Report No.456

epa Research

Roadway Run-off and Nutrient-loss Reduction

Authors: Owen Fenton, Karen Daly, John Murnane and Patrick Tuohy

www.epa.ie

Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

Our Responsibilities Include:

Licensing

> Large-scale industrial, waste and petrol storage activities;
> Urban waste water discharges;
> The contained use and controlled release of Genetically Modified Organisms;
> Sources of ionising radiation;
> Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

National Environmental Enforcement

> Audit and inspection of EPA licensed facilities;
> Drive the implementation of best practice in regulated activities and facilities;
> Oversee local authority responsibilities for environmental protection;
> Regulate the quality of public drinking water and enforce urban waste water discharge authorisations;
> Assess and report on public and private drinking water quality;
> Coordinate a network of public service organisations to support action against environmental crime;
> Prosecute those who flout environmental law and damage the environment.

Waste Management and Chemicals in the Environment

> Implement and enforce waste regulations including national enforcement issues;
> Prepare and publish national waste statistics and the National Hazardous Waste Management Plan;
> Develop and implement the National Waste Prevention Programme;
> Implement and report on legislation on the control of chemicals in the environment.

Water Management

> Engage with national and regional governance and operational structures to implement the Water Framework Directive;
> Monitor, assess and report on the quality of rivers, lakes, transitional and coastal waters, bathing waters and groundwaters, and measurement of water levels and river flows.

Climate Science & Climate Change

> Publish Ireland's greenhouse gas emission inventories and projections;
> Provide the Secretariat to the Climate Change Advisory Council and support to the National Dialogue on Climate Action;
> Support National, EU and UN Climate Science and Policy development activities.

Environmental Monitoring & Assessment

> Design and implement national environmental monitoring systems: technology, data management, analysis and forecasting;
> Produce the State of Ireland's Environment and Indicator Reports;
> Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
> Oversee the implementation of the Environmental Noise Directive;
> Assess the impact of proposed plans and programmes on the Irish environment.

Environmental Research and Development

> Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
> Collaborate with national and EU environmental research activity.

Radiological Protection

> Monitoring radiation levels and assess public exposure to ionising radiation and electromagnetic fields;
> Assist in developing national plans for emergencies arising from nuclear accidents;
> Monitor developments abroad relating to nuclear installations and radiological safety;
> Provide, or oversee the provision of, specialist radiation protection services.

Guidance, Awareness Raising, and Accessible Information

> Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
> Promote the link between health and wellbeing, the economy and a clean environment;
> Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
> Promote radon testing in homes and workplaces and encourage remediation where necessary.

Partnership and Networking

> Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

Management and Structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

Roadway Run-off and Nutrient-loss Reduction

Authors: Owen Fenton, Karen Daly, John Murnane and Patrick Tuohy

Identifying pressures

The Nitrates Directive aims to protect water quality across Europe by preventing nutrients from agricultural sources from polluting ground and surface waters, and by promoting good farming practices. All EU Member States are required to prepare National Nitrates Action Programmes that outline rules for the management and application of livestock manures and other fertilisers. Ireland's Nitrates Action Programme (Article 17.20) states "There shall be no direct runoff of soiled water from farm roadways to waters". Despite existing regulation, there has been minimal research in Ireland pertaining to the source, content, pathway, mobilisation and impact of roadway runoff, how to find where runoff interacts with waters, and solutions to help stop this interaction and minimise the consequences of soiled water from farm roadways entering waterways. The Roadrunner project reviewed mitigation measures to treat roadway runoff, developed an on-farm visual tool to find and document connectivity between roadway runoff and waters, and provided the evidence base to define roadway runoff as a unique sub-component of the nutrient transfer continuum.

Informing policy

The Roadrunner project has, for the first time, quantified the scale of the problem of soiled runoff entering our waterways from internal farm roadways. Policymakers should be aware that concentrations of nitrogen and phosphorus in soiled runoff waters are much higher than previously expected, with soiled roadway runoff having a similar profile to dairy-soiled water and even cattle slurry in some cases. Concentrations of phosphorus trapped in sediments on roadways surrounding fields were up to ten times more than anticipated. This trapped phosphorus can remain stored in the ground for long periods, and is released into waterways when it rains. This leads to year-round pollution of waterways, where it was previously thought that this pollution eased when cattle were wintering in sheds. The project also found that soiled waters have the highest risk of entering waterways when they drain into open ditches connected to the farmyard. There are typically 3-4 areas with direct connectivity to waters on any given farm. These findings have direct implications for Ireland's Nitrates Action Programme.

Developing solutions

To support the mitigation of this problem, the project has identified key intervention points on farmyards where water, soil and sediments can become particularly enriched with nutrients, including: 100 metre radius around the farmyard, underpasses, waiting areas associated with underpasses, water troughs situated along roadways, roadway junctions or anywhere that impedes animal movement – these areas should be targeted to reduce the soiling of runoff waters. The project developed a Farm Roadway Visual Assessment Booklet. This handbook aims to describe visual assessment indicators for identifying the extent of connectivity between roadway runoff and waters; and helps users to examine the structure and configuration of the entire roadway network and evaluate its pollution risk potential. It was co-developed with stakeholders for use by farm advisors, and is a good starting point for those looking to resolve those issues. Other mitigation measures trialed during the project include a low-cost diversion bar which could be placed on roadways at a cost of €100 per unit. However, further validation is required.

EPA RESEARCH PROGRAMME 2021–2030

Roadway Run-off and Nutrient-loss Reduction

(2018-W-MS-38)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Teagasc

Authors:

Owen Fenton, Karen Daly, John Murnane and Patrick Tuohy

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2021–2030. The EPA Research Programme is a Government of Ireland initiative funded by the Department of the Environment, Climate and Communications. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research, and was co-funded by the Department for Agriculture, Food and the Marine (DAFM).

The authors would like to acknowledge the members of the project steering committee, namely Jenny Deakin (EPA), Eoin McAleer (Local Authority Waters Programme), Cathal Somers (Teagasc), Monica Rivas Casado (Independent Advisor), Michael O'Donoghue (DAFM), Averil Gannon (Department of Housing, Local Government and Heritage), Donal Grant (Department of Housing, Local Government and Heritage) and Eoin Riordan (Department of the Environment, Climate and Communications). The authors would also like to acknowledge the post-doctoral contract researcher Dr Paul Rice, who was hired to work on the project.

DISCLAIMER

Although every effort has been made to ensure the accuracy of the material contained in this publication, complete accuracy cannot be guaranteed. The Environmental Protection Agency, the authors and the steering committee members do not accept any responsibility whatsoever for loss or damage occasioned, or claimed to have been occasioned, in part or in full, as a consequence of any person acting, or refraining from acting, as a result of a matter contained in this publication. All or part of this publication may be reproduced without further permission, provided the source is acknowledged.

This report is based on research carried out/data from 2018 to 2022. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2021–2030
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-80009-166-5 April 2024

Price: Free Online version

Project Partners

Owen Fenton
Teagasc
Johnstown Castle
Wexford
Tel.: +353 53 9171271
Email: owen.fenton@teagasc.ie

John Murnane
School of Engineering
University of Limerick
Limerick
Tel.: +353 61 202700
Email: john.murnane@ul.ie

Karen Daly
Teagasc
Johnstown Castle
Wexford
Tel.: +353 53 9171271
Email: karen.daly@teagasc.ie

Patrick Tuohy
Teagasc
Moorepark
Cork
Tel.: +353 53 9171271
Email: Patrick.tuohy@teagasc.ie

Contents

List of Figures

List of Tables

Executive Summary

In Ireland, as of 1 January 2021, roadway run-off within farms is not permitted to enter waters (EU Nitrates Directive, Article 17.20). Results from this ROADRUNNER project show that internal farm roadways are a sub-component of the nutrient transfer continuum (NTC) and define source, mobilisation, transport, delivery and impact elements for the first time.

Nutrient sources (dissolved and particulate fractions) on internal dairy farm roadways originate predominantly from surface deposits of cow excreta. The highest concentrations are found where cow movement may be impeded, e.g. roadway junctions, around farmyards, before and after cow underpasses and stand-off areas, and around water troughs. In some cases, nutrients are also transported via run-off from higher surrounding areas to roadway networks, e.g. from adjacent fields, farmyards and public roadways. The highest risks of nutrient and sediment loss with connectivity to waters typically occur within 100 m of farmyards, while the highest connectivity risks occur where farmyards are connected to open-drainage ditches or where there are roadway run-off connections. In addition to surface deposits, the underlying roadway material can become enriched with nutrients over time in areas where high phosphorus (P) concentrations are likely. This accumulated legacy P on and within farm roadways could be released during rainfall.

Mobilisation occurs during rainfall events and is dependent on the timing, magnitude and intensity of these events. Farm roads therefore represent a category of semi-pervious areas with the potential to generate infiltration-excess surface run-off. However, not all rainfall events will lead to roadway run-off, which can take time to generate.

Transport and delivery are dependent on the connectivity of farm roadways to waters. Roadway run-off can discharge directly to surface water bodies (e.g. open-drainage ditches) or indirectly (via public roadways, farmyards and underpasses), and can be connected to surface water and/or groundwater. Leaching losses to groundwater from semi-pervious roadway surfaces have also been reported.

Impact is measured by environmental degradation of water bodies via nutrient losses. Unlike catchment-scale sources, farm roadways can be a source of high P and sediment losses during summer months, leading to excessive plant and algal growth with consequent impacts on aquatic life and human health, particularly in the context of drinking and bathing water quality. It is therefore critical to mitigate such impacts by preventing direct or indirect farm roadway run-off discharges into waters.

Mitigation strategies to break connectivity between farm roadway run-off and waters include the management of animals using roadways (e.g. increasing cow flow movement) and management of the physical roadway (e.g. low-cost water-diversion bars and camber alterations). Roadway run-off diversion bars were trialled to divert roadway run-off from roadways into fields, and these proved an effective low-cost measure that could be used on farms in Ireland. Other roadway run-off and in-ditch measures to mitigate nutrient losses should be tested.

Identification of connectivity issues can be assessed by farmers and advisors using a visual assessment booklet, produced under this project. This approach is adaptable to all farm types and should be automated and rolled out nationally, especially in priority areas for action. Applying this methodology to field data from seven dairy farms in south-east Ireland, a semi-quantitative risk assessment model, which was developed under this project, established that 8.4% of roadway sections examined included all components of the NTC and required run-off mitigation measures. The model assessed the likelihood of connectivity to waters with resultant impact on water quality to develop five overall risk categorisations: very low, low, moderate, high and very high. A colour-coded risk assessment roadway map was then created to guide future management.

Future research should focus on scaling up this farm-scale visual assessment approach to the national scale for all farms. It should also investigate water and sediment nutrient loads from roadway run-off and their contribution at the catchment scale. There is a need to identify and map farm roadways within priority areas for action, to delineate critical roadway sections with connectivity to waters, and to measure the impact of this connectivity on incidental and temporal catchment-scale pollution for differing farm types. There is a need to co-design, develop, cost and assess the effectiveness of a variety of on- and off-roadway mitigation measures and management options to reduce farm roadway run-off.

1 Introduction

On farms in Ireland, internal roadways come in many shapes and sizes, with a variety of hard surfaces. The densities of internal farm roadways vary due to factors such as geographical area, climate, soil type and farm enterprise type. Farms with more highly textured and poorly drained soils tend to have a higher density of roadways and open-drainage ditches than farms with other soil types, with dairy farms requiring the highest densities. Farm roadways are semi-permeable and surface water flow is facilitated along them for short periods during and after rainfall; this is termed roadway run-off (Fenton *et al.*, 2021a). Farm roadways, open-drainage ditches (five categories in terms of connectivity ranking) and culverts exert significant influence on hydrological and geomorphological processes (Thomas *et al.*, 2016). Unfortunately, some farm roadway run-off contains significant deposits of soil, animal manure, urinate and machinery contamination. Such pollutant loads contain suspended sediment (SS), dissolved nutrients (nitrogen (N) and phosphorus (P)) and bacteria such as *Escherichia coli* and can cause the significant deterioration of surface water quality. Farm type is important here with respect to the type and nutrient profile of the source, and it should be noted that the ROADRUNNER project focused on the roadway run-off connectivity on dairy farms. The loss of nutrients to watercourses can negatively affect water quality. In rivers, N and P losses can result in excessive plant and algal growth. This reduces the amount of oxygen in the river and suffocates sensitive fauna. Excessive fine sediment in a river can smother the streambed habitat and clog the gills of many sensitive mayfly species. From a human health perspective, bacterial contamination of watercourses is a significant issue, particularly in the context of drinking water and bathing water quality. To safeguard water quality, therefore, farm roadway run-off should be prevented from directly entering waters.

Readers should be aware that Article 17(20) of the European Union (Good Agricultural Practice for Protection of Waters) Regulations 2017 states: "There shall be no direct runoff of soiled water from farm roadways to waters from 1 January 2021. The occupier of a holding shall comply with any specification for farm roadways specified by the Minister for Agriculture, Food and the Marine pursuant to this requirement" (Government of Ireland, 2017). This rule applies to all farms and every type of road, not just those used by animals. It should also be noted that the definition of "waters" used in this report matches that of these current regulations (Government of Ireland, 2017). According to this definition, waters include:

> a) any (or any part of any) river, stream, lake, canal, reservoir, aquifer, pond, watercourse, or other inland waters, whether natural or artificial, b) any tidal waters, and c) where the context permits, any beach, river bank and salt marsh or other area which is contiguous to anything mentioned in paragraph (a) or (b), and the channel or bed of anything mentioned in paragraph (a) which is for the time being dry, but does not include a sewer.

Interestingly, although regulated, there is a dearth of data needed to characterise the nutrient content in roadway run-off, and no data exist on source, mobilisation, pathway, delivery and impact, making it impossible to include roadways as a sub-component of the nutrient transfer continuum (NTC). Moreover, there are no visual or modelling tools to aid different stakeholders in the identification of sections of farm roadway that are connected to waters and therefore in need of management. It should be noted that the current regulations in place in Ireland did not form the boundaries of the current project. Instead, a broader view was taken and the project reviewed a broader set of mitigation measures used to manage roadway run-off internationally. This is important, as some of the mitigation measures presented herein facilitate roadway run-off management after delivery to an open-drainage ditch, i.e. waters.

