The average monthly precipitation over the calendar year 1997 in Dripsey was 120 mm and 106 mm at Cork Airport. The highest monthly precipitation in 1997 at Dripsey was 261 mm in August. The lowest monthly precipitation of 35 mm was in March. The Winter (December 1996, January 1997 and February 1997) three-month total in Dripsey was 311.4 mm. The summer (June, July and August) three-month total in Dripsey in 1997 was 477.6mm. The summer total was 44 % greater than the winter total. Because of the high levels of summer precipitation, phosphorus transport to streams is an all-year-round phenomenon. Reports from other countries with drier summer climates should not be used to guide Irish nutrient management strategies as they fail to highlight the sensitivity of Irish agricultural catchments to the often-wet summers.

❸ The water table depth at the top of the hillslope ranged from 1.3 m to 1.9 m below the surface. At the bottom of the hillslope (20 m from the stream) the water table depth ranged from 0.4 m to 1.3 m. The bottom at the hillslope, with its particularly thin depth of unsaturated zone, predisposes the riparian zone to frequent periods of saturation. The shallow type of water table found in this hillslope predisposes the riparian zones (about 100 on either side of the stream) to frequent saturation. Phosphorus spread on such riparian zones is highly susceptible to being lost to streams. The assessment of the water table depth should be part of any strategy for nutrient management because of the high risk that water tables close to the surface pose for nutrient transport.

❹ We define sub-surface flow as the sum of groundwater flow plus interflow (from the unsaturated zone). Sub-surface flow is 80 % of the total annual streamflow. Only 20 % of streamflow is surface overland flow. Consequently, most phosphorus travels to the stream via sub-surface flow and is therefore in dissolved form. This finding is at odds with results of studies from other countries.

❺ In this hillslope we identified an active interflow zone at a depth of 10 cm to 40 cm below the surface. On occasions of no surface overland flow, infiltrated rainwater is transported to the stream via this sub-surface interflow layer. Phosphorus found in this zone albeit in concentrations decreasing from the surface) is available in dissolved form and also travels via this route to the stream. The interflow layer at 10 cm to 40 cm depths below the surface is responsible for the transport of dissolved phosphorus to streams.

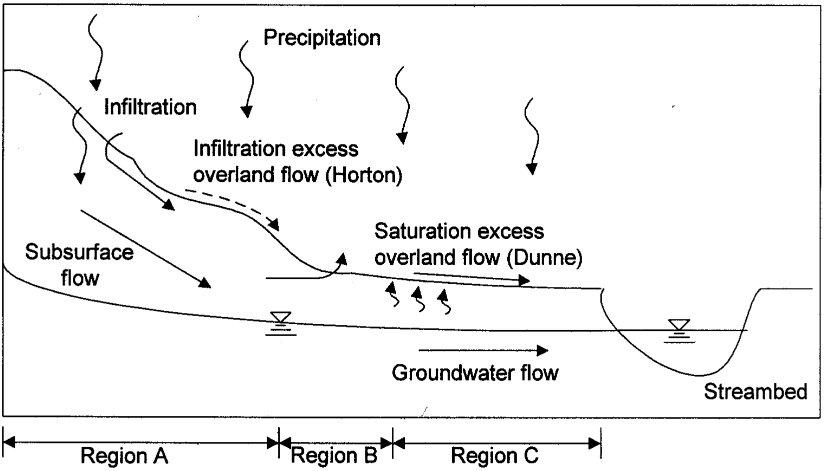


Figure 13: Transport mechanisms of precipitation from a hillside

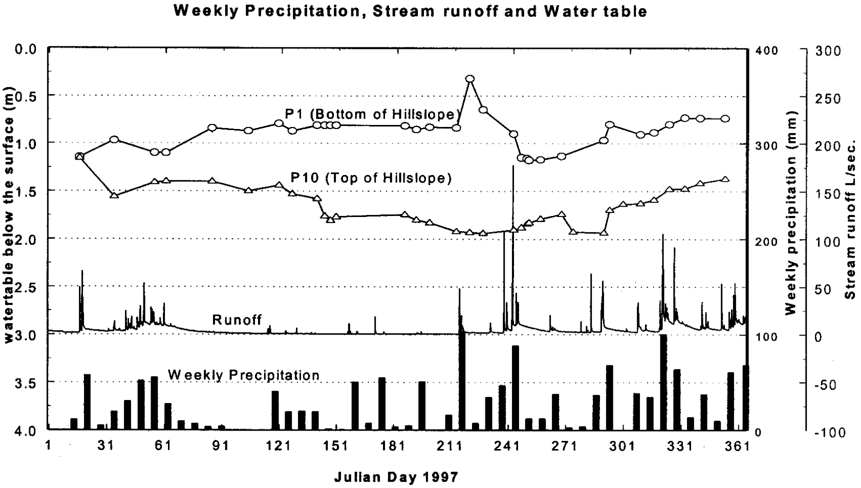


Figure 14: Watertable depths and weekly precipitation time series for 1997

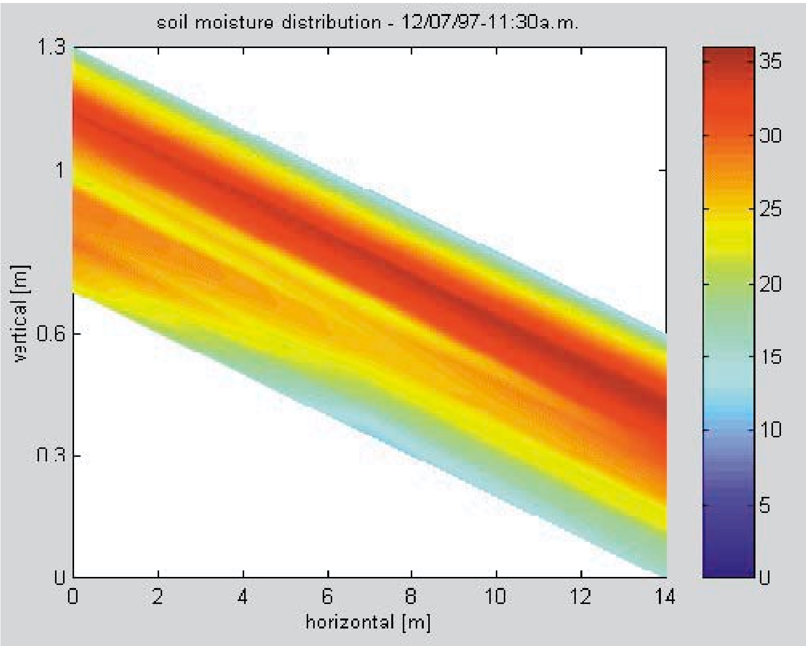


Figure 15: 2-D Soil Moisture in the plot 31/05/97

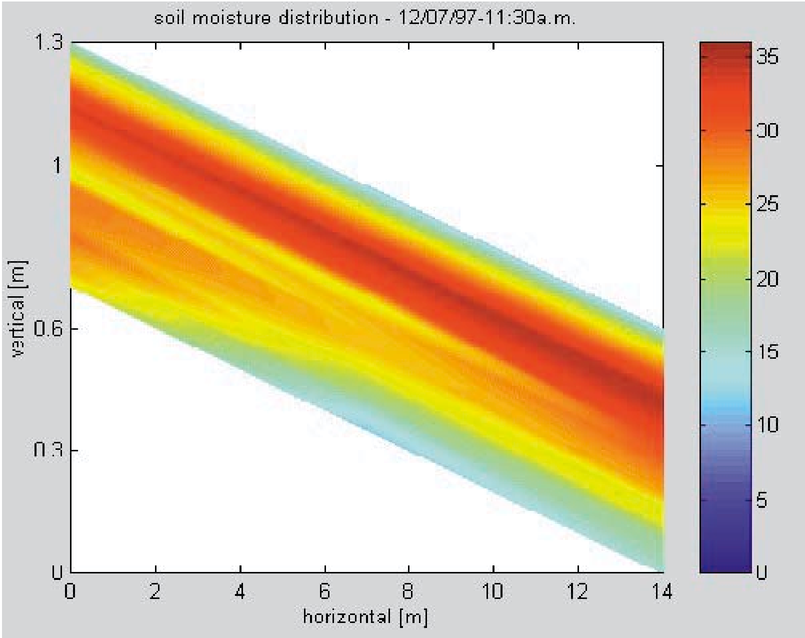


Figure 16: 2-D Soil Moisture distribution in the plot 12/07/97, 11.30 a.m.

