

EPA STRIVE Programme 2007-2013

Eutrophication from Agricultural Sources

(2000-LS-2-M2)

Integrated Report

(Main reports available for download on <http://www.epa.ie/downloads/pubs/research/water/>)

Prepared for the Environmental Protection Agency

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ACKNOWLEDGEMENTS

This report is published as part of the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme 2007–2013. The programme is financed by the Irish Government under the National Development Plan 2007–2013. It is administered on behalf of the Department of the Environment, Heritage and Local Government by the Environmental Protection Agency which has the statutory function of coordinating and promoting environmental research. The project was part funded by Teagasc.

The authors acknowledge the significant contribution of the hard-working LS-2 project participants and dedicated project steering committee for their time, critical comments and encouragement. The steering committee members included S. Jarvis, T. Edwards, S. Rekolainen, M. Keegan, O. Oenema, P. Toner, P. Duggan and C.J. Watson. The project team gratefully acknowledge the comments received from Teagasc research staff including Drs J. Murphy, P. Dillon, N. Culleton, J. Finn and S. Crosse. Finally, the patience and support of the EPA officers, K. Richards, H. Walsh, A. Wemaere and B. Donlon is fully appreciated and acknowledged by the team.

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EPA STRIVE Programme 2007-2013

Published by the Environmental Protection Agency, Ireland

PRINTED ON RECYCLED PAPER



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Preface: Overview of the Project LS-2: Eutrophication from Agricultural Sources

The objective of this large-scale integrated research project LS-2: Eutrophication from Agricultural Sources, commissioned in 2000, was to supply scientific data to underpin appropriate actions or measures that might be used in the implementation of national policy for reducing nutrient losses to waters from agricultural sources.

The research, including desk, laboratory, field-plot, farm and catchment studies, was conducted by teams in Teagasc, the colleges of the National University of Ireland at Dublin, Cork and Galway, Trinity College Dublin, the University of Limerick and the University of Ulster at Coleraine.

The large-scale project was made up of three main projects, LS-2.1, LS-2.2 and LS-2.3, each with a number of individual studies (Figure 1). A study, LS-2.1.5: Farmyards, included in the original LS-2 scoping document was not commissioned as part of the final LS-2 research project.

The project LS-2.1: Pathways of Nutrient Loss to Water with Emphasis on Phosphorus Losses aimed to quantify and rank the magnitude of phosphorus (P) loss from soil, grazed pastures and the application of slurry and fertiliser to water so as to identify effective mitigation strategies.

The project LS-2.2: Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water aimed to develop three modelling approaches that explored the sources of P and the hydrological processes that transport it from land to water.

The project LS-2.3: Effects of Agricultural Practices on Nitrate Leaching aimed to measure nitrate-nitrogen leaching from an intensively managed dairy farm on a soil that is considered high risk for nitrate leaching.

Integrated synthesis reports for the LS-2.1, LS-2.2 and LS-2.3 main projects and the reports from each of the individual projects are available for download on the EPA website at <http://www.epa.ie/>.



Figure 1: Overview of the project LS-2: Eutrophication from Agricultural Sources

Executive Summary

The objective of this large-scale integrated research project was to supply scientific data to underpin appropriate measures or actions that might be used in the implementation of national policy for reducing P and nitrogen (N) losses to waters from agricultural sources.

The results:

- identified the importance of considering a range of soil physical and chemical characteristics in the development of measures for managing nutrient losses from agriculture to water;
- suggested the need to focus more targeted mitigation measures in high-risk areas for nutrient loss from agriculture to water;
- underpinned the basis of existing advice and measures for reducing nutrient losses from agriculture to water, i.e. the importance of avoiding P and N inputs in excess of agronomic requirements.

A high-risk area is defined as one where a source of available nutrients and an active hydrological link coincide within the catchment of a water body at risk of pollution.

The knowledge generated by the project will assist in the design and development of measures that are spatially targeted, environmentally effective and cost effective compared with those based on a 'one size fits all' approach. Such measures will require consideration of the source, hydrological pathway, the vulnerability of the water body and the size of the area involved.

Modelling studies of P and N identified approaches that can be used and developed to identify high-risk areas at a range of scales. The standard agronomic soil P test was

shown to be a useful indicator of P loss potential. The project identified the need for the nationwide measurement of soil P on a field-by-field basis and the completion of the detailed county-level soil surveys to fully exploit the modelling potential in identifying high-risk areas and their responses to mitigation measures.

The project contributed knowledge to address the question of the extent to which environmental objectives at the catchment scale (to meet specified water quality targets) can be achieved by measures to reduce nutrient losses at field or farm scale while at the same time maintaining agronomic production efficiency. However, it also identified the need to put in place long-term monitoring programmes in a number of contrasting catchments (soils type and managements). These will provide synchronous data on the chemical and ecological parameters of water quality (edge of field and in-stream) and land-use activity to develop our knowledge of the relationships between the source, pathway and impact factors over a range of scales. This output is required to further refine and target measures and thus contribute towards the achievement of the water quality targets set in the Water Framework Directive (WFD) (Council of the European Communities, 2000).

A long-term multi-catchment monitoring programme offers the potential to evaluate and demonstrate the impact of existing or new agri-environmental policies and their interactions with measures to control nutrient losses to the environment. In addition, it can provide an opportunity for sociological research to assist in identifying the appropriate societal measures and interventions required to achieve a sustainable agriculture with a protected environment in a viable rural economy.

1 Integration

This report represents a synthesis and integration of the results from the large-scale integrated project LS2: Eutrophication from Agricultural Sources (2000-LS-2-M2). The main objective was to supply scientific data to underpin appropriate actions or measures that might be used in the implementation of national policy for reducing P and N losses to water from agricultural sources. The research, including desk, laboratory, field-plot, farm and catchment studies, was conducted by teams in Teagasc, the colleges of the National University of Ireland at Dublin, Cork and Galway, Trinity College Dublin, the University of Limerick and the University of Ulster at Coleraine. A total of 11 research projects (Figure 1), ranging from six-month desk studies to four-year field investigations, were completed successfully. A coordinating project was tasked with managing the 11 LS-2 projects outlined in the Preface and integrating the results (in this report) published in the 24 final and synthesis reports arising from the research (Appendix 1). These reports will be made available on the EPA website when published. In addition, a list of the peer-reviewed published papers, those accepted for publication, those in review, the PhD, MEngSc and MSc theses and some of the technical publications arising from the research up to June 2007 is provided in Appendix 2.