1.1 Internal Farm Roadways

Internal farm roadways, which are also referred to as laneways in New Zealand (Monaghan and Smith, 2012), tracks in the USA (Adams *et al.*, 2014) and stock lanes in the EU (Lucci *et al.*, 2010), form part of the overall catchment road network (Kröger *et al*., 2012). Typical farm roadways are configured so that surface water drains to adjacent land or a watercourse to prevent ponding and waterlogging. The main function of roadway networks on grassland farms is to facilitate controlled stock movement so that grass use can be maximised to enhance farm sustainability and profitability. An intensive roadway system reduces on-farm labour requirements and streamlines the movement of animals to make grazing management easier, particularly during inclement weather conditions. Internal farm roadways in Ireland typically occupy 1–2% of the grassland area, but their configuration and layout vary significantly between and within farms mainly as a result of farmer preference, enterprise type (e.g. grassland vs tillage and beef vs dairy), farm layout and landscape (affecting roadway length or slope).

Roadway run-off is a significant contributor to the diffuse source pollution of waters. For example, in a study of a 38 km^2 agricultural watershed in south-central New York, it was found that 94% of roadway open-drainage ditches discharged into natural streams and effectively doubled the drainage density (Buchanan *et al*., 2013). In addition, an export coefficient of 0.49 kg P/ha was allocated to roadways in a US catchment (Endreny and Wood, 2003) and it has been reported that the level of P loading from roadway run-off may approach or exceed that of agricultural run-off from fields (Easton *et al*., 2007, 2008). Farm roadway design and construction in Ireland to date has not prioritised or included run-off diversion away from waters. Surface water run-off would typically discharge into adjacent waters where accessible, and roadway drainage is normally considered only where steep gradients increase the possibility of the scouring and erosion of road surface layers. Frequently, farm roadways located closer to farmyards are better constructed and maintained, while those at the outer locations of the farm tend to be underdeveloped and neglected over time. Many roadways are also developed incrementally, where the farm layout may be reconfigured or new land acquired. This can lead to variable farm roadway configurations, constituent materials, surface conditions, gradients, crossfalls, lengths and widths. In addition, road networks that have been in place for some time may be suitable for lower livestock numbers than exist at present. Even if well maintained, such roadways tend to be compromised in terms of width and consequently may reduce livestock movement and comfort (Teagasc, 2017). Traversing farm animals may therefore encounter variability in roadway layouts and types. Poor roadway surface conditions, such as those with potholes, uneven and damaged surfaces, grassy margins, excessive surface waste and excessive shelter or shading, which lead to damp and dirty surfaces and obscure the view, all contribute to uncomfortable and inefficient livestock movement. Other maintenance issues such as poorly located water drinking troughs or fencing that is too close to the road edge also prevent efficient livestock movement.

1.2 Objectives

The primary objectives of the ROADRUNNER project were to characterise the nutrient content of roadway run-off, collate the data needed to solidify roadway run-off as a sub-component of the NTC, create visual and modelling tools to locate and rank the risk of roadway run-off connectivity with waters on dairy farms, review roadway run-off on–off mitigation options and test a mitigation measure in terms of its capacity for roadway run-off diversion on a dairy farm.

2 Farm Internal Roadways as Part of the Nutrient Transfer Continuum

Preventing fresh water deterioration caused by contamination with point and diffuse agricultural sources rich in P and N remains a key environmental priority (Fenton *et al.*, 2019). Nutrient losses from agricultural catchments are an aggregate of several source and transport interactions. Farm roadway surfaces can be regarded as semi-pervious and can contribute significantly to catchment-scale nutrient losses when connected to receiving waters (Srinivasan and McDowell, 2009). These semi-pervious areas also represent active sub-surface loss pathways. Both surface and sub-surface losses can be significant at the catchment scale because of the amount of time animals spend on farm roadways (Monaghan and Smith, 2012). The impacts of farm roadway run-off are distinct from the impacts of other diffuse losses (e.g. from fields) during dry seasons, when below average rainfall occurs.

2.1 Nutrient Transfer Continuum Framework

The concept of the NTC is not new and has been used extensively to document the source, mobilisation, transport, delivery and impact of nutrient losses from agricultural landscapes to waters. There are several sub-components of the NTC that need to be explored in more detail, with hard surfaces being one of these. For the inclusion of a new sub-component in the NTC, information on all aspects of the NTC must be gathered and presented in a coherent manner. To do this, a mix of desktop study and field work was carried out as part of the ROADRUNNER project.

For the project, a dairy farm (Johnstown Castle) in south-east Ireland was selected, which after use of *The Farm Roadway Visual Assessment Booklet* (Fenton *et al.*, 2021b) we identified as having

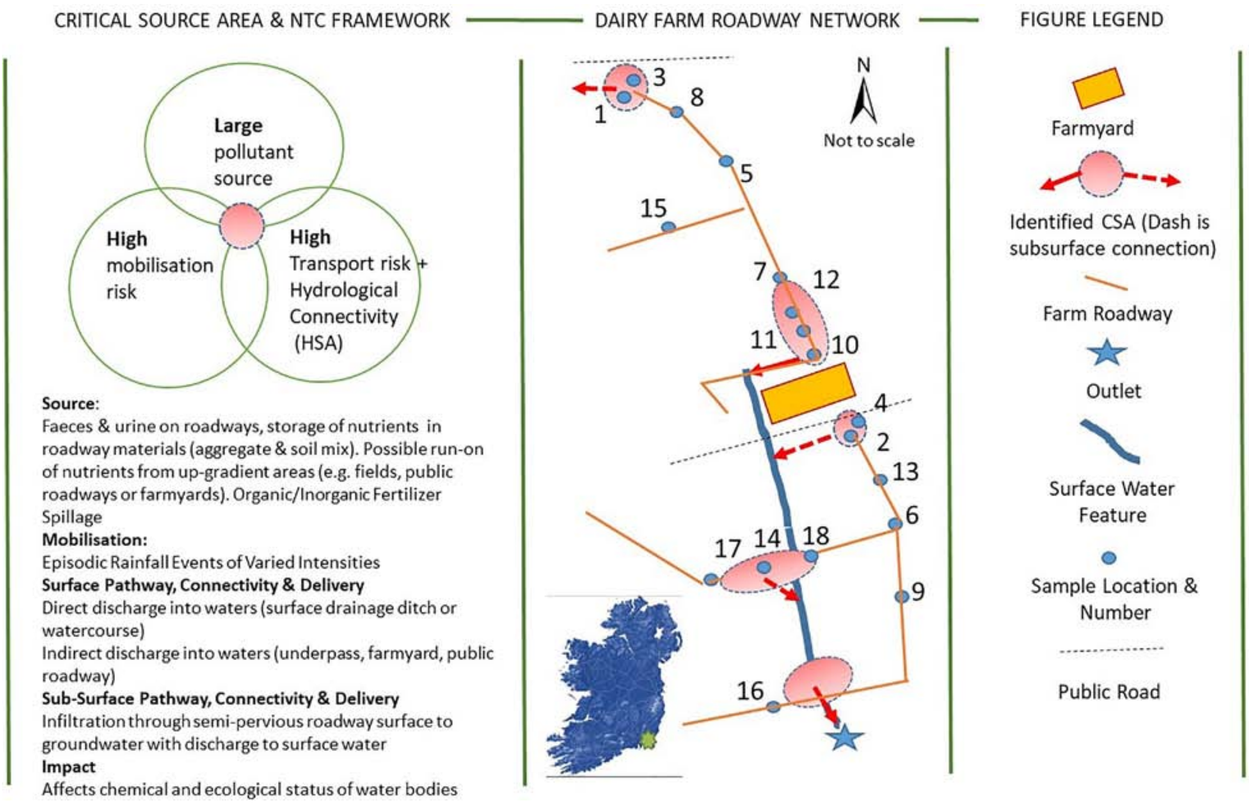

Figure 2.1. Sample locations and NTC framework for farm internal roadways and roadway run-off. Adapted from Fenton *et al.* (2022); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

connections with waters. The roadway network was mapped and 18 locations (initially 17, as described in Fenton *et al*. (2021a), but an additional location beside a dairy-soiled water lagoon was added in 2022) were selected to examine the different parts of the NTC using visual or sampling techniques. These locations were representative of roadway areas where cow flow was impeded in some way and the levels of defecation and urination were therefore likely to be higher (Figure 2.1). The roadway surfaces in each of these areas were sampled (avoiding fresh defecation material and focusing only on roadway aggregate and soil materials) over several months, and these samples were analysed for various nutrient and metal concentrations. Ancillary data for each of these sites were also gathered to complete information pertaining to the NTC. Table 2.1 presents the average results of the entire farm roadway network (18 locations). The results indicate that P concentrations were elevated regardless of location, cow flow conditions or proximity to the farmyard. Location 18 had the same characteristics as nearby locations, with elevated P concentrations in roadway surfaces extending the critical source area (CSA) for this area to the top of the roadway slope (Figure 2.1).

Based on the data used in Fenton *et al*. (2022) and additional data gathered thereafter (four sampling events, in September, October, November and December 2022), the entire network was highlighted as a P store, which merits its inclusion in the NTC framework. This has implications for the management of roadway networks during both open grazing (cows are outside and not housed) and closed grazing (cows are housed during the hydrologically active period), as the source of P on the roadway network is present throughout the year and available to be lost

Table 2.1. Whole-farm average concentrations for all roadway sampling locations across the sampling occasions

Month	Concentration (mg/kg)	pH	Pm	M3-P	Km
September	Average	6.91	44.29	154.94	240.53
	Stdev	0.44	21.77	57.52	74.69
October	Average	6.99	55.11	162.79	221.12
	Stdev	0.30	31.58	88.05	80.03

Km, Morgan's K test; M3-P, Mehlich-3 P test; pH, potential of hydrogen; Pm, Morgan's P test; Stdev, standard deviation.

in roadway run-off. The NTC framework (Haygarth *et al*., 2005) links source to the impact on agricultural landscapes and was used by Wall *et al*. (2011) and Shore *et al*. (2013) in Ireland to examine nutrient source and impact in their assessment of national action programmes at the meso-catchment scale. To apply the continuum to dairy farm roadways, information on source mobilisation transport and hydrological connectivity delivery and impact must be conceptualised and collated. A delivery point or area is where run-off enters waters.

The following NTC sub-component information applies to internal roadways on dairy farms (Figure 2.1) and could be easily modified to fit other farm types, e.g. beef and sheep farms:

- P sources (dissolved and particulate fractions) originate from cow faeces and urine deposited on roadway surfaces (see full review by Fenton *et al*., 2021a). Large volumes of dung (1.5–2.7 kg per deposit; 1–1.5 deposits per cow per day with 4–8 g P/kg of deposit) and urine, although lower volumes than those deposited in fields, are deposited on roadways in the open-grazing period (McDowell *et al*., 2020). The P in soil becomes incorporated around stone aggregates from animal hooves and machinery. Limited amounts of organic and inorganic fertiliser from farm activities may fall on these surfaces (slurry and dairy-soiled water). In some cases, run-on can move nutrients from more elevated areas to the roadway network, e.g. from fields or public roadways or farmyards (Fenton *et al*., 2021a). The P originating from these composite sources/deposits is stored and is available for release as legacy P sourced from roadway materials (present study) during rainfall. The concentration of P is likely to be high because slow downwards mobility of P is expected to occur in the roadway materials (because of the influences of highly compacted roadway material, alkaline pH and limestone content).
- Internal farm roadways on dairy farms have been recognised as a sub-component of the NTC (Fenton *et al*., 2022). Mean P and SS concentrations in 18 run-off events over 12 months from a section of dairy farm roadway entering an adjacent P-impacted stream were measured in New Zealand. Across 18 events, the mean run-off volume and dissolved reactive P (DRP, mg/L), particulate P (mg/L) and SS

(mg/L) concentrations (± standard error (range)) were 588 L ± 123 L (53–1751 L), 0.301 ± 0.053 (0.004–2.312), 2.046 ± 0.556 (0.010–6.640) and 2720 ± 1103 (26–4950), respectively (McDowell *et al*., 2020). The source component of the transfer continuum stems from a large volume of dung (1.5–2.7 kg per deposit; 1–1.5 deposits per cow per day with 4–8 g P/kg of deposit) and urine being deposited on these roadways on a regular basis (McDowell *et al*., 2020).

- Mobilisation occurs during precipitation (which is dominated by rainfall and dependent on timing, magnitude and intensity) (Fenton *et al*., 2021a).
- Transport is controlled by the connectivity of the roadways to waters (directly into open-drainage ditches or a surface water body, or indirectly into public roadways, farmyards or underpasses (can be connected to surface water or groundwater) (Fenton *et al*., 2021a; present study)). Sub-surface leaching losses to groundwater from these semi-pervious areas have also been documented (Srinivasan and McDowell, 2009).
- The loss of nutrients to water bodies can negatively affect the chemical and ecological status of waters, exerting a significant impact distinct from the impacts of other sources at the catchment scale during the summer months (Monaghan and Smith, 2012; Srinivasan and McDowell, 2009). In rivers, N loss and particularly P loss can result in excessive plant and algal growth. This growth and decay cycle reduces the amount of oxygen in the river and suffocates sensitive fauna. Excessive fine sediment in a river can smother the streambed habitat and clog the gills of many sensitive mayfly species. From a human health perspective, bacterial contamination of watercourses is a significant issue, particularly in the context of drinking water and bathing water quality. To safeguard against harmful impacts, soiled farm roadway run-off must be prevented from directly or indirectly entering waters (Teagasc, 2021).
- To break connectivity before the delivery of roadway run-off to waters, mitigation measures are needed, including those mentioned by Fenton *et al*. (2021a), which include a mixture of cow management (e.g. increasing cow flow) and on-roadway/off-roadway options, e.g. low-cost water-diversion bars (using concrete or roadway materials to 25 mm height) and roadway camber adjustments. The mitigation measure deployed should also involve managing the P source.