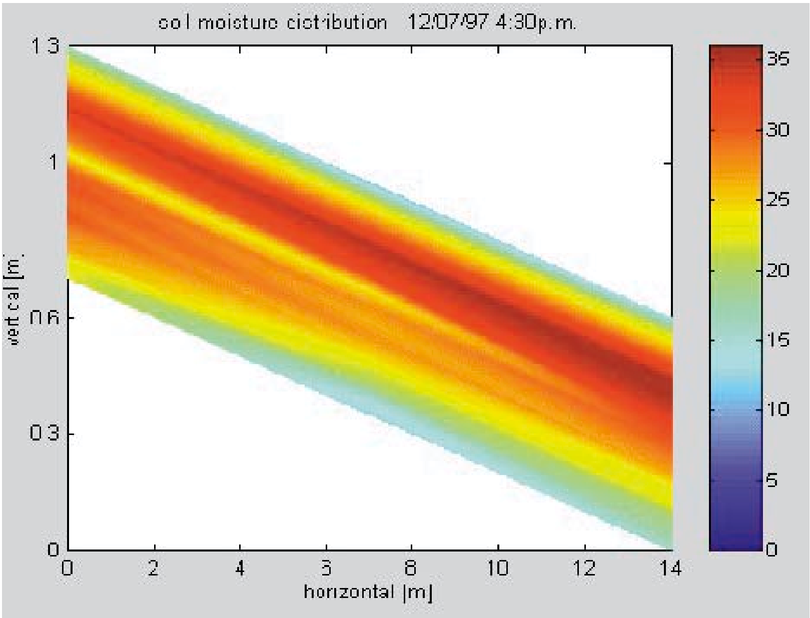


Figure 17: 2-D Soil Moisture in the plot 12/07/97, 4.30 p.m.

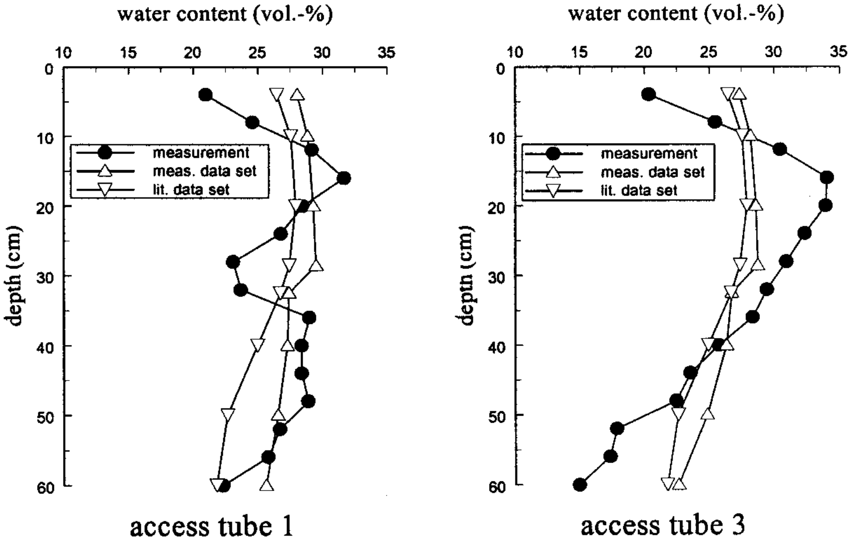


Figure 18: Typical vertical soil moisture profiles in the plot, 28 June 1997, highlighting the interflow layer at a depth of 10-30 cm.

4.4 PHOSPHORUS DESORPTION FROM IRISH SOILS (SECTION B)

Karen Daly
TEAGASC, Johnstown Castle

Introduction

This work attempted to describe soil phosphorus (P) sorption and desorption characteristics for a range of Irish agricultural soils. The project sought to identify soils vulnerable to P loss by desorption by comparing soil P characteristics in various soil types. Dominant soil properties controlling P sorption and desorption in soils were identified when soils were subjected to laboratory analysis of P and non-P parameters.

Materials and Methods

Sampling

Agricultural grassland soils were selected so that a range of soil properties could be provided . Soils representing a range fo soil associations were located using The General Soil Map of Ireland. Eleven soil associations were chosen to best represent importmant agricultural grassland soils around the country, varying in parent material, drainage, soil type and soil chemical characteristics. Soils of various P status were collected, so that each soil type included soils with a range of P levels. Soil samples were taken on a field-by-field basis during the period November 1996 to February 1997, prior to spreading of manures and fertilisers to ensure soils did not receive any P applications within four months sampling. At each field, approximately 30-40 soil cores, at a depth of 10 cm, were taken and combined as a composite sample to represent each field. The soil association number, principal soil type, parent material and location for all soils collected are outlined in Table 9.

Table 9: Location and description of soils selected based on the General Soil Map of Ireland.

Soil Association	Principal Soil	Parent Material	County
14	Acid Brown Earths	Ordovican Shale Glacial Till	Wexford
15	Brown Podzolics	Sandstone, Shale Glacial Till	Cork
22	Gleys	Carboniferous Shale Glacial Till	Kilkenny
25	Gleys	Sandstone Glacial Till	Cavan
26	Gleys	Basalt Glacial Till	Antrim
29	Acid Brown Earths	Silurian Shale Glacial Till	Monaghan
32	Degraded Grey Brown Podzolics	Limestone Glacial Till	Mayo
33	Shallow Brown Earths	Shallow Limestone Till	Galway
34	Grey Brown Podzolic	Limestone Glacial Till	Tipperary
40	Gleys and Shale	Till of Irish Sea Origin, Limestone	Wexford
44	Basin Peats		Kildare

Phosphorus testing

All samples were extracted for plant available P, desorbable P, total P, total inorganic and organic P. Plant available P was determined by two methods, Morgan's extractable P (Pm) and acid oxalate extractable P (Pox). Morgan's reagent was chosen since it is used as the national soil test to assess the fertility status of agricultural soils for fertiliser recommendations.

Phosphorus desorption to solution was determined by the iron-oxide paper strip test (Pfeo), water extractable P (Pw) and calcium chloride extractable P (Pcacl). Total P (Pt) was determined by the ignition method. Total inorganic P (Pin) was determined using the same method on non-ignited samples and total organic P (Po) was estimated by difference.

A single point sorption index was used to estimate the remaining P sorption capacity in soils. Soils (0.4 g) were suspended for 24 hours in 0.01 M $CaCl_2$, with a solution P concentration of 15 mgP/l. The final concentration in solution at equilibrium was used to obtain the P sorption index (PSI). Total P sorption capacity (PSCt) was estimated (PSI + Pox) and degree of P sorption saturation (DPSS) estimated (Pox/PSCt).

Non Phosphorus analyses

Extracts of Morgan's reagent were analysed for available K, Mg and Ca and acid oxalate extracts were analysed for amorphous forms of Al (Alox) and Fe (Feox). Organic matter was measured by loss on ignition and the results expressed as % weight loss after soils were ignited at 500°C. The pH of soils was estimated as part of the procedure for lime requirement of soils using the glass calomel electrodes. The cation exchange capacity of soils was measured by ammonium saturation.

Data treatment:
Laboratory analysis of samples was carried out in duplicate and an average value for each parameter was taken. All soil phosphorus data were expressed in mg P/l using the soil bulk densities. Statistical analysis of the data was carried out in SAS using the Proc Corr command to derive correlations among variables. The correlation coefficient R refers to linear correlations only, the direction of which is denoted by positive and negative signs (+/-). The significance of R and R^2 values are denoted by symbols *, ** and *** for significance levels p= 0.05, 0.01 and 0.001, respectively.

Results

The P characteristics in this dataset included sorption/desorption tests, P fractions, and agronomic soil P tests. The soil P data showed a high degree of intercorrelation among the various P tests. The three desorption tests, as described by Pfeo, Pw and Pcacl, were correlated positively with each other. Pfeo correlated strongly with Pw (R^2 = 0.71,***, +) but weakly with Pcacl (R^2 = 0.26,***, +). Pcacl and Pw were also weakly correlated (R^2 = 0.40,***, +). Phosphorus desorption tests correlated strongly with the agronomic test, Pm (Figure 19), whilst Pox correlated with Pfeo and Pw but not Pcacl. The Pfeo test correlated with Pm (R^2 = 0.60,***, +) and Pox (R^2 = 0.59,***, +) while Pw correlated with Pm (R^2 = 0.61,***, +) but weakly with Pox (R^2 = 0.33,***, +).

The agronomic tests in this dataset correlated with each other (R^2 = 0.27,***, +) and with P desorption and sorption as described above. However, Pox exhibited a stronger association with Pt (R^2 = 0.45,***, +) and Pin (R^2 = 0.46,***, +) than Pm.

The degree of P sorption saturation (DPSS) was positively correlated with the agronomic soil test, Pm, (R^2 = 0.46, ***, +). The DPSS variable correlated with desorption variables Pfeo (R^2 = 0.59, ***, +), Pw (R^2 = 0.64, ***, +) presented in Figure 20, and Pcacl (R^2 = 0.20, ***, +).