The research projects posed questions in relation to quantifying the relative importance of the factors affecting P loss from land that included not only soil-test P (STP) levels, but also management factors such as grazing, slurry and fertiliser spreading. These questions were also considered in catchment monitoring and modelling-based studies that attempted to link sources and pathways to provide a measure or estimate of impact. The use of an agronomic soil P test as an indicator of potential P loss was also evaluated. It should be noted that no measurement of farmyards, as a source of nutrient loss from agriculture to water, was made during this research.

In 2000, research relating to the contribution of agriculture to N losses was generally not considered to be as urgent as it was for P loss. Consequently, the national N loss from agriculture to water research programme, prior to the LS-2 project, was not as well developed as it was for P loss. However, positive relationships between excessive N loadings from grassland management systems and reduced groundwater quality in vulnerable areas were identified in some studies (e.g. Richards, 1999) – results that were consistent with international research (e.g. Jarvis, 2000). Consequently, one of the research questions posed in the project LS-2.3: Effects of Agricultural Practices on Nitrate Leaching focused on determining the possibility of achieving statutory water quality targets for groundwater nitrate-N concentrations under an intensively managed dairy farm in an area with a soil type vulnerable to leaching.

This integrated report summarises some of the important scientific evidence produced by LS-2 and outlines its implications and limitations in terms of recommending measures to control N and P losses from agricultural sources and their transport to water.

1.1 Context and Background

An adequate supply of nutrients, including P and N, are essential for healthy crop and animal production. The development of soil fertility research in the mid-nineteenth century, the adoption of industrial processes to manufacture inorganic fertiliser in the early to mid-twentieth century, and the development and adoption of more intensive agricultural systems have resulted in a significant increase in the nutrient reserves of soils in many countries, including Ireland. In the case of P, Irish farmers were advised in the period from the 1950s to the late 1970s that a build-up in soil P levels would provide a P 'reserve' for future use. However, in the late 1990s evidence was accumulating (e.g. Tunney, 1990), including

that from Environmental Research Technological Development and Innovation (ERTDI) funded research (Tunney et al., 2000) suggesting that excessive P applications leading to elevated STP levels¹ were a significant source of P available for transfer from soil to water. This earlier research was set against a background of declining national water quality over the previous three decades and provided knowledge and recommendations in relation to controlling P loss and transfer to water. In 2000, the introduction of the WFD created a renewed sense of urgency in developing the measures to control nutrient inputs to water, including those from agriculture, which are central to achieving its objective of good ecological status for all waters by 2015.

The source–pathway–impact conceptual model is used to provide a framework for the integration of the outcome of the LS-2 research in this report. ‘Source’ is broadly defined by the N or P potential inputs to waters directly or indirectly derived from the soil or applied fertiliser and manure management. However, for a source to be a threat to water quality, a hydrological ‘pathway’ connecting the soil and water body must be present. The pathways for the nutrients entrained in the water generally include overland flow to surface water and/or percolation (matrix and preferential flow) to groundwater. Where a nutrient source combines with a hydrological pathway from the field to the water there is an increased risk that the nutrients will actually be transported to receiving waters. The ‘impact’ of the nutrients delivered to fresh water is eutrophication – the accelerated growth of algae or aquatic plants in response to the nutrient enrichment. The only distinction between P and N in relation to eutrophication is that the former is usually the limiting nutrient in freshwaters and the latter seems to have this role in marine (not necessarily estuarine) waters. The levels of plant growth sufficient to cause detrimental effects on water use probably requires above-natural levels of both nutrients. In addition, high levels of nitrate in surface or groundwater make them unfit for use as drinking water.

In this research, ‘impact’ is more narrowly interpreted as the nutrient level measured in the water sampled rather than its measured ecological impact. As such, there was more emphasis on the source and pathway components than on the water quality impacts with the exception of LS-2.1.7: Relative Eutrophic Effects of Seasonal Discharges of Phosphorus to Water, which reviewed the eutrophic effects of the temporally variable P exports from land to water.

1.2 Source

Nutrient sources in the landscape occur naturally from nutrient cycling in soils and from atmospheric deposition. However, in terms of grassland agriculture the more important sources from both agronomic and environmental perspectives are those derived from inputs of fertiliser, N fixation, feed, minerals, manure and plant residues (Bundy et al., 2005). It is generally accepted that increasing nutrient inputs to agriculturally managed grassland soils create an increased potential source for nutrient loss and transfer to water. The present research provided evidence of the potential nutrient contributions from grassland soils to water such as those arising from elevated STP levels, grazing animals and both fertiliser and slurry spreading. It highlighted the importance of the physical and chemical properties of soils, which are characteristics of soil type, as determinants of the potential for nutrient loss and transfer to water.

1.2.1 Source: Soil Type – Soil Chemistry and Nutrient Loss Potential

Phosphorus in the soil solution is available for plant uptake and for removal from the soil to water moving in overland flow and/or in subsurface pathways. The supply of P in soil solution is mediated by a number of chemical and biochemical processes. The present research has further developed our understanding of how soil chemistry influences soil P sorption and desorption (two of the chemical processes involved). Essentially, this refers to the soil’s capacity to chemically sorb added P and to desorb the P back to the soil solution. Peaty soil types have a low capacity to adsorb added P and do not create a P reserve. It is therefore hypothesised that peat soils (> 20% organic matter

¹ Throughout this report, elevated STP levels refer to those above that required to sustain crop and animal production in grass-based enterprises. Generally, this implies that soil P levels > 8 or 10 mg/l for grassland are considered as being elevated for grassland and tillage respectively.

(OM)) pose a greater risk of P loss to water when surface applications of P are not used by the crop in the year of application. The agronomic concept of P 'build-up' is less certain in peat soils as they have neither the P sorption capacity nor the high-binding energies. Therefore, P management and advice needs to be tailored to account for this.