2.2 Critical Source Area and Mitigation

Farm roadways can provide connectivity at delivery points within diffuse CSAs or variable source areas. However, in the absence of breakthrough point(s) the roadway itself becomes a CSA, meaning that the source is present as deposits (see Figure 2.1 for source list) on the roadway surface and in the roadway materials, that the transport potential is high and that, after rainfall, transport initiates overland flow on the roadway surface due to the physical characteristics of the roadway (Fenton *et al*., 2021a), which if connected to waters through a delivery point will have an impact on water quality. In reality, though, several points or sections along a roadway combine to form a potential CSA where a source of pollutants coincides with an area of high mobilisation and with hydrologically sensitive areas, which have the highest propensity for generating surface run-off and transporting pollutants (Thomas *et al*., 2016). The identification of CSAs and delivery points to waters on roadways for the present study was conducted visually using the techniques outlined in section 3.1.

A CSA approach is likely to be more effective in terms of mitigation than simply treating these areas as point sources. Therefore, sources with high P concentrations (due to animal deposits and materials) need management in areas of the farm roadway network that have a high transport potential (Shore *et al*., 2015a).

On the study farm site, the following areas (representing 6.8% of the roadway sections identified, equating to five distinct areas on the farm) were identified as CSAs and therefore as being in need of mitigation measures to prevent impact:

- Locations 10, 11 and 12 form a composite CSA where mobilisation is high during high-intensity rainfall due to the road gradient. This is a hydrologically sensitive area with delivery to waters through an open drain. Discharge directly enters a second-order stream behind the farmyard.
- The underpass and adjacent stand-off area (locations 2 and 4) form a composite CSA where

mobilisation is high during rainfall towards the underpass, with transport to a collection tank at its base. The underpass tanks that discharge directly into water need to be reconfigured and managed (Figure 2.1).

- Location 16 and the adjacent roadway sections form a composite CSA where mobilisation is high and water is discharged directly (delivered) into a stream at the lowest point of the roadway.
- Locations 14, 17 and 18 form a composite CSA where discharge directly enters a stream. Sampling at location 18 showed high concentrations where soiled water was removed from a lagoon; this is another management issue that could be resolved easily. A diversion on both sides of the roadway into neighbouring fields here combined with a berm around the opening would disconnect the roadway run-off generated in this area with waters.

3 Evaluating Connectivity Risk: Farm Roadway Run-off into Waters

The ROADRUNNER project developed two tools for evaluating the connectivity risk of roadway run-off on farms. The first of these tools was co-designed with the Agricultural Sustainability Support and Advisory Programme (ASSAP) and Local Authority Waters Programme (LAWPRO) and is envisaged to be used by advisors and farmers to help them comply with current regulations in Ireland. The first tool can be utilised quickly and updated throughout the year as the roadway network develops. The second is a semi-quantitative tool that can be used to identify which roadway sections pose the highest connectivity risk. The second tool involves more field work and, for it to be effective, it would need to be scaled up and automated. Some preliminary work has been conducted in this regard and a table of data sources and layers for the parameters used in the tool is presented.

3.1 Visual Assessment Booklet

A visual handbook was developed to help users quickly identify where roadway run-off is connected with waters on a farm. This booklet is freely available on the Teagasc website (Fenton *et al*., 2021b, available online: www.teagasc.ie/publications/2021/the-farm-roadway-visual-assessment-booklet.php). It contains visual indicators that can be used to:

- identify the extent of connectivity (direct or indirect) between roadway run-off and waters. This is important, as roadways near waters potentially confer a high pollution risk and therefore need to be identified and assessed as a priority;
- examine the structure and configuration of the entire roadway network and evaluate its pollution risk potential.

All visual indicators can be used to document areas where future farm roadway management will be needed. The routine assessment of farm roadways allows improved management and maintenance; it is hoped that this handbook will provide a practical and useful guide for the management of any internal farm roadway network.

3.1.1 What are visual indicators?

These are recognisable features that can help to identify connectivity between roadway run-off and waters. In addition, visual assessment indicators can identify sections of roadway that may need improvement.

The initial step of the visual assessment process identifies priority areas for run-off management away from waters. The user is asked to do the following:

- **First**, print off a farm map (e.g. land parcel identification system) or satellite image or sketch out their own map of the farm/farm roadway network.
- **Second**, walk the roadway network and find and note where direct connectivity occurs between roadway run-off and waters. Table 3.1 provides a guide to highlighting potential examples on a dairy farm. This observational work is best carried out during or immediately after a rainfall event, when farm roadway run-off is visible. This process should be repeated over time. This step produces an output as in Figure 3.1.

The second part of the visual assessment process enables the user to note sections of the roadway network that are problematic because of the structure or configuration of their network. Using the same or a new map or sketch, other visual indicators for the roadway network (as shown in Table 3.2) must also be noted. This involves assessing the condition of the farm roadways for defects that may be causing problems. These relate to roadway structural deficiencies that lead to poor roadway integrity and loss of sediment. Roadway configuration deficiencies (e.g. road too narrow for livestock numbers, sharp bends and obstructions such as drinking troughs, and inappropriately located gates or gaps) may also be evident and these can reduce the speed of animal

Table 3.1. Direct connectivity points where roadway run-off enters waters, the impact of this connectivity and the associated visual indicators

Features used to identify direct roadway run-off connectivity with waters	Impact	Visual indicator	Photographic example
Run-off directly entering waters located beside the roadway	Transfer of sediment, nutrients and bacteria to waters	Visible flow of roadway run-off during or after rainfall events for short periods into waters; formation of permanent run-off channels or rills on roadway; visible discharge or delivery points	 
Run-off directly entering waters below the roadway, at a bridge or culvert	Transfer of sediment, nutrients and bacteria to waters	At a bridge crossing, run-off channels on both sides and on the bridge itself Colour of waters affected by roadway run-off containing faeces and sediment	
		No barrier to break direct connectivity of roadway run-off with waters at a bridge	

Table 3.1. Continued

Features used to identify direct roadway run-off connectivity with waters	Impact	Visual indicator	Photographic example
Run-off indirectly entering waters from a farm roadway via a public roadway	Transfer of sediment, nutrients and bacteria to waters when the road is soiled	Run-off channels and rills, discharge points present on public roadway Evidence of flow from farm roadway onto public roadway and into waters, during rainfall events	
Run-off from a public roadway indirectly entering waters via a farm roadway	Transfer of sediment, nutrients and possibly bacteria to waters	Evidence of flow from public roadway onto farm roadway and subsequently into waters In this example, during a rainfall event, run-off from the public road enters the drain inside the farm gate	

Table 3.1. Continued

Features used to identify direct roadway run-off connectivity with waters	Impact	Visual indicator	Photographic example
Run-off from an underpass via channels or connecting roadways	Transfer of sediment, nutrients and bacteria to waters	Evidence of flow from an underpass to waters Direct connection may be at the end of infrastructure	
Run-off from a farmyard via connecting roadway	Additional soiled water due to increased effective area of the farmyard	Flow from upslope roadways entering the farmyard	

Adapted from Fenton *et al.* (2021b); photo credits from the authors of the booklet: Fenton, O., Daly, K., Rice, P., Tuohy, P. and Murnane, J. Additional photos from Somers, C.

movement and increase the level of soiling (i.e. create nutrient and *E. coli* sources) on the roadway. When it rains, such deposits can become temporarily mobilised and enter waters where direct or indirect connectivity exists. An example output from this part of the process is presented in Figure 3.2.

The final part of the visual assessment process brings other pieces of information together for the areas that have been identified in the preceding steps. These pieces of information are then added to the final output map, which can be used to guide roadway run-off management plans. These plans may include information on the gradient (% slope) along the length of a farm roadway, which is estimated by dividing the difference between the elevations of two points by the distance between them and then multiplying the result by 100:

- The difference in elevation between points is called the rise. The distance between the points is called the run.

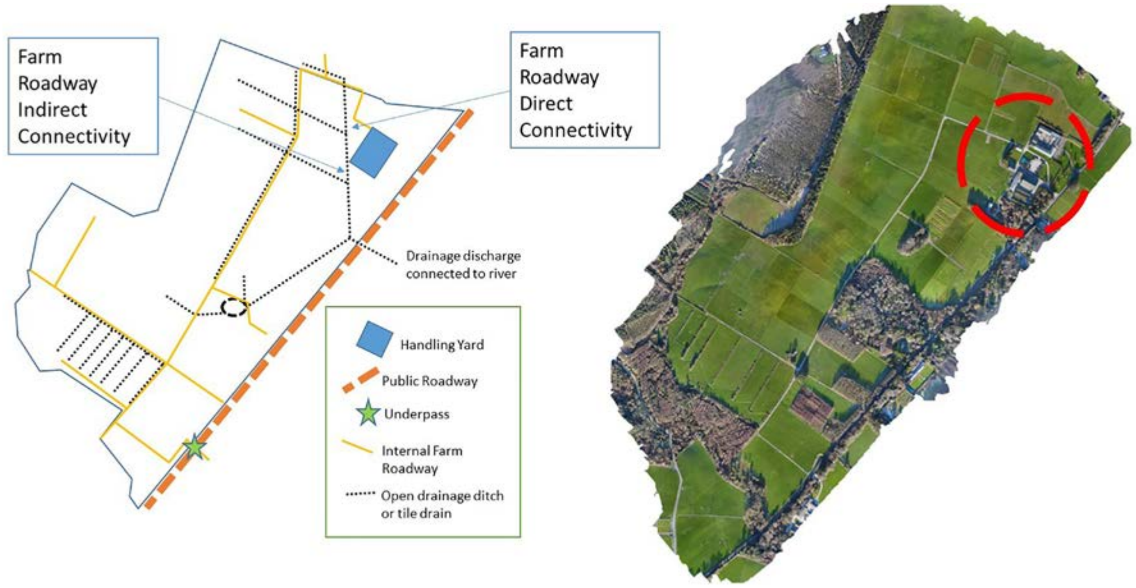

Figure 3.1. An example of a farm showing all connections with waters. The left side of the figure shows a sketch and the right shows a satellite image of the farmyard, with the area within a 100 m radius of the farmyard represented in red.

- Slope (%) equals (rise/run) × 100.
- The user should document this figure on their map, e.g. 1% (gentle), 5% (moderate) or 10% (significant). Examples of these slopes are given in Figure 3.3.

Crossfall (also called camber) of a farm roadway: some roadways near waters may have a level or sloping crossfall towards waters, which creates potential connectivity risks. It is extremely important to ensure that a road has a good crossfall located away from waters. The life of the roadway can be extended by removing surface water as quickly as possible. This can be achieved by constructing a crossfall of between 1 in 15 and 1 in 20 to one or both sides of the roadway, which ensures that potholes are less likely to develop and consequently reduces maintenance costs. A roadway that slopes to one side is easier to construct and machinery runs better on it. However, where there is a considerable gradient along the length of the roadway, the crossfalls may be insufficient on their own to prevent scouring due to fast-flowing surface water. In such cases, additional measures such as low ridges, cut-off drains and shallow channels may be needed at intervals across the roadway, to divert the surface water to a non-connected area (e.g. field) before it builds in volume and momentum.

Roadway width: the width of roadways depends on the number of cows in the herd. Guidance on standard sizes is given in Table 3.3.

The information in Table 3.3 will enable the user to decide whether or not the roadways are fit for the herd size in question. A stock-proof fence should be positioned about 0.5 m from the edge of the roadway. This would allow cows to utilise the full width of the roadway, while preventing them from walking along the grass margin. A cow track in the grass margin usually means that the fence is too far from the edge of the roadway and also that the surface of the roadway is likely to be poor.

Presence or absence of a buffer (riparian zone): the “area” between the roadway and waters, termed a buffer, is important, as it can disconnect roadway run-off from waters. If this land is maintained in permanent vegetation next to waters, it is termed a riparian buffer and provides a physical barrier that helps prevent run-off from being washed from roads/fields into waters. The establishment of a dense grassy buffer strip, through either natural regeneration or sowing, can help in the interception of surface run-off all year round. Sowing is generally best for the speedy establishment of a buffer strip. Recent good agriculture and environmental condition (GAEC) advice states that

Table 3.2. Additional visual indicators that indicate structural and configuration problems associated with connectivity where roadway run-off enters waters

Problems	Visual indicators	Photographic examples
Structural problems can lead to insufficient foundations due to shallow depth of material or soft soil Poor-quality roadway material or use of poorly bound roadway materials	Roadway sinking into sub-soil becomes more pronounced with repeated animal and farm traffic loading. This causes sinking of the roadway, uneven gradients and breakthrough of soil Animals may be forced to walk in single file due to discomfort caused by poor surface conditions	
	Failure of materials leads to structural breakdown of road surface and evidence of run-off rilling	

Table 3.2. Continued

Problems	Visual indicators	Photographic examples
	Breakdown of unconsolidated material	
Structural and configuration problems may slow down animal flow	Animals slow and the soiling of roadway surface occurs as full roadway width is not in use; this may lead to potholes	

Table 3.2. Continued

Problems	Visual indicators	Photographic examples
	Potholes specifically around drinking troughs. This causes animals to slow, increasing the soiling of the roadway surface **Note:** A farm with a grassland stocking rate over 170 kg N/ha must have livestock drinking points at least 20 m from watercourses (regardless of a barrier such as a roadway or hedgerow between the trough and the watercourse). Animals cannot be given access to streams for drinking	
	Animal hoof prints. Evidence of animals slowing and soiling of an overly soft or dirty roadway surface. Poor-quality roadway material or accumulation of dirt/muck	

Table 3.2. Continued

Problems	Visual indicators	Photographic examples
	Same problems as above, but this time due to machinery. Poor-quality roadway material. Breakdown of surfacing material from the action of traffic, frost and rain. Roadway is not elevated above the field surface so surface drainage is not accommodated	
Configuration problems can lead to excessive roadway gradients	Build-up of soiled run-off at bottom of slope with no diversion into a field. Scouring of roadway surface	
	Evidence of wheel rutting and surface scouring. Promotes run-off along roadway length to further increase surface scouring and prevents run-off into fields	

Table 3.2. Continued

Problems	Visual indicators	Photographic examples
Configuration problems due to tight bends	Evidence of animals slowing and soiling the roadway surface. There is also evidence of wheel rutting	
Configuration and structural problems may lead to ponding	No relief or crossfall on the roadway causes ponding. Buffer (Grass margin) here is <3 m and not considered enough to stop direct connectivity to waters Ponding can lead to connectivity with waters	

Table 3.2. Continued

Problems	Visual indicators	Photographic examples
	Combination of ponding and wheel rutting evident	
Configuration problems leading to excessive shading	Natural shading of roadway with vegetation. Shading prevents the roadway from drying out after rainfall events. This causes problems over time	
	Man-made feature shading beside the farmyard, exacerbating surface wetness and erosion. Prevention of surface from drying and soiled surface leads to problems over time	

Table 3.2. Continued

Problems	Visual indicators	Photographic examples
Configuration problems leading to elevation of roadway below surrounding land	A roadway level that is same as the surrounding land does not enable roadway run-off management. The sections that have connectivity with waters should be marked on users' maps Entry of run-off to waters can be further along the roadway	
	Roadway lower than the surrounding land and does not enable roadway run-off management where connectivity to waters occurs. The sections that have connectivity with waters should be marked on users' maps	

Adapted from Fenton *et al.* (2021b); photo credits from the authors of the booklet: Fenton, O., Daly, K., Rice, P., Tuohy, P. and Murnane, J. Additional photos from Somers, C.