Table 10: Correlation matrix of R values for all data on the 90 soils, values in bold type are significant at the p = 0.001 level

	Pm	Pfeo	Pw	Pcacl	DPSS	PSCt	PSI	Pt	Pin	Pox	Alox	Feox	%O.M
Pm	1.00												
Pfeo	0.77	1.00											
Pw	0.78	0.84	1.00										
Pcacl	0.67	0.52	0.64	1.00									
DPSS	0.68	0.77	.080	0.45	1.00								
PSCt	0.22	0.55	0.25	-0.07	0.42	1.00							
PSI	-0.43	-0.13	-0.47	-0.55	-0.36	0.65	1.00						
Pt	0.27	0.49	0.33	0.06	0.35	0.71	0.40	1.00					
Pin	0.40	0.55	0.41	0.18	0.49	0.62	0.19	0.82	1.00				
Pox	0.52	0.77	0.58	0.22	0.74	0.90	0.25	0.67	0.68	1.00			
Alox	-0.17	0.03	-0.26	-0.34	0.02	0.68	0.71	0.54	0.51	0.42	1.00		
Feox	-0.26	0.08	-0.25	-0.31	-0.13	0.58	0.71	0.46	0.37	0.32	0.52	1.00	
%O.M	0.09	-0.23	-0.14	0.39	-0.33	-0.57	-0.41	-0.25	-0.20	-0.49	-0.35	-0.20	1.00

Table 11: Ranges of Pfeo and Pw values in each soil group, across similar STP (Pm) ranges

Soil Class	No of Soils	%OM	Soil Type	PM mg/l	PfeO mg/l	Pw mg/l	PSCt mg/l	DPSS %
S1	29	<12	Brown earths, podzolic soils	2.0-16.9	6.8-46.4	2.7-21.9	319-1043	39-79
S2	40	12.1-20	Gleys	1.9-16.8	6.8-48.9	1.9-15.5	358-1064	39-75
S3	11	20.1-30	Peaty gley, peaty podzols	4.2-18.5	7.8-39.7	5.8-15.1	519-987	41-70
S4	10	>30	Peats	1.9-18.7	3.7-17.2	1.3-10.4	68-766	22-61

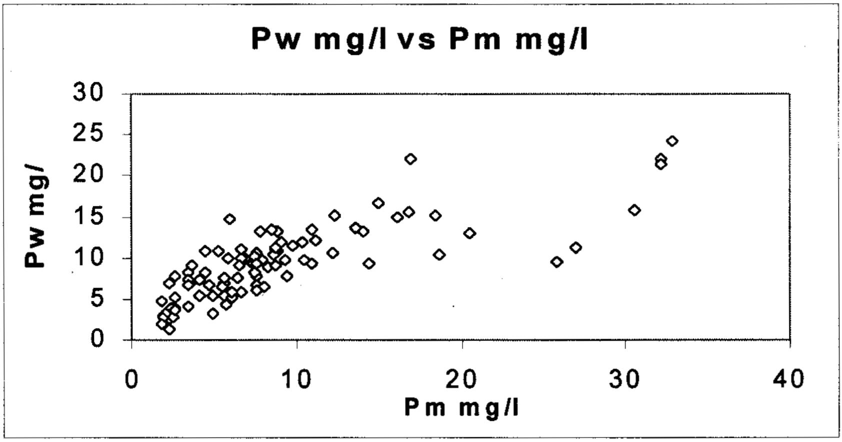


Figure 19: Scatter plot of Morgan's P (Pm) against P desorption (Pw).

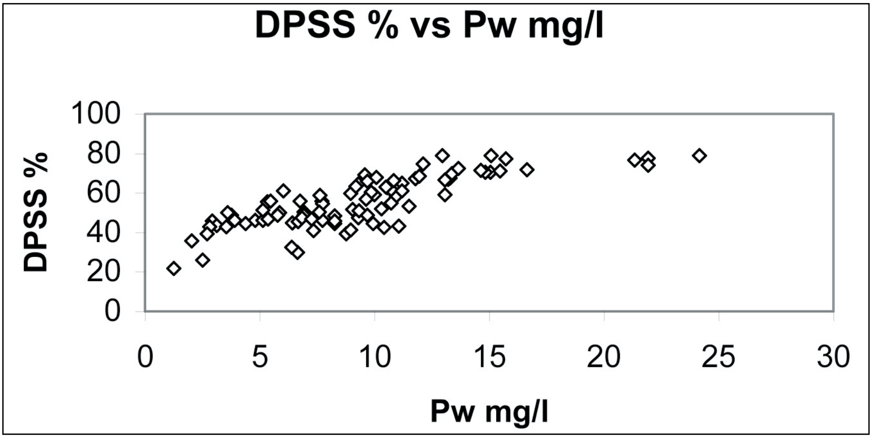


Figure 20: Scatter plot of P De (Pw) against P saturation (DPSS)

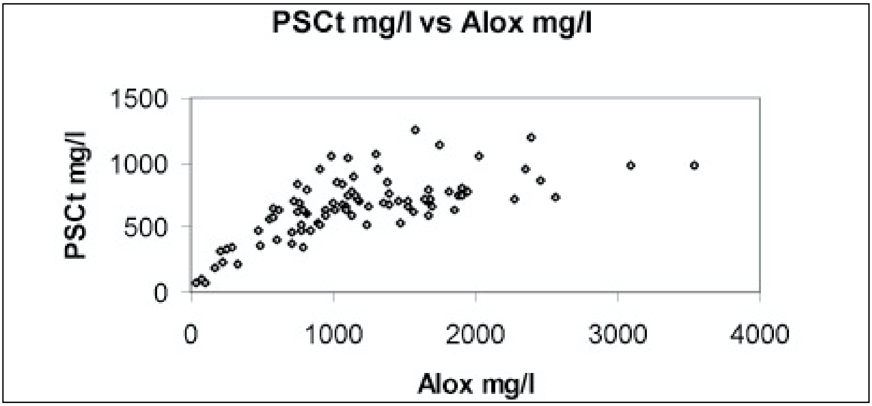


Figure 21: Scatter plot of total P sorption capacity (PSCt) against Alox.

The total phosphorus sorption capacity (PSCt) correlated positively with Alox ($R^2 = 0.46$, ***, +) depicted in Figure 21, and Feox ($R^2 = 0.33$, ***, +) and negatively with %OM ($R^2 = 0.33$, ***, -). Soil properties identified with PSI in these data were Alox ($R^2 = 0.50$***, +) and Feox ($R^2 = 0.50$***, +) and %OM ($R^2 = 0.17$***, -). Correlations among soil data are presented in a correlation matrix of R values in Table 10 with highlighted values significant at the $p = 0.001$ level. Although no direct correlation could be found between Pw or Pfeo and %OM in these data, the high organic matter soils in the dataset appeared to return lower values for Pw and Pfeo over similar ranges of Pm compared to the mineral soils. The dataset was then divided into sub-sets according to soil type, defined by % OM, so that sorption and desorption values could be compared among broadly different soil groups. Soils were described by four classes (S1, S2, S3 and S4) and P desorption over similar ranges of Pm were compared. The range of desorption values for each group is given in Table 11.

Discussion

There was a clear relationship between the magnitude of P sorption and desorption, and P status in soils used in this study. Over the range of soils types analysed in this study, high P status soils desorbed more P to solution than low P status soils. Phosphorus sorption from solution was limited by high P status. The correlations derived between the desorption/sorption tests and Pm over the range soil types demonstrated the importance of soil P status in determining the magnitude of these reactions. The degree of P sorption (DPSS) saturation in soils was estimated from measurements of PSI and Pox in the dataset, and the strong relationship between this variable and P desorption tests indicated that soils saturated with P were vulnerable to P loss by desorption. The DPSS in the full dataset ranged from 22% to 79% with a mean value of 55% saturation over the range of grassland soils sampled in this work. The mineral soils were up to 79% (S1) and 75% (S2) saturated with P indicating heavy applications of P to these soils. Other workers have used the DPSS as a variable to predict potential P loss from soil to water. The relationship between Pw and DPSS ($R^2 = 0.64$, ***, +) in this work concurs with other researchers who suggested that readily desorbable P (or Pw), increased as soils were increasingly saturated by P additions, thus, the risk of environmentally significant P losses from these soils is high.

The strong positive correlations between Alox and Feox and sorption (measured as PSI, and PSCt) suggested that amorphous forms of Alox and Feox are important soil properties controlling P sorption in soils. However, when values of PSCt and PSI were compared between soil groups, the peat soils (S4 group) had a lower mean PSCt of 279 mg/l compared to mean values of 620 and 794 mg/l for mineral soils of S1 and S2, respectively. Similarly, when P desorption values were compared across the four soil groups, the peat soils returned lower values of Pfeo and Pw when compared against mineral soils at similar P status. Thus sorption (PSI and PSCt) and desorption (Pw and Pfeo) processes were affected by high amounts of organic matter in soils. In addition, peat soils had lower amounts of Alox and Feox and therefore fewer sites available for sorption/desorption reactions to occur. While P may react with Alox and Feox in mineral soils, where it is in abundance, soils do not have the capacity to chemically sorb P in less available forms. Therefore, when P is added to peats it is readily available and found mostly in the soil solution. The implications are that peat soils are unsuitable for excess P application in fertiliser or manure, owing to their low capacity to chemically sorb added P.

The results from this research have identified P status, OM and amounts of Alox and Feox in soils as the dominant soil variables in P sorption and desorption reactions. While mineral soils had greater capacity for P sorption and desorption, in terms of P loss vulnerability, these soils were up to 79% (S1) and 75% (S2) saturated with P and, therefore, risk losses to water at elevated soil P levels. Also, since peat soils had lower P sorption capacities, these soils risk losses to water if amended with fertiliser and manure P that may remain in the soil solution.

4.5 NATIONAL PHOSPHORUS MODEL (SECTION C)

Karen Daly, Brian Coulter
TEAGASC, Johnstown Castle

Paul Mills
Trinity College Dublin

Introduction

This project derived available information on land use, land management, soil type and water quality for 35 Irish river subcatchments (Figure 22). The objective was to describe river P levels using these data so that areas at risk of diffuse P losses and the variables controlling these losses could be identified.