Mineral soil types, on the other hand, readily adsorb P which can build up and create a potential for desorption to the soil solution. Within mineral soils, chemical factors such as pH, the concentrations of aluminium (Al) and iron (Fe) and the percentage OM control the pattern of high sorption and desorption capabilities observed in non-calcareous soils (pH < 6).

In the LS2 studies undertaken, these soils compared with calcareous mineral soils (pH > 6) desorbed more P to solution at elevated STP levels. This perhaps is due to the high potential of non-calcareous soils for P storage and hence release (when chemical binding is not strong), and/or to the low solubility of P associated with calcium in calcareous soils. The results support the concept that differences in soil P chemistry between soil types should be considered in assessing the potential risk of P loss from soils to water.

These effects of soil chemistry on P loss potential were demonstrated in the water quality data from the LS-2.1.1a: Soil and Phosphorus – Catchment Studies project (Figure 2).

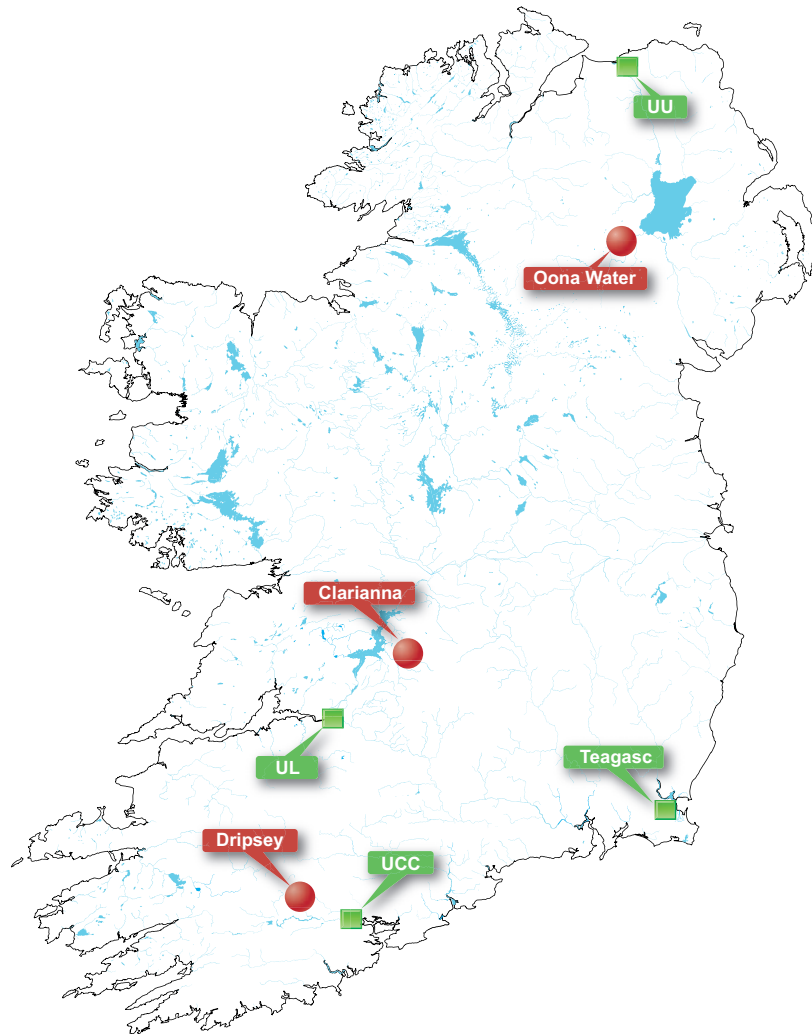


Figure 2: The geographic locations of the Dripsey, Clarianna and Oona Water catchments and institutions involved used in LS-2.1.1a: Soil and Phosphorus – Catchment Studies

All three catchments were generally characterised by elevated STP levels (up to 10–12 mg/l). In the Clarianna catchment, the lower in-stream P concentrations measured were at least partially explained by the presence of calcareous soils and their lower P desorption capacities at high STP levels combined with the general absence of overland flow and interflow. In contrast, the higher in-stream P concentrations in the Oona Water and Dripsey catchments might be explained by the dominance of non-calcareous soils in these catchments with their high sorption capabilities and desorption potential at elevated STP combined with a greater occurrence of overland flow.

Note that the role played by soil chemistry in the processes governing P loss from agriculture to water is different from that controlling N loss. While the research presented on P demonstrates the varying ability of different soil types to retain and release P to the soil solution, the nitrate ion generally remains in the soil solution and is not sorbed by the soil due to its negative charge.

1.2.2 Source: Management Factors

The research reviewed and assessed (LS-2.1.2: Grazed Pastures, LS-2.1.3/4: Slurry and Fertiliser Spreading, LS-2.1.7 and LS-2.3) some of the management factors that contribute to nutrient loss and transfer from grassland soils to water. The research ranged from literature reviews to laboratory, small-plot, field and farm-scale studies. The focus was on the role of management factors in determining the risk associated with source and pathway factors that contribute to nutrient loss and transfer to water.

A point worth noting is that the role of the management variables studied or reviewed in this research in creating a source of nutrient loss (i.e. a risk) is not only a consequence of the management itself but is also influenced and determined by interactions with soil type, soil nutrient levels and rainfall. The results generally support the conclusion that management factors that contribute to surplus nutrients in the soil system or change soil properties to predispose it to the flow of water over or through the soil create a higher potential for nutrient loss and transfer to water.

1.2.2.1 Management Factors: Grazing

Grazing of small plots (0.5 m²) by cattle increased the quantity but not the overall concentration of P in the overland flow water (from simulated rainfall – 25 mm/hr) in LS-2.1.2b: Grazed Pastures – Small Plot Study. The presence of cattle led to temporary physical changes in the topsoil – i.e. compaction – which altered its drainage characteristics and created the potential for increased overland flow volumes. These changes persisted over the winter following the grazing season. However, the soils ‘recovered’ when the animals were excluded during the grazing season in the following year. This result highlighted the importance of the interactions between management and soil types in determining the potential for nutrient loss – in this case changes in soil drainage characteristics arising from grazing.

In a parallel study over three years (LS-2.1.2a: Grazed Pastures – Field Plot Study), the difference in P loss from six 1 ha (approx.) plots cut or grazed were not significant overall, though it was for some individual run-off events. The results from this study indicated that the influence of the grazing animal on P loss was small relative to that of elevated STP levels. As both these grazing studies were conducted under good management practices, different results, i.e. higher P losses, may apply where animals are out-wintered under poor grazing management practices.