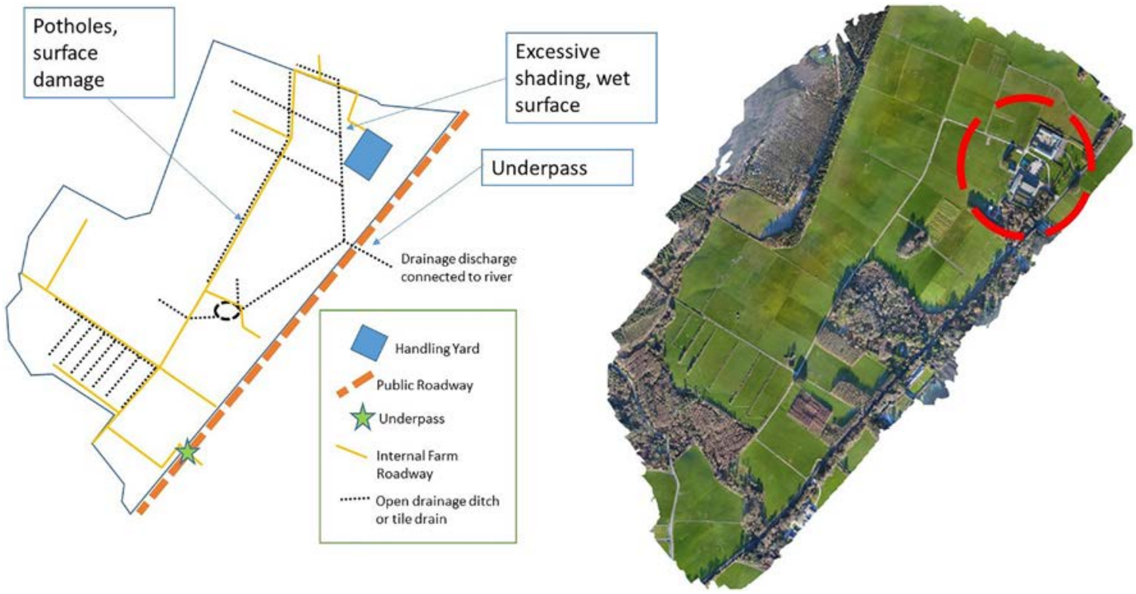

Figure 3.2. An example of the same farm as that shown in Figure 3.1, showing other visual indicators along the roadway network.

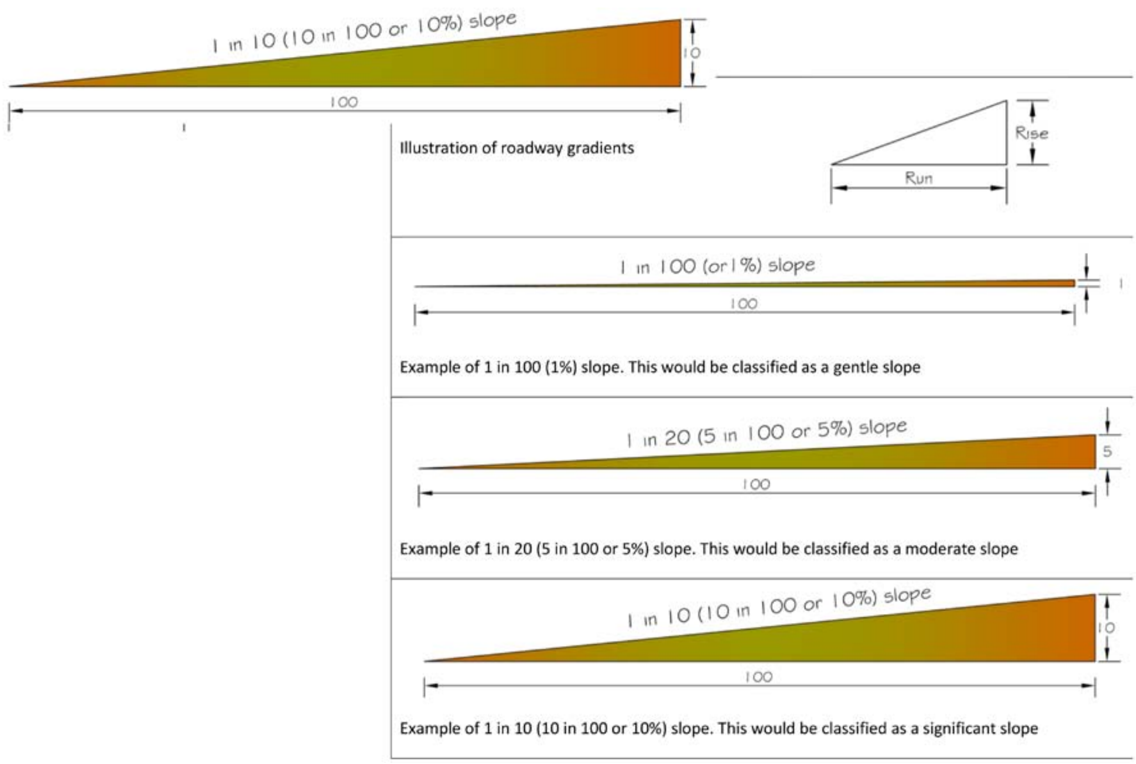

Figure 3.3. Examples of gentle, moderate and significant slopes.

Table 3.3. Herd size and corresponding roadway width

Herd size (number of cows)	Roadway width (m)
50	3.5
100	4.0
150	4.5
200	5.0
250	5.5
300	6.0

a minimum buffer width of 3 m is considered suitable for disconnecting roadway run-off from waters, while a buffer width of less than 3 m or the absence of a buffer is considered unsuitable. Users should note the width (metres) of the buffer and its location on the map (see Table 3.4).

Natural or man-made features: it is important that users note on their map the locations of natural or man-made barriers that may prevent management options from being implemented. In such cases, more specific options such as roadway relocation or removal of the barriers may be considered. Examples of such barriers are given in Table 3.5.

Figure 3.4 represents a simple example of combining all the information gathered in steps 1 and 2 and noting some additional information where appropriate.

This approach is expected to be iterative and adapted over time to keep track of roadway run-off management on dairy farms. This could also be used as a record for the farmer to show future plans for sections that have been identified as connected to waters.

3.2 Development and Validation of a Semi-quantitative Risk Model to Identify Roadway Sections in Need of Roadway Run-off Management on Dairy Farms

A semi-quantitative risk assessment model was created as part of the ROADRUNNER project. Full details of model development and the associated sensitivity analysis are presented by Rice *et al*. (2022). In brief, this involved first selecting parameters (based on expert opinion and a review of the literature) that would represent various parts of the NTC as outlined in previous sections, i.e. source, mobilisation, transport, delivery and impact of nutrient losses. These parameters consisted of different variable types, i.e. continuous (e.g. length of roadway (m)) or categorical (e.g. yes or no; low, medium or high). These data were collated from field work carried out on farms, and, in combination with a likelihood and impact score, enabled five risk categories (very low, low, moderate, high and very high) to be assembled. These corresponded to a traffic light scheme of risk (Figure 3.5), which was included in a colour-coded map to facilitate discussions between the farmer and advisor and the development of a mitigation plan for the roadway network. Roadway sections in the high and very high risk categories were deemed worthy of management. This enabled roadway sections to be categorised in terms of their need, or lack thereof, for roadway run-off management. The results of the field work showed that 8.4% of the roadway sections examined were in risk categories that required management, which is comparable to the proportion deemed in need of management by the

Table 3.4. Examples of buffer width and corresponding connectivity

<3m width	3 m width	>3 m width
No buffer with connectivity between run-off and waters	Buffer that breaks connectivity to waters	Buffer with high disconnectivity to waters, e.g. a field or wide riparian zone
		

Table 3.5. Examples of barriers to management options

Sub-soil	Bedrock	Man-made
		
Watercourse on left with no stock proof barrier and exposed compacted sub-soil on right	Watercourse on left with stock proof barrier and bare rock on right	Wall on right. Other examples could be a building or a storage facility. It is especially relevant to note where waters are on the opposite side

Adapted from Fenton *et al.* (2021b); photo credits from the authors of the booklet: Fenton, O., Daly, K., Rice, P., Tuohy, P. and Murnane, J. Additional photos from Somers, C.

visual assessment approach. It is important to note that the model is capable of identifying only roadway sections where connectivity between roadway run-off and waters exists, and not the associated impact of such connectivity on that water body. Collecting the input data needed to ascertain a risk category for a given roadway section is time consuming. The model is for dairy farms but is adaptable to other farm types. A simplified version of the model that could be automated should be developed for use on larger scales, and the use of proxy variables supported by existing remote-sensing layers could be used to develop the continuous and categorical variables needed, e.g. the use of high-resolution digital elevation

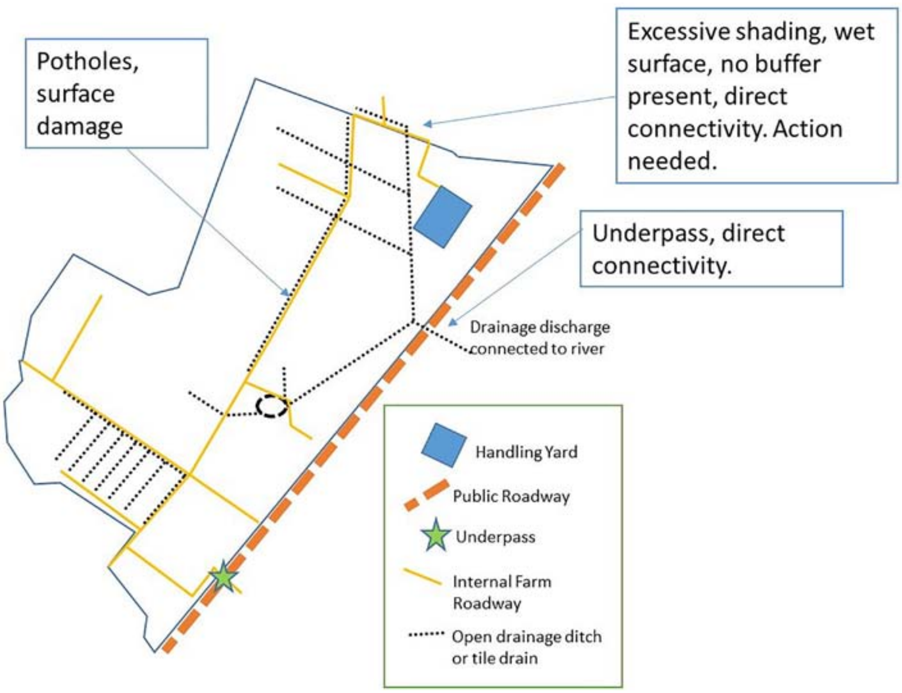

Figure 3.4. Example of a map indicating features facilitating and barriers to effective roadway run-off management.

Equal Risk Score Ranges	Risk Classification	Decision on Mitigation
110-134	Very low	No
135-158	Low	No
159-182	Moderate	No
183-206	High	Yes
207-230	Very high	Yes

Figure 3.5. An example showing the risk classification, decisions on the need for mitigation and an output map for a given farm roadway section developed within the project. Adapted from Rice *et al*. (2022); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

models, provided by the roll-out of national light detection and ranging (LiDAR) systems, could provide roadway dimensional parameters. Such improvements would enable the identification of farm internal roadway sections with connectivity to water problems at the landscape level. An application of this would be as a mapping layer for use by LAWPRO and ASSAP within priority areas for action with identified water quality issues.

4 Review of Options for Roadway Run-off Management

Because roadway run-off is probably being diverted and discharged from existing farm roadway networks for maintenance purposes, the pollution starting position of such roadway networks is not neutral. Agricultural landscapes today are designed to speed up water flow instead of retaining and slowing it. As a result of many roadway sections acting as a hard surface conduit, sediment and dissolved pollutants are transported from farms to waterways at a rapid rate. In the event of a rainfall event, critical (stored in the roadway media) or incidental (farmyard run-on and on-roadway faeces and urine) losses of nutrients can be incorporated into roadway run-off and may be discharged directly into a field, ditch (at breakthrough discharge points), public roadway or surface water body (delivery discharge point) (Thomas *et al*., 2016). However, if managed correctly, roadways can also serve as contaminant-retention features.

The management of run-off on roadways can include measures such as (i) flow attenuation through diversion or (ii) chemical amendments to the roadway surfaces (e.g. through the use of alum, ferric chloride or polyaluminium chloride) to flocculate nutrients from suspension and bind them to roadway sediments. The degree of flow attenuation can be reduced by introducing diversion structures such as grade breaks or channels at regular intervals on sloped roads. Crossfall manipulation of the roadway is another diversion technique (LEAF, 2010), although diversion along a roadway to a ditch or direct discharge into a field would be easier at some locations than others. For example, diversion of run-off may be prohibitive in locations where ponding may occur because of the soil type, or near watercourses, where diverting discharge away from such features would be difficult. In Ireland, diverting roadway run-off to a field or a ditch (not applicable under the current regulations) slows water movement from land to surface waters during periods of peak rainfall. Depending on the soil or sediment conditions at the discharge point, this phenomenon will occur to varying degrees. Flow can also be slowed through mechanical means, such as sub-soiling in fields or installing weirs or gates in ditches, particularly where soil infiltration rates are inadequate for preventing diverted run-off from ponding or reaching a watercourse. In some tillage scenarios, water retention and attenuation of nutrients in the roadway run-off may be facilitated by using ponded areas as sinks while continuing to break connectivity (Thomas *et al*., 2016). Such ponded areas may be in the form of vegetated scrape bunds (LEAF, 2010), soakages (DAFM, 2019) or vegetated areas. The use of engineered treatment systems to intercept diverted roadway run-off at or near surface run-off pathways is incentivised and in place in many landscapes (e.g. in forestry (Akbarimehr and Naghdi, 2012)). For example, in-ditch woodchip biological denitrifying bioreactors have been reported to treat approximately 20% of available N during peak flow conditions through the conversion of nitrate (NO_3^-) to di-nitrogen (N_2) gas. Other examples include permeable P-sorbing media beds, which have been reported to treat approximately 20–30% of the DRP load in ditch networks (Penn *et al*., 2007).