Methods

The model developed in this work used water quality and stream flow data collected for thirty-five river subcatchments as the dependent data, and landuse data and agricultural datasets as independent variables. The independent variables, and the sources of data used in deriving them, are listed briefly as follows:

- Soil test P levels (Teagasc soil test data; overland flow study from Section A)
- Landcover patterns (CORINE landcover database)
- Fertiliser and manure P applications (Teagasc)
- Ratio of dairy cattle to total cattle numbers (agricultural census data on animals and crops, Central Statistics Office (CSO))
- Long term rainfall patterns as estimates for runoff (MetEireann)
- P desorption (soil P desorption study from Section B; the General Soil Map of Ireland)

The P levels of soils were represented by a single variable ('SoilP') which was derived as an index for each catchment. This was calculated using existing soil test P results from Teagasc combined with information on P concentrations measured in overland flow from fields at different soil P levels in Section A. Essentially, a weighting was assigned to soil P levels and used as a multiplier to calculate a soil P value for each area. Similarly, information on soil P desorption was taken from results in Section B and applied to soil type data in each catchment. Soil types were assigned a desorption weighting as a multiplier to calculate a desorption index for each catchment. This variable is denoted by the term 'Despn'.

The land use in each catchment was taken from the CORINE database which categorised land as high production grassland (Higrass), low production grassland (Lograss), seminatural areas (Seminat) and peatland areas (Peat). Seminatural and peatland areas were combined as one variable in some of the statistical analysis and renamed 'Semipeat'. Fertiliser P and manure P use in each catchment is represented by the variables 'Fert' and 'Manure'.

River P levels were expressed as flow-weighted P concentrations (MRP) using molybdate reactive P concentrations (EPA) and daily mean flow data (OPW) for the period 1991-1994.

Statistical analysis

All of the variables were combined to see if significant correlations existed. River P levels (MRP) were then modelled using multiple regression and Principal Components Analysis. In a model validation step, some additional data was supplied to investigate whether or not the models derived could accurately predict observed values. Observed and predicted values were compared using correlation and linear regression analysis denoted by R^2 values, the direction of which is denoted by positive and negative signs (+/-). Significance levels are denoted by the symbols *, ** and *** for significance levels $p = 0.05$, 0.01 and 0.001 respectively.

GIS techniques

Extensive use of GIS technology was made during the preparation and analysis of the various datasets. Most of the work was carried out with Arc/Info and ArcView software systems from ESRI Inc. Raster grid modelling was carried out with the Spatial Analyst extension module of ArcView. All map plots were produced using ArcView. The principal procedures performed in the GIS included:

- Preparation of catchment and subcatchment boundaries,
- Area weighting of polygon zonal data,
- GIS overlay of multiple map layers,
- Conversion of point datasets to zonal patterns using spatial interpolation techniques (e.g. rainfall and soil test P level datasets),
- Spatial aggregation of datasets to provide corrected summaries of nested catchment areas.

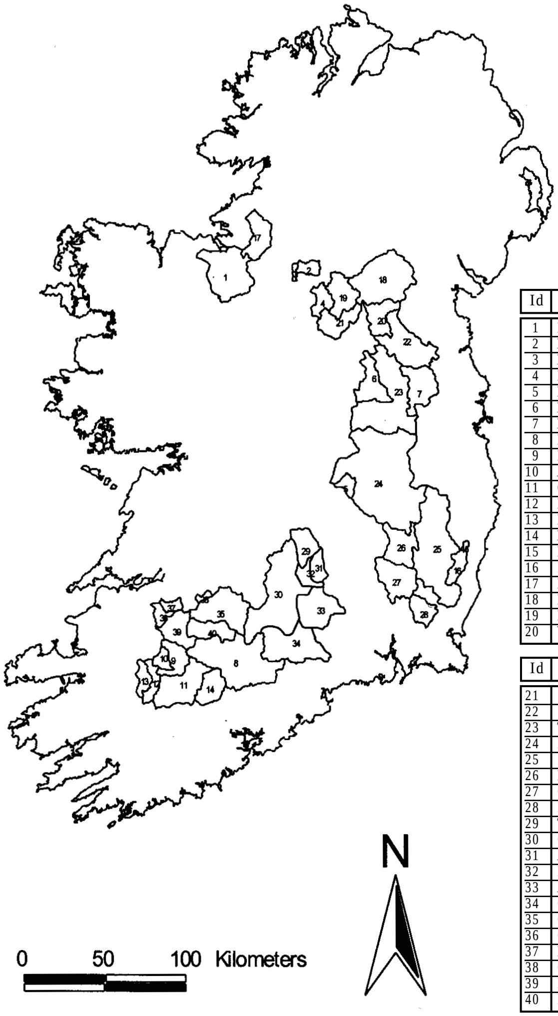
Results

Relationships among variables in the model

Correlation coefficients between river MRP values, calculated as winter, summer and annual MRP values and the agricultural and landuse datasets were derived. Fertiliser P use in a catchment was represented by the variable Fert, and was positively correlated with high production grassland areas denoted as Higrass ($R^2 = 0.46$, ***, +) and negatively correlated with peatland areas ($R^2 = 0.45$, ***, -). Although the correlation between annual river MRP values (AnMRP) and the landuse category Higrass was weak ($R^2 = 0.23$, **, +), the scatter plot in Figure 23 depicted separate trends, indicated by two trend lines or clusters. From the results of the cluster analysis and interpretation of scatter plots, two clusters of subcatchments were derived and the data were divided into two separate populations (clusters), denoted here as clusters A and B. Initial inspection of annual MRP values in the two clusters indicated that values in cluster A exceeded those in cluster B. In addition, summer MRP values in cluster A exceeded winter values, indicating some seasonality in the data. However, no seasonal effects were apparent in MRP data of cluster B. The catchment characteristics in each cluster were significantly different and examination of the data concluded that cluster A catchments had mostly poorly drained or wet soils (gleys, peats and peaty gleys) whilst B catchments had mostly well drained dry soils (brown earths and brown and grey brown podzolics). This was also reflected in the river flow data for each cluster, where cluster A areas had higher river flows than B areas. Thus the data appeared to cluster according to soil type and catchment hydrology. Soil type in cluster A and B catchments were described as 'wet' and 'dry' soils, respectively, and this was used to categorise other areas of the country as A or B type catchments.

Modelling MRP values in cluster A

Four variables were included in a Principal Components Analysis for cluster A type catchments, namely, SoilP, Higrass, Semipeat and Despn. Four components were generated and the first selected since it carried 71 percent of the variability in the data. The first component (M1) was then used in a regression step to describe MRP values in these catchments, using the winter, summer and annual MRP values in an attempt to find the best model that fits the data in these catchments. The results of this regression step are summarised in Table 12.



Id	Catchment	River
1	Ballysadare	Ballysadare
2	Killywillin	Blackwater
3	Kiltybardon	Yellow
4	Derreskit	Cullies
5	Mountmellick Owenass	Barrow
6	Killyon Deel	Boyne
7	Navan	Boyne
8	Ballyduff	Blackwater
9	Riverview Allow	Blackwater
10	Allens Bridge Dalua	Blackwater
11	CSET Mallow	Blackwater
12	Duarrigle	Blackwater
13	Duncannon	Blackwater
14	Killavullen	Blackwater
15	Pallis	Bann
16	Ferns	Bann
17	Dromahair	Bonet
18	Butler's Bridge	Annalee
19	Belturbet	Erne
20	Virginia	Boyne

Id	Catchment	River
21	Sallaghan	Erne
22	Slane	Boyne
23	Trim	Boyne
24	Bestfield	Barrow
25	Enniscorthy Slaney	Slaney
26	Royal Oak	Barrow
27	Graiguenamanagh	Barrow
28	Dunanore Boro	Slaney
29	Thurles	Suir
30	Cahir	Suir
31	Athlummon	Suir
32	Beakstown	Suir
33	Anner	Anner
34	Clonmel	Suir
35	Croom	Maigue
36	Castleroberts	Maigue
37	Rathkeale	Deel
38	Grange Bridge	Deel
39	Deel Bridge	Deel
40	Bruree	Maigue

Figure 22: Map of catchment areas used in the model

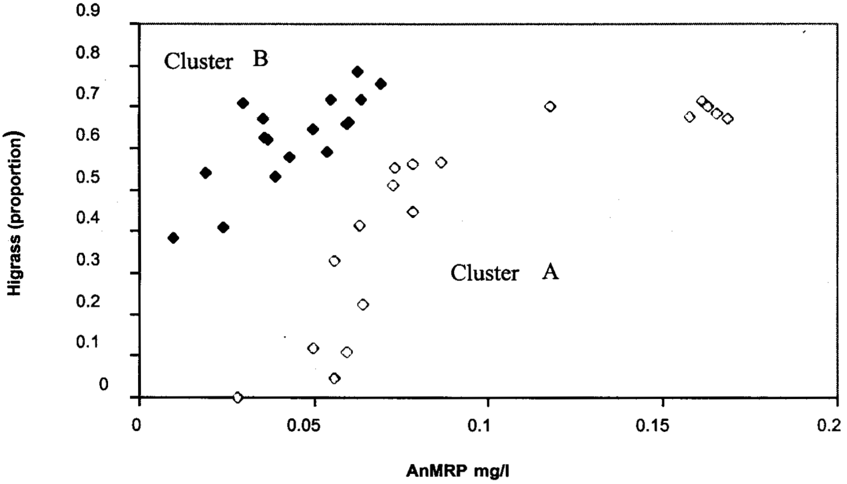


Figure 23: Scatter plot of Higrass against Annual MRP values depicting a clustering of data

Table 12 Adjusted linear regression model of annual and seasonal MRP values in cluster A using the first principal component M1 as the dependent variable.