The LS-2.1.2c: Grazed Pastures – Phosphorus Dynamics in a Grazed Grass Ecosystem study showed that the deposition of dung by the grazing animal played a major role in the rate of P recycling and highlighted the possibility that areas of increased dung deposition (e.g. around ring feeders or drinking troughs) may create sources of increased potential for P loss. In addition, key relationships between fertiliser P applications and increased P concentrations in herbage and the concentrations and forms of P in dung were identified as factors associated with elevated STP on grazed pastures that may increase the risk of P loss to water. Higher fractions of soluble P in the manure were also associated with the higher rates of fertiliser applications. The potential consequence of the higher soluble P content in manure is shown by a study

reported in the literature (Ebeling et al., 2002). The concentrations and loads of P measured in overland flow were four to five times greater following manure applications from animals receiving surplus P in their diets compared with those following manure applications from animals fed low P diets.

In LS-2.3.1.1: Farm Scale Study, the impact of grazing animals on leached nitrate N was measured. In two of the three years of observation, significant differences were measured in the nitrate-N concentrations of soil pore water among the different management areas typically found on a grassland farm. The 'grazed dirty water irrigation' and the 'two-cut silage' areas had significantly higher mean concentrations compared with the 'grazed' and 'one-cut silage' areas. However, no relationship was found between these concentrations and total N inputs or the number of grazing days within each management area. In contrast, in the LS-2.3.1.3: Groundwater study, a positive correlation was found between the numbers of days that the herd grazed a particular plot in a single grazing season and the average concentration of nitrate N in the groundwater in the following recharge period.

1.2.2.2 Management Factors: Slurry and Fertiliser Spreading

In the LS-2.1.3/4 studies, a review of the literature on the contribution of slurry and fertiliser spreading to P and N loss was undertaken. The contribution of these management activities to P loss was also briefly reviewed in the LS-2.1.7 desk study. The impacts of fertiliser, slurry and dirty water management on nitrate leaching were measured in the LS-2.3 project.

It is evident from the literature that application of slurry and fertiliser at rates above those advised for agronomic purposes should be avoided to reduce the potential for nutrient loss from soil to water. The accumulation of nutrients surplus to plant growth requirements in the soil or soil pore water will increase the potential for loss and transport to surface and groundwater where a clear hydrological pathway exists. For example, in the LS-2.3

project, the risk of elevated nitrate-N concentrations in groundwater was associated with grassland management treatments that resulted in excessive autumn/early winter N loadings in the soil water. Agronomic fertiliser P strategies require the build-up of STP to the levels needed to support crop and animal production. However, excessive slurry or fertiliser applications leading to STP levels above agronomic needs have been shown in this research and many other studies in developed agricultural regions to be a significant potential source of P loss.

In general, the LS-2.1.3/4 and LS-2.1.7 reviews reported that the timing of applications is an important factor determining the scale of nutrient loss following manure and fertiliser applications. In the former, a review of Irish experimental data from the late 1970s and early 1980s indicated that the potential for loss of nutrients in overland flow was greatest when heavy rainfall occurred in the days immediately following their application. This finding is supported by results from the literature (e.g. Patterson et al., 2005).

Slurry and fertiliser applications outside the grass growing season can contribute to nutrient losses. For example, late autumn and early spring applications of N (fertiliser and dirty water treatments) in the LS-2.3.1.2: Soil Investigation study resulted in elevated nitrate-N concentrations in soil pore water at 1 m depth. This study also demonstrated the higher risks associated with fertiliser application at rates above those advised for crop growth at similar times of the year.

In the LS-2.1.3/4 projects a methodology was developed to identify the number of safe slurry-spreading days across the country, based on an examination of national rain gauge records using a filter of set duration, magnitude and shape. Where a sequence of days all had less rainfall than the defined filter, then a safe spreading day was allotted. The results were in line with expectations of a greater number of days available in the south and east of Ireland compared with the north and west. However, the need to consider also antecedent soil moisture conditions as a prerequisite for decision support in relation to the suitability for slurry or fertiliser spreading was acknowledged.

1.2.2.3 Management Factors: Dirty Water

The importance of considering the N contribution from, and the timing of, dirty water applications was identified in the LS-2.3 project. The LS-2.3.1.2 study reported that high (50 mm) and medium (25 mm) rates of dirty water applied to small plots in winter without antecedent N fertiliser inputs resulted in the concentrations of nitrate N in the soil pore water exceeding the EU maximum admissible concentration (MAC) of 11.3 mg/l set in the Nitrates Directive and drinking water legislation. The results suggested that the dirty water was not only adding an N source but was also influencing the pathway factor because of the associated hydraulic load. However, the same rates of dirty water irrigation in summer did not have this effect. In this study, low dirty water irrigation (10 mm) rates at any time of year did not result in elevated soil pore nitrate-N concentrations.

1.3 Soil P Test as an Indicator of P Loss Potential from Soil

There has been a considerable international debate regarding the suitability of soil P tests as predictors of P loss from soils to water because elevated STP levels have been identified as a potential cause of P loss. Traditionally, STP has been used to provide an estimate of the plant available P in soils. In Ireland, the agronomic soil P test uses Morgan's reagent on a soil sample taken to a depth of 10 cm and oven dried at 40°C. However, its suitability as an environmental indicator has been questioned in terms of the sample depth and extraction solution which might differ from the chemical character of the water that transports P from soil, and the depth to which this water interacts with soil. Therefore, the efficacy of the test for environmental risk purposes was evaluated against a range of other possible soil P tests in LS-2.1.6: Environment Soil Phosphorus Test study. The results indicated that the current sampling depth, oven drying technique and use of Morgan's reagent provided a good indicator of P concentrations in overland flow when compared against measured edge-of-field losses from grass fields with high and low STP levels. This concurs with other published studies that have used Morgan's P test as an indicator of potential P loss from soil (e.g. Tunney, 2002).

1.4 Pathways

Aspects of the role and importance of the nutrient source in determining the risk of nutrient loss and transfer from grassland soils to water have been noted above. However, the risk of impact is low or non-existent unless the transport link or hydrological pathway exists between the potential sources and a receiving water body.