4.1 Existing On-roadway Management Options

In view of the potential of farm roadways to increase their hydrological connectivity with waters (Shore *et al*., 2013; Thomas *et al*., 2016), their design should include measures to retain pollutant loads using controlled discharge points for off-road treatment. The first step in such off-road treatment is the separation of nutrient-enriched sediment from liquid run-off (LEAF, 2010). This can be accomplished by attenuating flow during peak rainfall periods, which mutes run-off and therefore decreases the load transfer of nutrients and sediment (Haygarth *et al*., 2005). A relatively small number of on-roadway management options have been described in the literature (e.g. Scheetz and Bloser, 2009; STTI, 2018). Most of these relate to modifying road surfaces, whether they are new or existing. The chemical amendment of roadway surfaces (which is now being promoted to reduce emissions related to housing) has received attention in New Zealand, and the ROADRUNNER project involved a sensitivity analysis of how much attenuation would result from such applications (McDowell *et al*., 2020). Such tests have not been carried out in an Irish context and would involve the amendment of roadway materials with metal salts, e.g. polyaluminium chloride designed to trap P *in situ*. In the New Zealand study, the total P (92%), SS (98%) and *E. coli* (76%) loads from the amended surfaces were lower than from the control surfaces over the monitoring period (McDowell *et al*., 2020). However, an uncertainty analysis conducted as part of the ROADRUNNER project showed that the amount of dung P deposited on the roadway (based on the number of cows, P content of dung and number of deposits likely on roadways) could be 10-fold greater than those found by McDowell *et al*. (2020).

4.2 Roadway Surface Modifications or Amendment

A key objective of roadway surface modifications is to direct roadway run-off to discharge points that are isolated from watercourses and where flow can be attenuated, ideally in an adjacent field, prior to off-road treatment. While many of these modifications are relatively cheap and easy to implement, their effectiveness is dependent on the selection of an appropriate option for any given situation.

Modifications to the surface profile of roadways may entail constructing a single camber away from watercourses so that run-off is directed to adjacent fields and attenuated naturally by the soil. In cases where roadways are located some distance away from watercourses, the use of a double camber may be suitable, that is a continuous cross slope that runs from the roadway centreline, on both sides of the centreline, to the edge, to facilitate attenuation by fields on both sides of the roadway (Scheetz and Bloser, 2009). The main factors that influence the depth of water retained by roadway surfaces are the length and slope of run-off flow paths, the texture depth of the roadway and rainfall intensity (Galloway *et al*., 1971). Run-off flow paths are influenced by both cross-sectional and longitudinal gradients. Where a roadway has a relatively low longitudinal gradient (i.e. the road is relatively flat), the flow path is mainly influenced by the slope of the crossfall. On the other hand, where a roadway has a steep longitudinal gradient, high velocity flows or flow channelling may occur, leading to an increased risk of surface erosion and nutrient transport to downstream discharge points. Roadway surfaces can also be at lower levels than the surrounding ground, leading to inflows from adjacent fields. In these cases, it may be necessary to raise the roadway profile to reduce or eliminate these inflows (Sheetz and Bloser, 2009). When raising the road profile, it may be necessary to construct a “French mattress” or underdrain to enable hydraulic connectivity between both sides of the roadway (Penn State Center for Dirt and Gravel Roads Studies, 2019), so that the roadway does not cause a build-up of water on either side and act as a barrier to the natural movement of water. Wemple and Jones (2003) reported that roadway sections in a steep forested catchment altered the magnitude and timing of the catchment hydrography, mainly during large rainfall events where flows were diverted more quickly to drains. In a similar study, which assessed the hydrological connectivity between NO_3^- and P to streams, the authors established that the timing and number of rainfall events and antecedent ground conditions significantly influenced run-off and mobilised N and P fluxes (Outram *et al*., 2016). A simple and effective roadway management option that would allow surface water to drain into adjacent fields is the removal of sections of roadside berms; however, in doing this, care must be taken not to weaken the structure and integrity of the road.

On-roadway surface run-off diversions generally comprise physical structures or barriers designed to intercept surface water and direct it to designated outlets. This is illustrated by a grade break, which comprises a localised elevated ramp on the road and creates a reverse gradient that directs surface water to a designated outlet. The spacing of grade breaks depends on the number of available outlets for run-off and the roadway longitudinal slope; however, their effectiveness on roadways with steep slopes (i.e. $>10\%$) is reduced (Penn State Center for Dirt and Gravel Roads Studies, 2019). The use of old mine conveyor belts (Penn State Center for Dirt and Gravel Roads Studies, 2019) embedded at an angle into roadways to divert longitudinal flow has also been trialled in the USA as an alternative to grade breaks (Scheetz and Bloser, 2009). However, while these conveyor belts are reported to be effective for water diversion and flexible enough for the movement of farm vehicles, there is a lack of information on their impact on the movement of farm animals.

Open-channel drains across farm roadways have also been proposed as an effective method of intercepting roadway run-off and are also visible and accessible, meaning that they can be cleared of trapped solids if necessary. However, these open-channel drains could be an obstruction and there is a risk of farm animals accidentally stepping into them, meaning that they may be a suitable option for roads used only for machinery rather than for farm animals (Fenton *et al*., 2021a). The depth and spacing of open-channel drains are dependent on the surface run-off volumes that must be intercepted (STT1, 2018); however, a practical drawback of their use is that the channels might fill up with loose material, which would reduce their capacity to intercept roadway run-off.

In cases where the roadway run-off volume is high, the use of overflow structures, including infiltration areas, swales and buffer areas such as scrape bunds (LEAF, 2010), to attenuate flows may be considered. This involves simply restricting or partially restricting downstream flow and redirecting it to the overflow structures. In Cambridgeshire, UK, a scrape bund was reported to be effective at retaining roadway run-off and diffuse pollutants from a sloping field (LEAF, 2010), with 24 hours being suggested by the authors as the optimum retention time for accommodating a subsequent rainfall event. Liljaniemi *et al*. (2003) reported insignificant differences between upstream and downstream flows in concentrations of chemical oxygen demand, total P, orthophosphate (PO_4^+), total N, ammonium (NH_4^+), nitrite (NO_2^-), NO_3^-, iron (Fe) and aluminium (Al) in an evaluation of overflow areas constructed to attenuate diffuse pollution from forest drains. The authors also suggested that to control diffuse pollution, wider buffers with more extensive overland flow areas would be required.

4.3 Roadway Rerouting

Where soil at field gates on roadways is a direct source of pollution because of compaction and poaching, the gate may need to be relocated and the roadway rerouted to where soil disturbance is less likely, or allowance should be made for multiple access points, to decrease the level of traffic at any one location. It may also be necessary to include an attenuation area or run-off trap to retain sediment and roadway run-off, particularly where the soil may have poor attenuation and limited capacity to treat roadway run-off and recycle nutrients.

4.4 Existing Off-roadway Management Options

4.4.1 Adjacent fields

Fields adjacent to farm roadways are some of the most effective and obvious resources for roadway run-off treatment, and they also provide indirect diffuse pathways to watercourses. Frequently, minor berms can be formed along the boundary between the roadway and the field due to cow movement and so field boundaries that are closest to roadways should be adapted to facilitate roadway run-off entry into the field. The nature and drainage properties of the soil determine the fate of roadway run-off entering the field, and these can be determined from knowledge of the infiltration rate of water through the soil surface down into the soil profile and quantifying the hydrological response of the soil to precipitation. Infiltration rates are directly dependent on antecedent soil moisture and rainfall amounts. Physical properties such as soil/sub-soil thickness and permeability are important site-specific factors, and it is also important to consider the run-off to infiltration ratio (Misstear *et al*., 2009). A recharge coefficient (30–90%) is multiplied by the total available water to calculate the recharge volume (Fitzsimons and Misstear, 2006). More heavily textured soils with a low recharge coefficient and shallow water table are more prone to ponding than lightly textured soils. Roadway run-off infiltration rates may also be impeded by man-made landscape features in some soils (e.g. walls), and this may result in the formation of temporary and localised settlement ponds that need to be fenced and managed to periodically remove sediment. It has been recognised that these features have a natural seepage and denitrification capacity (Chibuike *et al*., 2019); however, where temporary settlement ponds need to be drained, one option might be to pipe water to a “dry closed drain”. This arrangement assumes no connectivity to a receiving watercourse and that infiltration within the “dry drain” attenuates nutrients (DAFM, 2019).

It is important to have knowledge of recharge volumes to understand nutrient transport. In terms of P in a well-drained soil (i.e. with a high recharge coefficient) for example, during the early stages of a rainfall event shallow macropore networks connect the flow pathways, and sub-surface P concentrations typically mirror those of surface run-off, while matrix flow dominates once saturation occurs. Matrix flow induces slower transport in more heavily textured soils, while, in the deeper soil profile, P concentrations are influenced by bulk soil P concentrations. Deeper soils have lower concentrations of available soil P than surface soils, particularly where organic or chemical fertilisers are applied. Higher infiltration rates and reduced contact time can result in less desorption and mobilisation by overland flow along the surface of fields with free-draining soils. A high rate of rainfall and high initial moisture content can produce large overland flow volumes, which are largely driven by hydrological loads (Kurz *et al*., 2005). It is very important to take into account infiltration rates across soil types when developing a multi-criteria P risk assessment scheme. It is also possible for external factors such as compaction, which decreases porosity by increasing soil bulk density, to affect the recharge coefficient. Several soil properties and processes, including saturated and unsaturated hydraulic conductivity, water retention, plant growth, soil workability and chemical processes, are affected by changes in bulk density. The formation of compacted soil horizons may result from poorly timed agricultural practices, such as high stocking rates and the use of farm machinery in adverse conditions (Creamer and O'Sullivan, 2018).

In addition to the physical qualities of soil influencing hydrological pathways for nutrients, chemical processes in soil result in the release of P and N from the soil matrix. As well as water purification, soils also have many primary productivity (food, fuel and fibre) functions, recycle nutrients, provide natural habitats and sequester carbon (Coyle *et al*., 2016). Each of these functions depends largely on local soil properties and land use management, including soil drainage (Schulte *et al*., 2014), and where roadway run-off discharges into a field, purification is an important soil function (Wall *et al*., 2017).

Physico-chemically adsorbed nutrients within soil can desorb into solution, and this, along with the physical detachment of soil particles/sediments, can result in soluble and particulate losses of P (Sandström *et al*., 2020). Fenton *et al*. (2009) proposed a model that correlated NO_3^- concentration and denitrification rates with soil and sub-soil permeability. Therefore, more heavily textured soils offer more protection in terms of water purification; however, some studies have reported NO_3^- conversion to ammonium or gaseous phases in both mineral and organic soils (Clagnan *et al*., 2019). Soils with high concentrations of legacy P or high soil test P (i.e. > 8 mg/L Morgan's P) present a higher risk of P loss into a connected hydrological pathway than soils that are low in P (Kurz *et al*., 2005). As well as soil acidity (i.e. pH), organic matter content, clay mineralogy and the presence of amorphous aluminium, iron and calcium, other factors that affect these processes are those that affect the chemical composition of soil (Daly *et al*., 2015). These factors influence the rates at which P can be removed from the soil matrix into solution. For example, soils with a low pH will retain nutrients in an insoluble form, while neutral soils provide the right conditions for P solubilisation where desorption can occur. Soils that are acidic typically contain a high percentage of soil Al, and soils with a high Al to P ratio can fix P into forms that are insoluble (Daly *et al*., 2015). In the same way, clay minerals and amorphous forms of Ca may react with P in high concentrations, resulting in the formation of largely insoluble Ca–P precipitates (McLaughlin *et al*., 2011; McLaren *et al*., 2014; Daly *et al*., 2015). To minimise diffuse P losses, it would therefore be advantageous to divert roadway run-off into fields with a high propensity to fix P or generate insoluble P precipitate. While most of the soil P reactions occur on the surfaces of clay minerals without interference from other soil constituents, the presence of large amounts of organic matter (> 20% by loss on ignition) may occlude these reaction (sorption/desorption) sites, leading to high concentrations of soluble soil P that cannot be physico-chemically adsorbed to the soil matrix (Daly *et al*., 2001; González Jiménez *et al*., 2018; González Jiménez *et al*., 2019). Consequently, hydrological pathways via soils with high organic matter content are likely to have high P concentrations in soil solution, with limited capacity to adsorb additional P originating from roadway run-off. Soils with high organic matter content are therefore likely to exacerbate diffuse P losses, and so the diversion of roadway run-off into fields with high organic matter soils is unlikely to assimilate any P in roadway run-off. The diversion of run-off into tillage fields or fields with poor grass cover could also increase the risk of particulate P losses to water bodies, as the physical detachment of soil particles into overland flow contributes to particulate P losses from agriculture (Roberts *et al*., 2017).