Y	Variable	Coefficent	*s.e. coefficient	Probability	R^2
WinMRP	Constant M1	0.086 -0.041	0.007 0.007	<0.0001 <0.0001	0.69
SumMPR	Constant M1	0.117 -0.049	0.009 0.009	<0.0001 <0.0001	0.64
AnMRP	Constant M1	0.097 -0.040	0.007 0.007	<0.0001 <0.0001	0.68

*s.e = standard error

The first component (M1) is treated as a new variable in the regression step and is described by the following equation:

$$M1 = -1.21*Higrass - 1.86*Despn - 0.15*SoilP + 2.81*Semipeat + 4.08.$$

Multiple regression model for cluster B

A multiple regression approach was used to predict summer MRP values for cluster B catchments using Higrass, Lograss and SoilP variables. These variables were uncorrelated in this dataset, thus their use was justified in a multiple regression model.

Summer MRP values gave the best fit to the catchment data with an $R^2 = 0.62$ as opposed to annual MRP values which gave an $R^2 = 0.33$, when regressed against the same variables. The multiple regression model predicting summer MRP values in cluster B catchments is described in Table 13.

Table 13 Multiple regression model of summer MRP vlaues in cluster B catchments using land use and Soil P as dependent variables.

Y	Variable	Coefficent	*s.e. coefficient	Probability	R^2
SumMPR	Constant Higrass Lograss Soil P	-0.056 0.074 -0.211 0.018	0.031 0.032 0.082 0.006	0.0924 0.0349 0.0215 0.0115	0.62

*s.e = standard error

Classification of predicted values

To predict MRP values for other catchments, areas were classed as either A or B type catchments according to the predominant soil types ('wet' or 'dry') and the appropriate model was applied to predict MRP values on a national scale. The predicted MRP values from each model were broken down into four classes A1/B1 to A4/B4, similar to median ortho-P concentrations given in the EPA water quality classifications. These ranges are outlined in Table 14. On the national map (Figure 24) the areas of cluster A show predicted values of winter MRP and the areas of cluster B show predicted values of summer MRP.

Table 14 Predicted MRP ranges and MRP class with EPA water quality classifications

MRP Class	MRP Range mg/l	EPA median ortho-P range and associated pollution class
A1/B1	0.000 - 0.030	0.015 - 0.03 (unpolluted)
A2/B2	0.031 - 0.060	0.045 (slightly poluted)
A3/B3	0.061 - 0.100	0.07 (moderatley polluted)
A4/B4	> 0.1	> 0.1 (heavy/gross pollution)

Model validation

Measured total P (TP) values from 17 sub-catchments of the Lough Conn and Lough Mask areas were supplied by the EPA. Although the models in this study predicted MRP values, the Loughs Conn and Mask TP results were the only data available for use in a validation step. The catchments were classed as either type A or B, depending on the dominant soil type, and the appropriate model was run to predict MRP values. Predicted and observed values were compared using single linear regression, the results of which are outlined in Table 15.

Table 15: Model validation using linear regression of predicted MRP values vs. observed TP values, (n = no. of catchments, p = probability)

TP vs Modelled Parameter	Cluster	n	R^2	p
TP vs. WinMRP	A	7	0.69	0.02
TP vs. SumMRP	A	7	0.68	0.02
TP vs. AnMRP	A	7	0.67	0.02
TP vs. SumMRP	B	10	0.30	0.1
TP vs. AnMRP (A) & Sum MRP (B)	A & B	17	0.57	0.005

Discussion

Clustering effect

When correlated to selected catchment parameters, the MRP values highlighted some clustering among the data and separate models were derived for catchments types A and B. The existence of clusters was explained in terms of soil hydrology, since the relationship between the MRP and high production grassland variables clustered according to 'wet' and 'dry' soils. Visualising the catchments in terms of 'wet' and 'dry' soils on the GIS, elucidated the clustering effect in the statistical approach and provided a useful guide to assigning a cluster category to other areas of the country, so that the appropriate model could be applied.

Seasonal effects

A seasonal effect in MRP data for cluster A catchments was observed, i.e., where summer MRP values significantly exceeded winter values, while no such difference in MRP values exists for cluster B catchments. The seasonality in the data could be explained in terms of a dilution effect. In cluster A catchments, the lower river P concentrations in winter could be due to a dilution of values during the high rainfall season. This dilution effect is possibly more evident in A type areas because they generated more overland flow compared to B type areas.

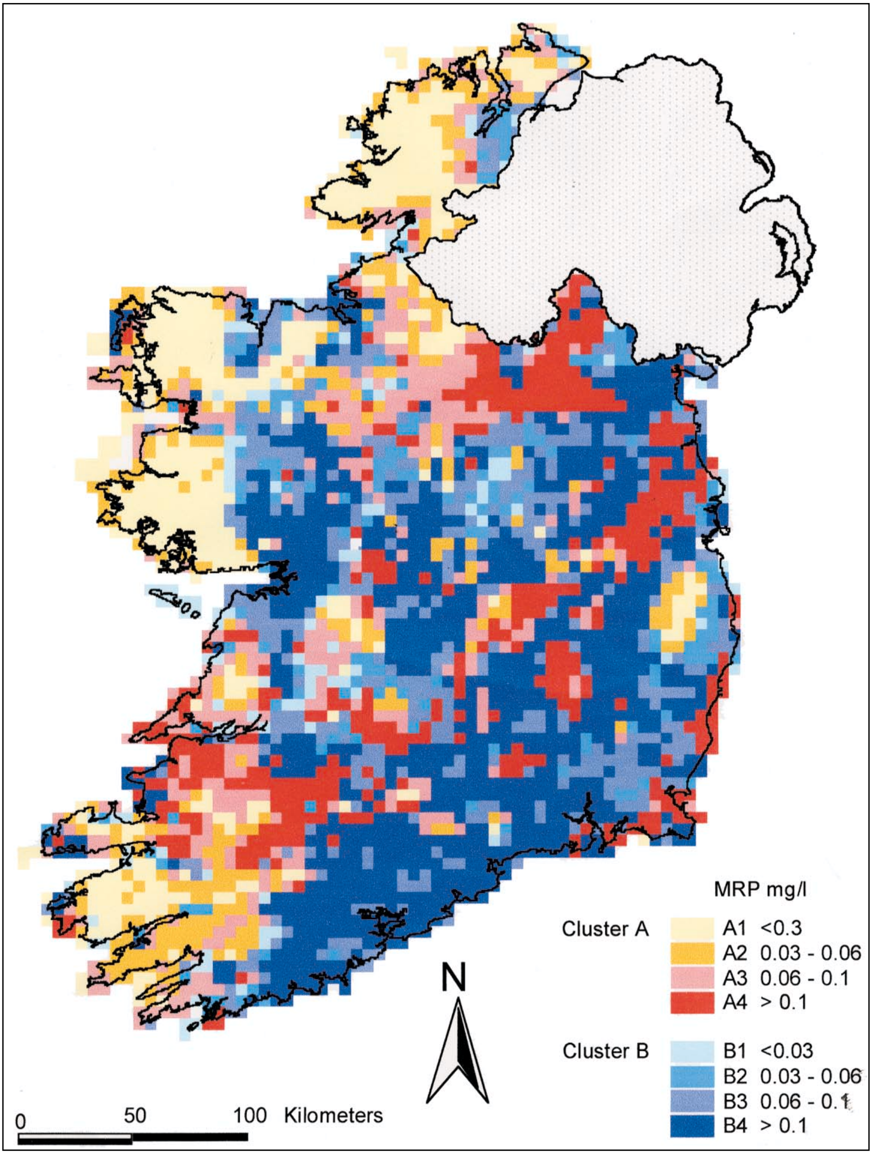


Figure 24: Map of predicted MRP values for cluster A and B type areas

Model components

The components of the model for cluster A catchments were essentially land use (Higrass, Semipeat), soil type (Despn) and SoilP. Since the soils of catchments in cluster A were essentially wet soils, indicated by higher proportions of gleys, peaty gleys and peats, the occurrence of the desorption variable in the model could be interpreted in terms of soil hydrology or soil wetness, rather than soil P desorption. For wet catchments in cluster A, MRP values exhibited a seasonal effect and were generally higher than those in cluster B. The 'Semipeat' variable in the cluster A model had a negative weighting in the principal component and was negatively correlated with MRP. This would suggest that low MRP concentrations were associated with seminatural and peatland areas. However, if the mathematical sign (i.e., +/-) of the coefficient (or component weighting) associated with variables in a model, is an indicator of whether the variable is a source or a sink for P, then high production grassland (Higrass), SoilP and Despn were sources of P, while 'Semipeat' was a sink. The Higrass variable in cluster A was positively correlated with fertiliser P applications ($R^2 = 0.79$, ***, +), which could exacerbate P loss to water.