The pathway reflects the soil hydrology, which is determined by the interaction between rainfall and a number of soil, landscape and land-use variables, including soil-drainage characteristics, topography and management. As such, in terms of diffuse nutrient transfers from grassland soils, pathway characteristics vary in type, space and time.

1.4.1 Phosphorus Pathways

In terms of impact on P loss as discussed in this report, it is generally accepted that pathways variously refer to hydrological storm flowpaths such as overland flow, interflow and subsurface flow by vertical matrix and/or macropore flow. Overland flow occurs when there is physically no more pore space available in the soil to receive additional water (saturation excess) due to a high water table or the topographical position of the area (e.g. an area of springs at the bottom of a slope) in the landscape or when the volume of water arriving on the soil exceeds its infiltration capacity (infiltration excess). Saturation excess overland flow can also occur when soils become saturated as a consequence of poor percolation through parts of the lower soil horizon (e.g. plough pan) or where the water table reaches the surface. In general, the perched water table is a more important contributor to surface run-off under Irish grassland conditions. Infiltration excess overland flow can occur as a consequence of intensive rainfall on soils with low infiltration, e.g. on the lower slopes of fields or where soil conditions and/or managements have resulted in reduced infiltration capacities. In addition, artificial drainage affects soils hydrology, which may have implications for nutrient loss by increasing hydraulic conductivity.

These pathways (type) operate on an episodic basis (time) and from discrete areas (space) of stream and river catchments. Overland flow is greatest during storm events while this flow pathway is largely inactive at other times. In Ireland, research, including that from the LS-2.1.1a study, suggests that in most situations over 95% of overland flow occurs on about 18 days of the year (< 5% of the time).

1.4.2 Nitrogen Pathways

The transport of N from agricultural soils to water is more generally concerned with the vertical movement of water down through the soil profile. As a consequence, leaching and groundwater recharge occurs only when water inputs to the soil from rainfall exceed water removal by evapotranspiration and storage in non-conducting soil pores. Under Irish conditions, this generally occurs from late autumn to early spring. In the three studies of the LS-2.3 project reported here, the pathway for N loss refers to the vertical movement of drainage water from the soil surface to groundwater. The experimental area (soil and groundwater) was considered to be highly vulnerable although representative of just less than 5% of Irish land. It was described as a shallow topsoil (0.3 to 0.4 m) overlying 0.4 m of a very gravely silty/sandy layer, below which was a thick sandy layer of soil and subsoil overlying a fractured/fissured karstic reef limestone. The subsoil is classified as SAND. Recharge flow rate was estimated at 4.5 mm/day giving a mean travel time of about 130 days to a depth of 900 mm in winter time. In deeper soils with heavier, less well-drained subsoils, travel times will be considerably longer except where these have been drained artificially.

Changes and/or transformations in the forms and fractions of P and N that can occur during transport through or over soils add complexity to the pathway. For example, P sorption occurring along the pathway or entrapment of particulate P in landscape features such as riparian zones or wetlands can reduce P loads on rivers and lakes. Alternatively, these zones may act as a source of P. Nitrate N in soil pore water can denitrify under anaerobic soil conditions resulting in reduced concentrations.

1.5 Soil Type: Soil Drainage Class and Nutrient Loss Pathways

The LS-2.1.1a study illustrates the effect of soil type on the hydrological response of the catchment and ultimately on P loss. The predominant soil types in the three catchments were characterised as follows.

Dripsey: Neutral soils, mostly brown podzolic with some gleys, impeded to free draining on Old Red Sandstone-derived soil.

Oona Water: Drumlin soils, mostly surface and groundwater water gleys of moderately acidic nature, impeded drainage on till-derived soil.

Clarianna: Calcareous soils of neutral to alkaline pH representing a mix of grey brown podzols, gleys, peats and brown earths, very free draining except for small areas.

The reported P transfers to water were ten times higher in both the Dripsey and Oona Water catchments than those from the Clarianna catchment even though STP levels were similar (up to 10–12 mg/l). The hydrological responses measured and data from soil property maps indicate that the hydrology of the Dripsey and Oona Water was dominated by the overland and subsurface flow pathways, while infiltration and percolation pathways dominated in the Clarianna. Contrasting soil chemical properties between the former two catchments (non-calcareous) and the latter (calcareous), noted above, also contributed to the observed differences in P transfers. In addition, there was some evidence of P adsorption within the deep deposits of calcareous sand and gravels in the Clarianna.

It is interesting to note that the P transfers per unit area in the smallest catchment areas monitored, where the P contribution from sources other than fields was negligible, were not greatly different from those of the larger catchment areas where these other sources were contributing to the measured losses of P. An observed difference, however, was a decrease in P transfer per unit area in the Dripsey (2.7–1.6 kg/ha/yr) and Clarianna (0.7–0.2 kg/ha/yr) catchments as scale increased, and the opposite in the Oona Water catchment (2.4–3.1 kg/ha/yr).

The impeded drainage characteristics of the soils and the steeper slopes of the Oona Water catchment, particularly in its upper reaches, produced a more rapid response to rainfall (flashy) compared with the Dripsey and Clarianna catchments. There was also a higher transfer of particulate P in the Oona Water, compared with the other two catchments. This was attributed to the flashier, and potentially more erosive, run-off.

The project LS-2.2: Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water identified the effect of soil type on soil hydrology and its relevance to the transport of nutrients, particularly P, to surface waters. These studies used three different modelling approaches, each of different degrees of complexity and operating at different spatial scales, to identify the factors controlling P loss from soils, so that risk areas could be better identified.

The first modelling approach used existing physically based models (HSPF, SWAT and SHETRAN)² that successfully simulated the flow component of P loss in the three catchments of the LS-2.1.1a study. These models defined the pathway using equations that combined soil texture data from the General Soil Map of Ireland (Gardiner and Radford, 1980) with topology, land use maps and rainfall data.

The second modelling approach sought the simplest relationships between catchment variables and water quality in 76 subcatchments. In the absence of detailed soil maps for each subcatchment, the percentage gley in each soil association from the General Soil Map of Ireland was used to generate a run-off risk index for soils.