4.4.2 Open-drainage ditch

Roadway run-off can also be diverted via discharge points to drainage ditches in conjunction with or as an alternative to discharging into fields. It is important, however, to distinguish between drainage ditches and first- or second-order small streams, into which roadway run-off should never be directly discharged. First- or second-order small streams may arise from rainfall events or seepage through sub-soils, soils, aquifers and springs or lake outlets and are typically defined by a channel width of < 3 m (Biggs *et al*., 2017). First- or second-order small streams may extend a short distance from the source and may be temporary or perennial and positioned within the headwater of a river. Early work on drainage ditches showed that these networks had the potential to retain sediment, nutrients and *E. coli* (Nguyen and Sukias, 2002; Nguyen *et al*., 2002). In a review of the design and maintenance of ditches with the aim of optimising the mitigation potential of these often extensive networks, Dollinger *et al*. (2015) noted the following important overarching points when considering ditch networks as suitable places for roadway run-off discharge. First, individual ditch sections or "reaches" that make up a ditch network can be defined according to their landscape position and chemistry and so are not homogeneous. On this basis, five ditch categories have been defined: farmyard connection, outlet, out-flow, secondary and disconnected (Moloney *et al*., 2020). In addition, ditch categories are ranked according to how efficiently they act as connectors between point and diffuse sources of agricultural P and adjacent surface waters. The key to water quality improvement using a ditch classification system as proposed by Moloney *et al*. (2020) is breaking the pathway and implementing the right measure in the right place at the right time. Such an approach could be useful in informing decisions regarding the selection and implementation of in-ditch mitigation measures on farms. As an example, the mitigation potential of a particular measure implemented in an outlet ditch connecting a large land area to a stream is likely to differ significantly from mitigation potential of the same measure implemented in a disconnected ditch. Typically, ditch maintenance is based on maximising flow to the outlet by dredging or deepening the ditch, and this may have positive and negative effects on nutrient attenuation. As an example, ditch networks with low slopes have been found to have the potential to retain fine sediment (see, for example, Shore *et al*., 2015a), while in some cases ditches with exposed sub-soil and sediment were shown to immobilise nutrients in drainage waters (Shore *et al*., 2015b). It was also found that attenuation may not always occur and, where it does, it can change over time, as P inputs can affect the source-sink P dynamics of sediment along an agricultural ditch network (Ezzati *et al*., 2020). Peak flows can be muted by the provision of additional storage, and this may also mitigate flooding and dilute nutrients. While in-ditch vegetation can take up nutrients from diverted roadway run-off, the attenuation capacity across nutrient species is not uniform, e.g. in vegetated versus non-vegetated ditches of similar landform and size. In a study that examined the nutrient mitigation capacity of vegetated and non-vegetated agricultural drainage ditches of similar size and landform in the Mississippi Delta, Moore *et al*. (2010) found no significant differences in mitigation of NH_4, NO_3^- or dissolved inorganic P but reported significant differences in mitigation of total inorganic P loads. Other studies have reported similar or contrasting results (Kröger *et al*., 2007, 2008; Smith and Papas, 2007).

A key objective of water retention features is to slow down or attenuate water flow; this increases the residence time, which increases the opportunities for biogeochemical N transformations to occur. A US study that investigated low-grade in-ditch weir installations and measured associated N loads found that attenuated NO_3^- loads were reduced by 79% ± 7.5% with weir installations and by 73% ± 9% without weir installations (Kroger *et al*., 2012). This reduction was reported to be as high as 92% in a 6-year study conducted in Italy (Tolomio and Borin, 2018). Constructed wetlands (Badlec, 2016), controlled drainage and in-ditch techniques (Woli *et al*., 2010), and buffers (Braskerud, 2002) are some of the most commonly used engineered measures. Ditches provide an ideal location for engineered structures, such as ditch filters or in-ditch cartridges, to hold nutrients in drainage waters. There are also many methods designed to trap sediment in ditches or fields;

however, permanent options need to be maintained and temporary options (e.g. silt curtain) may need to be replaced. Options to build in extra capacity (e.g. reshaping the ditch to a trapezoidal profile and allowing it to become vegetated) and attenuate water (e.g. control weirs) also exist, but, in this report, it is the systems used for the treatment of nutrients in drainage waters that are reviewed. The use of different adsorbents (Ezzati *et al*., 2019) and in-ditch structures filled with filtration materials have gained popularity as an easily installed, cost-effective, low-maintenance technology (Bibi *et al*., 2015). The performance of in-ditch structures has, to date, mainly been evaluated in terms of their ability to treat single contaminants, predominantly DRP (Penn *et al*., 2007) and NO_3^- (Addy *et al*., 2016; Christianson and Schipper, 2016). Some recent studies have also examined combined treatment of P and N by combining individual nutrient removal technologies (Ibrahim *et al*., 2015) and ditches, as a receptor of roadway run-off can treat these nutrients and sediment through either natural or enhanced attenuation.

Reactive filters are used as engineered options to remove a percentage of the nutrient load by directly targeting discharging ditch nutrients. In the case of P treatment, the filter contains P-sorbing material, which can then be extracted once it becomes saturated (Penn and Bowen, 2017). The saturation of the filter media will depend on its characteristics (Ezzati *et al*., 2019) and, to enable good levels of removal, in-ditch systems should allow water flow through the structure, set at a gradient to an outlet and with upstream DRP concentrations in the region of 0.2–0.3 mg/L (Penn and Bowen, 2017). Given that the highest concentrations of DRP are likely to occur downstream of roadway discharge points, reactive filters should be located at these points for optimum treatment. Ideally, seasonal filtered grab samples are taken along a ditch to establish the DRP concentrations; however, if these are not available, estimates may be established from relationships between water-extractable P and soil test P in adjoining fields. Engineered denitrifying bioreactors filled with carbon-sourced materials such as straw, woodchip, compost or corn cob have been successfully used to convert NO_3^- into N_2 gas within ditch systems. Research in this area is now focused on systems that do not result in pollution swapping but instead enable the treatment of nutrients (N and P) and sediments simultaneously (Fenton *et al*., 2016).

4.4.3 New options needing pilot-scale testing

New containment/mitigation measures for farm roadways should be explored and assessed before they are considered viable and effective options for farmers, and such measures should be suitable for retrofitting to existing farm roadways or installation in new farm roadway networks. The use of such interventions would be envisaged for only relatively few circumstances, that is, those where more simple interventions may not be possible because of site-specific restrictions (roadway configuration relative to watercourses, soil type, topography, etc.). Two possibilities are presented in this section.

The first is a roadway run-off containment measure in the form of a sedimentation/settlement tank. The key operating principle for this measure is that the roadway run-off would be routed through an underground tank similar to a conventional passive septic tank system (Fenton *et al*., 2021a). The tank would comprise two compartments: the first would operate as a sedimentation chamber, while the second would contain the supernatant liquid, which would discharge via a high-level outlet pipe or opening. The roadway draining to this tank could be constructed with either a single or a double cross-sectional camber to route the flow into permanent channels running along its length. “Grade breaks” may also be placed at intervals along the roadway, typically where longitudinal gradients are > 5–10%, to reduce the occurrence of stream flow and associated surface erosion along the roadway length. The outlet channel should divert roadway run-off to the sedimentation tank and an “overflow” to the field may be included in the tank storage system, which would also act as a visual aid for indicating when the tank is full. The tank could be located parallel to the roadway to facilitate the emptying and transport of slurry for spreading on suitable lands by farm machinery. The size of the sedimentation tank would be determined by considering factors such as the length of roadway being served, the proximity to farmyards or cattle-holding areas, the extent of the anticipated pollutant load, and the location of junctions, drinking troughs and field gates (White *et al*., 2001; Oudshoorn *et al*., 2008). The clarified liquid outflow from the sedimentation tank could be discharged into nearby fields or dry ditches, or to a swale downstream of the tank, all with sufficient nutrient-attenuation capacity. This type of system is perceived to be low maintenance and to contain valuable slurry solids within a fixed chamber of the tank that can be easily emptied as needed, despite an initial outlay.

The second possibility for a new containment/mitigation measure is a bioretention area. This would operate in a manner similar to that of a sedimentation tank, except that swales or bermed holding areas to attenuate the outflow and facilitate sedimentation would replace the tank. Although relatively inexpensive to install, this system would require a large amount of land and may require more maintenance than a sedimentation tank system due to sediment build-up. It may also be more difficult to clean using farm equipment such as vacuum slurry tankers. In addition, the use of retention areas may result in nutrient leaching into groundwater through soil/sub-soil (Murnane *et al*., 2018) and therefore would require the inclusion of impermeable barriers in their construction. The retention areas, however, would improve quality and promote biodiversity in a similar manner to that of integrated constructed wetlands (Woods Ballard *et al*., 2015).

4.4.4 Local costs and considerations

The management of roadway run-off must be viewed as a long-term objective requiring a greater level of total farm enterprise management, and there are many varied roadway run-off management options available, which provides flexibility to landowners. The cost of management options is one of the many factors influencing landowners' willingness to adopt best management practices or voluntary measures (Bragina *et al*., 2019). A conceptual framework developed by Liu *et al*. (2018) highlights the importance of considering scale, tailoring information and incentives, and considering the farm profits expected in decisions about adopting best management practices. Therefore, fair and equitable financial incentive schemes may be a viable option for managing these important pollutant loss pathways effectively.

In this report, roadway run-off management options were divided into on- and off-roadway management options. Their associated costs may vary considerably because of many variables (e.g. materials, labour costs and construction methods). In addition, the levels of maintenance and care required after installation may vary and this may be a deterrent to adoption (Welch *et al*., 2001; Tosakana *et al*., 2010). Many projects and databases have been developed with best management practices to minimise nutrient losses to waterways, e.g. the EU COST Action 869 Mitigation Options for Nutrient Reduction in Surface and Groundwaters and SERA17 (Innovative Solutions to Minimise Phosphorus from Agriculture). While these projects and databases are not directly related to roadway run-off, they cover options that in some cases deal with run-off from agricultural landscapes.

The European Union Water Framework Directive (Directive 2000/60/EC) requires all Member States to protect and improve the quality of all waters. Member States are required to prevent the deterioration of waters, which must achieve at least good status. The treatment of roadway run-off before it is discharged into a stream may require a licence under the Water Pollution Act in Ireland. At present, for example, discharges from integrated constructed wetlands treating dairy-soiled water on Irish farms to a surface water body require a discharge licence. In Ireland, the onus to demonstrate that any discharge into a surface water body is not causing water pollution is on the licence holder. This would require testing water at an accredited laboratory with resultant additional cost and ongoing inspection requirements, which may not be palatable to some landowners. In addition, recent water protection measures within the nitrates action plan regulations include the prevention of direct run-off from farm roadways to waters in Ireland (European Union (Good Agricultural Practice for Protection of Waters) Regulations 2017). This policy instrument came into effect on 1 January 2021 and the definition of "waters" used in these regulations is as follows:

> a) any (or any part of any) river, stream, lake, canal, reservoir, aquifer, pond, watercourse, or other inland waters, whether natural or artificial, b) any tidal waters, and c) where the context permits, any beach, river bank and salt marsh or other area which is contiguous to anything mentioned in paragraph (a) or (b), and the channel or bed of anything mentioned in paragraph (a) which is for the time being dry, but does not include a sewer (Government of Ireland, 2017).

Therefore, in terms of this report, options for roadway run-off may or may not be applicable under these regulations. Table 4.1 summarises the mitigation measures applicable to roadway run-off; however, it is

Table 4.1. Mitigation options with indicative costs, descriptions and references

Roadway run-off management option	Cost	Description	References
On-roadway			
Surface profile modifications	Low for new roads; medium for existing roads[a]	Create single or double camber to direct run-off to designated outlets	Scheetz and Bloser (2009) Penn State Center for Dirt and Gravel Roads Studies (2019) – French mattress
Surface diversions	Low	Grade break diversions – create elongated hump on road to direct road run-off to designated outlets	Penn State Center for Dirt and Gravel Roads Studies, 2019 – grade break
	Low for new roads; medium for existing roads (dependent on local availability of rubber belts)	Conveyor belt diversion – intermittent placement of rubber belts (old mine conveyor belts) protruding from road surface to divert surface flow to designated outlets	Penn State Center for Dirt and Gravel Roads Studies (2019) – grade break
	Low for shallow channels, increasing to medium for deeper channels on roads not suitable for use by farm animals	Open-channel drains to intercept and redirect flows to designated outlets	STT1 (2018)
Overflow structures	Low	Swales – create localised depressions to attenuate roadway run-off	LEAF (2010)
	Low (€80)[b]	In-ditch grassland sediment trap	LEAF (2010)
Buffer areas	Low (€220)	Scrape bunds	LEAF (2010). See also recent research on grass buffer widths by Praat *et al.* (2020)
Chemical amendments	Medium/high[c]	Application of coalescing chemicals (e.g. alum, polyaluminium chloride and ferric chloride) to farm roads to flocculate and retain nutrients on the surface	Brennan *et al.* (2011); O'Flynn *et al.* (2012); Murnane *et al.* (2018)
Discharge points	Low	Ongoing maintenance of interface between field and roadway	Teagasc (2017)
Off-roadway*			
In-ditch retention barriers	€55–120	Allow soil particles to settle and hold back water within the drainage network to reduce peak flows in the main watercourse. Need maintenance	LEAF (2010)
In-ditch wetland	€900–1000	May need discharge licence, which increases cost Slow the flow of, and store and filter nutrients and sediment run-off	LEAF (2010)
In-ditch woodchip bioreactor	<€420	May need discharge licence, which increases cost	Chase *et al.* (2019)

Table 4.1. Continued

Roadway run-off management option	Cost	Description	References
In-ditch DRP/NH_4^+ structure	€850	May need discharge licence, which increases cost. According to studies conducted in the USA, Al-coated steel slag filters for the treatment of surface run-off cost approximately $300 to $400 per ton of slag (personal communication, G. Feyereisen, USDA, January 2022)	Penn and Bowen (2017); Penn *et al.* (2017)

[a]Costs may increase to high if the road profile needs to be raised and underdrain (French mattress) provided.

[b]Maintenance costs of emptying the sediment from the trap not included.

[c]Costs will vary in accordance with road characteristics such as slope, distance from farmyard and the extent and frequency of road use by cattle.

worth noting that none of the measures that promote connectivity with waters, e.g. that permit roadway run-off to enter an open-drainage ditch, is applicable under current Irish regulations.