Soil test P levels and soil P desorption are known variables affecting P loss from soil to water. However, that 'semipeat' is a sink for P in this model is less easily explained in the same way that forestry is often cited as a sink for trapping nutrients. Seminatural and peatland areas are not intensively farmed areas and therefore do not get surplus applications of P in the same way that high production grassland areas do, which may explain the negative weighting. In addition, seminatural areas and peatlands are usually associated with peat and peaty gley soils. These soils have a low capacity for storing P and usually generate overland flow due to poor infiltration. If this land cover class is located near the stream or river, then partial area theory suggests that its contribution to overland flow into a waterbody will be significant. In addition, if nutrients are moving from a neighbouring cultivated or high production grassland area, then seminatural areas will be unable to 'trap' nutrients in the same way that forested areas do. If this was the case in cluster A catchments, then the higher MRP levels in these catchments could be due to the combination of catchment hydrology and a predominant soil cover, unable to sorb or trap nutrients moving from a landscape where excessive overland flow is generated.

The catchments of cluster B are defined as drier catchments by the flow data (lower overland flow) and predominant soil type (well drained soils), relative to cluster A. The modelling step for these catchments used multiple regression with Higrass, Lograss and SoilP as variables. The coefficients assigned in the model indicated that Higrass and SoilP may have acted as sources, and the Lograss variable, a sink for P. The identification of different catchment types (wet and dry) in this work highlights the importance of catchment hydrology in transporting nutrients from land to water.

This is a first attempt at modelling P loss from agricultural land to water in Ireland. Further work, based on the approach developed in this study, is necessary for more reliable predictions of P loss to water.

5.0 DETAILS OF OUTPUT AND DELIVERABLES

5.1 LITERATURE REVIEW

The co-ordinator, Dr. H Tunney, was the senior editor of a book entitled “Phosphorus Loss from Soil to Water” published by the Centre for Agriculture and Bioscience International (CABI), Wallingford, Oxon, England. This book was published in 1997 and contains a comprehensive literature review on this area of work. In addition, there was an OECD sponsored workshop on innovative measures to control P losses from agriculture to water, held in Greenmount College, Co. Antrim in June 1998 and the papers presented, are published in the Journal of Environmental Quality (Volume 29, No. 1, Jan.-Feb. 2000, p. 1-176).

There is an Internet Website based on the EU COST 832 Action, Quantifying the Agricultural Contribution to Eutrophication (http://www.ab.dlo.nl/eu/cost832/welcome.html/). This website contains useful information on P loss to water.
The final report, published by the EPA, contains a list of relevant references.

5.2 MEETINGS OF THE PROJECT GROUP

The project group had five meetings during the course of the project to co-ordinate the work, discuss methodology, discuss results and agree on preparation of the report. Four of the meetings were at Johnstown Castle and one at University College Cork. In addition to progressing the work, the meetings provided an opportunity for all participants to see the field plots for measuring P loss at Johnstown Castle and in the Dripsey catchment, Co. Cork. In addition to the five formal meetings, there was ongoing contact between individual members of the project team on various aspects of the work.

5.3 INTERIM PROGRESS REPORTS

Interim progress reports on the different stages of the work were prepared and forwarded to the EPA, as required in the project specifications. Three progress reports were submitted for Jan-June 1996, July-Dec 1996 and Jan-June 1997. This End of

Project Report covers the entire duration of the project, April 1996 to December 1998, and in addition to the reports published by the EPA is the main output from the work. In addition, the project team presented interim results at two Lakes Workshops organised by the EPA. Results of the project were also presented at a seminar on the results of the Environmental R&D Programme, organised by the EPA and held at the EPA headquarters, Johnstown Castle, Wexford, on the 1st May 1998. Some of the results of this work were also presented at the OECD Workshop in Antrim in June 1998.

5.4 DRAFT CODE OF BEST PRACTICE TO REDUCE P LOSS FROM AGRICULTURAL FIELDS TO WATER

The five sections (A to E), in Chapter 4, dealing with the main work areas cover the major outputs for the project as laid out in the Project Specifications and in the Contract Document. In addition the Contract Document undertook to outline a draft code of best practice to reduce P loss from agricultural soils to water insofar as the results justified. A first approximation of a draft code of best practice is summarised in the Recommendations (Chapter 7 below).

6.0 OVERALL CONCLUSIONS

Each of the five main sections in Chapter 4 (4.1 to 4.5) summarises the main results and conclusions. An attempt is made here to draw together a brief summary of the main findings of the study. The conclusions from the field plots (sections A, D and E) are summarised first, followed by the work on soil P desorption for representative soils and the National P model (sections B and C).

6.1 SMALL PLOT FIELD STUDIES ON P LOSS TO WATER (JOHNSTOWN CASTLE, CO. WEXFORD AND DRIPSEY, CO. CORK)

The dissolved reactive P (DRP) for 1997, for the lowest P site (Warren 1, 4 mg P per litre soil) was 0.70 kg per ha and for the highest P site (Cowlands, 17 mg P per litre soil) was 4.77 kg per ha (see Table 16). For the three sites at Johnstown Castle, the DRP export, for the 144 days from November 1997 to March 1999, was 0.11, 0.30 and 1.16 kg ha for the low, medium and high soil P sites, respectively. The DRP loss from the Dripsey site for 1997 was estimated at 1.64 kg P per ha and is in broad agreement with the results for the Johnstown Castle sites. Losses of 1.9 kg P water soluble P per ha were found in the Lee-STRIDE study in 1993, in a subcatchment of the Dripsey.

Total dissolved P (TDP) accounted for about 80 percent of total P (TP) loss and DRP accounted for about 70 percent of TP. Particulate P in suspended solids generally accounted for less than 20 percent of TP loss from these four grassland sites.

A summary of the estimated annual (1997) P losses for the four sites is shown in Table 16. The estimate for the 144 days at the median soil P (Warren 2) site was extrapolated to 365 days based on the full year information and the 144 day results at the other two sites at Johnstown Castle.

Table 16 Summary of anual (1997) DRP loss from the four grassland field sites, without point sources, and site characteristics

Site	Soil P mg/l	DRP loss kg/ha	DRP loss less 40%	Catchment area ha	Rainfall mm	Overland flow mm	Slope %	Soil type
Warren 1	4	0.70	0.42	1.54	1232	795	3	Gley
Warren 2	8	1.26 (est.)	0.76	1.09	1232	632(est.)	4	Gley
Dripsey 1*	10	1.64	0.98	14.5	1443	289	4	Podsol
Cowlands	17	4.77	2.86	0.46	1232	443	3	Gley

* Dripsey site was on a diary farm in Cork the other sites were at Johnstown Castle, Wexford.

There was an exceptional rainfall event between the 3rd and 7th of August 1997 when about 150 mm of rain fell in a four-day period. The overland flow after this event carried more than 40% of the total annual DRP loss for 1997. This is atypical and is likely to occur less than once in 30 years. Therefore, there is an additional column in Table 16 showing DRP loss less 40% which may be more typical of DRP loss in an average year. Large differences in rainfall between years will lead to large differences in P loss to water and the distribution of rainfall throughout the year will influence the annual distribution of P loss. The pattern of rainfall in Ireland means that, unlike many other countries, P loss to water can be considered an all-year-round phenomenon.

Figure 25 shows a summary of the highly significant relationship between soil test P (Morgan's) and DRP loss at the four sites in 1997. It also shows the 40 percent lower loss that may be more representative of an average year.

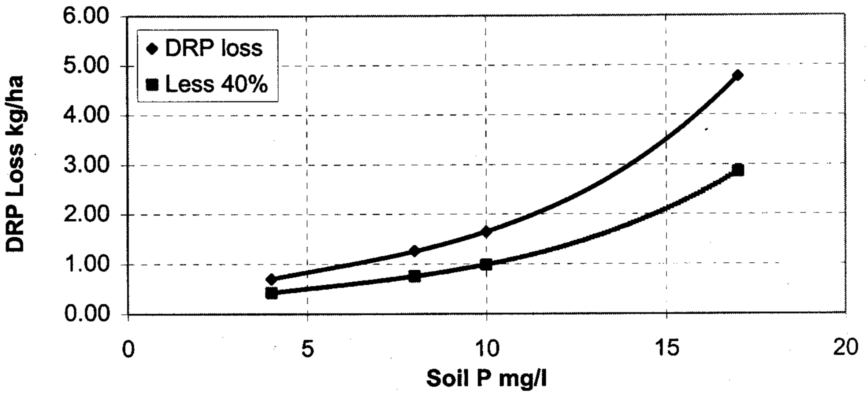


Figure 25: Summary of relationship between soil test P (Morgan's) and annual DRP loss (in 1997) to water at the four field sites studied, based on the values shown in Table 16.

It is estimated that P loss to water should be of the order of 0.35 kg P per ha per year, or lower, for good water quality (Tunney, H., R. H. Foy and O. C. Carton. 1998. 'Phosphorus inputs to water from diffuse agricultural sources'. In: Eutrophication in Irish Waters. ed: James G. Wilson. Publ: Royal Irish Academy, Dublin. pp. 25-39). Based on this the relationship in Figure 25, for an average year (the lower line), indicates that for catchments represented by the sites in this study, the soil test P (STP) should be on the lower end of the range that gives optimum or near optimum production. Many studies indicate that optimum or near optimum can be obtained with STP in the range of 4 to 6 mg P per litre soil (Morgan's test).