The third modelling approach, from LS-2.2.1 Field-by-Field Assessment, developed a P and N ranking scheme for ranking fields in mini-catchments (and catchments) in terms of risk of generating loss of the nutrients to waters by considering factors including overland/subsurface flow risks, STP and proximity and connectivity to receiving waters.

The NCYCLE_IRL model (a model to predict N fluxes in Irish grasslands), which formed part of the LS-2.3.1.1 study, highlighted the influence of soil type and drainage status for herbage production and N flows in grassland soils. Well-drained soils mineralise greater quantities of N, partly due to enhanced aerobic soil conditions. The NCYCLE_IRL model predicts an average of about 20% more total N losses in well-drained compared with poorly drained soils. The model predicts that well-drained sandy loams will lose most of the N surplus through leaching of nitrate, while poorly drained clay loams will lose more N through denitrification.

1.6 High-Risk Areas

The results from the various individual projects completed as part of this large-scale integrated project focus attention on the different nutrient transfer responses observed in areas with different soil types, based on either or both their physical and chemical properties. In general, a high-risk area can be defined by the coincidence of a nutrient source, a hydrological pathway and a vulnerable water body. However, as the results from the various N and P loss modelling projects indicate, there are differences in terms of high-risk areas for N and P.

The LS-2.1.1a study showed higher P losses in the Oona Water and Dripsey catchments compared with the Clarianna catchment. This difference was attributed to differences in soil physical and chemical characteristics between the catchments. Therefore, more targeted measures to control P loss and transfer may be required for areas with characteristics similar to those of the Oona Water and Dripsey compared with areas similar to the Clarianna. The high-risk area for P is conceptually similar to the critical source area approach reported in the literature (Gburek and Sharpley, 1998) on diffuse P loss from agricultural sources. It developed from research which showed that most (80%) of the P entering water from diffuse agricultural sources originates from a small (20%) proportion of the catchment or the so-called '80:20 rule'.

² Hydrological Simulation Program – FORTRAN (HSPF), Soil Water and Analysis Tools (SWAT), Système Hydrologique Européen TRANsport (SHETRAN).

The experimental site chosen for the LS-2.3 project brought together the general characteristics of a nitrate vulnerable zone (NVZ) identified in the 1991 Nitrates Directive. The directive indicated that an NVZ was a land area that drains into waters that are or might be affected by nitrate pollution from agricultural sources unless action is taken to reduce the pollution. The farm used has a potential source (an intensively managed dairy enterprise), a hydrological pathway (a shallow, free-draining soil), a winter drainage season when rainfall exceeds evapotranspiration and a vulnerable groundwater body. Mean concentrations of nitrate N in the groundwater beneath the farm during the first and second monitoring years were 15.2 mg/l and 11.9 mg/l, respectively, and exceeded the maximum admissible concentrates (MAC) set in the Nitrates Directive and drinking water legislation. The average nitrate-N concentrations in the soil pore water were less than the drinking water MAC in the three measurement years. However, there was a trend for increased N loadings to result in elevated concentrations of nitrate N in soil pore water and groundwater. The NCYCLE_IRL model indicated that for similar N inputs lower losses would be expected from areas with heavier, poorly drained soils as these have a different hydrological pathway.

These results suggest that, for both N and P, there may be a need to consider more spatial targeting of measures in areas that represent high risk in order to control nutrient losses from grassland to water in addition to the generally applied 'one size fits all' measures, such as crop-fertilising strategies based on balanced nutrient inputs/outputs. Therefore, measures should be focused on high-risk areas to ensure their efficacy and cost effectiveness from both a water-quality and agronomic perspective. The high-risk area approach can be applied at a range of scales from field to catchment as suggested by the results of a number of the projects, e.g. the LS-2.2.1 study.

1.7 Impact

Nutrient concentrations were measured in streams, rivers and groundwater as part of the LS-2 project. The impact on the ecological status of the adjacent surface and groundwaters or at larger catchment or hydrogeological scales was not a significant element in the present research. It is worth noting, in this regard, that the impact of agriculture on water quality not only includes the potential for eutrophication, but also possible contamination with pathogens, pesticides and both organic and particulate matter.

Haygarth et al. (2005) noted that the challenge of connecting the soil nutrient source through the pathway to the observed nutrient transfers to water becomes more difficult as the spatial and temporal scales of the water system become larger. For example, the dilution of P load per unit area as catchment scale increased was observed within the Dripsey and Clarianna catchment areas and was interpreted as being due to increasing groundwater inputs at larger scales. However, in the Oona Water, P load per unit area increased at the larger catchment scale. The available data suggested other P sources, such as septic tanks, may have been present in the Oona Water catchment as evidenced by relatively high P concentrations at low flow in summer when eutrophic impacts within the river would be greatest. In this surface-water dominated catchment, if the premise that soil P loss is mainly dependent on storm pathways for mobilisation and transfer through the river network is accepted, then little of these low flow transfers, which constitute a minor percentage of total annual exports, are likely to originate from the soil source.

The data from the present research and its interpretation has highlighted the challenge of linking field scale nutrient transfers to overall catchment losses and water-quality impacts. Monitoring nutrient transfers at the edge-of-field scale helps to determine the magnitude of the exports from agricultural soils and to assess the effectiveness of farm-scale mitigation measures. This knowledge is used to develop measures generally applied at farm scale. However, from the WFD perspective, the effectiveness of these farm-based measures on water quality is assessed at catchment scale. Further research focused on the link between field scale losses and catchment water quality targets is required to ensure cost-effective measures from a competitive agricultural perspective while ensuring the more stringent WFD water quality targets are met. The LS-2.3 final synthesis report (ERTDI Report 58, 2007)

highlighted the importance of further developing the modelling strategies initiated to address the issue of scaling up these to address larger areas. The focus of the present research has been on intensive grassland. However, in a catchment management context, particularly in the south and east of the country, there is a need to take cognisance of the potential impact of tillage operations.

Long-time frames will be necessary to observe water-quality responses to mediation efforts at farm scale in large catchments. Future challenges include assessing the relative contributions of the different nutrient sources during all river flow ranges (to determine whether sources are being effectively managed) and the efficacy of monitoring regimes to fully capture the dynamic nature of nutrient transfers, especially in flashy river systems.