Now that these regulations are in effect, the measures that are most likely to be effective are those that break the connection between the source/pathway and the receptor (stream). This process begins with determining the risk of pollution of surface waters from roadway run-off, a process that must be carried out methodically, perhaps using a risk assessment tool that ranks a wide variety of parameters, such as farm road type, usage and characteristics; soil type and its assimilative capacity; surface water proximity; and the frequency and nature of precipitation. Within that context, it is suggested that a targeted approach be used and a hierarchical suite of potential options for roadway run-off management be considered. If such an approach is adopted, it is likely that the use of adjacent fields will be the most commonly utilised of these management options in Ireland, as this does not incur excessive costs in terms of attenuating flows and the assimilation of nutrients, such as N, P, SS, *E. coli* and emerging contaminants. Two basic measures that should prevent losses of particulate nutrients are the creation of a buffer zone (typically ≥3 m) between farm roadways and surface waters and the re-cambering of the farm roadway to direct run-off from waters. However, for it to remain effective, it is important that the buffer zone is maintained by stock-proof fencing. The removal of obstructions to animal movement along the farm roadway (e.g. sharp bends, drinking troughs, inadequate width and inappropriately located gateways), to reduce the time spent by animals travelling the road and hence reduce the source pollution load, is another relatively straightforward measure that would be beneficial. In addition, the inclusion of grade breaks along steep lengths of the farm roadways to direct flows to diffuse sections of adjacent fields may also enhance protection, as this would mobilise a greater natural treatment area (i.e. soil) than would be mobilised if all roadway run-off were to be discharged at a single location off the farm roadway. There may, however, be cases where these relatively straightforward measures may not be feasible (e.g. if soil capacity is insufficient to attenuate flows or loads), or where the measures are insufficient to reduce the source pollution load and break the connectivity. In these situations, more complex and expensive management options may be required, including on-roadway measures (e.g. earth bunding, buffer zones, overflow structures and the application of chemical amendments) and off-roadway measures (e.g. engineered attenuation measures or in-ditch treatments). In extreme cases, it may be necessary to relocate the roadway. It is likely, however, that, in Ireland, visible low-maintenance measures will be favoured initially by farmers and the regulation authorities. However, each site is unique and it is important to recognise that the generalisation of roadway run-off management options to all farms would be misguided and instead a strategy of “right place, right management option” should be followed.

5 Recommendations: Future Research Needs

Options for field testing mitigation measures and their efficacy and impact at the catchment scale should be investigated. There is surprisingly little literature relating to the testing and costing of on- or off-roadway management options, although roadway run-off is widely acknowledged as a pollutant source. Inferences can, however, be made from examples of other land uses, such as forested areas, around the world (e.g. Grayson *et al*., 1993; Lane and Sheridan, 2002; Hill and Pickering, 2009; Laurance *et al*., 2009).

Future research in Ireland should focus on field work and the collection of high-resolution data. Pilot-scale set-ups could intercept roadway run-off on a flow-weighted basis, thereby providing spatial and temporal characterisation data. As farms vary considerably in their geographical location (soil type and rainfall distribution), stocking rate and infrastructure, datasets should be built that can compare and contrast systems. For example, for dairy management systems, the decisions made may be quite different in the future, as many will transition to an automated system or change traditional routines, i.e. once/twice/thrice a day milking. Such changes to dairy management systems would have different knock-on effects regarding animal access to roadways, time spent on the roadway network, volume of traffic and associated defecation. A robotic milking approach enables a “semi-forced” or “free cow traffic” system, which has implications for farm roadway defecation. Furthermore, for many reasons, livestock farming systems are continually changing in terms of intensity and the expansion/contraction of animal numbers.

There is also a need to consider roadway run-off in the context of a changing climate. Wetting and drying patterns on farms are changing and this affects the soil’s capacity to store, transit and attenuate pollutants. Such changes will also have an effect on the spatial and temporal mobilisation and connectivity of roadway run-off. In times of flooding and drought, farm roadways may be negatively affected in terms of quality, and on-roadway/off-roadway management options designed for normal conditions are likely to suffer functional failure when encountering extremes (e.g. events occurring once every 100 or more years).

The development of a farm roadway classification system that can be used to divide farm roadway networks into prescribed sections with an associated risk in terms of nutrient, sediment and *E. coli* losses in roadway run-off is needed. As an added layer, a visual tool to describe the quality of individual roadway sections should also be developed, as this could be used as a parsimonious tool by landowners or advisors for quickly identifying roadway sections in need of intervention. These sections could then be matched with the management options proposed herein. As lameness in cows is a significant animal welfare concern, research on hoof health, with an emphasis on the role of farm roadways in terms of both run-off and surface quality, is important.

5.1 Take-homes for Different Stakeholders

Farmers and advisors: roadway run-off contains high concentrations of nutrients and should be diverted safely away from waters. Areas of the roadway network that need management in terms of roadway run-off can be identified using visual assessment and this must be conducted for all farms to guide future management. On the farms investigated, an average of four distinct areas for roadway run-off management were identified. Those within 100 m of the farmyard and especially those connected to an open-drainage ditch should take priority in terms of implementing mitigation measures, as they will most likely be sources of relatively high levels of nutrients.

Research: areas of roadway networks on farms that need management in terms of roadway run-off can be identified using the semi-quantitative risk assessment model. This needs to be automated and scaled up. This model could then be used as a desk-based tool to guide advisors before farm visits and discussions relating to the visual assessment booklet (Fenton *et al*., 2021b).

Policy: run-off originating from farmyards that is connected to open-drainage ditches should be disconnected from internal farm roadways. Exceptions should be considered for the diversion of roadway run-off into open-drainage ditches where there are appropriate in-ditch mitigation measures that slow the flow of nutrients and sediment and hold them in place before they reach a water body presents a solution to areas where no diversion to a natural buffer exists.

The information obtained on completion of the *The Farm Roadway Visual Assessment Booklet* (Fenton *et al*., 2021b) by a farm could form the basis of a roadway run-off management plan and be used as part of its inspection process.

References

Adams, R., Arafat, Y., Eate, V., Grace, M.R., Saffarpour, S., Weatherley, A.J. and Western, A.W. (2014). A catchment study of sources and sinks of nutrients and sediments in south-east Australia. *Journal of Hydrology* 515, 166–179.

Addy, K., Gold, A.J., Christianson, L.E., David, M.B., Schipper, L.A. and Ratigan, N.A. (2016). Denitrifying bioreactors for nitrate removal: a meta-analysis. *Journal of Environmental Quality* 45, 873–881.

Akbarimehr, M. and Naghdi, R. (2012). Reduction of erosion from forest roads and skid trails by management practices. *Journal of Forest Science* 58, 165–169.

Bibi, S., Farooqi, A., Hussain, K. and Haider, N. (2015). Evaluation of industrial based adsorbents for simultaneous removal of arsenic and fluoride from drinking water. *Journal of Cleaner Production* 87, 882–896.

Biggs, J., von Fumetti, S. and Kelly-Quinn, M. (2017). The importance of small waterbodies for biodiversity and ecosystem services: implications for policymakers. *Hydrobiologia* 793, 3–39.

Bragina, L., Micha, E., Roberts, W.M., O'Connell, K., O'Donoghue, C., Ryan, M. and Daly, K. (2019). Spatial and temporal variability in costs and effectiveness in phosphorus loss mitigation at farm scale: a scenario analysis. *Journal of Environmental Management* 245, 330–337.

Braskerud, B.C. (2002). Design considerations for increased sedimentation in small wetlands treating agricultural runoff. *Water Science & Technology* 45, 77–85. https://doi.org/10.2166/wst.2002.0209

Brennan, R.B., Fenton, O., Rodgers, M. and Healy, M.G. (2011). Evaluation of chemical amendments to control phosphorus losses from dairy slurry. *Soil Use and Management* 27, 238–246.

Buchanan, B.P., Archibald, J.A., Easton, Z.M., Shaw, S.B., Schneider, R.L. and Todd Walter, M. (2013). A phosphorus index that combines critical source areas and transport pathways using a travel time approach. *Journal of Hydrology* 486, 123–135.

Chase, E.H., Schneider, R.L., Baker, N.J. and Dunn, S.J. (2019). Retrofitting the rural roadside ditch network to treat nitrogen from agricultural runoff using woodchip bioreactors. Paper presented at the 12th International Conference on Low-volume Roads, 15–18 September 2019, Kalispell, MT. Transportation Research Circular, Drainage and Stream Crossings Section, pp. 320–324.

Chibuike, G., Burkitt, L., Bretherton, M., Camps-Arbestain, M., Singh, R., Bishop, P., Hedley, C. and Roudier, P. (2019). Dissolved organic carbon concentration and denitrification capacity of a hill country sub-catchment as affected by soil type and slope. *New Zealand Journal of Agricultural Research* 62, 354–368.

Christianson, L.E. and Schipper, L.A. (2016). Moving denitrifying bioreactors beyond proof of concept: introduction to the special section. *Journal of Environmental Quality* 45, 757–761.

Clagnan, E., Thornton, S.F., Rolfe, S.A., Wells, N.S., Knoeller, K., Murphy, J., Tuohy, P., Daly, K., Healy, M.G., Ezzati, G., von Chamier, J. and Fenton, O. (2019). An integrated assessment of nitrogen source, transformation and fate within an intensive dairy system to inform management change. *PLoS One* 14, e0219479.

Coyle, C., Creamer, R.E., Schulte, R.P.O., Sullivan, L.O. and Jordan, P. (2016). A functional land management conceptual framework under soil drainage and land use scenarios. *Environmental Science & Policy* 56, 39–48.

Creamer, R. and O'Sullivan, L. (2018). *The Soils of Ireland*. World Soils Book Series. Springer International Publishing AG, Cham. https://doi.org/10.1007/978-3-319-71189-8

DAFM (Department of Agriculture, Food and the Marine) (2019). Minimum specification for farm roadways, S199. DAFM, Dublin.

Daly, K., Jeffrey, D. and Tunney, H. (2001). The effect of soil type on phosphorus sorption capacity and desorption dynamics in Irish grassland soils. *Soil Use and Management* 17, 12–20.

Daly, K., Styles, D., Lalor, S. and Wall, D.P. (2015). Phosphorus sorption, supply potential and availability in soils with contrasting parent material and soil chemical properties. *European Journal of Soil Science* 66, 792–801.

Dollinger, J., Dagès, C., Bailly, J.-S., Lagacherie, P. and Voltz, M. (2015). Managing ditches for agroecological engineering of landscape. A review. *Agronomy for Sustainable Development* 35, 999–1020.

Easton, Z.M., Gerard-Marchant, P., Walter, M.T., Petrovic, A.M. and Steenhuis, T.S. (2007). Identifying dissolved phosphorus source areas and predicting transport from an urban watershed using distributed hydrologic modeling. *Water Resources Research* 43, W11414.

Easton, Z.M., Walter, M.T. and Steenhuis, T.S. (2008). Combined monitoring and modeling indicate the most effective agricultural best management practices. *Journal of Environmental Quality* 37, 1798–1809.

Endreny, T.A. and Wood, E F. (2003). Watershed weighting of export coefficients to map critical phosphorus loading areas. *Journal of the American Water Resources Association* 39, 165–181.

Ezzati, G., Healy, M.G., Christianson, L., Feyereisen, G.W., Thornton, S., Daly, K. and Fenton, O. (2019). Developing and validating a decision support tool for media selection to mitigate drainage waters. *Ecological Engineering*, X2.

Ezzati, G., Fenton, O., Healy, M.G., Christianson, L., Feyereisen, G., Thornton, S., Chen, Q., Fan, B., Ding, J. and Daly, K. (2020). Impact of P inputs on source-sink P dynamics of sediment along an agricultural ditch network. *Journal of Environmental Management* 257, 109988.

Fenton, O., Richards, K.G., Kirwan, L., Khalil, M.I. and Healy, M.G. (2009). Factors affecting nitrate distribution in shallow groundwater under a beef farm in South Eastern Ireland. *Journal of Environmental Management* 90, 3135–3146.

Fenton, O., Healy, M.G., Brennan, F.P., Thornton, S.F., Lanigan, G.J. and Ibrahim, T.G. (2016). Holistic evaluation of fieldscale denitrifying bioreactors as a basis to improve environmental sustainability. *Journal of Environmental Quality* 4, 788–795.

Fenton, O., Mellander, P-E., Daly, K., Wall, D.P., Jahangir, M.M.R., Jordan, P., Hennessey, D., Huebsch, M., Blum, P., Vero, V. and Richards, K.G. (2019). Integrated assessment of agricultural nutrient pressures and legacies in karst landscapes. *Agriculture Ecosystems Environment* 239, 246–256.

Fenton, O., Tuohy, P., Daly, K., Moloney, T., Rice, P. and Murnane, J.G. (2021a). A review of on-farm roadway runoff characterisation and potential management options for Ireland. *Water, Air, & Soil Pollution* 232, 89. https://doi.org/10.1007/s11270-021-05027-0

Fenton, O., Daly, K., Rice, P., Tuohy, P. and Murnane, J. (2021b). *The Farm Roadway Visual Assessment Booklet*. Teagasc, Carlow, Ireland. Available online: www.teagasc.ie/publications/2021/the-farm-roadway-visual-assessment-booklet.php (accessed 24 January 2024).

Fenton, O., Rice, P., Murnane, J.G., Tuohy, P. and Daly, K. (2022). Dairy farm roadway surface materials as a P-source within the nutrient transfer continuum framework. *Frontiers in Environmental Science* 10, 878166. https://doi.org/10.3389/fenvs.2022.878166

Fitzsimons, V.P. and Misstear, B.D.R. (2006). Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. *Hydrogeology Journal* 14, 548–561.

Galloway, B.M., Schiller, R.E. and Rose, J.G. (1971). *The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths*. Research Report 138-5. Texas Transport Institute, Texas A&M University, College Station, TX. Available online: https://static.tti.tamu.edu/tti.tamu.edu/documents/138-5.pdf (accessed 13 February 2020).

González Jiménez, J.L., Healy, M.G., Roberts, W.M. and Daly, K. (2018). Contrasting yield responses to phosphorus applications on mineral and organic soils from extensively managed grasslands: implications for P management in high ecological status catchments. *Journal of Plant Nutrition and Soil Science* 181(6), 861–869.

González Jiménez, J.L., Healy, M.G. and Daly, K. (2019). Effects of fertiliser on phosphorus pools in soils with contrasting organic matter content: a fractionation and path analysis study. *Geoderma* 338, 128–135.