A recent study in Ireland shows results that indicate, when plotted, a good relationship between STP and molybdate reactive P (MRP), which is likely to be closely related to DRP, for grassland sites that do not have inputs from farmyards or other point sources (Torpey, P. and M. A. Morgan. 1999. P Profile of water, soil and sediment in a farm drainage system. Agricultural Research Forum, UCD, 25th and 26th March 1999. Ed: P. O'Kiely et al. pp. 25-26). This work indicates that water quality of 0.035, the target level set for good water quality in the 1998 Phosphorus Regulations, is achieved at a STP of the order of 4 to 6 mg P per litre soil. In addition, another study indicates a somewhat similar relationship between P in water and STP

(Sibbesen, E. and A. N. Sharpley. 1997. 'Setting and justifying upper critical limits for phosphorus in soils'. in: Phosphorus Loss from Soils to Water. ed: H. Tunney et al. publ: CABI, Wallingford, Oxon. UK. pp. 151-176). This study shows water soluble P, for a number of catchment streams in Denmark, where the level of 0.035 mg P per litre is reached at a soil test of about 16 to 20 mg P per kg soil, Olsen P which corresponds to about 4 to 5 mg P per litre of soil in the Morgan's test.

These three separate studies, referenced here, all appear to have the same conclusion that for good water quality the STP should be in the lower range for optimum or near optimum agronomic production. This is an important conclusion from the present study. There may be other sites where higher STP could be compatible with good water quality, perhaps in catchments with predominantly limestone soils, for example. Further studies will be necessary to establish how widely the results found in this study apply to other soils and catchments.

At the stream monitoring points in the Dripsey, P loss was highest at peak flow, during and after heavy rainfall. Peak P loss from these fields appeared to be associated with fertiliser or slurry spreading followed by heavy rain. At this site DRP varied from 0.01 mg P per litre at baseflow to more than 2.0 mg per litre during peak flow floods in January 1997. Potassium and suspended solids followed a similar trend to P, with the highest concentrations at peak flow events but nitrate showed an opposite trend indicating a dilution effect.

At Johnstown Castle the flow trends and P concentrations were broadly similar to the Dripsey, with peak P concentrations occurring at or near peak flow. On average, DRP concentration was approximately ten times higher on the highest soil P site (Cowlands) compared to the lowest soil P site (Warren 1). The highest P concentrations were found, particularly at the highest soil P site, during summer overland flow events, after fertiliser P was applied in the spring and when the animals were grazing the fields. There was a wide range in P concentrations between events at the same site, depending mainly on time of year and the flow during the event.

Water sampling of drains at a separate site at Johnstown Castle, used for intensive beef production, indicated that concentrations of P were of the same order as the concentration found in overland flow from the highest soil P site. In some situations, the loss of P to water via drains may be significant and higher than previously thought.

The P loss in subsurface flow was not measured at the three overland flow sites at Johnstown Castle. Therefore, the values shown are likely to be an underestimate. However, it is likely that most of the loss was in overland flow at these sites.

Most of the P load to water occurred during about 20 rainfall and run off events during the year (1997) and a high proportion of this occurred during about five events. During these events not only does the water level increase in the streams but the P concentration in the water also increases at the same time giving a significant increase in the P load, particularly on sites with high soil P levels. Most of the P loss (load) to water occurs during very heavy rain, with over about 20 mm in one day or when several wet days occur in succession.

Treading of grazing animals that leads to poaching and the manure they produce at grass may contribute to increased P loss. On intensive grassland, fertiliser and animal manure is applied to the soil surface and accumulates in the top few centimetres, which may be almost saturated with P and this is the soil that interacts with rainwater during heavy rainstorms. This may help explain the high P losses on grassland soils with high P levels found in this study.

In the hydrometeorological study in the Dripsey, subsurface flow made up 80% of the total stream flow, with only 20% in overland surface flow. Therefore, at this site it is likely that most of the P travels to the stream in dissolved form via subsurface flow. In this hillslope, active interflow was identified at a depth varying from 10 to 40 cm below the soil surface, the size of the interflow layer increased with heavy rainfall. On occasions when there was no surface overland flow, rainwater that infiltrates into the soil is transported to the stream via this subsurface interflow layer. Phosphorus found in this layer is in dissolved form and travels this route to the stream. Water table at the top of the hillslope ranged from 1.3 m to 1.0 m below the soil surface. At the bottom of the hillslope, 20 m from the stream, the water table ranged from 0.4 to 1.3 m. This shallow water table predisposes the riparian zone, on either side of the stream, to frequent saturation. This situation may exist in many areas of the country and P spread on such riparian zones is particularly susceptible to being lost to streams.

Results of the one farm studied in the Dripsey area indicate that farmyard P losses constituted between 25 and 30% of total farm P losses. However, more work is required on a range of representative farmyard conditions before the contribution of farmyards to the farm P loss could be estimated on a national scale.

6.2 SOIL P DESORPTION AND NATIONAL P MODEL

There was a clear relationship between the magnitude of P sorption and desorption, and P status in soils used in this study. Phosphorus status was defined here as soil test P (STP) measured by the agronomic test Morgan's P (Pm). Over the range of soil types analysed in this study, high P status soils desorbed more P to solution than low P status soils. Phosphorus sorption from solution was limited by high P status. The correlation coefficients derived between the desorption/sorption tests and Pm over the range of soil types demonstrated the importance of soil P status in determining the magnitude of these reactions. The degree of P sorption saturation (DPSS) in soils was estimated from measurements of P sorption index (PSI) and oxalate extractable P (Pox) in the dataset, and the strong relationship between this variable and P desorption tests indicated that soils saturated with P were vulnerable to P loss by desorption. The DPSS in the full dataset ranged from 22% to 79% with a mean value of 55% saturation over the range of grassland soils sampled in this work. The mean value of DPSS ranged between approximately 40 and 60% between the 4 soil groups with higher mean values of DPSS in the mineral soil groups of S1 (55%) and S2 (59%) indicated heavy applications of P to these soils. The DPSS has been used as a variable to predict potential P loss from soil to water by other workers. The relationship between water soluble P (Pw) and DPSS ($R^2 = 0.64$) in this work concurs with other researchers who suggested that readily desorbable P (or Pw), increased as soils were increasingly saturated by P additions, thus, the risk of environmentally significant P losses from these soils is high.

The soils studied were classified into categories S1 to S4 based on the organic matter (OM) content, S1 had the lowest content (<12%) and S4 are predominantly peat soils (>30% OM).

The multiple regression equations described PSI and P desorption using Pm and non-P properties such as %OM and amounts of Al and Fe. These equations identified %OM as a significant variable in predicting P desorption/sorption over the range of soil types in the data. The negative co-efficient assigned to the %OM variable in the multiple regression equations predicting sorption (PSI) and desorption (Pfeo and Pw) indicated that these reactions were inhibited by high %OM. The results show that high organic matter soils (S4 group) were characterised by lower desorption and sorption values when compared to the mineral soils, over similar ranges of Pm. When values of total P sorption capacity (PSCt) and PSI were compared between soil groups, the peat soils (S4 group) had a lower mean total P sorption capacity PSCt of 279.18 mg/l, compared to mean values of 620.24 and 794.06 mg/l for mineral soils of S1 and S2, respectively. Thus sorption (PSI and PSCt) and desorption (Pw and Pfeo) processes were affected by high amounts of organic matter in soils.

The negative correlation between %OM and PSI in peat soils (S4) suggested that as %OM increased, P sorbed from solution to soil (PSI) decreased. This has been observed by other workers, and it was postulated that high amounts of organic matter may block sorption sites in soils, thus suppressing P sorption.

P Loss Vulnerability

The results from this research have identified P status, OM and amounts of Al and Fe in soils as controlling variables in P sorption and desorption reactions. Desorption was greater in high P status soils. However, at similar P status, the range of desorption values across the four soil groups indicated that the peat soils of the S4 group had lower desorption and sorption values compared to the mineral soils. There is an OM effect in these soils, which not only inhibited desorption but suppressed P sorption also. The implication of this finding is that peat soils are unsuitable for large P application in fertiliser or manure, particularly owing to their low capacity to chemically adsorb added P. In addition, peat soils had lower amounts of Al and Fe and, therefore, fewer sites available for sorption/desorption reactions to occur.

The mineral soils were characterised by high desorption values and at high soil P levels lost more P to solution than the organic soils. In terms of P loss vulnerability, mineral soils of high P status risk losses to water, while organic soils with lower sorption capacities risk losses to water if amended with fertiliser and manure.

National Soil P Model

Riverine P and flow data were collected for 35 river subcatchments dispersed around the country. These data were modelled using variables, such as soil P levels, soil desorption, land-use, fertiliser and manure P use. Attempts to predict flow-weighted P concentrations (MRP) in river catchments were unsuccessful when all of the catchments were pooled and the analysis placed catchments into two clusters.