2 Relevance to Policy

The objective of this large-scale integrated research project was to supply scientific data to underpin appropriate actions or measures that might be used in the implementation of national policy for reducing P and N losses to waters from agricultural sources.

2.1 Policy Issues

The measures adopted to achieve compliance with WFD water quality targets by 2015 are likely to present a challenge for agriculture. This challenge is set against the background of current water quality problems and the changes occurring in agriculture.

The 2005 European Environment Agency's report *The European Environment – State and Outlook* summarises the Irish water quality position as 'Eutrophication of rivers, lakes and tidal waters continues to be the main threat to surface waters with agricultural run-off and municipal discharges being the key contributors.' The EPA's *Water Quality in Ireland 2005* report adds to this statement by noting that 'this could again aptly describe the current position with the addition that the first of these pressures also poses the greatest threat to the quality of the groundwater resource.'

The increased pressure to achieve challenging environmental goals is occurring at a time when agriculture is also experiencing a period of rapid change. Policy drivers include the reform of the Common Agricultural Policy, EU enlargement, more liberal world trade in agricultural products and increasing emphasis on rural development. Achieving a balance between these somewhat conflicting goals will require the generation and transfer of knowledge to all stakeholders.

In the context of policy issues it is worth noting the recently published proposal for an EU Soil Framework Directive. Its objective is to establish 'a common strategy for the protection and sustainable use of soil based on the principles of integration of soil concerns into other policies'.

Some of the common soil properties (type, organic matter, hydrological properties) and landscape features (topography, land use) that might be used in the risk-assessment methodologies to identify soil areas at risk are also relevant to identifying waters at risk.

The LS-2 project, in keeping with its primary objective, has provided knowledge to underpin appropriate measures that might be used in the implementation of national policy for reducing P and N losses from agricultural sources in the context of the WFD and other EU legislation.

2.2 Implications for Stakeholders

2.2.1 Nutrient Balance Measures

This research identified the potential for grassland soils to contribute to unsustainable P and N loss and transfer to water under certain circumstances. It provided scientific data to underpin existing knowledge concerning the link between farm and field nutrient surpluses that result in elevated STP levels and/or excess N in soil pore water at the start of the drainage season, and the increased potential for nutrient transfer from soil to water. The results suggest the following:

- The importance of considering the nutrient contribution from manure applied to grassland to avoid nutrient surpluses must continue to receive more focused attention from farmers and relevant support from all those involved in advising them. This will require not only educational programmes, but also the study of the factors, including sociological and policy issues that affect the adoption of nutrient management practices and technologies by farmers.
- The potential of a simple farm nutrient balance tool which takes account of farm fertiliser, animal feed concentrates and mineral inputs and farm outputs in crop and animal produce should be considered as a means of highlighting potential nutrient surpluses.

The potential for nutrient surpluses on grass-based farming systems is addressed by S.I. 378 of 2006 (Department of Environment, Heritage and Local Government, 2006) which puts statutory limits on N and P inputs to grassland that reflect crop requirements. Rising energy prices will contribute to higher fertiliser costs adding a further incentive to reduce fertiliser inputs on grassland farms.

2.2.2 Complete Nutrient Management

Many of the LS-2 reports emphasise the importance of nutrient management.

- It is suggested that a more complete nutrient management process might include a field risk assessment component, possibly based on the P or N ranking schemes developed in the LS-2.2.1 study, particularly in subcatchments or areas that have been identified as being high risk.

2.2.3 The Importance of Soil Type

The LS2 projects identified the importance of soil type in determining the potential for nutrient loss from soil and transfer to water. The LS-2.3 projects were conducted in an area that was considered vulnerable in terms of leaching (shallow, free-draining soils overlying a karst aquifer) giving a clear hydrological pathway (and, indeed, impact). The monitoring programme found groundwater nitrate-N concentrations exceeded the EU MAC for drinking water. Associated modelling studies suggested that lower leaching losses would be expected in less vulnerable areas (deeper, heavier soils) under similar management. The LS-2.1.2 studies highlighted the interactions between the impact of management practices on soil hydrology and the quality of overland flow from agricultural land. The findings underline the importance of interactions between management practices, nutrients in soil and soil biology for the release of nutrients to drainage water.

- The application of this knowledge focuses attention on using these soil characteristics in conjunction with P (and N) source data to identify areas at high risk of nutrient loss. This moves the mitigation debate towards the identification and focusing of measures on catchment areas with high risk – spatial targeting – as being more effective than the more conventional – ‘one size fits all’ – approach.

This may not be too surprising to many involved in agriculture as the role of soil type in determining its productivity or output potential is well known and accepted. For example, over 20 years ago a correlation was established between drainage class and land productivity, reflecting in part its influence on soil nutrient transformations and crop growth potential.

2.2.4 Modelling

The P and N modelling studies undertaken have identified methodologies that can be used to assist in the identification of high-risk areas at catchment scale. This can contribute to a more targeted mitigation approach to high-risk areas in catchments which should improve the efficacy and cost effectiveness of the measures employed. National soil databases exist, including a classification system on acidic mineral, basic mineral and peat prepared by the Teagasc Spatial Analysis Group. Detailed soil county maps are available for 44% of the country and provide drainage classifications for soils that can be applied at catchment scale. However, it should be noted that the scales used for the soil survey maps are generally not suitable for soil type identification at the field level without the use of ground ‘truthing’.

- The need for the detailed county soil survey to be completed for the rest of the country was highlighted. The need for a national field-by-field STP survey was also identified. The combination of national STP data with datasets of high overland flow and P desorption risk will provide more precise identification of high-risk areas for P loss across all river basin districts.

2.2.5 Future Needs

There is a requirement for the further development and validation of the modelling approaches identified in this research. This will develop our understanding of the processes that determine nutrient loss and transfer from soil to water. It will also facilitate the evaluation of measures or ranges of measures to reduce such loss at different scales over a wide range of soil, land use and climatic conditions.