Government of Ireland (2017). *European Union (Good Agricultural Practice for Protection of Waters) Regulations 2017*. S.I. No. 605/2017. Available online: https://www.irishstatutebook.ie/eli/2017/si/605/made/en/print

Grayson, R.B., Haydon, S.R., Jayasuriya, M.D.A. and Finlayson, B.L. (1993). Water quality in mountain ash forests – separating the impacts of roads from those of logging operations. *Journal of Hydrology* 150, 459–480.

Haygarth, P.M., Condron, L.M., Heathwaite, A.L., Turner, B.L. and Harris, G.P. (2005). The phosphorus transfer continuum: linking source to impact with an interdisciplinary and multi-scaled approach. *Science of the Total Environment* 344, 5–14.

Hill, W. and Pickering, C.M. (2009). *Evaluation of Impacts and Methods for the Assessment of Walking Tracks in Protected Areas*. Cooperative Research Centre for Sustainable Tourism, Gold Coast, Queensland.

Ibrahim, T.G., Goutelle, A., Healy, M.G., Brennan, R., Tuohy, P., Humphreys, J., Lanigan, G., Brechignac, J. and Fenton, O. (2015). Mixed agricultural pollutant mitigation using woodchip/pea gravel and woodchip/zeolite permeable reactive interceptors. *Water, Air, & Soil Pollution* 226, 1–11.

Kadlec, R.H. (2016). Large constructed wetlands for phosphorus control: a review. *Water* 8, 243. https://doi.org/10.3390/w8060243

Kröger, R., Holland, M.M., Moore, M.T. and Cooper, C.M. (2007). Hydrological variability and agricultural drainage ditch inorganic nitrogen reduction capacity. *Journal of Environmental Quality* 36, 1646–1652.

Kröger, R., Holland, M.M., Moore, M.T. and Cooper, C.M. (2008). Agricultural drainage ditches mitigate phosphorus loads as a function of hydrological variability. *Journal of Environmental Quality* 37, 107–113.

Kröger, R., Dunne, E.J., Noval, J., King, K.W., Mclellan, E., Smith, D.R., Strock, J., Boomer, K., Tomer, M.D. and Now, G.B. (2012). Downstream approaches to phosphorus management in agricultural landscapes: regional applicability and use. *Science of the Total Environment* 442, 263–274.

Kurz, I., Coxon, C.E., Tunney, H. and Ryan, D. (2005). Effects of grassland management practices and environmental conditions on nutrient concentrations in overland flow. *Journal of Hydrology* 304, 35–50.

Lane, P.N. and Sheridan, G.J. (2002). Impact of an unsealed forest road stream crossing: water quality and sediment sources. *Hydrological Processes* 16, 2599–2612.

Laurance, W.F., Goosem, M. and Laurance, S.G.W. (2009). Impacts of roads and linear clearings on tropical forests. *Trends in Ecology & Evolution* 24, 659–669.

LEAF (Linking Environment and Farming) (2010). *SUDS – Sustainable Drainage Systems to Explore the Effectiveness of Different Pathway Options in Slowing Down the Flow of Surface Run-Off and Trapping Sediment From Different Farm and Field Locations*. LEAF, Warwickshire, UK.

Liljaniemi, P., Vuori, K.-M., Tossavainen, T., Kotanen, J., Haapanen, M., Lepistö, A. and Kenttämies, K. (2003). Effectiveness of constructed overland flow areas in decreasing diffuse pollution from forest drainages. *Environmental Management* 32, 602–613.

Liu, T., Bruins, R.J. and Herberling, M.T. (2018). Factors influencing farmers' adoption of best management practices: a review and synthesis. *Sustainability* 10, 432.

Lucci, G.M., McDowell, R.W. and Condron, L.M. (2010). Potential phosphorus and sediment loads from sources within a dairy farmed catchment. *Soil Use and Management* 26, 44–52.

McDowell, R.W., Daly, K. and Fenton, O. (2020). Mitigation of phosphorus, sediment and *Escherichia coli* losses in runoff from a dairy farm roadway. *Irish Journal of Agricultural and Food Research* 59, 201–205. http://doi.org/10.15212/ijafr-2020-0117

McLaren, T., Guppy, C., Tighe, M., Moody, P. and Bell, M. (2014). Dilute acid extraction is a 505 useful indicator of the supply of slowly available phosphorus in Vertisols. *Soil Science Society of America Journal* 78, 139–146.

McLaughlin, M.J., McBeath, T.M., Smernik, R., Stacey, S.P., Babasola, A. and Guppy, C. (2011). The chemical nature of P accumulation in agricultural soils – implications for fertiliser management and design: an Australian perspective. *Plant and Soil* 349, 69–87.

Misstear, B., Brown, L. and Daly, D. (2009). A methodology for making initial estimates of groundwater recharge from groundwater vulnerability mapping. *Hydrogeology Journal* 17, 275–285.

Moloney, T., Fenton, O. and Daly, K. (2020). Ranking connectivity risk for phosphorus loss along agricultural drainage ditches. *Science of the Total Environment* 703, 134556.

Monaghan, R.M. and Smith, L.C. (2012). Contaminant losses in overland flow from dairy farm laneways in southern New Zealand. *Agriculture, Ecosystems & Environment* 159, 170–175.

Moore, M.T., Kröger, R., Locke, M.A., Cullum, R.F., Steinriede Jr., R.W., Testa III, S., Lizotte Jr., R.E., Bryant, C.T. and Cooper, C.M. (2010). Nutrient mitigation capacity in Mississippi Delta, USA drainage ditches. *Environmental Pollution* 158, 175–184.

Murnane, J.G., Fenton, O. and Healy, M.G. (2018). Impacts of zeolite, alum and polyaluminum chloride amendments mixed with agricultural wastes on soil column leachate, and CO_2 and CH_4 emissions. *Journal of Environmental Management* 206, 398–408.

Nguyen, L. and Sukias, J. (2002). Phosphorus fractions and retention in drainage ditch sediments receiving surface runoff and subsurface drainage from agricultural catchments in the North Island, New Zealand. *Agriculture, Ecosystems & Environment* 92, 49–69.

Nguyen, L., Nagels, J. and Sukias, J.P.S. (2002). Faecal contamination and the removal of Escherichia coli (*E. coli*) in drainage ditches. In Currie, L.D. and Loganathan, P. (eds), *Dairy Farm Soil Management*. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, pp. 261–266.

O'Flynn, C.J., Fenton, O. and Healy, M.G. (2012). Evaluation of amendments to control phosphorus losses in runoff from pig slurry applications to land. *CLEAN: Soil, Air, Water* 40, 164–170.

Oudshoorn, F.W., Kristensen, T. and Nadimi, N.S. (2008). Dairy cow defecation and urination frequency and spatial distribution in relation to time-limited grazing. *Livestock Science* 113, 62–73.

Outram, F.N., Cooper, R.J., Sünnenberg, G., Hiscock, K.M. and Lovett, A.A. (2016). Antecedent conditions, hydrological connectivity and anthropogenic inputs: factors affecting nitrate and phosphorus transfers to agricultural headwater streams. *Science of the Total Environment* 545–546, 184–199.

Penn, C.J., Bryant, R.B., Kleinman, P.J.A. and Allen, A.L. (2007). Removing dissolved phosphorus from drainage ditch water with phosphorus sorbing materials. *Journal of Soil and Water Conservation* 62, 269–276.

Penn, C.J. and Bowen, J.M. (2017). Phosphorus removal structures as a short-term solution for the problem of dissolved phosphorus transport to surface waters. In *Design and Construction of Phosphorus Removal Structures for Improving Water Quality*. Springer International, Cham, Switzerland, pp. 35–63.

Penn, P., Chagas, I., Klimeski, A. and Lyngsie, G. (2017). A review of phosphorus removal structures: how to assess and compare their performance. *Water* 9, 583.

Penn State Center for Dirt and Gravel Roads Studies (2019). *Technical Bulletins*. Available online: www.dirtandgravel.psu.edu/general-resources/technical-bulletins (accessed 13 February 2020).

Praat, J. P., Macintosh, K. A., Brown, L. and Burkitt, L. (2020). Effect of riparian widths for reducing contaminants from dairy-farm laneways. Paper presented at Farmed Landscape Research Centre Workshop, New Zealand Hydrological Society Conference, Massey University, New Zealand.

Rice, P., Daly, K., Tuohy, P., Murnane, J.G., Nag, R. and Fenton, O. (2022). Evaluating connectivity risk of farm roadway runoff with waters – development and sensitivity analysis of a semi quantitative risk model. *Science of the Total Environment* 851, 158114. https://doi.org/10.1016/j.scitotenv.2022.158114.

Roberts, W.M., Gonzalez-Jimenez, J.L., Doody, D.G., Jordan, P. and Daly, K. (2017). Assessing the risk of phosphorus transfer to high ecological status rivers: integration of nutrient management with soil geochemical and hydrological conditions. *Science of the Total Environment* 589, 25–35.

Sandström, S., Futter, M.N., Kyllmar, K., Bishop, K., O'Connell, D.W. and Djodjic, F. (2020). Particulate phosphorus and suspended solids losses from small agricultural catchments: links to stream and catchment characteristics. *Science of the Total Environment* 711, 134616.

Scheetz, B.E. and Bloser, S.M. (2009). *Environmentally Sensitive Maintenance on Agricultural Roads to Reduce Nutrient and Sediment Pollution in the Kishacoquillas Watershed.* Pennsylvania State University, PA. Available online: https://dirtandgravel.psu.edu/wp-content/uploads/2022/03/CIG_Final_Report.pdf (accessed 9 January 2024).

Schulte, R.P.O., Creamer, R.E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C. and O'hUallachain, D. (2014). Functional land management: a framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environmental Science & Policy* 38, 45–58.

Shore, M., Murphy, P.N.C., Jordan, P., Mellander, P.-E., Kelly-Quinn, M., Cushen, M., Mechan, S., Shine, O. and Melland, A.R. (2013). Evaluation of a surface hydrological connectivity index in agricultural catchments. *Journal of Environmental Modelling & Software* 47, 7–15.

Shore, M., Jordan, P., Mellander, P.-E., Kelly-Quinn, M. and Melland, A.R. (2015a). An agricultural drainage channel classification system for phosphorus management. *Agriculture, Ecosystems & Environment* 199, 207–215.

Shore, M., Jordan, P., Mellander, P.-E., Kelly-Quinn, M., Daly, K., Sims, J.T., Wall, D.P. and Melland, A.R. (2015b). Characterisation of agricultural drainage ditch sediments along the phosphorus transfer continuum in two contrasting headwater catchments. *Journal of Soils and Sediments* 16, 1643–1654.

Smith, D.R. and Pappas, E.A. (2007). Effect of ditch dredging on the fate of nutrients in deep drainage ditches of the midwestern United States. *Journal of Soil and Water Conservation* 62, 252–261.

Srinivasan, M.S. and McDowell, R.W. (2009). Identifying critical source areas for water quality: 1. Mapping and validating transport areas in three headwater catchments in Otago, New Zealand. *Journal of Hydrology* 379, 54–67.

Teagasc (2017). *Farm Roadways – Design and Construction*. Available online: www.teagasc.ie/publications/2017/dairy-farm-infrastructure-handbook.php (accessed 25 January 2024).

Thomas, I.A., Jordan, P., Mellander, P.-E., Fenton, O., Shine, O., Ó Huallacháin, D., Creamer, R., McDonald, N.T., Dunlop, P. and Murphy, P.N.C. (2016). Improving the identification of hydrologically sensitive areas using LiDAR DEMs for the delineation and mitigation of critical source areas of diffuse pollution. *Science of the Total Environment* 556, 276–290.

Tolomio, M. and Borin, M. (2018). Water table management to save water and reduce nutrient losses from agricultural fields: 6 years of experience in North-Eastern Italy. *Agricultural Water Management* 201, 1–10.

Tosakana, N.S.P, Van Tassell, L.W., Wulfhorst, J.D., Boll, J., Mahler, R., Brooks, E.S. and Kane, S. (2010). Determinants of the adoption of conservation practices by farmers in the Northwest Wheat and Range Region. *Journal of Soil and Water Conservation* 65, 404–412.

Wall, D., Jordan, P., Melland, A.R., Mellander, P.E., Buckley, C., Reaney, S.M. and Shortle, G. (2011). Using the nutrient transfer continuum concept to evaluate the European Union Nitrates Directive National Action Programme. *Environmental Science and Policy* 14, 664–674.

Wall, D.P., O'Sullivan, L., Debeljak, M., Trajanov, A., Schroder, J., Bugge Henriksen, C., Creamer, R.E., Cacovean, H. and Delgado, A. (2017). *Key Indicators and Management Strategies for Water Purification and Regulation*. Technical Public Report D3.2, Landmark Project.

Welch, E.W., Frederick, J. and Marc-Aurele Jr., P.E. (2001). Determinants of farmer behaviour: adoption of and compliance with best management practices for nonpoint source pollution in the Skaneateles Lake Watershed. *Lake and Reservoir Management* 17, 233–245.

Wemple, B.C. and Jones, J.A. (2003). Runoff production on forest roads in a steep, mountain catchment. *Water Resources Research* 39(8). https://doi.org/10.1029/2002WR001744

White, S.L., Sheffield, R.E., Washburn, S.P., King, L.D. and Green, J.T. (2001). Spatial and time distribution of dairy cattle excreta in an intensive pasture system. *Journal of Environmental Quality* 30, 2180–2187.

Woli, K.P., David, M.B., Cooke, R.A., McIsaac, G.F. and Mitchell, C.A. (2010). Nitrogen balance in and export from agricultural fields associated with controlled drainage systems and denitrifying bioreactors. *Ecological Engineering* 36, 1558–1566. https://doi.org/10.1016/j.ecoleng.2010.04.024

Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R. and Kellagher, R. (2015). *The SuDS Manual (C753F)*. CIRIA, London.

Abbreviations

ASSAP	Agricultural Sustainability Support and Advisory Programme
CSA	Critical source area
DRP	Dissolved reactive phosphorus
LAWPRO	Local Authority Waters Programme
NTC	Nutrient transfer continuum
SS	Suspended sediment

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

epa Research

EPA Research

Webpages: www.epa.ie/our-services/research/
LinkedIn: www.linkedin.com/showcase/eparesearch/
Twitter: @EPAResearchNews
Email: research@epa.ie