The statistical analyses used to develop and test the models indicated that predicted and observed river P concentrations were clustered according to catchment hydrology. Two clusters of catchments were identified. Those in cluster A were comprised of soils that were predominantly wet and poorly drained. Cluster B catchments had predominantly well drained soils. Flow data collected for the rivers in each catchment verified the clustering criteria. The 'wet' catchments in cluster A had significantly higher river MRP levels than the 'dry' catchments in cluster B. The following conclusions were drawn:

- High soil P, soil P desorption and high production grassland contribute to MRP values in rivers, and
- Wet catchments deliver more P to rivers than dry catchments, highlighting the importance of soil hydrology in the transport of P losses from agricultural landscapes.

The model derived for cluster A catchments predicted river MRP levels with 68 percent of the variation in annual MRP river values explained in the model. The model predicted annual MRP values for independent catchments with acceptable accuracy, i.e. predictions in agreement with measured total P (R^2=69%). The model derived for catchments in cluster B explained 62 percent of the variation in summer MRP levels for these catchments. The model predicted values of summer MRP for an independent set of cluster B type catchments and were compared with observed total P values (R^2=29%).

Implications of the National P Model

The methodology developed for the model provided an objective approach to modelling P losses on a national scale and the model provides a good risk assessment map for catchment management (even if not yet providing accurate forecasts of P loss). As current catchment management programmes progress, detailed water quality and land use data will become available. Thus, the methodology derived in this work could be adapted to rural subcatchments with adequate data, to enable more accurate forecasts of diffuse P losses.

The catchment models derived in this work identified some of the driving variables for predicting river P concentrations. The occurrence of 'types' of catchments as described by the clustering effect indicated that critical source areas may exist. Further work in this area could explore the concept of losses that are hydrologically driven in areas with predominantly poorly drained soil cover, and the possibility that soils with elevated P status under these conditions contribute to diffuse losses of P. This would require catchment-scale studies with good data resolution (such as the current Derg/Ree and Three Rivers studies) to identify the possibility of critical source areas or catchment 'hotspots' under Irish conditions.

Lack of data can limit modelling studies in their attempt to explain environmental processes. Future modelling studies exploring nutrient losses to water in Irish catchments would be greatly enhanced if data were to include simultaneous water quality and land management monitoring and, better data on the distribution of soil test P levels. Proper validation of the models derived in this work would require new datasets (1995-1997 Water Quality Report) so that future models may be refined and used as tools for water quality management.

7.0 RECOMMENDATIONS AND ACTIONS

The Good Code of Agricultural Practice to protect water from pollution by nitrates (Department of the Environment and Local Government and the Department of Agriculture, Food and Forestry, Dublin, 1996) and the limits set in the Rural Environment Protection Scheme, provide a basis to help farmers to reduce water pollution by nitrates and phosphates.

The results of this project provide important information on the quantities of P loss from fields under Irish conditions as outlined in Chapter 4. It has also helped to build up expertise and a better understanding of how this important water quality problem is addressed in other countries. However, it is also evident that because of the limited time scale and field sites covered in the present study, compared with the very wide variations in soil, climate, farming conditions and vulnerability of water bodies that exist at a national scale, recommendations from this study can not be considered applicable in all conditions without considerable further work. Therefore, the following recommendations should be viewed as a start to solving the problem of P loss from agriculture and its impact on eutrophication and not as the complete answer.

7.1 TENTATIVE PRIORITIES - RECOMMENDED WAYS OF REDUCING P LOSS FROM AGRICULTURE TO WATER

On the basis of the findings of this study at a number of sites in Wexford and Cork, the project team have put forward the following recommendations for ways of reducing P loss from agricultural lands to water. It is emphasised that at this stage these are the recommendations of the study team, not the project sponsors.

1. Reduce Farmyard Losses

Reduce and, where possible, eliminate direct and indirect loss of nutrients from farmyards to water courses. This will give the most rapid response and could reduce loss from agriculture by the order of 30 percent (as in this study), probably more in some areas and less in others. There will be a significant cost in collecting and storage of dirty water and roofing farmyard areas to ensure that direct loss is prevented. In addition, there will be cost and good management involved in ensuring that dirty water is disposed in a manner that minimises subsequent impact on the receiving water.

2. Correct Rates of Spreading of Animal Manure and Fertiliser

Spreading of manures and fertilisers should be carried out at rates that minimise the risk of subsequent loss to water. Fertiliser and animal manure P should be spread at rates to meet the removals in milk, meat and crops sold off the farm, where the soil P is adequate for optimum production. This may mean spreading no fertiliser or imported manure P on soils that already have soil P levels above what is required for economic response. On some intensive dairy farms, for example, there may be more P in purchased concentrates than is removed from the farm in milk and meat. The correct technical advice should be obtained before farmers carry out manure spreading. Soil P tests will be necessary to determine P requirements.

3. Correct Time of Spreading

Spreading of P in slurry and fertiliser should be carried out at times of the year that minimise the risk of P loss to water. This means spreading at times that will ensure that the risk of overland flow, for an extended period after spreading, is as low as possible. For the best conditions, this will mean spreading when soil is dry enough to take machinery and weather forecast is good, in spring and after a first cut or second cut of silage. From a biological point of view, it is best to spread slurry when plants need nutrients most, during the growing season. Spreading at the correct time will require adequate winter storage facilities for slurry.

4. Riparian or Sensitive Areas

Particular care is necessary on riparian zones that slope towards rivers, streams and other water courses, as these areas are likely to have a high water table and the risk of loss in overland flow to water is greatest. Often these areas are flat, intensively farmed with high soil P levels and used for manure spreading in preference to higher ground on a farm where it may not be so convenient to operate machinery. Targeting these areas, that could be considered vulnerable zones in terms of risk of P loss, is a relatively new concept and would involve special attention to rate and timing of P application and avoiding excessive build up of soil P levels. It may also be important to avoid over-grazing and poaching in these areas. But more work is required to measure the effectiveness of control measures in these areas. In general, areas where most overland flow is likely to occur will be the areas where the risk of P loss is greatest. Therefore, greater care in rates and timing of spreading and soil P levels are likely to give greater reductions than in areas where there is little or no risk of runoff.

5. *Soil P should not be Excessive*

There is strong evidence, in this study and elsewhere, that the higher the soil P the higher will be the risk of P loss to water. It is, therefore, prudent not to build up soil P levels above that necessary for optimum agronomic production. In some highly vulnerable areas (e.g. catchments of western lakes) where the more pristine waters need to be protected, it may be necessary to consider maintaining soil P lower than the agronomic optimum[1]. In the longer term, research and improved technology may enable more intensive agriculture to develop in vulnerable areas without affecting water quality.

[1] This will involve discussion with landholders on possible rates of payment to compensate for lost production where this is likely to occur.

6. *Nutrient Management Planning (NMP)*

The implementation of nutrient management planning will increase awareness of the nutrient balance on the farm and where surpluses and risks of loss are greatest. The adoption of nutrient management plans on all farms would help to reduce P loss and also help many farmers by reducing their fertiliser cost.

7. *Other Measures*

There are undoubtedly other measures that could be considered that would help reduce P loss to water. For example, some farming systems leak more than others, as in dairying which uses relatively high inputs of nutrients and large quantities of water are used, which may contribute to increased P loss to water, if not carefully stored and spread. Therefore, areas with high concentrations of intensive dairying may create more risk of P loss to water. Natural heathland and forestry are likely to have the lowest P loss per unit area.

Changing from intensive dairying to a more extensive system or other farming enterprise may require compensation considerations.

Measures that reduce soil compaction and thereby reduce overland flow may also help reduce P loss, the use of special wetland areas that would reduce the concentration of P in water may also help in areas where this is practical.

There are other factors, in addition to soil test P, that influence P loss to water. There is need for further work to identify the importance of these factors (which include rainfall, soil type and infiltration rates, proximity to water, stocking rates, etc.) in the determination of P loss to water.

7.2 ACTIONS

Many or all of these options could be considered to give good water protection. In addition, there is need for a cost benefit analysis to establish the most appropriate measures that are compatible with sustainable farming and environmental protection in different catchments. However, the most appropriate actions to take to protect waters from P from agriculture are likely to be developed by effective co-operation between the local authorities, the EPA, the Department of the Environment and Local Government, Department of Agriculture and the farming community. This should be done, based on the best information available for individual catchments. The information provided in this report addresses the objectives set out in the EPA project specification. In conclusion, it should be stated that there is need for further studies and information to ensure that measures put in place are the most appropriate and cost effective to maintain a healthy balance between a good agriculture and good water quality.

ACKNOWLEDGEMENTS

This project has been undertaken as part of the Environmental Monitoring, R&D sub-programme of the Operational Programme for Environmental Services, 1994-1999. It has been part financed by the European Union through the European Regional Development Fund. The sub-programme is administered on behalf of the Department of the Environment and Local Government by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research. The balance, of more than 50%, of the funding for the work described in this report was provided by Teagasc, Trinity College Dublin and University College Cork.

In addition to the participants and authors listed at the start of this report, many people in all the three organisations made major contributions to the successful conduct and completion of the project. Their contribution is gratefully acknowledged in field and laboratory work, in addition to invaluable helpful discussions and comments. The expert help with field and laboratory work by A. Fanning, T. O'Donnell and J. Scott at Teagasc, Johnstown Castle, is acknowledged.

The secretarial skills of Ms. Eleanor Spillane, Teagasc in preparing the report is gratefully acknowledged.

The assistance and guidance received from EPA staff who made a significant contribution during the project is also sincerely acknowledged by the project partners.