- This will require a long-term and detailed monitoring programme which concurrently records land-use activity, edge-of-field water quality, in-stream water quality (chemical and ecological data and groundwater) in a number of catchments. Such catchments could be considered in terms of a national project of excellence, forming a platform for integrated knowledge generation and transfer required to contribute to the achievement of the balance between a profitable agriculture and a sustainable rural environment.
- The case for such an exercise is further strengthened as questions remain in relation to the more precise relationships between nutrient management at farm-field scale and their efficacy and cost effectiveness at larger catchment scales.

- The proposed approach will also facilitate the inclusion of measurements to quantify the contributions of farmyards to diffuse agricultural pollution which were not made in the present research.

Many of the LS-2 project reports stressed the importance of developing more focused educational and information programmes for farmers located in high-risk areas. This should include the development of guidance documents that will assist them to implement and integrate the management practices that will reduce the nutrient loadings.

While significant progress has been made, the LS-2 research demonstrated that the identification of the sustainable measures to control nutrient losses from farm fields at catchment scale remains difficult because of the temporal and spatial complexity of the nutrient sources, soils and the rates and timings of the delivery to receiving waters. However, it is important to accept that not taking any action until there is certainty and agreement about these actions is an unrealistic option in consideration of the legally binding obligations to achieve the very specific and challenging WFD water quality targets by 2015. Therefore, the need remains for improved dialogue and feedback between policy makers, farmers and researchers.

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Acronyms

MAC	maximum admissible concentrations
NVZ	nitrogen vulnerable zone
OM	organic matter
STP	soil-test phosphorus
WFD	Water Framework Directive

Appendix 1: 2000–LS-2 Eutrophication from Agricultural Sources – Projects and Reports

Table 1 2000-LS-2.1-M2: Pathways for Nutrient Loss to Water with Emphasis on Phosphorus Losses³

Reference	Title	Lead organisation	Project leader	Report and lead report author(s)
2000-LS-2.1-M2	Pathways for Nutrient Loss to Water with Emphasis on P Losses	Teagasc	H. Tunney	Final synthesis report Tunney et al. (2007) ERTDI Report 75
2000-LS-2.1.1a	Soil and Phosphorus – Catchment Studies	University College Cork	G. Kiely	Final and synthesis reports Kiely et al. (2007) ERTDI Report 76
2000-LS-2.1.1b	Phosphorus Chemistry of Mineral and Peat Soils in Ireland	Teagasc	H. Tunney	Final report Daly and Styles (2005) ERTDI Report 38
2000-LS-2.1.1b	Phosphorus Concentration and Flow	Teagasc	H. Tunney	Final report Doody et al. (2006) ERTDI Report 40
2000-LS-2.1.2	Grazed Pastures	Teagasc	H. Tunney	Final synthesis report Tunney et al. (2007) ERTDI Report 66
2000-LS-2.1.2a	Field Plot Study. The Impact of the Grazing Animal on P, N, K and SS Loss from Grazed Pastures	Teagasc	H. Tunney	Final report Tunney et al. (2007) ERTDI Report 68
2000-LS-2.1.2b	Small Plot Study. The Impact of Grazing Animals on Nutrient Losses to Water	Teagasc	I. Kurz	Final report Kurz et al. (2006) ERTDI Report 41
2000-LS-2.1.2c	Phosphorus Dynamics in a Grazed Grassland Ecosystem	Trinity College Dublin	D. Bourke	Final report Bourke et al., in preparation ERTDI Report 77
2000-LS-2.1.3/ 2000-LS-2.1.4	Slurry and Fertiliser Spreading	Teagasc	D. Ryan	Final and synthesis reports Ryan et al., in preparation ERTDI Report 82
2000-LS-2.1.6	Environmental Soil Phosphorus Test	Teagasc	K. Daly	Final report Daly and Casey (2003) ERTDI Report 14
2000-LS-2.1.7	Relative Eutrophic Effects on Water Bodies	Trinity College Dublin	K. Irvine	Final report Jennings et al. (2003) ERTDI Report 13

³ All published reports in these appendices available at <http://www.epa.ie/>

Table 2 2000–LS–2.2–M2: Eutrophication from Agricultural Sources – Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water

Reference	Title	Lead organisation	Project leader	Report and lead report author(s)
2000-LS-2.2-M2	Eutrophication from Agricultural Sources – Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water	Teagasc	K. Daly	Final report Daly (2006) ERTDI Report 43
2000-LS-2.2.1	Field-by-Field Risk Assessment	University College Dublin	W.L. Magette	Final and synthesis reports Magette et al. (2007) ERTDI Report 79
2000-LS-2.2.2	A Comparison of SWAT, HSPF and SHETRAN/GOPC Phosphorus Models for Three Irish Catchments	University College Dublin	M. Bruen	Final and synthesis reports Nsar and Bruen (2006) ERTDI Report 39
2000-LS-2.2.2	Modelling Phosphorus Losses from Soils – Relating Catchment Characteristics to Phosphorus Concentrations in Irish Rivers	Teagasc	K. Daly	Final report Daly (2006) ERTDI Report 42

Table 3 2000–LS–2.3: Eutrophication from Agricultural Sources – Effects of Agricultural Practice on Nitrate Leaching

Reference	Title	Lead organisation	Project leader	Report and lead report author(s)
2000-LS-2.3	Eutrophication from Agricultural Sources – Effects Of Agricultural Practice on Nitrate Leaching	Teagasc	M. Ryan	Synthesis report Carton et al. (2007) ERTDI Report 58
2000-LS-2.3.1.1 (Sections 1 of 3 and 3 of 3)	Effects of Agricultural Practices on Nitrate Leaching – Farm Scale	Teagasc	M. Ryan	Final report Ryan et al.
2000-LS-2.3.1.1 (Section 2 of 3)	Effects of Agricultural Practices on Nitrate Leaching – N Cycle	Teagasc/IGER*	M. Ryan	Final report del Prado et al.
2000-LS-2.3.1.2	Effects of Agricultural Practices on Nitrate Leaching – Soil Investigation	Teagasc	J. Mulqueen	Final report Gibbons et al.
2000-LS-2.3.1.3	Effects of Agricultural Practices on Nitrate Leaching – Groundwater Study	Trinity College Dublin	P. Johnston	Final report Bartley et al.

¹ Available at <http://www.epa.ie/EnvironmentalResearch/ReportsOutputs/> (accessed 29/08/2007).

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Appendix 2: LS-2 Project Publications

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